THE EFFECTS OF REPRESENTATION AND ANALOGY ON ENGINEERING IDEA GENERATION

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THE EFFECTS OF REPRESENTATION AND ANALOGY ON ENGINEERING IDEA GENERATION

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God Almighty has brought me;
the love of family has supported me;
the joy of friendship has uplifted me,
and with the guidance
given by Jesus Christ,
I have arrived!

(Author unknown)

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SUMMARY

The use of examples in idea generation is a common practice intended to provide inspiration from existing products to the designing of new ones. Examples can be taken from the Internet, engineering textbooks, analogical databases, literature, a company's prior designs, or from a competitor company, prior work by the designer, and many other sources. These examples are represented in various ways, such as hand sketches, pictures, computer-aided designs (CAD), physical models, activity diagrams, shape grammars, text descriptions, etc. Design representations can also be broken down by function in the form of functional models and decompositions. The use of these visual or physical examples allows engineers to get a clearer picture of how a design or component works and enables them to have a better understanding of the overall design and function. Each representation has inherent advantages and disadvantages in the way that they portray a design.

Examples are sources for analogies. Analogies from nature, where biological organisms have solved challenging problems in novel ways, are very useful in engineering idea generation and solution retrieval. This process is called biologically inspired design. Engineers often use biologically inspired design to solve problems while increasing creativity and expanding the solution space. Using this method, engineers are able to learn from nature and apply biological principles to real world engineering problems to make effective designs and produce innovative solutions.

It is important to have a clearer understanding of how the use of the representations and characteristics of examples as external stimuli affect the idea generation process in engineering design. Understanding these processes will be invaluable in offering guidelines for how engineering design should be done and what types of external stimuli should be used to allow for innovation and creativity to be enhanced.

This dissertation presents four studies that focus on understanding ways that examples can be used to improve the idea generation process. Three of these studies focus on how the representation of externally imposed examples, which may be used as analogues, influences creativity during idea generation while also minimizing design fixation, which occurs when designers adhere to the features of their own initial design solutions or to features of existing examples. The fourth study focuses on the use of examples as sources for analogical mapping and how these examples produce innovative solutions during idea generation.

The first study compares CAD, sketch, and photograph representation presented individually. The second study compares CAD and sketch representation presented together, and the third study examines function tree and sketch representations. The fourth study looks at the real-world context and impact of examples used as sources for analogical mapping to inspire innovative solutions. The results of the studies show that CAD representations of good examples are effective in allowing engineers to identify the key working principles of a design and help to develop higher quality design concepts. CAD representations also cause more fixation to the example's features. Function trees do not cause nor break fixation compared to a control condition, but do reduce fixation compared with sketches. Biological examples can be successfully used as analogues during engineering idea generation to create novel and effective design solutions to relevant and real-world engineering problems.

CHAPTER 1

INTRODUCTION

Creativity is sought everywhere: in the arts, entertainment, business, mathematics, engineering, medicine, the social sciences, and the physical sciences (Perl, 2008). In engineering especially, there is a need to create innovative and novel products and ideas, this drives profits in industry and groundbreaking findings in the research field (CITEC Business Solutions, 2011; Lafley & Charan, 2008). In order for creativity to be prevalent in engineering, design research that investigates and develops methods, and also evaluates them, is crucial for both academia and industry. This dissertation specifically studies how the representations of externally imposed examples affect performance in idea generation. I also look at how the use examples as sources for analogical mapping in engineering design influence idea generation.

Many phenomena may hinder creativity in engineers, one of which includes design fixation (Jansson & Smith, 1991). When engineers design, it is common for them to use examples to inspire new ideas during early concept generation. However, copying the features from these examples may hinder the engineer's own creativity and limit their solution space. Fixation to a designer's own initial ideas can also occur. Design fixation can happen to individuals, teams, whole firms (especially large ones), and to entire industries (Crismond & Adams, 2012). Studies in engineering and psychology have shown that design fixation is exhibited by novice and experts engineers alike (Cardoso & Badke-Schaub, 2011; Cardoso, Badke-

Schaub, & Luz, 2009; Linsey, et al., 2010; Ullman, Dietterich, & Stauffer, 1988; Ullman, Stauffer, & Dietterich, 1987; Viswanathan & Linsey, 2011; Ward, 1994; Wiley, 1998). Youmans and Arcizewski (Youmans & Arciszewski, 2012) describe this limitation as anchoring a designer's creative thoughts and actions in the past at the stage of design when creative thinking may have its greatest effect. With our rapidly changing world, talented engineers with the skills to provide innovative products, systems and services, are needed more than ever (Duderstadt, 2008). Since design fixation is one of the challenges faced by engineers, as it limits creativity, it is important to investigate ways to mitigate this fixation in engineers, both novices and experts, during idea generation.

Various types of representations are used during the conceptual stage of the engineering idea generation process, but little attention has been paid to how the representations of these examples affect creativity, innovation, and design fixation (Jansson & Smith, 1991). Since the emergence of the Internet, examples for engineers to use in design and idea generation have become readily available and accessible within mere seconds. These examples are usually presented randomly through search engines with little attention paid to grouping these examples found in the search results by representation. This is not surprising since little attention has been paid to analyzing externally imposed examples by representation. This dissertation will do that, and also contribute to the existing work by analyzing CAD, sketch, photo and function tree representations. Computer tools for analogy or analogical databases have recently emerged to help designers find relevant analogies or examples, and to help them map and transfer the analogies appropriately, this is discussed further in the literature review chapter in this dissertation. These tools however, do not group or filter the images of the analogies by representation. The findings of the studies in this dissertation will be able to offer recommendations for how these analogical databases should be structured and what types of features would be beneficial for the designer while using a database to search for useful analogies.

Drawing inspiration from examples by analogy can be a powerful tool for innovative design during conceptual idea generation (Chan, et al., 2011). Design by analogy is a method in which designers apply appropriate and relevant features from existing example solutions to solve design problems (Bhatta, Goel, & Prabhakar, 1994; Goel, 1997; Goel & Bhatta, 2004; Qian & Gero, 1996). The examples are the sources for analogical mapping to a different target domain. Thus, analogies use examples as sources. It is however important to note that the converse is not true, i.e. examples alone do not make analogies.

Design by analogy is a very innovative method that engineers use to solve problems while increasing creativity and expanding the solution space. In engineering design, analogies are often used in conceptual design to aid in generating new and novel design ideas and for developing innovative solutions (Benyus, 1997; Eckert, Stacey, & Earl, 2005; Goel, 1997; Helms, Vattam, & Goel, 2009; Leclercq & Heylighen, 2002; Vattam, Helms, & Goel, 2007; Vattam, Helms, & Goel, 2008; Vincent & Mann, 2002; Vogel, 2000; Wilson, Rosen, Nelson, & Yen, 2010), the use of analogies also aims to enhance creativity (Goel, 1997; Mak & Shu, 2004; Shu, Ueda, Chiu, & Cheong, 2011; Vattam, Helms, & Goel, 2009). Designers can use analogies by drawing inspiration from biology or nature by implementing biologically inspired design. Biologically inspired design is a type of analogical design where inspiration is taken from biology to solve engineering problems. Engineers are able to use their engineering knowledge to translate these biological solutions into technologies and products that meet real world challenges.

In this dissertation, four studies focused on improving idea generation are presented. Three studies look at the effects of the representation of examples on engineering idea generation and creativity, and the fourth study looks at how the examples used as source analogues during analogical design influence engineering idea generation and produce innovative solutions.

1.1 Engineering Design Representations

A wide variety of representations is implemented in mechanical engineering design. These representations may be sketches, line drawings, photographs, computer–aided designs (CAD), functional models, or text descriptions. Larkin and Simon (1987) explore the use of diagrams in problem solving and conclude that effective diagrammatic representations (e.g. CAD, sketches, photographs, line-drawings, etc.) hold many advantages over textual representations. They concluded that diagrams group all useful information together, allowing for further processing and thus, avoiding an arduous search for the elements needed to make a problem-solving inference. This grouping of information also allows the problem-solver to avoid having to match and understand symbolic labels that purely textual information may give. Likely due to these disadvantages of textual descriptions, diagrammatic representations are more popular for representing engineering ideas and designs.

Sketching has been a popular method for early idea conceptualization. When engineers are faced with a problem (trivial or non-trivial) they instinctively reach for a pencil and paper (Jenkins & Martin, 1993). Sketching allows ideas to be quickly and effectively explored and communicated, and is fundamental to ideation and design (Rodhe, 2011; Tohidi, Buxton, Baecker, & Sellen, 2006). Traditional disciplines such as industrial design, graphic design, architecture, and also mechanical engineering, make extensive use of sketches to develop, explore, communicate, and evaluate ideas (Tohidi, et al., 2006). Figure 1.1 shows an example of sketches being used in the conceptual stage of design. However, with changes in technology, CAD renderings and photographs are increasing in use over sketching. With the advent of computer modeling and drafting packages, i.e., CAD, which are readily available and intuitive, engineering students tend to sketch less (Grenier, 2008; Schmidt, Hernandez, & Ruocco, 2012; Ullman, Wood, & Craig, 1990). Grenier's study (2008) also showed that students did not choose sketching as a form of design during the early stages of conceptualization. This result is also seen in a study by Westmoreland et al. (2011) where visual representations (sketches, line drawings, CAD, and photographs) are analyzed for their usage in Capstone Design. Westmoreland found that students rarely used sketches until specifically prompted. Students are also increasingly reluctant to hand in rough sketches when they can quickly transform them to CAD (Westmoreland, et al., 2011). Photographs are increasingly popular due to the availability of digital cameras including those on smartphones and due to the ability to copy images off the Internet.

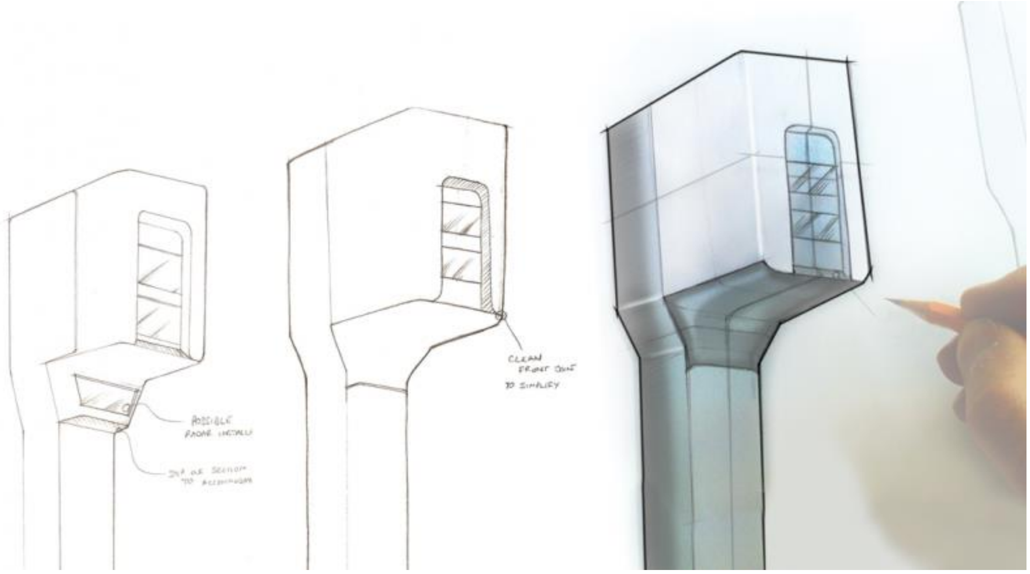


Figure 1.1: Various sketches of the Smart Pole used to communicate ideas and solutions with clients early in the design process (Crown International, 2014)

Other useful forms of representing mechanical engineering designs are as functional models and decompositions. Dym , Little, and colleagues (Dym, Little, Orwin, & Spjut, 2004) describe engineering design as the set of decision making processes and activities used to determine the form of an object given the functions desired by the customer. Conceptualizing, defining, or understanding a product or system in terms of function is a fundamental aspect of engineering design (Otto & Wood, 2001; Pahl & Beitz, 1996; Pahl, Beitz, Feldhusen, & Grote, 2007; Ullman, 1992; Ulrich & Eppinger, 1995). Figure 1.2 and Figure 1.3 show various types of function models. Figure 1.2 shows a function tree of a wind energy collection system with all the functions of the system listed hierarchically, and Figure 1.3 shows a function structure of an electrical vibrating razor with the energy, material and signal (EMS) flows (Otto & Wood, 2001). Functional modeling provides an abstract yet direct method for understanding and representing a product's overall function

(Hirtz, Stone, McAdams, Szykman, & Wood, 2002). Functional models are used in the idea generation process as well as for enhancing existing products. Viola et al. (2012) state that functional models are advantageous when used in engineering idea generation because the abstract view of function trees fosters the search for alternative solutions thus avoiding biased ones. Ullman (1992) also explains that engineers are able to explore and discover more solutions to engineering problems by first mapping customer needs to functional descriptions. These descriptions are then used to generate and select concepts that best satisfy underlying functional requirements, leading to solutions that are more robust. By first satisfying the functional requirements of customer needs, the designer is less prone to focus on the physical features of the design and the features of existing designs (Caldwell & Mocko, 2012).

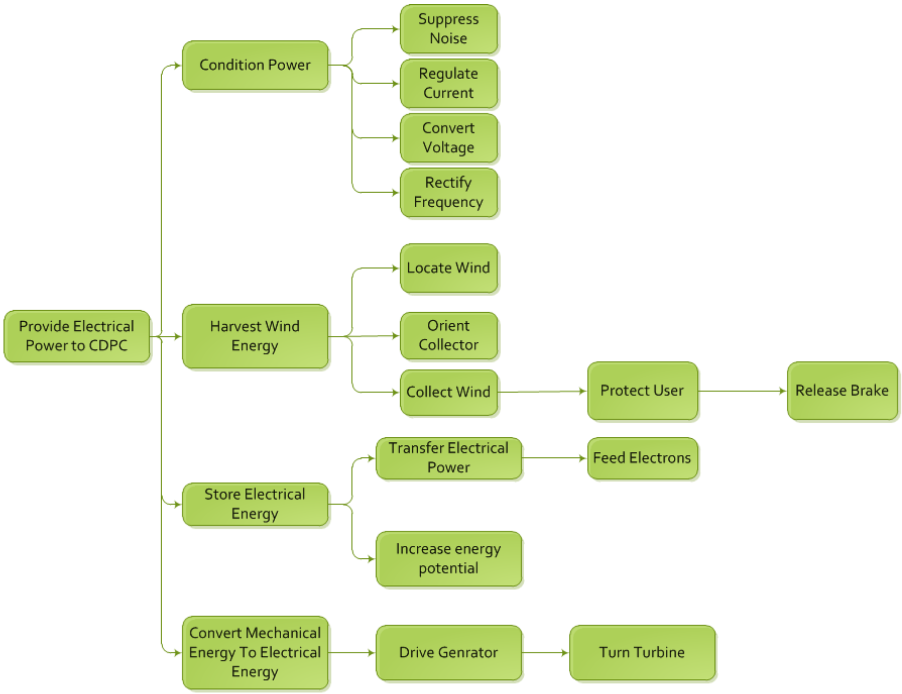


Figure 1.2: Function tree of a wind energy collection system that stores to an energy bank (EDGE - The Engineering Design Guide and Envrionment, 2012)

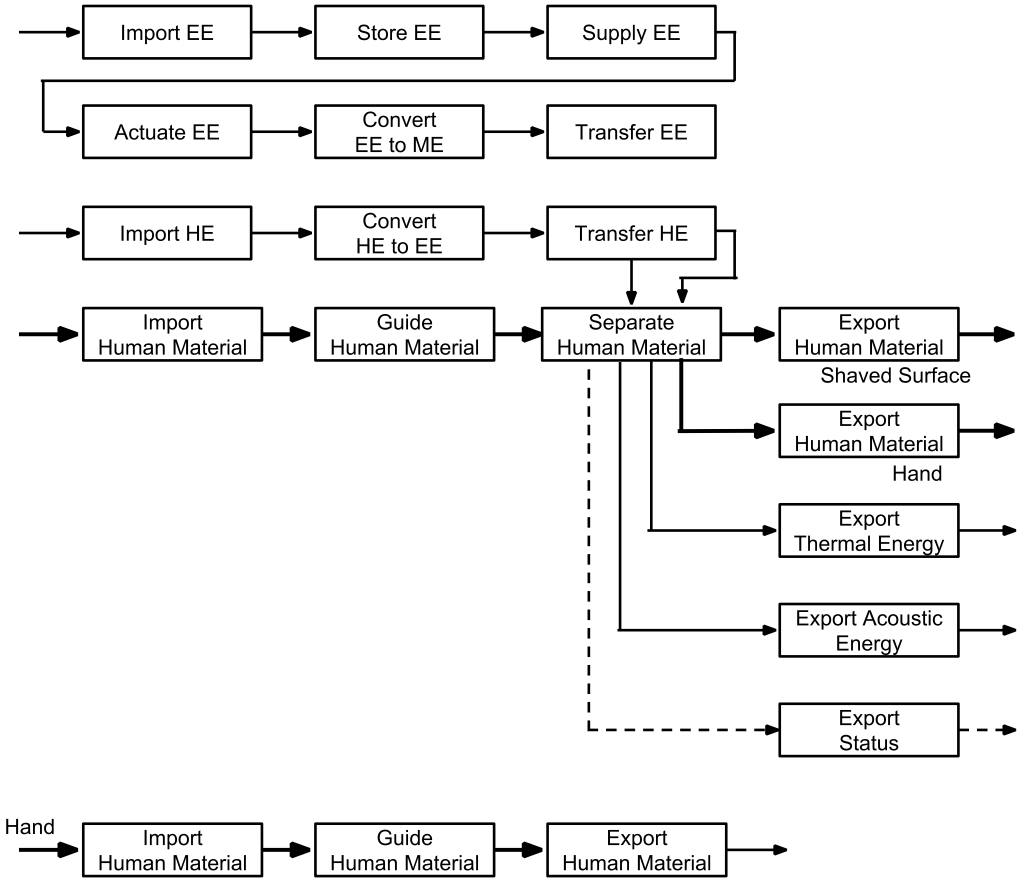


Figure 1.3: Function structure of a vibrating razor (Oregon State University Design Lab, 2009)

The various representations that have been discussed thus far allow engineers to convey information to other designers, and appear in the examples that designers use when they are developing new ideas. Studies have shown that designers fixate to examples given to them whether they are in the form of sketches, line drawings, photographs, or physical models (Cardoso & Badke-Schaub, 2011; Cardoso, et al., 2009; Christensen & Schunn, 2005; Kiriyama & Yamamoto, 1998; Linsey, et al., 2010; Purcell & Gero, 1996; Viswanathan & Linsey, 2011;

Viswanathan & Linsey, 2012a, 2012b; Viswanathan & Linsey, 2013a; Viswanathan & Linsey, 2010). Previous studies on design fixation have compared other representations, including line drawings to photographs (Cardoso & Badke-Schaub, 2011; Cardoso, et al., 2009), sketches to physical models (Viswanathan & Linsey, 2013b; Youmans, 2011), and sketches to textual representations (McKoy, Vargas-Hernández, Summers, & Shah, 2001). All of these studies have also presented poor examples where design fixation hurts the process. Two of the studies in this dissertation explore the use of effective or good examples in studying design fixation. Using a good example allows for other trends to be explored, such as how effective principles are identified in a design as seen in the first study. The first study uses a good example to explore CAD, sketch and photo representations presented individually and how they affect design fixation and creativity during idea generation, and the second study in this dissertation uses a good example to explore CAD and sketch representations presented together to explore their effects during idea generation.

1.2 The Use of Analogies in Engineering Design

Analogies are also often used in the idea generation process to allow for domains other than engineering to be explored for effective solutions. The specific type of analogy explored in this dissertation is biologically inspired design, where examples from biology are used as source analogues. Biologically inspired design uses biological solutions to solve engineering problems in a different and innovative way. In the conceptual stage of engineering design, designers are tasked with searching for innovative and novel ideas. However, because humans are imperfect search engines (Busby & Lloyd, 1999), they tend to limit their solution space or focus on a narrow range of solutions approaches (Wilson, et al., 2010) and overlook valuable solutions (Perttula, 2006). To overcome this limitation, various techniques are used during idea generation to explore the solution space more effectively and efficiently. One of these techniques includes drawing inspiration from solutions in biology or nature. Biologically inspired design has been very useful in solving engineering problems in an innovative and new way. Figure 1.4 shows an example of a biologically inspired design in the development of the Bionic Handling Assistant by Festo (2014) which won the German Future Award in 2010 (The Robot Report, 2010). It was modeled on the trunk of an elephant, and has 11 degrees of freedom, which allows for a variety of task-specific travel paths.

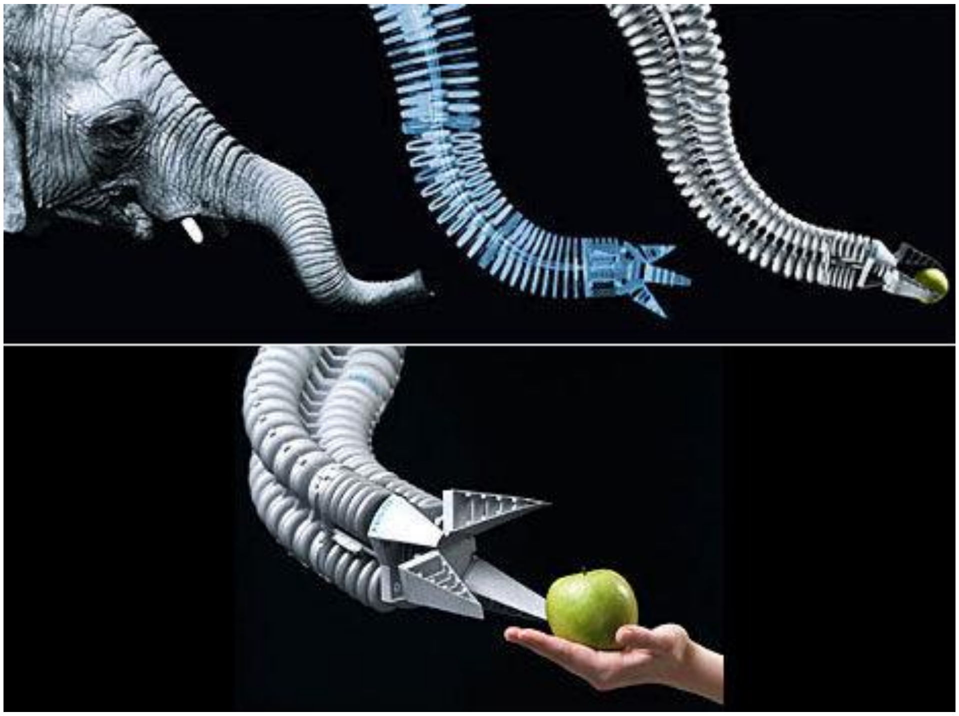


Figure 1.4: Robotic arm design inspired by an Elephant Trunk (Web Ecoist, 2014c)

The Japanese bullet train was redesigned to solve a loud booming noise problem that it made when it exited tunnels. Inspiration was drawn from a Kingfisher bird (Figure 1.5), which dives into the water from the air without making a splash (Earth Sky, 2012; Web Ecoist, 2014a). The front of the trains were redesigned to mimic the beak of the Kingfisher, this solved the noise problem and improving the fuel efficiency by 20% (Web Ecoist, 2014b).

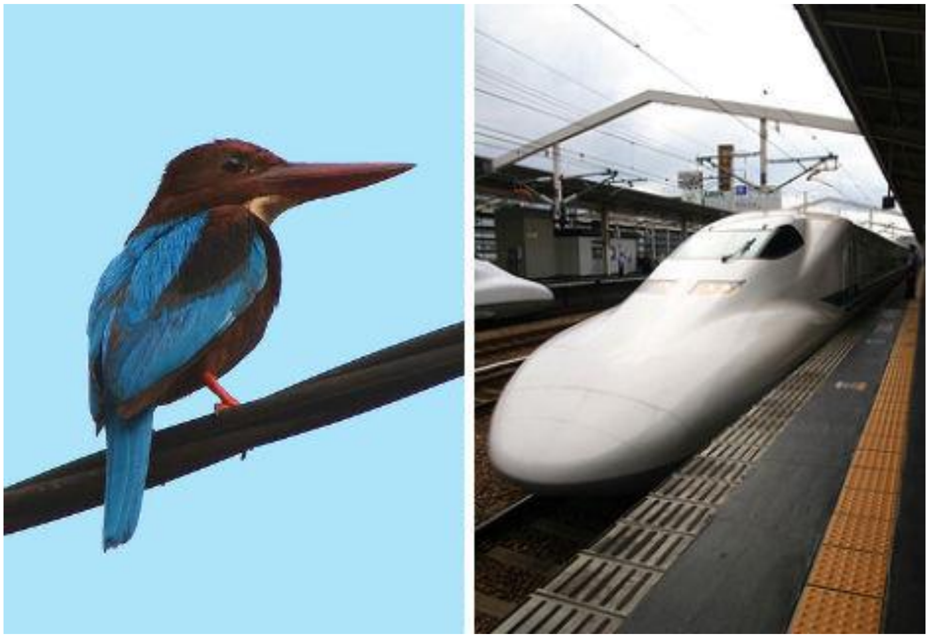


Figure 1.5: The nose of the Japanese bullet train is designed like a Kingfisher Beak (Web Ecoist, 2014b)

The fourth study in this dissertation explores the use of examples as biologically inspired analogues during the idea generation process for a design solution that will reduce the installation costs of solar photovoltaic (PV) systems.

1.3 Research Questions

The studies presented in this dissertation aim to provide insight into the use of examples in idea generation during conceptual design. This dissertation investigates and explains how and why externally imposed examples may affect performance in mechanical design idea generation. I look at whether there are specific ways that examples should be represented during idea generation and how that affects design fixation and creativity. I also look at how examples used during analogical mapping aids the idea generation process and how they produce innovative solutions.

The following research questions are proposed:

RQ1. In idea generation, what type of example representations aid in reducing design fixation while increasing the generation of creative and novel solutions?

RQ2. When given examples represented in different forms (CAD or a sketch), will engineers be biased or fixated towards one representation over the other regardless of the type of example?

RQ3. Do function trees of designs help to mitigate fixation during idea generation? In addition, do they improve the quality of ideas?

RQ4. How do the use of examples as analogues during biologically inspired design aid the idea generation process in engineering to produce effective design concepts in a real-world context?

In response to these research questions, three controlled experiments and one protocol study were performed to gain insights on how representation and analogy influence idea generation in engineering. The corresponding hypotheses for these research questions are also discussed in each of the studies.

1.4 Reader's Guide

The remainder of this dissertation is organized as follows. Chapter 2 describes related work on idea generation, design fixation, functional modeling in idea generation, design by analogy, and biologically inspired design. Additionally, I provide a link between these previous studies and my dissertation studies. Chapter 3 describes the first study, which looks at how CAD, sketch and photograph representations presented individually affect design fixation and creativity. Chapter 4 describes the second study, which expands on the first by presenting CAD and sketch representations, presented together and individually, to see how they affect design fixation and creativity. The third study is outlined in Chapter 5; this study looks at design fixation and creativity in terms of function trees and their effectiveness on mitigating fixation. Chapter 6 describes the fourth and final study, which looks at the use of examples during idea generation from a biologically inspired approach. Chapter 7 provides overall conclusions, which include contributions of the results from the studies as well as limitations. A discussion of future work is also briefly described in this chapter. Appendices and references follow.

CHAPTER 2

LITERATURE REVIEW

Idea generation can be defined as the process of generating, developing, and communicating ideas, where an idea is understood as a basic element of thought that can either be visual, concrete, or abstract (Jonson, 2005). Conceptual design, of which idea generation is an essential part, is the front-end process that occurs very early in the engineering design process. The conceptual design phase is the stage at which possible solution concepts and ideas can be determined (Pahl & Beitz, 1996), and also where feedback can be elicited from end users or design stakeholders to decide upon which ideas will be further developed or pursued (Schrage, 1999). This process is achieved by abstracting the essential problem or design requirement(s), establishing function structures, searching for suitable working principles, and then combining those principles into a working design (Pahl & Beitz, 1996).

Idea generation in the design process first begins in the mind's eye (Ferguson, 1992). The representation of ideas directly influences idea generation. A number of different representation options are available to designers, but little is known about how they influence design fixation. In this chapter, the differences among various representations used in idea generation are presented and discussed.

2.1 Representations in Idea Generation

During the idea generation process, examples of existing solutions are commonly used to provide inspiration to designers. These representations could be in the form of sketches, line drawings, CAD, photographs, or even verbal and textual representations. Each conveys different types of information. The definitions of these visual representations are given below.

Sketch – A sketch is a freehand drawing made without the use of drawing instruments (John, 2009; Lieu & Sorby, 2008).

Line drawing – A line drawing is an image made up of straight and curved lines created with drawing instruments (traditional drafting) or with a computer (John, 2009).

CAD – A computer-aided design is a visual image created with a formal computer-aided drawing software package (e.g., Pro/ENGINEER, Solid Works, and AutoCAD). These images can be also be modified, analyzed and optimized with the specialized software package (Sarcar, Rao, & Narayan, 2008; Westmoreland, et al., 2011).

Photograph – A photograph is an image that is produced with the use of a camera. The image is an exact replica of what the human eye would perceive at an instant in time (Westmoreland, et al., 2011).

It is important to note that these representations might be used in two modes during idea generation. The first mode of representation is external, where examples are shown to design engineers as stimuli for inspiration in the design task. The second mode of representation is how the designers represent their ideas, i.e., self-generated representations. This dissertation is only concerned with varying external representations to see how they influence design fixation. The self-generated mode is kept constant (as sketches).

Sketching is a popular method for developing and representing ideas. It is commonly used together with text or written language in group idea generation meetings (Van der Lugt, 2005). Various studies have been done on the role of sketching in design (Macomber & Yang, 2011; Yang, 2009; Yang & Cham, 2007) and state that sketching during idea generation improves the overall quality and realism of the design. Even though there has been a decline in the use of sketching among engineering students, it does offer advantages over other representations (Westmoreland, et al., 2011). A critical part of generating concepts, sketching promotes creative thought (Goel, 1995; Goldschmidt, 1994). Sketching is advantageous because it is economical, simple, and easy to correct and revise (Jonson, 2002). It also allows the designer to obtain immediate visual and kinesthetic feedback (Contero, Varley, Aleixos, & Naya, 2009).

One advantage of sketches is its inherent ambiguity (Contero, et al., 2009; Goel, 1995; Jonson, 2002; Stacey, Eckert, & McFadzean, 1999). Sketches are inexact in nature (Jenkins & Martin, 1993), and thus lack regularity and contain a certain type of looseness or “sketchiness,” which makes it prone to having different interpretations. Rather than inducing uncertainty or confusion, ambiguity in design sketches can be a source of creativity as it allows for the re-perceiving and re-interpreting of figures or images (Tversky, et al., 2003), or for alternative interpretations by another designer or team member (Shah, 1998). Tversky et al. (2003) explain that sketches hold the created constructions in view of the designer, freeing the mind to examine and evaluate. Their findings also show that novice and experienced designers make new inferences from their own sketches.

In contrast to a sketch's potential for ambiguity, photographic and CAD representations possess richer representation. Photographs usually contain colors and visual depth. The same can be said for CAD representations, which in addition have a cleaner, more defined look. Due to the fact that CAD and photographic representation are by nature more exact representations, the idea they are trying to convey is less subjective to a group of observers (Veisz, Joshi, & Summers, 2012), i.e., as the fidelity of the representation increases, the ambiguity decreases. CAD and photo representations also provide a richer representation compared to simpler schematic representations such as sketches and line drawings. CAD representations can be advantageous over a photograph because CAD models can contain more dimensional information, show hidden lines, and display hidden components. However, there is research that states that CAD tools, (when used to create designs) have the potential to negatively impact the design process (Robertson, Walther, & Radcliffe, 2007; Veisz, et al., 2012). Robertson, in multiple studies (Robertson & Radcliffe, 2009; Robertson, et al., 2007) (which comprised of an observational case study of a small engineering team, and an extensive survey of 255 CAD users), found that CAD tools may limit the designer through interfering with the designer's intent, i.e., the CAD program constrains the thinking and problem solving of the designer (Robertson & Radcliffe, 2009; Robertson, et al., 2007). In addition, these studies found that CAD tools might cause premature fixation when the designer resists changing complex or highly detailed models. Robertson et al. also warn that the overuse of CAD tools may decrease motivation and creative abilities. Another disadvantage that CAD may have compared to sketching is that digital design is still currently slower than sketching (Thilmany, 2006).

Studies have shown that the amount and type of information that designers access when interpreting different types of representations vary (Casakin & Goldschmidt, 1999; Kavakli & Gero, 2001, 2002; Kokotovich & Purcell, 2000; Menezes & Lawson, 2006; Suwa & Tversky, 1997). A few studies have also examined the impact of design representations on customers. Schumann et al. (1996) surveyed architects and architectural students and found that they preferred to show initial designs to clients using sketches and final versions in CAD. They also discussed the fact that sketches encourage discourse about a design while CAD tends to imply that the image can no longer be altered. A study by Macomber and Yang (2011) examined customer responses and preference of objects drawn in styles ranging from rough hand sketches to rendered CAD drawings. This study showed that the subjects preferred hand drawings with the highest level of finish to the CAD drawings. They also noted that the complexity and familiarity of an object influenced perceptions. This study did not capture the usefulness of these various representations but rather merely a visual preference. It is entirely possible that the preference and usefulness of various representations do not necessarily correlate. This second study in this dissertation will measure the differences in an engineer's or designer's behavior when they use various representations of examples to design.

The studies discussed so far have explored how a designer's creativity is enhanced or limited by what representations they use in their idea generation or design process, and how different external representations influence design and provide information to the viewer. The design fixation studies in this dissertation specifically focuses on the latter and its influence on design fixation, i.e. how external representations affect ideation and creativity.

2.2 Functional Models in Idea Generation

Functional models in engineering design represent critical aspects of the design that need to be met in order to satisfy customer needs. By mapping customer needs first to function, more solutions may be systematically explored (Ullman, 1992). Function trees, a type of functional model, are hierarchical structures that start from high-level functional requirements and work through to lower-level detailed functions (Otto & Wood, 2001; Pahl & Beitz, 1996). Function trees and models are often used in the conceptual stages of design because they encourage the designer to focus on the intended use and purpose of product rather than on the physical solution (Caldwell & Mocko, 2012). This could prove to be advantageous by allowing designers not to focus on or to *de-fixate* from specific features. However, this has not been tested; the third study in this dissertation will do so. Pahl and Beitz (2007) also suggest that functional models may allow designers to better explore the solution space by allowing functions to be linked in several ways, e.g., function trees, function structures/function flow diagrams (Otto & Wood, 2001), and functional analysis and allocation (Manning, 2013).

Function trees allow a design to be represented in a functional view as opposed to a physical view, e.g., CAD, sketch, photo, etc. These two complimentary views can convey different information. The functional view focuses on *what* the system must do to produce the required operational behavior, and the physical view focuses on *how* the system is constructed (Defense Acquisition Press, 2001). Function trees are advantageous in engineering design because they provide a well-represented graphical overview of the systems requirements and components (Viola, et al., 2012).

In systems engineering, more complex functional representations are used in the form of Functional Analysis and Allocation. Functional Analysis and Allocation is a process of translating system level requirements into detailed functional and performance criteria. The result of the process is a defined functional architecture with allocated system requirements that are traceable to each system function (Manning, 2013). When systems engineers design new products, they perform functional analysis to refine the new product's function requirements. Functional analysis uses functional flow block diagrams and timeline analysis resulting in a functional architecture that describes the system not just physically, but also in terms of functions and performance parameters. (Booth, Reid, & Ramani, 2013; Caldwell & Mocko, 2012; Caldwell, Sen, Mocko, & Summers, 2011; Caldwell, Thomas, Sen, Mocko, & Summers, 2012; Defense Acquisition Press, 2001). The functional analysis allows the engineers to: map the product's' functions to physical components; guarantee that all necessary components are listed (and that no unnecessary components are requested); and understand the relationships between the new product's components (Viola, et al., 2012).

Other functional representations have been studied and developed in engineering design research. Some examples include the Function-Behavior-Structure (FBS) model developed by Gero et al. (Gero, 1990; Gero & Kannengiesser, 2000, 2004, 2007), the Function Behavior-State (FBSt) model by Umeda et al. (Umeda, Ishii, Yoshioka, Shimomura, & Tomiyama, 1996; Umeda, Takeda, Tomiyama, & Yoshikawa, 1990; Umeda, Tomiyama, & Yoshikawa, 1995), and Structure-Behavior-Function (SBF model) by Goel (Goel & Bhatta, 2004; Goel & Murdock, 1996; Goel, Rugaber, & Vattam, 2009). These models were all developed independently. The FBS model represents the process of designing (Gero & Kannengiesser, 2000) where the basic assumption is the existence of three classes of variables required in the design process that are linked together by process which transform one class into another. The functions are the intended actions of the design, the structure refers to the specific form of the design, and the behavior refers to actual performance of the structure (Sen, 2009). Goel et al.'s SBF framework is a modeling language for a teleological description of complex systems (Gero & Kannengiesser, 2007) using structure, behavior, and function.

The types of functional representation studied in this dissertation are function trees. The functions used in function trees are in the form of action verbs that are necessary to system objectives. Due to the various levels that a function tree or model may have and the various degrees of abstraction or conceptual detail that may occur at each level (Booth, et al., 2013; Caldwell & Mocko, 2012; Caldwell, et al., 2012), a standardized set of function-related terminology known as the functional basis (Hirtz, et al., 2002; Stone & Wood, 2000) has been developed. The functional basis was developed to eliminate semantic confusion and to represent product function as a common language. Also to address the need for standard terminology in functional design, Kirschman and Fadel (1998) have also developed a taxonomy of elemental mechanical functions that may be used during functional decomposition. A standardized representation of functions for use in software and computer-based design has also been developed by Szykman et al. (1999).

A study by Chulvi et al. (2012) compared the creativity and time spent on three different design methods (brainstorming, SCAMPER, and Functional Analysis) in a protocol experiment involving Ph.D. students and design engineers. The results showed that the participants using the functional analysis method spent the most time in understanding tasks that needed to be analyzed. Chulvi concluded that functional analysis fosters the analysis of the design problem compared to the other two methods. Another study by Smith et al. (2012) compared different types of morphological charts, i.e., function trees combined with means of the functions (function means analysis is a method of modeling a product by the systematic decomposition of functions based upon the law of Hubka (Hubka & Eder, 1988), which states that casual relationships exist between functions and means (Robotham, 2002)). Some of the morphological charts in the study had more functions than means, while others had more means than functions. The results of the study showed that adding more functions to a morphological chart failed to improve results, which indicates that more elaborate function trees with unnecessary functions were not beneficial to the design process.

The third study in this dissertation will investigate the effectiveness of function models (function trees) as a type of representation in idea generation process for solving design problems.

2.3 Design Fixation

Design fixation refers to the blind, and sometimes counterproductive, adherence of designers to example features and to their own initial ideas (Jansson & Smith, 1991). Design fixation can also be thought of as the designer's reluctance (or inability, in some cases) to consider multiple strategies to formulate and solve a design need. (Condoor & LaVoie, 2007). The use of any example tends to make designers sensitive to the features of the example because they act as external stimuli. This is especially true for the visual representations such as the ones discussed, i.e., CAD, photo, and sketch (Goldschmidt & Smolkov, 2006). While the use of these visual examples is intended to provide inspiration to the designers, these examples tend to fixate them to the features of the example and tend to hinder their creativity. There have been numerous studies in engineering design and in psychology that have dealt with the topic of fixation (Cardoso & Badke-Schaub, 2011; Christensen & Schunn, 2005; Jansson & Smith, 1991; Linsey, et al., 2010; Purcell & Gero, 1996; Viswanathan & Linsey, 2010; Wiley, 1998; Youmans, 2011; Youmans & Arciszewski, 2012), all of which use various examples to induce fixation. Cognitive science studies suggest that limits of short-term and working memory may contribute to design fixation (Kohn & Smith, 2009; Smith, 1995).

Design fixation can happen to individuals, teams, whole firms (especially large ones), and to entire industries (Crismond & Adams, 2012), and studies in engineering and psychology have shown that both novice and experts are susceptible to design fixation (Cardoso & Badke-Schaub, 2011; Cardoso, et al., 2009; Jansson & Smith, 1991; Linsey, et al., 2010; Ullman, et al., 1988; Ullman, et al., 1987;

Viswanathan & Linsey, 2011; Ward, 1994; Wiley, 1998). Design fixation has been found to exist among engineers in their attachment to early solution ideas, concepts (Cross, 2001) and design decisions (Gero, 2011). Designers appear to hang on to their principal solution concept for as long as possible, even when detailed development of the scheme reveals unexpected difficulties and shortcomings in the solutions concept (Cross, 2001). Rowe (Rowe, 1991) also observed that initial designs dominantly influence subsequent problem-solving directions, and then even when severe problems are encountered, a considerable effort is made to make the initial idea work rather than stand back and adopt a fresh point of departure. A similar phenomenon was also found by Ullman (Ullman, et al., 1988) in protocol studies of experienced mechanical engineering designs. Designers in this study typically pursued a single design proposal even when problems arose. These designers also preferred to apply patches rather than develop a better idea or solution. Ball et al. also found the same trend of reluctance to change in students (Ball, Evans, & Dennis, 1994). They regarded this behavior as indicating fixation on initial concepts, and a reliance on a simple and sufficient design strategy in contrast to a more well-defined process of design optimization (Cross, 2001).

Fixation to examples by professional design engineers has been empirically verified by Jansson and Smith (Jansson & Smith, 1991), and also by Wiley (Wiley, 1998). Linsey at al. show that even design faculty, who study and teach design on a regular basis, do not know when they are being influenced or fixated by misleading or poor information (Linsey, et al., 2010). Compared to novices, experts create significantly more ideas, but also fixate more to example features (Viswanathan & Linsey, 2011). These findings, which show that fixation occurs in groups with diverse expertise, indicate the strength and importance of its effects in the design process (Linsey, et al., 2010).

According to Perttula (2006) and Liikkanen (2010), example exposure may not be necessarily detrimental. The benefits of examples or external stimuli have been investigated under the topic of cognitive simulation where design and psychology researchers have shown that idea exposure can positively influence one's ability to produce ideas (Brown, Tumeo, Larey, & Paulus, 1998; Coskun, Paulus, Brown, & Sherwood, 2000; Dugosh & Paulus, 2005; Perttula & Sipilä, 2007). Though these studies were not strictly measuring fixation, examples do offer benefits to designers such as aiding in the convergence of ideas in teams (Fu, Cagan, & Kotovsky, 2010) and helping designers to determine whether existing ideas meet design requirements (Hannah, Joshi, & Summers, 2012). Purcell and Gero (1996) state that the form or representation used in examples, e.g., sketch or CAD, appears to establish the conditions for fixation to occur. Thus, exploring the use of various representations in idea generation is very beneficial towards better understanding the dynamics of fixation in design.

In design fixation experiments, poor examples are typically used to induce fixation and to investigate trends across various parameters. It has been shown that poor examples produce a higher amount of fixation compared with good ones (Fu, et al., 2010). Fixation studies with good examples are usually designed to measure fixation as well as additional trends. For instance, Fu et al. (2010) measured how team convergence is influenced by good and poor examples as well as how teams fixate to the examples given, and Hannah et al. (2012) measured the confidence levels in designers' abilities to determine if a design met customer needs with low and high fidelity representations of examples. Fixation studies using poor examples (Linsey, et al., 2010; Viswanathan & Linsey, 2013a, 2013b, 2013c) have been used to solely measure fixation to features of the examples, as designers' blindly copying the poor features of an example without realizing that they are doing it is the very definition of fixation and an undesirable attribute for engineering designers to possess.

The examples used in the representation experiments in this dissertation are within-domain or near examples. Marsh et al. (Marsh, Landau, & Hicks, 1996) found that within domain examples biased the participants' creation of solutions towards the features contained in the example, causing fixation. Since the aim of the representation studies are to identify ways to mitigate fixation, within-domain examples were selected to cause fixation so that the defixation effects of the example's representation could be studied.

Most of the previous research studies on design fixation have used examples that were represented in only one form, predominantly sketches (Fu, et al., 2010; Jansson & Smith, 1991; Purcell & Gero, 1992). Little research has been done in comparing various types of representations to see how they influence fixation.

2.4 Representations and Design Fixation

Only a few studies have specifically explored the influence of representations on design fixation. For example, Cardoso and Badke-Schaub (2011) investigated if design fixation can be reduced by the type of representation used. In their study, they compared a line drawing to a photo measuring differences in quantity, quality, and originality (using a “yes/no” criterion for originality). They found that both line drawings and photographs caused design fixation. There were no significant differences between the line drawing and the photo for quantity, quality, or originality. An experiment by McKoy et al. (2001), which used teams in an undergraduate course, compared the design solutions to a design problem where examples were given and represented either as a sketch or as text. The results from the McKoy study showed that groups who received a sketch example had higher novelty and quality scores than the groups with the text description of the example (only quality and novelty were measured for this experiment).

In the digital age, it is important to investigate other types of representations that can be used for the idea generation process. Recent studies have shown that CAD has emerged as an idea generation tool across design domains (Jonson, 2005). However, the usefulness of CAD representations in reducing fixation has not been critically studied. This dissertation will do so.

2.5 Analogical and Biologically Inspired Design

Design-by-analogy is a method in which designers transfer and apply appropriate and relevant features from existing solutions to solve similar design problems (Bhatta, et al., 1994; Goel, 1997; Goel & Bhatta, 2004; Qian & Gero, 1996). The use of analogy in design has been argued to be crucial to the creative design process (Casakin & Goldschmidt, 1999; Goel, 1997; Goldschmidt, 2001), and it plays an important role in innovation and creativity (Bhatta, et al., 1994; Goel, 1997). Gentner & Markman (1997) state that analogies play an important role in conceptual change, which is a crucial aspect of creativity. Analogies are often used in the idea generation process to transfer knowledge through analogical mapping from a source domain. The source domain contains the analogous phenomena that is mapped to the target domain, which contains the problem to be solved by analogy (Gentner & Markman, 1997).

Analogies may be classified by their similarity, or the conceptual distance between the source and target domains (Wilson, et al., 2010), and this distance may be “near” or “far” (distant) (Gentner & Markman, 1997). Dahl and Moreau (Dahl & Moreau, 2002) give an example to illustrate this: designers creating a new freeway system could draw a near analogy to an existing freeway system in another city, or a distant analogy from a human circulatory system. Near analogies occur when the source domain is similar to the target domain, where both the surface-level attributes and the relations among them can be easily mapped and transferred. In the case of distant analogies, the source and target domain are not so easily mapped, leaving the mapping to be on a structural level (Dahl & Moreau, 2002).

The distance between domains, or the conceptual distance, has been argued to be positively correlated with level of creativity (Dahl & Moreau, 2002), as well as increasing the probability of achieving breakthrough innovation (Schild, Herstatt, & Lüthje, 2004); thus distant analogies are more likely to be associated with extraordinary forms of creativity (Ward, 1998) and are considered to be the main drivers of truly innovative thought (Holyoak, 1996). Analogies can come from similar products and tools or come from biology or nature. When biological systems are used as analogues, this transfer or mapping is called biologically inspired design.

Biologically inspired design uses analogies to biological systems to develop innovative solutions for engineering design problems (Benyus, 1997; Helms, et al., 2009; Vattam, et al., 2007; Vattam, et al., 2008; Vincent & Mann, 2002; Vogel, 2000). In biologically inspired design, the source domain is biology, while the target domain is engineering. Because the analogies in biologically inspired design are distant, solutions to the source problems cannot be easily transferred as mentioned earlier, and have to go through a translating and abstraction process (Thorbjørn & Kautsar Anggakara, 2013). The level of abstraction needed for the transfer of distant analogies increases the cognitive effort in the biologically inspired process, as both the target and source need to be abstracted to a functional level (Dahl & Moreau, 2002; Shu, et al., 2011). Helms et al. (Helms, et al., 2009) have identified two processes for biologically inspired design based on two different starting points: problem-driven and solution driven. In the problem-driven approach, an identified problem is the starting point and designers look for analogies in nature to solve the problem. The solution-driven approach, on the other hand, starts with having a biological source of interest, and then goes on to find a problem to which the biological principle may be applied (Vattam, Helms, & Goel, 2010).

There are many accounts of successfully biologically inspired products in engineering design and science, the most famous of which may be the development of Velcro by George de Mestral, after examining seeds of the burdock root that had attached themselves to his dog while they were on a walk. Case studies of biologically inspired designs in engineering include Vincent and Mann's (Vincent & Mann, 2002) transfer of the design of pine cones to design clothing that can regulate body temperature and Cutkosky's design of the StickyBot (Autumn, Dittmore, Santos, Spenko, & Cutkosky, 2006; Kim, et al., 2008; Santos, Heyneman, Kim, Esparza, & Cutkosky, 2008), a machine that mimics the van der Waals forces used by a gecko's foot to climb smooth surfaces. McEwan's design of mechanical Platelets™ (McEwan, Chirnside, & Ryan, 2010) that locate and seal costly pipeline leaks in the oil and water industry, inspired by the human body's healing mechanism in small wounds, is also a successful implementation of biologically inspired design in engineering.

Currently, there is little understanding of the process of biologically inspired design as a design activity or procedure. Vincent et al. (Vincent, Bogatyreva, Bogatyrev, Bowyer, & Pahl, 2006) provide a normative model of how biologically inspired design could be done through BioTRIZ, and Helms et al. (Helms, et al., 2009) provide a descriptive account of the biologically inspired design process through an in situ study conducted on the practices and products of designers. Glier et al. (Glier, Tsenn, McAdams, & Linsey, 2012) discuss tools that have been developed to aid designers in effective biologically inspired design, these include functional modeling and biological keyword searches; they also discuss Vincent et al.'s BioTRIZ. Databases and online repositories for supporting biologically inspired design have also been attempted and created, these include DANE (Vattam, Wiltgen, Helms, Goel, & Yen, 2011), SAPPHIRE (Chakrabarti, Sarkar, Leelavathamma, & Nataraju, 2005), IDEA-INSPIRE (Chakrabarti, et al., 2005; Sarkar & Chakrabarti, 2008) and AskNature (www.asknature.org).

One of the processes that can be applied to biologically inspired design is design thinking (Thorbjørn & Kautsar Anggakara, 2013). Design thinking is defined as the design-specific cognitive activities that designers apply during the [conceptual] process of designing (Visser, 2006). Thorbjørn and Anggakara (Thorbjørn & Kautsar Anggakara, 2013) use design thinking as a perspective to explore the biologically inspired process, and Cagan et al. (Cagan, et al., 2013) provide an overview of empirical studies in design thinking which includes biologically inspired design approaches. Lockwood (Lockwood, 2010) states that design thinking is not a substitute for professional design, but rather a methodology for innovation and enablement. In using design thinking as a methodology within the biologically inspired field, one adopts the tools and mindset of design to approach the process of turning lessons from nature into viable concepts in the human domain (Thorbjørn & Kautsar Anggakara, 2013).

One of the activities used in design thinking is divergent thinking and convergent thinking. According to creativity and design research (Cross, 2000; Pugh, 1991; Roozenburg & Eekels, 1995), design activities in conceptual design should contain both divergent and convergent steps. In the divergent steps, a range of unique and diverse ideas or solutions is generated to solve a problem. During the convergent steps, or during convergence, evaluations and selections are made to find the "right" or "correct" solution to the problem (Liu, Chakrabarti, & Bligh, 2003). Since the goal of conceptual design is to generate good design concepts, an important step in achieving this goal is to create a large number of concepts. Research has also shown that the higher the number of generated concepts is, the greater the probability of generating solutions will be (Mulet & Vidal, 2008), the chances of obtaining a good product will also rise (Chakrabarti & Bligh, 1996). At the same time, if a large number of solution concepts are generated, the evaluation stage can become excessively arduous. One of the design thinking models suggested for conceptual design consists of approaching the solution by going through several levels of abstraction and repeating cycles of divergence and convergence (Mulet & Vidal, 2008). Mulet and Vidal (2008) explain that conceptual design has a first stage that is essentially divergent and second stage that is convergent, with these convergence operations consisting of evaluating the designs and making selections that best fit the design problem at hand. Liu and Chakrabarti (Liu, et al., 2003) also argue that applying divergent and convergent steps in the design process would increase the effectiveness of the explorability of the concepts with minimum compromise to the richness of the solution space explored.

Vattam et al. (Vattam, et al., 2008) have developed a conceptual framework called compound analogical design, which is a type of analogical design that contains compound solutions, i.e. solutions that are derived from different biological sources. This framework is similar to that of conceptual combination (Ward, 2001, 2004; Ward, Smith, & Vaid, 1997; Wilkenfeld & Ward, 2001). Vattam's framework incorporates the interaction between analogical transfer and problem functional decomposition. Vattam et al. conclude that the use of compound analogies and the process of decomposition of the target problem to different levels, allow for the retrieval of biological as well as engineering analogues with cues taken from each level. They also conclude that once mapping is established between an engineering function and a biological one, this leads to the transfer of the associated biological mechanisms to the engineering domain. This interchange between functional decomposition and the making of analogies is the key to achieving successful compound solutions in bio-inspired design (Vattam, et al., 2008).

2.6 Summary

This section has reviewed the existing literature on idea generation in mechanical engineering design. The diagrammatic representation used during idea generation were described and discussed, these include sketches, photographs and CAD models. The inherent properties of how these representations affect creativity and the idea generation process were discussed. Functional models used during mechanical engineering design were discussed and the claims in the literature that state that functional representations help designers to avoid biased solutions and allow for more solutions to be explored were presented. This dissertation will experimentally test these anecdotal claims.

The concept of design fixation as it pertains to engineering design was discussed in this section. The studies that have explored design fixation were listed and explained. There are design fixation studies that have focused on how the representation of the example presented influences fixation to the example features as well as to the designer's own ideas. These studies have explored sketches, photographs, line drawing, physical models, and text, but none have explored how the CAD representations of examples affect design fixation, this dissertation will do so.

The use of analogical transfer in biologically inspired design during the engineering design process was explored. A distinction between fixation and analogical transfer should be noted. The transfer that occurs during analogical design is a conscious transfer or features from an example or analogue that aid in the design process. Fixation on the other hand occurs when features from the example are unconsciously copied or when the exposure to that example limits the designer's solution space. Fixation is termed as bad when the features that are copied are negative or poor features that are detrimental to the design being developed and the design process at large. Is fixation is occurring to a good example, then the consequences are not necessary detrimental to the design solution.

In the analogical and biologically inspired design review section, various studies were listed that explain the mechanism of transfer and how examples are used as source analogues during transfer. Successful case studies of biologically inspired design and transfer were listed. Biologically inspired design is a nascent field for which process understanding is only now becoming developed. This study will add to the body of work on biologically inspired design by describing the process of an effective implementation of biological examples as analogues in a real-world context of mechanical engineering design.

CHAPTER 3

STUDY 1 – THE EFFECTS OF REPRESENTATION ON DESIGN FIXATION

This study includes an experiment that was designed to assess if, and to what extent, fixation occurs in engineering idea generation based on the representation of the example given. The participants in this experiment were asked to solve a design problem with the help of an example represented in various ways. The representations explored include CAD, photo, and sketch. A control group is also included.

3.1 Hypotheses

Hypothesis 1: Fixation

Based on prior literature that states that the ambiguity of sketches helps to promote ideation (Contero, et al., 2009; Goel, 1995; Jonson, 2002; Tversky, et al., 2003), I hypothesize that more well-defined/high fidelity representations, e.g., CAD or photo, will cause designers to fixate more to the features of that example; thus, fixation can be reduced with less well-defined examples, e.g., a sketch.

Hypothesis 2: Identification of Working Principles of the Design

From the study by Hannah et al. (Hannah, et al., 2012), which found that designers were better able to determine if high fidelity representations met design or customer requirements compared with low fidelity representations, I hypothesize that CAD and photo representations will allow designers to be able to better identify the key or working principles of the design. I expect that they will copy these features more in their design concepts and solutions.

Hypothesis 3: Quality

In line with the second hypothesis, I also hypothesize that the CAD and photo representations will produce a higher quality of design solutions compared with the sketch condition.

3.2 Design Task

The design task given to the participants was to design a device to shell peanuts in developing countries. This task has been used in previous studies (Fu, et al., 2010; Linsey, Green, Murphy, Wood, & Markman, 2005; Linsey, Markman, & Wood, 2012; Linsey, et al., 2010; Viswanathan & Linsey, 2011; Viswanathan & Linsey, 2012b), and follows the same approach, i.e., description of the example design, time given to read the problem, and time given to generate ideas. This problem was chosen because it is practical, appropriate for engineers, and able to be solved in diverse ways. The problem description, customer needs, and instructions provided to the participants are shown in Figure 3.1. The description of the example solutions given are described in later sections.

Design Problem - Device to Shell Peanuts

Problem Description:
In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal of this project is to design and build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African peanut farmers. The target throughput is approximately 50 kg (110 lbs.) per hour.

Customer Needs:
- Must remove the shell with minimal damage to the peanuts.
- Electrical outlets are not available as a power source.
- A large quantity of peanuts must be quickly shelled.
- Low cost.
- Easy to manufacture.

Figure 3.1: Problem description, customer needs, and instructions provided to participants

3.3 Participants

The participants in this study were senior undergraduate students in mechanical engineering at Texas A&M University. Eighty participants in total participated in this experiment with twenty participants per condition in each of the four conditions.

3.4 Experimental Conditions

In order to explore how various representations affect fixation and creativity in the engineering idea generation process, the participants were randomly assigned into four experimental conditions. Each condition received a different representation of the same existing solution of a peanut shelling device. The peanut sheller example given to participants is the Universal Nut Sheller, designed by inventor and humanitarian Jock Brandis (Brandis, 2012; Connors, 2008). Jock Brandis and his non-profit organization, The Full Belly Project, design and distribute technology for developing countries. Instructions on how to build this peanut sheller can be found on the Instructables webpage (Instructables, 2012). This peanut sheller is considered to be a good because it is easy to manufacture, low cost, sustainably powered (human energy), efficient, and effective. The design essentially satisfies all of the customer needs.

The four conditions used in this experiment are based on the types of representations given, i.e., CAD, photo, sketch, and no representation. I designed the experiment so that all conditions would contain the same amount of information, but represented in various ways. To do this, all the conditions needed to have a view of the inner workings of the peanut sheller. This was easy to produce via sketch or CAD modeling, but an inner view photo view of the sheller was unavailable. In order to provide the same amount of information to the experiment participants, a high fidelity wire-frame view, the same given to the CAD, was added to the photo condition.

The experiment conditions and the representations they received are:

- CAD: the example was represented as a CAD model (Figure 3.3).
- Photo: same example represented as a photograph (with a CAD wireframe) (Figure 3.4).
- Sketch: same example as the CAD and Photo conditions, but represented as a sketch (Figure 3.5).

- Control: no example was given; this condition is used as a baseline to measure design fixation.

A description for the example solution (Figure 3.2) was also provided to the participants on the same sheet of paper as the problem description, customer needs, and example representation.

Solution Description:

The peanuts are loaded from the top of the system; the user rotates the handle, which pushes the nuts towards the tapered gap between the interior and exterior wall of the machine. The shell of the nut is broken at the point where the gap is sufficiently narrow to cause enough friction to crack open the shells. The kernels and shell fragments fall into a basket and are later separated by winnowing.

Figure 3.2: Solution description given to the CAD, photo plus CAD, and sketch conditions

Figure 3.3: Example given to the CAD condition

Figure 3.4: Example given to the Photo condition (Larchmont Gazette, 2009; Nourish-International, 2007)

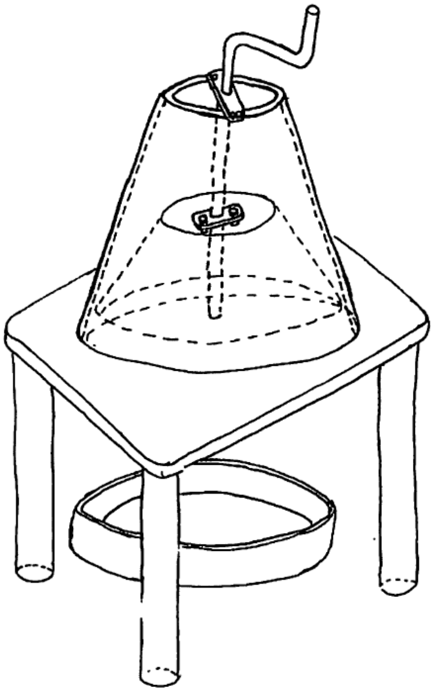


Figure 3.5: Example given to the Sketch condition

3.5 Experimental Procedure

The experiment occurred in a controlled classroom setting. Half of the participants (in all four conditions) were run in the spring semester and the other half in the fall semester. Since all students were in the same design class, they had learned the same material. Participation in the experiment was voluntary, and the students who participated were compensated with either extra credit in their class or a monetary award.

The design task and example were handed to each student on paper. They were then given five minutes to review and understand the design task. During this time, they were encouraged to ask questions concerning the experiment or design task; no questions were asked. After the initial review period, the participants were given 45 minutes to complete the idea generation section of the design task. All participants were required to use the entire 45 minutes. The participants were asked to sketch each of their design solutions one idea per page and to describe how the design worked by adding short text descriptions and by labeling parts of the design. They were also asked to generate as many solutions as possible, while maximizing quality, novelty, and variety. As an incentive to create many solutions, they were told that participants who showed superior effort in their idea generation would receive a prize or bonus. This bonus was given to all the participants in the form of a monetary award at the end of the experiment in addition to the compensation for experiment participation.

3.6 Evaluation Metrics

To measure fixation, creativity, and the overall effectiveness of the solutions generated, six metrics were used: quantity of non-redundant ideas, number of repeated example features, percentage of example features used, quality of concepts, novelty of concepts, and variety of concepts. Four of these metrics, the quantity (non-redundant), quality, novelty, and variety of ideas are based on definitions proposed by Shah, et al. (2000), and further developed by Linsey (2011; 2005; 2010; 2007). For the purpose of this study, an idea is defined as a feature of the generated solutions that solves at least one function in the functional basis (Linsey, et al., 2010) .

Table 3.1 shows the features and ideas counted within the example solution that was provided to the participants. A design concept refers to each solution that a participant generates to solve the design task.

Each of the participants' concepts were broken down into ideas and scored using these metrics. To ensure the reliability of the metrics, an inter-rater agreement was performed by two independent raters, and a Pearson's or Cohen's Kappa correlation was determined. Cohen's Kappa is a statistical measure of inter-rater agreement for qualitative (categorical) items (Carletta, 1996); this measure was used to the quality metric described in section 3.6.4. Pearson's correlation is a measure of the linear relationship between continuous variables, which are variables that can take on any value within a finite or infinite interval (Pearson, 1895). The other metrics are measured on a continuous scale, thus the appropriate statistical measure, Pearson's, is used.

Table 3.1 was used as a guideline by the raters to determine the features copied from the example. The inter-rater agreement was done on 50% of the data for all metrics. Studies have shown that independent experts with domain knowledge can reliably assess quantity and quality of ideas (Linsey, et al., 2011), as well as the creativity (novelty and variety) in engineering design (Christiaans, 1992, 2002; Kudrowitz & Wallace, 2013; Linsey, et al., 2011; Linsey, et al., 2005; Viswanathan & Linsey, 2012a; Viswanathan & Linsey, 2013d).

A detailed description of the metrics used and evaluation performed is given below.

3.6.1 Quantity of Non-Redundant ideas

This measure of fixation gauges how a participant's ideas are limited due to exposure to an example. It measures the quantity of ideas generated by the participants minus ideas taken from the example and any repeated ideas. A control condition is used as a baseline to measure fixation. If the participants in the conditions with examples produce fewer ideas than the control, then fixation is occurring. A Pearson's correlation of 0.83 was obtained which shows the measure is reliable.

3.6.2 Number of Repeated Example Features

This metric is also a measure of fixation that assesses how often the participants copy or fixate to ideas or features of the example given. The control condition also acts as a baseline for measuring fixation in this metric. If the participants in the conditions with examples copy more ideas from those examples than the control group, then fixation to the example is occurring. The Pearson's correlation for this metric is 0.80, which shows the measure is reliable.

3.6.3 Percentage of Example Features Used

This metric also measures fixation, but to the features of the example given. It measures how many of the features of the example (out of all the available features) are used in the design solutions. The Pearson's correlation for this metric is also 0.80, the same as the number of repeated example features metric.

3.6.4 Quality of Design Concepts

Quality is measured based on the feasibility of the design concepts and how well it meets design specifications or customer needs (Shah, Smith, & Vargas-Hernandez, 2003). A three-point rating scale developed by Linsey et al. (2011) is used to measure the quality of design concepts generated. A score of zero is given for designs that are not technically feasible and do not meet any of the customer needs. A score of one is given if the design partially meets the customer needs (1-3 customer needs). A score of two is given for designs that meet most or all of the customer needs (4-5 customer needs). A Cohen's Kappa of 0.57 was obtained. This Cohen's Kappa is an acceptable level of agreement (Clark-Carter, 1997).

3.6.5 Novelty

Novelty measures how unusual or unexpected a concept is compared to the ideas produced by other participants. (Nelson, Wilson, Rosen, & Yen, 2009; Shah, et al., 2003). Each idea is sorted into bins, and the novelty is calculated as one minus the frequency of ideas in a bin (Linsey, et al., 2005; Viswanathan & Linsey, 2012a). See Linsey et al. (2011) for more details on the blind sorting procedure for the novelty (and variety) scores. The formula used is given by Equation (1). The Pearson's correlation is 0.95.

$$\begin{aligned} Novelty &= 1 - Frequency\ of\ ideas \\ &= 1 - \frac{\#\ of\ ideas\ in\ a\ bin}{Total\ number\ of\ ideas\ per\ participant} \end{aligned} \tag{1}$$

3.6.6 Variety

Variety measures the solution space explored during the idea generation process. It is defined as the degree to which the concepts from a single designer were dissimilar from other concepts from that designer (Nelson, et al., 2009; Shah, et al., 2003). The variety is calculated as the number of bins a participant's ideas occupy divided by the total number of bins (Linsey, et al., 2011; Viswanathan & Linsey, 2012a) . The formula is given by Equation (2). The Pearson's correlation is 0.92.

$$Variety = \frac{\#\ of\ bins\ \ a\ participant's\ ideas\ occupy}{Total\ number\ of\ bins} \tag{2}$$

Table 3.1: Functions of the example solution (Full Belly peanut sheller)

Function	Features from Example
[Material]	
guide	double tapered conic surface
	tapered conic surface
	rotation of grinding surface
import	opening at top sheller
position	table top
	table legs
	bolts with plate nuts to position sheller parts
remove (shell)	friction of grinding surface
	sufficient gap between grinding surface to crack shells but keep nuts intact
store	bin/basket
separate (nut and broken shell)	winnowing
[Energy]	
import / export	hand crank/handle
	shape same as example
transmit	shaft

3.7 Results

One-way ANOVA was used for the statically analysis of the data in this experiment. The data for this experiment satisfied the homogeneity of variance assumption for all metrics ($p > 0.05$); however, the data was not normality distributed for the novelty and variety metrics (novelty: p = 0.001, 0.001, 0.053, 0.001 for the four conditions; variety: p = 0.178, 0.077, 0.020, 0.247 for the four conditions). Due to the large sample sizes and the central limit theorem, the normality of the data can be assumed and thus ANOVA is robust enough to the violation of normality for the novelty and variety metrics. (Howell, 2012; Tabachnick & Fidell, 2007).

3.7.1 Quantity of Non-Redundant Ideas

Results from the quantity of non-redundant ideas generated by the participants (Figure 3.6) show that fixation to their own ideas is present. The participants in the three example conditions (CAD, Photo, and Sketch) generated fewer ideas than the control, indicating fixation is present. The results were analyzed using a one-way analysis of variance (ANOVA) where F(3, 79) = 7.39, $p < 0.001$, and $MS_{error} = 0.05$.

Figure 3.6 and the pair-wise t-tests among the CAD, Photo, and Sketch condition show that the number of ideas generated by these three conditions are not statistically significant when compared to each other. These results show that the type of representation used does not significantly influence the degree of design fixation, and all representations evaluated in this experiment cause fixation to about the same extent. This shows that Hypothesis 1 is not supported.

These results are consistent with those found by Cardoso and Badke-Schaub (2011), which showed that there were no significant differences when comparing the quantity of ideas of only the photo and line drawing conditions. However, there were significant differences when comparing both conditions to the control condition.

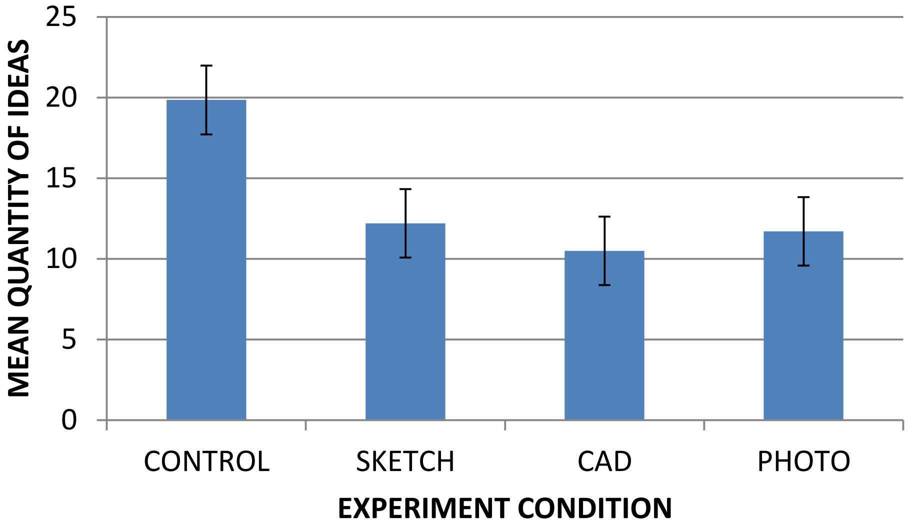


Figure 3.6: The mean quantity of non-redundant ideas across conditions. All error bars show (±1) standard error.

3.7.2 Number of Repeated Example Features and Percentage of Example Features Used

Other indicators of design fixation are the number of times participants repeat features from the examples provided and the percentage of the features from the example that are used. Figure 3.7 shows the distribution of the mean number of repeated example features across all four conditions, and Figure 3.8 shows the mean percentage of example features used in the participants' design concepts also across all four conditions. The ANOVA results for the number of repeated features and percentage of examples features used are F(3, 79) = 2.516, $p = 0.065$, and MS_{error} = 44.327 and F(3,79) = 3.698, $p = 0.015$, and MS_{error} = 0.037, respectively. In Figure 3.7 and Figure 3.8, fixation is again shown to be present. The participants in the CAD, photo, and sketch conditions are copying more features from the example than the control condition. Even though the participants from the control condition have not seen the example, features from the example will appear in their designs. The repetition of example features in the designs supports the quantity results and shows that the type of representation used does not influence fixation to the example features, but that fixation is present.

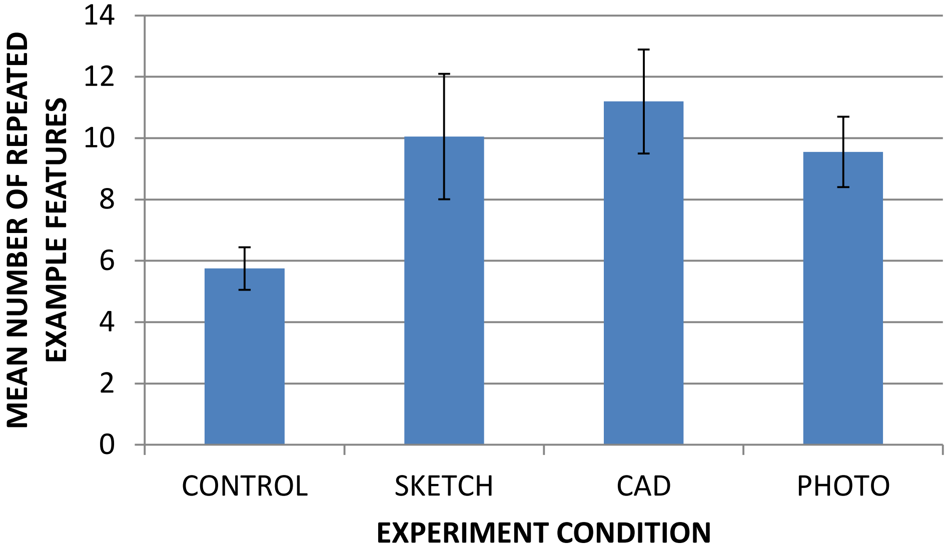


Figure 3.7: The mean number of repeated example features across conditions. All error bars show (±1) standard error.

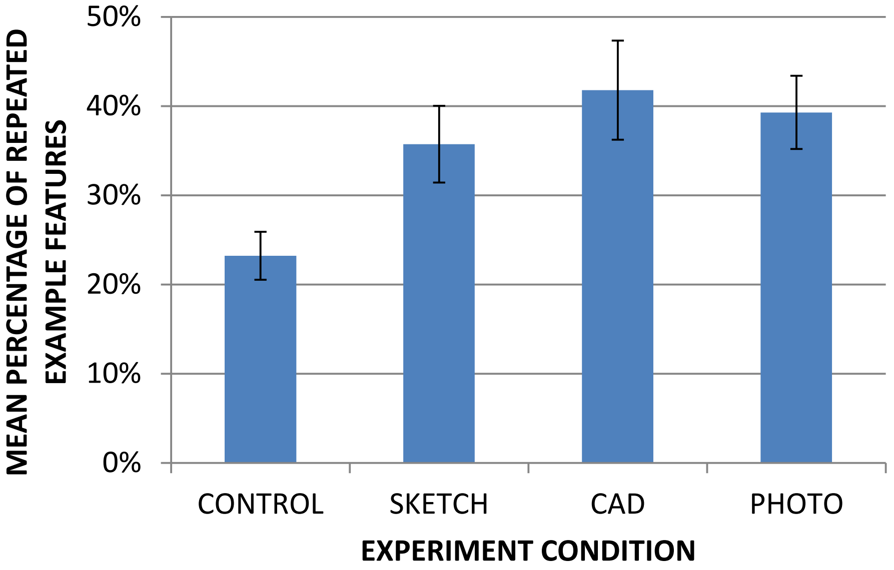


Figure 3.8: The mean percentage of example features used across conditions. All error bars show (±1) standard error.

3.7.3 Quality of Design Concepts

The results from the quality of concepts metric (Figure 3.9) show that the CAD and photo condition produced significantly higher quality ideas compared to the control and sketch conditions. The t-test pairwise comparisons for CAD to control and sketch conditions respectively are: p = 0.035 and 0.018; t-test pairwise comparison for photo to control and sketch conditions respectively are: p = 0.05 and 0.039; ANOVA F(3,79) = 3.250, p = 0.021, and MS_{error} = 0.089. The CAD and photo quality scores were not significantly different from each other. The control and sketch conditions were also not significantly different from each other. These results support hypothesis 2, which stated that the CAD and photo conditions would produce a higher quality compared to sketch.

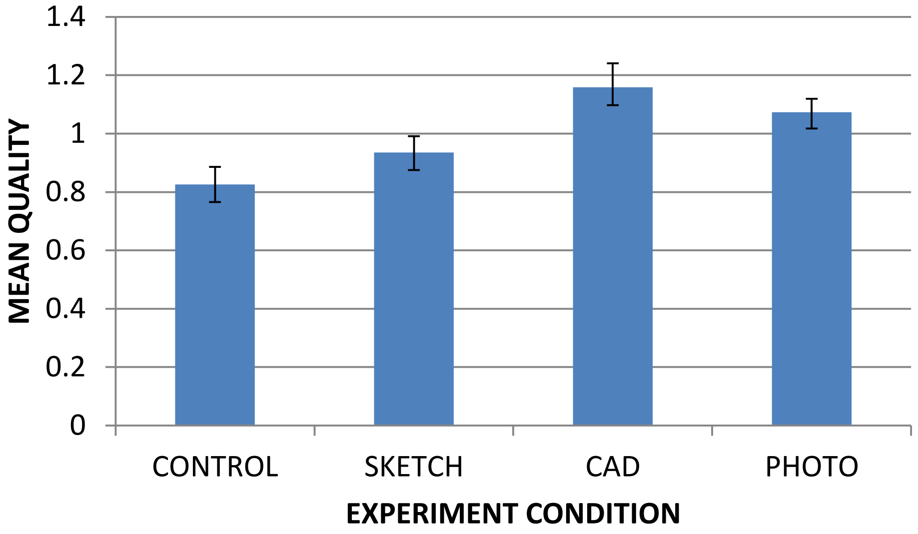


Figure 3.9: The mean quality of design concepts across conditions. All error bars show (±1) standard error.

Figure 3.10 shows the percentage of high quality design concepts. High quality in this sense means design concepts with a score of 2. The graph shows that the CAD condition produced the highest number of quality concepts.

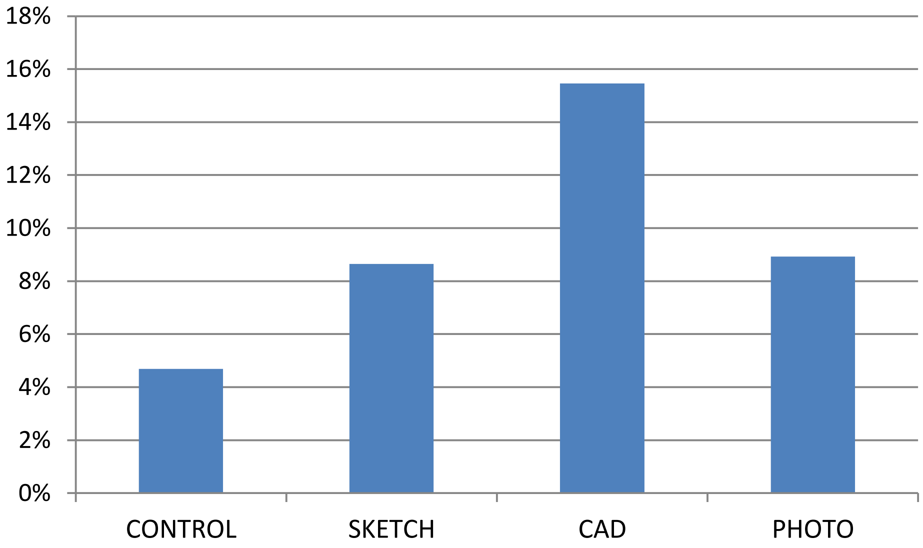


Figure 3.10: Percentage of High Quality Design Concepts

3.7.4 Novelty and Variety

The results for the novelty and variety metrics (Figure 3.11 and Figure 3.12) show that there are no statistically significant differences (ANOVA novelty F(3,79) = 0.716, p = 0.545, and MS_{error} = 0.037; variety F(3,79) = 1.559, p = 0.206, and MS_{error} = 0.038). Prior studies (Linsey, et al., 2011; Viswanathan & Linsey, 2012a; Viswanathan & Linsey, 2013d) have also not seen differences in novelty and variety in idea generation studies. It is possible that the novelty and variety metrics are not sensitive enough to detect differences.

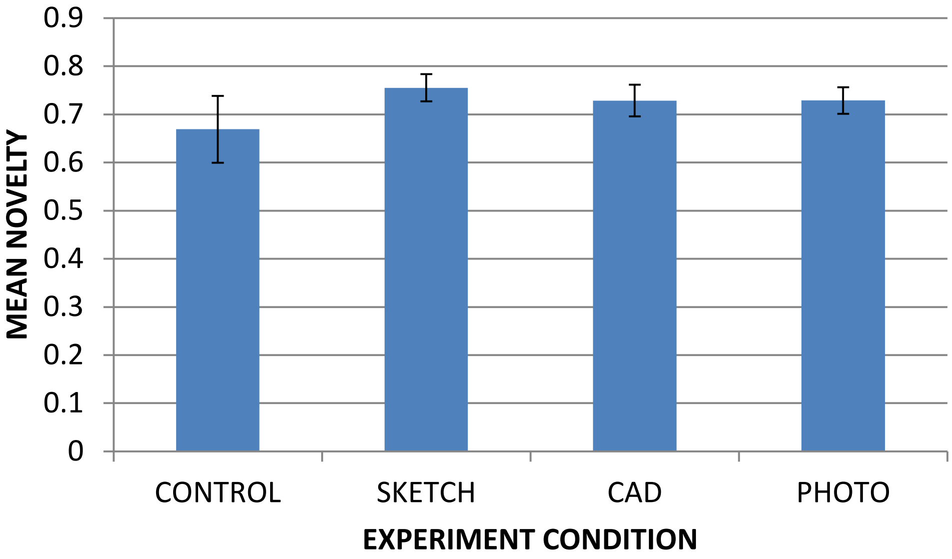


Figure 3.11: The mean novelty across conditions. All error bars show (±1) standard error.

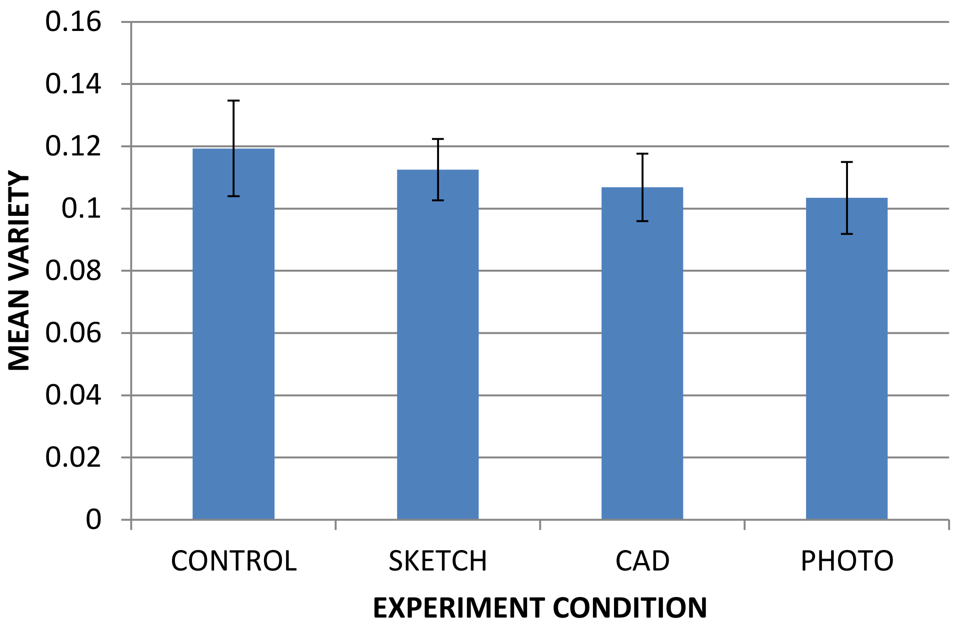


Figure 3.12: The mean variety across conditions. All error bars show (±1) standard error.

3.7.5 Effective Principles Copied from the Example

Since this experiment uses a good example, I hypothesized that the various representations of the example would offer different benefits regarding the participants' abilities to identify the working or effective principles of the design. As discussed earlier, being able to identify and copy these key features is not necessarily a negative consequence of fixation. For the Full Belly peanut sheller, I identified the principles and functions of the design (from

Table 3.1) that made the design effective: the double taper, taper, rotation, friction, and sufficient gap.

Figure 3.13 shows the mean percentage of all of the five effective principles copied from the example for four conditions (ANOVA: F(3,15) = 1.793; *p* = 0.05, and MS_{error} = 0.21). We see that the CAD and photo condition copied significantly more of the effective principles from the example compared to the control and sketch conditions. The t-test pairwise comparisons for CAD to control and CAD to sketch conditions respectively are *p* = 0.023 and 0.042, and the t-test pairwise comparison for photo to control and sketch conditions respectively are: *p* = 0.044 and 0.05. There are no significant differences between the control and sketch conditions or between the CAD and photo conditions. These results show that the participants in the CAD and photo conditions were able to better identify the effective principles of the given examples based on their representations; these results support Hypothesis 3. Figure 3.14 shows the breakdown of each of the principles that were copied; the graph also shows that the CAD and photo conditions copied more of each of the principles than the other conditions.

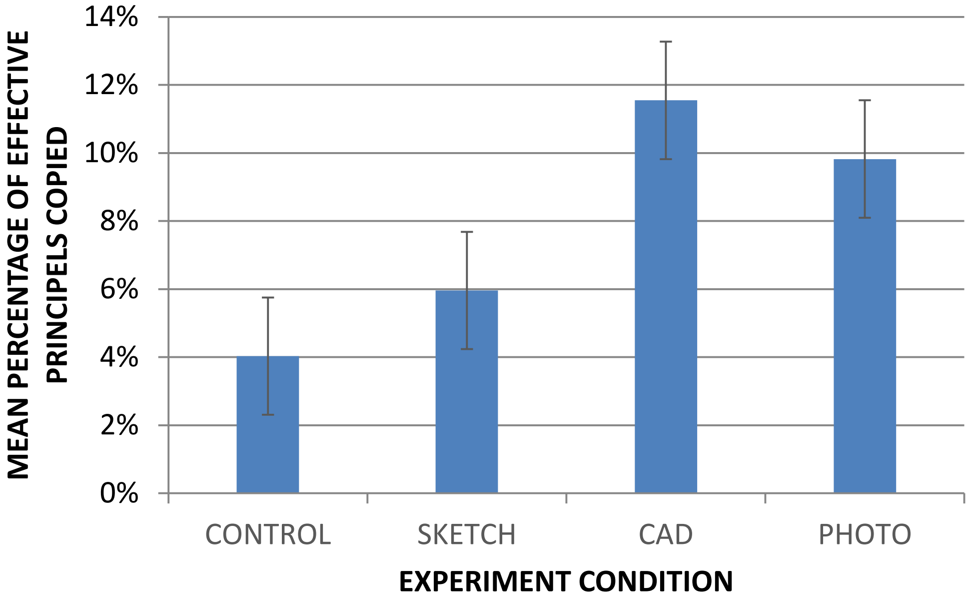


Figure 3.13: The mean percentage of effective principles copied form the example

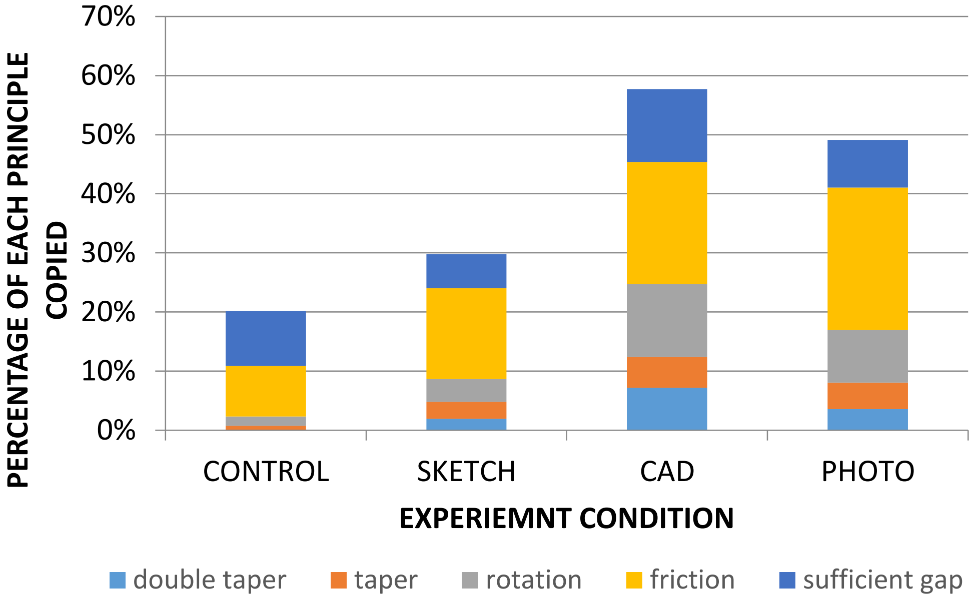


Figure 3.14: The percentage of each principle copied

3.8 Discussion of Results

The data from the three measures of design fixation (quantity of ideas, number of repeated features, and percentage of repeated features) show consistent results that all three representations (CAD, photo, and sketch) do result in design fixation, but the degree of fixation is not significantly different across the three representations. The hypothesis stating that more well-defined or high fidelity representations cause a higher degree of fixation is not supported. These results are consistent with the Cardoso and Badke-Schaub study (2011).

This study intentionally kept the information across the representations as similar as possible to measure the influences inherent in the representations. This work does not necessarily contradict previous research that indicates that sketches, likely due to their greater capability for ambiguous representation, may provide more opportunities for creativity and re-interpretation (Shah, 1998; Suwa & Tversky, 1997; Tversky, et al., 2003). The current study did not vary the amount of information that is typically contained in each representation. It is entirely possible that designers should use sketches in the early phases of design because they have more potential for ambiguity. This warrants further investigation.

The results from the quality of design concepts metric provide interesting results. Here, the participants in the CAD and photo conditions were initially shown to have produced a statistically significant higher quality of design concepts compared to the control and sketch conditions. The results of the percentage of effective principles copied from the example also produced similar results, i.e., the CAD and photo conditions copied significantly more of the effective principles than the control and sketch conditions. Though the quality and percentage of effective principles copied from the example for the CAD condition were higher compared to the photo condition, they were not significantly different. This data shows that high fidelity representations such as CAD and photographs allow for a clearer depiction of what the working principles of the example are that make it effective. This in turn leads to higher quality ideas as designers copy these features.

It would appear that providing a good example is advantageous over a poor one. Even though the fixation still occurs when a good example is presented regardless of the type of representation, CAD and photo conditions allow for the good features of the example to be copied. This experiment suggests CAD and photo representations are preferable over sketches in the early design or conceptual stages of design when idea generation is taking place. The results from this study also indicate that databases of effective or good design examples should include CAD and photo-like images of the design solution that indicate clearly how the device works.

CHAPTER 4

STUDY 2 – ASSESSING THE EFFECTS OF CAD AND SKETCH REPRESENTATIONS IN IDEA GENERATION

In the first study (Chapter 3), where single CAD, sketch and photograph representations were compared, the results showed that there were no significant differences in the amount of fixation to the example. The results also showed that the quality scores were higher for the high fidelity representations (CAD and photo) with no significant differences between CAD and photo. During idea generation, it is unlikely that only one example would always be used for inspiration. Sometimes multiple examples are used at once, and they may be represented in different ways. As discussed in the literature review in Chapter 2, these representations possess inherent attributes that allow information about the design to be observed by the viewer in different ways. The results from study 1 in Chapter 3 also showed that CAD representations allow for the working principles of the design to be better identified. I would like to see if this attribute of CAD representations holds true when presented with another representation, or if there is a bias to a towards one representation based solely on the representations attributes or on the designers preference. This study presents an experiment that will assess the effects of sketch and CAD representations when they are presented together during engineering idea generation. I particularly want to see how the presence of one or two examples, and their representation as either a CAD or sketch affects design fixation, quality and creativity and if there is a bias to a particular representation irrespective of the example. I also want to investigate if the quality scores will be higher if two examples are presented as opposed to one, since combining two good features from different designs might result in a better overall design. I also look at if conditions that have two differently represented examples will produce a higher quality of design compared with conditions that have both examples represented in the same way. The full list of hypotheses is discussed in detail in section 4.1.

The participants in this experiment were asked to solve a design problem with the help of either one example or two examples. Two similarly effective examples for the design task were distributed into a 3x3 factorial experiment design to form 9 conditions (the representation of Design A: CAD, Sketch, no representation, and the representation of Design B: CAD, Sketch, no representation were the two factors), where the number of examples and types of representation will vary. This is explained in detail in the Method section. A control condition where participants did not receive an example is also included. In addition to the design task given in the experiment, a survey was also given to the participants to assess preferences and opinions about the design examples and representations.

4.1 Hypotheses

Hypothesis 1: Fixation

When two examples are presented together with different representations (i.e. CAD and Sketch), fixation will occur at a higher rate to the features of the example represented as a CAD.

Hypothesis 2: Quality (Comparing Representations)

The presence of two different representations will allow for a greater quality of ideas compared with the same representation (e.g. CAD & Sketch vs. CAD & CAD).

Hypothesis 3: Quality (Comparing Number of Example Given)

Being presented with two effective examples will result in higher quality solutions compared to being presented with one effective example.

Hypothesis 4: Quantity

The presence of more than one example will produce a greater quantity of ideas.

4.2 Design Task

The design task was the same as in Study 1: design a device to shell peanuts in developing countries. A different example from the one used in Studies 1 and 2 was given in this study and will be discussed in detail in Section 5.4.

4.3 Participants

The participants were senior undergraduate Capstone students in mechanical engineering at the Georgia Institute of Technology. 110 students participated in this experiment and were randomly assigned to each of the nine conditions, with 12 to 13 participants per condition.

4.4 Experimental Conditions

Two different and effective designs of a peanut sheller (Design A – Full Belly Sheller (Brandis, 2012; Connors, 2008). and Design B – Maya Pedal Power Nut sheller (MayaPedal, 2013)) were used in this experiment. These peanut shellers were used because they are easy to manufacture, low cost, sustainably powered (human energy), efficient, and effective. The designs essentially satisfy all of the customer needs.

The two different ways in which these examples were represented were in CAD and Sketch form. A 3x3 factorial design was used to create the conditions for this experiment, this was done because there is more than one independent variable, and this design will allow us to explore trends between all design representations for each design. The two factors for the 3x3 factorial design are (1) the representation of Design A and (2) the representation of Design B. Each of these factors has three levels: CAD representation, Sketch representation and No representation. This gives nine different conditions, including a control. Figure 4.1, Figure 4.2, Figure 4.3, and Figure 4.4 show the various designs and representations for the experiment, and Table 4.1 shows the layout of the factorial design with the different conditions. The figures of the Maya Pedal sheller do not show any internal views of the design, because these views do not contain any information about the mechanism of the sheller. All of the mechanism and operations of the peanut sheller are external.

The example that came first was juxtaposed to remove any bias to the order of the presented examples. For instance, for condition 1 were both examples were represented as CAD, half of the participants received Design A as CAD and then Design B as CAD in the order in which the examples were presented in the packets, and the other half received Design B first, then then Design A second. The same thing was also done for the conditions that received different representations.

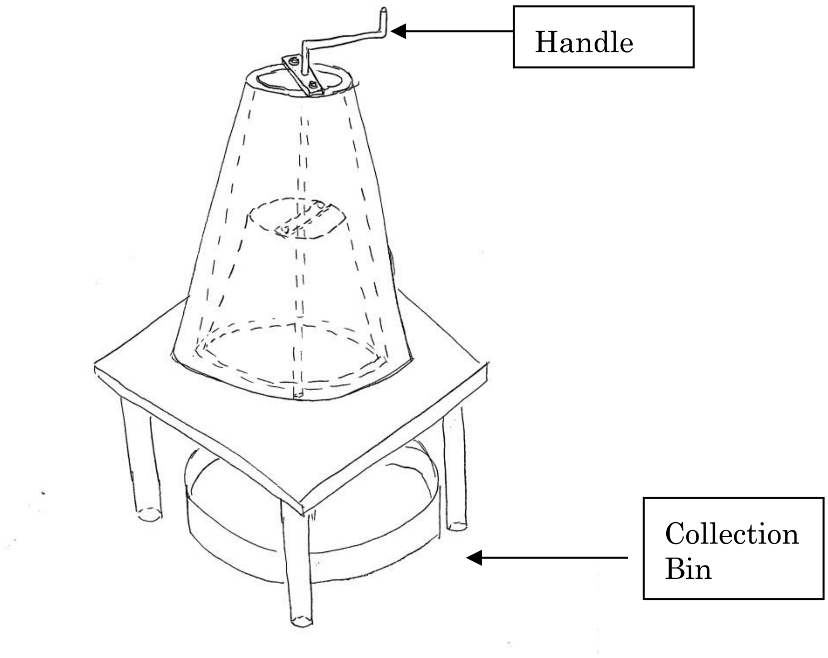


Figure 4.1: Sketch of Design A Full Belly Sheller

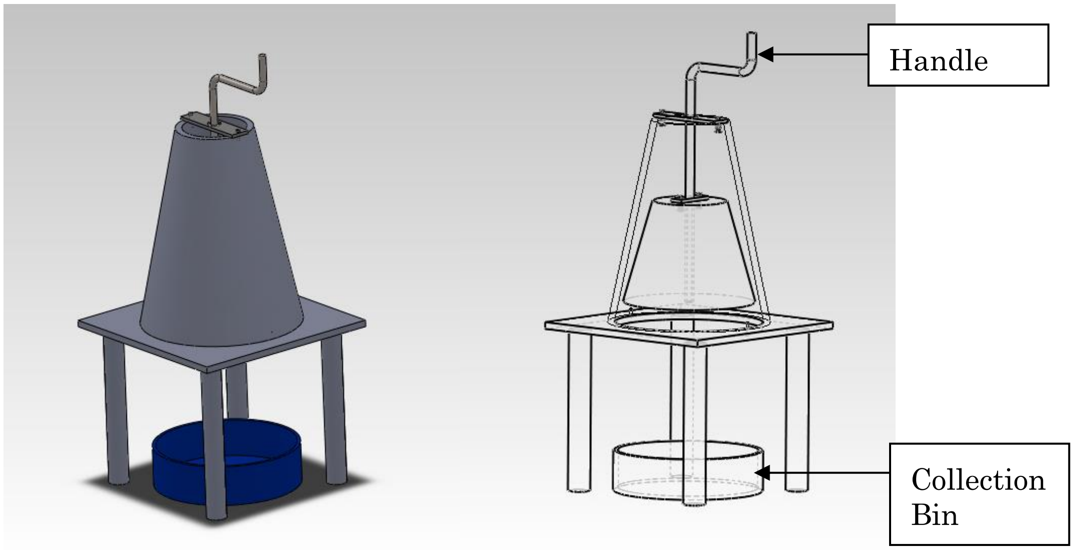


Figure 4.2: CAD of Design A Full Belly Sheller

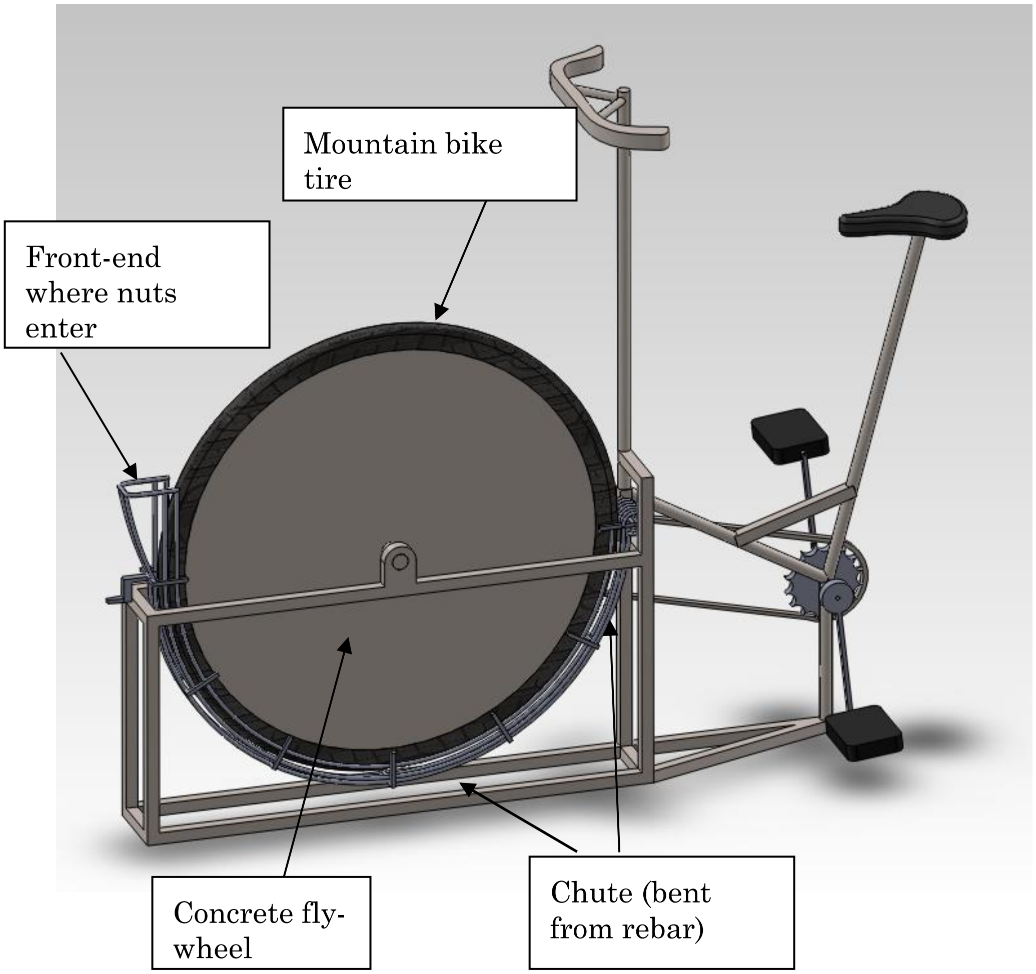


Figure 4.3: CAD of Design B Maya Pedal Sheller

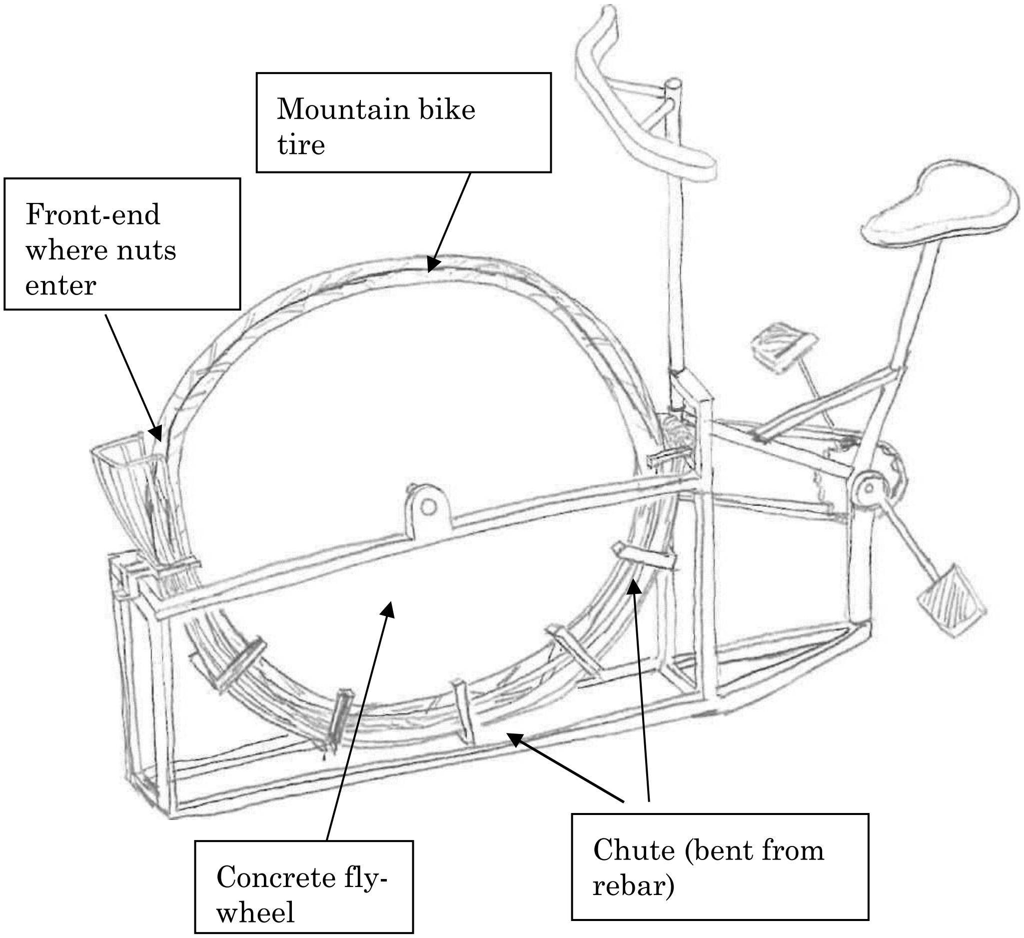


Figure 4.4: Sketch of Design B Maya Pedal Sheller

Table 4.1: 3x3 Factorial Design Showing the 9 Conditions

		Representation of Design A		
		CAD	Sketch	None
Representation of Design B	CAD	① CAD A & CAD B	② Sketch A & CAD B	③ CAD B
	Sketch	④ CAD A & Sketch B	⑤ Sketch A & Sketch B	⑥ Sketch B
	None	⑦ CAD A	⑧ Sketch A	⑨ Control

As in study 1, a description for the example solution for each design was also provided to the participants on the same sheet of paper as the problem description, customer needs, and example representation. The solution description for the full belly sheller is shown in Figure 3.2, and the solution description for the Maya Pedal sheller is seen in Figure 4.5.

Solution Description:
The peanuts are loaded from the top of the system; the user rotates the handle, which pushes the nuts towards the tapered gap between the interior and exterior wall of the machine. The shell of the nut is broken at the point where the gap is sufficiently narrow to cause enough friction to crack open the shells. The kernels and shell fragments fall into a basket and are later separated by winnowing.

Figure 4.5: Solution Description for Design B, Maya Pedal

4.5 Experimental Procedure

The experimental procedure used in this study is the same as in Study 1. Participants were run through the experiment in the spring and fall semesters. For the spring semester, not all the participants were seated at every other seat in the classroom, some were seated close together.

4.6 Evaluation Metrics

The evaluation metrics used in this study are the same as in Study 1. Table 4.2 shows the features and ideas counted within the example solutions that were provided to the participants.

A survey was also given to the participants to assess their preferences in regard to the type of representation (CAD or Sketch), type of example (Design A or Design B), and how useful and complex the design examples given to them were in the idea generation task. Demographic information was also collected in the survey. The full surveys are listed in Appendix B.

Table 4.2: Functions of the Example Solutions (Full Belly and Maya Pedal Sheller)

Function	**Features from Design A – Full Belly**	**Features from Design B – Maya Pedal**
[Material]		
guide	double tapered conic surface	chute
	tapered conic surface	
	rotation of grinding surface	
import	opening at top sheller	entrance of chute
position	table top	bicycle frame
	table legs	same shape as example
	bolts with plate nuts to position sheller parts	boxed frame
remove (shell)	friction of grinding surface	friction from grinding (1 solid surface, the other netted)
	sufficient gap between grinding surface to crack shells but keep nuts intact	tire on flywheel
store	bin/basket	
separate (nut and broken shell)	winnowing	
[Energy]		
import / export	hand crank/handle	bike/foot pedal
	shape same as example	same shape as example
store		wheel/flywheel
		concrete flywheel
transmit	Shaft	bicycle chain drive

4.7 Results

Two-way ANOVA was used for the statically analysis of the data in this experiment. The data for this experiment satisfied the homogeneity of variance assumption for all metrics ($p > 0.05$); however, the data was not normality distributed for variety metric (p = 0.096, 0.293, 0.280, 0.023, 0.437, 0.047, 0.010, 0.654, 0.017 for the nine conditions). Due to the large sample sizes and the central limit theorem, the normality of the data can be assumed and thus ANOVA is robust enough to the violation of normality for the variety metric (Howell, 2012; Tabachnick & Fidell, 2007).

4.7.1 Relative Difference of the Number of Example Features Copied

I am using the relative difference of the number of features copied from the example because only assessing the number of features that were copied from a single example is of no significance in this study and provides no interesting results. Because I am trying to measure the bias to one example based on representation, what is interesting is how many features were copied from one example relative to the other example. This is the relative difference of example features copied. This also provides a single value that can be used in the ANOVA analysis.

Since a factorial design was used in this experiment, a two-way ANOVA test was carried out to check interactions between the two independent variables or factors. The two factors for the analysis are the type of representation of Design A and the type of representation of Design B. Each of these factors has three levels, which are CAD representation, Sketch representation and No representation. The relative difference of the number of features copied (normalized to account for the difference in the number of features analyzed in Designs A and B) was used for to perform the two-way ANOVA.

The results showed significant main effects for the representations of Design A and Design B where F(2, 101) = 5.32, p = 0.006 and where F(2, 101) = 6.84, p =

0.002 respectively. The results also showed that the interaction between the representations of these two design examples was not significant where F(4, 101) = 0.98, p = 0.42. Table 4.3 shows the full two-way ANOVA results. That there is not a significant interaction means that the two factors are not interacting with each other to predict the outcome of the metrics used. In a practical sense, this means that the type of example, and the type of representation are not influenced by each other, they are individually contributing to the outcome.

With these results, we can consider the effects of the type of representation and example separately while analyzing the results from the two-way ANOVA. Figure 4.6 shows the relative difference of the number of features copied for the 9 conditions. The main effects plots for each of the two-way ANOVA factors (Representation A and Representation B), and the interaction plot for this metric are shown in Figure 4.7, Figure 4.8, and Figure 4.9 respectively.

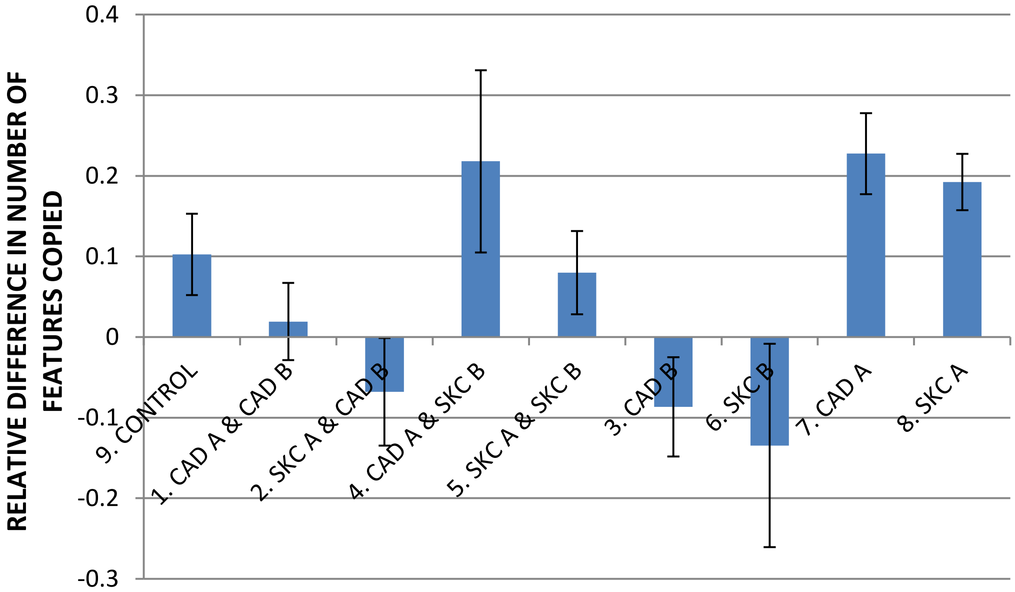


Figure 4.6: Relative Difference of the Number of Features Copied from The Examples. All error bars show (±1) standard error.

Table 4.3: Relative Difference two-way ANOVA results

Tests of Between-Subjects Effects					
Source	Sum of Squares	Degrees of Freedom	Mean Square	F	p-value
Main Effect: RepA	0.68	2	0.34	5.32	0.006
Main Effect: RepB	0.88	2	0.44	6.84	0.002
Interaction: RepA * RepB	0.25	4	0.06	0.98	0.42
Error	6.49	101	0.06		
Total	8.70	110			

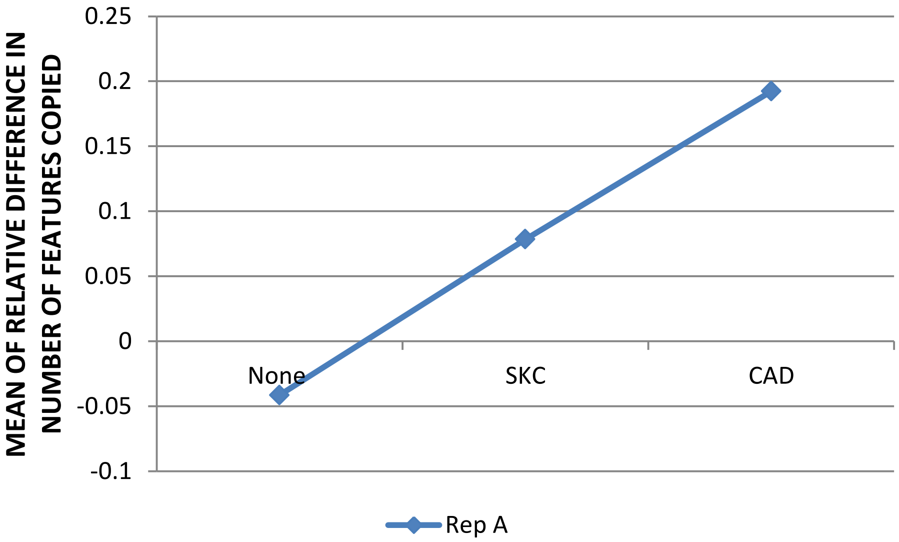


Figure 4.7: Main effects plot for Representation A for the Example Features Copied.

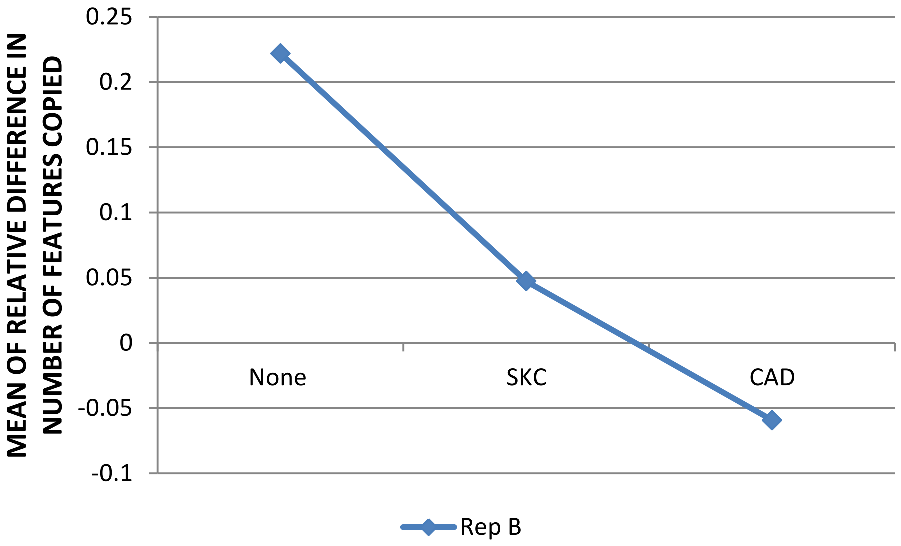


Figure 4.8: Main effects plot for Representation B for the Example Features Copied

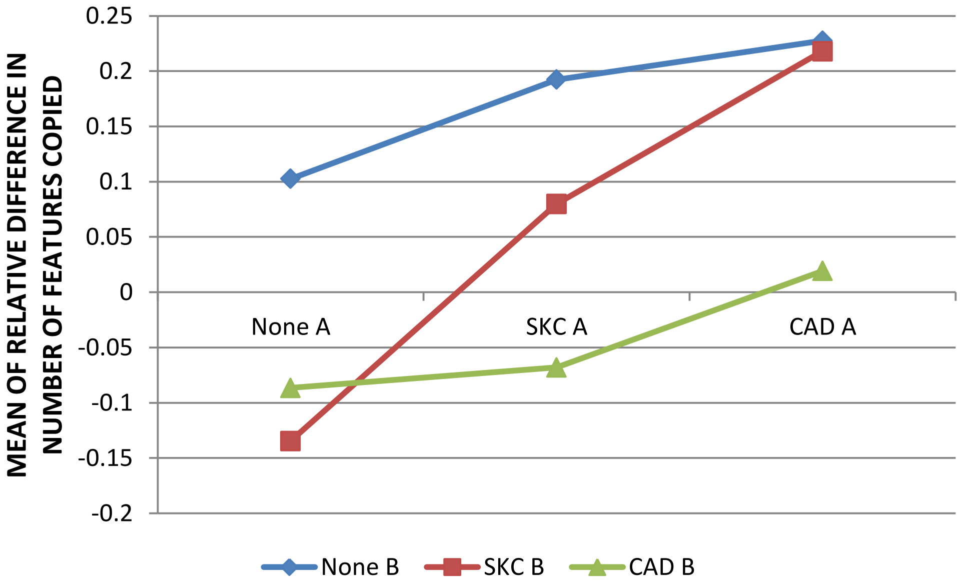


Figure 4.9: Interaction plot showing the three levels for each example.

4.7.2 Percentage of Example Features Copied From the Example

Looking at the conditions with two examples, Figure 4.10 shows the results of the percentage of example features copied from each of the two examples. The table also includes the control. Based on the results from the two-way ANOVA, we know that there are main effects based on the type of representation of designs (Table 4.3). Hypothesis 1 stated that for conditions with a CAD and Sketch representation, participants would fixate more to the features of the CAD example. A-priori t-tests were done on the conditions with two examples (conditions 1, 2, 4 and 5) to see if there was a significant difference copied from a design example based on representation. Table 4.4 shows the p-values from the a-priori analysis.

Table 4.4: A-priori p values for Conditions with Multiple Representations

Same or Different Representation	p-value	Condition Number & Description
Same Representation	0.89	1: CAD A & CAD B
Same Representation	0.93	5: Sketch A & Sketch B
Different Representation	0.007	2: Sketch A & CAD B
Different Representation	0.001	4: CAD A & Sketch B

We see very interesting results here. Fixation is occurring for all conditions. However, for conditions 2 and 4, where both a CAD and Sketch representation are given, we see that fixation to the CAD example is significantly higher irrespective of the example. The p values for these two conditions are 0.007 and 0.001 respectively. These are statistically significant results. For conditions 1 and 5 where two examples of the same representation are given, we see that there is no significant difference in the amount of features copied from the example. Hypothesis 1 is supported as such. It appears that the CAD representation is more likely to cause them to fixate over the Sketch representation when both representations are present. A Pearson's correlation of 0.86 was obtained for this metric.

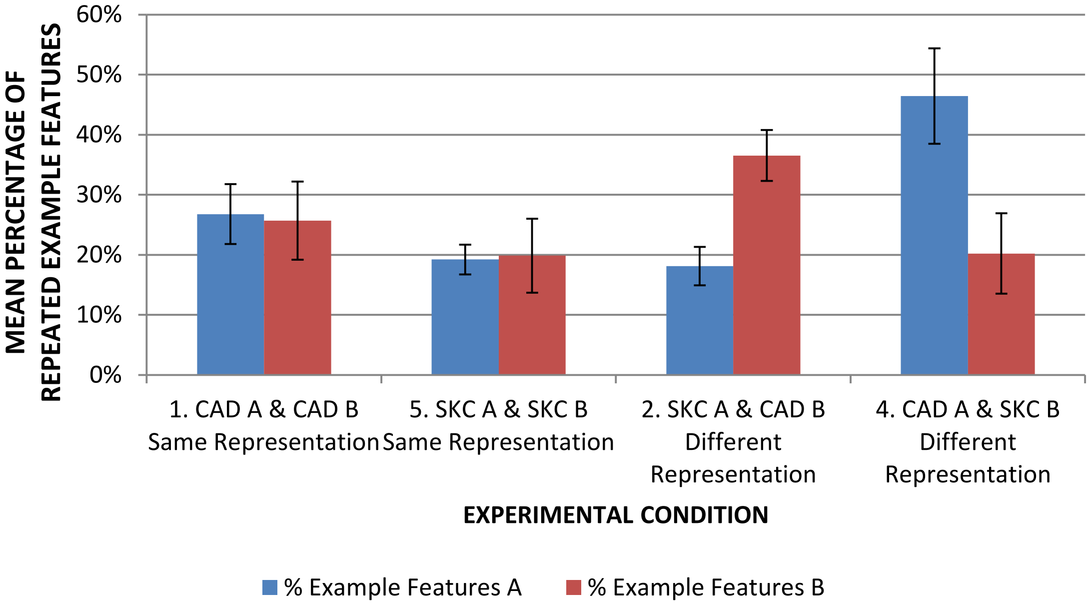


Figure 4.10: The mean percentage of example features used across conditions. All error bars show (±1) standard error.

4.7.3 Quantity of Non-Redundant Ideas

Results from the quantity of non-redundant ideas generated by the participants Figure 4.11 show that fixation to their own ideas is present. We see that all conditions, regardless of the number of examples received, are fixating with no statistically significant differences. The two-way ANOVA results give the main effects for representation of Design A and Design B to be F(2, 101) = 1.24 , p = 0.29 and F(2, 101) = 0.13, p = 0.88 respectively. We also see that there is no interaction between these two factors F(4, 101) = 0.33, *p* = 0.86. Table 4.5 shows the full two-way ANOVA results. The main effects and interaction plots are shown in Figure 4.12, Figure 4.13, and Figure 4.14.

Hypothesis 4 stated that the presence of more than one example will produce a greater quantity of ideas. This hypothesis is not supported since the number of features copied from the example features is not significantly influenced due to one example or more than one example being present. A Pearson's correlation of 0.88 was obtained for this metric.

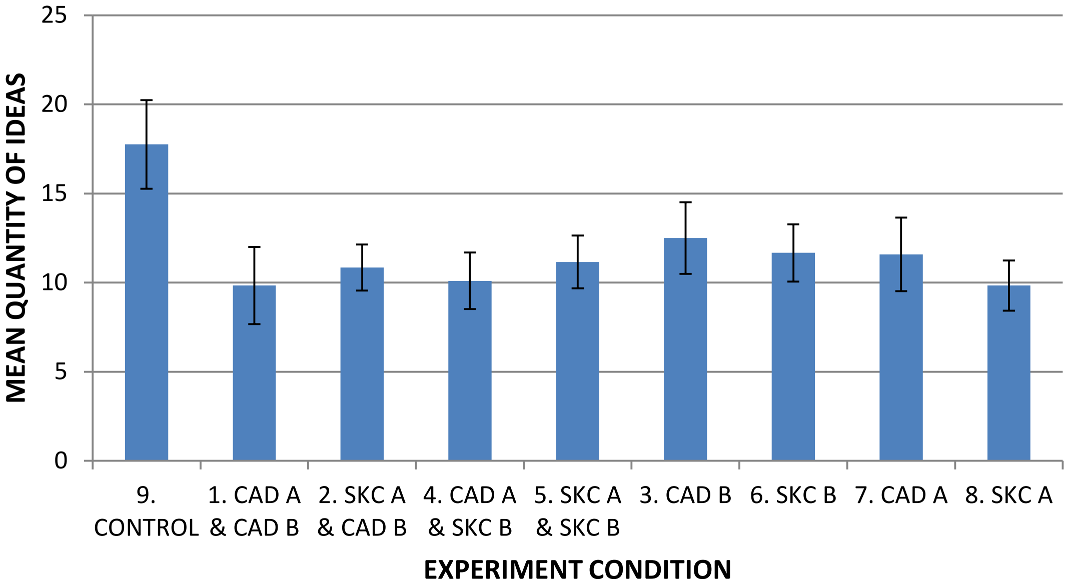


Figure 4.11: The mean quantity of non-redundant ideas across conditions. All error bars show (±1) standard error.

Table 4.5: Quantity of non-redundant ideas two-way ANOVA results

Tests of Between-Subjects Effects					
Source	Sum of Squares	Degrees of Freedom	Mean Square	F	P-value
Main Effect: RepA	88.7	2	44.4	1.24	0.29
Main Effect: RepB	8.92	2	4.47	0.13	0.88
Interaction: RepA * RepB	46.6	4	11.6	0.33	0.86
Error	36144	101	35.9		
Total	17177	110			

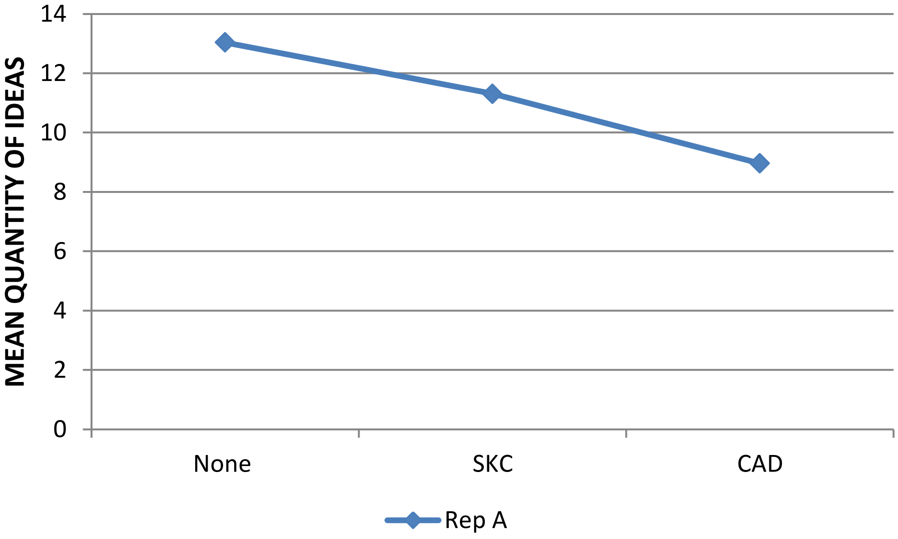


Figure 4.12: Main effects plot for Representation A for the Quantity of Non-Redundant Ideas

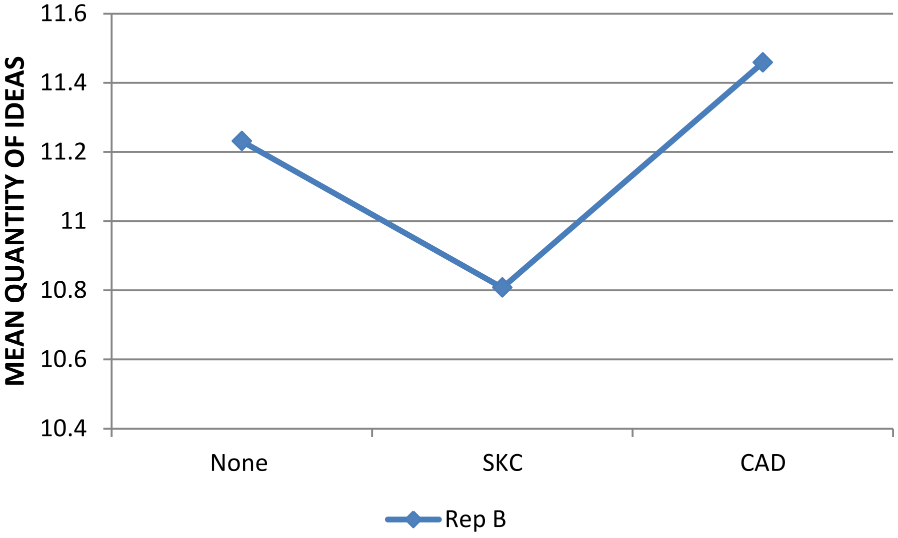


Figure 4.13: Main effects plot for Representation B for the Quantity of Non-Redundant Ideas

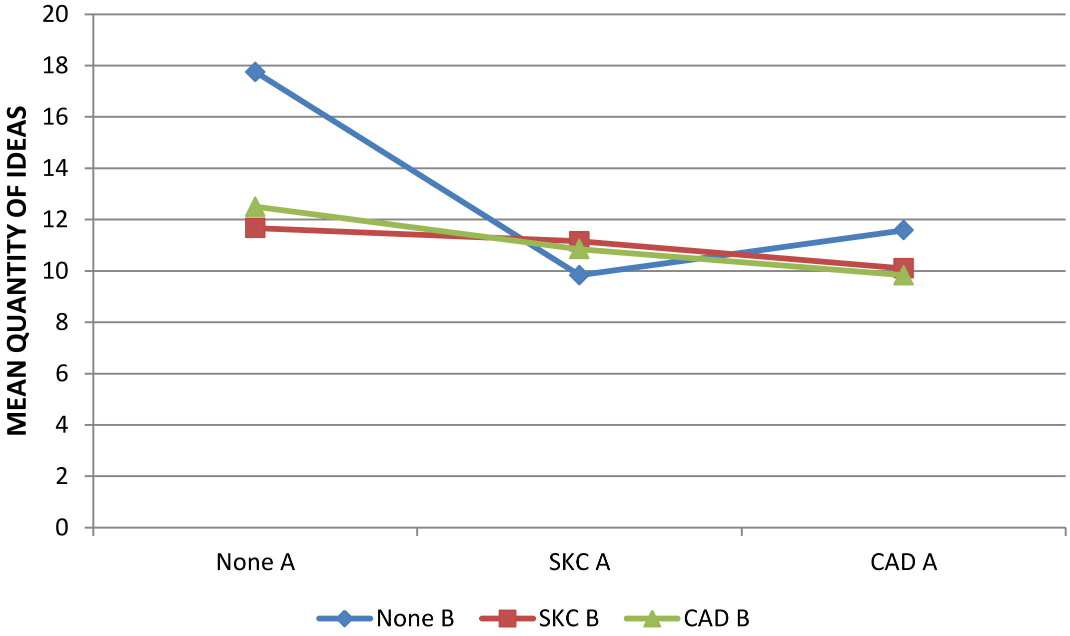


Figure 4.14: Interaction plot for Quantity of Non-Redundant Ideas

4.7.4 Quality of Design Concepts

The results from the quality of concepts metric are shown in Figure 4.15. The two-way ANOVA results give the main effects for representation of Design A and Design B in terms of quality to be F(2, 101) = 4.65 , $p = 0.01$ and F(2, 101) = 10.5, $p < 0.001$ respectively. There are statistically significant differences here. We also see that there is no interaction between these two factors F(4, 101) = 0.2, $p = 0.94$. Table 4.6 shows the full two-way ANOVA results. The main effects and interaction plots for quality are shown in Figure 4.16, Figure 4.17, and Figure 4.18. A discussion of the two quality hypotheses is given below. A Cohen's Kappa correlation of 0.72 was obtained for this metric.

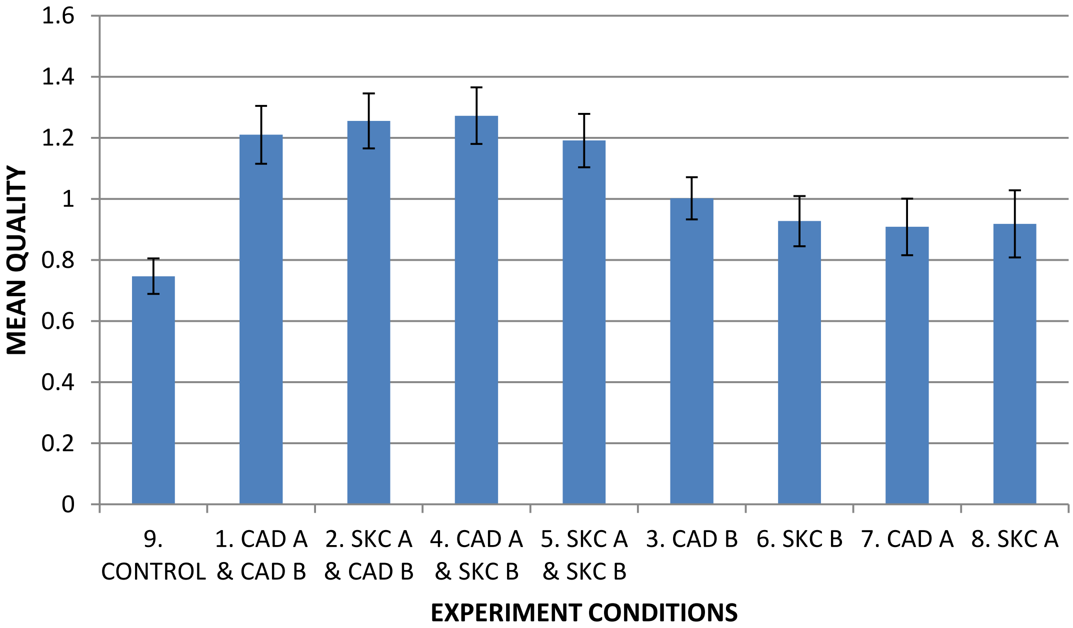


Figure 4.15: The mean quality of design concepts across conditions. All error bars show (±1) standard error.

Table 4.6: Quality two-way ANOVA results

Tests of Between-Subjects Effects					
Source	Sum of Squares	Degrees of Freedom	Mean Square	F	p-value
Main Effect: RepA	0.95	2	0.49	4.65	0.01
Main Effect: RepB	2.17	2	1.09	10.5	0.000
Interaction: RepA * RepB	0.08	4	0.02	0.20	0.94
Error	10.3	101	0.10		
Total	137	110			

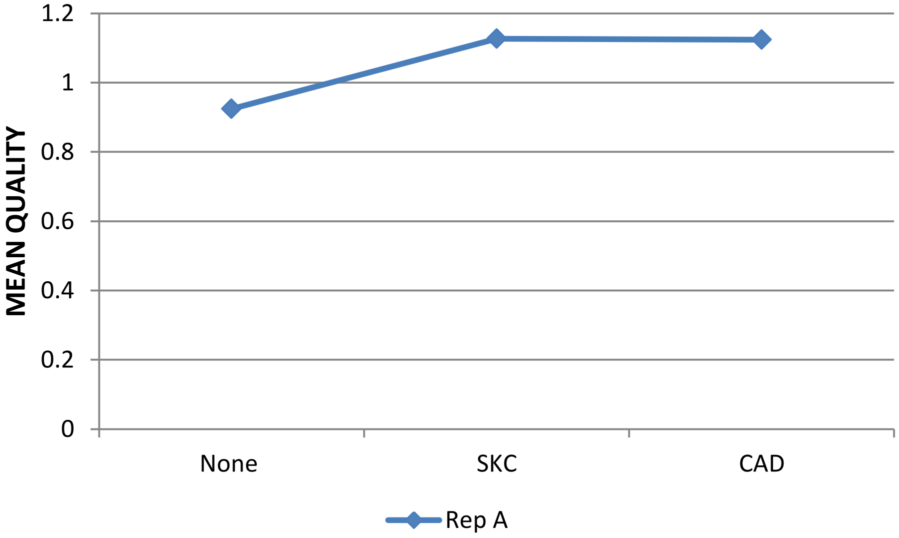


Figure 4.16: Main effects plot for Representation A for the Quality of Design Concepts

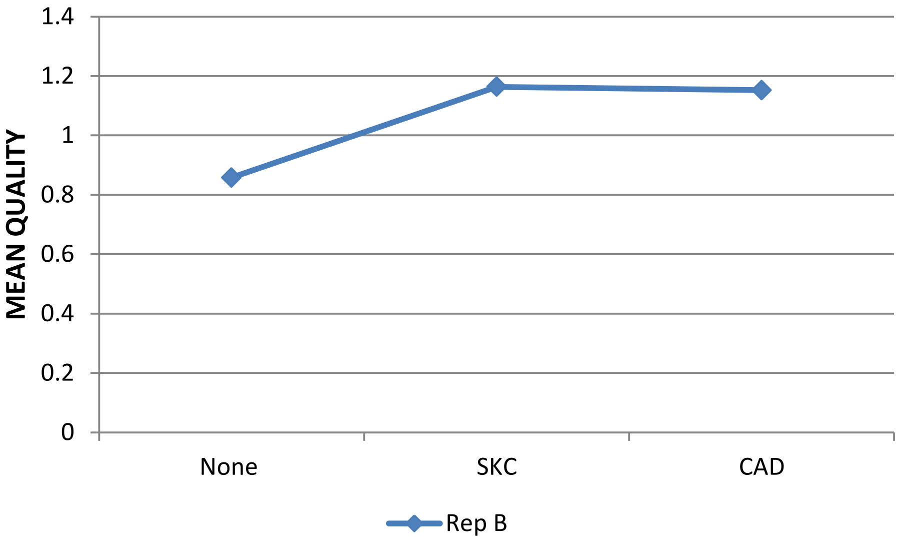


Figure 4.17: Main effects plot for Representation B for the Quality of Design Concepts

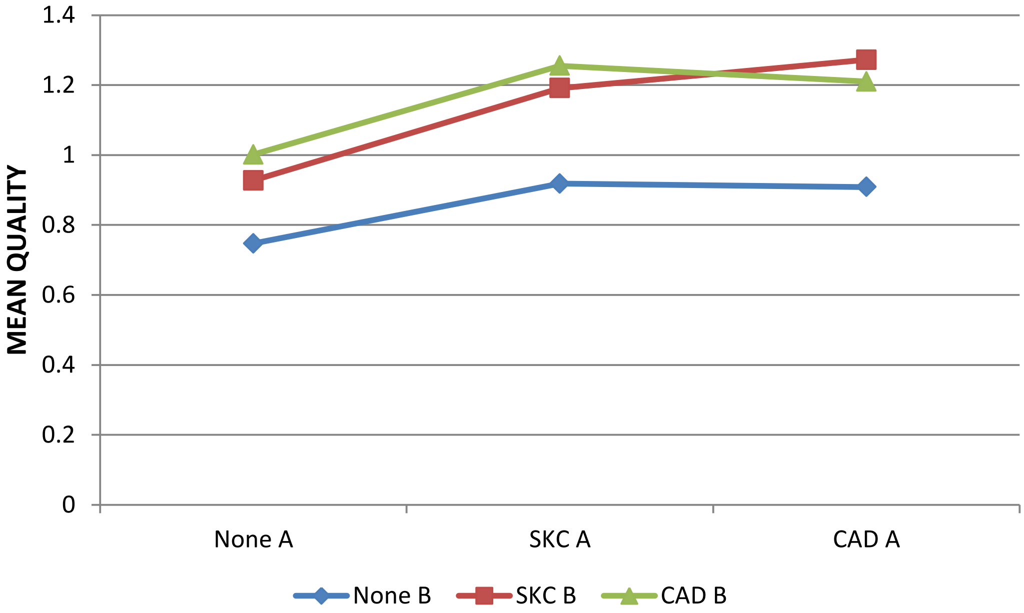


Figure 4.18: Interaction plot for Quality of Design Concepts

The percentage of high quality design concepts is shown in Figure 4.19. Consistent with the average quality scores, the results show the condition with two examples produced higher quality scores compared with conditions with one example.

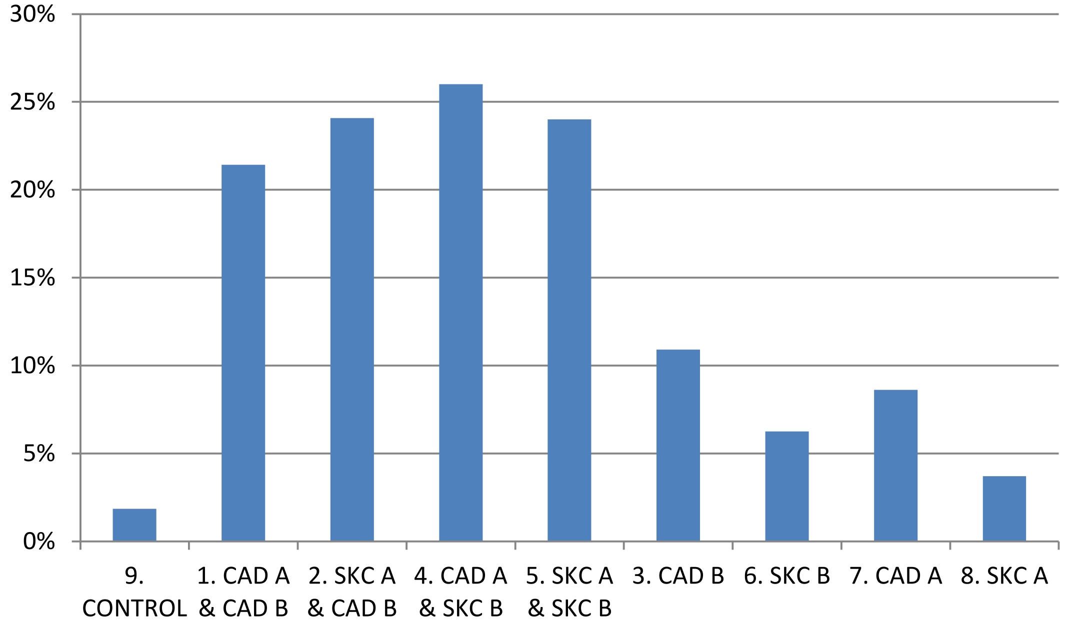


Figure 4.19: Percentage of High Quality Design Concepts

4.7.4.1 Quality: Comparing Representations

Due to the main effects of both Representation A and Representation B being statistically significant, post hoc t-tests were done to compare the nine conditions with each other. The conditions with two examples consisted of groups that had the same representation for both examples and different representations for both examples (e.g. CAD and CAD compared with CAD and Sketch). Hypothesis 2 stated that the presence of two different representations would allow for a greater quality of solutions compared with the same representation. However, no statistically significant results were seen (Table 4.7). This hypothesis is not supported. The presence of more than one example will produce higher quality designs regardless of if the examples are represented in the different ways or in the same way

Table 4.7: Comparing conditions with two examples and same representation with conditions with two examples and different representations

Conditions	p-value
CAD A & CAD B and Sketch A & CAD B	0.62
CAD A & CAD B and CAD A & Sketch B	0.54
CAD A & CAD B and Sketch A & Sketch B	0.99
Sketch A & CAD B and CAD A & Sketch B	0.89
Sketch A & CAD B and Sketch A & Sketch B	0.61
CAD A & Sketch B and Sketch A & Sketch B	0.53

4.7.4.2 Quality: Number of Example Given

Hypothesis 3 states being presented with two effective examples would result in higher quality solutions compared to being presented with one effective example. A post hoc t-test was also done to test this hypothesis. Comparing the conditions with one example to each other and to the control, no significant differences were seen. However, comparing the conditions with two examples with the control, we see statistically significant differences for all cases (see Table 4.8). Comparing the conditions with two examples with the conditions with one example also showed significant results for all conditions (Table 4.9 and Table 4.10). We see that participants who had two examples compared to one produced significantly higher quality design concepts. Hypothesis 3 is supported.

Table 4.8: Participants given two examples produce higher quality solutions than the control

Conditions Compared, condition numbers are in parenthesis	p-value
(1) CAD A & CAD B with (9) Control	0.001
(2) Sketch A & CAD B with (9) Control	0.000
(4) CAD A & Sketch B with (9) Control	0.000
(5) Sketch A & Sketch B with (9) Control	0.001

Table 4.9: Participants given two examples (same representation) produce higher quality solutions than the conditions with one example

Conditions Compared, condition numbers are in parenthesis	p-value
(1) CAD A & CAD B with (3) CAD B	0.008
(1) CAD A & CAD B and (6) Sketch B	0.007
(1) CAD A & CAD B and (7) CAD A	0.006
(1) CAD A & CAD B AND (8) Sketch A	0.007
Conditions Compared, condition numbers are in parenthesis	p-value
(5) Sketch A & Sketch B with (3) CAD B	0.006
(5) Sketch A & Sketch B and (6) Sketch B	0.005
(5) Sketch A & Sketch B and (7) CAD A	0.005
(5) Sketch A & Sketch B AND (8) Sketch A	0.007

Table 4.10: Participants given two examples (different representation) produce higher quality solutions than the conditions with one example

Conditions Compared, condition numbers are in parenthesis	p-value
(2) Sketch A & CAD B with (3) CAD B	0.006
(2) Sketch A & CAD B and (6) Sketch B	0.010
(2) Sketch A & CAD B and (7) CAD A	0.008
(2) Sketch A & CAD B AND (8) Sketch A	0.010
Conditions Compared, condition numbers are in parenthesis	p-value
(4) CAD A & Sketch B with (3) CAD B	0.010
(4) CAD A & Sketch B and (6) Sketch B	0.007
(4) CAD A & Sketch B and (7) CAD A	0.006
(4) CAD A & Sketch B AND (8) Sketch A	0.008

4.7.5 Novelty and Variety

The results for the novelty and variety metrics (Figure 4.20 and Figure 4.24) show that there are no statistically significant differences among all nine conditions. The main effects for the representation of the designs with respect to novelty are not significant, F(2, 101) = 0.02 , p = 0.98, and F(2, 101) = 0.12, p = 0.89. The interaction is also not significant, F(4, 101) = 0.43, p = 0.79. Table 4.11 shows the full two-way ANOVA results for Novelty. The variety metric also gives similar results, the main effects are no significant (F(2, 101) = 0.004 , p = 0.99, and F(2, 101) = 1.3, p = 0.28). The interaction is also not significant F(4, 101) = 0.17 , p = 0.96. Table 4.12 shows the full two-way ANOVA results for Variety. The main effects and interactions plots for Novelty are shown in Figure 4.21, Figure 4.22, and Figure 4.23. The main effects and interaction plots for Variety are shown in Figure 4.25, Figure 4.26, and Figure 4.27.

These results for novelty and variety show that there are differences for these metrics based on the type of representation of the examples and based on if one or two examples are presented. The same results (no significant differences were seen in study 1. Again, the way these metrics are measured may not be sensitive enough to measure difference. Discussion for improvement of these metrics is discussed in the conclusions in Chapter 7. Pearson's correlations of 0.87 and 0.91 were obtained for the Novelty and Variety metrics respectively.

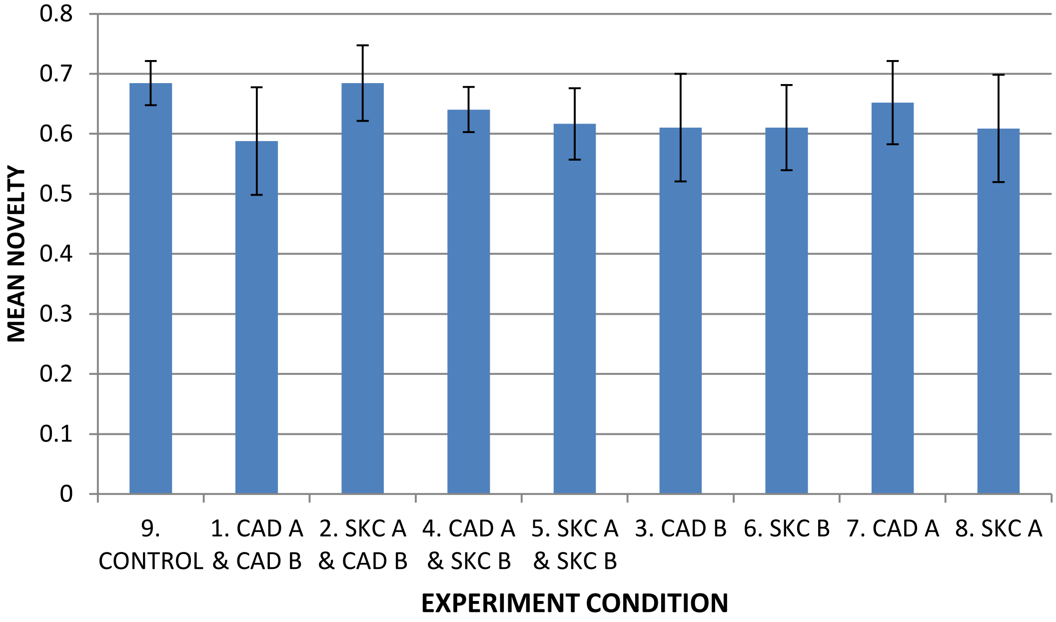


Figure 4.20: The mean novelty across conditions. All error bars show (±1) standard error.

Table 4.11: Novelty two-way ANOVA results

Tests of Between-Subjects Effects					
Source	Sum of Squares	Degrees of Freedom	Mean Square	F	p-value
Main Effect: RepA	0.002	2	0.001	0.02	0.98
Main Effect: RepB	0.01	2	0.01	0.12	0.89
Interaction: RepA * RepB	0.10	4	0.03	0.43	0.80
Error	6.01	101	0.07		
Total	50.2	110			

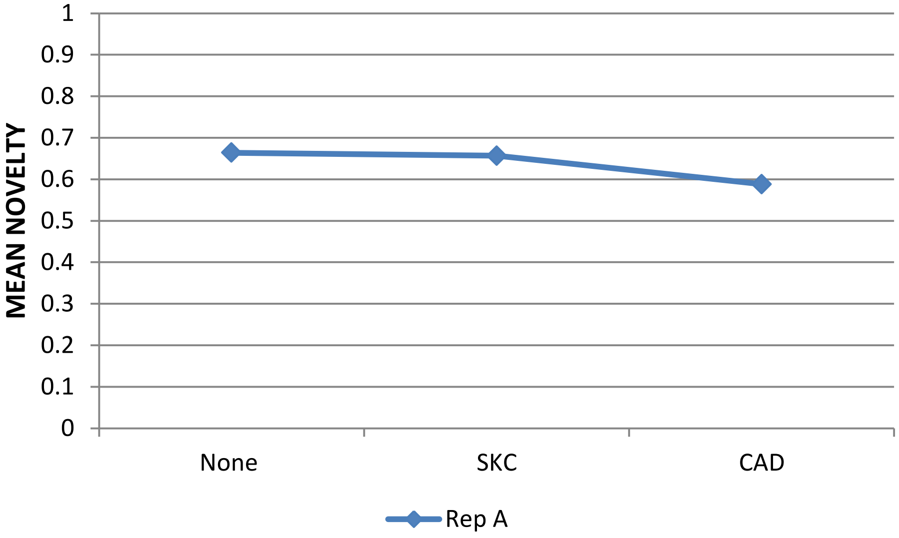


Figure 4.21: Main effects plot for Representation A for the Novelty

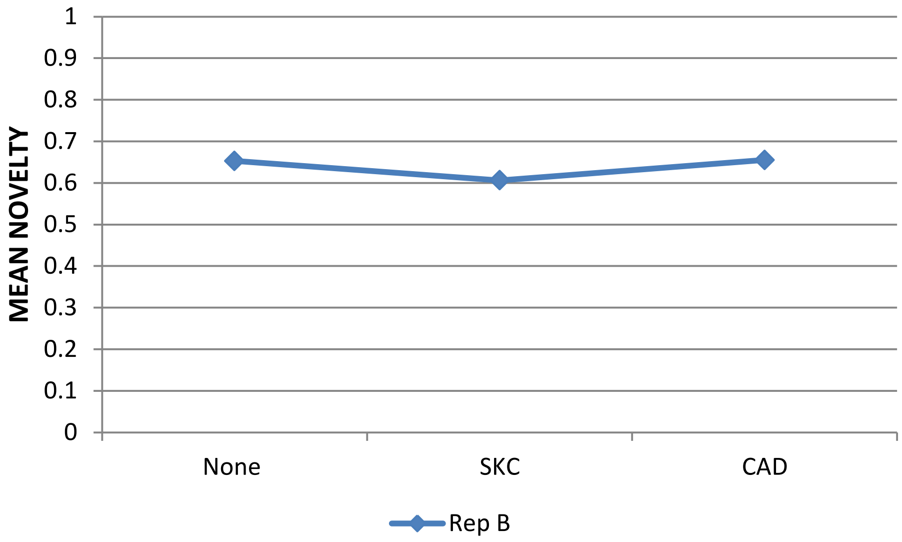


Figure 4.22: Main effects plot for Representation B for the Novelty

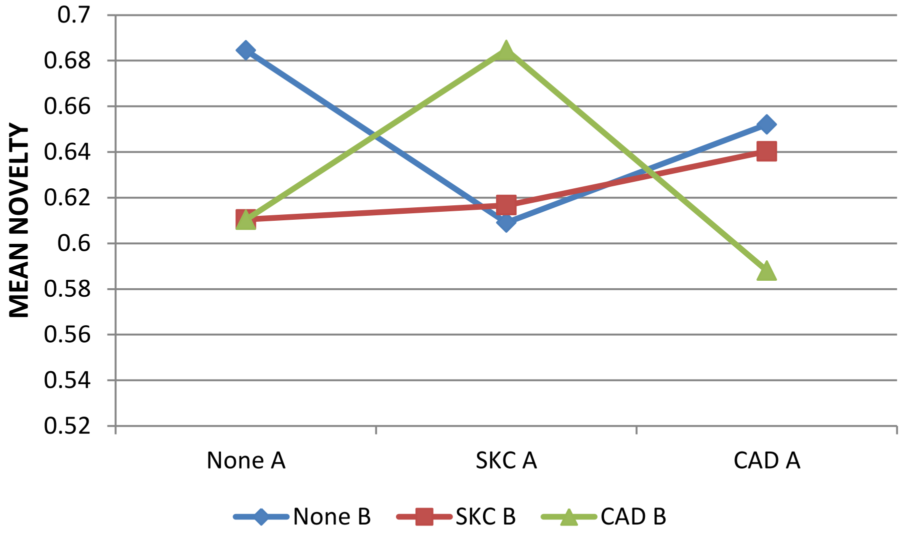


Figure 4.23: Interaction plot for Novelty

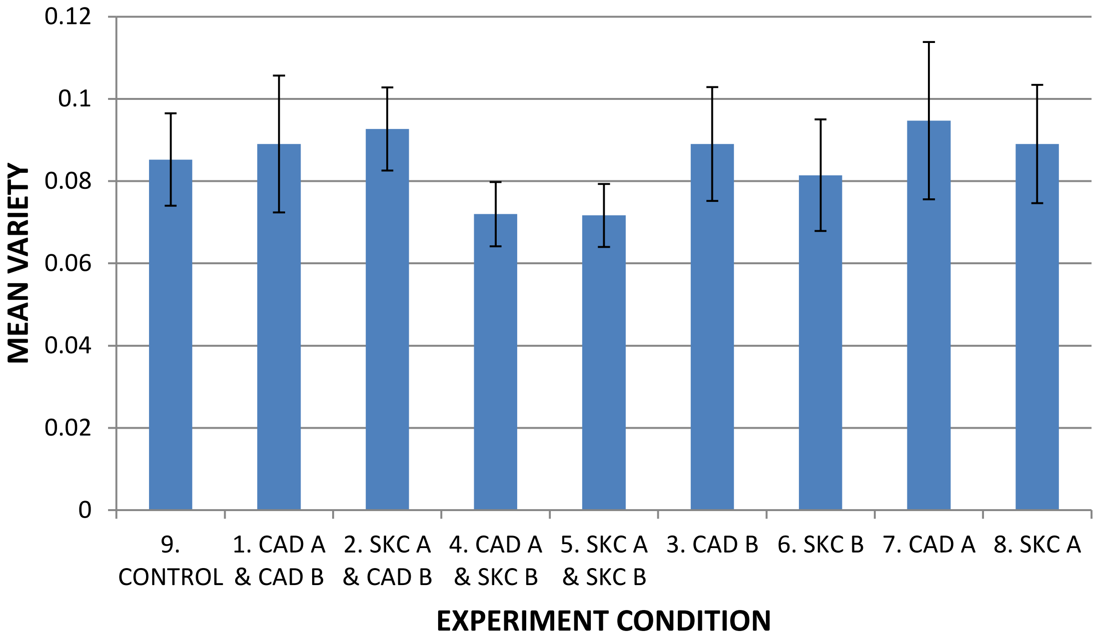


Figure 4.24: The mean variety across conditions. All error bars show (±1) standard error.

Table 4.12: Variety two-way ANOVA results

Tests of Between-Subjects Effects					
Source	Sum of Squares	Degrees of Freedom	Mean Square	F	p-value
Main Effect: RepA	1.500E-005	2	7.501E-006	0.004	0.99
Main Effect: RepB	0.005	2	0.003	1.30	0.29
Interaction: RepA * RepB	0.001	4	0.000	0.18	0.97
Error	0.21	101	0.002		
Total	1.01	110			

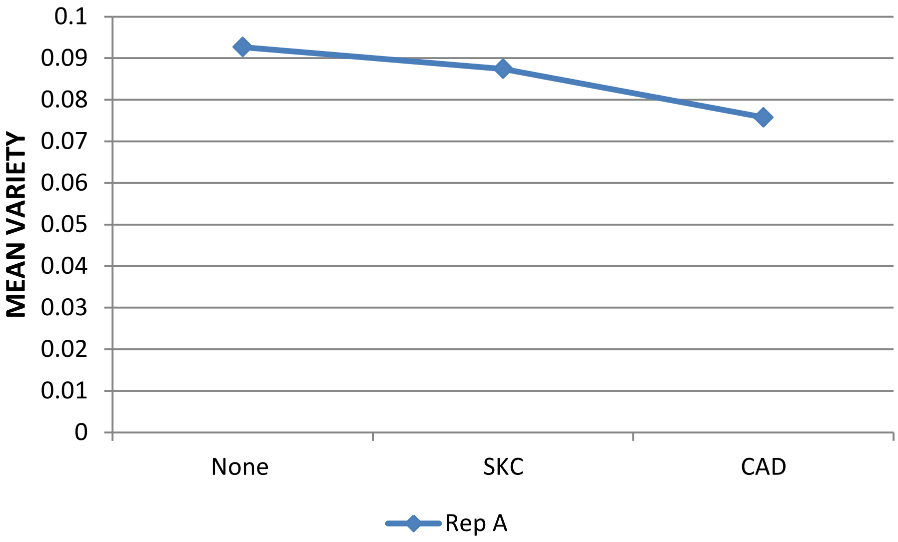


Figure 4.25: Main effects plot for Representation A for the Variety

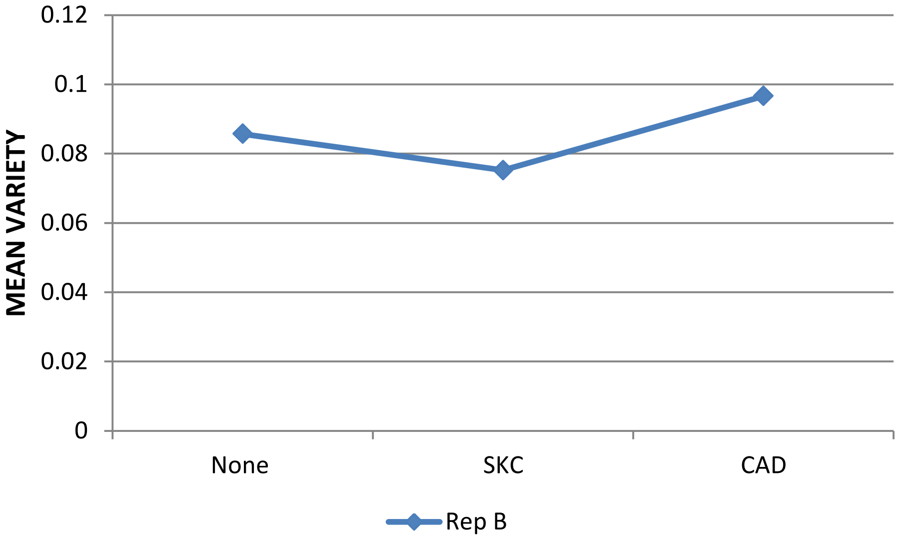


Figure 4.26: Main effects plot for Representation B for the Variety

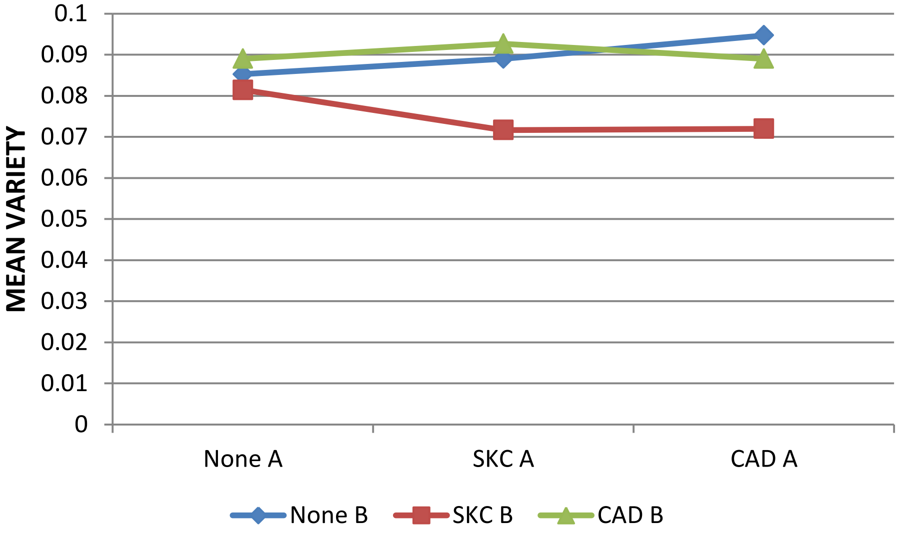


Figure 4.27: Interaction plot for Variety

4.7.6 Survey

A survey was given to the participants in all the conditions. For the conditions that received two design examples with the same representation, they were asked if they had a preference between the designs, i.e. Design A or Design B. If they specified that they did, they were asked to indicate which design they preferred. They were also asked which of the designs they perceived as more useful and as more complex.

The participants who received two design examples with different representations were also asked if they had a preference. If yes, they were asked which design they preferred, which design was more useful, and which design was more complex. In addition, they were asked which representation they preferred (i.e. CAD or Sketch).

The participants in the conditions with one example were asked if an addition example would have been useful during their idea generation. The Control condition was asked if an example provided to them would have been useful in their idea generation task. The full surveys given to all the conditions can be found in the Appendix B.

4.7.6.1 Participants Receiving the Same Representation

For the participants that preferred a design, 47% preferred Design A (The Full Belly Sheller) and 53% preferred Design B (the Maya Pedal Sheller). A Chi Square test $\chi^2(1,N=21) = 15.4$, $p = 0.79$, shows that there is no statistically significant difference in the preference level of the two designs, meaning that the participants preferred them equally. In terms of how useful the designs were in the idea generation task, 15% of the participants found Design A to be more useful, 20% found Design B to be more useful, and 65% found both to be equally useful. A Chi Square test $\chi^2(1,N=33) = 22.1$, $p = 0.86$ shows no statistically significant differences in how the participants perceived the designs to be useful. 30.8% of the participants found Design A to be more complex, 32.5% found Design B to be more complex, and 36.7% found both designs to be equally complex. A Chi Square test $\chi^2(1,N=29) = 13.6$, $p = 0.46$ again shows no differences in how the participants perceived the designs to be complex.

These results show that the participants who received two examples with the same representation did not have any preference to the either of the example. They also found the examples to the useful to their idea generation to about the same degree. The complexity of the two examples were also perceived to be the same.

4.7.6.2 Participants Receiving the Different Representations

The participants who received the design examples represented differently were asked which representation they preferred, 80.9% preferred the CAD representation and 19.1% preferred the Sketch representation. A Chi Square test $\chi^2(1,N=21) = 8.05$, $p = 0.005$ shows that there is a statistically significant difference in the participants' preference. Clearly, they preferred the CAD representation over the Sketch. This supports the results seen in the percentage of example features copied metric, where more features from the CAD example were copied than from the sketch example. It would appear that the participants have a significant preference to the CAD representation.

When asked which design they preferred, 58% answered Design A, and 42% answered Design B. A Chi Square test $\chi^2(1,N=24) = 19.2$, $p = 0.66$ shows that there is no preference in the designs. Since this includes two conditions (conditions 2 and 4) that received the examples represented in different ways, I will also analyze each of these two conditions separately to make sure that no effects due to the representation are missed. There were 12 participants each for both conditions. In condition 2, six participants received Design A as a CAD and Design B as a sketch, the other six received Design A as a CAD, and Design as sketch. The same procedure was carried out for condition 4. Table 4.13 shows the breakdown of the even distribution of the example representations in both conditions. As explained in experimental conditions in section 4.4, the examples were juxtaposed when presented to the participants, and the order of which example was presented first was varied equally. For Condition 2, 58% preferred Design A, and 42% preferred

Design B, and for condition 4, 50% preferred Design A and 50% preferred Design B. The statistical analysis shows no statistically significant differences (p = 0.56 and p = 0.95 respectively). These results show that there was no effect on the preference of Design A or Design B based on representation.

Table 4.13: The breakdown of Conditions 2 and 4 by Representation

	Condition 2	Condition 4
Design A	6 CAD	6 Sketch
Design B	6 Sketch	6 CAD

22.7% of the participants ranked Design A as more useful, 24.6% ranked Design B as more useful, and 52.7% ranked both as equally useful. A Chi Square test $\chi^2(1,N=38) = 4.21$, p = 0.52 shows no significant differences. In terms on complexity, 23.8% ranked Design A as more complex, 62.5% ranked Design B as more complex, and 13.6 ranked both to be equally complex. A Chi Square test $\chi^2(1,N=25) = 3.24$, p = 0.19 shows no statistically significant differences. These results show that the participants perceived the two examples to be equally useful to their idea generation. They did not tend to copy more features from one example because the felt that it was more useful. The same goes for the complexity, the participants were not drawn to an example because it was less complex or more complex. They also did not reject an example and copy more or less features from it because of its complexity. These results continue to support the case that the representation of the example if the reason for more features being copied.

4.7.6.3 *Participants Receiving One Example*

For the participants who received only one example, 68.8% indicated that an additional example would not have been useful during their idea generation, and 31.2% stated that an additional example would have been useful. A Chi Square test $\chi^2(1,N=47) = 7.68$, $p = 0.006$ shows a statistically significant difference in the participants' preference levels. The results from the quality metric showed that exposure to two examples producing higher quality scores compared with exposure to one example. It may be that the participants in this condition realized they were fixating and could not see any benefit of an additional example. It is also possible that the one example presented to them did not help them immensely in their idea generation. This is not conclusive, but it more of an assumption, as I did not test this.

4.7.6.4 *Participants Who Received No Example*

75% of the participants in the control condition, who received no example, stated that an example would be useful to them during idea generation. 25% stated that an example would not have been useful. A Chi Square test $\chi^2(1,N=12) = 3$, $p = 0.001$ shows a statistically significant difference in preference. It appears that the participants would rather design without an example. This may beneficial in some ways in not beneficial in some other ways. For example, though fixation is present due to the example exposure, the quality of concepts generated does increase when two examples are presented as opposed to one example presented.

4.8 Discussion of Results

The results from this study show that there are differences in the way that designers perceive CAD and Sketch images. Fixation to a CAD example is significantly higher compared with the Sketch example. It appears that CAD representations cause the designers to focus on them more and copy more of the features of CAD examples. This is further supported by the data from the survey where the majority of participants significantly preferred the CAD example to the sketch example. This result could be interpreted in many ways, one of which could be that CAD representations are detrimental or disadvantageous for idea generation because they cause fixation. However, as discussed in the literature review, fixation is not necessarily a negative consequence. If the aim is to draw attention to a particular example or component of a design, then CAD representations would likely be the ideal choice. This has implications for engineering education in the sense that since CAD representations capture the attention more and allow for the key principles to be identified (as seen in study 1), then instructors may want to represent examples of new machines or components that they want to teach to students in the form of a CAD drawing. This is also the same for design engineers who are trying to learn about a product or design in industry.

Other results show that though the participants copy more features from a CAD, there is an equal level of fixation for CAD versus sketch as seen in the results from the quantity of non-redundant features metric. This shows that though there is a bias to one representation, it does not limit the total number of redundant ideas generated.

The quality scores offer very interesting results. The quality of the solutions for the conditions with two examples is significantly higher compared with the conditions that only received one example. This result shows that conditions with multiple examples, as opposed to one, will increase quality. This was hypothesis 3, which was supported. The types of representations presented when multiple examples are presented have no effect on quality. One of the quality hypotheses (hypothesis 2) stated that conditions with different example representations would produce higher quality solutions compared with conditions where both examples are represented the same way. The results from this experiment show that this is not the case. As long as more than one example is present, the quality will increase. The novelty and variety scores offer no differences again indicating that a more sensitive or improved metric for measuring creativity needs to be explored.

Overall, the results from this study offer very interesting insights for designers and engineers, as well as engineering educators. CAD representations appear to be beneficial over sketch based on the reasons discussed above. The results from the survey also show that the participants had a significant preference to CAD representations compared to sketch representations. This is interesting and should be explored further to determine exactly why this is occurring. In summary, further studies on CAD representations compared with other forms of representations should also be explored to offer a more robust understanding of the advantages of CAD designs in engineering idea generation.

CHAPTER 5

STUDY 3 – THE EFFECTS OF FUNCTION TREES IN MITIGATING DESIGN FIXATION DURING IDEA GENERATION

This study comprises of an experiment that was designed to assess the effectiveness of function trees in reducing fixation to the features of an example. This experiment investigates if an example represented as a function tree reduces fixation compared to the same example represented as a sketch. The participants in this experiment were asked to solve a design problem with the help of an example. Four conditions with four corresponding representations were used. The four representations included a sketch of the example, a function tree example, a sketch with a function tree of the example presented together to see if there are any advantages in having a function tree present with sketch, and a control condition.

5.1 Hypotheses

Hypothesis 1: Fixation

Based on Viola et al.'s (Viola, et al., 2012) statement that the abstract view of function trees fosters the search for alternate solutions, I hypothesize that function trees will reduce fixation compared to sketch representations.

Hypothesis 2: Quality

I also hypothesize that function trees will produce higher quality designs since function trees enable designers to explore solutions systemically by mapping function trees to customer needs.

5.2 Design Task

The design task was the same as in Study 1 and Study 2: design a device to shell peanuts in developing countries. A different example from the one used in Studies 1 and 2 was given in this study and will be discussed in detail in Section 5.4.

5.3 Participants

The participants in this experiment were sophomore and junior undergraduate students at the Georgia Institute of Technology. Thirty-nine juniors and twenty-two sophomores participated. The juniors and sophomore were evenly distributed across the four conditions in this study. The participants were randomly assigned. Three conditions had 15 participants each and the fourth condition had 16 participants. One participant was removed from the third condition because he/she had seen the design problem before; this was discovered through a questionnaire given at the end of the experiment, which asked if the participants had seen the design problem prior to the experiment.

5.4 Experimental Conditions

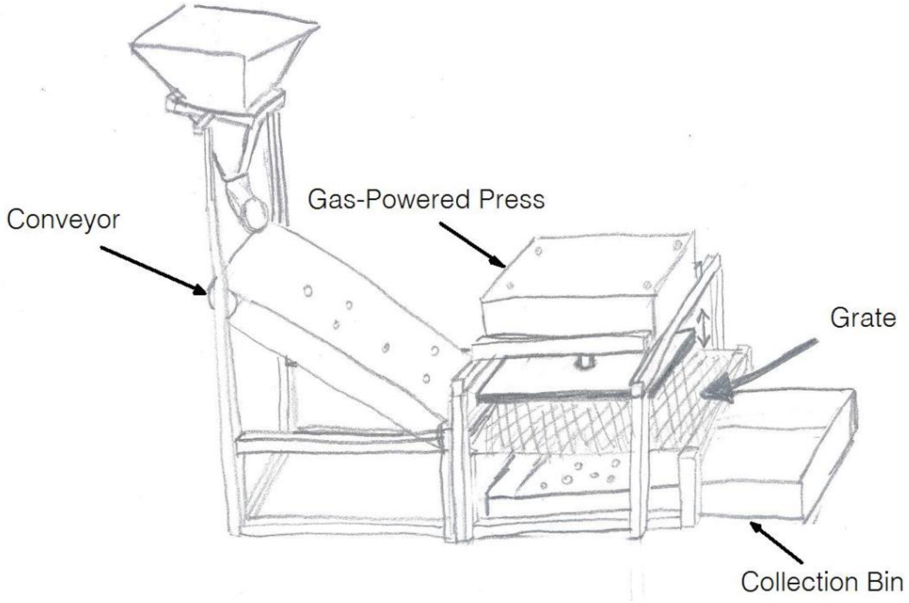
Four experimental conditions were designed for this experiment to measure the usefulness of function trees in reducing design fixation. A poor design example, a gas-powered press sheller, was given to the participants in various representations. Figure 5.1 shows the example and the solution description. Figure 5.2 shows the function tree of the example. The design chosen is one that has been used in other studies (Fu, et al., 2010; Linsey, et al., 2010; Viswanathan & Linsey, 2013a, 2013b, 2013c). In the first study in which it was used (Linsey, et al., 2010), the authors chose the example based upon features commonly found in participant solutions from prior experiments. Studies have shown that common examples cause more fixation than novel or unusual ones (Perttula & Sipilä, 2007), and poor examples cause more fixation than good examples (Fu, et al., 2010). The design is poor because it uses a gas-powered press, which uses an unsustainable and expensive energy source that would not be effective in the context of the design problem. This example was chosen because it has been proven to cause fixation, and I want to see how function trees may help to reduce this fixation. Table 5.1 shows the features and ideas within the gas-powered peanut sheller example that was provided to the participants.

Table 5.1: Functions of the example solution (Gas-powered press peanut sheller)

Function	**Features from Example**
[Material]	
guide	sloped surface
	conveyor
import	hopper
remove (shell)	crushing plate
separate (nut and broken shell)	winnowing
store	bin/basket
position	Table legs
[Energy]	
convert	Gas press

The experiment conditions and the representations given were:

- Sketch: the example was represented in the form of a sketch (Figure 5.1)
- Function tree: the example was decomposed into a function tree (Figure 5.2).
- Function tree & Sketch condition: the sketch of the example as well as the function tree were presented to the participants
- Control: no example or representation was provided



Solution Description: This system uses a gas powered press to crush the peanut. The peanuts are pressed against the grate and the shells are broken. The grate separates the nuts from the broken shells; the nuts then fall into a collection bin.

Figure 5.1: Sketch of example used in Study 3

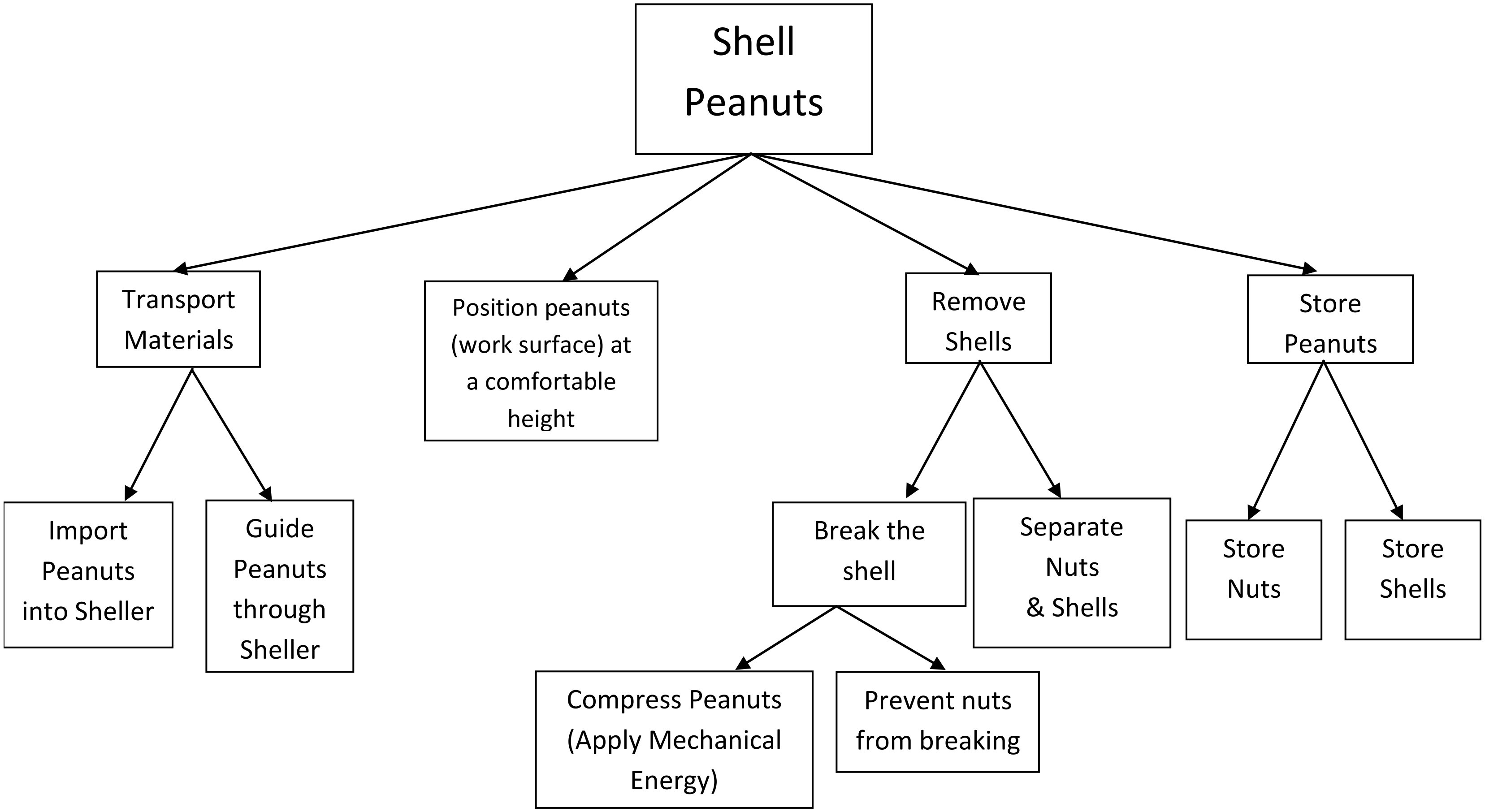


Figure 5.2: Function tree of example used in Study 3

5.5 Experimental Procedure

The experimental procedure used in this study is the same as in Studies 1 and 2. However, this experiment took place in a controlled laboratory setting and not a controlled classroom setting.

5.6 Evaluation Metrics

The evaluation metrics used in this study are the same as in Studies 1 and 2. Another metric, Percentage of Solutions using a Gas Engine, was added to this experiment. This was done in order to measure the fixation to the poor or negative feature the example used here, i.e., the gas-powered press.

5.7 Results

Non-parametric Kruskal-Wallis tests were performed on the data in this experiment. This non-parametric test was used because the data did not satisfy the normality and homogeneity of variance requirements, i.e. the data was not normally distributed. The p-values for the normality and homogeneity of variance tests were above 0.05 for all metrics, $p > 0.05$. Therefore, one-way ANOVA results would not be reliable. Pair-wise a-priori comparisons using Mann-Whitney tests were also employed, which are equivalent to t-tests for non-parametric data.

5.7.1 Quantity of Non-Redundant Ideas

Figure 5.3 shows the results from the quantity of non-redundant ideas metric. The Kruskal-Wallis test gives $\chi^2 = 2.19$, df = 3, $p = 0.083$. Fixation is present in the sketch condition. There is a statistically significant difference when comparing the sketch and the control condition (Mann-Whitney test, U(3) = 79, Z =-1.394, *p* = 0.038). However, there are no statistically significant differences when comparing the function tree condition to the control and the sketch & function tree condition to the control. Comparing the sketch condition to the function tree condition, we see that there is a significant difference (Mann-Whitney test, U(3) = 83.5, Z = -1.21, *p* = 0.043), but there is no significant difference when comparing both the sketch and function tree conditions to the sketch & function tree condition. These results show that, while the function tree condition does not break fixation, it does reduce fixation compared to the sketch condition. Hypothesis 1, which stated that function trees would reduce fixation compared to sketch representations, is supported. The combination of a sketch and function tree does not provide any benefit for reducing or breaking fixation. A Pearson's correlation of 0.87 was obtained for this metric.

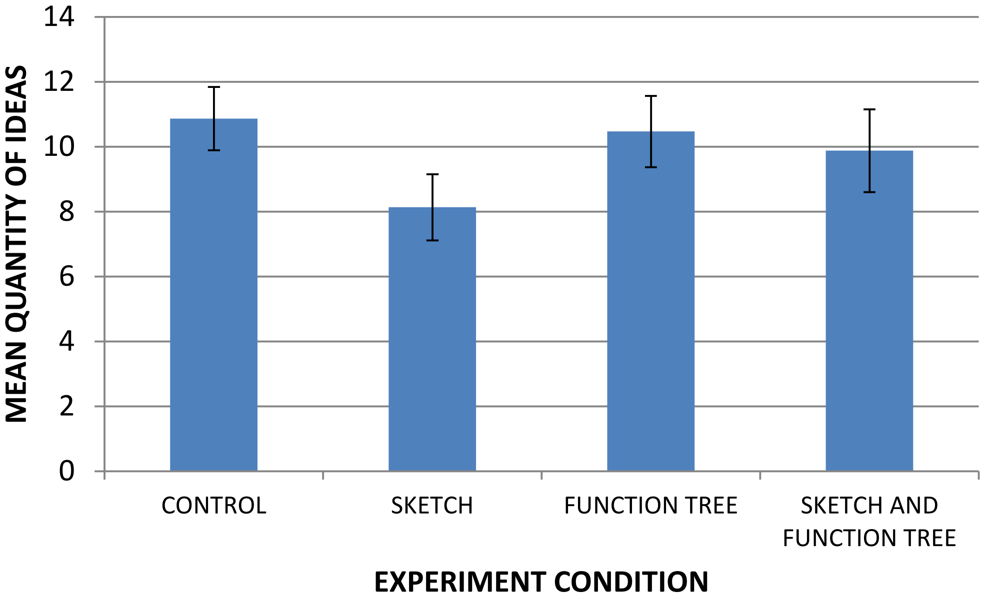


Figure 5.3: The mean quantity of non-redundant ideas across conditions. All error bars show (±1) standard error.

5.7.2 Number of Repeated Example Features and Percentage of Example Features Used

The repeated example features and percentage of example features used gives similar results as the quantity of non-redundant ideas metric. All three metrics are indicators of fixation. For this metric, it is important to note that we cannot compare all conditions with each other. The two conditions that cannot be compared are the sketch and the function tree conditions. Since participants within the function tree condition received the function of the example but not the means or features, their using an example feature does not necessarily indicate fixation to the example but rather fixation to features required to meet the functional need of the design problem. The function tree condition in this metric also acts as a control for examining the benefits of having a sketch and a function tree together during idea generation. From Figure 5.4, we see that fixation is present for the sketch and sketch & function tree conditions; the Mann-Whitney test comparing the control to the two conditions respectively are $U(3) = 22.5$, $Z = -3.748$, $p < 0.001$ and $U(3) = 16$, $Z = -4.122$, $p < 0.001$. When we compare the control to the function tree condition, there is no statistically significant difference ($U(3) = 51.5$, $Z= -2.551$, $p = 0.127$). This result shows that having a function tree as a stimulus compared to no stimuli does not make much of a difference. The function tree neither causes nor reduces fixation. This is consistent with the results from quantity of non-redundant features metric, and these results also support hypothesis 1.

The results also show that the greatest amount of fixation is present in the sketch & function tree condition. There are statistically significant differences when comparing the sketch & function tree condition to both the sketch condition and the function tree condition ($U(3) = 87$, $Z= -1.31$, $p = 0.031$ and $U(3) = 37$, $Z= -3.3\text{-}2$, $p = 0.001$ respectively). This tells us that having a combination of a sketch and function tree actually reinforces fixation to the features of the example. The percentage of example features copied, Figure 5.5, gives similar results. The Kruskal-Wallis test results for the two metrics are $\chi^2 = 28.46$, $df = 3$, $p < 0.001$ and $\chi^2 = 30.4$, $df = 3$, $p < 0.001$, respectively. A Pearson's correlation of 0.97 was achieved for these two metrics.

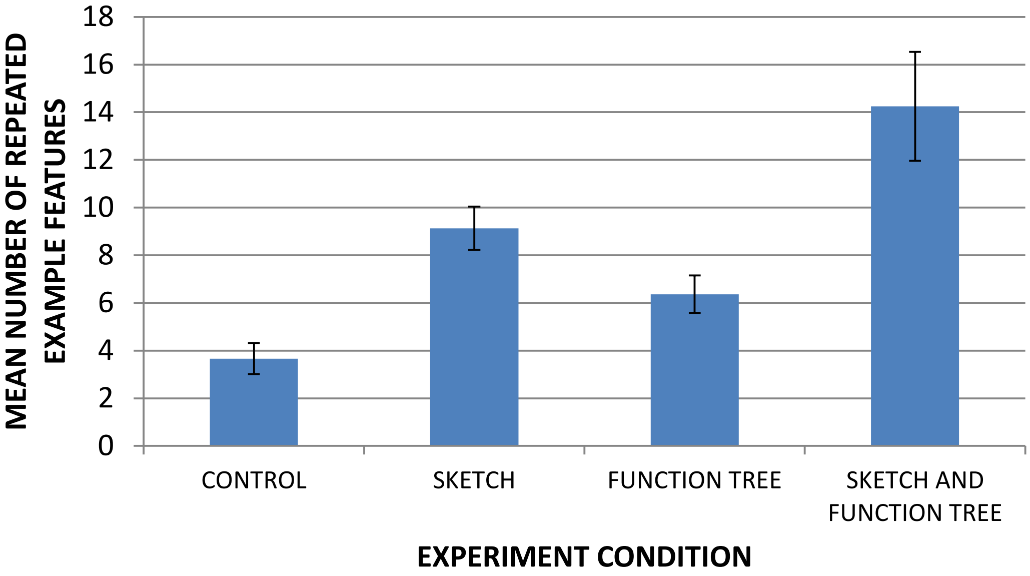


Figure 5.4: The mean number of repeated example features across conditions. All error bars show (±1) standard error.

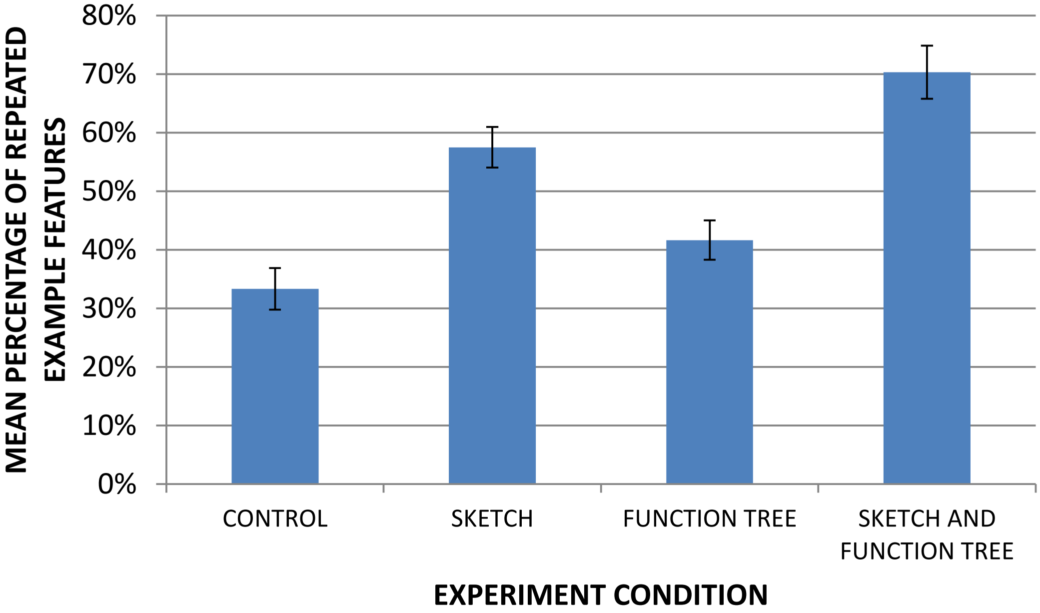


Figure 5.5: The mean percentage of example features used across conditions. All error bars show (±1) standard error.

5.7.3 Quality of Design Concepts

The results from the quality of design concepts, displayed in Figure 5.6, show that the function tree condition has the highest quality score and that there is a statistically significant difference when compared to the other three conditions. The Mann-Whitney results are U(3) = 77.5, Z = -1.485, $p = 0.039$; U(3) = 88.5, Z= -1.015, $p = 0.043$; and U(3) = 76.5, Z = -1.737, $p = 0.036$ for the control, sketch, and sketch & function tree conditions, respectively. There are no statistically significant differences when comparing the other conditions to each other. The Kruskal-Wallis test gives $\chi^2 = 3.57$, df = 3, $p = 0.08$. These results show that a function tree representation increases quality over having a sketch or even a sketch in combination with a function tree; Hypothesis 2 is supported. We also see here that the combination of a sketch and function tree does not give any added benefits compared to sketch alone in producing high quality solutions. A Pearson's correlation of 0.67 was obtained for the quality metric.

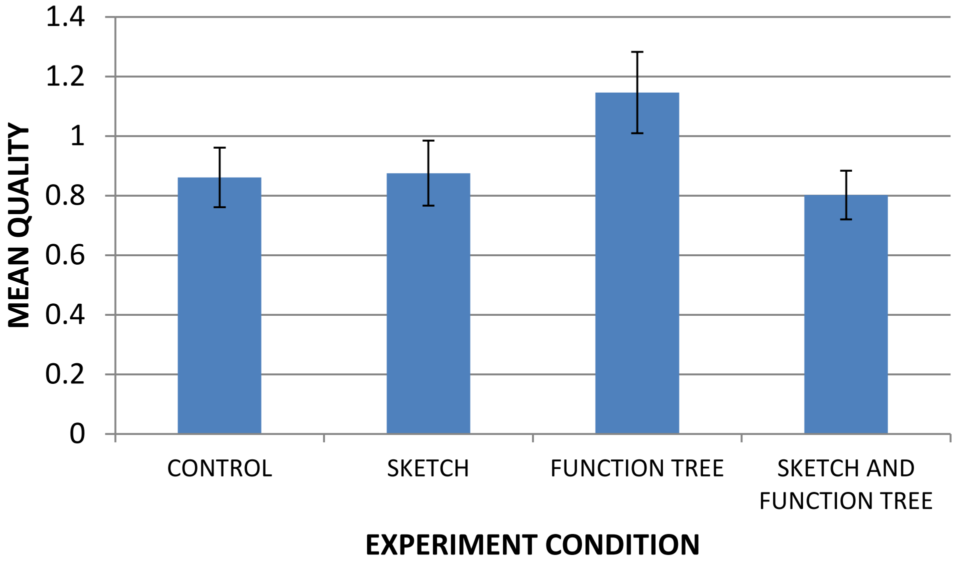


Figure 5.6: The mean quality of design concepts across conditions. All error bars show (±1) standard error.

Figure 5.7 shows the percentage of high quality design concepts. The results show that the function tree produced the highest amount of high quality design concepts.

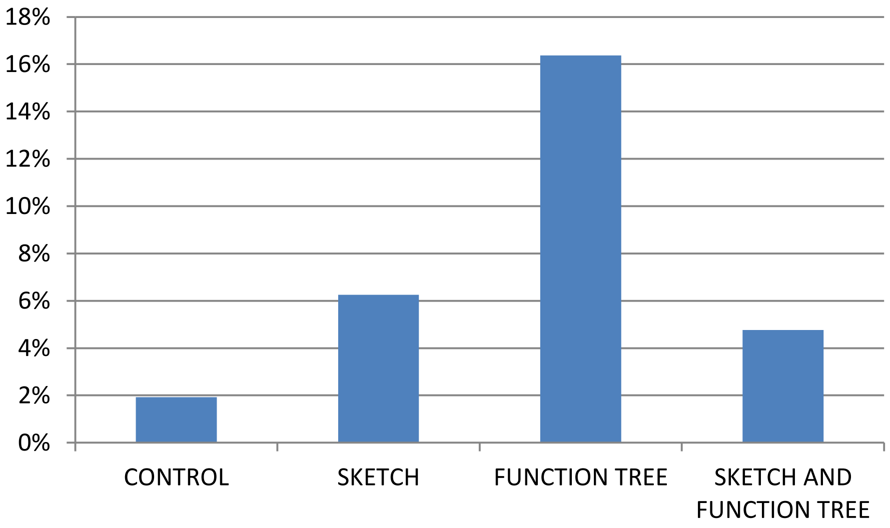


Figure 5.7: Percentage of High Quality Design Concepts

5.7.4 Novelty and Variety

The novelty and variety results are shown in Figure 5.8 and Figure 5.9, respectively. There are no significant differences when comparing conditions for the two metrics. This was also seen in studies 1 and 2. The Kruskal-Wallis test gives $\chi^2 = 0.762$, df = 3, $p = 0.859$ for the novelty scores and $\chi^2 = 0.107$, df = 3, $p = 0.991$ for the variety scores. Again, the novelty and variety metrics may lack sensitivity. Pearson's correlations of 0.91 and 0.86 were obtained for the novelty and variety scores, respectively.

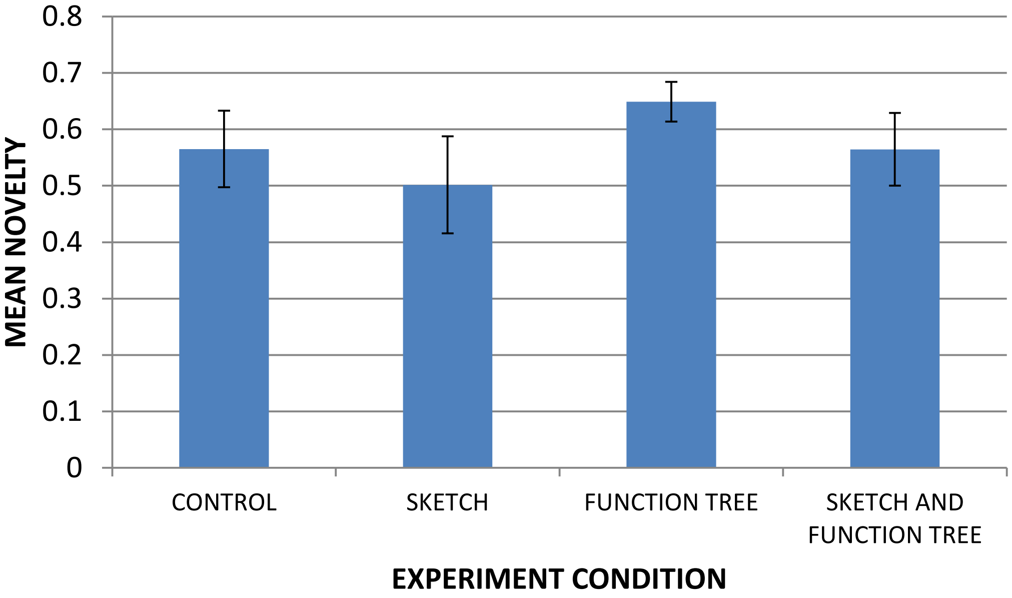


Figure 5.8: The mean novelty across conditions. All error bars show (±1) standard error.

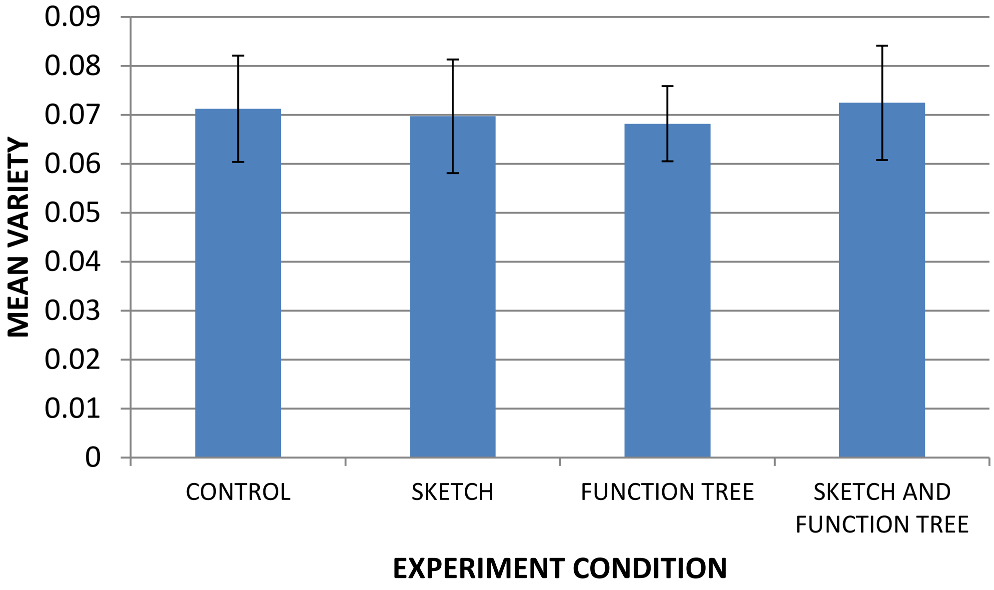


Figure 5.9: The mean variety across conditions. All error bars show (±1) standard error.

5.7.5 Percentage of Solutions Using a Gas Engine

From Figure 5.10, we see that sketch and sketch & function tree conditions used gas engines as an energy source for their design solutions. The control and function tree conditions did not use any gas engines in their designs. This was somewhat expected as the control group did not receive an example with one in it. The function tree did not include the means of crushing, i.e., the gas-powered press. Though the sketch & function tree condition used a higher percentage of gas-powered solutions compared to the sketch condition, the difference is not significant (p = 0.21). These results show evidence of fixation to the type of energy source in the example. The presence of the function tree in the sketch & function tree condition does not help to break this fixation. A Pearson's correlation of 0.88 was obtained for the percentage of solutions using a gas engine.

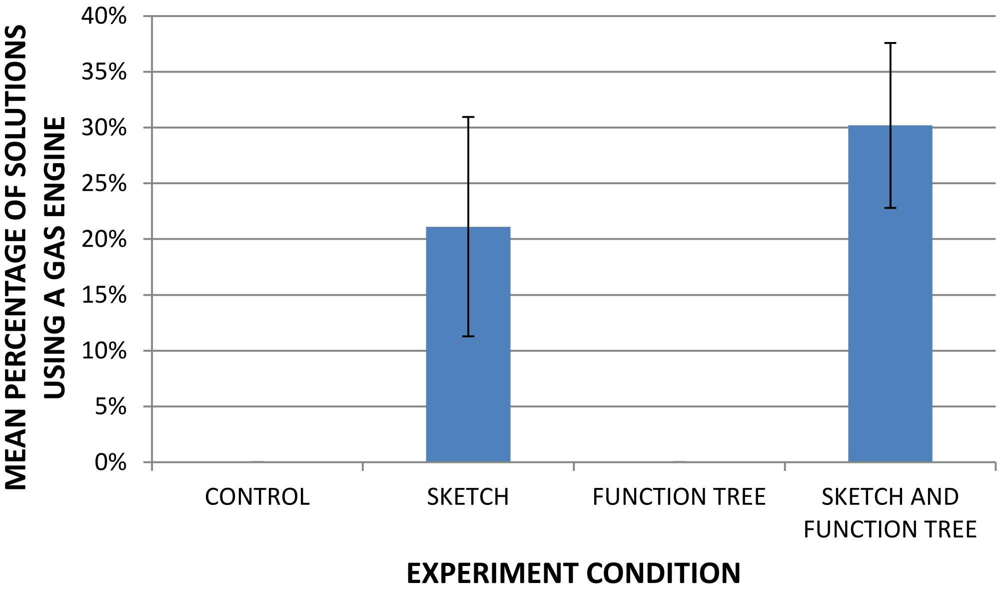


Figure 5.10: The mean percentage of solutions using a gas-powered press across conditions. All error bars show (±1) standard error.

5.8 Discussion of Results

The results from this study show that function tree representations are effective in reducing fixation when compared to a sketch representation. No difference is seen when comparing the function tree to the control condition, which indicates that function trees do not break fixation, but more importantly, also do not cause fixation. This supports Hypothesis 1, which states that function trees will reduce fixation compared to a sketch representation. No differences were seen when comparing the function tree to the sketch & function tree condition as well. These results show that having these two representations together has no effects on fixation on one's own ideas.

When we look at fixation to the features of the example, we again see that there is no significant difference between the control and function tree condition. This indicates that functional representations of examples do not cause fixation. When comparing the sketch with the sketch & function tree condition, we see that the sketch & function tree condition is highly fixated to the features of the example, compared to just the sketch condition alone. This tells us that having a combination of a sketch and function tree reinforces fixation to the features of the example. It is likely that, when the participants see the functions that need to be met in the function tree, they tend to meet and satisfy those functions with features from the given example that they are viewing at the same time. The same trend is seen when comparing the function tree to the sketch & function tree condition: fixation increases when a sketch and function tree are both present. These results indicate that the benefits of fixation reduction when using function trees are only present when the function tree is used alone; the addition of a sketch to the function tree promotes fixation.

The quality results show another benefit of the function tree: the quality score for the design concepts in the function tree condition is significantly higher than the scores for all of the other three conditions. I believe this is so because the function tree clearly lays out all the functions that need to be met without introducing specific or extraneous features like a sketch representation does. This result supports the second hypothesis.

The novelty and variety scores show no differences across all conditions. It appears that all conditions successfully explored the design space to the same degree, or that this metric is not sensitive enough as seen in studies 1 and 2. The percentage of energy sources using a gas engine metric shows fixation to the gas engine in the sketch and sketch & function tree conditions with no significant differences between the two. The combination of the sketch and function tree did not break the fixation to this poor feature of the example.

This study has provided very interesting results pertaining to the use of function trees in engineering design. The results show that that function trees of examples are more effective at reducing fixation compared with sketch representations. Function trees also do not cause fixation either to a designer's ideas or to the features of the example. While function trees do not break fixation, they do produce a higher quality of solution concepts compared to having a sketch example, a combination of a sketch and a function tree, or when no example is present at all. I initially believed that providing more information to designers, i.e., a sketch and a function tree together, would increase any benefits given by the function tree. The results show that this is not the case and that the combination of these representations in an idea generation task increases fixation while also reducing quality.

The results from this study indicate that function trees are a viable representational form to be used in idea generation procedures to avoid fixation and improve the quality of generated ideas and solutions.

CHAPTER 6

STUDY 4 – USING ANALOGIES IN ENGINEERING IDEA GENERATION

This study describes the implementation process of biological examples as sources analogues during engineering idea generation to develop solutions for a real-world problem. In support of the Department of Energy SunShot Initiative, a national collaborative effort to make solar energy cost-competitive with other forms of electricity by the end of the decade, solar panel designs were carried out by engineering and architectural design teams. Solar Photovoltaic (PV) systems were developed using analogical design, and more specifically, bio-inspired design. Some systems were also designed using non-biological analogues. This study outlines the procedures and methods used for the problem-driven biologically inspired design approach taken. Analyses on the effectiveness of the design solutions and concepts developed are also presented.

6.1 The Context of the Study

Solar energy offers a number of strategic benefits to the United States. Replacing fossil-fuel combustion with solar energy reduces emissions of human-induced greenhouse gases (GHGs). Sunlight is a free resource. Thus, installed solar technologies have a very low operating cost and require minimal non-solar inputs. This provides insurance against conventional fuel supply disruptions and price volatility (Margolis, Coggeshall, & Zuboy, 2012). Despite these benefits, solar energy currently supplies only a small fraction of the U.S. energy needs. To make solar energy competitive with the wholesale rate of electricity without additional subsidies, balance of system (BoS) costs must be reduced. Solar photovoltaic (PV) system prices incorporates module as well as balance of system costs, these balance of systems include the inverter, mounting and racking hardware and labor, electrical hardware and labor, monitoring equipment and soft costs associated with inspection, interconnection agreement, overheads, and profit (Goodman, Yen, Gentry, Nagel, & Amador, 2012). Currently, BoS accounts for more than 40% of the total installed cost of the solar energy systems.

The U.S. Department of Energy (DOE) is providing a strong, coordinated effort through its SunShot Initiative to enable solar energy technologies to become increasingly cost competitive with conventional electricity-generation technologies in the United States over the decade. Launched in 2011, the SunShot Initiative aims to reduce the price of solar energy systems by about 75% between 2010 and 2020 (Margolis, et al., 2012). Achieving this target is expected to make the unsubsidized cost of solar energy competitive with the cost of other currently operating energy sources, paving way for a rapid, large-scale adoption of solar electricity across the United States. In support of this initiative, the U.S. DOE awarded a grant to researchers at the Georgia Institute of Technology to develop commercially-ready, next generation solar PV BoS designs (Suniva, 2011). The project, titled "SIMPLE BoS" (Solar, Installation, Mounting, Production, Labor and Equipment), is led by the Georgia Tech Research Institute (GTRI) in collaboration with the Rocky Mountain Institute, a nonprofit think-and-do tank, and industry partners Suniva, Inc., and Radiance Solar. Suniva is a solar panel manufacturing firm, and Radiance Solar is a solar power installations provider that offers distinct services in system design and engineering, construction, as well as operating & maintenance, solar energy consulting, and large-scale project development.

A unique aspect of the SIMPLE BoS process is the partnership with the Center for Biologically Inspired Design (CBID) and the College of Architecture's Digital Fabrication Lab (DFL) at Georgia Tech. The School of Mechanical Engineering is also involved in the project. Through CBID partnership with engineers, architects, and biologists, interdisciplinary research into biosensors, biomaterials, locomotory, biosystems, and cognition has been accomplished (Center for Biologically Inspired Design, 2005). By embracing an interdisciplinary approach, innovative ideas for solving current problems with solar panel design can be designed and revised for efficiency (Goodman, et al., 2012). The DFL supports manufacturing, fabrication, prototyping, construction, and the subsequent testing and analysis of fabricated assemblies and materials. The resources of the laboratory have been used to quickly realize the SIMPLE BoS mockups supporting early phase design decisions, see Figure 6.1.

Within the parameters of the DOE grant, the specific goal of the SIMPLE BoS team is reducing the racking/mounting hardware and labor costs by 50%.

This study also looks at the real-world context and impact of examples used as sources for analogical mapping to inspire innovative solutions. It outlines the process taken by the SIMPLE BoS team to develop solar PV systems through biologically inspired design. The design process utilized the industry partners and industries mentioned above, as well as students in a College of Architecture (COA) studio class and Mechanical Engineering (ME) Capstone groups. For this project, some systems were also designed using non-biological analogues. I also provide analyses and results of the evaluations made on the designs by comparing the effectiveness of the biological and non-biological inspired products in meeting functions essential to the system's reliability and cost effectiveness.

Figure 6.1: A Residential house mockup developed during early-phase design

6.2 Project Participants

As mentioned earlier, the SIMPLE BoS team comprised of industry professionals and researchers. Also included in the team, for specific parts of the project, were students in a College of Architecture (COA) Studio course and

Mechanical Engineering (ME) Capstone teams. For clarity, the GTRI, Suniva, and Radiance Solar participants will be referred to as the design professionals, and the students involved in the project will be referred to as the design students.

6.3 Method and Approach

In this section, I present and analyze the process taken in the conceptual stage of the SIMPLE BoS project. I discuss the first five steps in an eight-step process to achieve the goals of the SunShot Initiative grant. Table 6.1 gives an outline of the SIMPLE BoS process.

Table 6.1:SIMPLE BoS Process

Step	What	Who
1.	Functional Decomposition	SIMPLE BoS Team – GTRI, Suniva, and Radiance Solar
2.	Solution Retrieval	CBID (Biology and Mechanical Engineering Faculty), GTRI
3.	Concept Transfer	COA Studio & ME Capstone Students
4.	Concept Generation	COA Studio & ME Capstone Students
5.	Concept Down Selection	Expert Review Panel – Suniva, Radiance, GTRI
6.	Prototypes	ME, Biology, COA, GTRI
7.	Down Selection/Validation	GTRI, COA/DFL, Radiance
8.	Detailed design and Analysis	GTRI, COA/DFL, Radiance

6.3.1 Functional Decomposition

Redesigning and simplifying solar PV racking systems requires the identification of functional requirements that can be reduced to a key set of functions for which inspiration can be found, and solution concepts developed. The first step taken in the project was to decompose and prioritize SIMPLE BoS functions by means of a functional decomposition. During a one-day seminar, attended by the design professionals and the design students, a theoretical background and analytical skill for solar analysis was provided. Presentations on the specific functions of each solar PV panel module and racking component took place, with each function tracked in terms of the material, information, or energy purpose it served.

Functional decompositions were created by the design students and the design professionals. Representatives from Suniva identified the functions and costs associated with the PV module, while Radiance Solar completed a live installation on a mock-up roof to illustrate the functions associated with the balance of systems. The resulting functional decompositions were further prioritized to isolate topics that embodied concepts in a complete and easily transferrable manner; this was done by the design professionals and experts. The design professionals made priorities based on the functions that incur the majority of the material, hardware, and labor costs, eventually settling on six key functions: *ground equipment, accommodate handling, fix position, maintain electrical connection, align array,* and *transfer heat to environment* (Figure 6.2). The functional decomposition aligns with the Theory of Inventive Problem Solving (TRIZ) (Altshuller, 1984), which states that ideal results can be summarized and reduced to a manageable number, designed in terms of desired function, and expressed in general terms. This approach allows for greater interdisciplinary interaction, increasing creativity by transferring ideas outside each specific area of expertise, a necessity to the SIMPLE BoS team (Vincent, et al., 2006). The biological domains with its rich inventory of highly evolved solution concepts can be mined for inspiration using general functions as keywords.

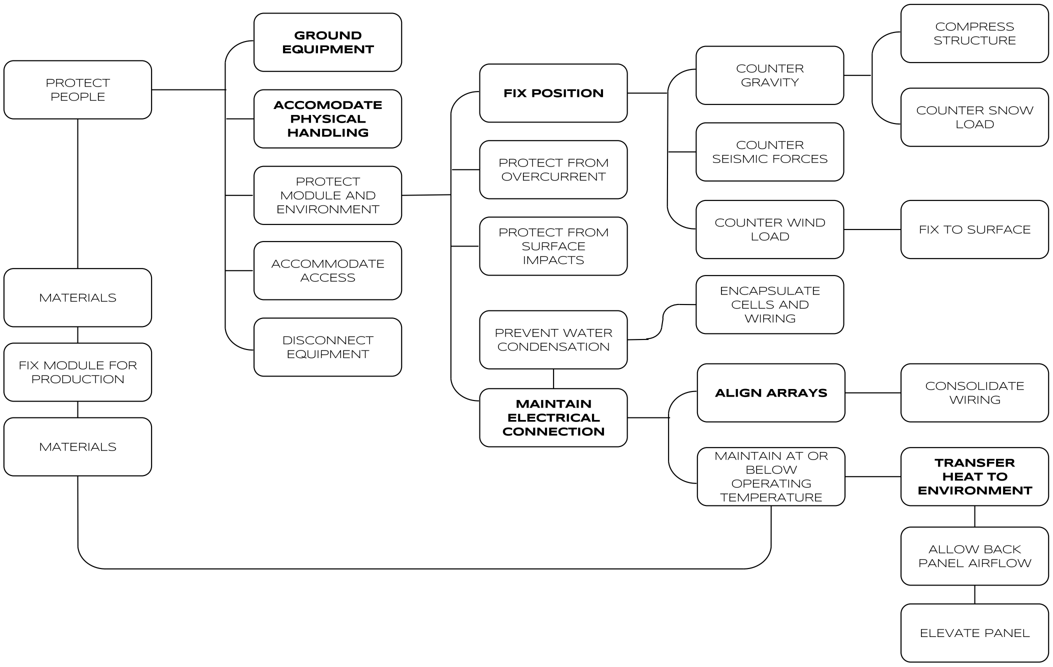


Figure 6.2: Functional Decomposition and Key Functions

6.3.2 *Solution Retrieval*

In this problem-driven approach to biologically inspired design, the starting point was already identified: reduce the BoS cost of solar PV systems. The next step was to look for biological examples to act as source analogues from which design teams would draw inspiration for the solar PV designs. The design process began with the submission of example organisms and systems for study by biology consultants (professors in the Department of Biology at Georgia Tech). The biology consultants researched champion adaptor organisms that exemplified the six functions of interest that were identified during the functional decomposition. Based on characteristics such as flow regime and scale, the design professionals and the biology consultants collaborated to down select organisms that were considered most likely to be transferrable to an engineering solution. This group researched each organism to refine their knowledge of biological concepts. Fourteen biological organisms to be used as analogues were identified and presented to the design students (Table 6.2). Multiple biological organisms were identified because literature has shown that it is often difficult to create many solutions based on one single analogue (Gadwal & Linsey, 2011; Holyoak & Thagard, 1989; Krawczyk, Holyoak, & Hummel, 2005), and that multiple analogues will increase the rate at which the design problem is solved (Gadwal & Linsey, 2011; Gick & Holyoak, 1980; Keane, 1988; Markman & Gentner, 1993). An index containing the fourteen organisms was provided to the design students that illustrated each unique mechanism, and its working principle, along with references for further study. According to Mak and Shu (Mak & Shu, 2004), the most successful analogical transfers happen at higher abstraction levels, i.e. analogies based on the working principles of the biological entities, rather than it's form or behavior. Table 6.3 shows an example of how one of the analogues (Limpet) was presented to the design students.

Table 6.2: List of Biological Analogues Presented
To the Design Team

Connection (Folding)
1) Hornbeam & beech leaves
2) Earwigs
3) Beetles (Coleoptera)
4) Cockroaches

Linkages
5) Fish jaws
6) Mantis shrimp

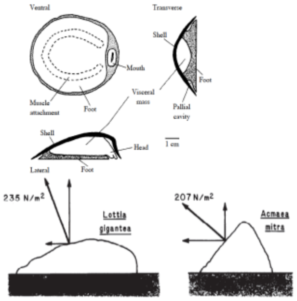
Lift/Drag
7) Tree leaves
8) Humpback whale flippers
9) Limpet shells

Attachment (gripping)
10) Gecko
11) Snakes
12) Cockroaches

Tensegrity / Structure,
13) Cell structure/Bones & muscles
14) Manta ray

A biological principle, Hierarchy, was explained to the students during the seminar as one of the analogue sources. In biology, hierarchical structures are assemblages of molecular units or their aggregates that are embedded or intertwined with other phases, which in turn are similarly organized at increasing size levels (Tirrell, et al., 1994). These multilevel architectures are capable of conferring unique properties to the engineering structure. The hierarchal design approach optimizes each aspect of the proposed structure starting with the lowest level of fabrication (Vincent, 2002). This principle influences designs by focusing on simple, repeatable units that can fit varied spaces without customization. Compared to the current engineering approaches in biologically inspired design, the hierarchical model offers a higher level of efficiency, a greater level of flexible properties, and an increased level of interaction(Goodman, et al., 2012; Vincent, 2002).

Table 6.3: Example of the Limpet Shell Analogue Presented to the Design Students

Name	**Scientific Name**	**Mass/Height/ Length**	**Environment**	**Reynolds Number**
Limpet	Lottia, Acmaea, Patella, etc.	2-5cm long	Rocky shores	10000–10^6
Mechanism	**Motivation**	**Diagram**	**Comments**	**Reference Text**
Cone shape provides axisymmetric protection from extreme hydrodynamic forces	Shells are exposed to flow speeds upwards of 20 m/s with varying directions		Axi-symmetrical protection from aerodynamic forces could be achieved with similar shapes. Tradeoffs between Drag and lift could be achieved by varying the radius-to-height ratio.	[14],[15], [16]

6.3.3 *Concept Transfer*

The next step in the SIMPLE BoS process required small design groups, comprising of the design students, to translate the biological solutions to solar PV solution concepts with diagrammatic representations and textual narratives of the affordances (Figure 6.3). Through this process, 39 initial design concepts were produced. Figure 6.4 shows an example of a concept developed from the Manta Ray analogue during the concept transfer step.

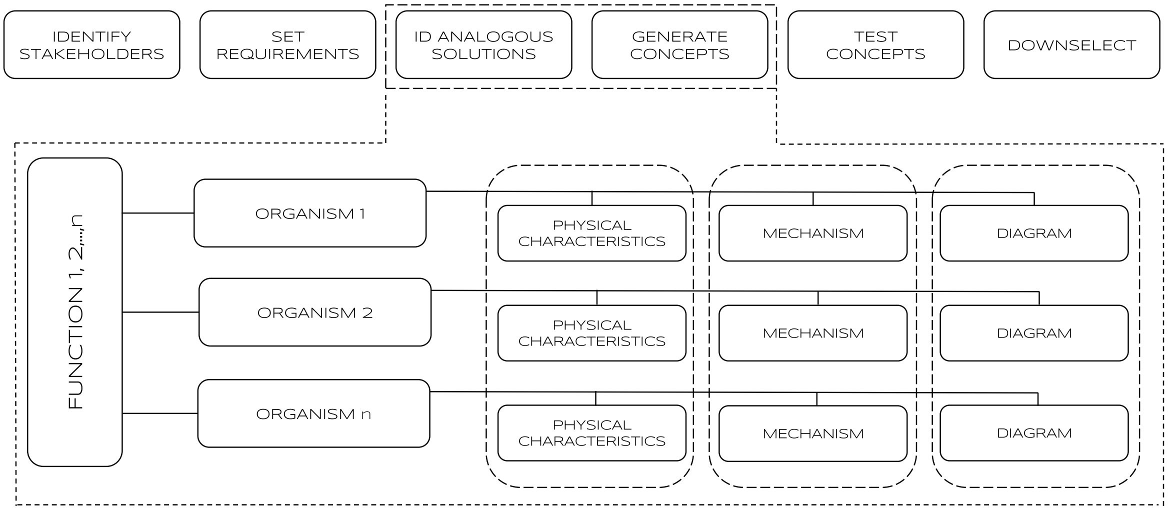
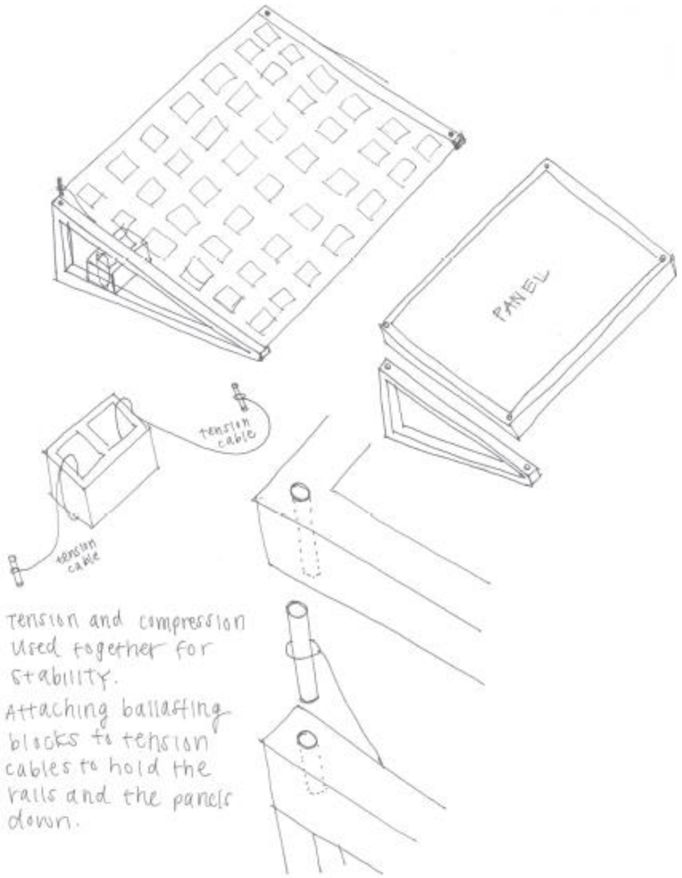


Figure 6.3: Illustrated Design Process



Tension and compression used together for stability.
Attaching ballasting blocks to tension cables to hold the rails and the panels down.

Figure 6.4: Example of Concept Transfer from the Manta Ray Analogue

6.3.4 Concept *Generation*

During the concept generation step, the design students were asked to generate designs for solar PV panels that would meet the six key functions determined during functional decomposition. They were told to either build on the design concepts derived during the concept transfer step or create non-biological inspired designs. Through aggregation into a solutions catalogue, the solutions concepts generated during the concept transfer step were made available to the design students at large with the goal of developing application specific concepts composed of single or multiple solution concepts, or compound solutions. The design student teams first described the system, including the source of biological inspiration, whether it applied to residential, commercial, or utility uses and the predicted advantages of the novel solar PV solution.

To account for intellectual property, each group listed potentially patentable advances and ideas, as well as citing the use of previously patented design aspects. The outcome of this step in the project was a total of 23 design concepts (11 Residential, 6 Commercial, and 6 Utility). Fourteen provisional patents were also developed at this stage of the process.

An important step in design development was creating an installation narrative, which specified the procedure necessary for manufacturing, shipping, and installing the proposed system, including part count, tools needed, and the potential for automation. After all the design specifics were completed, students performed a cost analysis and risk assessment. The cost of the manufacturing methods, component fabrication, installation, and labor were all estimated. The risk assessment specified code implications based on the changes to current industry standards, and the potential changes from the standard PV module and wiring set-up. At each step of the process, the design professionals engaged with the design student teams to review concepts, validate data, and propose refinements.

6.3.5 Concept Down Selection

The next step in the SIMPLE BoS process was to refine and down select the design concepts developed by the design students in the concept generation step. This was done by an expert review panel consisting of the design professionals. A pairwise comparison was done for six requirements identified by the design professionals that would allow one design to stand out over another. The six requirements used in the pairwise comparison are Function, Labor Cost, Capital Cost, Reliability, kWh Production, and Manufacturability. Through the pairwise comparison scores, 3 Residential, 3 Commercial, and 2 Utility concepts were selected for proof-of-concept designs. Through the proof-of-concept mockups, these designs were further down selected for prototyping. Three final designs were selected for prototyping: Solar Curb/Anaconda (Commercial), Integrated Electrical Frame/Mega Module (Residential), and the Solar Ridge (Residential).

The Solar Curb/Anaconda was inspired by limpet shell and hierarchy analogues, the Solar Ridge design was inspired by tree leaves and hierarchy analogues, and the Integrated Electrical Frame/Mega Module was inspired by the hierarchy analogue.

6.4 Results

Various analyses were done on the designs developed for the solar PV systems. In this section, I analyze the effectiveness of the biologically inspired method by comparing how well the biologically inspired and non-biologically inspired designs were able to meet the functions outlined by the design professionals. I also discuss design trends seen throughout the SIMPLE BoS process.

6.4.1 Percentage of Key Functions Met

The 23 design concepts generated during the concept generation phase were analyzed to see how many of the six key functions for the solar PV design, identified during functional decomposition, they met. Out of the 23 designs, 9 were biologically inspired, and 14 were not. Figure 6.5 shows the results for this analysis. We see that the biologically inspired designs met a significantly higher percentage of the key functions compared to the non-biologically inspired design. Independent t-test results give: t(21)=-3.9, p <0.001. The Cohen's Kappa inter rater is 98.7%. It is also interesting to note that final three designs selected for prototyping are biologically inspired.

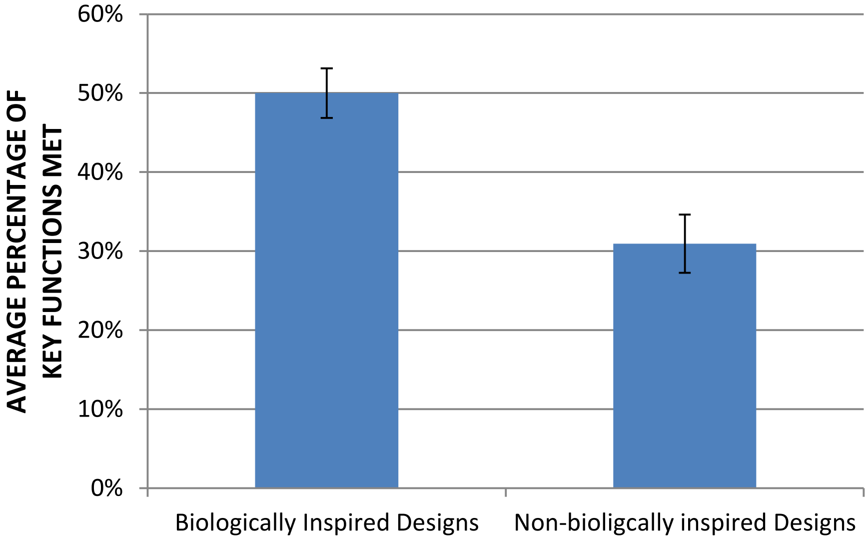


Figure 6.5: Comparison of Percentage of Key Functions Met. All error bars show (±1) standard error.

6.4.2 Divergent and Convergent Design Thinking

Many instances of divergence and convergence are seen in the design generation and selection of the solar PV concepts. The first occurrence of divergence is in the creating of functional decompositions by the design professionals and design students. Convergence is used by the design professionals to select the six functions that were key to reducing material, hardware, and labor costs. Divergent and convergent steps are also seen in the solution retrieval by the biology consultants and the design professional. First, they selected a list of organisms that exemplified the six key functions, and then down selected them by which were mostly likely to transfer to an engineering solution. We again see various cycles of divergence and convergence from the 39 initial design concepts developed in the concept transfer step, to the 23 design developed during concept generation, and then to the down selection and refinement of these concepts through the pairwise comparisons. These steps were key in helping to manage the number of solutions generated and in evaluating and selecting the best designs to meet the SIMPE BoS project objectives. It is also observed that these divergent and convergent design steps were done through a collaboration of industry professionals and design students. This union is not always a perfect match as students tend to propose impractical ideas and industry professionals and experts are often bogged down in designs that are iterative. However, this collaboration was instrumental to the success of this project, and might indicate that teams containing novices and experts should be explored as a way to apply biologically inspired design to engineering tasks.

6.4.3 Analogues Used in Idea Generation

The analogues used during the concept transfer and concept generation were analyzed to see how many, or if all of them, were used and what may have caused these outcomes. Figure 6.6 shows the percentage of times each analogue was used for creating the designs.

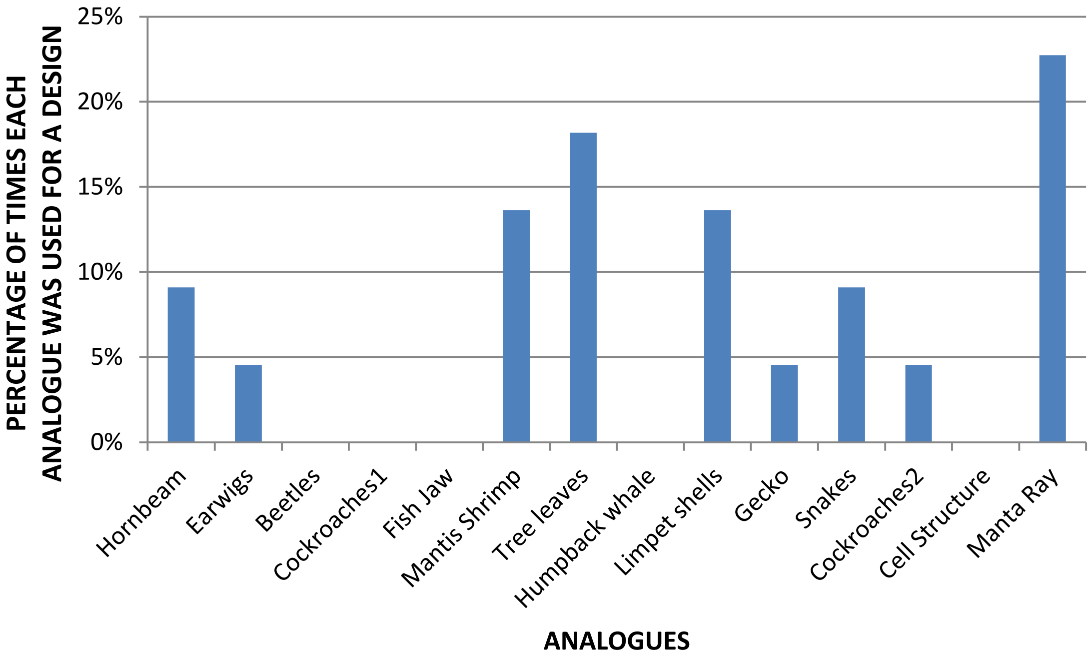


Figure 6.6: Percentage of Times Each Analogue Was Used For a Design

From the plot, we see that the mantis shrimp, tree leaves, limpet shells, and manta ray were the most used analogues. I wanted to see what may have caused this trend, so I performed further analysis. I looked at the number of images that were used when the analogues were presented to the design team like in Table 6.3. The analogues with the highest number of images used to present the analogues are the mantis shrimp, tree leaves, limpet shells, gecko, and manta ray (Table 6.4). This list of analogues with the most images contains all of the most used analogues. It appears that the design teams were more likely to use an analogue based on the number of images presented. This may have happened because more images may have given them a better understanding of the analogue. This data is interesting, but further studies are needed to be fully understand this trend.

Table 6.4: Analogues and the Number of Images Presented

Analogue	**Number of Images**
1) Hornbeam & beech leaves	2
2) Earwigs	3
3) Beetles (Coleoptera)	3
4) Cockroaches	2
5) Fish jaws	1
6) Mantis shrimp	**4**
7) Tree leaves	**7**
8) Humpback whale flippers	2
9) Limpet shells	**5**
10) Gecko	**4**
11) Snakes	1
12) Cockroaches	3
13) Cell structure/Bones & muscles	1
14) Manta ray	**4**

6.4.4 Compound Solutions

The design concepts generated in the concept transfer step were made available to all of the design student teams in order to encourage the development of designs with multiple solution concepts. Though the design teams were not specifically instructed to use the compound analogical design framework, we see instances of compound solutions: designs containing solutions from different biological analogues.

The Solar Ridge design (Figure 6.7) incorporated both tree leaf and hierarchy analogues. Inspired by tree leaf connections, the Solar Ridge design utilizes existing ridge beams to secure panels along a single line, hinging panels along the side of a structure. Existing trusses can be connected to the new ridge beam, which is then connected to a conduit/hinge upon which the panel racking is placed. Frameless PV panels can slide into the racking system, and additional legs allow for angle customization. The biological principle of hierarchy influenced the Solar Ridge design (as well as other design solutions) by inspiring the design team to confront the cost associated with the many field installation steps of current solar panel racking and mounting systems. The solar ridge eliminates the need for multiple mounting points by introducing a central ridge beam across existing trusses. By shifting focus first to reduction of design complexity and cost, the tree leaf and hierarchical model solar ridge concept works as an integrated system solution capable of reconciling functional requirements (Goodman, et al., 2012).

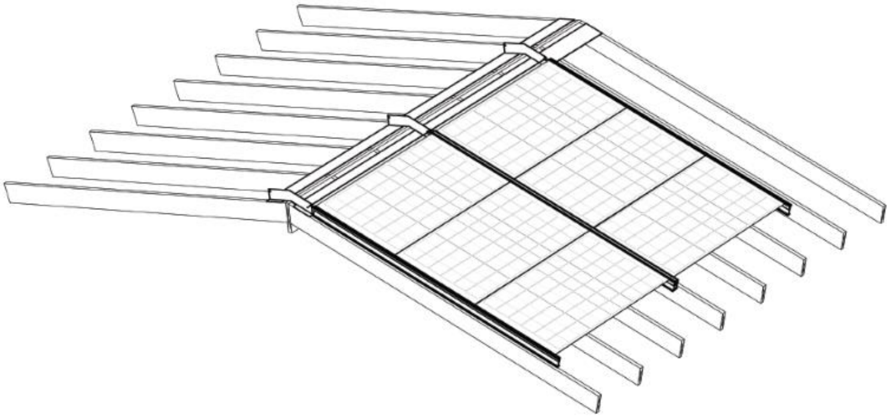


Figure 6.7: Solar Ridge Design Inspired by Tree Leaves and Hierarchy

The Solar Curb/Anaconda design (Figure 6.8) was inspired by limpet shell geometry and hierarchy. The Solar Curb was initially developed as a simple joint racking and mounting system for commercial applications in order to fulfill the key concepts of accommodate handling, align array, and fix position It later incorporated the use of a shielding plate to reduce the aerodynamic lift caused by wind loading, a concept drawn from the design of the limpet shell. The low angle of this system reduces wind loading so that roof penetrations or ballasting requirements are either minimal or unnecessary. The low ballasting requirements further increases the ease of installation. More complete integration can be achieved by incorporating the wiring system into the curb, which could also operate as a ballast tray. A particularly noteworthy affordance in the solar curb is a self-squaring system. Once the first assembly is easily squared on the roof due to its long geometry, subsequent rows are then self-squared through the assembly process.

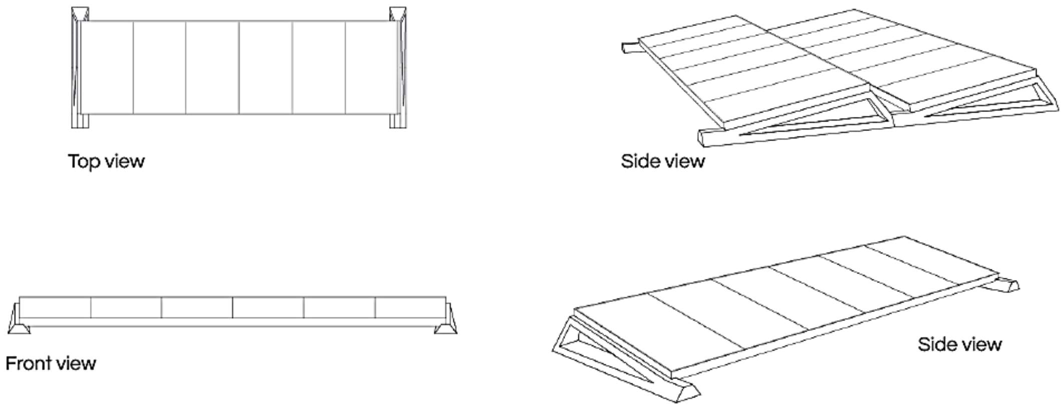


Figure 6.8: Solar Curb Design Inspired by Limpet Shells and Hierarchy

One of the designs developed during the concept generation step involved combining two concepts, from the concept transfer step, that were both inspired by tree leaves. While this is not a compound design in the sense of combining two different analogues, we see two conceptual designs being merged into one for overall design efficiency. The two concepts, the pivot and solar leaf (Figure 6.9) embraced similar qualities of tree leaves that allow the panels to pivot around a central point or off-central point (pivot), and allows panels to be mounted to a central bar, but not to each other, allowing individual panels to move independently based on wind patterns. Both these solution concepts inspired the creation of a proof of concept for a commercial solar ladder, a design that aggregates panels along a simple, shared frame. The solar ladder design was not carried further because of the increased number of electrical and mechanical connections needed for production.

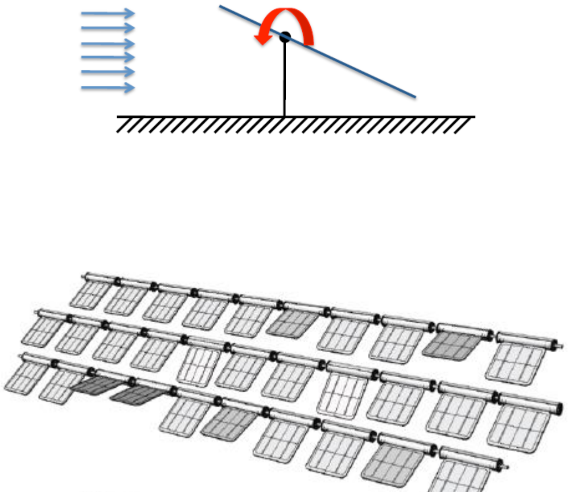


Figure 6.9: Pivot and Solar Leaf Concepts

6.4.5 *Cost Analysis and Efficiency of Designs*

In order to evaluate the effectiveness of this biologically inspired approach to the design of the solar PV panels, a cost analysis was performed to see if the overall goal of the project was successfully achieved. The cost analysis was done by breaking down the costs attributed to each of the six key functions of the solar PV design. The three final designs were compared to industry standard average racking hardware installation and mounting labor costs across multiple installations. The data for these costs were gathered from Radiance Solar and the Rocky Mountain Institute.

Figure 6.10 shows the cost of labor breakdown for the Solar Ridge/Anaconda design. From the data, we see that the Solar Curb/Anaconda design reduced the labor cost, compared to the industry standard by 57% (from 0.095 $/Watt to 0.041 $/Watt). This well exceeds the goal of the SIMPLE BoS project, which was to reduce the hardware and labor cost by 50%.

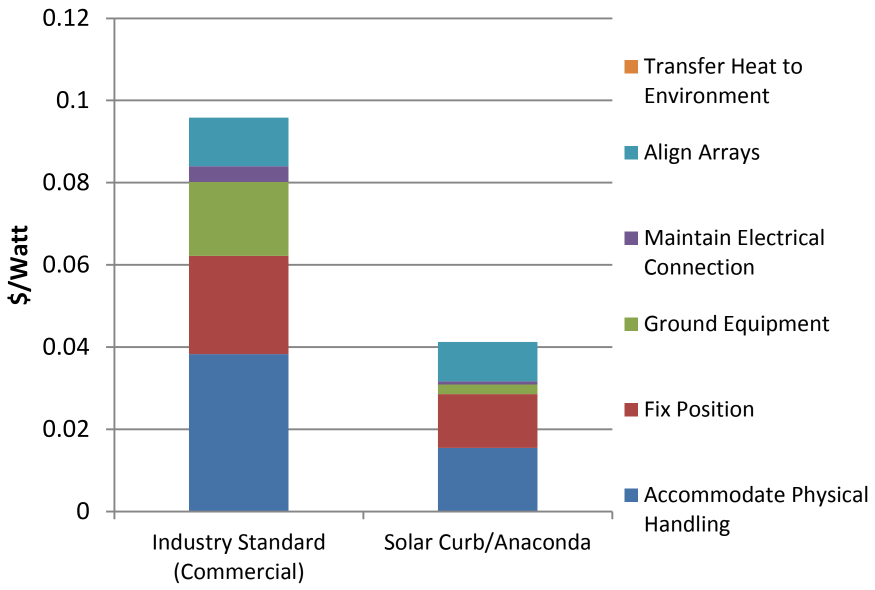


Figure 6.10: Installation and Labor Cost for the Solar Curb/Anaconda

The cost comparison for the Solar Ridge is seen in Figure 6.11. There is a 52.8% reduction in cost achieved by the Solar Ridge design (from 0.15 $/Watt to 0.071 $/Watt). This also exceeds the goals for the SIMPLE BoS project.

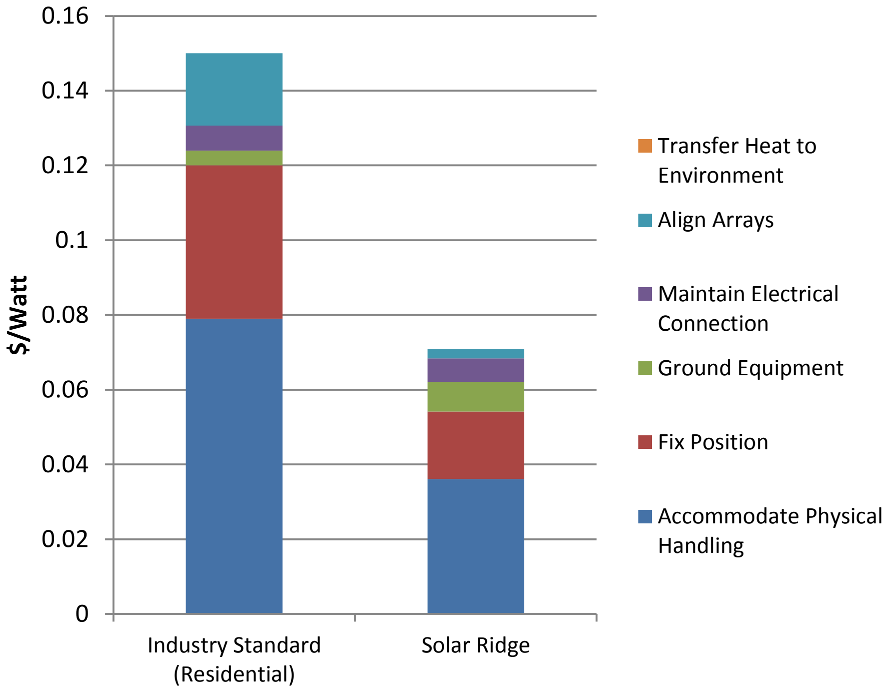


Figure 6.11: Installation and Labor Cost for Solar Ridge

The cost analysis for the Integrated Electrical Frame/Mega Module (Figure 6.12) was performed a little differently. The Integrated Electrical Frame/Mega Module is not a PV solar panel, but rather a PV module frame redesign and aggregation from a standard module. The module has no installation cost, as it is integrated into whatever racking system to which it is attached. Because the Integrated Electrical Frame/Mega Module is not a racking system, it is not part of the SunShot Initiative. The design is however innovative and novel, and an improvement over existing standard module frames.

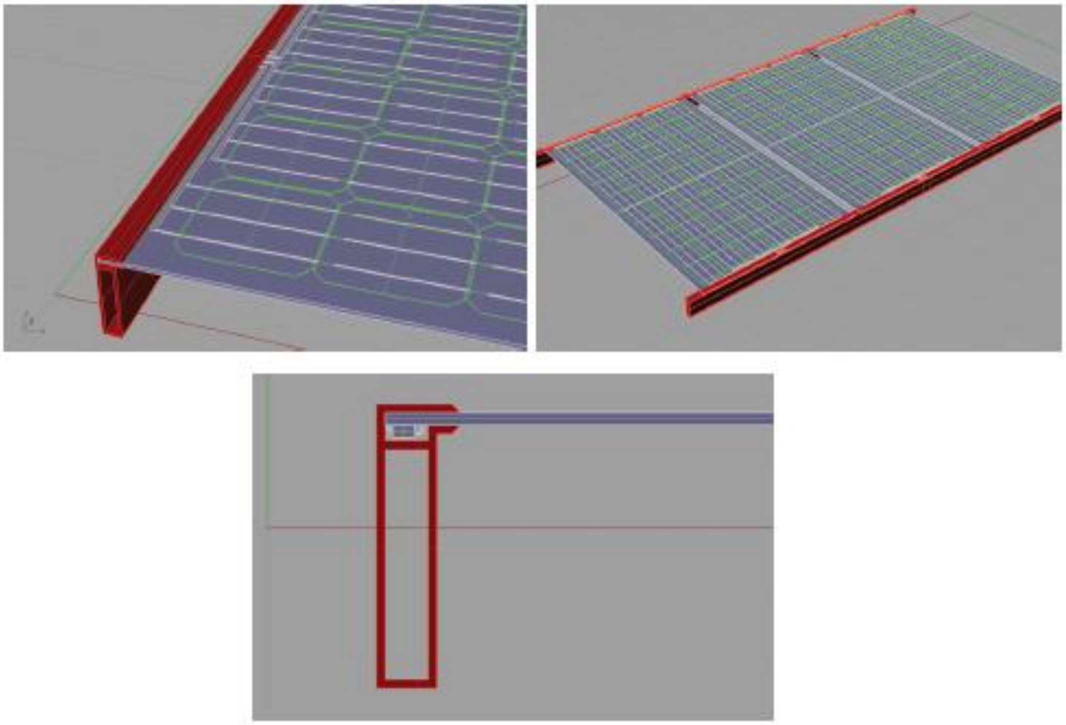


Figure 6.12: Integrated Electric Frame/Mega Module Design

Prototyping for the Integrated Electrical Frame/Mega Module was initially proposed using a composite material. Attempted implementation and further cost analysis of the Composite Mega Module revealed that that material was too expensive and would offer no cost benefits over standard frames. The composite material was returned to the manufacturer and aluminum was chosen as the new material.

Figure 6.13 shows the hardware cost for this aluminum Integrated Electrical Frame/Mega Module design compared with the costs of other similar integrated modules. As mentioned before, since this design is not part of the SunShot design, it did not need to meet the objective of a 50% price reduction. However, a 25% decrease in hardware costs (0.10 \$/Watt to 0.075 \$/Watt) is achieved, which is a significant improvement over other similar commercial frames. It also replaces the standard junction box with a more cost-effective integrated electrical frame.

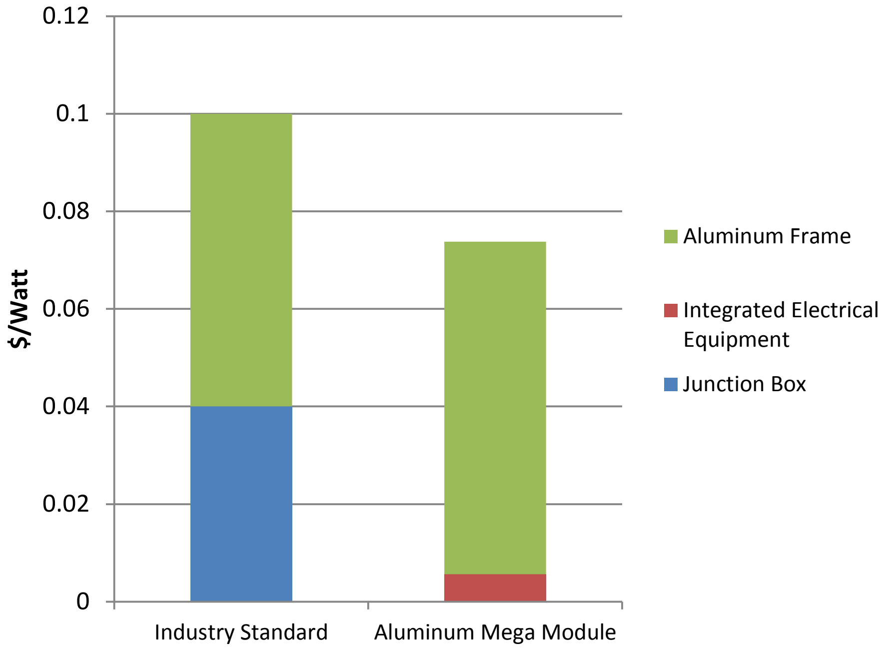


Figure 6.13: Hardware Cost for Aluminum Integrated Electrical Frame/Mega Module

6.5 Discussion of Results

This study focused on the use of examples as sources for analogical mapping and how these examples produce innovative solutions during idea generation. It looked at the real-world context and impact of examples used as sources for analogical mapping to inspire innovative solutions through biologically inspired design. This study described a successful biologically inspired approach to the design of low cost solar PV systems. The approach to the design process was outlined and the overall results of the SIMPLE BoS project were explained and discussed.

The functional decomposition performed to identify these key functions was an important step to identify the functions that needed to be met to reduce the solar PV costs. From the results of the project, we see that the designs inspired by biological analogues were able to meet the key functions of the solar PV design more successfully than the non-biologically inspired designs.

The three designs that were selected from the generated concepts were all biologically inspired. Compounded solutions were also seen in two out of the three designs. The use of divergent and convergent steps was also instrumental to managing the number of generated solutions and in evaluating and selecting the best designs. The collaboration between the industry experts and architecture and engineering students was also seen to have contributed to the success of the project.

The SIMPLE BoS project goals to reduce the installation and labor costs of solar PV modules was also realized by the final two PV module designs (Solar Curb/Anaconda, Solar Ridge), and a significant cost reduction was seen in the Integrated Electrical Frame/Mega Module design.

In fulfillment of the DOE SunShot Initiative, work is currently being done to develop and manufacture the selected designs. These designs will undergo proof of concept and prototyping based on wind-tunnel analysis, more detailed cost analysis, and field-testing prior to internal and DOE review. Designs carried through these next steps will be re-evaluated by the SIMPLE BoS team and further refined, specifically focusing on preparation for commercialization.

CHAPTER 7

CONCLUSIONS

This chapter presents a summary and the overall conclusions of the results from the four studies discussed in this dissertation. The principal contributions of this work are also discussed. The limitations of this research are identified, and recommendations for future work are presented.

7.1 Overall Conclusions

This dissertation presented four studies focused on improving the idea generation process in engineering. These studies explored the effects of example exposure on the performance of engineers and the effectiveness of the solutions produced during ideation, both in an experimental setting and in a real-world context. The first three experiments explored the effects of the example's representation on design fixation, quality, and creativity, and the fourth study analyzed the use of examples as analogues in a biologically inspired design study to produce high quality and creative design for solar PV systems. Each chapter presented the conclusions of the studies, but I will again summarize these findings here.

The first study explored design fixation due the representations of the examples presented during an engineering idea generation task. The representations explored were CAD, photo, and sketch. A control condition was also included. The corresponding examples were of an effective design, and the examples were presented individually. The results from this study showed that fixation, to one's own ideas and to the features of the example, is not dependent on representation. Fixation occurs due to the example, but the degree of fixation is not significantly different across the conditions. The quality scores for the design concepts generated were significantly higher for the CAD and photo representations compared to the sketch and control. There were no significant differences when comparing the CAD and photo representations. This shows that exposure to CAD and photo examples helps the designer produce better quality design concepts. The novelty and variety scores in this study were not significant across any of the conditions. In fact, this trend is seen for all of the studies that use this metric (studies 1, 2, and 3). It is possible that all conditions produced equally novel and diverse ideas, or the case may be that the novelty and variety metrics are not sensitive enough to measure the differences across the conditions. This implies that a better metric may need to be developed. This is discussed further in the future work section in this chapter. In this study, the different conditions were also analyzed to determine what the participants were fixating to the most. The results from this analysis showed that the CAD and photo conditions were better able to identify the key working principles of the design. The participants copied these features more in the CAD and photo conditions than the sketch condition. This shows that CAD and photo representations of examples enable designers to identify the key features of the designs. This result supports the quality scores of the CAD and photo condition being the highest. If these conditions copied the working principles of the effective example the most, then it makes sense that their quality scores were higher. Discussion on the principal contributions of this study can be found in the research contributions section in this chapter.

The second study compared CAD and sketch representations of examples, when presented together (with the same representation and with different representations), and when presented individually. Two different effective examples were used. The results here showed that for the conditions that received more than one example represented in different ways, (i.e. CAD and sketch), the participants copied more of the features of the CAD example regardless of the example (i.e. example A or B). These results show that CAD representations cause more fixation over sketches when they are presented together. For the conditions that received the examples represented in the same way, there was no difference in the amount of features copied from the two examples. The survey results from this study also showed a significant preference and affinity for CAD representation over sketches by the participants, it is likely that they draw the attention more than sketches do. The quantity of non-redundant ideas showed no significant differences across the conditions in this study. This shows that though the participants copy more from the CAD representation, it does not limit the number of ideas generated. The quality scores showed that the conditions who received two examples produced higher quality designs than the conditions that received one example. The novelty and variety scores showed no significant differences.

The third study explored the use of function trees in mitigating design fixation. Four conditions were used where participants received either a sketch, a function tree, a sketch & function tree of the example, or no example. The results from this study showed that while function trees do not break fixation, they also do not cause fixation. Function trees also produce a lower amount of fixation to the participants ideas compared with sketch representations. When function trees and sketches are presented together, the benefits offered by the function tree are erased. Having these two representations together in fact increases fixation. In regard to quality, function trees produce higher quality scores than the sketch condition, and higher quality scores than the function trees & sketch condition. The novelty and variety scores showed no differences. This study provided interesting results pertaining to the use of function trees in engineering design. Function trees are a viable representational form for idea generation and for reducing design fixation or not causing as much fixation compared with sketches.

The fourth study explored the real-world context and impact of examples used as sources for analogical mapping. The design task in this study was to reduce the mounting and racking costs of solar photovoltaic (PV) systems by 50%. The study took a biologically inspired approach towards realizing the projects goals. This study laid out the steps and processes that led to a successful realization of the goals of the project. Functional decompositions were implemented and were very helpful in identifying the key functions that needed to be met by the new designs. The analogues that were chosen for the analogical transfer were examples selected by biology experts and design professionals. The concept transfer and generation were performed by design students and design professionals. The results of this study showed that the designs that were biologically inspired met more of the key functions of the design than the non-biologically inspired designs. Divergent and convergent steps throughout the design process was also very beneficial to the study and added to its success. The analogues that were presented to the design teams with the most images were also selected and used more often in the concept transfer and generation process, and compound solutions were also seen in the design outcomes. The final three designs that were selected for prototyping, based on the pairwise comparison scores, all contained biologically inspired features. Two of these designs were racking systems, which both exceeded the project's goal of cost reduction by 50%. The third design was a not a PV module, but rather a PV module frame redesign and aggregation from a standard module. The cost reduction for this design was 25%, which is a great improvement over similar existing systems.

This section has summarized the results from the four studies in this dissertation; the next section will identify and discuss how these results contribute to the engineering design research field.

7.2 Design Fixation, Cognitive Load, and Mental Models

This section presents the findings from the fixation studies contained in this dissertation and discusses how it pertains to cognition and mental models. Explanatory and prescriptive descriptions of the findings are offered.

Cognitive Load Theory is an instructional theory that starts from the idea that our working memory is limited with respect to the amount of information it can hold, and the number of operations it can perform on that information (Gerven, Paas, Merriënboer, Hendriks, & Schmidt, 2003; Sweller, 1988, 1989). A mental model is a psychological representation of the environment and its expected behavior (Holyoak, 1984). From a functional view, Rouse and Morris (1986) state that the role of mental models is to provide a conceptual framework for describing, explaining, and predicting future system states. Johnson-Laird (1980) also states that mental models allow individuals to understand phenomena, make inferences, and experience events by proxy.

Fixation limits or decreases the cognitive load by limiting the (available) solution space that the designer explores due to exposure to the example. The designers identify the example that is being viewed as a model for what the solution to the design task should be. During the design stages, the designer categorizes the task based on the model or peanut sheller example that they are viewing and not on concepts or scientific principles (Condoor & LaVoie, 2007).

In study 1, fixation was occurring to the same degree for the CAD, photo, and sketch conditions. There were no significant differences. This shows that the cognitive load of the participants was decreased by the same amount. The results from the effective principle copied metric shows that the CAD and photo conditions were better able to identify the working principles of the example. It appears that CAD and photo representations (with less ambiguity) increase understanding of the example, thus allowing the participants to reason through the behavior and structural components of the example. This allows for a better mental model of the example to be developed which in turn allows them to identify the working principles of the example. These results have important implications for engineering designers. Since mental models are often surprisingly erroneous for both novice and experts (Gentner & Stevens, 1983), the finding that CAD and photo representations helps to build better or more accurate mental models is important for engineers as they build design tools and as they teach engineering.

Study 2 compared sketch and CAD representations to check for biases towards one particular representation over another. When the same type of representation is used for both examples, there are no differences seen in the amount of features copied from the example. However, when the CAD and sketch are presented together, there is a significant increase in the number of features copied from the CAD example over the sketch example. The survey results also show that there is a strong preference for CAD images over sketch. Similar to the cognitive effects seen in study 1, the CAD representation likely helps the participants to build a better understanding and mental model, thus causing them to copy the CAD features more. Something that is also very interesting is that the behavior of the participants changes when different representations are presented. This juxtaposing of an inferior (sketch) and superior (CAD) representation causes more CAD features to be copied than when both inferior and both superior representations are presented. This is similar to the Decoy Effect in marketing and psychology (Huber, Payne, & Puto, 1982), where consumers will tend to have a specific change in preference between two options when also presented with a third option that is asymmetrically dominated. This result is very useful for presenting designs to customer or consumers, the designer may be able to drive the customer to choose a particular design based on the representation alone. For engineering, this means that retrieval tools should likely represent all results in one type of representation to allow the user to choose which solution to use by themselves rather than biasing the user to unconsciously pick one example over the other based on representation, i.e. CAD over sketch.

For the last fixation study on function trees, the function tree further decreases the cognition load on the designer. With diagrammatic representations, the designer is able and likely to do mental simulations of the images (e.g. rotation) that they see. With function trees, since the designer does not see an image, they cannot perform any of these simulations, freeing up their working memory and in turn decreasing the cognitive load. This happens because the function tree encapsulates the behavior of the example without exposing any structural detail. This is useful for engineering design in the sense that if the designer becomes aware that there is a high degree of fixation occurring to diagrammatic representations, they can switch to functional representations to reduce the cognitive load, and thus reduce fixation.

7.3 Research Contributions

The principal contributions of this work are as follows:

- Design fixation has been empirically qualified based on representation. These studies have also provided further support for the presence of design fixation in engineering design.
- It is now clear that representation does play a role in the occurrence of design fixation. CAD and photo representations cause more fixation than sketch representations. As previously discussed, this is not necessarily a negative consequence since this fixation to the CAD and photo representations caused the identification of the key working features of a design when a good example is used. If the objective were to draw attention to particular features in a design, then a CAD representation

would be the ideal choice. This finding is applicable in engineering design practice when engineers are trying to understand existing designs of products. This impact does not only relate to individual design efforts, since example exposure is conceptually similar to the exchange of ideas that takes place among designers during group idea generation meetings. CAD and photo example representations also produce higher quality design concepts compared with sketch example representations and no example. Though this work is not focused on engineering education, this finding is also applicable in the field. Engineering instructors should depict and/or choose examples in CAD form to teach students new concepts.

- This dissertation provides recommendation for how example representations should be grouped during idea generation sessions. Presenting CAD and sketch representations together produce a bias to the CAD and cause more fixation to the CAD example. Presenting multiple examples all in CAD form or all in sketch form produced no differences in the amount of fixation to the example. To prevent fixation to one particular example, all representations should be the same during idea generation. Multiple examples should be used instead of only one example, since the quality of the designs produced when more than one example is presented is higher than only one example being present.
- I have provided experimental evidence of the benefits of function trees in engineering design idea generation. The anecdotal claims in textbooks have been verified. Function trees offer advantages over sketch

representation in reducing design fixation. Function trees do not cause fixation, and also do not break fixation. Compared with sketches, function trees show a lower degree of design fixation. Function trees should not be used together with diagrammatic representations as this increases fixation to the features of the example presented. These findings can act a springboard to benefit engineering researchers as they continue to improve techniques for idea generation and product design.

- The representations of engineering examples will need to be taken into account as engineering researchers develop methodology and theories about the engineering design process. This research has shown that these representations matter.
- I have presented steps for the effective implementation of biologically inspired design. This adds to the ongoing research to identify how biologically inspired design should be done successfully. Designs for the low-cost installation of solar panels were realized and the DOE SunShot Initiative was fulfilled.
- My research provides guidelines for engineering designers and researchers as they develop computer-based example retrieval tools for design. This includes analogical databases. The examples and analogues provided by these databases should be able to be filtered by representation to allow the designer to choose the analogue that would best map into a target solution. This research indicates that CAD and photo examples or analogues would be the best choice.

7.4 Limitations

The design fixation studies in this dissertation were performed in a similar manner to the previous studies on design fixation and idea generation available in literature. The majority of these studies have used novice engineers as the participants. This group is an area of interest, as it is important to explore the dynamics of design fixation among various levels of expertise. Though it is likely that these findings are transferrable to engineering design experts, research that directly evaluates fixation in professional and practicing engineers is needed.

In the SIMPLE BoS study, the design concepts inspired by the non-biologically inspired examples were not tracked. The examples used were not documented. Another aspect that was not documented was whether the participants used similar steps, e.g. concept transfer, concept down selection, compound solutions, etc. in the design steps.

7.5 Recommendations for Future Work

The work in this research provides several avenues for continuing work. In this section, I discuss future work that could be done to improve the idea generation process.

Form vs. Function

The results from this research have shown that function trees have benefits over sketches in reducing design fixation during idea generation to the participants own ideas. I believe that more work should be done to investigate this trend by comparing function trees to other type of diagrammatic representations and physical models. The complexity of the function trees could also be varied; morphological charts and function structures should also be explored. There are a vast number of studies that could be explored by juxtaposing these various functional representations. I am particularly interested in finding out if the complexity of the functional model would affect design fixation, or if no changes would be seen.

In terms of how design fixation to the example occurs, I believe that it would be important to have a better understanding of what exactly causes fixation. In the first study in this dissertation, I explored how the participants were fixating to the key features of the design example. These features were a mix of the functional features and surface features. Studies should be done to investigate fixation to the structure, function, and behavior of the example. This is of course inspired from the work discussed earlier by Gero (Gero, 1990; Gero & Kannengiesser, 2000, 2004, 2007), Goel (Goel & Bhatta, 2004; Goel & Murdock, 1996; Goel, et al., 2009), and Umeda (Umeda, et al., 1996; Umeda, et al., 1990; Umeda, et al., 1995).

Novelty and Variety Measures

No differences were seen in the novelty and variety scores used in this study; this may suggest that these metrics need improvement. These metrics were developed by Shah (Shah, et al., 2003) and further refined by Linsey (Linsey, et al., 2005), and it is the go-to system for measuring ideation effectiveness in design studies. Nelson et al. (Nelson, et al., 2009) have proposed a new model that will measure novelty and variety as one single metric. Srinivasan and Chakrabarti

(Srinivasan & Chakrabarti, 2010) have also offered refinements to existing metric. Though refinements and improvements have been offered, these new metrics have not been robustly tested to see if they offer significant improvements over Shah's metric. Research to investigate and test these novelty and variety metrics is needed.

Expert Studies

Finally, more design fixation research with design experts and professionals needs to be done to add to the current work in this field. At present, most of the design fixation studies are done on novice engineers. Design fixation has been shown to be present in both novices and experts, thus research that directly tests these trends in experts is necessary.

APPENDIX A – MATERIALS FROM STUDY 1

Experiment 1 Script

Howdy!

As your instructor told you, this is a voluntary activity. Those who volunteer can either earn $10 or extra credit in this class. There is also an opportunity to win a prize. The person who generates the greatest number of solutions will win a prize. Those who do not wish to participate in this experiment may leave now.

The experiment packets will not be distributed to you. Please do not start reading until I tell you to do so.

After every one gets a packet

Your packet contains 2 consent forms, an instruction sheet, a design problem sheet and a few blank sheets. You need to read the consent form first and sign it if you agree to participate. The second copy of the form is for your reference. You also need to agree not to discuss the details of this experiment with your friends until after Jan 1st, 2013, since that can bias the results of our future experiments.

Wait for the participants to read and sign the consent forms

You will not have 5 minutes to read the design problem in your packet. If you have any questions during this time, please let me know

Record any questions

You will now have 45 minutes to generate solutions for the design problem. Please generate as many solutions as possible for the problem. You are not allowed to discuss anything with your neighbor during the experiment. If you have any questions, please raise your hand. We will come to you to answer your questions. Please do not ask the questions aloud.

You may leave all your materials including the consent form on your seat at the end of the experiment.

Your time starts now!

Idea generation time

at the end of 45 minutes **Please stop the idea generation now. If you had seen this design problem before this experiment, please make a note on the front page of your packet indicating so.**

At the end of the experiment **Since you all generated many ideas for the design problem, we will give you a prize. You will all receive an extra $10. Please come down and fill out the sheet with me and I will give you the payment slips. If you opted for money as the compensation for your participation, please let me know before you fill out the sheet.**

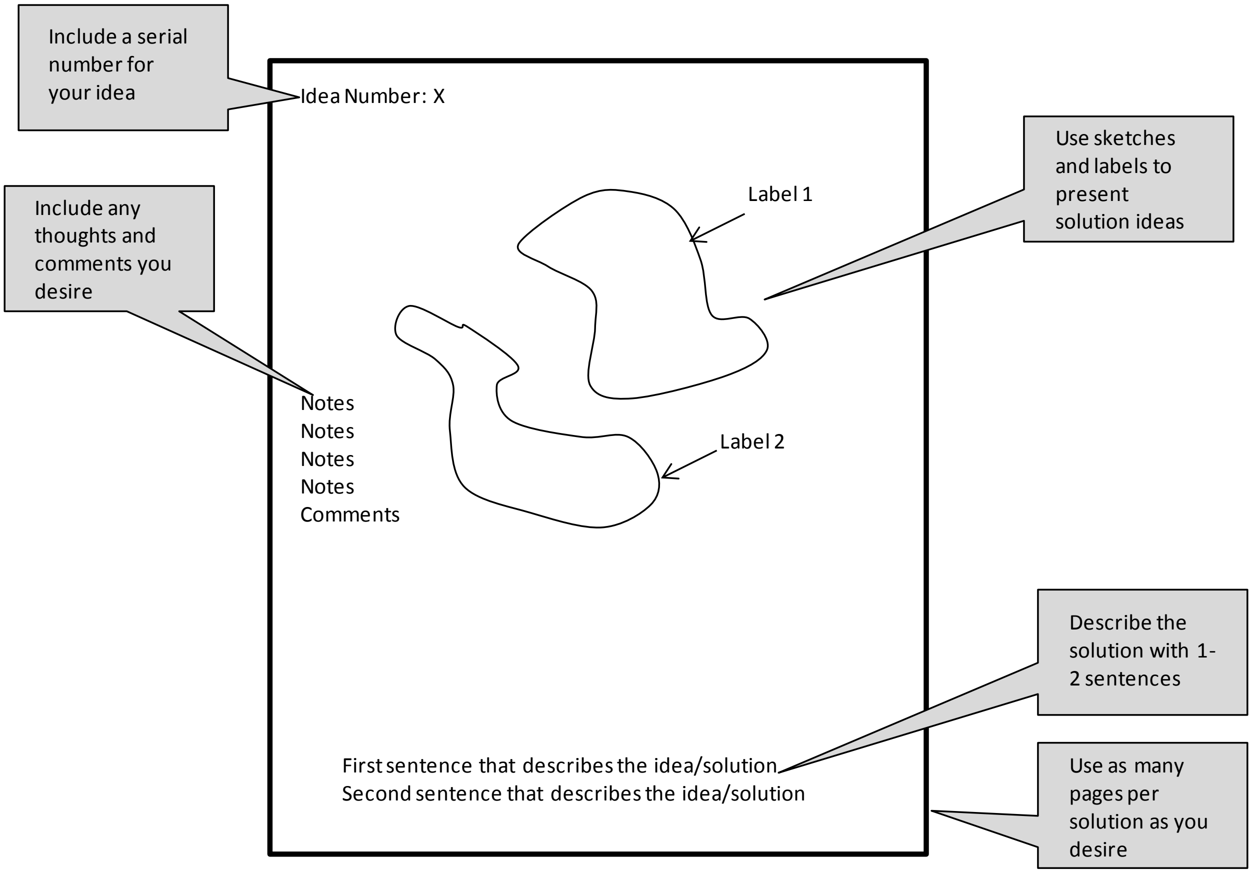
Instructions (This instruction sheet was used for Studies 1, 2, and 3)

Instructions

Consider the design problem on the following page. Please read these instructions and the design problem description carefully. You will be given up to 5 minutes to read this information, followed by 45 minutes to create design solutions to the design problem. Your goal is to create ***as many solutions to the problem as possible***, while maximizing quality, novelty and variety.

Use provided sheets of paper to record your solutions. Each solution should be on a separate page.

An adequate solution should include a sketch of the solution, labels of major elements, and a 1-2 sentence description of how the solution works. Please feel free to record any thoughts or comments that you might have as you develop each solution."



Design Problem Sheet Given to the Control Condition

Design Problem - Device to Shell Peanuts

Problem Description:

In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal of this project is to design and build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African peanut farmers. The target throughput is approximately 50 kg (110 lbs) per hour.

Customer Needs:

- Must remove the shell with minimal damage to the peanuts.
- Electrical outlets are not available as a power source.
- A large quantity of peanuts must be quickly shelled.
- Low cost.
- Easy to manufacture.

Design Problem Sheet Given to the CAD Condition

Design Problem - Device to Shell Peanuts

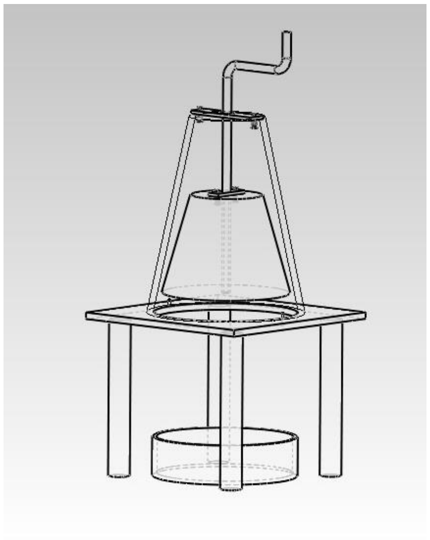
Problem Description:

In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal of this project is to design and build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African peanut farmers. The target throughput is approximately 50 kg (110 lbs) per hour.

Customer Needs:

- Must remove the shell with minimal damage to the peanuts.
- Electrical outlets are not available as a power source.
- A large quantity of peanuts must be quickly shelled.
- Low cost.
- Easy to manufacture.

Consider the following solution as an example that might be created for this design problem.



Solution Description:

The peanuts are loaded from the top of the system; the user rotates the handle, which pushes the nuts towards the tapered gap between the interior and exterior wall of the machine. The shell of the nut is broken at the point where the gap is sufficiently narrow to cause enough friction to crack open the shells. The kernels and shell fragments fall into a basket and are later separated by winnowing.

Design Problem Sheet Given to the Photo Condition

Design Problem - Device to Shell Peanuts

Problem Description:

In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal of this project is to design and build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African peanut farmers. The target throughput is approximately 50 kg (110 lbs) per hour.

Customer Needs:

- Must remove the shell with minimal damage to the peanuts.
- Electrical outlets are not available as a power source.
- A large quantity of peanuts must be quickly shelled.
- Low cost.
- Easy to manufacture.

Consider the following solution as an example that might be created for this design problem.

Solution Description:

The peanuts are loaded from the top of the system; the user rotates the handle, which pushes the nuts towards the tapered gap between the interior and exterior wall of the machine. The shell of the nut is broken at the point where the gap is sufficiently narrow to cause enough friction to crack open the shells. The kernels and shell fragments fall into a basket and are later separated by winnowing.

Design Problem Sheet Given to the Sketch Condition

Design Problem - Device to Shell Peanuts

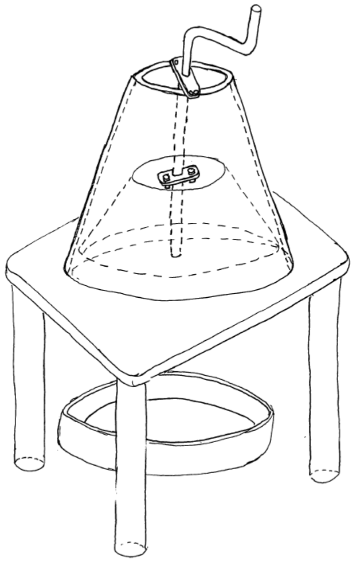
Problem Description:

In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal of this project is to design and build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African peanut farmers. The target throughput is approximately 50 kg (110 lbs) per hour.

Customer Needs:

- Must remove the shell with minimal damage to the peanuts.
- Electrical outlets are not available as a power source.
- A large quantity of peanuts must be quickly shelled.
- Low cost.
- Easy to manufacture.

Consider the following solution as an example that might be created for this design problem.



Solution Description:

The peanuts are loaded from the top of the system; the user rotates the handle, which pushes the nuts towards the tapered gap between the interior and exterior wall of the machine. The shell of the nut is broken at the point where the gap is sufficiently narrow to cause enough friction to crack open the shells. The kernels and shell fragments fall into a basket and are later separated by winnowing.

APPENDIX B – MATERIALS FROM STUDY 2

Experiment 2 Script

Check List

1. Experiment Packets
2. Stop watch
3. Cash
4. “I got my money” sheets
5. Extra blank sheets
6. Stapler
7. Paper clips
8. Extra consent forms

1. *Consent*

After all participants have arrived, hand out the experiment packets.

Hello and thank you for taking time to participate in this research study today. Please turn off and put away all cell phones. For this study, you are not supposed to monitor time using your watches or cell phones.

You are being asked to participate in a research study on engineering design. You are not required to participate in this study and may end your participation at any time.

You will be asked to generate ideas to solve multiple design problems. The study will require just a little bit over an hour of your time.

Your effort will be compensated with either payment of up to $20 or with extra credit in your Capstone class. Participants who show superior effort will be given a bonus in the form of extra money or extra bonus points depending on which type of compensation you choose.

Please fill out the cover page with your name, capstone professor and other information listed on the page.

Please read the consent form, there are two copies, one for you to hand back to me and one for you to keep for your records. Please let me know if you have any questions about the experiment.”

Wait until all of the participants have finished reading to proceed with the experiment. Then say**, If you agree to participate please sign one of the consent forms.**

Wait for participants to sign the consent forms

Collect the consent forms.

Please put aside your copy of the consent forms.

You must agree to not discuss any aspects of the study with other students in mechanical engineering at Georgia Tech until after May 31st 2014 since this will bias the results. Your participation is voluntary. Are there any questions before we begin?

2. *Design Problem and Idea Generation*

This experiment is seeking to understand the engineering idea generation. Today your task will be to generate as many ideas as possible that could help to solve the given design problem. This experiment has two sections. In the first section you will asked solve a design problem, and in the second section, you will answer a short survey; please do not begin the survey until you are asked to do so. The goal is to generate as many solutions as possible to the given design problem. If you have seen this design problem before, please make a note of this in your packet.

Please read the packets that have been given to you. The first sheet gives you the instructions to solve the problem and the remaining sheets give you the details of the design problem. You have 5 minutes to read the design problem. I will give you instructions to begin at the end of five minutes.

Your five minutes starts now.

at the end of 5 min **Do you have any questions?**

Record if any.

You will now have 45 minutes to generate as many ideas as you can for the design problem. Please generate as many solutions as possible to solve this design problem. Please read the problem. If you have any questions, please let me know. Feel free to remove the staples/clips that bind your packets together. If you need extra paper at any time, please raise your hand and we will bring it to you. If you need extra paper clips, we have some as well.

You may start now.

at the end of 45 minutes **Please stop the idea generation now. If you had seen this design problem before this experiment, please make a note on the front page of your packet indicating so.**

Turn to the last page or pages of your packet to the survey.

3. *Survey*

Please read through the survey and answer the questions accurately, you will have a few minutes to answer the survey questions.

give them about 5-7 minutes to fill out the survey

Please listen to the next set of instructions very carefully:

1. **If you have not finished with the survey, you may continue**
2. **If you have finished with the survey and requested extra credit, you may leave your packets on desk in front of you and leave. We will send your names to your respective professors for your extra credit.**
3. **If you have finished the survey and requested for money, please bring your packets down to us**

----

at the end of 10 minutes **Please stop completing the survey.**

Thank you for your participation and I will make sure that you will receive your extra credit. This concludes your portion of the study. Please remember to not discuss this study with your classmates until after May 31st, 2014 since this will bias the data. If you have any questions about this study I can answer them at this time.

Design Problem Sheet and Survey Given to Condition 1: CAD A & CAD B

Design Problem - Device to Shell Peanuts

Problem Description:

In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal of this project is to design and build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African peanut farmers. The target throughput is approximately 50 kg (110 lbs) per hour.

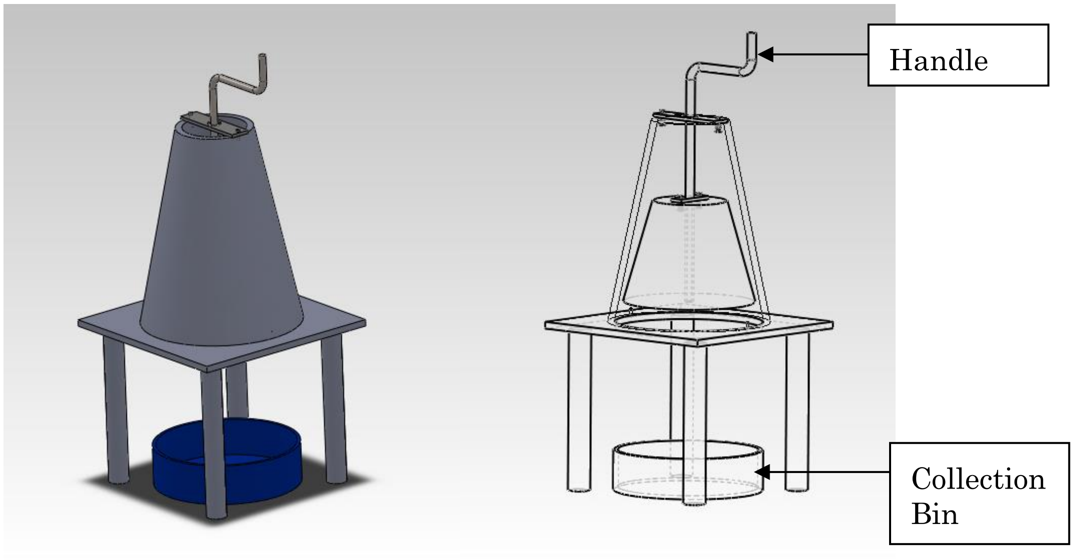
Customer Needs:

- Must remove the shell with minimal damage to the peanuts.
- Electrical outlets are not available as a power source.
- A large quantity of peanuts must be quickly shelled.
- Low cost.
- Easy to manufacture.

Two different Design Examples have been provided for you on the next 2 pages.

Design Example A

Consider the following solution as an example that might be created for this design problem.

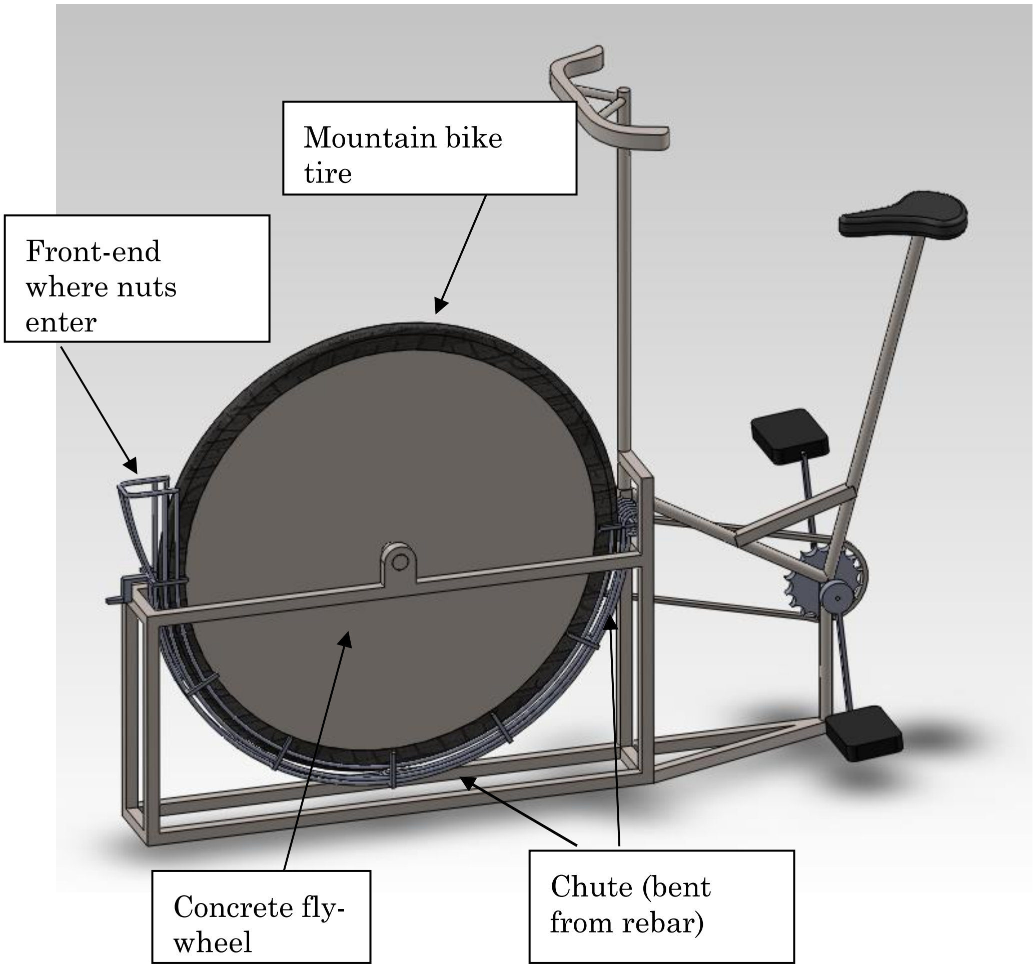


Solution Description:

The peanuts are loaded from the top of the system; the user rotates the handle, which pushes the nuts towards the tapered gap between the interior and exterior concrete walls of the machine, the walls are formed from molds. The shell of the nut is broken at the point where the gap is sufficiently narrow to cause enough friction to crack open the shells. The kernels and shell fragments fall into a basket and are later separated by winnowing.

Design Example B

Consider the following solution as an example that might be created for this design problem.



Solution Description:
This design of a pedal powered nut sheller utilizes a bicycle to power a device for shelling peanuts. As the machine is pedaled, nuts are fed into the front end. Once the nut enters the chute, the spinning mountain bike tire breaks the shells, and at the same time ejects the nuts. The action is aided by converting the bike wheel into a concrete fly-wheel.

Survey

1. From the <u>design examples</u> (Design A or Design B) given to you, did you find that you preferred one design over the other?

Please check one:
No ___ Yes ___

- If no, please move on to question 2
- If yes, which design did you prefer? Design A ___ Design B___. Please provide a brief explanation why you preferred one design over the other.

2. From the <u>design examples</u> (Design A or Design B) given to you, which was more useful to you during your idea generation?

Please check one:
Design A ___
Design B ___
Both were equally useful ___

3. From the <u>design examples</u> given (Design A or Design B), which do you think is more complex?

Please check one:
Design A ___
Design B ___
Both are equally complex ___

4. What is your gender?
a. Female
b. Male

5. What is your age? ______________

6. What is your major? ______________________________

7. Overall GPA _______________

8. GPA in Major _______________

9. Year in School
Undergraduate:
___ Freshman ___Sophomore ___Junior ___ Senior
Graduate:
___1st year ___ 2nd year ___ 3rd ___ 4th ___5 or more

Please state any additional comments you have about the experiment. Use the back of the paper if needed.

Design Problem Sheet and Survey Given to Condition 2: SKC A & CAD B

Design Problem - Device to Shell Peanuts

Problem Description:

In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal of this project is to design and build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African peanut farmers. The target throughput is approximately 50 kg (110 lbs) per hour.

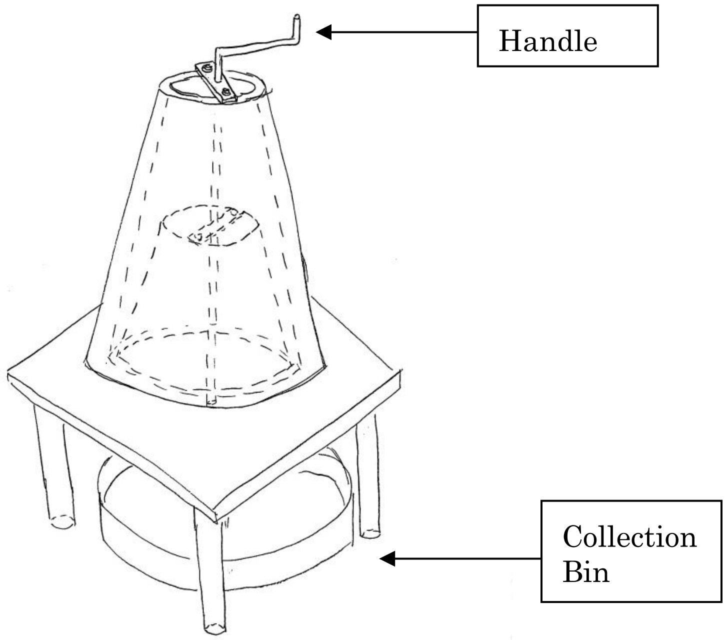
Customer Needs:

- Must remove the shell with minimal damage to the peanuts.
- Electrical outlets are not available as a power source.
- A large quantity of peanuts must be quickly shelled.
- Low cost.
- Easy to manufacture.

Two different Design Examples have been provided for you on the next 2 pages.

Design Example A

Consider the following solution as an example that might be created for this design problem.

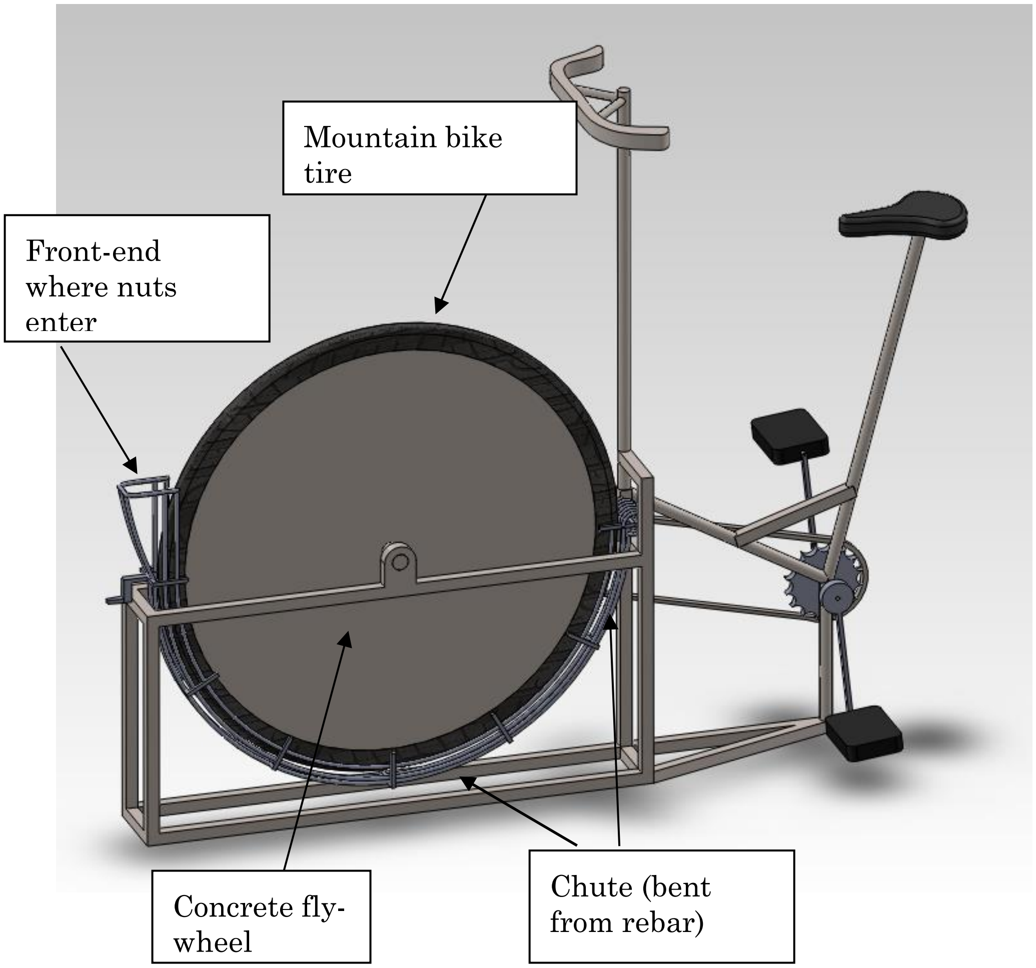


Solution Description:

The peanuts are loaded from the top of the system; the user rotates the handle, which pushes the nuts towards the tapered gap between the interior and exterior concrete walls of the machine, the walls are formed from molds. The shell of the nut is broken at the point where the gap is sufficiently narrow to cause enough friction to crack open the shells. The kernels and shell fragments fall into a basket and are later separated by winnowing.

Design Example B

Consider the following solution as an example that might be created for this design problem.



Solution Description:

This design of a pedal powered nut sheller utilizes a bicycle to power a device for shelling peanuts. As the machine is pedaled, nuts are fed into the front end. Once the nut enters the chute, the spinning mountain bike tire breaks the shells, and at the same time ejects the nuts. The action is aided by converting the bike wheel into a concrete fly-wheel.

Survey

1. From the representations (i.e. CAD or sketch) of the design examples given to you during this experiment, which one did you prefer? Please only state which representation you preferred and not the design.

Please check one. I preferred the: CAD example _____ Sketched Example _____
Please provide a brief explanation why.

2. From the design examples (Design A or Design B) given to you, did you find that you preferred one design over the other?

Please check one:
No ___ Yes ___

- If no, please move on to question 3
- If yes, which design did you prefer? Design A ___ Design B___. Please provide a brief explanation why you preferred one design over the other.

3. From the <u>design examples</u> (Design A or Design B) given to you, which was more useful to you during your idea generation?

Please check one:
Design A ___
Design B ___
Both were equally useful ___

4. From the <u>design examples</u> given (Design A or Design B), which do you think is more complex?

Please check one:
Design A ___
Design B ___
Both are equally complex ___

5. What is your gender?
    a. Female
    b. Male

6. What is your age? ______________

7. What is your major? _______________________________

8. Overall GPA _______________

9. GPA in Major _______________

10. Year in School
Undergraduate:
___ Freshman ___Sophomore ___Junior ___ Senior
Graduate:
___1st year ___ 2nd year ___ 3rd ___ 4th ___5 or more

Please state any additional comments you have about the experiment. Use the back of the paper if needed.

Design Problem Sheet and Survey Given to Condition 3: CAD B

Design Problem - Device to Shell Peanuts

Problem Description:

In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal of this project is to design and build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African peanut farmers. The target throughput is approximately 50 kg (110 lbs) per hour.

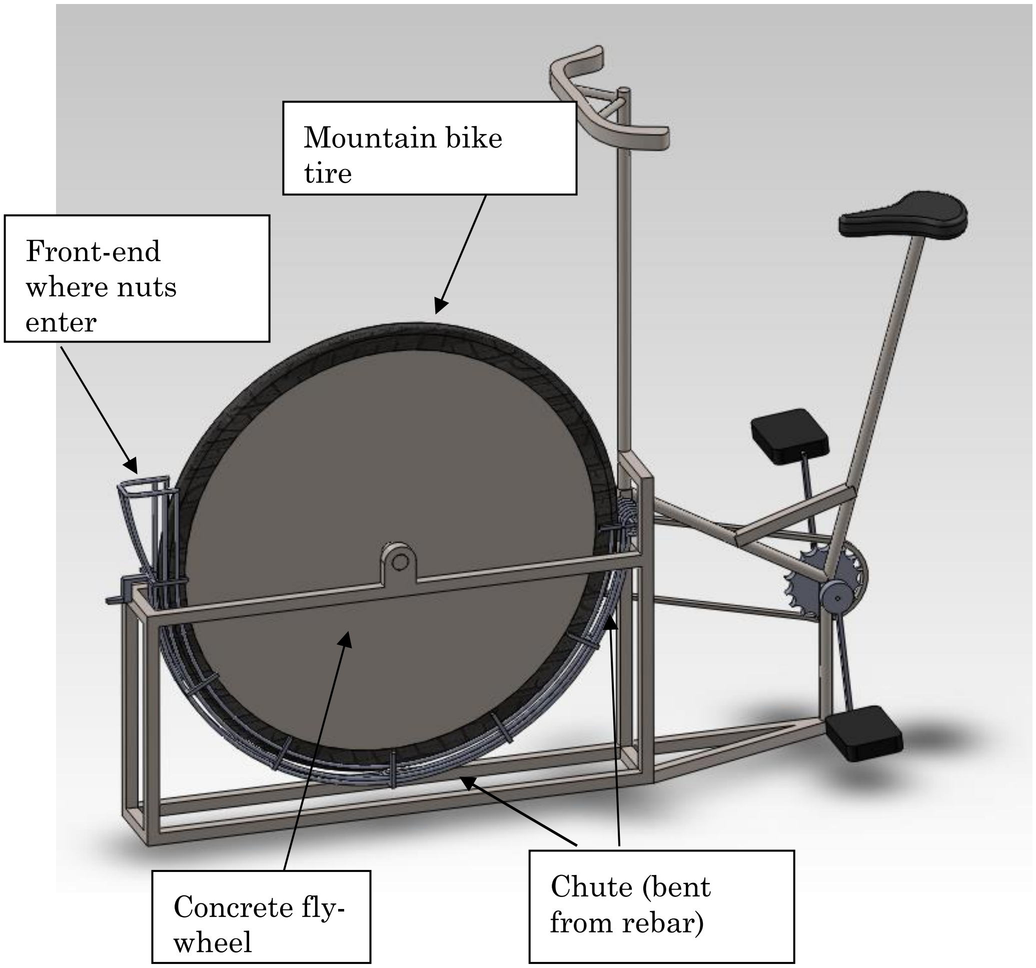
Customer Needs:

- Must remove the shell with minimal damage to the peanuts.
- Electrical outlets are not available as a power source.
- A large quantity of peanuts must be quickly shelled.
- Low cost.
- Easy to manufacture.

A Design Example has been provided for you on the next page.

Design Example

Consider the following solution as an example that might be created for this design problem.



Solution Description:

This design of a pedal powered nut sheller utilizes a bicycle to power a device for shelling peanuts. As the machine is pedaled, nuts are fed into the front end. Once the nut enters the chute, the spinning mountain bike tire breaks the shells, and at the same time ejects the nuts. The action is aided by converting the bike wheel into a concrete fly-wheel.

Survey

1. Would an additional example (i.e. more than 1 example) have been useful to you in your idea generation?

Please check one
No ___
Yes ___. If yes, please provide a brief explanation

2. What is your gender?
    a. Female
    b. Male

3. What is your age? ______________

4. What is your major? _______________________________

5. Overall GPA _______________

6. GPA in Major _______________

7. Year in School

Undergraduate:
___ Freshman ___Sophomore ___Junior ___ Senior
Graduate:
___1st year ___ 2nd year ___ 3rd ___ 4th ___5 or more

Please state any additional comments you have about the experiment. Use the back of the paper if needed.

Design Problem Sheet and Survey Given to Condition 4: CAD A & SKC B

Design Problem - Device to Shell Peanuts

Problem Description:

In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal of this project is to design and build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African peanut farmers. The target throughput is approximately 50 kg (110 lbs) per hour.

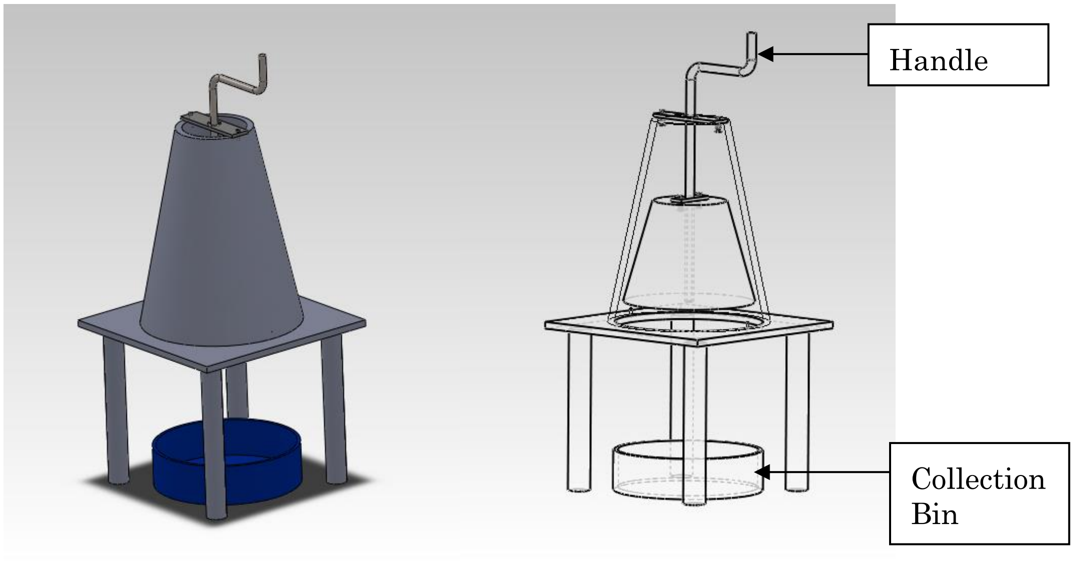
Customer Needs:

- Must remove the shell with minimal damage to the peanuts.
- Electrical outlets are not available as a power source.
- A large quantity of peanuts must be quickly shelled.
- Low cost.
- Easy to manufacture.

Two different Design Examples have been provided for you on the next 2 pages.

Design Example A

Consider the following solution as an example that might be created for this design problem.

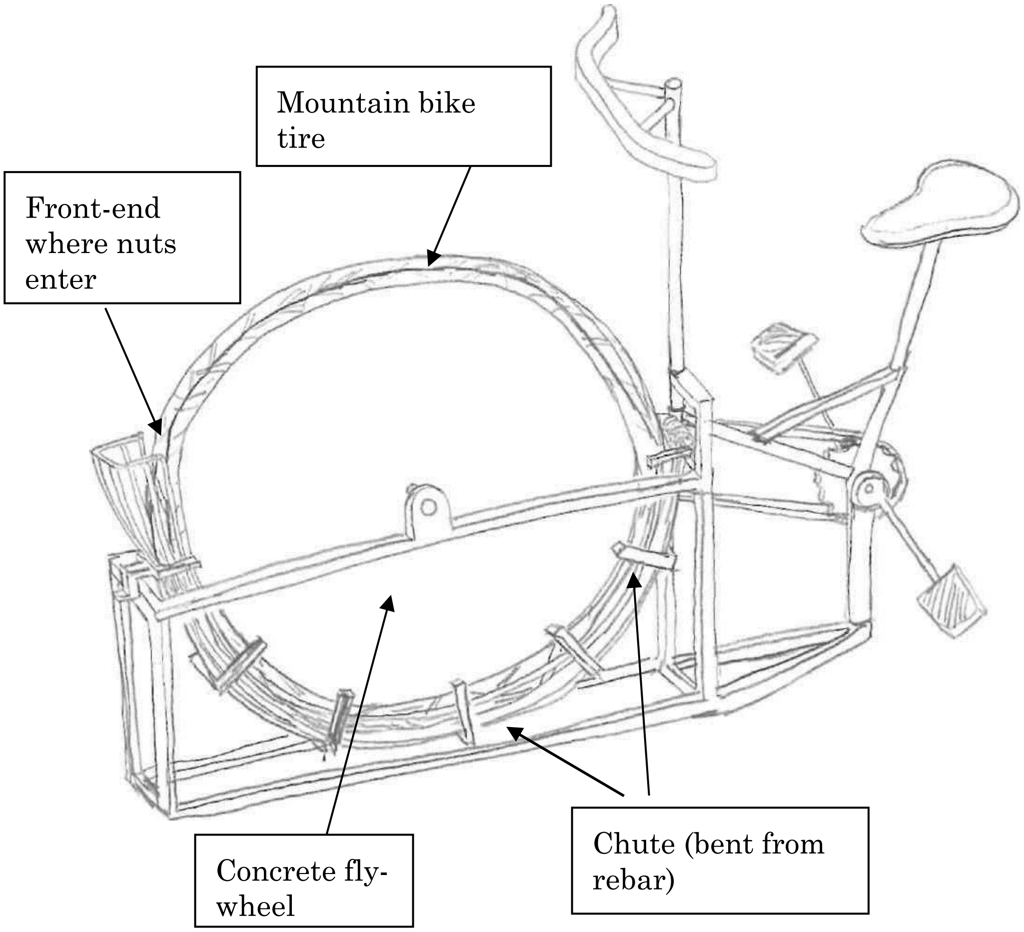


Solution Description:

The peanuts are loaded from the top of the system; the user rotates the handle, which pushes the nuts towards the tapered gap between the interior and exterior concrete walls of the machine, the walls are formed from molds. The shell of the nut is broken at the point where the gap is sufficiently narrow to cause enough friction to crack open the shells. The kernels and shell fragments fall into a basket and are later separated by winnowing.

Design Example B

Consider the following solution as an example that might be created for this design problem.



Solution Description:

This design of a pedal powered nut sheller utilizes a bicycle to power a device for shelling peanuts. As the machine is pedaled, nuts are fed into the front end. Once the nut enters the chute, the spinning mountain bike tire breaks the shells, and at the same time ejects the nuts. The action is aided by converting the bike wheel into a concrete fly-wheel.

Survey

1. From the representations (i.e. CAD or sketch) of the design examples given to you during this experiment, which one did you prefer? Please only state which representation you preferred and not the design.

Please check one. I preferred the: CAD example _____ Sketched Example _____
Please provide a brief explanation why.

2. From the design examples (Design A or Design B) given to you, did you find that you preferred one design over the other?

Please check one:
No ___ Yes ___

- If no, please move on to question 3
- If yes, which design did you prefer? Design A ___ Design B___. Please provide a brief explanation why you preferred one design over the other.

3. From the <u>design examples</u> (Design A or Design B) given to you, which was more useful to you during your idea generation?

Please check one:
Design A ___
Design B ___
Both were equally useful ___

4. From the <u>design examples</u> given (Design A or Design B), which do you think is more complex?

Please check one:
Design A ___
Design B ___
Both are equally complex ___

5. What is your gender?
   a. Female
   b. Male

6. What is your age? ______________

7. What is your major? _______________________________

8. Overall GPA _______________

9. GPA in Major _______________

10. Year in School
Undergraduate:
___ Freshman ___Sophomore ___Junior ___ Senior
Graduate:
___1st year ___ 2nd year ___ 3rd ___ 4th ___5 or more

Please state any additional comments you have about the experiment. Use the back of the paper if needed.

Design Problem Sheet and Survey Given to Condition 5: SKC A & SKC B

Design Problem - Device to Shell Peanuts

Problem Description:

In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal of this project is to design and build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African peanut farmers. The target throughput is approximately 50 kg (110 lbs) per hour.

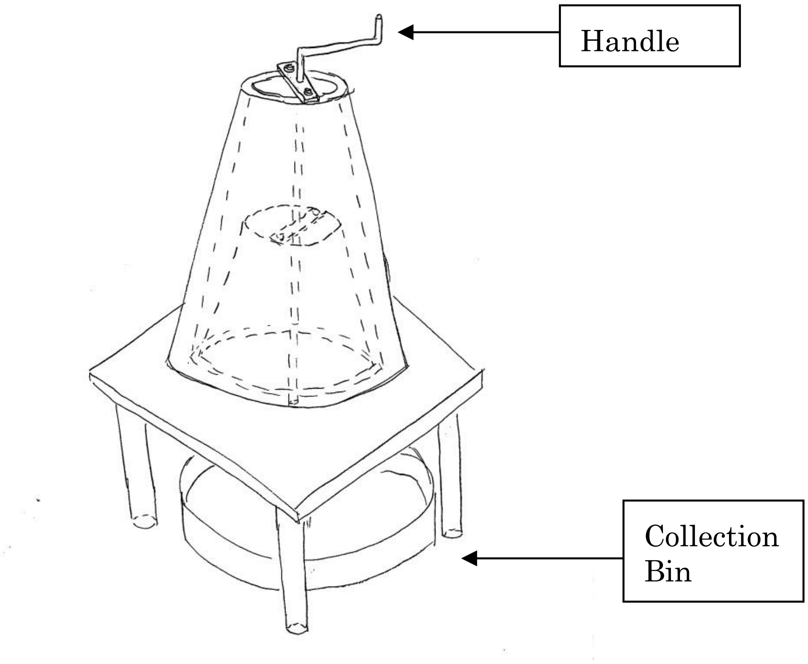
Customer Needs:

- Must remove the shell with minimal damage to the peanuts.
- Electrical outlets are not available as a power source.
- A large quantity of peanuts must be quickly shelled.
- Low cost.
- Easy to manufacture.

Two different Design Examples have been provided for you on the next 2 pages.

Design Example A

Consider the following solution as an example that might be created for this design problem.

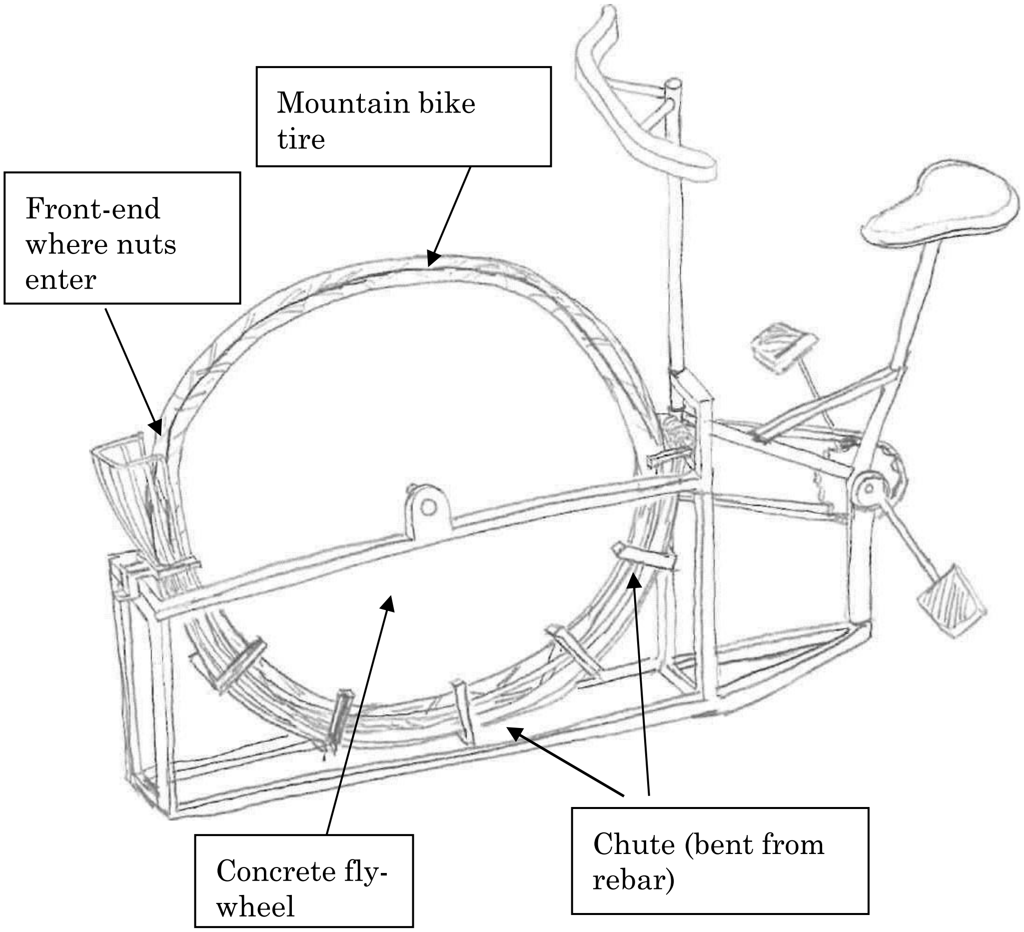


Solution Description:

The peanuts are loaded from the top of the system; the user rotates the handle, which pushes the nuts towards the tapered gap between the interior and exterior concrete walls of the machine, the walls are formed from molds. The shell of the nut is broken at the point where the gap is sufficiently narrow to cause enough friction to crack open the shells. The kernels and shell fragments fall into a basket and are later separated by winnowing.

Design Example B

Consider the following solution as an example that might be created for this design problem.



Solution Description:

This design of a pedal powered nut sheller utilizes a bicycle to power a device for shelling peanuts. As the machine is pedaled, nuts are fed into the front end. Once the nut enters the chute, the spinning mountain bike tire breaks the shells, and at the same time ejects the nuts. The action is aided by converting the bike wheel into a concrete fly-wheel.

Survey

1. From the <u>design examples</u> (Design A or Design B) given to you, did you find that you preferred one design over the other?

Please check one:
No ___ Yes ___

- If no, please move on to question 2
- If yes, which design did you prefer? Design A ___ Design B___. Please provide a brief explanation why you preferred one design over the other.

2. From the <u>design examples</u> (Design A or Design B) given to you, which was more useful to you during your idea generation?

Please check one:
Design A ___
Design B ___
Both were equally useful ___

3. From the <u>design examples</u> given (Design A or Design B), which do you think is more complex?

Please check one:

Design A ___
Design B ___
Both are equally complex ___

4. What is your gender?
    a. Female
    b. Male

5. What is your age? ______________

6. What is your major? _______________________________

7. Overall GPA _______________

8. GPA in Major _______________

9. Year in School
Undergraduate:
___ Freshman ___Sophomore ___Junior ___ Senior
Graduate:
___1st year ___ 2nd year ___ 3rd ___ 4th ___5 or more

Please state any additional comments you have about the experiment. Use the back of the paper if needed.

Design Problem Sheet and Survey Given to Condition 6: SKC B

Design Problem - Device to Shell Peanuts

Problem Description:

In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal of this project is to design and build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African peanut farmers. The target throughput is approximately 50 kg (110 lbs) per hour.

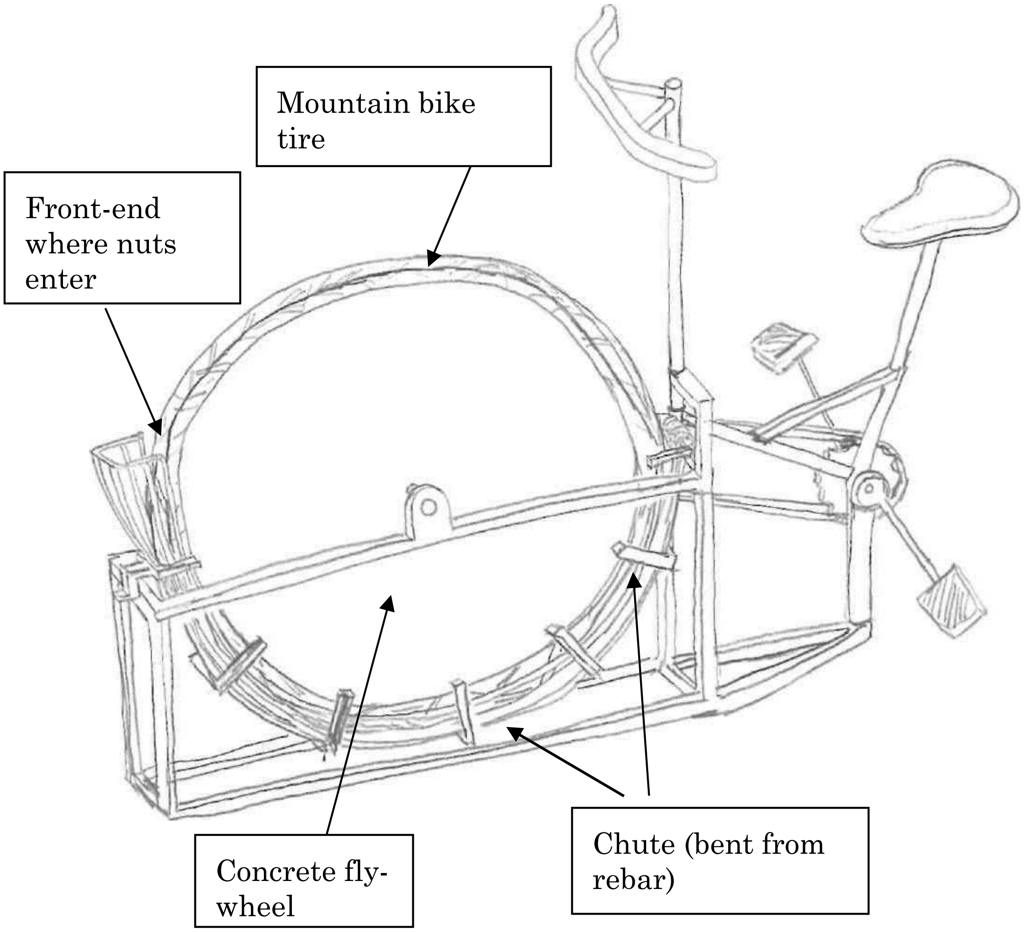
Customer Needs:

- Must remove the shell with minimal damage to the peanuts.
- Electrical outlets are not available as a power source.
- A large quantity of peanuts must be quickly shelled.
- Low cost.
- Easy to manufacture.

A Design Example has been provided for you on the next page.

Design Example

Consider the following solution as an example that might be created for this design problem.



Solution Description:

This design of a pedal powered nut sheller utilizes a bicycle to power a device for shelling peanuts. As the machine is pedaled, nuts are fed into the front end. Once the nut enters the chute, the spinning mountain bike tire breaks the shells, and at the same time ejects the nuts. The action is aided by converting the bike wheel into a concrete fly-wheel.

Survey

1. Would an additional example (i.e. more than 1 example) have been useful to you in your idea generation?

Please check one
No ___
Yes ___. If yes, please provide a brief explanation

2. What is your gender?
a. Female
b. Male

3. What is your age? ______________

4. What is your major? _______________________________

5. Overall GPA _______________

6. GPA in Major _______________

7. Year in School
Undergraduate:
___ Freshman ___Sophomore ___Junior ___ Senior
Graduate:
___1st year ___ 2nd year ___ 3rd ___ 4th ___5 or more

Please state any additional comments you have about the experiment. Use the back of the paper if needed.

Design Problem Sheet and Survey Given to Condition 7: CAD A

Design Problem - Device to Shell Peanuts

Problem Description:

In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal of this project is to design and build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African peanut farmers. The target throughput is approximately 50 kg (110 lbs) per hour.

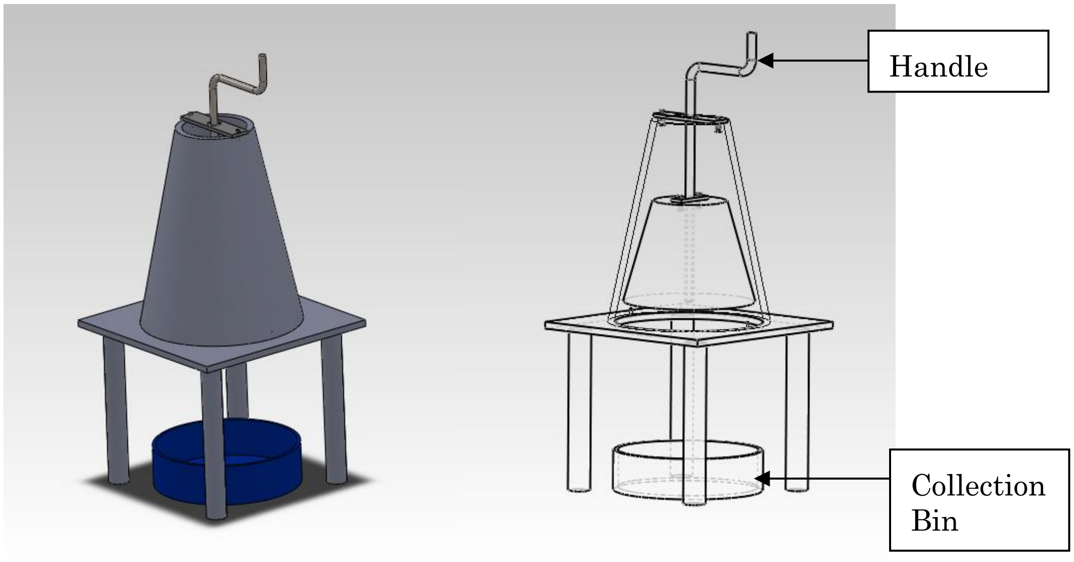
Customer Needs:

- Must remove the shell with minimal damage to the peanuts.
- Electrical outlets are not available as a power source.
- A large quantity of peanuts must be quickly shelled.
- Low cost.
- Easy to manufacture.

A Design Example has been provided for you on the next page.

Design Example

Consider the following solution as an example that might be created for this design problem.



Solution Description:

This design of a pedal powered nut sheller utilizes a bicycle to power a device for shelling peanuts. As the machine is pedaled, nuts are fed into the front end. Once the nut enters the chute, the spinning mountain bike tire breaks the shells, and at the same time ejects the nuts. The action is aided by converting the bike wheel into a concrete fly-wheel.

Survey

1. Would an additional example (i.e. more than 1 example) have been useful to you in your idea generation?

Please check one
No ___
Yes ___. If yes, please provide a brief explanation

2. What is your gender?
  a. Female
  b. Male

3. What is your age? _______________

4. What is your major? __________________________________

5. Overall GPA ________________

6. GPA in Major ________________

7. Year in School
Undergraduate:
___ Freshman ___Sophomore ___Junior ___ Senior
Graduate:
___1st year ___ 2nd year ___ 3rd ___ 4th ___5 or more

Please state any additional comments you have about the experiment. Use the back of the paper if needed.

Design Problem Sheet and Survey Given to Condition 8: SKC A

Design Problem - Device to Shell Peanuts

Problem Description:

In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal of this project is to design and build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African peanut farmers. The target throughput is approximately 50 kg (110 lbs) per hour.

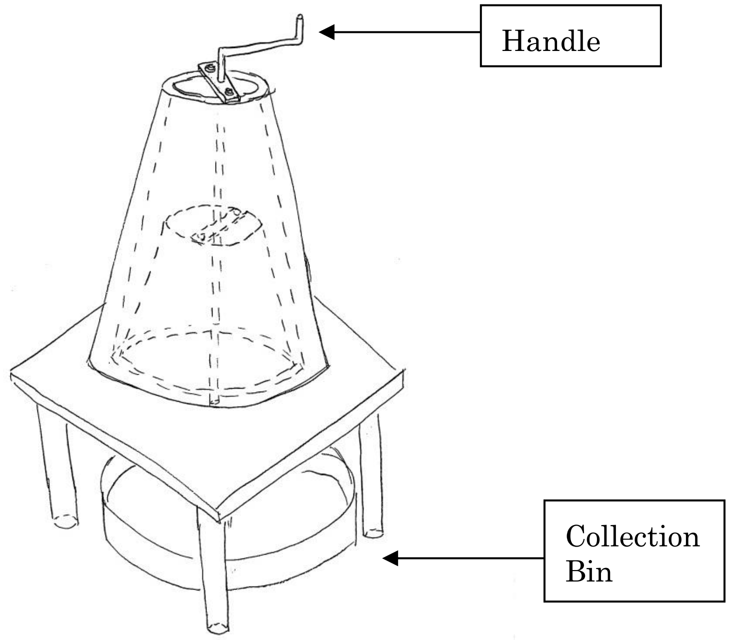
Customer Needs:

- Must remove the shell with minimal damage to the peanuts.
- Electrical outlets are not available as a power source.
- A large quantity of peanuts must be quickly shelled.
- Low cost.
- Easy to manufacture.

A Design Example has been provided for you on the next page.

Design Example

Consider the following solution as an example that might be created for this design problem.



Solution Description:

This design of a pedal powered nut sheller utilizes a bicycle to power a device for shelling peanuts. As the machine is pedaled, nuts are fed into the front end. Once the nut enters the chute, the spinning mountain bike tire breaks the shells, and at the same time ejects the nuts. The action is aided by converting the bike wheel into a concrete fly-wheel.

Survey

1. Would an additional example (i.e. more than 1 example) have been useful to you in your idea generation?

Please check one
No ___
Yes ___. If yes, please provide a brief explanation

2. What is your gender?
   a. Female
      b. Male

3. What is your age? ______________

4. What is your major? _______________________________

5. Overall GPA _______________

6. GPA in Major _______________

7. Year in School
Undergraduate:
___ Freshman ___Sophomore ___Junior ___ Senior
Graduate:
___1st year ___ 2nd year ___ 3rd ___ 4th ___5 or more

Please state any additional comments you have about the experiment. Use the back of the paper if needed.

Design Problem Sheet and Survey Given to Condition 9: Control

Design Problem - Device to Shell Peanuts

Problem Description:

In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal of this project is to design and build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African peanut farmers. The target throughput is approximately 50 kg (110 lbs) per hour.

Customer Needs:

- Must remove the shell with minimal damage to the peanuts.
- Electrical outlets are not available as a power source.
- A large quantity of peanuts must be quickly shelled.
- Low cost.
- Easy to manufacture.

Survey

1. Do you think it would have been useful or helpful if you were given an example of an existing solution for this design problem to help you in your idea generation process?

Please check one:
No ___
Yes ___
If yes, please provide a brief explanation

2. What is your gender?
   a. Female
   b. Male

3. What is your age? _______________

4. What is your major? _________________________________

5. Overall GPA ________________

6. GPA in Major ________________

7. Year in School

Undergraduate:
___ Freshman ___Sophomore ___Junior ___ Senior
Graduate:
___1st year ___ 2nd year ___ 3rd ___ 4th ___5 or more

Please state any additional comments you have about the experiment. Use the back of the paper if needed.

APPENDIX C – MATERIALS FROM STUDY 3

Experiment 3 Script

Check List

1. Experiment Packets
2. Stop watch
3. Cash
4. “I got my money” sheets
5. Extra blank sheets
6. Stapler
7. Paper clips
8. Extra consent forms

1. *Consent*

As participants arrive, show them to their workstations and hand them the experiment packets.

Hello and thank you for taking time to participate in this research study today. Please turn off all cell phones. For this study, you are not supposed to monitor time using your watches or cell phones. Please keep your watches and cell phones in your backpack.

Wait for the participants have turn off their cell phones and/or put away their watches.

You are being asked to participate in a research study on engineering design. This experiment will require approximately 1 hour. You are not required to participate in this study and may end your participation at any time.

Your effort will be compensated with either payment of up to $10 or with extra credit in your Capstone class. Participants who show superior effort will be given a bonus in the form of extra money or extra bonus points depending on which type of compensation you choose.

The packet in front of you contains 2 copies of a consent form, an instruction sheet, a design problem and a few blank sheets. Please read the consent form and sign it if you agree to participate. Please let me know if you have any questions about the experiment. You also need to agree not to

discuss the details of this experiment with your friends until after Dec 31st, 2013, since that can bias the results of our future experiments.

Wait for all participants to sign the consent forms

Collect the consent forms.

Please put away your copy of the consent forms.

4. *Design Problem and Idea Generation*

This experiment is seeking to understand engineering idea generation. Today your task will be to generate as many ideas as possible that could help to solve the given design problem.

The sheet in front of gives you the instructions to solve the problem and the remaining sheets give you the details of the design problem. You have 5 minutes to read the instructions and design problem. I will give you further instructions at the end of the 5 minutes. Please do not begin the design task until I tell you to do so.

Your five minutes starts now.

Start stopwatch. Give 5 minutes for the participants to read the instructions and design problem

at the end of 5 min **Do you have any questions?**

Record if any.

You will have now have 45 minutes to generate solutions.

Please generate as many solutions as possible for the problem. You are not allowed to discuss anything with your neighbor during the experiment. If you have any questions, please raise your hand, and I will come to you to answer your questions. Please do not ask the questions loud. If you need extra sheets of paper, please let me know and I will bring some to you.

Your 45 minutes starts now

!

Start stopwatch: Idea generation time

at the end of 45 minutes **Please stop the idea generation now.**

The last page of your packet contains a brief survey, please answer the questions listed.

5. End & Payment

At the end of the experiment:

Thank you for your participation. This concludes the experiment.
Please listen to this important announcement: If you have seen this design problem before, please write a note stating so on the front of your packet

Wait for about 30 seconds to give them to write.

Please bring your packets to me and I will check them and then give you your payment

Look through pages and tell students that they have produced multiple ideas so they will receive $15

(If they have the option of extra credit, say: If you have opted for extra credits for your design class, your name will be sent to your professor after the completion of the experiment)

Please come to the desk to sign for and receive your money.
Please remember to not discuss this study with your classmates until after December 31st, 2013 since this will bias the data. If you have any questions about this study, I can answer them at this time.

Design Problem Sheet Given to the Control Condition

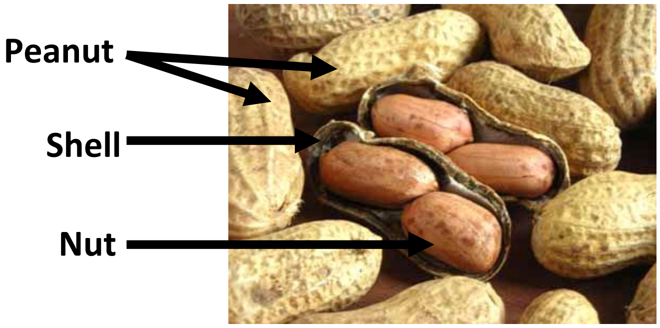
Design Problem - Device to Shell Peanuts

Problem Description:

In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal of this project is to design and build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African peanut farmers. The target throughput is approximately 50 kg (110 lbs) per hour.

Customer Needs:

- Must remove the shell with minimal damage to the peanuts.
- Electrical outlets are not available as a power source.
- A large quantity of peanuts must be quickly shelled.
- Low cost.
- Easy to manufacture.



Design Problem Sheet Given to the Sketch Condition

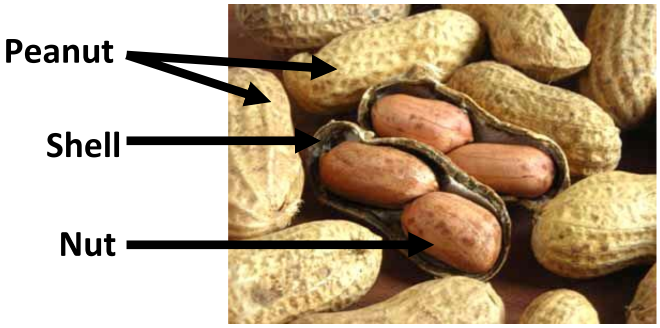
Design Problem - Device to Shell Peanuts

Problem Description:

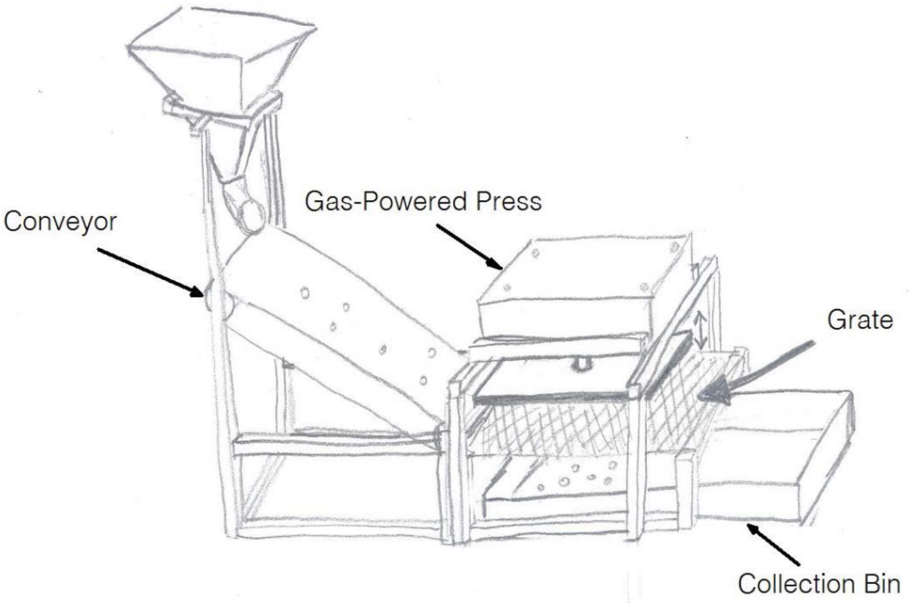
In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal of this project is to design and build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African peanut farmers. The target throughput is approximately 50 kg (110 lbs) per hour.

Customer Needs:

- Must remove the shell with minimal damage to the peanuts.
- Electrical outlets are not available as a power source.
- A large quantity of peanuts must be quickly shelled.
- Low cost.
- Easy to manufacture.



Consider the following solution as an example that might be created for this design problem.



Solution Description: This system uses a gas powered press to crush the peanut. The peanuts are pressed against the grate and the shells are broken. The grate separates the nuts from the broken shells; the nuts then fall into a collection bin.

****Note to Readers: The Problem Description, Customer Needs and Peanut Sheller image and solution description all appeared on one page in the packet given to the participants*

Design Problem Sheet Given to the Function Tree Condition

Design Problem - Device to Shell Peanuts

Problem Description:

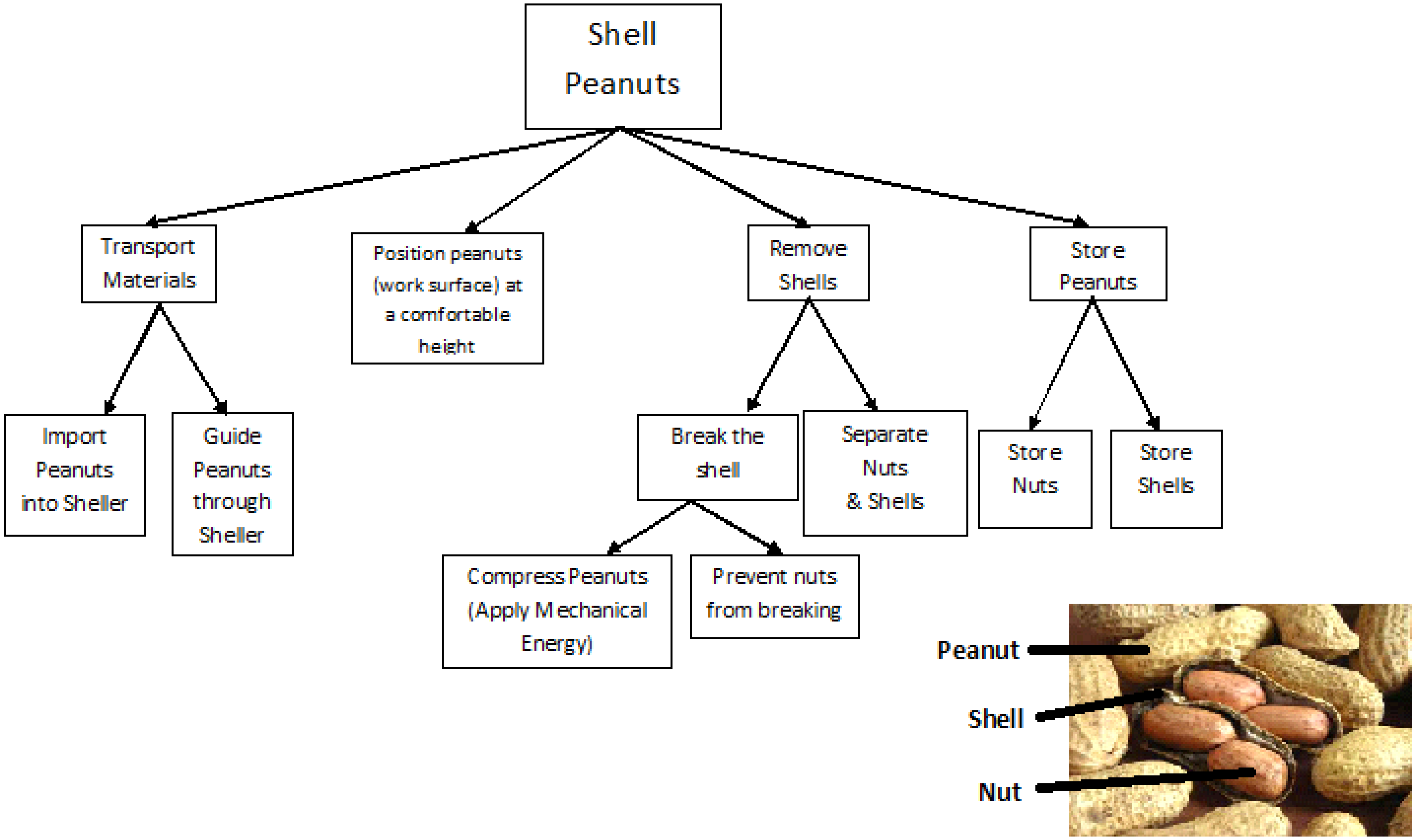
In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal of this project is to design and build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African peanut farmers. The target throughput is approximately 50 kg (110 lbs) per hour.

Customer Needs:

- Must remove the shell with minimal damage to the peanuts.
- Electrical outlets are not available as a power source.
- A large quantity of peanuts must be quickly shelled.
- Low cost.
- Easy to manufacture.

The Function Tree of an example solution is given on the next page to help you in your idea generation.

The <u>Function Tree</u> of an example solution is given below to help you in your idea generation; it shows the functions and sub-functions of the example.



Design Problem Sheet Given to the Sketch & Function Tree Condition

Design Problem - Device to Shell Peanuts

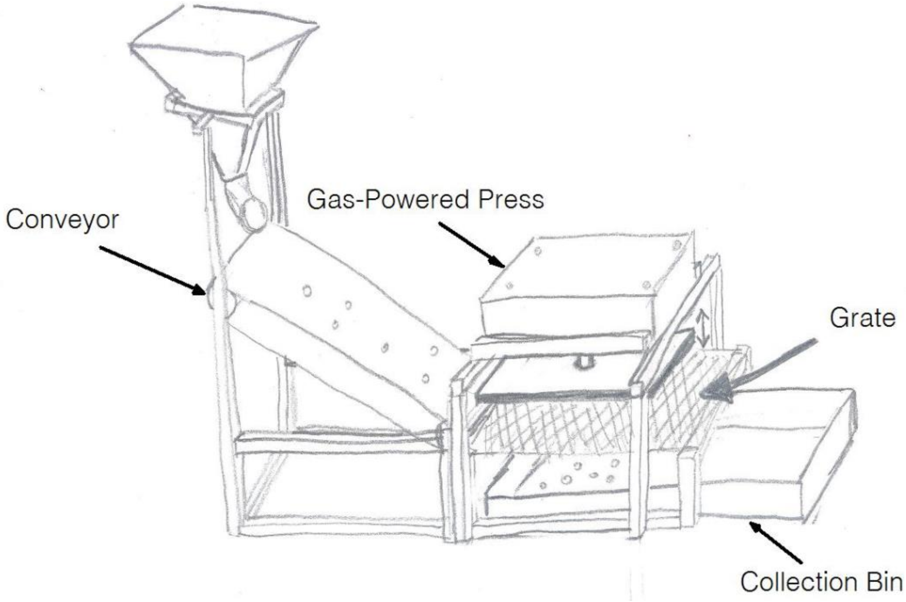
Problem Description:

In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal of this project is to design and build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African peanut farmers. The target throughput is approximately 50 kg (110 lbs) per hour.

Customer Needs:

- Must remove the shell with minimal damage to the peanuts.
- Electrical outlets are not available as a power source.
- A large quantity of peanuts must be quickly shelled.
- Low cost.
- Easy to manufacture.

Consider the following solution as an example that might be created for this design problem.



Solution Description: This system uses a gas powered press to crush the peanut. The peanuts are pressed against the grate and the shells are broken. The grate separates the nuts from the broken shells; the nuts then fall into a collection bin.

****Note to Readers: The page with the function tree was also included.*

Survey given to all Conditions in Study 3

Survey

1. Did you hear about this design problem ahead of time? This will NOT affect the credit you receive

Please circle one answer

YES NO

If yes, did you generate solutions before the session?

YES NO

APPENDIX D – MATERIALS FROM STUDY 4

SIMPLE BoS Utility System Pairwise Comparison

Function	Tripod System	Solar Hammock	Solar Truss	Solar Canopy	Urban Forest	Solar Container
Tripod System		0	0	0	0.5	0
Solar Hammock	1		0	0.5	1	0
Solar Truss	1	1		0	1	0.5
Solar Canopy	1	0.5	1		1	0
Urban Forest	0.5	0	0	0		0
Solar Container	1	1	0.5	1	1	
	4.5	2.5	1.5	1.5	4.5	0.5

Cost	Tripod System	Solar Hammock	Solar Truss	Solar Canopy	Urban Forest	Solar Container
Tripod System		0	0	0	0	0
Solar Hammock	1		0	0	0	0
Solar Truss	1	1		0	0	0
Solar Canopy	1	1	1		1	1
Urban Forest	1	1	1	0		0.5

Solar Container	1	1	1	0	0.5	
	5	4	3	0	1.5	1.5

kWh Production	**Tripod System**	**Solar Hammock**	**Solar Truss**	**Solar Canopy**	**Urban Forest**	**Solar Container**
Tripod System		0	0.5	0	0	0
Solar Hammock	1		0.5	0.5	0	0.5
Solar Truss	0.5	0.5		0	1	0.5
Solar Canopy	1	0.5	1		1	0.5
Urban Forest	1	1	0	0		0
Solar Container	1	0.5	0.5	0.5	1	
	4.5	2.5	2.5	1	3	1.5

Multifunctionality	**Tripod System**	**Solar Hammock**	**Solar Truss**	**Solar Canopy**	**Urban Forest**	**Solar Container**
Tripod System		0	1	1	1	1
Solar Hammock	1		0.5	0.5	1	1
Solar Truss	0	0.5		0.5	1	1
Solar Canopy	0	0.5	0.5		0.5	0
Urban Forest	0	0	0	0.5		0

Solar Container	0	0	0	1	1	
	1	1	2	3.5	4.5	3

Install Time	**Tripod System**	**Solar Hammock**	**Solar Truss**	**Solar Canopy**	**Urban Forest**	**Solar Container**
Tripod System		0	1	0	0	1
Solar Hammock	1		1	0	0	1
Solar Truss	0	0		0	0	1
Solar Canopy	1	1	1		1	1
Urban Forest	1	1	1	0		1
Solar Container	0	0	0	0	0	
	3	2	4	0	1	5

Reliability	**Tripod System**	**Solar Hammock**	**Solar Truss**	**Solar Canopy**	**Urban Forest**	**Solar Container**
Tripod System		0	0	0	0	0
Solar Hammock	1		0.5	0	1	0
Solar Truss	1	0.5		1	1	0.5
Solar Canopy	1	1	0		0.5	0
Urban Forest	1	0	0	0.5		0

Solar Container	1	1	0.5	1	1	
	5	2.5	1	2.5	3.5	0.5

Manufacturability	**Tripod System**	**Solar Hammock**	**Solar Truss**	**Solar Canopy**	**Urban Forest**	**Solar Container**
Tripod System		0	1	0	0	0
Solar Hammock	1		0	0	0	0
Solar Truss	0	1		0	0	0
Solar Canopy	1	1	1		1	1
Urban Forest	1	1	1	0		1
Solar Container	1	1	1	0	0	
	4	4	4	0	1	2

System	**Tripod System**	**Solar Hammock**	**Solar Truss**	**Solar Canopy**	**Urban Forest**	**Solar Container**
Total Score	26	17.5	16	5	14.5	11

SIMPLE BoS Commercial System Pairwise Comparison

Function	**Curb**	**WASP**	**Canopy**	**Hextile**	**Fold**	**Clip**
Curb		0	0	0	0	0
Wasp	1		1	0.5	1	1
Canopy	1	0		0	0	0
Hextile	1	0.5	1		0	0
Fold	1	0	1	1		0
Clip	1	0	1	1	1	
Total	5	0.5	4	2.5	2	1

Cost	**Curb**	**WASP**	**Canopy**	**Hextile**	**Fold**	**Clip**
Curb		0	0	0	0	0
Wasp	1		0	1	1	1
Canopy	1	1		1	1	1
Hextile	1	0	0		0	0
Fold	1	0	0	1		0

Clip	1	0	0	1	1	
Total	5	1	0	4	3	2

kWh Production	**Curb**	**WASP**	**Canopy**	**Hextile**	**Fold**	**Clip**
Curb		0	1	0	0.5	0.5
Wasp	1		1	0	1	1
Canopy	0	0		0	0	0
Hextile	1	1	1		1	1
Fold	0.5	0	1	0		1
Clip	0.5	0	1	0	0	
Total	3	1	5	0	2.5	3.5

Multifunctionality	**Curb**	**WASP**	**Canopy**	**Hextile**	**Fold**	**Clip**
Curb		1	1	1	0	0
Wasp	0		1	0.5	0	0
Canopy	0	0		0	0	0
Hextile	0	0.5	1		0	0
Fold	1	1	1	1		0.5
Clip	1	1	1	1	0.5	

Total	2	3.5	5	3.5	0.5	0.5

Install Time	**Curb**	**WASP**	**Canopy**	**Hextile**	**Fold**	**Clip**
Curb		1	0	1	1	0
Wasp	0		0	1	1	0
Canopy	1	1		1	1	1
Hextile	0	0	0		0	0
Fold	0	0	0	1		0
Clip	1	1	0	1	1	
Total	2	3	0	5	4	1

Reliability	**Curb**	**WASP**	**Canopy**	**Hextile**	**Fold**	**Clip**
Curb		0	0	0	0	0
Wasp	1		1	1	1	1
Canopy	1	0		1	1	1
Hextile	1	0	0		0	0
Fold	1	0	0	1		1
Clip	1	0	0	1	0	
Total	5	0	1	4	2	3

Manufacturability	Curb	WASP	Canopy	Hextile	Fold	Clip
Curb		0	0	0	0	0
Wasp	1		0	0	1	1
Canopy	1	1		1	1	1
Hextile	1	1	0		1	1
Fold	1	0	0	0		1
Clip	1	0	0	0	0	
Total	5	2	0	1	3	4

System	Curb	WASP	Canopy	Hextile	Fold	Clip
Total Score	25	7.5	10	16.5	16.5	14.5

SIMPLE BoS Residential System Pairwise Comparison

Function	Solar Ridge	Integrated Electrical Frame	3kW Residential Rack	Fast Foot	Standing Seam	Double Skin	SSIP PVT	Solar Leaf	Solar Louver	Tesselated Solar	Integrated Fast Foot
Solar Ridge		0	0.5	0	0	0	0	0	0	0	1
Integrated Electrical Frame	1		1	0	0	0	0	0	0	0	0.5
3kW Residential Rack	0.5	0		0	0	0	0	0	0	0	0
Fast Foot	1	1	1		0	0	0	0	0	0	1
Standing Seam	1	1	1	1		1	0	1	0	0.5	1
Double Skin	1	1	1	1	0		0	0	0	0	1
SSIP PVT	1	1	1	1	1	1		1	0	1	1
Solar Leaf	1	1	1	1	0	1	1		1	1	1
Solar Louver	1	1	1	1	1	1	1	0		1	1
Tesselated Solar	1	1	1	1	0.5	1	0	0	0		1

Integrated Fast Foot	0	0.5	1	0	0	0	0	0	0	0	
	8.5	7.5	9.5	6	2.5	5	2	2	1	3.5	8.5

Cost	**Solar Ridge**	**Integrated Electrical Frame**	**3kW Residential Rack**	**Fast Foot**	**Standing Seam**	**Double Skin**	**SSIP PVT**	**Solar Leaf**	**Solar Louver**	**Tesselated Solar**	**Integrated Fast Foot**
Solar Ridge		1	1	0	0	0	0	0	0	0	1
Integrated Electrical Frame	0		1	0	0	0	0	0	0	0	0
3kW Residential Rack	0	0		0	0	0	0	0	0	0	0
Fast Foot	1	1	1		0	0	0	0	0	0.5	1
Standing Seam	1	1	1	1		1	0	0.5	0	1	1
Double Skin	1	1	1	0	0		0	0	0	0	0
SSIP PVT	1	1	1	1	1	1		1	0	1	1
Solar Leaf	1	1	1	1	0.5	1	0		0	1	1
Solar Louver	1	1	1	1	1	1	0	1		1	1

Tesselated Solar	1	1	1	0.5	0	1	0	0	0		1
Integrated Fast Foot	0	1	1	0	0	1	0	0	0	0	
	7	9	10	4.5	2.5	6	0	2.5	0	4.5	7

kWh Production	**Solar Ridge**	**Integrated Electrical Frame**	**3kW Residential Rack**	**Fast Foot**	**Standing Seam**	**Double Skin**	**SSIP PVT**	**Solar Leaf**	**Solar Louver**	**Tesselated Solar**	**Integrated Fast Foot**
Solar Ridge		0.5	0.5	0.5	0.5	0	1	0	0.5	0	0
Integrated Electrical Frame	0.5		0.5	0.5	0.5	0	1	0	0.5	0	0
3kW Residential Rack	0.5	0.5		0.5	0.5	0	1	0	0.5	0	0
Fast Foot	0.5	0.5	0.5		0.5	0.5	1	0.5	0.5	0	0.5
Standing Seam	0.5	0.5	0.5	0.5		0	1	0	0.5	0	0
Double Skin	1	1	1	0.5	1		1	0	1	1	1
SSIP PVT	0	0	0	0	0	0		0	0	0	0

Solar Leaf	1	1	1	0.5	1	1	1		0.5	0	0.5
Solar Louver	0.5	0.5	0.5	0.5	0.5	0	1	0.5		0	0
Tesselated Solar	1	1	1	1	1	0	1	1	1		0
Integrated Fast Foot	1	1	1	0.5	1	0	1	0.5	1	1	
	6.5	6.5	6.5	5	6.5	1.5	10	2.5	6	2	2

Multifunctionality	**Solar Ridge**	**Integrated Electrical Frame**	**3kW Residential Rack**	**Fast Foot**	**Standing Seam**	**Double Skin**	**SSIP PVT**	**Solar Leaf**	**Solar Louver**	**Tesselated Solar**	**Integrated Fast Foot**
Solar Ridge		1	0	1	1	1	1	1	1	1	0
Integrated Electrical Frame	0		0	0	0	0	0	0	0	0	0
3kW Residential Rack	1	1		0	0	1	1	1	1	1	0
Fast Foot	0	1	1		1	1	1	1	1	1	1
Standing Seam	0	1	1	0		1	1	1	1	1	0

Double Skin	0	1	0	0	0		1	0.5	0.5	1	0
SSIP PVT	0	1	0	0	0	0		0	0	0	0
Solar Leaf	0	1	0	0	0	0.5	1		0	0.5	0
Solar Louver	0	1	0	0	0	0.5	1	1		0.5	0
Tesselated Solar	0	1	0	0	0	0	1	0.5	0.5		0
Integrated Fast Foot	1	1	1	0	1	1	1	1	1	1	
	2	10	3	1	3	6	9	7	6	7	1

Install Time	**Solar Ridge**	**Integrated Electrical Frame**	**3kW Residential Rack**	**Fast Foot**	**Standing Seam**	**Double Skin**	**SSIP PVT**	**Solar Leaf**	**Solar Louver**	**Tesselated Solar**	**Integrated Fast Foot**
Solar Ridge		0.5	1	0	0	0	0	0	0	1	0
Integrated Electrical Frame	0.5		1	0	0	0	0	0	0	0	0
3kW Residential Rack	0	0.5		0	0	0	0	0	0	0	0
Fast Foot	1	1	1		0	0	0	0	0	0	1

Standing Seam	1	1	1	1		1	0	0	0	1	1
Double Skin	1	1	1	0	0		0	0	0	0	0
SSIP PVT	1	1	1	1	1	1		1	0	1	1
Solar Leaf	1	1	1	1	1	1	0		0	1	1
Solar Louver	1	1	1	1	1	1	1	1		1	1
Tesselated Solar	0	1	1	1	0	1	0	0	0		1
Integrated Fast Foot	1	1	1	0	0	1	0	0	0	0	
	7.5	9	10	5	3	6	1	2	0	5	6

Reliability	**Solar Ridge**	**Integrated Electrical Frame**	**3kW Residential Rack**	**Fast Foot**	**Standing Seam**	**Double Skin**	**SSIP PVT**	**Solar Leaf**	**Solar Louver**	**Tesselated Solar**	**Integrated Fast Foot**
Solar Ridge		1	1	0	0	0.5	0	0	0	0	0
Integrated Electrical Frame	0		0	0	0	0	0	0	0	0	0

3kW Residential Rack	0	1		0	0	1	0	0	0	0	0
Fast Foot	1	1	1		0	0	0	0	0	0	1
Standing Seam	1	1	1	1		1	0	0	0	0.5	1
Double Skin	0.5	1	0	0	0		0	0	0	0.5	1
SSIP PVT	1	1	1	1	1	1		0.5	1	1	1
Solar Leaf	1	1	1	1	1	1	0.5		1	1	1
Solar Louver	1	1	1	1	1	1	0	0		1	1
Tesselated Solar	1	1	1	1	0.5	0.5	0	0	0		0.5
Integrated Fast Foot	1	1	1	0	0	0	0	0	0	0.5	
	7.5	10	8	5	3.5	6	0.5	0.5	2	4.5	6.5

Manufacturability	**Solar Ridge**	**Integrated Electrical Frame**	**3kW Residential Rack**	**Fast Foot**	**Standing Seam**	**Double Skin**	**SSIP PVT**	**Solar Leaf**	**Solar Louver**	**Tesselated Solar**	**Integrated Fast Foot**
Solar Ridge		1	0	1	1	0	0	0	0	0	1

Integrated Electrical Frame	0		0	0	0	0	0	0	0	0	0
3kW Residential Rack	1	1		1	1	0	0	0	0	0	1
Fast Foot	0	1	0		0	0	0	0	0	0	0
Standing Seam	0	1	0	1		1	0	0	0	0	0
Double Skin	1	1	1	0	0		0	0	0	0	0
SSIP PVT	1	1	1	1	1	1		1	0	0	0.5
Solar Leaf	1	1	1	1	1	1	0		0	0	0
Solar Louver	1	1	1	1	1	1	1	1		1	1
Tesselated Solar	1	1	1	1	1	1	1	1	0		1
Integrated Fast Foot	0	1		1	1	1	0.5	1	0	0	
	6	10	5	8	7	6	2.5	4	0	1	4.5

System	Solar Ridge	Integrated Electrical Frame	3kW Residential Rack	Fast Foot	Standing Seam	Double Skin	SSIP PVT	Solar Leaf	Solar Louver	Tesselated Solar	Integrated Fast Foot
Total Score	43	52	49	33.5	25	30.5	16	13.5	9	20.5	34.5

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