AN ABSTRACT OF THE DISSERTATION OF

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Title: Towards a Guided Framework for Innovative Engineering Through the Generation and Evaluation Stages of Concept Design.

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Irem Y. Tumer

This work proposes a framework of concept generation and evaluation that takes into consideration the benefit of creativity and innovation in current market trends. By educating engineers in how to increase creativity in concept design and assess it quantitatively, the next generation of designers will be a step ahead of the market. This research begins with an in-depth survey of current creativity assessment methods in engineering in order to determine where the limitations currently lie in this field of study. The limitations discovered based on this unique analysis were used as motivation for the development of the proposed creativity assessment method. Specifically, we introduce a set of metrics that break down concepts to their component and subfunction level to assess the novelty and quality of component solutions – called the Comparative Creativity Assessment (CCA) Method. Secondly, we break down market-tested innovative products to isolate innovation information to utilize in concept generation inspiration – called the Repository of Innovative Products (RIP). Finally, revisions to the initial CCA method and RIP are proposed and analysis of past data results are

compared to the new revised results. Revisions to the CCA method include additional metrics that factor in interaction effects from function pairing and component assemblies deemed innovative as well as eliminate evaluator subjectivity in the analysis. Observations from the experiments conducted are presented in a Lessons Learned chapter.

Towards a Guided Framework for Innovative Engineering Through the Generation and Evaluation Stages of Concept Design

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Head of the School of Mechanical, Industrial, and Manufacturing Engineering

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Dean of the Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

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Sarah Kay Oman, Author

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How do I tell everyone in my life, past and present, how much I depended on them and their love in order to get me to this point?

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Towards a Guided Framework for Innovative Engineering Through the Generation and Evaluation Stages of Concept Design

Chapter 1: Introduction

1.1 OVERVIEW

The two research questions of this dissertation are: (1) can creativity be assessed in the concept evaluation phase of engineering design through the use of specifically tailored creativity assessment equations, and (2) can creativity be fostered and increased in concept generation through the use of archived innovative information drawn from previously market-tested innovative products? These questions are addressed in the following chapters through the development of the Comparative Creativity Assessment (CCA) method and the Repository of Innovative Products (RIP). Furthermore, revisions of certain aspects of the creativity assessment equations are presented to produce a more robust method of creativity evaluation that has little to no human subjectivity. Information gathered through the research experiments involved in the investigation of satisfying the research questions produced lessons learned for problem formulation of design creativity experiments in engineering.

This dissertation is structured using the Manuscript Option: Chapters 3-5 are publications written throughout the last four years, submitted to various journals in Engineering Design. Each manuscript is preceded by a Heading Page that provides information on manuscript title, co-authors, journal name, and submission date. The State of the Art for each manuscript is summarized in the Chapter 2 Literature Review for completeness and ease of reference.

1.2 ORGANIZATION OF DISSERTATION

Chapter 3 presents and discusses the analysis of concepts generated during two mechanical engineering design course projects by means of creativity assessment methods. A survey of creativity assessment methods is presented and summarized, which provides a unique opportunity to compare and contrast creativity analysis methods. This survey is the motivation behind the creation of the Comparative Creativity Assessment (CCA) and Multi-Point Creativity Assessment (MPCA) methods.

Chapter 4 then uses the creativity assessment methods to explore how archived innovation information can be used to foster and increase creativity. The method outlined in Chapter 4 is conducted in two parts: first, innovative products are compared to ordinary products in order to isolate innovative functions and components, and, second, those innovative components and functions are used to generate an innovative concept to demonstrate the utility of implementing the Repository of Innovative Products (RIP) into the Design Repository (DR). The Design Repository is an online database of product and component information that employs several concept design tools within the database. An initial case study and a classroom study comparing the DR concept generation method against RIP are presented with statistical evaluation.

Chapter 5 presents revisions to the CCA method developed in Chapter 3 that reduces the subjectivity of the analysis. The new method utilizes information regarding the combination effects of multiple functions to determine the level of creativity for each function in the design problem. This reduces the subjectivity of setting the weights of each function based on the evaluator's opinion on function importance, which is an issue identified in Chapter 3.

Chapter 6 discusses lessons learned from the experiments ran for the CCA and RIP development which provided valuable insight into experiment and design problem formulation.

Conclusions and Future Work are discussed in the final section of the dissertation.

1.3 INTELLECTUAL MERIT

This research capitalizes on several gaps in current literature and studies on creativity and innovation in concept design. Using the Repository of Innovative Products to aide creativity in concept design will streamline concept generation process through online archived innovation information. Furthermore, there is currently no method found that allows designers to assess their possible concepts for creativity in the concept evaluation phase. The metrics and their revisions provide a unique way to assess concepts with low subjectivity. Lastly, the validation studies conducted for the proposed concept generation and evaluation methods provided valuable lessons learned for concept design problem formulation that researchers could use in similar design theory experiments.

1.4 BROADER IMPACT

Researchers in academia and industry will significantly benefit from the research presented herein. Educators can use the results to teach creativity in all aspects of the conceptual design process at an early stage of students' educations in order to satisfy the, "crucial need to teach about "real world" engineering design and operations that call for critical judgment and creativity (Felder, Woods et al. 2000)." Industry in the United States has been increasing the national push for more innovation in order to be the world industrial leader. Aiding creativity early in the design stage through the structure of the problem, the method of concept generation, and the way the concepts are evaluated will make way for innovation in industry.

1.5 MOTIVATION

The main motivation in this research began with a survey of creativity assessment methods. Once this comparison was done, the apparent gap in literature for a method to analyze concepts for creativity void of judges' subjectivity spurred on the research presented herein. Ongoing research at Oregon State University has investigated ways to improved automated design using the Design Repository (DR) including how to aid and assess creativity of concepts generated using features of the DR. The research presented in Chapter 4 is positive progress towards this end goal. The framework proposed for the encompassing motivation of this research is a method for engineers to use that relies on captured innovation information in the Design Repository to generate creative ideas that are then automatically assessed for creativity.

The research presented in this dissertation is several steps towards this end goal by providing the method of assessment, void of human subjectivity, and the method of concept generation that utilizes innovation information from market-tested products. What is left to reach the end goal is to program the assessment method into the DR and continually expand the Repository of Innovative Products (RIP) with each years' products featured in numerous published lists. This ever-expanding RIP must then be integrated into the DR along with the creativity assessment and then tested in classroom and industry experiments to determine the overall utility of the proposed method.

1.6 FUTURE DIRECTION

The development of the RIP concept generation inspiration and CCA evaluation method are two steps forward in the overarching goal of a framework for automated concept design. At its most basic, concept design in engineering is broken down into four steps: define the problem, generate ideas, evaluate those ideas, and chose the final design. The RIP and

CCA methodologies tackle the central two steps of concept design and the Lessons Learned chapter provides details on how to guide engineers in accomplishing the first step of concept design within the Design Repository.

In this fashion, the end framework that this research strives to accomplish is illustrated in Figure 1.1, where a designer would use the Design Repository to guide them through the entire concept design process.

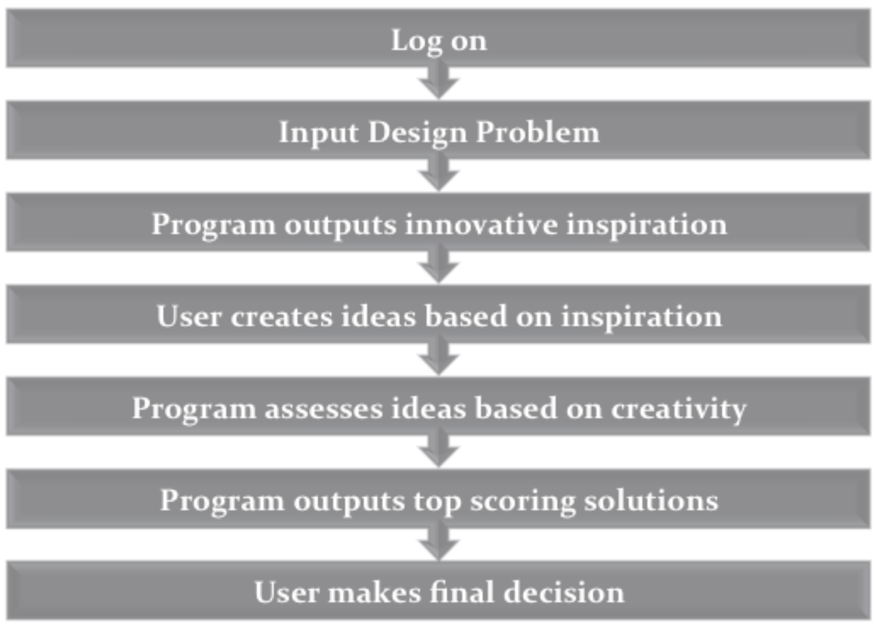

Figure 1.1: Future functionality of Design Repository utilizing RIP inspiration and CCA evaluation method

Chapter 2: Literature Review

This chapter presents a general overview of the State of the Art in certain aspects of concept design. Much of this information is repeated in upcoming chapters in order to keep the manuscripts as close to the original, submitted copy of the journal articles. The information is included here for completeness and ease of reference.

2.1 DEFINING CREATIVITY AND INNOVATION

Creativity can be classified into four broad categories: the creative environment, the creative product, the creative process, and the creative person (Taylor 1988). Just as creativity can be broken into four categories (environment, product, process, and person), the category of the creative person can also be divided into psychometric and cognitive aspects (Sternberg 1988). Psychometric approaches discuss how to classify "individual differences in creativity and their correlates," while the cognitive approach "concentrates on the mental processes and structures underlying creativity (Sternberg 1988)."

Some define creativity in the context of people, such that those who develop new, unusual thoughts are considered creative (Csikszentmihalyi 1996). In the context of design, the definition of creativity is very near the same: creativity is "work that is novel (i.e., original, unexpected), high in quality, and appropriate (Sternberg, Kaufman et al. 2002)." Indeed most definitions of creativity focus on the idea of novelty or originality, such as Cropley and Cropley stating that creativity is discovering unknown solutions to arrive at unexpected answers that generate novelty (Cropley and Cropley 2005). A study on measuring the effectiveness of idea formulation methods emphasizes novelty and quality to satisfy concept design requirements (Shah, Vargas-Hernandez et al. 2003).

Creativity in the broadest terms is simply the ability to look at the problem in a different way or to restructure the wording of the problem such that new and previously unseen possibilities arise (Linsey, Markman et al.). The terms *creativity* and *innovation* have been defined and redefined in almost every text based upon the needs of the authors and research in question (Shah, Kulkarni et al. 2000; Cropley and Cropley 2005; Liu and Liu 2005; Linsey, Markman et al. 2008). Several other sources mention novelty in their definitions of creativity, stating that an idea is creative if it is both novel and valuable or useful (Liu and Liu 2005). Shah, et al. also refer to novelty frequently as well as quality of the idea as it pertains to satisfying initial requirements in creative designs (Shah, Kulkarni et al.).

Work conducted by University of Massachusetts Dartmouth and University of Texas Austin expands on originality by evaluating it on a five-point scale where a concept may be "common", "somewhat interesting", "interesting", "very interesting", or "innovative" (Genco, Johnson et al. 2011). Each concept is rated at the feature level, but the maximum feature-level score is assigned as the overall originality score.

The definitions for innovation embody a central theme: innovation is the implementation of creative ideas (Amabile, Conti et al. 1996; Elizondo, Yang et al. 2010). Innovation can be categorized as either incremental or radical, namely that *incremental* is the normative approach of creating slight improvements to an existing idea, and *radical* is an approach that introduces a breakthrough product or technology into the market, causing chaos (Saunders, Seepersad et al. 2009).

A study done by Saunders, et al. went further into understanding what innovation is in engineering design by defining characteristics of marketed innovative products. The characteristics can be categorized into functionality, architecture, environmental interactions, user interactions, and cost (as a secondary characteristic) (Saunders, Seepersad et al. 2009).

2.2 AUTOMATED DESIGN REPOSITORY

The idea of an artifact rich design repository came to life as a research prototype called the Design Repository, currently maintained at Oregon State University. The Functional Basis, a well received set of function and flow terms intended to comprehensively describe product function, was a crucial portion of the repository framework (Otto and Wood 2001; Hirtz, McAdams et al. 2002; Dieter and Schmidt 2008). A common design language was needed to allow for the universal capture of design information, particularly design intent. Using functional descriptions of products and the Functional Basis (Hirtz, McAdams et al. 2002), all functions of products and components could be captured, stored, and reused in a computer based system. Studies were performed on current repository systems such as product data management systems, CAD based knowledge system, and architectural knowledge based systems. After studying these systems a Design Repository system emerged (Bohm, Stone et al. 2006). The Design Repository (DR) allows for the capture of customer need information, component basis designations, manufacturer, failure modes, sensory information, and much more (Bohm, Stone et al. 2006). The DR may be accessed at: http://designengineeringlab.org/delabsite/repository.html (2011).

The DR allows for the creation of two important conceptual design tools, the function component matrix (FCM) and the design structure matrix (DSM). The function component matrix (FCM) is a mapping of the components in a product to the functions those components carry out (Bohm, Stone et al. 2005). Using multiple product FCMs, a chi-matrix can be computed that shows the connection between the functions and components of multiple products. This matrix can be used to create various concepts by analyzing the number of connections between function and components (Strawbridge, McAdams et al. 2002).

The design structure matrix (DSM) is a matrix that represents the interaction between components in a product (Shooter, Keirouz et al. 2000), and is key to concept generation. This matrix allows the analysis of which components work together, which is then used to create concepts with components of known compatibility (Bryant, McAdams et al. 2005). Concept generation tools were created for the DR and in 2005 a study was done on the concepts produced by the repository using a Morphological Matrix technique versus hand-generated concepts. This study showed that 71.43% of the concepts that were hand-generated could have been produced using the Morphological Matrix method with the repository. It was concluded that a more mature repository could "conceivably generate 100% of the manually generated concepts" (Bohm, Vucovich et al. 2005).

An interactive morphological matrix called MEMIC (Morphological Evaluation Machine and Interactive Conceptualizer) was developed for the DR to guide designers in concept generation by outputting feasible components for an inputted functional model (Bryant, Stone et al. 2008). This allowed for automatic concept generation that included information on components that frequently interfaced with each other. The user interface for MEMIC is a list of all the functions required in the design problem with a pull down menu of possible components for each function. Features of MEMIC include the designer asking the program to output random components for every function instead of selecting a component by hand for each function. MEMIC also has the ability to select components for each function based on the frequency of the components solving the function in question. For example, some components solve a particular function 75% of the time within the DR, while others components only solve that function 2% of the time in the DR. MEMIC can output a "Most Common Configuration" and a "Least Common Configuration" based on these frequencies.

Critical to the research undertaken in this work, what the DR lacks is a strategy to record the innovation level of existing products or artifacts. Currently, the statistics on artifact frequency of occurrence in the products detailed in the repository are used as a proxy for innovation with the less frequent artifact solutions for a given function considered as potentially innovative. Chapter 4 begins the process of having a repeatable and formalized means to archive the innovativeness of products as part of the Design Repository.

2.3 FOSTERING CREATIVITY AND INNOVATION

During the conceptual design phase, many designers begin with loose constraints and requirements and must use these to build an understanding of the problem and possible directions to the solution. The goals of many problems are vague and, in many cases, there is no clear definition of when the design task is complete and whether the design is progressing in an acceptable direction (Yamamoto and Nakakoji). This is the motivation behind the creation of many design and ideation methods such as Mindmapping (Otto and Wood 2001), CSketch (Shah 2007), Design-by-Analogy (Linsey, Markman et al. 2008; Linsey, Wood et al. 2008), TRIZ/TIPS, Synectics (Blosiu), and Historical Innovators Method (Jensen, Weaver et al. 2009).

Forced but structured stimuli have been proven to aid in creative processes. Methods of concept generation must be careful with this fact, as negative stimuli can be detrimental to creativity, such as stimulus that sparks off-task conversations (Howard, Culley et al.). The presence of design representations with a high degree of superficial detail (such as in detailed prototypes) in the physical design environment tend to inhibit ideation and restrict the retrieval of far-field analogies from memory (Christensen and Schunn 2007).

For many engineers, structured concept generation can be the most effective means to generate effective solutions. Ideation methods provide structure and time constraints to the concept design process and lead designers to explore a larger solution space (Shah, Smith et al. 2003), as well as include all members of the design team (Ulrich and Eppinger 2000). Such ideation methods also provide the capacity for designers to generate ideas they would not otherwise have been able to be based exclusively on their intuition. These methods aid designers and students in generating a multitude of ideas before subjectively evaluating all alternatives. The most commonly used methods are: *Morphological Analysis* (Cross 2000; Ullman 2010), *Method 6-3-5* (Pahl and Beitz 1988; VanGundy 1988) (VanGundy 1988; Shah 2007), (Linsey, Green et al. 2005), and the *Theory of Inventive Problem Solving (TRIZ)* (Savransky 2000; Clausing and Fey 2004; Shulyak 2008; Ullman 2010).

Numerous additional papers and texts detail more ideation methods that can be used for both individual concept generation and group efforts (Buhl 1960; Pahl and Beitz 1988; Hinrichs 1992; Pugh 1996; Sonnentag, Frese et al. 1997; Akin and Akin 1998; Huang and Mak 1999; Cross 2000; Ulrich and Eppinger 2000; Gautam 2001; Kroll, Condoor et al. 2001; Moskowitz, Gofman et al. 2001; Otto and Wood 2001; Song and Agogino 2004; Linsey, Green et al. 2005; Cooke 2006; Hey, Linsey et al. 2008; Linsey, Markman et al. 2008; Mayeur, Darses et al. 2008; Ullman 2010). However, the gap in the current state of the art in ideation methods is stated at the end of section 2.1; specifically that there are few methods that satisfy a need for automated concept generation techniques that utilize past product data for inspiration.

2.4 ASSESSING GENERATED CONCEPTS

This section is split into two types subjects regarding assessment techniques: manual and automated. Manual assessment methods involve the designers evaluating each concept they generate by hand, while automated assessment methods work towards programming assessment through archived information on concepts and products. Automated assessment methods are still in the early phases of development, but are briefly discussed here to provide the motivation to the research presented later on.

2.4.1 Manual Assessment Methods

Once the concepts have been generated using one or more of the ideation methods, designers are faced with yet another difficult problem: how does the designer decide which idea is best or the most preferred? What exactly makes a design stand out from other designs? In order to answer these questions, evaluation methods have been developed that aid the decision-making process. The act of choosing a design from a set of alternatives is a daunting task comprised of compromise, judgment, and risk (Buhl 1960). Designers must choose a concept that will satisfy customer and engineering requirements, but most designs rarely cover every requirement at hand or every requirement to the same degree, or else the decision-making process would be simple. Decision-making at the concept design stage is even more difficult as there is still very limited information about the ideas that designers can use to make a decision (Ullman 2010). Commonly used evaluation processes include the *Weighted Objectives Method* (Pahl and Beitz 1988; VanGundy 1988; Jones 1992; Fogler and LeBlanc 1995; Roozenburg and Eekels 1995; Cross 2000), *Pugh's Method* (Pugh 1996) or the *Datum Method* (Roozenburg and Eekels 1995; Pugh 1996; Ulrich and Eppinger 2000; Ullman 2010). Critical goals of Pugh's Method or the Datum Method are to obtain consensus in a team environment and to enable further concept generation through the combination and revising of designs based on preferred features or characteristics.

Other, more comprehensive methods can be found throughout the literature that provide a broader procedural guide to the entire decision making process. Methods such as Robust Decision Making (Ullman 2006) provide designers with a detailed account of what decision making entails, how to make robust decisions within team settings, and how to best evaluate alternatives. Many engineering design textbooks, such as Otto and Wood's *Product Design* (Otto and Wood 2001), Ullman's *The Mechanical Design Process* (Ullman 2010), Paul and Beitz's *Engineering Design* (Pahl and Beitz 1988), and Ulrich and Eppinger's *Product Design and Development* (Ulrich and Eppinger 2000), provide an overview of how to make decisions when faced with numerous alternatives, which are very effective, but do not necessarily focus on creativity.

A form of creativity assessment is the *Creative Product Semantic Scale (CPSS)* based on the framework of the Creative Product Analysis Matrix (CPAM) created by Susan Besemer (Besemer 1998; Besemer and O'Quin 1999; O'Quin and Besemer 2006). The CPSS is split into three factors (Novelty, Elaboration and Synthesis, and Resolution), which are then split into nine different facets for analysis. Each of these nine facets are evaluated using a set of bipolar adjective item pairs on a 7-point Likert-type scale (Besemer 1998), with a total of 54 evaluation word pairs. Examples of these adjective item pairs include useful--useless, original--conventional, and well-made--botched (Besemer 2008). The Likert-type scale allows raters to choose from seven points between the two adjectives in order to express their opinion on the design. Non-experts in any domain or field of study can use the CPSS. However, a possible downside to the CPSS method is that the recommended minimum number of raters needed for the study is sixty and takes considerable time to go through all 54 adjective pairs for each individual concept. In the case of limited time and personnel resources, this method is not practical.

Similar to the CPSS method, the *Consensual Assessment Technique (CAT),* uses raters to assess concepts against each other using a Likert-type scale system (Kaufman, Baer et al. 2008) on 23 criterion based on: novelty, appropriateness, technicality, harmony, and artistic quality (Horng and Lin 2009). This method requires the judges to have experience within the domain, make independent assessments of the concepts in random order, make the assessments relative to each other, and assess other dimensions besides creativity.

A method created by Redelinghuys, called the C_EQe_x-technique, has been readapted into the *REV (Resources, Effort, Value) technique.* This method involves a set of equations that evaluate product quality, designer expertise, and designer creative effort (Redelinghuys 1997; Redelinghuys 1997). This is the only method found thus far that evaluates both the product and the designer. Also, the evaluation of the designer does not involve the divergent thinking tests used by many psychological creativity tests. Instead, it looks at the educational background and relevant experience of the designer(s) along with how much effort they put into the creative design process. In this way, the assessment method must evaluate not only the product, but the process as well. The REV technique requires not only the subject (designer), but also an assessor and a reference designer (a real or fictional expert of the field in question).

Finally, Shah's metrics measure the creativity of groups of ideas and has been used prolifically in the literature (Nelson, Wilson et al. 2009; Oman and Tumer 2010; Schmidt, Vargas-Hernandez et al. 2010; Srivathsavai, Genco et al. 2010) and been adapted on several occasions to meet individual researchers' needs (Nelson, Wilson et al. 2009; Oman and Tumer 2009; Oman and Tumer 2010). The set of metrics to compare the different methods are based upon any of four dimensions: novelty, variety, quantity, and quality (Shah, Smith et al. 2003; Shah, Vargas-Hernandez et al. 2003). The methods can be analyzed with any or all of the four dimensions, but are based primarily on judges' subjective scoring, so that the functions perceived as most important for a design are given the greatest emphasis.

The major downfall to these methodologies is the reliance on the judges' perception of creativity. Subjectivity can produce inconsistent data. The inter-rater reliability is not guaranteed unless extensive training in conducted prior to concept evaluation.

2.4.2 Automated Assessment Methods

Computerized concept generation techniques, spanning the broad AI topics of knowledge representation and reasoning (Hirtz, McAdams et al. 2002), promise engineers a faster realization of potential design solutions based upon previously known products and implementations. While the area of automated concept generation has made great strides in recent years, most methods still require the user to indicate desired functionality. Two of the automated concept generation methods under development today rely solely on the user's ability to develop functional descriptions of their desired product. Both of these methods make use of the repository of design information (described in above), including component connection information and component functionality based on formalisms for describing function or purpose in engineering design (Stone and Wood 2000; Hirtz, McAdams et al. 2002).

The bank of empirical knowledge relating components to functions leads to the development of relational matrices (Bryant, McAdams et al. 2005; Bryant, Stone et al. 2005) and graph grammar rules (Kurtoglu, Campbell et al. 2005; Kurtoglu and Campbell 2009) that, when combined with a search mechanism, automatically creates conceptual designs. Aiding the methods set forth by Bryant and Kurtoglu (Kurtoglu, Campbell et al. 2005; Kurtoglu, Campbell et al. 2009) is a component naming taxonomy spanning 140 different component classifications. With the open-endedness or large degree of variability in conceptual design, numerous solutions are created through the search mechanisms (on the order of thousands). Presenting these thousands of solutions to the user is similar to an Internet search that produces thousands of results. It is overwhelming to the user and impractical to expect that such a large number of alternatives will be useful to the designer. As a result, the proof of concept Designer Preference Modeler (Kurtoglu and Campbell 2007; Kurtoglu and Campbell 2009) was created to find, within the large set of results, which concepts were most meaningful to the designer. By ranking select concepts, the search mechanism learns what aspects of the concept the user prefers, and seeks solutions that maximize the predicted preference. Initial results for this method are promising, but the impact they have on the design process is still unclear.

What is missing in the above line of research is the incorporation of a metric that indicates the innovation level of the automatically generated concepts. This will give designers the option to choose innovative product ideas early in the design stage. Calculating concept rank based on an objective measure of innovation, automated concept generators can predict the innovation in the concept independent of designer preference or bias.

2.5 DESIGN PROBLEM FORMULATION

The literature regarding problem formulation in design focuses on several specific issues within designing experiments and problems. For example, Linsey, et al. discuss how the complexity of the problem affects student perception of functional modeling (Linsey, Viswanathan et al. 2010). Moor and Drake address how project management during the design process affects engineering projects (Moor and Drake 2001). Lyons and Young present an interesting approach to student learning and design by forcing students to design their own experiments, thus teaching design of experiments (DOE) through hands-on problem solving (Lyons and Young 2001). Atman et al. examine the differences between using student and expert engineering experience during concept generation in order to better understand efficient characteristics in engineering design processes (Atman, Adams et al. 2007).

Two methodology studies present interactive computer solutions to produce more efficient design problems. Russo and Birolini focus on how to reformulate an already existing design problem (Russo and Birolini 2011) while Dinar et al. discuss how to formally represent the design problem that aides designers in the conceptual design stage for novice to expert users (Dinar, Shah et al. 2011).

Rodriguez et al. provide the most unique study regarding design problem formulation and creativity (Rodriguez, Mendoza et al. 2011). They present recommendations for designers through the entire conceptual design process that may aid creativity in the hypothesis generation, response variables, experiment factors, type of experiment, and the execution of said experiment. This study provides a broad perspective on the entire DOE aspect, but do present six factors of the "ideation task" that pertains to the design problem formulation specifically. These six factors include: fertility (number of ideas), domain (necessary knowledge), complexity, engagement (incentive or motivation for participants), ambiguity (level of constraints), and level of detail.

What the Rodriguez et al. study provides are recommendations that are not necessarily specific to increasing or aiding creativity in the design of experiment. Additionally, the study looks at a much broader perspective of design experiment formulation based on the study of eleven previous published papers. The Rodriguez et al. study is also limited to examining the planning and execution of concept generation studies and does not look further into concept evaluation.

The information gathered by Rodriguez et al. and various other studies are discussed in Chapter 6 and compared to lessons learned from the research presented Chapters 3 and 4.

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Chapter 3: A Comparison of Creativity and Innovation Metrics and Sample Validation Through in-class Design Projects

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This chapter introduces a new perspective/direction on assessing and encouraging creativity in concept design for application in engineering design education and industry. This research presents several methods used to assess the creativity of similar student designs using metrics and judges to determine which product is considered the most creative. Two methods are proposed for creativity concept evaluation during early design, namely the Comparative Creativity Assessment (CCA) and the Multi-Point Creativity Assessment (MPCA) methods. A critical survey is provided along with a comparison of prominent creativity assessment methods for personalities, products, and the design process. These comparisons culminate in the motivation for new methodologies in creative product evaluation to address certain shortcomings in current methods. The chapter details the creation of the two creativity assessment methods followed by an application of the CCA and MPCA to two case studies drawn from engineering design classes. The contents of this chapter will be published in the Research in Engineering Design journal and was co-authored by Sarah Oman, Irem Y. Tumer, Kris Wood, and Carolyn Seepersad (Oman, Tumer et al. 2012).

3.1 INTRODUCTION

This research delves into efforts to understand creativity as it propagates through the conceptual stages of engineering design, starting from an engineer's cognitive processes, through concept generation, evaluation, and final selection. Consumers are frequently faced with a decision of which product to buy – where one simply satisfies the problem at hand and another employs creativity or novelty to solve the problem. Consumers typically buy the more creative products, ones that "delight" the customers and go beyond expectation of functionality (Horn and Salvendy 2006; Saunders, Seepersad et al. 2009; Elizondo, Yang et al. 2010). Many baseline products may employ creative solutions, but although creativity may not be required for some products, creative solutions are usually required to break away from baseline product features and introduce features that delight customers. In engineering design, creativity goes beyond consumer wants and needs; it brings added utility to a design and bridges the gap between form and function.

Creativity can be classified into four broad categories: the creative environment, the creative product, the creative process, and the creative person (Taylor 1988). This paper briefly discusses the creative person and focuses on the creative product and process before introducing methods of assessing creative products. A survey of creativity assessment methods is introduced that examines previously tested methods of personality, deductive reasoning, and product innovation.

Specifically, this chapter introduces a new perspective/direction on assessing and encouraging creativity in concept design for engineering design education and industry alike. This research first presents a survey of creativity assessment methods, then proposes several methods used to assess the creativity of similar student designs using metrics and judges to determine which product is considered the most creative. The survey presents a unique comparison study in order to find where the current gap in assessment methods lie, to provide the motivation for the formulation of new creativity assessments. Namely, two methods are proposed for creativity concept evaluation during early design: the Comparative Creativity Assessment (CCA) and the Multi-Point Creativity Assessment (MPCA). The CCA is based upon research done by Shah, et al. (Shah, Vargas-Hernandez et al. 2003) and evaluates how unique each sub-function solution of a design is across the entire design set of solutions (Linsey, Green et al. 2005). The MPCA is adapted from NASA’s Task Load Index (2010) and Besemer’s Creative Product Semantic Scale (Besemer 1998) and requires a group of judges to rate each design based on adjective pairs, such as original/unoriginal or surprising/expected.

The Background section introduces and elaborates on the concept of creativity, studies on how to increase creativity during the concept generation phase, and finally methods to determine the most creative product or concept in a set of designs. The next section provides a critical survey and comparison of prominent creativity assessment methods for personalities, products, and the design process. These comparisons culminate in the motivation for a new methodology in creative product evaluation to address certain shortcomings in current methods. Section 3.4 details two possible creativity assessment methods followed by an application of those methods to two case studies drawn from engineering design classes in Section 3.5. The students in these classes were divided into teams and tasked with the 2008 and 2009 ASME Student Design Competition projects: a remote-controlled Mars rover and an automatic waste sorter, respectively (Oman and Tumer 2009; Oman and Tumer 2010). Lessons learned and conclusions drawn from the application of the methods to the two case studies are presented along with where this research can go in Future Work.

3.2 BACKGROUND

3.2.1 Creativity of a Person, Product, and Process

Just as creativity can be broken into four categories (environment, product, process, and person), the category of the creative person can also be divided into psychometric and cognitive aspects (Sternberg 1988). Psychometric approaches discuss how to classify "individual differences in creativity and their correlates," while the cognitive approach "concentrates on the mental processes and structures underlying creativity (Sternberg 1988)."

Cognitive aspects of the creative person may encompass intelligence, insight, artificial intelligence, free will, and more (Sternberg 1988). Csikszentmihalyi discusses where creativity happens by saying:

> "There is no way to know whether a thought is new except with reference to some standards, and there is no way to tell whether it is valuable until it passes social evaluation. Therefore, creativity does not happen inside people's heads, but in the interaction between a person's thoughts and a sociocultural context. It is a systemic rather than an individual phenomenon (Csikszentmihalyi 1996)."

Creativity in the broadest terms is simply the ability to look at the problem in a different way or to restructure the wording of the problem such that new and previously unseen possibilities arise (Linsey, Markman et al.).

Cropley and Cropley (Cropley and Cropley 2005) describe the opposite of creativity, *convergent thinking*, as "too much emphasis on acquiring factual knowledge … reapplying it in a logical manner … having clearly defined and concretely specified goals … and following instructions." Their description of *divergent thinking* correlates with several other definitions of creativity, stating that it "involves branching out from the given to envisage previously unknown possibilities and arrive at unexpected or even surprising answers, and thus generating novelty (Cropley and Cropley)." Several other sources mention novelty in their definitions of creativity, stating that an idea is creative if it is both novel and valuable or useful (Liu and Liu 2005; Chulvi, Mulet et al. 2011).

During the conceptual design phase, a designer begins with loose constraints and requirements and must use these to build an understanding of the problem and possible directions to the solution. The goals of the problem are vague and, in many cases, there is no clear definition of when the design task is complete and whether the design is progressing in an acceptable direction (Yamamoto and Nakakoji). This is the motivation behind the creation of many design and ideation methods such as Mindmapping (Otto and Wood 2001), CSketch (Shah 2007), Design-by-Analogy (Linsey, Markman et al. 2008; Linsey, Wood et al. 2008), TRIZ/TIPS, Synectics (Blosiu), and Historical Innovators Method (Jensen, Weaver et al. 2009).

A useful definition for creativity and innovation of engineering products is provided by Cropley and Cropley, in which creativity is defined as a four-dimensional, hierarchical model that must exhibit relevance and effectiveness, novelty, elegance, and 'generalizability' (Cropley and Cropley 2005). In this regard, relevance must be satisfied and refers to a product simply solving the problem it is intended to solve. If only relevance is satisfied the solution is *routine*. If the solution is relevant and novelty is also satisfied as described previously in this section, then the product/solution is *original*. When the product is *original* and also pleasing to look at and goes beyond only the mechanical solution, it is *elegant*. Lastly, when the solution is *elegant* and generalizable such that it is broadly applicable and can be transferred to alternate situations to open new perspectives, then the product is *innovative* (Cropley and Cropley 2005).

Work conducted by UMass and UT Austin further expands on originality by evaluating it on a five-point scale where a concept may be "common", "somewhat interesting", "interesting", "very interesting", or "innovative" (Genco, Johnson et al. 2011). Each concept is rated at the feature level, but the maximum feature-level score is assigned as the overall originality score.

Combining the definitions, creativity in this research is described as *a process to evaluate a problem in an unexpected or unusual fashion in order to generate ideas that are novel.* Also, creativity (noun) refers to novelty and originality. Innovation is then defined as *creativity that embodies usefulness in order to realize an impact on society (i.e. application of said creativity) through a new method, idea, or product.*

With creativity and innovation defined for the purposes of this paper, the remainder of the Background section discusses aspects of engineering design that can factor in creativity into the design process.

3.2.2 Ideation Methods: Fostering Creativity and Innovation

Forced but structured stimuli have been proven to aid in creative processes. Negative stimuli can be detrimental, such as stimulus that sparks off-task conversations (Howard, Culley et al.). Likewise, the presence of design representations with a high degree of superficial detail (such as in detailed prototypes) in the physical design environment tend to inhibit ideation and restrict the retrieval of far-field analogies from memory (Christensen and Schunn 2007).

Unfortunately, many designers opt not to use ideation methods because of the seemingly cumbersome steps that create long bouts of work, "in which doubt, ambiguity, and a lack of perseverance can lead people to abandon the creative process (Luburt)."

Thus, effective methods of ideation should be, at a minimum, environmentally controlled, stimulating, and engaging to the subjects. Other aspects of creativity can include thinking outside the box by evaluating the assumptions to a problem and then, "imagining what is possible if we break them (Pierce and Pausch)."

For many engineers, structured concept generation can be the most effective means to generate effective solutions. Ideation methods provide structure and time constraints to the concept design process and lead designers to explore a larger solution space (Shah, Smith et al. 2003), as well as include all members of the design team (Ulrich and Eppinger 2000). Such ideation methods also provide the capacity for designers to generate ideas they would not otherwise have been able to be based exclusively on their intuition. These methods aid designers and students in generating a multitude of ideas before subjectively evaluating all alternatives. The most commonly used methods are: *Morphological Analysis* (Cross 2000; Ullman 2010), *Method 6-3-5* (Pahl and Beitz 1988; VanGundy 1988) (VanGundy 1988; Shah 2007), (Linsey, Green et al. 2005), and the *Theory of Inventive Problem Solving (TRIZ)*

(Savransky 2000; Clausing and Fey 2004; Shulyak 2008; Ullman 2010). Extensive research involving TRIZ has produced simpler adaptations to the methodology, such as Advanced Systematic Inventive Thinking (ASIT), which can then be combined with design theories in engineering practice, such as the C-K theory (Reich, Hatchuel et al. 2010).

Numerous additional papers and texts detail more ideation methods that can be used for both individual concept generation and group efforts (Buhl 1960; Pahl and Beitz 1988; Hinrichs 1992; Pugh 1996; Sonnentag, Frese et al. 1997; Akin and Akin 1998; Huang and Mak 1999; Cross 2000; Ulrich and Eppinger 2000; Gautam 2001; Kroll, Condoor et al. 2001; Moskowitz, Gofman et al. 2001; Otto and Wood 2001; Song and Agogino 2004; Linsey, Green et al. 2005; Cooke 2006; Hey, Linsey et al. 2008; Linsey, Markman et al. 2008; Mayeur, Darses et al. 2008; Ullman 2010).

Any of these methods can be used to aid creativity as ideas are being generated and are taught to engineers in education and industry alike. Several methods are used by the students whose designs are analyzed in Section 3.5. The issue regarding concept generation methods is determining which is the most effective for research or industry needs. Lopez-Mesa and Thompson provide an analysis of design methods based on research and industry experience and further delve into the relationship between product, process, person, and environment (Lopez-Mesa and Thompson 2006). Section 3.3.3 outlines assessment methods that attempt to answer this question by comparing the results of many commonly used ideation methods.

3.2.3 Evaluation Methods: Assessing Creativity and Innovation

Once the concepts have been generated using one or more of the ideation methods, designers are faced with yet another difficult problem: how does the designer decide which idea is best or the most preferred? What exactly makes a design stand out from other designs?

In order to answer these questions, evaluation methods have been developed that aid the decision-making process. The act of choosing a design from a set of alternatives is a daunting task comprised of compromise, judgment, and risk (Buhl 1960). Designers must choose a concept that will satisfy customer and engineering requirements, but most designs rarely cover every requirement at hand or every requirement to the same degree, or else the decision-making process would be simple. Decision-making at the concept design stage is even more difficult as there is still very limited information about the ideas that designers can use to make a decision (Ullman 2010). Commonly used evaluation processes include the *Weighted Objectives Method* (Pahl and Beitz 1988; VanGundy 1988; Jones 1992; Fogler and LeBlanc 1995; Roozenburg and Eekels 1995; Cross 2000), *Pugh's Method* (Pugh 1996) or the *Datum Method* (Roozenburg and Eekels 1995; Pugh 1996; Ulrich and Eppinger 2000; Ullman 2010). Critical goals of Pugh's Method or the Datum Method are to obtain consensus in a team environment and to enable further concept generation through the combination and revising of designs based on preferred features or characteristics.

Other, more comprehensive methods can be found throughout the literature that provide a broader procedural guide to the entire decision making process. Methods such as Robust Decision Making (Ullman 2006) provide designers with a detailed account of what decision making entails, how to make robust decisions within team settings, and how to best evaluate alternatives. Many engineering design textbooks, such as Otto and Wood's *Product Design* (Otto and Wood 2001), Ullman's *The Mechanical Design Process* (Ullman 2010), Paul and Beitz's *Engineering Design* (Pahl and Beitz 1988), and Ulrich and Eppinger's *Product Design and Development* (Ulrich and Eppinger 2000), provide an overview of how to make decisions when faced with numerous alternatives, which are very effective, but do not necessarily focus on creativity as a design requirement. Educators and industry employ varying decision-making methods like the ones mentioned above as they all have different advantages.

It is important to note that the methods discussed in this section do not assess creativity specifically. Furthermore, while many different methods of creativity assessment exist, there has not been a thorough comparison done in the literature; specifically, there is no survey within the literature that summarizes the methods available to designers for assessing creativity of personality, product, or process. As a result, the next section presents a survey and comparison of evaluation methods specifically designed to assess creativity. Tables 3.1-3.3 present a unique comparison of these methods not yet found in literature. This provides the motivation for adapting current methods to fit a unique application of creativity analysis detailed in the section after, as applied to the comparison of designs generated during an engineering design course and evaluated with respect to their creativity.

3.3 CREATIVITY STUDIES: A SURVEY AND COMPARISON

The past several decades have witnessed numerous studies on creativity, some domain-specific such as engineering and others applicable to a wide range of disciplines. The following section provides a comparison of studies on creativity and innovation, summarized in Tables 3.1-3.3. Currently, no comprehensive literature search documents and evaluates creativity assessment methods in order to determine holes in current research within this particular domain. These tables works to fill this gap in literature. Comparisons are discussed for each of the three evaluation categories (person/personality, product, and groups of ideas). Table 3.1 details unique methods to assess products or fully formed ideas and provide information on how the concepts are evaluated within each method along with the variables of analysis. Table 3.2 outlines methods to assess the person or personality and Table 3.3 details methods to assess groups of ideas.

The first column presents the names of the proposed assessment methods and any acronyms associated with the method. If no name is presented, the main author is used to name the method unless the paper is describing someone else's work, as is the case in Chulvi, Mulet, et al who present three methods of previous authors. How the metric evaluates the category of the table (product, person/personality, or groups of ideas) is given in the third column. The fourth column provides a short description of the assessment procedure while the fifth column details the variables or variable categories used to assess creativity of the person, product, or set of ideas. The Validation column provides a short description of the experiment or case study presented in the article used in this literature survey. For example, the methods by Moss, Sarkar, and Justel are presented in the article by Chulvi et al. (2011) and the Validation column presents the experiment done by Chulvi et al. The final column outlines the most appropriate time during the design phase to implement the assessment method (for example, some methods only evaluate the principles of the design while others need a fully formed concept or prototype to evaluate).

Tables 3.1-3.3 provides a distinctive opportunity for easy comparison of known methods of creativity assessment. For example, all the methods detailed for assessing products use judges with likert-type scales except Innovative Characteristics method, which allows simple yes/no answers. All the person/personality methods use surveys to determine personality types. Of the two methods outlined that evaluate groups of ideas, the refined metrics propose modifications to the original Shah's metrics to increase the effectiveness of several metrics within the method.

Table 3.1: Comparison of Creativity Assessment Methods for Products

Evaluation Methods for Products						
Method	**Source**	**How does it Evaluate?**	**Method of Evaluation**	**Variable Categories in Evaluation**	**Validation within Paper**	**Stage of Design**
Creative Product Semantic Scale (CPSS)	Besemer 2006	judges (>60)	7-point Likert-type scale with 55 adjective pairs	Novelty (surprising, original), Resolution (logical, useful, valuable, understandable), and Elaboration and synthesis (organic, wellcrafted, elegant)	Description of over 12 studies using CPSS in last decade	At sketching stage or anytime thereafter
Consensual Assessment Technique (CAT)	Amabile 1982	judges (unspecified number)	5-point Likert-type scale with open scale	novelty, appropriateness, technicality, harmony, artistic quality	8 studies with 20-101 participants (children to college age) making collages or poems. Analyzed by 6-20 judges of varying expertise	After completed art project, poem, or product
Student Product Assessment Form (SPAF)	Reis 1991 (Horn 2006)	judges (unspecified number)	5-point Likert-type scale with 15 scoring items	originality, achieved objective, advanced familiarity, quality beyond age/grade level, attention to detail, time/effort/energy, original contribution	50 experts and experienced teachers validated method with interrated reliability of 0.8	Fully developed work (sketch, writing, science work)
Innovative Characteristics	Saunders DETC 2009	judges (minimal number)	Yes/No on whether product is better than a datum	Functionality, Architecture (size, layout, use of physical environment), Environmental interactions (material flow, energy flow, information flow, infrastucture interaction), User interactions (physical demands, sensory demands, mental demands), Cost (purchase cost, operating cost)	Analyzed 95 products featured in published Top Innovative Products lists from 2006-08	Marketed products
Industry Preferences	Elizondo 2010	judges (unspecified number)	10-point Likert-type scale with 17 scoring items	Differentiability, Creativity, Probability of Adoption, Need Satisfaction	Senior design products judged by industry and academic experts (unspecified numbers)	At end of design course (fully developed prototype)
Quality scale	Linsey 2007	judges (unspecified number)	4-point Yes/No flow chart with three questions	Technically feasible, technically difficult for context, existing solution	2x3 factorial experiment over 2 weeks using senior college students in 14 teams of 4-6 students	Fully developed sketches
Moss's Metrics	Moss 1966 (Chulvi 2011)	judges (unspecified number)	0-3 scale ratings by judges	Product of judges ratings on usefulness (abaility to meet requirements) and unusualness (reverse probability of idea being in group of solutions)	12 Ph.D. students or professionals placed in four teams, working in 3 one-hour sessions (presented in Chulvi 2011)	Fully developed sketch or anytime thereafter
Sarkar and Chakrabarti Metrics	Sarkar 2008 (Chulvi 2011)	metrics with judges	Degree of novelty based on SAPPhIRE constructs and	Novelty constructs (action, state, physical phenomena, physical, organs, inputs, parts) and degree of usefulness (importance of function, number of users, length of usage, benefit of product)		Fully developed sketch or anytime thereafter
Evaluation of Innovative Potential (EPI)	Justel 2008 (Chulvi 2011)	judges (unspecified number)	Judges rate requirement (0-3-9 scale), accomplishment (1-3-9 scale), and novelty (0-3 scale)	Importance of each requirement, Accomplishment (satisfaction of each requirement), Novelty (not innovative or incremental, moderate, or radical innovation)		Fully developed sketch or anytime thereafter
Resource-Effort-Value (REV)	Redelinghuys 1997	metrics	Evaluate designer against experts and assess design for values regarding engr. Requirements	quality of the product, satisfaction of engineering requirements, expertise of the designer	Case study with two company teams solving same complex problem	Before concept generation and after fully developed sketch

Table 3.2: Comparison of Creativity Assessment Methods for Person/Personality

Evaluation Methods for Person/Personality						
Method	**Source**	**How does it Evaluate?**	**Method of Evaluation**	**Variable Categories in Evaluation**	**Validation within Paper**	**Stage of Design**
Adjective Checklist (ACL)	Gough 1983 (Cropley 2000)	survey/judges	300-item set of adjectives used for self-rating or rating by observers	Measures 37 traits of a person, can be pared down for specific interests	Has been reduced to fit specific needs in multiple studies with reliability ranging from 0.41 to 0.91	At any point in design
Creative Personality Scale (CPS)	Gough 1992 (Cropley 2000)	survey/judges	30-item set of adjectives from ACL set (see above)	18 positive adjective weights (wide interests, original, etc), 12 negative adjective weights (conventional, common, etc.)	Reported reliability in various studies from 0.40 to 0.80.	At any point in design
Torrance Tests of Creative Thinking (TTCT)	Torrance 1999 (Cropley 2000)	survey/judges	Test split into verbal and nonverbal (figural) sections with question activities	fluency (number responses), flexibility (number of categories), originality (rarity of responses), elaboration (detail of responses), abstractness, resistance to premature closure	Studies report median interrater reliability 0.9-0.97 and retest reliability between 0.6-0.7	At any point in design
Myers-Briggs Type Indicator (MBTI)	Myers 1985 (McCaulley 2000)	survey	93 Yes/No questions	introversion/extroversion, intuition/sensing, feeling/thinking, perception/judgment	Used prolifically throughout the literature since 1967.	At any point in design
Creatrix Inventory (C&RT)	Byrd 1986 (Cropley 2000)	survey	9-point Likert-type scale of 28 scoring items	Creative thinking vs risk taking matrix with 8 styles (Reproducer, Modifier, Challenger, Practicalizer, Innovator, Synthesizer, Dreamer, Planner)	Reports .72 retest reliability but no other data provided. Argues scale possesses "face validity"	At any point in design
Creative Reasoning Test (CRT)	Doolittle 1990 (Cropley 2000)	survey	40 riddles	Riddles split into two 20-riddle levels	Reports split-half reliability between 0.63-0.99 and validity of 0.70 compared to another personality test	At any point in design

Table 3.3: Comparison of Creativity Assessment Methods for Groups of Ideas

Evaluation Methods for Groups of Ideas						
Method	**Source**	**How does it Evaluate?**	**Method of Evaluation**	**Variable Categories in Evaluation**	**Validation within Paper**	**Stage of Design**
Shah's Metrics	Shah 2000, 2003	metrics with judges	Breakdown of how each concept satsifies functional requirements, number of ideas generated	Quality, Quantity of ideas, Novelty, Variety within dataset	Example evaluations for each category given from student design competition concepts	At sketch or prototype stage
Shah's refined metrics	Nelson 2009	metrics with judges	New way from Shah's metrics to calculate Variety and combines it with Novelty. Inputs and Variables remain the same.	Quality, Quantity of ideas, Novelty, Variety within dataset	None given.	At sketch or prototype stage
Adjusted Linkography	Van Der Lugt 2000	metrics	Determines how related certain function solutions are to each other based on graphical link chart	link density (number of links, number of ideas), type of link (supplementary, modification, tangential), and self-link index (function of # ideas particular designer generated)	Undergrad students (unspecified number) in groups of 4 in a 90-minute design meeting broken into 4 phases	At physical principles or sketching stage
Modified Linkography	Vidal 2004	metrics	Determines how related certain function solutions are to each other based on link density using variables at right	number of ideas, number of valid ideas, number of rejected ideas, number of unrelated ideas, number of global ideas	60 first-year students divided into groups of five in 1-hour design blocks	At physical principles or sketching stage
Lopez-Mesa's Metrics	Lopez-Mesa 2011	metrics with judges	Count of concepts that satisfy each of the variables at right, judgement of criteria by judges	Variety (number of global solutions), Quantity (number of variants), Novelty (Percent of solutions generated by fewer number of group members, classification of paradigm change type), feasibility (time dedicated to solution, rate of attended reflections)	17 Ph.D. students or professors evaulated and placed in 4 groups, 45 minute design problem	At sketch or prototype stage
Sarkar Metrics	Sarkar 2008	metrics with judges	Count of concepts that satisfy each of the variables at right, judgement of criteria by judges	Quantity, Quality (size and type of design space explored), Solution representation (number of solutions by sketch, description, etc), Variety (comparison of less similar ideas to very similar ideas)	6 designers with grad degree and 3 years experience, no time constraint, given idea triggers throughout	At sketching stage

The remainder of the section goes into further detail on the methods outlined in Tables 3.1-3.3, organized by what the method analyzes (specifically product, person, or group of ideas). The final subsection details current limitations of creativity assessment to provide the motivation behind the creation of the CCA and MPCA detailed in the next section.

3.3.1 Person/Personality Assessment Methods

Sources claim that there are over 250 methods of assessing the creativity of a person or personality (Torrance and Goff 1989; Cropley 2000), thus the methods presented herein are only a small sample that include the more prominent methods found in literature, especially within engineering design.

Perhaps the most prominent of psychometric approaches to study and classify people are the *Torrance Tests of Creative Thinking (TTCT)* and the *Myers-Briggs Type Indicator (MBTI)*. The TTCT originally tested divergent thinking based on four scales: fluency (number of responses), flexibility (number of categories of responses), originality (rarity of the responses), and elaboration (detail of the responses). Thirteen more criteria were added to the original four scales and are detailed in Torrance's discussion in *The Nature of Creativity* (Torrance 1988).

The MBTI tests classify people in four categories: attitude, perception, judgment, and lifestyle. The attitude of a person can be categorized as either extroverted or introverted. The perception of a person is either through sensing or intuition and the judgment of a person is either through thinking or feeling. The lifestyle of a person can be classified as either using judgment or perception in decisions. Further detail can be found in (Myers and McCaulley 1985) and (McCaulley 2000). Although MBTI does not explicitly assess creativity, the method has been used for decades in creativity personality studies, examples of which include: (Jacobson 1993; Houtz, Selby et al. 2003; Nix and Stone 2010; Nix, Mullet et al. 2011).

The *Creatrix Inventory (C&RT)* is unique in that it analyzes a designer's creativity relative to his/her tendency to take risks in concept design. The scores are plotted on a creativity versus risk scale and the designer is "assigned one of eight styles: Reproducer, Modifier, Challenger, Practicalizer, Innovator, Synthesizer, Dreamer, and Planner (Cropley 2000)." Another unique approach to evaluating designers' creativity is the *Creative Reasoning Test (CRT).* This method poses all the questions in the form of riddles.

Further detail regarding personality assessment methods can be found in (Cropley 2000). Although useful to determine the creativity of people, these methods do not play any part in aiding or increasing the creative output of people, regardless of whether or not they have been determined to be creative by any of the above methods. The following subsections evaluate the creativity of the output.

3.3.2 Product Evaluation Methods

Srivathsavai et al. provide a detailed study of three product evaluation methods that analyze novelty, technical feasibility, and originality, presented by Shah et al. (Shah, Vargas-Hernandez et al. 2003), Linsey (Linsey 2007), and Charyton et al (Charyton, Jagacinski et al. 2008), respectively. The study analyzes the inter-rater reliability and repeatability of the three types of concept measures and concludes that these methods provide better reliability when used at a feature/function level instead of at the overall concept level. Furthermore, coarser scales (e.g., a three- or four-point scale) provide better inter-rater reliability than finer scales (e.g., an eleven-point scale). Two interesting points the study discusses are that most product creativity metrics only compare like concepts against each other and that most judges have to focus at a functional level to rate concepts. This brings about a call for metrics that can assess creativity of dissimilar concepts or products and allow judges to take in the entire concept to analyze the creativity of the entire product (Srivathsavai, Genco et al. 2010).

A similar comparison study by Chulvi et al. used three metrics by Moss, Sarkar and Chakrabarti, and the Evaluation of Innovative Potential (EPI) to evaluate the outcomes of different design methods (Chulvi, Mulet et al. 2011). These methods evaluate the ideas individually, as opposed to the study by Srivathsavai that evaluated groups of concepts. The metrics by Moss uses judges to evaluate concepts based on usefulness and unusualness on a 0-3 scale. The final creativity score for each concept is the product of the scores for the two parameters. The metrics by Sarkar and Chakrabarti also evaluates creativity on two parameters: novelty and usefulness. The calculation of novelty is based on the SAPPhIRE model of causality where the seven constructs (action, state, physical phenomena, physical effects, organs, inputs, and parts) constitute different levels of novelty from low to very high. The interaction of the constructs and levels are combined using function-behavior-structure (FBS). The usefulness parameter of the metrics is calculated based on the degree of usage the product has or will have on society through: importance of function, number of users, length of usage, and benefit. The two parameters, novelty and usefulness, are combined through metrics that essentially multiple the two measures. Lastly, the EPI method is modified by Chulvi et al. to only evaluate creativity and uses the parameters: importance of each requirement (on a 0-3-9 scale), degree of satisfaction for each requirement (on a 1-3-9 scale), and the novelty of the proposed design. Novelty is scored on a 0-3 scale by judges as to whether the design is not innovative (score of 0), has incremental innovation (score of 1), moderate innovation (score of 2), or radical innovation (score of 3). The Chulvi et al. study concluded that measuring creativity is easier when the designers used structured design methods as the outcomes are closer to the intended requirements and innovative solutions are easier to pick out from the groups. Furthermore, when these methods were compared to expert judges rating the designs on 0-3 scales for novelty, usefulness, and creativity, they found that the judges had a difficult time assessing and comparing usefulness of concepts. Experts also have a difficult time making a distinction between novelty and creativity.

Another form of creativity assessment is the *Creative Product Semantic Scale (CPSS)* based on the framework of the Creative Product Analysis Matrix (CPAM) created by Susan Besemer (Besemer 1998; Besemer and O'Quin 1999; O'Quin and Besemer 2006). The CPSS is split into three factors (Novelty, Elaboration and Synthesis, and Resolution), which are then split into different facets for analysis. The Novelty factor is split into original and surprise. Resolution is split into valuable, logical, useful, and understandable. Elaboration and Synthesis is split into organic, elegant, and well crafted. Each of these nine facets are evaluated using a set of bipolar adjective item pairs on a 7-point Likert-type scale (Besemer 1998), with a total of 54 evaluation word pairs. Examples of these adjective item pairs include useful--useless, original--conventional, and well-made--botched (Besemer 2008). The Likert-type scale allows raters to choose from seven points between the two adjectives in order to express their opinion on the design. Non-experts in any domain or field of study can use the CPSS. However, possible downsides to the CPSS method is that the recommended minimum number of raters needed for the study is sixty and it takes considerable time to go through all 54 adjective pairs for each individual concept. In the case of limited time and personnel resources, this method is not practical.

Similar to the CPSS method, the *Consensual Assessment Technique (CAT),* uses raters to assess concepts against each other using a Likert-type scale system (Kaufman, Baer et al. 2008) on 23 criterion based on: novelty, appropriateness, technicality, harmony, and artistic quality (Horng and Lin 2009). This method requires the judges to have experience within the domain, make independent assessments of the concepts in random order, make the assessments relative to each other, and assess other dimensions besides creativity (Amabile 1982).

A method created by Redelinghuys, called the C_EQe_x-technique, has been readapted into the *REV (Resources, Effort, Value) technique.* This method involves a set of equations that evaluate product quality, designer expertise, and designer creative effort (Redelinghuys 1997; Redelinghuys 1997). This is the only method found thus far that evaluates both the product and the designer. Also, the evaluation of the designer does not involve the divergent thinking tests used by many psychological creativity tests. Instead, it looks at the educational background and relevant experience of the designer(s) along with how much effort they put into the creative design process. In this way, the assessment method must evaluate not only the product, but the process as well. The REV technique requires not only the subject (designer), but also an assessor and a reference designer (a real or fictional expert of the field in question).

The metrics discussed in this subsection present unique ways of assessing products or ideas that have proven valuable to researchers. However, through this literature survey, several gaps in assessment methods have been observed, which are mitigated by the new, proposed CCA and MPCA methods. The following section discusses several methods of assessing groups of ideas with specific detail on one method developed by Shah et al. that are then adapted into the CCA method. Thus Section 3.3.3.1 presents the full metrics of Shah et al. before detailing how they are adapted into CCA in Section 3.4.

3.3.3 Assessing Groups of Ideas

The methods in Section 3.3.2 provide a means to assess individual ideas based on judging scales. Several methods of assessment take a step back from individual idea assessment and focus on the evaluation of groups of ideas.

Two methods of assessing groups of ideas use the principles of linkography, a graphical method of analyzing relationships between design moves (Van Der Lugt 2000; Vidal, Mulet et al. 2004). Van Der Lugt use the linkography premise to evaluate groups of ideas based on the number of links between ideas, the type of link, and how many designers were involved with each idea. The three types of links are supplementary (if one idea adds to another), modification (if one idea is changed slightly), and tangential (two ideas are similar but with different function) (Van Der Lugt 2000). The study done by Vidal et al. focuses on link density using the variables: number of ideas, number of valid ideas, number of rejected ideas, number of not related ideas, and number of global ideas (Vidal, Mulet et al. 2004).

Two other methods of assessing groups of ideas measure similar aspects of ideation method effectiveness, but use different variables to calculate them. The metrics by Lopez-Mesa analyze groups of ideas based on novelty, variety, quantity, and feasibility (quality) (Lopez-Mesa, Mulet et al. 2011), while the metrics presented by Sarkar in AI EDAM are based upon variety, quantity, quality, and solution representation (words vs visual, etc.) (Sarkar and Chakrabarti 2008). Lopez-Mesa et al. evaluate variety through the number of global solutions in the set of designs while Sarkar et al. compare the number of similar ideas to those with less similarity. Quality in the Sarkar et al. metrics is based on the size and type of design space explored by the set of ideas while feasibility according to Lopez-Mesa et al. refers to the time dedicated to each solution and the rate of attended reflections. Lopez-Mesa et al. provide a unique perspective on the representation and calculation of novelty compared to other group ideation assessment methods in that it is a characterization of change type (i.e. whether only one or two new parts are present versus an entire system change) and level of "non-obviousness" calculated by how many teams in the experiment also produced similar solutions (Lopez-Mesa, Mulet et al. 2011).

Shah et al.'s metrics measure the effectiveness of concept generation methods, i.e. groups of ideas, and has been used prolifically in the literature (Lopez-Mesa and Thompson 2006; Nelson, Wilson et al. 2009; Oman and Tumer 2010; Schmidt, Vargas-Hernandez et al. 2010; Srivathsavai, Genco et al. 2010) and been adapted on several occasions to meet individual researchers' needs (Nelson, Wilson et al. 2009; Oman and Tumer 2009; Oman and Tumer 2010; Lopez-Mesa, Mulet et al. 2011). The set of metrics created to compare the different concept generation methods are based upon any of four dimensions: novelty, variety, quantity, and quality (Shah, Smith et al. 2003; Shah, Vargas-Hernandez et al. 2003). The concept generation methods can be analyzed with any or all of the four dimensions, but are based on subjective judges' scoring. The original metrics and variables for this method are discussed in the next subsection. An important aspect of these metrics is that they were not developed to measure creativity specifically, rather the "effectiveness of [ideation] methods in promoting idea generation in engineering design (Shah, Kulkarni et al. 2000)." However, as the definitions of creativity and innovation detailed in Section 2.2.1 involve the inclusion of originality and usefulness, the dimensions of novelty and quality included in Shah et al.'s metrics can be adapted to suit the needs of creativity assessment, as discussed in the following sections.

3.3.3.1 Metrics by Shah, et al.

The original metrics provided by Shah et al. are presented here before discussing how the metrics are adapted to apply to individual concepts in a set of designs in the next section.

For each of the equations, the "stages" discussed refer to the stages of concept development, i.e., physical principles, conceptualization, implementation (embodiment), development of detail, testing, etc.

Novelty

Novelty is how new or unusual an idea is compared to what is expected. The metric developed for it is:

$$M_N = \sum_{j=1}^{m} f_j \sum_{k=1}^{n} S_{Njk} p_k \tag{1}$$

where M_N is the novelty score for an idea with m functions and n stages. Weights are applied to both the importance of the function (f_j) and importance of the stage (p_k). S_N is calculated by:

$$S_{Njk} = \frac{T_{jk} - C_{jk}}{T_{jk}} \times 10 \tag{2}$$

where T_{jk} is the total number of ideas for the function j and stage k, and C_{jk} is the number of solutions in T_{jk} that match the current idea being evaluated. Dividing by T_{jk} normalizes the outcome, and multiplying by 10 provides a scaling of the result.

Variety

Variety is measured as the extent to which the ideas generated span the solution space; lots of similar ideas are considered to have less variety and thus less chance of finding a better idea in the solution space. The metric for variety is:

$$M_V = \sum_{j=1}^{m} f_j \sum_{k=1}^{4} S_{Vk} b_k / n \tag{3}$$

where M_V is the variety score for a set of ideas with m functions and four (4) rubric levels. The analysis for variety uses four levels to break down a set of ideas into components of physical principles, working principles, embodiment, and detail. Each level is weighted with scores S_{Vk} with physical principles worth the most and detail worth the least. Each function is weighted by f_j, and the number of concepts at level k is b_k. The variable n is the total number of ideas generated for comparison.

Quality

Quality measures how feasible the set of ideas is as well their relative ability to satisfy design requirements. The metric for quality is:

$$M_Q = \sum_{j=1}^{m} f_j \sum S_{Qjk} p_k / (n \times \sum_{j=1}^{m} f_j) \tag{4}$$

where M_Q is the quality rating for a set of ideas based on the score S_{Qjk} at function j and stage k. The method to calculate S_Q is based on normalizing a set of numbers for each Quality criterion to a range of 1 to 10. No metric is given to calculate these S_Q values. Weights are applied to the function and stage (f_j and $p_{k,}$, respectively) and m is the total number of functions. The variable n is the total number of ideas generated for comparison. The denominator is used to normalize the result to a scale of 10.

Quantity

Quantity is simply the total number of ideas, under the assumption that, the more ideas there are, the greater the chance of creating innovative solutions. There is no listed metric for quantity as it is a count of the number of concepts generated with each method of design.

The four ideation assessment equations (Novelty, Variety, Quality, and Quantity) are effective in studies to determine which concept generation method (such as 6-3-5 or TRIZ) works to produce the most effective set of ideas.

The methods discussed in Section 3.3.3 outline ways to assess multiple groups of ideas to determine which *set* of ideas has more creativity or effective solutions. The following subsection outlines the limitations of current creativity assessment.

3.3.4 Limitations of Current Creativity Assessment

There is a lack of methodology to assess any group of ideas in order to determine the most creative idea out of the group. This limitation led to the adaptation of the above equations into the Comparative Creativity Assessment (CCA) – a method to do just such an assessment, which is detailed in the next section. The CCA is based off the two equations by Shah et al. that succeed in evaluating individual designs instead of the entire idea set. Furthermore, there is no method to simultaneously account for all of the aspects of creativity considered in this study and rank orders the concepts in terms of creativity. The work done by Shah et al. is widely used to assess concept generation methods, but was easily adaptable to suit the needs of this study.

The equations also bring to the table a method that reduces the amount of reliance of human judgment in assessing creativity – something not found in current literature. All other assessment methods, such as CAT and CPSS, rely on people to rate the creativity of the products or ideas based on set requirements. Furthermore, many judgment-based creativity assessments are very detailed and take considerable time to implement. The goal of the CCA is to reduce the level of subjectivity in the assessment while making it more repeatable and reliable. The Multi-Point Creativity Assessment (MPCA) is introduced next to combat a gap in judging methods for a quick, but detailed creativity assessment and is also discussed in the next section. The theory of the MPCA is based on a proven task analysis method developed by NASA and on the adjective pairing employed by the CPSS method. The MPCA provides an opportunity to combine the quick assessment technique of NASA's Task Load Index (TLX) and the method of evaluating aspects of creativity introduced by the CPSS method.

3.4 CREATIVITY METRICS DEVELOPMENT

The proposed creativity assessment method is an adaptation of Shah et al.'s previous metrics that provide a method to analyze the output of various ideation methods to determine which method provides the most effective results, detailed in the previous section. The following sub-section outlines how these metrics were adapted to suit new assessment requirements for evaluating concept creativity. Section 3.4.2 provides insight into how the proposed MPCA evaluation method was created based on previously established assessment methods.

3.4.1 Comparative Creativity Assessment (CCA)

With Shah et al.'s metrics, ideation methods can be compared side by side to see whether one is more successful in any of the four dimensions. However, the metrics are not combined in any way to produce an overall effectiveness score for each concept or group of ideas. Because the purpose of the original Shah's metrics was the ability to assess ideation methods for any of the four aspects, they did not help to assign a single creativity score to each team. The four areas of analysis were not intended to evaluate creativity specifically and were not to be combined to provide one score or rating. Shah, et al. best state the reasoning behind this: "Even if we were to normalize them in order to add, it is difficult to understand the meaning of such a measure. We can also argue that a method is worth using if it helps us with any of the measures (Shah, Vargas-Hernandez et al. 2003)." There is added difficulty to combining all of the metrics, as Novelty and Quality measure the effectiveness of individual ideas, while Variety and Quantity are designed to measure an entire set of ideas generated. Thus Variety and Quantity may be considered as irrelevant for comparing different ideas generated from the same method. With this in mind, two of the Shah's metrics above can be manipulated to derive a way to measure the overall creativity of a single design in a large group of designs that have the same requirements.

This paper illustrates how to implement the modified versions of the Novelty and Quality metric on a set of designs that aim to solve the same engineering design problem. For the purposes of assessing the creativity of a final design compared with others, the metrics developed by Shah, et al. were deemed the most appropriate based on the amount of time required to perform the analysis and ease of understanding the assessment method. However, the Variety and Quantity metrics could only evaluate a group of ideas, so only the two metrics that could evaluate individual ideas from the group, namely Novelty and Quality, could be used. Also, the original metrics focused not only on the conceptual design stage, but also embodiment (prototyping), detail development, etc within concept design. As the focus of this study is to assess the creativity at the early stages of concept generation, the metrics have to be further revised to account for only the conceptual design phase.

The following are the resulting equations:

Novelty:
$$M_N = \sum_{j=1}^{m} f_j S_{Nj} \tag{5}$$

$$S_{Nj} = \frac{T_j - R_j}{T_j} \times 10 \tag{6}$$

Quality:
$$M_Q = \sum_{j=1}^{m} f_j S_{Qj} \tag{7}$$

$$S_{Qj} = 1 + (A_j - x_j)(10 - 1)/(A_j - B_j) \tag{8}$$

CCA:
$$C = W_N M_N + W_Q M_Q \tag{9}$$

where
$$W_N + W_Q = 1 \tag{10}$$

and
$$\sum_{j=1}^{m} f_j = 1 \tag{11}$$

where the design variables are:

T_j = number of total ideas produced for criteria *j* in Novelty
i = number of ideas being evaluated in Quality
f_j = weight of importance of criteria *j* in all equations
m = total number of criteria in evaluation
R_j = number of similar solutions in T_j to criteria *j* being evaluated in Novelty
A_j = maximum value for criteria j in set of results
B_j = minimum value for criteria j in set of results
x_j = value for criteria j of design being evaluated
S_{Qj} = score of quality for criteria *j* in Quality
S_{Nj} = score of novelty for criteria *j* in Novelty
W_N = weight of importance for Novelty (W_N in real set [0,1])
W_Q = weight of importance for Quality (W_Q in real set [0,1])
M_N = creativity score for Novelty of the design
M_Q = creativity score for Quality of the design
C = Creativity score

In this paper, the theory behind the Novelty and Quality metrics is combined into the CCA (Eqn 8), in an attempt to assist designers and engineers in assessing the creativity of their designs quickly from the concept design phase. The CCA is aptly named as it aims to provide engineers and companies with the most creative solution so that they may create the most innovative product on the market. Emphasis in this study is placed solely on the concept design stage because researchers, companies, and engineers alike all want to reduce the amount of ineffectual designs going into the implementation stages (Ullman 2006). Other goals of creative concept design include identifying the most promising novel designs while mitigating the risk of new territory in product design.

As the metrics were not intended to be combined into a single analysis, the names of variables are repeated but do not always represent the same thing, so variable definitions must be modified for consistency. The original metric equations (Eqn. 1-4) are written to evaluate ideas by different stages, namely conceptual, embodiment, and detail development stages. However, as the analysis in this study is only concerned with the conceptual design stage and does not involve using any existing ideas/creations, the equations will only be evaluated at the conceptual stage, i.e., n and p_k in the Novelty equation equal one.

The major differences between the metrics created by Shah et al. and the Comparative Creativity Assessment used in this paper are the reduction of the summations to only include the concept design level, and the combination of Novelty and Quality into one equation. The resulting assessment will aid in quick and basic comparison between all the designs being analyzed. This equation takes each of the creativity scores for the modified Novelty (M_N) and Quality (M_Q) and multiplies each by a weighted term, W_N and W_Q, respectively. These weights may be changed by the evaluators based on how important or unimportant the two aspects are to the analysis. Thus, these weights are the only subjective aspect of the analysis and are based on customer and engineer requirements. This could prove advantageous as the analyses can be applied to a very wide range of design situations and requirements. Brown states it most concisely; "the advantage of any sort of metric is that the values do not need to be 'correct', just as long as it provides relative consistency allowing reliable comparison to be made between products in the same general category (Brown 2008)."

Note that both equations for Novelty and Quality look remarkably similar, however, the major difference is with the S_N and S_Q terms. These terms are calculated differently between the two creativity metrics and are based on different information for the design. The method to calculate S_Q is based on normalizing a set of numbers for each Quality criterion to a range of 1 to 10. Each criterion for the Quality section must be measured or counted values in order to reduce the subjectivity of the analysis. For example, the criterion to minimize weight would be calculated for device x by using the maximum weight (A_j) that any of the devices in the set exhibit along with the minimum weight (B_j). Equation 8 is set up to reward those designs which minimize their value for criteria j. If the object of a criterion for Quality is to maximize the value, then the places for A_j and B_j would be reversed. Other possible criteria in the Quality section may be part count, power required, or number of manufactured/custom parts.

It can be summarized that the main contributions of this research are the modifications to Equations 1 and 3 to develop Equations 5 and 7, plus the development of the new Equations 8-10. Furthermore, these metrics are proposed for use in a new application of assessing individual ideas through the combination of quality and novelty factors, an application that has not been found in previous research. Future analysis of the metrics will determine how to add variables into the metrics that capture interactions of criteria/functions and components. This is important in the analysis of creativity with regard to functional modeling in concept generation as many creative solutions are not necessarily an individual solution to one particular function, but the combination of several components to solve one or more functions within a design problem.

3.4.2 Multi-Point Creativity Assessment (MPCA)

To compare the results of the Comparative Creativity Assessment (CCA), two other forms of assessing creativity were performed on the devices: a simple rating out of ten for each product by the judges and the Multi-Point Creativity Assessment (MPCA).

The MPCA was adapted from NASA's Task Load Index (TLX) (2010), which allows participants to assess the workload of certain tasks. Each task that a worker performs is rated based on seven different criteria, such as mental demand and physical demand. Each criterion is scored on a 21-point scale, allowing for an even five-point division on a scale of 100. To develop a weighting system for the overall analysis, the participants are also asked to indicate which criteria they find more important on a list of pair-wise comparisons with all the criteria.

For example, in the comparison between mental and physical demand in the TLX, one might indicate that they feel mental demand is more important for the tasks being evaluated.

For the purpose of the creativity analysis, the TLX was adapted such that the criteria used are indicative of different aspects of creativity, such as unique, novel, and functional. Judges rated each device using the creativity analysis adapted from the NASA TLX system, herein called the Multi-Point Creativity Assessment (MPCA). After rating each device based on the seven criteria of creativity, the judges rate all the criteria using the pair-wise comparisons to create the weighting system for each judge. Figure 3.1 is an example score sheet used by the Judges to rate each device.

The final score, on a base scale of 10, is calculated by Equation 12:

$$MPCA = \frac{\sum_{h=1}^{g}\left(\left[\sum_{j=1}^{m} f_j \cdot S_{Mj}\right]/T\right)}{10g} \tag{12}$$

where the design variables are:

$MPCA$ = Multi-Point Creativity Assessment Score
f_j = weighted value for criterion j
S_{Mj} = Judge's score for criterion j
m = total number of criteria in the assessment
T = total number of pair-wise comparisons
g = total number of judges

Figure 3.2 is an example of a completed pair-wise comparison used to calculate the weights of the criterion, which are presented in Table 3.4. The premise for the pair-wise comparisons is to evaluate the judges' perception of what they think is more important for creativity analysis for each of the criteria. The criteria used for the MPCA are: original/unoriginal, well-made/crude, surprising/expected, ordered/disordered, astonishing/common, unique/ordinary, and logical/illogical. Using the information of judges' preferences for the criteria, a composite score can be calculated for each device. For example, between original and surprising, one judge may deem original more creative, while another thinks surprising is more important for creativity.

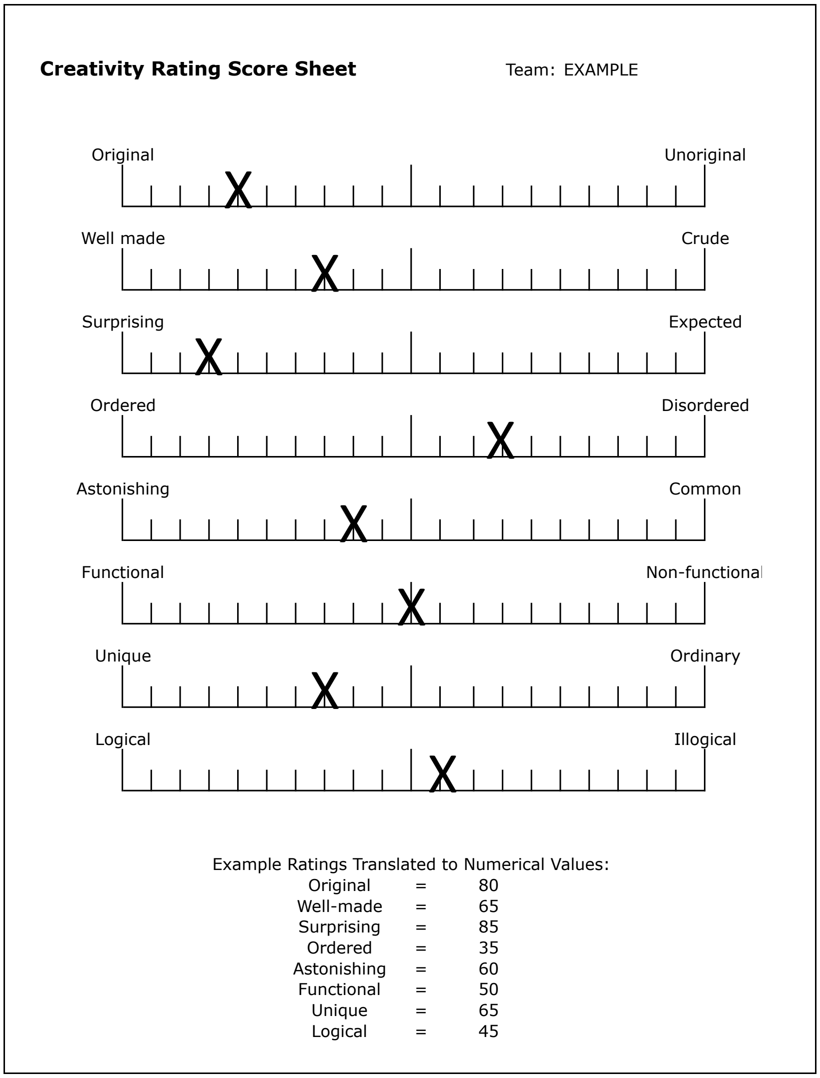

Figure 3.1: Example MPCA Score Sheet.

The example values for the weights (f_j) provided in Table 3.4 would be multiplied by each of the judges ratings for the criteria provided in Figure 3.1. Thus, an example calculation for the base summation of one design idea using the numbers provided in the Appendices becomes:

$$\left[\sum_{j=1}^{m} f_j \cdot S_{Mj}\right] / T = (6*80+2*65+5*85+2*35+4*60+3*50+4*65+2*45)/28 = 65.89$$

In the above calculation, the criteria are summed in the order presented in Figure 3.1. The full calculation for the MPCA of a particular design idea would then involve averaging all the judges' base summations for that idea (like the one calculated above) and dividing by ten to normalize to a base scale.

Figure 3.2: MPCA Pairwise Comparison Example

This proposed assessment method has the advantage over the CPSS method as it takes a fraction of the time and manpower, while still providing a unique opportunity to assess creativity through multiple aspects. The MPCA also takes into consideration judges' perceptions of creativity through the calculation of the weighted value for each criterion (f_j in Equation 12).

Table 3.4: Weighted Values for MPCA Calculation Example.

Totals for Weighted Values			
Criterion	f_i	Criterion	f_i
Original	6	Astonishing	4
Well-Made	2	Functional	3
Surprising	5	Unique	4
Ordered	2	Logical	2

As there is no similar method of creativity assessment that requires few judges and breaks creativity up into several aspects, validation of the method becomes difficult. However, it can be argued that the method, although newly developed, has been proven through the successful history of its origin methods. The base summation for the MPCA is the NASA derived equation for the TLX method calculation. The second summation and base scale of ten were added based on the CPSS methodology.

3.5 EXPERIMENTAL STUDIES

The proposed creativity assessment methods were developed to assess the creativity of concept designs that work to solve the same engineering design problem. Two studies were conducted during the development of the CCA and MPCA, one prior to the creation of the MPCA and use of the Judges' scoring as a pilot study. Lessons learned from the first study are applied in Study Two. The second study is more comprehensive, using all three methods of evaluation in comparison with statistical conclusions drawn from the data. Both studies used undergraduate, junior-level design team projects as the experiment subject and are described further in this section.

3.5.1 Study One: Mars Rover Design Challenge

3.5.1.1 Overview

Study One had 28 teams design a robotic device that could drive over 4” x 4” (10.2 cm x 10.2 cm) barriers, pick up small rocks, and bring them back to a target area on the starting side of the barriers for the 2008 ASME Student Design Competition (2009). Although each device was unique from every other device, it was also very evident that many designs mimicked or copied each other to satisfy the same requirements of the design competition problem. For example, 24 of the 28 designs used a tank tread design for mobility, while only four designs attempted wheeled devices.

3.5.1.2 Creativity Evaluation

To implement the creativity metrics, each design was first evaluated based on converting energy to motion (its method of mobility), traversing the barriers, picking up the rocks, storing the rocks, dropping the rocks in the target area, and controlling energy (their controller). These parameters represent the primary functions of the design task and make up the Novelty component of scoring.

Table 3.5 outlines the different ideas presented in the group of designs under each function (criterion) for the Novelty analysis, followed by the number of designs that used each particular idea. Below each function (criterion) name in the table is the weighted value, f_j, which puts more emphasis on the more important functions such as mobility and less emphasis on less important functions such as how the device is controlled. Note that all weights in the analysis are subjective and can be changed to put more emphasis on any of the criteria. This gives advantage to those engineers wanting to place more emphasis on certain functions of a design rather than others during analysis. The third column shows the R_j values (number of similar solutions in T_j to the function j being evaluated in Novelty), and all the T_j

values equal 28 for all criteria (28 designs total). The final column presents the score of novelty for each associated function solution (S_{Nj} in Equation 5 and 6).

Table 3.5: Fall 2008 Novelty Criteria and Types for CCA Calculation.

FUNCTION	SOLUTION	NUMBER OF DESIGNS	S_{Nj}
Move Device (f_1 = 0.25)	Track	24	1.43
	Manuf. Wheels	1	9.64
	4x Design Wheels	2	9.29
	8x Design Wheels	1	9.64
Drive Over Barrier (f_2 = 0.2)	Double Track	4	8.57
	Angle Track	15	4.64
	Single Track powered	2	9.29
	Wheels with Arm	1	9.64
	Wheels with ramp	1	9.64
	Angled wheels powered	1	9.64
	Tri-wheel	1	9.64
	Single track with arm	1	9.64
	Angled track with arm	2	9.29
Pick up rocks (f_3 = 0.2)	Rotating sweeper	10	6.43
	Shovel under	8	7.14
	Scoop in	9	6.79
	Grabber arm	1	9.64
Store rocks (f_4 = 0.15)	Angle base	11	6.07
	Flat base	10	6.43
	Curve base	2	9.29
	Hold in scoop	3	8.93
	Tin can	1	9.64
	Half-circle base	1	9.64
Drop rocks (f_5 = 0.15)	Tip vehicle	2	9.29
	Open door	8	7.14
	Mechanized pusher	5	8.21
	Reverse sweeper	4	8.57
	Open door, tip vehicle	3	8.93
	Drop scoop	3	8.93
	Rotating doors	1	9.64
	Leave can on target	1	9.64
	Rotating compartment	1	9.64
Control Device (f_6 = 0.05)	Game controller	3	8.93
	Plexiglass	5	8.21
	Remote controller	4	8.57
	Plastic controller	3	8.93
	Car controller	7	7.50
	Metal	5	8.21
	Wood	1	9.64

The calculation for each concept's Novelty score then becomes a summation of its S_{Nj} values for each function solution multiplied by the functions respective weighting. An example calculation for one of the devices is given below that uses the first choice listed for each of the functions. These choices are: track (move device), double track (drive over barrier), rotating sweeper (rick up rocks), angle base (store rocks), tip vehicle (drop rocks), and game controller (control device). The calculation of Novelty for the example concept becomes:

$$M_N = 0.25*1.43 + 0.2*8.57 + 0.2*6.43 + 0.15*6.07 + 0.15*9.29 + 0.05*8.93 = 6.11$$

The Quality section of the metrics evaluates the designs individually through the criteria of weight, milliamp hours from the batteries, the number of switches used on the controller, the total number of parts, and the number of custom manufactured parts. These criteria were created in order to determine which devices were the most complex to operate, the most difficult to manufacture, and the most difficult to assemble. The weight and milliamp hour criteria were part of the competition requirements and easily transferred to this analysis. Each device was evaluated and documented in regard to each of the criteria and then all the results were standardized to scores between 1 and 10. For example, the maximum weight for the design set was 2900 grams (A_j in Equation 8) and the minimum weight was 684 grams (B_j in Equation 8). Each design was weighed (x_j in Equation 8) and the weights were normalized to a scale of ten using the equation for S_{Qj}. The calculation for an example product weighing 2000 grams is:

$$S_{Q\_weight} = 1 + (2900 - 2000)(10 - 1)/(2900 - 684) = 4.66$$

The overall Quality score for the example would then sum the products of the S_Q values and the function weights (f_j). The above example shows how the equation to calculate the Quality score for a particular function (vehicle weight in this case) gives lower scores for higher values within the data set. The weighted values for each criterion in Quality are presented in Table 3.6, below. Thus, the above S_{Q_weight}=4.66 would be multiplied by f_{weight}=0.3 from the table in the calculation for M_Q.

Table 3.6: Quality Criteria Weighted Values for Study One.

Criteria	f_j value
weight	0.3
milliamp hrs.	0.2
# switches	0.2
# materials	0.2
# manuf. Parts	0.1

With all the variables for the Novelty and Quality metric components identified, each device is then evaluated. Once the Novelty and Quality criteria are scored for each device, the CCA is implemented to predict the most overall creative design of the set.

Table 3.7: Novelty, Quality, and Combined Creativity Scores for Study One.

	D1	**D2**	**D3**	**D4**	**D5**	**D6**		
Novelty (M_N)	6.1	5.2	8.4	6.3	6.2	5.0		
Quality (M_Q)	5.1	4.4	8.2	8.1	8.9	4.2		
CCA	5.7	4.9	***8.3***	7.0	7.3	4.7		
	D7	**D8**	**D9**	**D10**	**D11**	**D12**	**D13**	**D14**
Novelty (M_N)	5.0	5.5	5.3	6.2	5.0	6.6	8.1	5.4
Quality (M_Q)	5.8	5.5	6.3	9.6	7.8	6.5	6.8	6.2
CCA	5.3	5.5	5.7	7.6	6.1	6.5	7.6	5.7
	D15	**D16**	**D17**	**D18**	**D19**	**D20**	**D21**	
Novelty (M_N)	6.8	5.9	6.5	5.0	8.0	5.3	5.3	
Quality (M_Q)	9.1	7.0	7.9	6.5	6.1	8.2	7.7	
CCA	7.7	6.3	7.1	5.6	7.2	6.4	6.2	
	D22	**D23**	**D24**	**D25**	**D26**	**D27**	**D28**	
Novelty (M_N)	5.3	5.2	6.1	6.8	6.6	8.9	5.0	
Quality (M_Q)	6.6	8.5	8.9	7.6	7.6	5.5	6.9	
CCA	5.8	6.5	7.2	7.1	7.0	7.5	5.8	

Table 3.7 lists each device with an identifying name and their respective Novelty and Quality scores. The total creativity score C from the CCA following the Novelty and Quality scores is calculated using the weights W_N and W_Q, where W_N equals 0.6 and W_Q equals 0.4, giving more priority to Novelty. The subjectiveness of the metrics is needed so that they can be applied over a wide range of design scenarios. The advantage to this subjectiveness is that

the weights can be changed at any time to reflect the preferences of the customers or designers. This would be useful for situations in which a customer may want to focus more on the quality of the project and less on novelty, thus allowing evaluators to include creativity as a secondary focus if needed.

As highlighted in Table 3.7, the device with the highest Creativity score based on the revised metric is Device 3, pictured in Figure 3.3. It is interesting to note that D3 remains the highest scoring design of the set until the weights for Novelty and Quality are changed such that Quality's weight is greater than 0.6, at which point D10 (highlighted in Table 3.7) becomes the highest scoring because of its high Quality score. However, when the Novelty weight is increased above 0.85, D27 becomes the most creative based on the CCA because of its high Novelty score (highlighted in Table 3.7).

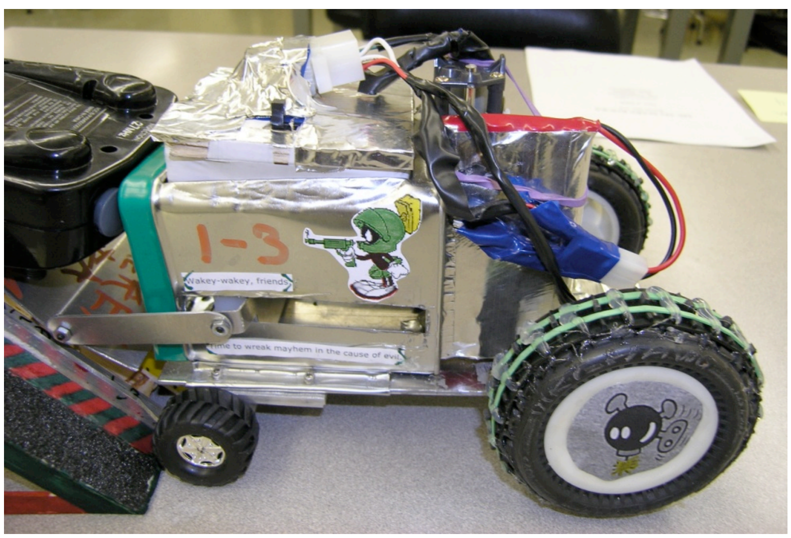

Figure 3.3: Device 3 – Device Evaluated as the Most Creative Mars Rover Design in Study One.

Figure 3.4 illustrates the relationship between the final CCA scores and varying the weights for Novelty and Quality. In the plot, the Novelty weight steadily increases by 0.1 to show how each device's overall score changes. This figure shows that although two devices can have the highest CCA score when the Novelty weight is high or low, only Device 3 is consistently high on CCA score (it is the only to score above 8.0 no matter what the weights).

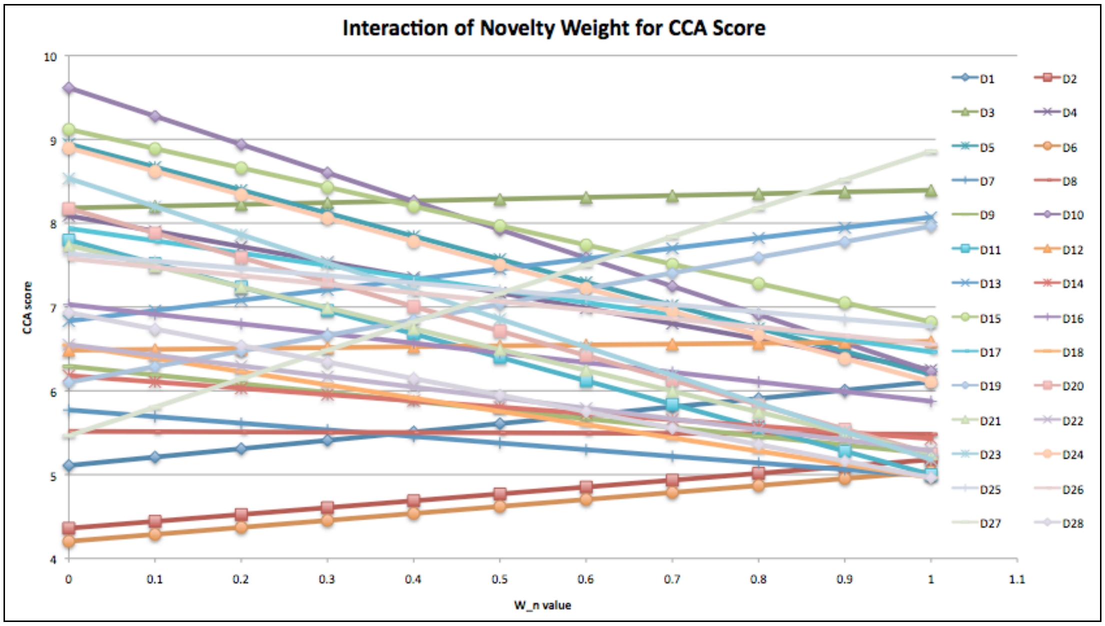

Figure 3.4: Relationship between Varying Novelty Weights and CCA score in Study One.

Device 3 is the most creative of the group because it embodies the necessary criteria for both Novelty and Quality such that the design is both unique and useful at the conceptual design phase. The design of Device 3 is unique because it was the only one to use four manufactured wheels (mobility) and a ramp (over barrier). Its solution for picking up the rocks (shovel under) and storing the rocks (flat compartment) were not quite as unique, but it was only one of five devices to use a mechanized pusher to drop the rocks and only one of four to use a remote controller. The combination of these concepts yielded a high Novelty score. Its high Quality score is largely due to the fact that it had the lowest milliamp hours and the lowest number of parts of all the devices. It also scored very well for weight and number of manufactured parts, but only had a median score for the number of switches used to control the device.

As stated previously, this analysis only deals with the conceptual design phase and not implementation. The majority of the designs actually failed during the end-of-project design competition due to many different problems resulting from a time constraint towards the end of the design process for the design teams. The emphasis of the project was on concept design and team work, not implementation of their design. Only two devices in the 28 designs were able to finish the obstacle course and most designs experienced a failure, such as component separation or flipping upside-down when traversing the barrier, which was all expected. Four months after the local design competition, at the regional qualifiers for the ASME Mars Rover competition, the majority of all the competing designs from around the Pacific Northwest performed in the same manner as the end-of-project design competition, even with months of extra development and preparation. This illustrates the difficulty of the design problem and the limitations placed on the original design teams analyzed for this study.

3.5.1.3 Lessons Learned from Study One

Several important contributions came from Study One that benefited the second experiment detailed in Section 3.5.2. The primary goal of the first study was determining the procedure for analyzing the student concepts using the CCA.

Study One also provided information regarding how the data needed to be collected from the student design teams and how the calculations were run. Data collection was done during and after the design competition, making it difficult to collect data. Organized Excel spreadsheets developed prior to the assessment of the designs would have proved to be more effective and efficient when it came to data collection. This aspect of data collection was employed in Study Two in order to use more reliable data from the students.

Study One showed that there needs to be less emphasis on the execution of the ideas developed by the students. This was evident from the results of the design competitions as the students lack the experience of design implementation at their current stage of education. They develop machining and design development skills in the next semester and during their senior design projects. This provided the motivation to assessing only at the concept design level with the metrics.

Some interesting trends were discovered when analyzing the results of the CCA scores. This is evident most prominently in Figure 3.4 as it shows that some concepts prove to be more creative regardless of the weightings for novelty and quality, while others were only creative based on one of the aspects. Other concepts proved to be not creative no matter what weightings were applied to the assessment.

3.5.2 Study Two: Automated Waste Sorter Design Challenge

3.5.2.1 Overview

Study Two consisted of 29 teams given seven weeks to design and create prototypes for the 2009 ASME Student Design competition, which focused on automatic recyclers (2010). The rules called for devices that automatically sort plastic bottles, glass containers, aluminum cans, and tin cans. The major differentiation between types of materials lay with the given dimensions of the products: plastic bottles were the tallest, glass containers were very short and heavy, and aluminum cans were lightweight compared to the tin cans of similar size. The tin cans were ferrous and thus could be sorted using magnets. Devices were given strict requirements to abide by such as volume and weight constraints, safety requirements, and most importantly, had to operate autonomously once a master shut-off switch was toggled (see Figure 3.5 for an example).

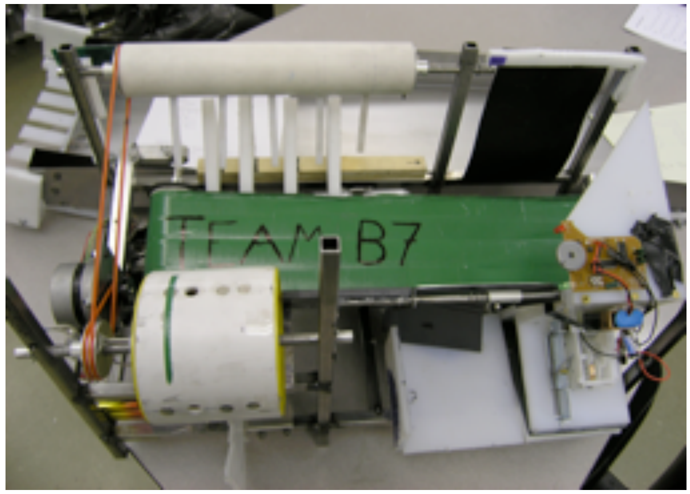

Figure 3.5: Example Waste Sorter for Study Two with functions to automatically sort plastic, glass, aluminum, and tin.

As with the devices for Study One, the teams created very similar projects, although each was unique in its own particular way. For example, 21 of the 29 devices sorted the tin cans using a motorized rotating array of magnets, yet within all the teams, there were 15 different strategies for the progression of sorting the materials (for example, plastic is sorted first, then tin, aluminum, and glass last).

All the devices were evaluated only at the concept design stage and not on the implementation. The students did not have time to place adequate attention on the implementation and testing of their devices. Many teams did not have any teammates with adequate experience in many of the necessary domains, such as electronics or programming. Thus, many concepts were very sound and creative, but could not be implemented completely within the time allotted for the project.

At the end of each study, the teams participated in a design exhibition where they are required to compete against other teams. Because less emphasis was placed on the implementation of their concepts, all the devices were very basic and limited in construction. Unfortunately, none of the devices were able to successfully sort the recyclable materials autonomously, but many functioned correctly if the recyclables were fed into the device by hand. The major downfall for the teams was their method of feeding the materials into their devices.

As the implementation of the team's projects was rushed at the end of the school term, proper documentation of the Quality aspects were not possible. Thus, the quality aspect of the Innovation Equation was not included this year in the creativity analysis and the results of the end-of-term competition are not presented.

3.5.2.2 Creativity Evaluation

Each team executed a design process that began with several weeks of systematic design exercises, such as using Morphological Matrices and Decision Matrices in order to promote the conceptual design process. Although every device seemed unique from the others, it was also evident that many designs mimicked or copied each other to satisfy the same requirements of the design competition problem. Study One provided valuable lessons learned that were implemented in Study Two, such as the inclusion of asking judges to rate the products and perform the MPCA.

The most basic assessment used was asking a panel of judges to score the devices on a scale from one to ten for their interpretation of creativity. The panel of judges was assembled post-competition in a private room and given the exact same set of information for each device, including pictures and descriptions of how the device operated. This procedure allowed for an acceptable interrater reliability for the study (> 0.75).

For the CCA, each device was documented for its methods in satisfying novelty features. The novelty criteria included how the device sorted each of the materials (plastic, aluminum, tin, and glass), in what order they were sorted, and how the outer and inner structures were supported.

Table 3.8: Study Two Novelty Criteria and Types for CCA Calculation.

FUNCTION	SOLUTION	# OF DESIGNS
Support Overall Structure ($f_5 = 0.15$)	Plexiglass	2
	Wood	2
	Wood struts	3
	Steel	3
	Steel box	8
	Peg board	1
	K'nex	1
	Steel struts	4
	Round light steel	1
	Round and Square	1
	Foam boards	2
	Tube	1
Support Inner Structure ($f_5 = 0.04$)	Parts	10
	Wood struts	4
	Wood and steel	3
	Steel struts	6
	K'nex	2
	Foam board	1
	Plexiglass	2
	Tube	1
Order of Sort ($f_6 = 0.01$)	P T G A	3
	G P T A	1
	T A P G	2
	P G T A	1
	G T P A	3
	T G A P	4
	T A G P	1
	G T A P	2
	T G P A	1
	ALL	2
	T P G A	3
	P T A G	1
	T P A G	1
	P T A/G	2
	T G A/P	2

FUNCTION	SOLUTION	# OF DESIGNS
Sort Aluminum ($f_1 = 0.2$)	Leftover	8
	Eddy current with magnet	2
	Height sensitive pusher	2
	Eddy current and punch	6
	Eddy current and gravity	1
	Height sensitive conveyor	2
	Height sensitive hole	3
	Metallic sensor	2
	Height sensitive ramp	1
	Weight sensitive ramp	1
	Weight sensitive balance	1
Sort Tin ($f_2 = 0.2$)	Rotating magnets	17
	Motorized magnet arm	5
	Magnet sensor pusher	3
	Swinging magnet	1
	Magnet sensor	2
	Motorized belt magnet	1
Sort Plastic ($f_3 = 0.2$)	Leftover	6
	Height sensitive pushers	10
	Height sensitive gravity	5
	Weight sensitive fan	4
	Height sensitive ramp	1
	Height sensitive conveyor	2
	Height sensor	1
Sort Glass ($f_4 = 0.2$)	Leftover	3
	Weight sensitive door	21
	Dimension sensitive door	1
	Weight sensor pusher	1
	Weight sensor	1
	Weight sensitive balance	1
	Height sensitive pusher	1

Table 3.8 contains data similar to Table 3.5 in Section 3.5.1.2, which outlines how many devices used a particular solution for each of the novelty criteria. The weighted values,

f_j, are presented below the title of each criterion. The weighted values used for this analysis were based on the competition's scoring equation and the overall structural design. The scoring equation places the same emphasis on all four waste material types, thus each of the sorting types was given the same weighted value. The method to support overall structure was given the next highest f_j value as it provides the majority of the support to the entire design. The method of supporting the inner structure, although important, does not garner as much emphasis in terms of creativity, which can also be said for the order of sort.

The results of all three creativity analyses are given in Table 3.9 below, with statistical analysis of the results presented in the next section.

Table 3.9: Study Two Creativity Scores for CCA, Judging Out of Ten, and MPCA.

Device #	CCA	Judging: Out of 10	MPCA
1	5.86	5.33	5.26
2	5.90	5.11	4.92
3	7.76	5.89	5.31
4	6.84	5.22	5.37
5	6.86	6.00	5.68
6	6.43	6.67	6.66
7	6.67	3.11	3.92
8	6.60	6.11	6.51
9	6.53	5.67	6.01
10	6.66	4.56	4.83
11	7.83	6.78	6.75
12	6.78	6.78	6.33
13	8.40	8.00	7.07
14	6.17	6.22	5.68
15	7.24	4.78	4.95
16	9.12	4.78	5.26
17	6.45	5.89	5.82
18	6.76	6.00	5.17
19	7.86	6.33	6.21
20	5.62	6.11	5.40
21	7.07	6.33	5.62
22	8.07	5.78	5.82
23	8.78	5.67	5.38
24	7.90	7.11	6.94
25	6.69	5.89	5.99
26	6.31	5.33	5.64
27	6.57	4.44	4.40
28	6.64	6.33	6.09
29	9.16	8.44	7.64

3.5.2.3 Statistical Analysis

Statistical analysis of the data from this study includes inter-rater reliability of the judges and different comparisons of results of the three different creativity ratings described previously.

The analysis of the three types of creativity assessment used averages of the judges' scores out of ten, the averages for each device from the Multi-Point Creativity Assessment, and the final scores from the Comparative Creativity Assessment. Thus, the scores from the CCA could be compared to two average creativity means to determine the validity of the method. This is done using an intraclass correlation (ICC), which allows one to test the similarities of measurements within set groups (Ramsey and Schafer 2002; Montgomery 2008).

The ICC was also used to determine the inter-rater reliability of the judges for both the Judges' scorings out of ten and the MPCA. The judges were nine graduate students at Oregon State University familiar with the class projects and were provided the same information regarding each project and the projects' features. The interrater reliability for the judges' ratings out of ten for each device was slightly higher than the MPCA interrater reliability at 0.820 and 0.779, respectively. The CCA method did not require judges. A previous study examined the interrater reliability and repeatability of several ideation effectiveness metrics, including the novelty portion of Shah's metrics (Srivathsavai, Genco et al. 2010). This study used found that the repeatability of the novelty metric at the feature level of analysis had above an 80% agreement between evaluators. This analysis successfully addresses the concern of interpretation of data sets for the novelty portion of Shah's metrics, and thus the novelty portion of the CCA as well.

The primary analysis for the validation of the CCA is a comparison of the means of the Judges' scorings out of ten and the MPCA, known as the intraclass correlation. However, these two means must first be verified using a bivariate correlation analysis, such as through SPSS statistical software (http://www.spss.com/).

Comparing the creativity scores for the MPCA and judges' ratings out of ten resulted in a high bivariate correlation coefficient (Pearson's r=0.925). This verifies that the two data sets are very similar to one another and thus can be used to determine whether or not the Innovation Equation results are also similar.

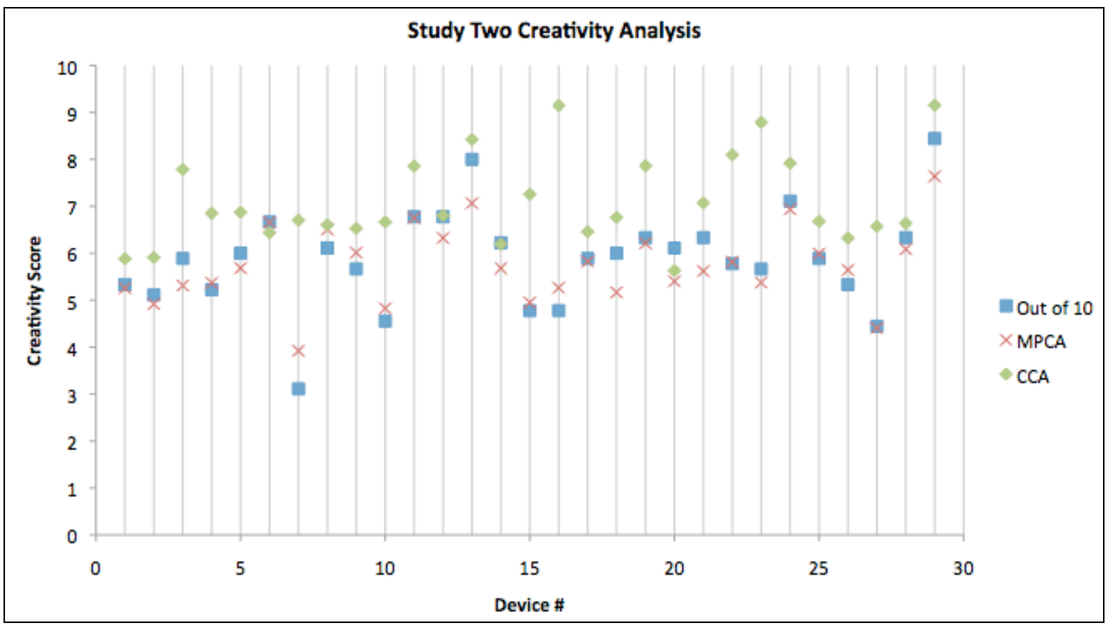

Figure 3.6: Comparison of Three Creativity Analyses in Study Two.

However, an intraclass correlation analysis on the three data sets yields a very low correlation coefficient (r=0.336). A scatter plot of the data depicts this lack of correlation and can be used to determine where the majority of the skewed data lies (see Figure 3.6). As shown in this plot, Devices, 3, 7, 15, 16, 22, 23, and 27 are the most skewed. Possible reasons behind the lack of correlation are discussed in the next section. By eliminating these devices from the analysis, the intraclass correlation rises significantly (r=0.700), thus proving partial correlation with Judges' scorings.

The data sets can be used to draw conclusions as to which device may be deemed as the most creative out of the 29 designs. A basic analysis of the data and graph shows that the most creative design is Device 29 (see Figure 3.7), which has the highest average creativity score. This can be attributed to the fact that it is one of the only devices to use sensors for all sorting functions and the one device to use plexiglass as its outer and inner supports.

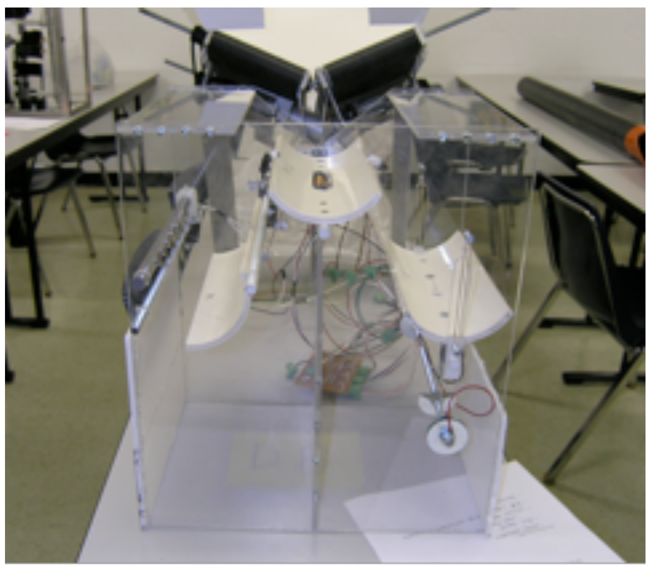

Figure 3.7: Most Creative Automated Waste Sorter (Device 29) based on its use of sensors for all sorting functions and a unique method of support.

3.5.2.4 Lessons Learned

The implementation of the CCA in Study One and both the CCA and MPCA in Study Two has taught some important lessons regarding the evaluation of conceptual designs. The large data set allowed statistical analysis of the results to push the future of quantitative creativity assessment in the right direction. These two studies have shown that metrics can be applied to a set of designs to assess the level of creativity of possible designs. These metrics can be used by engineers and designers to determine, in the early stages of design, which ideas may be the most beneficial for their problem statement by driving towards innovative products.

The distinct advantage of the CCA method is that there is very little human subjectivity involved in the method beyond determining the weights/importance of the subfunctions (f_j in Eqns. 5 and 7) and Novelty versus Quality (W_N and W_Q in Eqn. 9). The remainder of the subjectivity is with the interpretation of how each subfunction is satisfied for each design idea, which is dependent on the detail of the documentation or the description by the designers. Further studies will determine the amount of repeatability for this analysis, i.e., to determine whether any designer use the CCA method and obtain the same results as the researchers in this study.

Further detail on lessons learned from these experiments will be discussed in detail in Chapter 6.

3.6 CONCLUSIONS AND FUTURE WORK

This chapter presented and discussed the analysis of concepts generated during two mechanical engineering design projects by means of creativity assessment methods. First a survey of creativity assessment methods was presented and summarized in Tables 3.1-3.3 in Section 3.3, which provides a unique opportunity to compare and contrast analysis methods for personality types, product creativity, and the creativity of groups of ideas. This survey contributed to the motivation behind the creation of the Comparative Creativity Assessment and Multi-Point Creativity Assessment methods. In particular, the Multi-Point Creativity Assessment method was used in conjunction with a Comparative Creativity Assessment, derived from an initial set of creativity metrics from the design creativity literature. The methods proposed in this paper fill the gaps found in the current literature. The creation of the MPCA in conjunction with the CCA allowed for statistical analysis of the validity of these methods in analyzing creativity in design. Although there was limited statistical correlation between the judges' scorings of creativity and the CCA scores, this study provided valuable insight into the design of creativity assessment methods and experimental design. Supplemental studies will examine the repeatability of the CCA for users inexperienced with the method and how to increase the interrater reliability of the MPCA.

Further research into evaluation techniques includes how to assess risk and uncertainty in creative designs. With the inclusion of creativity in concept design, comes the risk of implementing concepts that are unknown or foreign to the engineers (Yun-hong, Wen-bo et al. 2007). By quantifying this risk at the concept design stage, engineers are further aided in their decision-making process, given the ability to eliminate the designs that are measured to be too risky for the amount of creativity it applies (Ionita, America et al. 2004; Mojtahedi, Mousavi et al. 2008). By defining all risk in a product at the concept design stage, designers can more effectively look past old designs and look for new, improved ideas that optimize the level of risk and innovation (Yun-hong, Wen-bo et al. 2007).

Current research interests delve into quantifying creativity in the concept generation phase of engineering design and determining how one can apply this concept to automated concept generation (Bohm, Vucovich et al. 2005). Ongoing work at Oregon State University focuses on using a cyber-based repository that aims to promote creativity in the early stages of engineering design by sharing design aspects of previous designs in an easily accessible repository. Various tools within the repository guide the designers through the design repository to generate solutions based on functional analysis. The Design Repository can be accessed from: http://designengineeringlab.org/delabsite/repository.html.

By combining creativity and innovation risk measurements into the conceptual design phase, engineers will be given the opportunity to choose designs effectively that satisfy customers by providing a creative product that is not risky by their standards, and also satisfy conditions set forth by engineering and customer requirements. This will be particularly helpful when utilizing automated concept generation tools (Bohm, Vucovich et al. 2005). Automated concept generation tools create numerous designs for a given problem, but leaves the selection of possible and probable ideas to the designers and engineers. Using creativity metrics in order to narrow the selection space would allow for easier decisions during the concept design phase of engineering.

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Chapter 4: The Development of a Repository of Innovative Products (RIP) for Concept Generation Inspiration in Engineering

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The research presented in this paper introduces the concept of computer-directed innovation in product design using archived innovation information. A method is formulated for identifying the innovative subsystems in a product and archiving that information in a reusable and searchable database. The innovation information, when archived in a design repository, can support automatic concept generation that is biased toward innovative concepts. This concept generation method is proposed as a tool for engineers to increase the creativity of designs and to assess their concepts based on creativity and innovation. Products featured in published lists of innovative products are reverse engineered to expose the component and functional relationships. A function subtraction method based on difference rewards is introduced to isolate innovation-related functions and components in order to populate a Repository of Innovative Products (RIP). Initial results from two classroom studies are presented to support the utility of the Repository of Innovative Products. Initial results show that the concepts generated using RIP inspiration are as creative as those generated from a comparative methodology developed and proven effective over the last several years, and provide support that computer-directed innovation is possible using the data collection method proposed for the entire online product database called the Design Repository (DR). The contents of this chapter have been submitted to the Journal of Engineering Design and co-authored by Sarah Kay Oman, Brady Gilchrist, Irem Y. Tumer, and Robert Stone (Oman, Gilchrist et al. 2012).

4.1 INTRODUCTION

For decades, researchers and designers have introduced numerous ways to find creative people, teach the creative process, and assess what is creative. From those creativity techniques, companies then attempt to incorporate the results into innovative products (Buhl

1960; Cropley and Cropley 2005). Here, creativity refers to novelty or originality, while innovation is the application of said creativity.

The goal of this chapter is to map the propagation of innovation from marketed, successful products down to the component and functional levels. From this information, trends can be deduced based on which functions and components contribute to the innovation in the products. These key functions and components can then be used in concept generation using automatic concept generation methods such as the Design Repository housed at Oregon State University (OSU).

The research achieves this goal by: (1) examining proven innovative products to determine what about that innovative product makes it unique and useful and record that information in a repository; and, (2) utilizing that information within concept generation techniques to increase the creativity of the output. The end goal of this research is to employ an innovation algorithm that creates product concepts where their innovation level can be predicted. Ongoing work has been presented by other Oregon State University authors that begin to investigate this goal (Rebhuhn, Gilchrist et al. 2012).

In the following, the Background section introduces the Design Repository and its concept generation method known as the Morphological Evaluation Machine and Interactive Comceptualizer (MEMIC), along with a review of design creativity and functional modeling. The Research Method section then details the methodology employed for this study to determine what constitutes innovation in recognized innovative products as compared to similar products that have not achieved such acclaim. Initial results of the case study in Section 4.3.3 provide initial support that computer-directed innovation is possible using the data collection method detailed in Section 4.3.2 for the entire Design Repository, which is currently used in the introduction to design course at Oregon State University (OSU). Section

4.4 details the two classroom studies that examined the application by engineering undergraduate students of the proposed Repository of Innovative Products (RIP) versus MEMIC. The classroom experiment results prove that RIP can produce concepts that are as creative as those produced from MEMIC output. Conclusions are drawn based on the results of the experiments and future work looks at ways to further this research.

4.2 BACKGROUND

Background is covered to review the state-of-the-art in creativity and innovation, a review of engineering design and functional modeling, a description of the Design Repository housed at Oregon State University, established methods of automated design, and the metrics used to evaluate the designs created in the case study and experiments.

4.2.1 Creativity and Innovation in Engineering Design

The terms *creativity* and *innovation* have been defined and redefined in almost every text based upon the needs of the authors and research in question (Shah, Kulkarni et al. 2000; Cropley and Cropley 2005; Liu and Liu 2005; Linsey, Markman et al. 2008).

In the context of design, the definition of creativity is very near the same: creativity is "work that is novel (i.e., original, unexpected), high in quality, and appropriate (Sternberg, Kaufman et al. 2002)." Most definitions of creativity focus on the idea of novelty or originality, such as Cropley and Cropley stating that creativity is discovering unknown solutions to arrive at unexpected answers that generate novelty (Cropley and Cropley 2005). Our definition of creativity in this work is: originiality and novelty as applied in the concept design stage.

The definitions for innovation embody a central theme: innovation is the implementation of creative ideas (Amabile, Conti et al. 1996; Elizondo, Yang et al. 2010). Innovation can be either incremental or radical, such that *incremental* is the normative approach of creating slight improvements to an existing idea, and *radical* is an approach that introduces a breakthrough product or technology into the market, causing chaos (Saunders, Seepersad et al. 2009). Our definition of innovation in this work is: the application of creativity into fully formed concepts or products.

A study done by Saunders, et al. went further into understanding what innovation is in engineering specifically by defining characteristics of marketed innovative products. The characteristics can be categorized into functionality, architecture, environmental interactions, user interactions, and cost (as a secondary characteristic) (Saunders, Seepersad et al. 2009).

Among the innovation research is a host of studies conducted to analyze levels of innovation in concepts (Redelinghuys 1997; Redelinghuys 1997; Besemer 1998; Plucker and Runco 1998; Redelinghuys 2000; Shah, Kulkarni et al. 2000; Shah, Vargas-Hernandez et al. 2003; Cropley and Cropley 2005; Horn and Salvendy 2006; O'Quin and Besemer 2006; Okudan and Shirwaiker 2006; Redelinghuys and Bahill 2006; Saunders, Seepersad et al. 2009; Elizondo, Yang et al. 2010; Oman and Tumer 2010). However, none of these studies work towards a methodology to analyze the innovation of automated concept generation. A goal in this paper is to enable the assessment of a product's innovativeness through automated concept generation, discussed in Section 4.3. The research presented herein is the first step towards implementing automated concept evaluation of innovation.

4.2.2 Engineering Design and Functional Modeling

A previous study has found that using structured methods throughout the design process has a positive effect on the quality of concept outcomes (Bryant, McAdams et al. 2006). Many methods allow new designers to learn to think further outside the box than more traditional forms of concept generation. Within engineering design, functional modeling is now "an essential part of engineering design education" and "more attention has been given to method development and teaching it in engineering design classes (Abbott and Lough 2007)" as a means of abstracting the motivating design problem (Ullman 2010).

Standard engineering design textbooks used in engineering courses (such as Pahl and Beitz, Otto and Wood, Ulrich and Eppinger, and Ullman) place emphasis on analysis of systems and problems at the functional level (Pahl and Beitz 1988; Ulrich and Eppinger 2000; Otto and Wood 2001; Ullman 2010). This is the process of first representing the overall problem or system through the main function regarding inputs and outputs. From there, the main function is broken down into various subfunctions based on their flow types: material, energy, or signal (information) (Bryant, McAdams et al. 2006; Abbott and Lough 2007). Representing problems through functional modeling provides numerous advantages in the design process, including: managing the complexity of large problems or systems, determining the relationships between components in a complex system for tracking inputs and outputs, classifying the importance of different functions in the system, aiding in modular design, and facilitates design by analogy (Pahl and Beitz 1988; Fantoni, Taviani et al. 2007).

Furthermore, functional representation has been used in the exploration of aiding innovation during concept design through the use of structured design methods, such as designing by analogy or group ideation sketching techniques (Pahl and Beitz 1988; Shah, Vargas-Hernandez et al. 2003; Parameswaran 2004; Linsey 2007). For example, one dissertation examined how the functional representation of the problem positively affected the innovative outcomes of solutions by the proposed design by analogy method, called Word-Tree Design-by-Analogy (Linsey 2007).

This method of abstracting the problem in order to generate ideas is used predominantly in the Design Repository, detailed in the next subsection.

4.2.3 Design Repository

The idea of an artifact rich design repository came to life as a research prototype called the Design Repository (DR), currently maintained at Oregon State University. A common design language was needed to allow for the universal capture of design information, particularly design intent. The Functional Basis is a well received set of function and flow terms whose goal is to comprehensively describe product function and is a crucial portion of the repository framework (Otto and Wood 2001; Hirtz, McAdams et al. 2002; Dieter and Schmidt 2008). Using functional descriptions of products and the Functional Basis (Hirtz, McAdams et al. 2002), all functions of products and the products' individual components were captured, stored, and reused in a computer based system. Studies have been performed on current repository systems such as product data management systems, CAD based knowledge system, and architectural knowledge based systems, leading to the creation of the Design Repository system (Bohm, Stone et al. 2006). Capturing crucial design data is an important step therefore a list of database fields was formulated, shown in Table 4.1.

Table 4.1: Design Repository Database Fields for Capturing Crucial design data (Bohm 2004)

Data Fields	Type	Relational	List Value
Artifact Name	Text		
Part Family	Text		
Part Number	Numerical		
Sub Artifact of	Text	X	
Quantity	Numerical		
Description	Text		
Artifact Color	Text	X	
Component Naming	Text	X	X
Assembly	Boolean		X
Supporting Function	Boolean		X
Input Artifact	Text	X	
Input Flow	Text	X	X
Subfunction	Text	X	X
Output Flow	Text	X	X
Output Artifact	Text	X	X
Physical Parameter Type	Text	X	X
Physical Parameter Value	Numerical		
Physical Parameter Metric	Text	X	X
Manufacturing Process	Text	X	X
Material	Text	X	X
Primary Identifier	Text	X	X
Failure Mode	Text	X	X
Risk Element	Text	X	X

The Design Repository allows for the capture of customer need information, component basis designations, manufacturer, physical parameters, failure modes, and sensory information (Bohm, Stone et al. 2006). The Design Repository is accessed at: http://designengineeringlab.org/delabsite/repository.html (2011).

These data fields allow for what is deemed to be a comprehensive capture of design data to help with the understanding and reuse of product information. Other files attached to the products include a functional model, assembly model, and visual picture (Bohm 2004). However, with the push to design more innovative products, one more field needs to be captured: the "innovativeness" of certain subsystems of products. The inclusion of this field would allow for the reuse of innovative component information in product development.

Critical to the research in this paper, what the Design Repository lacks is a strategy to record the innovation level of existing products or artifacts. Currently, the statistics on artifact frequency of occurrence in the products detailed in the repository are used as a proxy for innovation (i.e., the components that solve a given function less frequently are considered as potentially innovative). A goal in this research is to have a repeatable and formalized means to archive the innovativeness of products as part of the Design Repository. This will aid in teaching engineers to factor in creativity early in the design process.

4.2.3.1 Design Repository-Based Concept Generation Tools

The design repository has the capability to create two important conceptual design relationships: the Function Component Matrix (FCM) and the Design Structure Matrix (DSM). The FCM is a mapping of the components in a product to their individual functions (Bohm, Stone et al. 2005). Using multiple product FCMs, a chi-matrix can be computed that shows the connection between the functions and components of multiple products. This matrix can be used in the DR to help create concepts by analyzing the number of connections between function and components (Strawbridge, McAdams et al. 2002). The DSM represents the interaction between components in a product (Shooter, Keirouz et al. 2000), and is key to concept generation. This matrix allows the analysis of which components work together, which is then used to output concepts with components of known compatibility (Bryant, McAdams et al. 2005).

An interactive morphological matrix called MEMIC (Morphological Evaluation Machine and Interactive Conceptualizer) was developed for concept generation with the DR to guide designers by returning feasible components for a given functional model (Bryant, Stone et al. 2008). This allows for automatic concept generation that includes information on components that frequently interfaced with each other through the implementation of the DSM. The user interface for MEMIC is a list of all the functions required in the design problem with a pull down menu of possible components for each function. Features of MEMIC include the designer asking the program to output random components for every function instead of selecting a component by hand for each function. MEMIC also has the ability to select components for each function based on the frequency of the components solving the function in question. For example, some components solve a particular function 75% of the time within the DR (i.e., more common component solution), while other components only solve that function 2% of the time in the DR (i.e., a less common component solution). MEMIC can output a "Most Common Configuration" and a "Least Common Configuration" based on these frequencies. This feature was used in Part II (Section 3.3) of the Research Method Section for the case study. In 2005, a study was done on the concepts produced by the repository using the Morphological Matrix technique versus hand-generated concepts. This study showed that 71.43% of the concepts that were hand-generated could have been produced using the Morphological Matrix method with the repository. It was concluded that a more mature repository could "conceivably generate 100% of the manually generated concepts" (Bohm, Vucovich et al. 2005).

The Design Repository concept generation tools have been used in the classroom at Oregon State University for the past several years in order to teach students how to design based on functional modeling. The methods within the DR teach how to break down a complex problem into its more easily manageable functions and allow students to find inspiration for design problems in existing product data. The importance of functional modeling in concept design is a highly researched topic (Pahl and Beitz 1988; Ulrich and Eppinger 2000; Otto and Wood 2001; Ullman 2010) and can be summed up as "the ability to decompose a design task is fundamental to arriving at creative solutions (Stone and Wood 2000)." We will investigate and compare our method of concept generation to those methods to determine usability and utility.

4.2.4 Evaluation of Automatically Generated Concepts

Computerized concept generation techniques promise engineers a faster realization of potential design solutions based upon previously known products and implementations. While the area of automated concept generation has made great advancements in recent years, most methods still require the user to indicate desired functionality. Two of the automated concept generation methods under development today rely solely on the users' abilities to develop functional descriptions of their desired product. Both of these methods make use of the repository of design information (described above), including component connection information (i.e., the DSM) and component functionality (i.e., the FCM) based on formal descriptions of function or purpose in engineering design (Stone and Wood 2000; Hirtz, McAdams et al. 2002).

The bank of empirical knowledge relating components to functions leads to the development of relational matrices (Bryant, McAdams et al. 2005; Bryant, Stone et al. 2005) and graph grammar rules (Kurtoglu, Campbell et al. 2005; Kurtoglu and Campbell 2009) that, when combined with a search mechanism, automatically creates conceptual designs. With the open-endedness or large degree of variability in conceptual design, numerous solutions, often on the order of thousands, are created through the search mechanisms. This is overwhelming to the user and it is impractical to expect that such a large number of alternatives can be useful for the designer. As a result, the proof of concept Designer Preference Modeler (Kurtoglu and Campbell 2007; Kurtoglu and Campbell 2009) was created to find, within the large set of results, which concepts were most meaningful to the designer. By ranking select concepts, the search mechanism learns what aspects of the concept the user prefers, and seeks solutions that maximize the predicted preference. Initial results for this method are promising, but the impact they have on the design process has yet to be determined.

What is missing in the above line of research is the incorporation of a method that indicates the innovation level of the automatically generated concepts. By calculating concept rank based on an objective measure of innovation, automated concept generators can predict the innovation in the concept independent of designer preference or bias—a central theme in this research.

4.2.5 Metrics to Assess Creativity of Concepts – the CCA Method

Once concepts have been generated, metrics developed specifically for creativity evaluation can be used. Metrics created by Shah et al. (Shah, Vargas-Hernandez et al. 2003) evaluate groups of ideas to determine which ideation methods were most effective based on four criteria: quality, quantity, novelty, and variety. These metrics were the starting point to the development of the Comparative Creativity Assessment (CCA) method, which evaluates sets of ideas to determine a creativity score for each individual concept (Oman and Tumer 2009; Oman and Tumer 2010). Each concept is broken down into its functions and components and compared to all other concepts to determine how novel the component solution to each function is within the set. The CCA method score is calculated by the following:

Novelty: $$M_N = \sum_{j=1}^{m} f_j S_{Nj} \quad (1)$$

$$S_{Nj} = \frac{T_j - R_j}{T_j} \times 10 \quad (2)$$

Quality: $$M_Q = \sum_{j=1}^{m} f_j S_{Qj} \quad (3)$$

$$S_{Qj} = 1 + (A_j - x_j) * (10 - 1) / (A_j - B_j) \quad (4)$$

CCA: $$C = W_N M_N + W_Q M_Q \quad (5)$$

where $$W_N + W_Q = 1 \quad (6)$$

and $$\sum_{j=1}^{m} f_j = 1 \quad (7)$$

where the design variables are:

T_j = number of total ideas produced for criteria *j* in Novelty
f_j = weight of importance of criteria *j* in all equations
m = total number of criteria in evaluation
R_j = number of similar solutions in T_j to criteria *j* being evaluated in Novelty
A_j = maximum value for criteria j in set of results
B_j = minimum value for criteria j in set of results
x_j = value for criteria j of design being evaluated
S_{Qj} = score of quality for criteria *j* in Quality
S_{Nj} = score of novelty for criteria *j* in Novelty
W_N = weight of importance for Novelty (W_N in real set [0,1])
W_Q = weight of importance for Quality (W_Q in real set [0,1])
M_N = creativity score for Novelty of the design
M_Q = creativity score for Quality of the design
C = Creativity score

The advantage of this method is its ability to evaluate large sets quickly without the need of judges. These metrics are used to evaluate the output in the case study and experiments presented in sections 4.3.3.2 and 4.4, respectively.

4.3 METHOD

The initial study presented in this paper aims to answer two key questions: (1) how to record innovation information from market-tested products in a repository, and (2) how to generate new concepts based on that information gathered. Figure 4.1 below depicts the overall procedure used in the development of the Repository of Innovative Products (RIP) and is explained in more detail throughout this section.

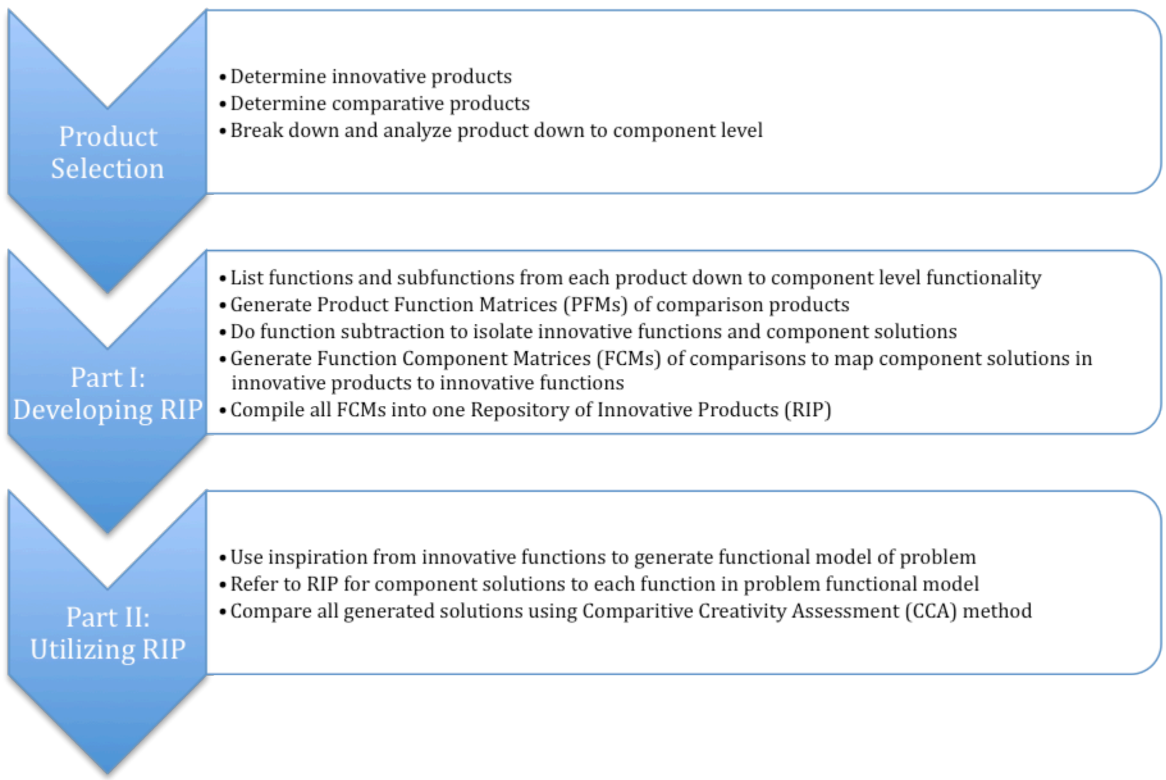

Figure 4.1: Procedure used in Generating and Testing the Repository of Innovative Products (RIP)

Section 4.3.2 presents Part I of the study, which aims to answer the first question and Section 4.3.3 presents Part II, a case study providing anecdotal evidence that the repository is a viable option for concept generation. This evidence provided the motivation behind the classroom experiments presented in Section 4.4.

4.3.1 The Products

The method begins with a study of products deemed innvoative in current and recent past market trends. Many of the products studied for this paper came from one or more of three published lists used in a previous study examining innovative characteristics of mechanical products done by Saunders, et al. (Saunders, Seepersad et al.). The lists included the 2006, 2007, and 2008 editions of Time Magazine's *Inventions of the Year*, Popular Science's *Best of What's New*, and Industrial Designers Society of America's *International Design Excellence Awards* (IDEA) (Saunders, Seepersad et al. 2009). Seven additional innovative products were added to this study from the 2009, 2010 and 2011 editions of TIME's *Best Inventions of the Year*, Popular Science's *Best of What's New*, and Good Housekeeping's *Very Innovative Products Awards*. Some products were mentioned in several sources, further confirming their innovativeness at that time.

The products included in this study are listed in Table 4.2, categorized by type of product. The product featured in the published innovative lists for each comparison is highlighted. The flying toys are products that are all considered innovative and were included in the analysis as a means to determine whether somewhat unrelated products could be compared using the proposed function subtraction methodology.

Once identified, the innovative products are compared to their common counterparts. The common products that were selected for comparison had similar functionality to the innovative products and had made no claims on their packaging or in the news of innovativeness. Several innovative products have multiple products to be compared against in the analysis that vary slightly in some way. For example, the innovative Ridgid Job Max was compared to two other multitools with slightly different power sources: the Craftsman NexTec is battery powered, whereas the Dremel MultiMax plugs into the wall.

Table 4.2: Common and Innovative Product Comparisons

Domain	Name
Palm Sander	Random Orbital Sander
	Black and Decker Palm Sander
	Versapak Sander
	Dewalt Sander
	Delta Sander
Fan	Dyson Air Multiplier
	Holmes Fan
Iron	Oliso Smart Iron
	Proctor Silex Iron
Flying Toy	E-Sky Honeybee Helicopter
	Airhawg Toy Plane
	Wowee Flytech Dragonfly
Nailgun	Bosch Brad Nailer
	Hitachi Brad Nailer
Palm Nailer	Milwaukee Palm Nailer
	Grip Rite Air Nailer
Floor Mop	Clorox Ready Mop
	Libman Wonder Mop
	Microfiber Floor Mop
Smoke Detector	KidSmart Vocal Smoke Detector
	First Alert Basic Smoke Alarm
Multi-Tool	Ridgid Jobmax
	Craftsman Nextec Multitool
	Dremel MultiMax
Tubing Cutter	Milwaukee Copper Tubing Cutter
	Ridgid Tube Cutter
Robotic Vacuum	Neato Robotix Vacuum Cleaner
	iRobot Roomba
Charging Station	Power Mat
	Dual Powered Charging Station

4.3.2 Part I: Identifying Innovation for Archival

The first step of the methodology identifies and isolates innovation information from the products listed in Table 4.2 through a proposed function subtraction method and records this information in a Repository of Innovative Products (RIP) for use in Part II of the study.

4.3.2.1 Part I Approach

Innovative function clusters and components are identified through a functional subtraction, where the functions from the ordinary products are subtracted from the functions of the innovative products. Product function matrices (PFM) are generated to compare the innovative and ordinary products side by side. The information for both types of products is drawn from the current Design Repository. If a positive value results from the subtraction, that function is then mapped back to the Function Component Matrix (FCM) of the innovative product to determine the component associated with that function. Table 4.3 is the PFM for the electronics charging station comparison and Table 4.4 is the FCM resulting from the PFM. The two products analyzed for electronic charging stations are the Powermat and the Journey's Edge Charging Station.

Table 4.3: Product Function Matrix for the Electronics Charging Station Comparison where Positive Values Indicate Innovative Functions of the Powermat.

	Power Mat	Journey's Edge Charging Station	Difference Values between Products
change electrical	0	10	-10
change solid	1	0	1
convert electrical to magnetic	2	0	2
convert human energy to mechanical	1	0	1
convert magnetic to electrical	1	0	1
export electrical	1	10	-9
export human material	2	0	2
export magnetic	1	0	1
export mechanical	1	0	1
export solid	1	1	0
export status	3	0	3
guide human energy	1	0	1
guide human material	2	0	2
import electrical	1	2	-1
import human energy	1	0	1
import human material	2	0	2
import solid	1	1	0
position solid	1	0	1
transfer electrical	4	25	-21

The PFM is generated from the design repository, which calculates the number of times each function is present in the product. For example, in Table 4.3, the *Export Solid* function is addressed by one component in both the *Power Mat* and the *Dual Powered Charging Station*. In contrast, a function like *Convert Electrical Energy to Magnetic Energy* (the third function in Table 4.3) only occurs in the *Power Mat* and is solved by two independent components.

In the rightmost column of the PFM, the value of the function for the ordinary product is subtracted from the value of the function for the innovative product. If the resulting subtraction has a value greater than 0 (those cells highlighted in Table 4.3), that function is identified as having innovative solutions to it. Future work will rework the methodology to determine the significance of the magnitude of the difference found in the subtraction method and how to apply this information into the output of RIP.

Table 4.4: Sample of the Function-Component Matrix (FCM) for Electronics Charging Station Comparison Wherein the Innovative Functions of the Powermat are Featured in Column Headers.

	magnetic field generator in Powermat	magnetic field receiver in Powermat	main circuit in Powermat	receiver case in Powermat	top cover in Powermat
change solid	0	0	0	0	0
convert electrical to magnetic	2	0	0	0	0
convert human energy to mechanical	0	0	0	1	0
convert magnetic to electrical	0	1	0	0	0
export status	0	0	2	0	0
export human material	0	0	0	1	1
export magnetic	0	1	0	0	0
export mechanical	0	0	0	1	0
guide human energy	0	0	0	1	0
guide human material	0	0	0	1	1
import human energy	0	0	0	1	0
import human material	0	0	0	1	1
position solid	1	0	0	0	0
Totals	3	2	2	7	3

From the PFM results, the functions are then mapped back to the FCM (a sample of which is presented in Table 4.4) produced for the innovative product and linked back to the components that solved the functions that were found to have innovative solutions. An example would be the function of *Export Magnetic Energy,* which is associated with the

Magnetic Field Generator in the *Power Mat*. When a comparison includes multiple products, the functional subtraction is performed on all common products independently, and then the functions that are common to the multiple subtractions are identified as innovative.

Supporting functions are left out of the FCMs of each product because they contribute little to the innovation of a product. Supporting functions essentially refer to the connecting structure of a product rather than the conceptual functionality, which typically include functions such as *Couple*, *Support*, or *Secure*.

4.3.2.2 Part I Results

All of the innovative components identified in the individual FCMs were compiled together into a Repository of Innovative Products (RIP), which includes 95 functions. Each function is paired with 1 to 35 components from the 14 innovative products analyzed. Each component in the RIP also contains information regarding the product it came from for organizational and explanatory purposes. For example, the function *Convert Electrical Energy to Mechanical Energy* can be solved using the motor from the Dyson Air Multiplier, Oliso Smart Iron, or the Milwaukee Copper Tubing Cutter; each of which may perform the function differently. Table 4.5 provides a small sample of the information contained within the RIP.

Table 4.5: Sample of Function and Component Solutions Contained within the Repository of Innovative Products (RIP), Showing the Component and Product that Solves the Function Innovatively.

Function	Component	Innovative Product
Actuate Mechanical Energy	trigger lock	Rigid job max
Change Mechanical Energy	main gear	E-Sky Honeybee Helicopter
	tail gear	E-Sky Honeybee Helicopter
	idler	Milwaukee copper tubing cutter
	ring gear	Milwaukee copper tubing cutter
	three gear carousel	Milwaukee copper tubing cutter
Regulate Electrical Energy	potentiometer	Rigid job max
Export Gas	steam chamber and hot plate	Oliso Smart Iron
	Nozzle	Air Hawg
	smoke collector	KidSmart smoke detector

Examining the functions associated with the documented innovation information, it was found that the elements that were deemed innovative in the products were not individual functions, but a collection of functions. Innovation was due to the combination of an entire set of functions rather than the individual function that mapped to product innovation. An example is the Oliso Smart Iron as seen in Figure 4.2, which contains an assembly in the base with feet that extend when the iron is in danger of burning a garment. The assembly consists of a drive shaft, lifting rods, feet, motor, gear and gearbox, case harness, sensors, and screws. Any of these components on their own would not be considered innovative, but the way that they interact in the Smart Iron produces functionality that no other iron exhibits.

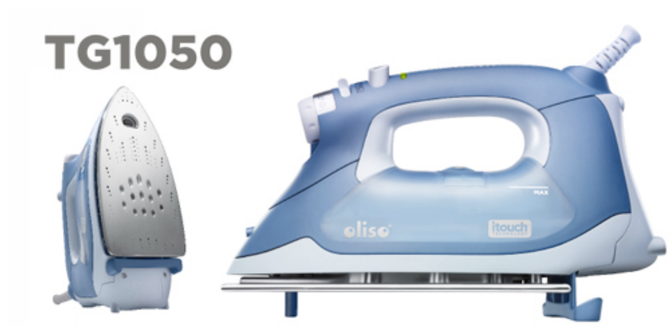

Figure 4.2: Oliso Smart Iron with "Digitally Activated Scorchguards" (2010).

For each innovative product FCM, the functions are grouped together into innovative function clusters and stored for use by the designer in the development of a functional model for an innovative toy product design used for Part II, discussed further in the next section.

4.3.3 Part II: Generating Computer-Directed Innovation

Once the innovation of market-tested products has been isolated into the RIP, the next step is to formulate a method for concept generation that uses the archived innovation information as inspiration for the designers.

4.3.3.1 Part II Approach

The overall procedure for the methodology begins by generating a functional model for the proposed problem then using inspirational output from RIP to choose component solutions to each function in the functional model. This procedure is described using an example problem in the following section.

The proposed concept generation process begins with a functional model that identifies potential function clusters that are most closely matched to innovative solutions. The innovative function clusters may also spur designers to use missing or different functions for their design problem that they would not originally have used.

A test case is formulated to test the functionality contained in RIP. In this case, an innovative toy product with hovering capability is posed: consider the development of a toy hovercraft that could be adapted on a larger scale if desired. Using the functional model, components for each function are randomly chosen from the RIP and MEMIC (see section 4.2.4) in order to develop a set of complete concepts for the hovercraft design problem that can be evaluated using the CCA method. Component solutions are randomly selected from RIP for the hovercraft case study as it is not fully integrated into the DR like MEMIC has been. The first 23 concepts developed from MEMIC used the random selection option, plus one concept used the "Most Common Solutions" option and one concept used the "Least Common Solutions" option. This provides comparison of the RIP concept to a concept developed with the most common component solutions for each function and a concept developed with the least common component solutions contained within the Design Repository.

The resulting RIP generated hovercraft product is described as follows: the concentrically rotating base plate of the Random Orbital Sander is combined with the fan of the Dyson Air Multiplier to form the propulsion of the hovercraft. The fan gives the hovercraft its lift and concentrically rotating application of the outer base plate to the fans gives the hovercraft stability. The nose of the Airhawg is used as the power supply using a pneumatic piston for power and shafts transfer that power to the fan assembly for lift. The base and foot of the Oliso Smart Iron are incorporated into a landing mechanism for the hovercraft. If the operator gets distracted or leaves the controls, the hovercraft uses the concept from the foot and base to recognize that the user is not paying attention and extends the landing gear. The entire hovercraft lands safely until the user regains control. Figure 4.3 is a rough model of the proposed product.

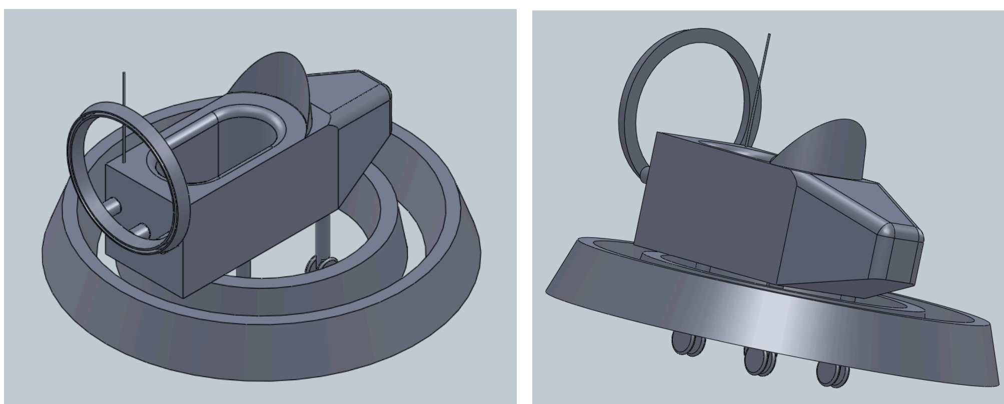

Figure 4.3: Iso Views of Rough Solid Model for Proposed Hovercraft Using Innovative Components such as the concentric fan at the base, the Airhawg Nose, and the Oliso Smart Iron Base and Foot Assembly for Automatic Deployment.

The next step for this case study is to determine whether the above proposed concept is innovative, and furthermore, more or less innovative than the current concept generation method used by the Design Repository: MEMIC.

4.3.3.2 Part II Results

In order to determine whether the proposed RIP hovercraft design is more innovative than the current method of concept generation for the DR, the RIP concept and 25 MEMIC concepts were comparatively analyzed based on the metrics presented in Section 4.2.5. The resultant scores for each of the concepts are presented in Table 4.6. The third column displays the difference between the highest scoring concept and the concept in question for comparison purposes.

Table 4.6: Toy Hovercraft Creativity Scores for Concepts Generated by RIP and MEMIC

Concept	Creativity Score	Difference from High Score
Concept 1	7.69	1.18
Concept 2	8.26	0.61
Concept 3	8.37	0.50
Concept 4	8.08	0.79
Concept 5	8.33	0.54
Concept 6	7.78	1.09
Concept 7	7.65	1.22
Concept 8	7.90	0.97
Concept 9	8.26	0.61
Concept 10	8.05	0.81
Concept 11	8.03	0.84
Concept 12	8.17	0.70
Concept 13	7.81	1.06
Concept 14	8.42	0.45
Concept 15	8.69	0.18
Concept 16	8.60	0.27
Concept 17	8.51	0.36
Concept 18	8.53	0.34
Concept 19	8.39	0.48
Concept 20	8.60	0.27
Concept 21	8.69	0.18
Concept 22	8.60	0.27
Concept 23	8.80	0.07
RIP Generated	8.87	0.00
Most Common	8.05	0.81
Least Common	8.87	0.00

The results of the analysis show that the RIP generated concept and the concept generated by MEMIC using Least Common component solutions are the highest scoring creative concepts of the set. This can be attributed to the fact that the RIP concept had nine components that were unique to the functions they solved (i.e., function-component pairs) and the Least Common configuration had seven unique function-component pairs. Figure 4.4

depicts the spread of differences between the two highest scoring concepts and all the other MEMIC concepts created.

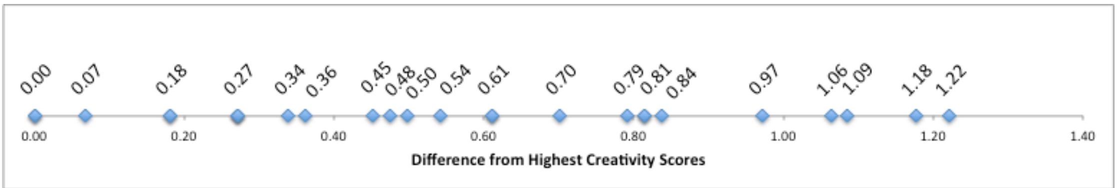

Figure 4.4: Plot of differences between Highest Scoring Concepts and All Other Concepts Generated for Toy Hovercraft Example

Table 4.7 shows the configurations for these two concepts with the scores attributed to the individual components, thus showing how both concepts received the same score. In the calculation for creativity, all functions are considered equally important (f_j are all equal), thus the total creativity score becomes an average of the individual component creativity scores (S_{Nj}).

Table 4.7: Configurations for the Two Most Creative Concepts with Individual Component Creativity Scores for the Hovercraft Case Study.

Function	RIP Components		Least Common MEMIC Components	
Import Control signal	electric wire	8.85	handle	8.85
Transfer control signal	circuit board	9.62	screw	8.85
Regulate EE	potentiometer	9.62	cover	9.23
Convert EE to ME	electric motor	5.00	electric wire	7.31
Transfer ME	Shaft	9.23	sensor	9.62
Convert ME to PE	Fan	7.69	wheel	8.46
Guide PE	valve	9.62	guiders	8.08
Export PE	Fan	8.85	guiders	7.69
Import human energy	guiders	9.62	blade	9.62
Guide human energy	case	9.62	reservoir	9.62
Import human material	housing	8.46	cap	9.62
Position human material	trigger	9.62	cover	9.62
Import EE	battery	9.62	connector	9.62
Transfer EE	electric wire	7.69	cover	9.23
export control signal	antenna	9.62	electric wire	6.92
export human energy	guiders	9.62	gear	8.85
Export human material	housing	8.46	electric wire	9.62
CREATIVITY SCORE:		8.87		8.87

If a component score is 9.62, then that concept is the only one to use that component solution for that particular function. Component scores of 9.23 indicate that there is one other concept that uses that component solution for the function in question. Thus, two other concepts that share a component solution have scores of 8.85, three other concepts have scores of 8.46, four other concepts have scores of 8.08, etc.

For example, the RIP component solution for *Import Control Signal* of an electric wire has a score of 8.85, meaning that, within the dataset, this concept and two others use an electric wire to solve that function.

The comparison of the top two scoring concepts in Table 4.7 shows that, although a concept may have the most unique component solutions (RIP concept has nine unique components), it can still score the same as another concept with fewer unique component solutions (Least Common configuration has only seven unique solutions). This can be attributed to the fact that the RIP concept has a very commonplace solution for *Convert Electrical Energy to Mechanical Energy* by using an *electric motor*.

4.4 VALIDATION: RIP VERSUS MEMIC CLASSROOM EXPERIMENTS

Next, a large-scale classroom experiment was carried out to determine the utility of RIP compared to the previously established MEMIC method in the Design Repository.

4.4.1 Experimental Setup

Two experiment runs were conducted over two different terms in a junior-level mechanical engineering design course. The experiments were run during the lab portion of the course, which splits the class into labs of approximately 20 students, with a total of 180 student participants. A script was used to ensure all labs received the same instructions throughout the experiment. In addition, to ensure consistency, only the principal investigator answered any questions asked by the students.

The classroom instruction prior to the experiment differed between the two experiment runs to determine if there would be statistically significant differences between the creativity of the output. The main difference in the instruction was the emphasis of functional modeling understanding. The classroom instruction for the Experiment Run #1 was limited to one 50-minute lecture, while Experiment Run #2 had two 50-minute lectures as well as a homework assignment to generate their own functional model. The difference in educational instruction created a two-factor experimental problem that was analyzed based on RIP versus MEMIC concepts as well as class and lab sections.

Prior to the beginning of the experiment, the students were shown an example design problem that utilized the basis of the RIP and MEMIC data given to the students. The example problem was how to generate power from rainwater collection. The example problem had the students step through the problem statement and functional model as a class before explaining the pages of example output from either RIP or MEMIC. The output was taken directly from the online repository and organized by function. For each function, between five and ten possible component solutions are presented by name and picture. This was done to reduce bias towards the operating platform of MEMIC and combat the issue that RIP has yet to be installed into the DR. The students were told multiple times that the possible component solutions given to them were meant only as inspiration and were not restricted to use only those solutions.

For the experiment, students were randomly given one of two types of concept generation packets that presented the design problem and functional model plus inspirational output: one contained possible component solutions from RIP and one contained solutions from MEMIC. The design problem asked them to develop ideas for an automated tennis ball collector. The participants were given 25 minutes to generate as many complete designs as possible that satisfied every function in the functional model. Any designs that were incomplete were discarded from the resulting data analysis.

At the end of the experiment, all concepts were collected from the students and analyzed by the principal investigator using the metrics discussed in Section 4.2.5. The results of the analysis are discussed in the next section.

4.4.2 Statistical Results

The CCA method presented in Section 2.5 is used to evaluate all the concepts generated in the two experiment runs. The advantage to the CCA method here is the dataset is too large to use any methods that require judges or evaluate concepts individually by hand. SPSS Version 19 was used to analyze the data generated in the experiments. Table 4.8 presents descriptive statistics on the Experiment Run #1 data sets along with the Kolmogorov-Smirnov p-value to determine normality (p-values below 0.05 prove the normality assumption is violated for that dataset). Table 4.9 presents similar information for Experiment Run #2.

Table 4.8: Descriptive Statistics for Experiment Run #1 Creativity Scores

	N	Minimum	Maximum	Mean	Std. Deviation	K-S Normality
RIPlab1	10	5.82	8.33	7.066	.75221	.192
RIPlab2	17	5.65	8.75	7.408	.83878	.182
RIPlab3	16	5.45	8.80	7.165	.90078	.010
RIPlab4	24	5.84	9.53	7.555	.96162	.200*
RIPlab5	13	5.97	8.93	7.451	.91997	.200*
MEMIClab1	21	6.16	8.99	7.731	.86249	.200*
MEMIClab2	24	5.75	9.66	7.329	.93719	.200*
MEMIClab3	22	5.77	9.03	6.968	1.08469	.200*
MEMIClab4	19	5.77	9.74	7.513	1.22650	.200*
MEMIClab5	12	5.95	9.67	7.468	1.12451	.200*

*. This is a lower bound of the true significance.

Table 4.9: Descriptive Statistics for Experiment Run #2 Creativity Scores

	N	Minimum	Maximum	Mean	Std. Deviation	K-S Normality
RIPlab1	16	6.67	8.30	7.513	.55138	.200*
RIPlab2	14	6.73	8.61	7.731	.60698	.200*
RIPlab3	21	6.83	9.28	7.770	.73695	.200*
RIPlab4	13	6.89	9.18	8.172	.60247	.200*
MEMIClab1	9	6.89	8.98	8.025	.75901	.200*
MEMIClab2	14	6.62	8.75	7.861	.61706	.200*
MEMIClab3	17	6.65	8.99	7.764	.63062	.125
MEMIClab4	10	6.87	9.22	7.915	.72201	.200*

*. This is a lower bound of the true significance.

Although only one data set has a non-normal distribution, some data sets proved to have unequal variance (Tests 1, 2, and 5 in Table 4.10 have Levene's p-values below 0.05), which violate the assumptions of parametric tests. It was determined that a nonparametric test was the most appropriate statistical analysis for the data, thus the Mann-Whitney test was used, summarized in Table 4.10, and discussed further in this section.

The analyses for this research require the datasets to be considered as larger, combined sets of concepts. In order to combine all the lab datasets together for the analyses presented in Table 4.10, statistical analysis of the individual labs was necessary using Kruskal-Wallis tests. Comparison of each lab dataset showed that only Experiment Run #2 RIPlab4 had a mean that was statistically different from the others in Experiment Run #2 RIP labs. As this was the only statistically different dataset, there was no strong evidence of differences in the labs, so the data could be pooled together to determine if certain larger sets of data are statistically different.

Table 4.10: Statistical Analysis of Two Engineering Education Creativity Experiments using Mann-Whitney Nonparametric Test

Test #	Comparison	p-value	Result
1	Experiment 1 vs Experiment 2	**0.000**	**Statistically Different**
2	Experiment 1 RIP vs MEMIC	0.884	No statistical difference
3	Experiment 2 RIP vs MEMIC	0.432	No statistical difference
4	RIP Experiment 1 vs 2	**0.003**	**Statistically Different**
5	MEMIC Experiment 1 vs 2	**0.002**	**Statistically Different**

Tests 1, 4, and 5 proved that the two runs of the experiment provided statistically different creativity scores when the data is grouped by RIP, MEMIC, and all the labs combined. Experiment Run #2 had higher creativity scores with less variability than Experiment Run #1 for both RIP and MEMIC and combining the two datasets to examine Experiment Run #1 versus Experiment Run #2. Tests 2 and 3 show that there is no statistical difference in the levels of creativity between RIP and MEMIC for either Experiment Run #1 or #2.

The overall results of the statistical analyses are positive regarding the utility of RIP. The experiment proved that RIP, in its early stages of development provides students with creative inspiration on par with that of a methodology that has been developed and perfected over the past several years. This is an encouraging result since MEMIC draws inspiration from thousands of components in the Design Repository and the RIP inspiration is still limited to only components from 14 innovative products. Further population of RIP will determine if more innovative inspiration will help increase the creativity of the output to a level greater than MEMIC. The results also provide positive reinforcement to emphasizing effective teaching in regards to functional modeling learning. Those students who received more comprehensive education on the usefulness of functional modeling in concept design generated ideas with greater creativity.

4.5 CONCLUSIONS

This study was conducted in two parts: first, innovative products were compared to ordinary products in order to isolate innovative functions and components through a function subtraction methodology and populate a innovative repository, and, second, the repository information was used to determine the utility of implementing the Repository of Innovative Products (RIP) into the Design Repository (DR). Once the utility of the RIP was determined, two classroom experiments were implemented to further validate the research into automated concept generation.

Initial results provide support that computer-directed innovation is possible using the data collection method proposed for the entire Design Repository. In Part II of the Method Development, analysis of the 25 MEMIC generated concepts against the proposed RIP hand-generated concepts shows that the RIP concept and the “Least Common Configuration” of MEMIC proved to be the most innovative solutions to the design problem.

The results of the experiment presented in Section 4.4 prove that the proposed RIP method of concept generation is as effective as the previously established and tested MEMIC method currently employed by the Design Repository. This provides the motivation to continue working on and populating RIP in order to provide a more robust inspirational output for engineering students learning concept generation and evaluation.

The desired end goal is an innovative concept design methodology using the Design Repository to aid in the creativity and innovation in engineering at the early stages of design. This research fills intriguing gaps in current methodologies to increase and evaluate creativity in concept design and how to draw analogies from previously successful innovative products. The methodology proposed through the Repository of Innovative Products provides a tool that incorporates innovation into all aspects of concept design in engineering.

4.6 FUTURE WORK

The Repository of Innovative Products (RIP) that was generated in this study is currently a separate entity from the Design Repository (DR). Efforts are currently focusing on implementing a more comprehensive analysis of all the products within the DR, with the end goal of having the entire repository analyzed for innovative component and function comparisons. This information will then work to the engineers' favor when using the automated concept generation tools. This will allow students to focus on ideas generated with more innovative components or to begin their concept generation process using functions that have been found to aid in innovative solutions. A goal of this research is to implement RIP into the Design Repository in such a way that MEMIC can output component solutions only from the RIP in the same manner it currently does in the DR.

Incorporated into an automatic concept generator such as MEMIC, the RIP could be a powerful tool for generating novel, creative concepts. The RIP could be used to generate a large number of compatible concepts then, using the CCA method, the concepts could be rank ordered with the highest scoring creative concept presented first.

Further future work entails a method to apply a similar theory of innovation scoring to the analysis and concept generation of complex systems. This work takes us a step closer to implementing consensus clustering in the design repository. The creative impact of an individual component on a design is important for making design decisions, but may not be easily calculated, especially at a complex system level. Interactions between components may complicate direct analysis of the creative value of a single component. Multiagent coordination problems face the same issue of credit assignment, as complex exchanges between agents may complicate accurate evaluation of an individual agent's performance (Tumer and Wolpert 2004).

Specifically, this work will make use of the "difference" reward, which has been shown in multiagent coordination problems to successfully capture the impact of an agent in the system (Agogino and Tumer 2008; Agogino and Tumer 2008). The difference reward looks at the entire system and compares the system to one in which an agent is removed. Viewing a design as a multiagent system, the same techniques may be applied in this research and is further discussed in another paper by Oregon State University researchers (Rebhuhn, Gilchrist et al. 2012).

Future work will compare a design's creativity metric with that of a design, which hypothetically lacks a particular component, or a "difference creativity" metric. The design repository provides a rich area of study for this "difference creativity" concept. Individual components may be found in a large number of products, and if their creative impact can be accurately assessed then a design-independent creativity of a component may be examined. Rather, this would focus on a component's potential for influencing the creativity in any design. For example, a component may have consistently high or low creative impact across different designs. This is a rich area of future study, and has potential to be a powerful tool to weight design repository suggestions toward more creative designs.

The result of this research could be strengthened if there were a more objective way of measuring the innovative products "innovativeness". A latent variable model can take care of the problem that innovativeness is inherently something unquantifiable (Hagenaars and McCutcheon 2002). There are attributes of products that lead to innovativeness. The latent variable model is capable of quantifying innovativeness of products based on product attributes and indicator scores. Using this metric for innovation, we can further delineate component's "Innovativeness" based on the innovativeness score that the product they came from has. This metric will be based the products' score on a scale of one to ten. This way of measuring innovativeness can be used on all products in the Design Repository to give higher resolution of the score of innovation for the components.

Depending on the target market for the product being developed, the designer could want to choose a target level of innovation to apply to the product. This could be done with the output of the design repository with the innovative function clusters and components appearing at the beginning of the list of solutions to functions. The component solutions could then be ordered by an innovation score based on the novelty of the component for the function in question. The user can then select the number of innovative components that would satisfy a target level of innovation. The expectation is that these innovative function clusters can be combined together to solve all of the functions necessary to form a useful product.

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Chapter 5: Revising the Comparative Creativity Assessment Method to Reduce Subjectivity by Including Function Combinations

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Previous research done by the authors presented a method to calculate the creativity of individual concepts in a set of designs (Oman and Tumer 2009; Oman and Tumer 2010; Oman, Tumer et al. 2012). Several limitations regarding this metrics are addressed and mitigated within this chapter, namely how to reduce the subjectivity of the function weights and factor in combination effects between two or more functions. Both these limitations are addressed by a major addition to the original metrics with data validation based on analyses of the original concept data (using the former method of setting the function weights) versus using the revised method. Statistical Analysis of the different methods to calculate creativity are discussed. The concents of this chapter will be submitted to the Journal of Mechanical Design and co-authored by Sarah Kay Oman, Irem Y. Tumer, and Robert Stone (Oman, Tumer et al. 2012).

5.1 INTRODUCTION

The terms *creativity* and *innovation* have different meanings or definitions dependent on the context or domain in question. For this research, *creativity* (noun) is what is considered novel and original. The verb form of *creativity* can be described as a process to evaluate a problem in an unexpected or unusual fashion in order to generate ideas that are novel. *Innovation* is creativity that embodies usefulness in order to realize an impact on society (i.e. the application of creativity) through a new method, idea, or product.

The Comparative Creativity Assessment (CCA) was developed in order to satisfy a gap in current research; there was no specific method to evaluate the creativity of concepts to determine, out of a group of ideas that satisfy the same design problem, which concept can be deemed the most creative in the set (Oman and Tumer 2009; Oman and Tumer 2010; Oman, Tumer et al. 2012). Several classroom studies were conducted using the CCA method to determine the validity and utility of such a method in evaluating concepts for creativity. It was determined that the weak point of the method was the subjectivity of the function weights in the analysis. Each function involved in the design problem was originally given a weight so that functions considered more important to creativity or the design problem are given greater weighting in the analysis. These weights were set by the evaluator or designer, i.e. the main source of subjectivity in the CCA method. The revisions presented herein eliminate this subjectivity by setting the weights based on the level of creative solutions in the set of concept component solutions for each function, i.e. those functions with fewer creative solutions are given greater weight in the analysis in order to reward less common creative solutions.

In the following chapter, the Background section briefly introduces concept design, discusses the Comparative Creativity Assessment (CCA) method developed in previous research, and introduces a calculation method that will be adapted to suit the revisions of the CCA method. Section 5.3 discusses how to revise the CCA method by adding a set of new metrics that reduce the subjectivity of the function weights by analyzing how much creativity is present within each function. This is done by taking into consideration that innovation of ideas can sometimes be attributed by the synergistic effect of two or more functions in the problem statement. Section 5.4 discusses the results of using the revised metrics on the data sets for two previous studies done that evaluated undergraduate design projects. The final section of this chapter summarizes the results and presents the complete, revised methodology of the CCA. Future work outlines further revision that rewards those concepts that exhibit creativity in the component solutions to the functions.

5.2 BACKGROUND

This section is broken into three parts: the first subsection introduces concept design and the motivation behind the development of the CCA method, Section 5.2.2 discusses the metrics for the CCA method (Oman, Tumer et al. 2012), and Section 5.2.3 outlines metrics used by Stone, et al (Stone, Wood et al. 2000) to calculate aggregate customer needs ratings that will later be adapted to calculate the combination effects of two or more functions in a problem.

5.2.1 Concept Design in Engineering

At the most basic level, conceptual design is a process that designers go through in order to develop new solutions to problems. It is an iterative process that takes designers from concept generation to concept evaluation to concept approval or back to generation. Most literature on concept design outlines the stages of concept design to better guide designers. Although the stages differ slightly by source, they describe the same basic premise (Pahl and Beitz 1988; Roozenburg and Eekels 1995; Ulrich and Eppinger 2000; Cooke 2006; Ullman 2010):

1. Define the problem and customer needs
2. Research previous solutions and expert opinions
3. Perform divergent thinking (generate many ideas)
4. Converge on the best solutions
5. Approve final concept or refine concept through iteration of previous steps

Conceptual design in the engineering domain is one of the most important parts of the design process (Ullman 2010). Once a concept is chosen for testing and production, engineers risk time and money on a product that could potentially fail. With that in mind, engineers look for ways to aid the concept generation and evaluation phases, such as methodologies to guide them.

5.2.1.1 Concept Generation Methods

The majority of ideation methods contain commonalities that are key to effective concept generation. In order to generate effective ideas, ideation methods employ divergent thinking. Divergent thinking fosters a more creative environment where the number of ideas generated is not hampered by early judgment. This brings to point the idea that the higher quantity of ideas produced will increase the number of quality ideas (Shah, Vargas-Hernandez et al. 2003). Divergent thinking also encourages designers to think outside the box, suspending judgment based on reality and plausibility (Pierce and Pausch 2007). The idea here is that the implausible ideas can spark creative, plausible ideas. In contrast, convergent thinking immediately narrows the solution space, which is unwanted at the concept generation stage, but welcome at the concept evaluation stage (VanGundy 1988).

Common concept generation methods include Method 6-3-5 (Pahl and Beitz 1988; VanGundy 1988; Shah 2007), Design-by-Analogy (Linsey 2007; Linsey, Wood et al. 2008; Ullman 2010), Morphological Analysis (Cross 2000; Ullman 2010), and the Theory of Inventive Problem Solving (TRIZ/TIPS) (Savransky 2000; Clausing and Fey 2004; Shulyak 2008; Ullman 2010). A number of commonly used engineering texts further discuss the importance of concept generation and include example methods (Buhl 1960; Pahl and Beitz 1988; VanGundy 1988; Pugh 1996; Cross 2000; Ulrich and Eppinger 2000; Otto and Wood 2001; Ullman 2010).

The vast majority of concept generation methods focus on developing one thing above all others: creativity (VanGundy 1988; Cross 2000; Cooke 2006). However, answering questions such as why we need creativity and what is creativity are not nearly as clear-cut. For the most part, sources justify the need for creativity as simply stating that the products that succeed best in the competitive market are the most creative out of similar consumer options (Mumford and Hunter 2005; O'Quin and Besemer 2006). Each source and domain defines creativity uniquely, putting different emphasis on certain attributes of creativity (Plucker and Runco 1998; Mumford and Hunter 2005), thus increasing the difficulty of setting metrics or assessment methods to evaluate creativity in more than one specific domain (Amabile 1982).

The concept of creativity is malleable enough that it can be adapted specifically for the purposes of evaluating concepts in the engineering domain.

5.2.1.2 Concept Evaluation Methods

To aid in the decision-making process once multiple concepts have been generated, numerous evaluation processes and methods have been developed. Commonly used processes include the *Weighted Objectives Method* (Pahl and Beitz 1988; VanGundy 1988; Jones 1992; Fogler and LeBlanc 1995; Roozenburg and Eekels 1995; Cross 2000), *Pugh's Method* (Pugh 1996) or the *Datum Method* (Roozenburg and Eekels 1995; Pugh 1996; Ulrich and Eppinger 2000; Ullman 2010). Many common engineering texts discuss how to make informed decisions (Pahl and Beitz 1988; Ulrich and Eppinger 2000; Otto and Wood 2001; Ullman 2010), but do not focus on concept evaluation methods specifically tailored for creativity.

Established methods of creativity concept evaluation methods include the Creative Product Semantic Scale (Besemer 1998; O'Quin and Besemer 2006), the Consensual Assessment Technique (Amabile 1982; Amabile, Conti et al. 1996), the Student Product Assessment Form (Horn and Salvendy 2006), Evaluation of Innovative Potential (Chulvi, Mulet et al. 2011), Resource-Effort-Value (Redelinghuys 1997; Redelinghuys 1997; Redelinghuys and Bahill 2006), and several unnamed methods developed to specifically suit the researchers' needs (Linsey, Laux et al. 2007; Saunders, Seepersad et al. 2009; Elizondo, Yang et al. 2010; Chulvi, Mulet et al. 2011). The current gap in concept evaluation methods is that there is no method that analyzes a set of concepts to determine the most creative without the use of judges. This was the motivation behind creating the Comparative Creativity Assessment (CCA) method.

5.2.2 The Comparative Creativity Assessment (CCA) method

This subsection is divided into the metrics for the CCA method and an outline of two studies done for the initial validation of the method. Studies One and Two provide the data used for comparison purposes with the revised metrics proposed in Section 5.3 later.

5.2.2.1 The CCA Metrics

The following information is detailed in a previous publication on the Comparative Creativity Assessment (CCA) method (Oman, Tumer et al. 2012). This method was originally adapted from metrics presented by Shah et al. that examined how to evaluated sets of ideas to determine which ideation methods were more effective in four categories: Quality, Quantity, Novelty, and Variety (Shah, Kulkarni et al. 2000; Shah, Vargas-Hernandez et al. 2003). Quality and Novelty were isolated and revised to suit the need of the researchers in developing a way to evaluate individual concepts in a set of designs to determine the creativity of each concept.

The CCA is calculated by:

Novelty:
$$M_N = \sum_{j=1}^{m} f_j S_{Nj} \tag{1}$$

$$S_{Nj} = \frac{T_j - R_j}{T_j} \times 10 \tag{2}$$

Quality:
$$M_Q = \sum_{j=1}^{m} f_j S_{Qj} \tag{3}$$

$$S_{Qj} = 1 + (A_j - x_j) * (10 - 1) / (A_j - B_j) \tag{4}$$

CCA:
$$C = W_N M_N + W_Q M_Q \tag{5}$$

where
$$W_N + W_Q = 1 \tag{6}$$

and $$\sum_{j=1}^{m} f_j = 1 \tag{7}$$

where the design variables are:

T_j = number of total ideas produced for criteria j in Novelty
f_j = weight of importance of criteria j in all equations
m = total number of criteria in evaluation
R_j = number of similar solutions in T_j to criteria j being evaluated in Novelty
A_j = maximum value for criteria j in set of results
B_j = minimum value for criteria j in set of results
x_j = value for criteria j of design being evaluated
S_{Qj} = score of quality for criteria j in Quality
S_{Nj} = score of novelty for criteria j in Novelty
W_N = weight of importance for Novelty (W_N in real set [0,1])
W_Q = weight of importance for Quality (W_Q in real set [0,1])
M_N = creativity score for Novelty of the design
M_Q = creativity score for Quality of the design
C = Creativity score

The end result of the analysis is a score out of ten for each concept based on its component solutions for each function or criteria. The important thing to note about the metrics is that the f_j values (weights of the functions) are all set by the designer or user and are thus subjective to their personal preference or opinion. Section 5.3 works to mitigate this subjectivity by using initial novelty and quality calculations to determine the levels of creativity present in each function. This information will then be used in the calculation of the function weights. Note that the previous research and the evaluation presented herein use the terms *criteria* and *function* interchangeably for the metrics. This is because the calculations can be done for design problems that have certain functions as well as criteria; i.e., some design problems may involve functional models in order to generate concept solutions and some problems may only ask for or evaluate certain criteria. Generally, the term *function* is used in this chapter for consistency.

Initial validation of the CCA method was conducted in two classroom studies at Oregon State University in junior-level mechanical engineering design courses. The following subsections briefly describe the two studies' design problems.

5.2.2.2 Study One: Mars Rover Design Problem

The design problem for Study One involved student design teams at Oregon State University developing a remote-controlled Mars Rover whose task was to drive over barriers, collect various rocks, and bring them back to a designated drop area in the shortest amount of time.

The Novelty criteria for Study One were: mobility, traversing the barriers, picking up the rocks, storing the rocks, dropping the rocks in the designated drop area, and how the energy was controlled. The Quality criteria were: weight, milliamp hours from the batteries, number of controller switches, number of parts, and number of manufactured parts. These criteria were used to represent how complex the system was to operate and manufacture. Further detail can be found in previous CCA methodology publications (Oman and Tumer 2009; Oman and Tumer 2010; Oman, Tumer et al. 2012).

5.2.2.3 Study Two: Automated Waste Sorter Design Problem

Study Two was a student design challenge to develop an automatic recycler that could autonomously sort aluminum (abbreviated AL in this chapter), tin, plastic, and glass. Each of these material sorts were used as criteria in the Novelty analysis of the CCA along with the method of designing the outer and inner structures and the order of sort of the materials. No quality analysis was included in this study. More information can be found in the previous CCA methodology publications (Oman and Tumer 2009; Oman and Tumer 2010; Oman, Tumer et al. 2012).

Study Two also provided a unique opportunity to compare the CCA creativity scores against two methods of creativity evaluation by judges. Judges were asked to rate each concept using a simple 1-10 rating scale as well as a newly developed method called the Multi-Point Creativity Assessment (MPCA). This method asked the judges to rate each concept based on seven adjective pairs: original/unoriginal, well-made/crude, surprising/expected, ordered/disordered, astonishing/common, unique/ordinary, and logical/illogical. The MPCA took into account the judges' opinions on the adjective pairs' importance for the calculation of creativity and produced a score out of ten for each concept. Thus, Study Two data had three creativity scores to analyze and compare against for statistical purposes.

5.2.3 Aggregate customer needs ratings

Stone, et al. present a method to develop product architectures using quantitative functional models (Stone, Wood et al. 2000). In this study, the functional model is split into modules based on dominant flows, branching flows, and convert-transmit flows. These are then assessed using customer needs ratings to determine which modules in a functional model are more important to the customer(s).

To compute the aggregate customer need ratings, the equation used is:

Function Importance $$s_j = \sum_{p=1}^{n} \left(\prod_{i=1}^{f_j} v_{ip} \right) \tag{8}$$

where the design variables are:

s_j = function importance
n = number of products
f_j = number of subfunctions in module j
v_{ip} = element corresponding to the *i*th subfunction of module *j* in the *p*th product

This calculation takes into consideration the effects of combinations of factors (hence the product calculation) in determining the importance of functions in a design problem. In this paper, this formulation will be used to revise the CCA computation in order to represent the effects of multiple innovative functions in concept designs along with calculations to determine the function weights, discussed in Sections 5.3 and 5.4.

5.3 CCA METRIC REVISION TO REDUCE SUBJECTIVITY

The CCA method relies on the user to set the weights of importance for each function based on their personal preferences. The revision to the metrics presented in this section reduces the reliance of user opinion in determining which functions should be given higher weights for creativity emphasis. The functions that have fewer innovative solutions are given greater weight in order to reward the fewer concepts that exhibit more creativity. Prior to this revision, users of the metrics set the values of the function weights based on the importance of each function. While this can be a valid form of calculating the creativity of the concepts, it does not put emphasis on the creativity of individual function and component solutions like the metrics are intended to do. By calculating the function weights instead of allowing the user to set them based on personal preference or opinion, the subjectivity of the CCA method is contained solely in the interpretation of the data from those who generated the concepts.

Several variations of calculating CCA scores using the revisions have been discovered in this research and are all presented herein to illustrate the sensitivity of the creativity solutions to the variation in the function weights. All the methods used to calculate the f_j values use the initial calculations of the S_{Nj} and S_{Qj} values to determine which functions have less variability in the component solutions. For example, in Study Two (the automated waste sorter problem), the set of component solutions to the function *Sort Glass* has only seven different solutions, while the criteria *Order of Sort* has 15 different solutions in the component solution set. Thus, *Sort Glass* will be given a higher function weight in order to reward those concepts that exhibit creativity that is harder to generate.

All equations and example calculations in Section 5.3 and subsequent subsections utilize Study Two data. Section 5.4 presents the complete results of the Revised metrics analysis using both Study One and Two.

5.3.1 Variations in Calculating Function Weights in CCA

Three variations to calculate the f_j values are presented that determine function creativity levels: pairwise function combinations, triple function combinations, and a simple ranking system (e.g. ranking the functions 1,2,3,…) based on either pairwise or triple function combination results (ranking results were the same for both methods). Equation 8 presented in the Background section is redone in order to calculate effects of function combinations and is used in the following metrics to finally calculate individual function creativity weights:

Combination Effect $$y_k = \sum_{p=1}^{n} \left(\prod_{i=1}^{m} v_{ip} \right) \tag{9}$$

where $$k = 1 \ldots g \tag{10}$$

and where the design variables are:

y_k = combination effect of combination k
g = total number of possible m-function combinations
n = number of concepts
m = number of subfunctions in function combination considered
v_{ip} = the S_{Nj} or S_{Qj} corresponding to the *i*th subfunction in the *p*th product

Once all y_k values have been calculated, they must be sorted in descending order and ranked accordingly (i.e., the highest value receives a rank of 1, etc.). The ranks are labeled as d_l, such that l = 1,2,3,… For example:

$y_{20} > y_4 > y_{16} > \ldots$ then y_{20} → ranked d_1=1, y_4 → ranked d_2=2, etc.

These ranks are used to calculated the creative function weights:

Function weight $$f_j = \frac{d_h}{\sum_{l=1}^{m} d_l} \tag{15}$$

where d_h is the lowest d_l value with function j represented in function combination k.

The computation for function creativity weights must be done after all S_{Nj} and S_{Qj} values have been calculated. Each calculation using the CCA method is a single instance analysis. This means the function combinations found to be innovative in one data set will be different from any other data set as each CCA calculation uses different functions and component solution sets to calculate the variables.

The following two subsections present an example of how the calculations are done using two and three function combinations, respectively. These calculations are discussed in greater detail in the Results subsection of this chapter as they utilize the data from Studies One and Two.

5.3.1.1 Pairwise Function Combinations

Equation 9 is adapted for creativity consideration for combinations of two functions to the following equation:

Pairwise Combination Effect $$y_k = \sum_{p=1}^{n} \left(\prod_{i=1}^{2} v_{ip} \right) \tag{12}$$

The pairwise combination effect (Equation 12) calculates the effect of two-function combinations in the problem statement. Thus, the calculation must be done for each and every possible pairwise configuration of functions. As an example, data from Study Two (the Automated Waste Sorter Problem) is presented and used to calculate the different possible sets of weights that can be used in the CCA method. Table 5.1 is the S_{Nj} representations for the first seven concepts in the Study Two dataset for each function. These are used in conjunction with the entire dataset (29 concepts total) to calculate the creativity of each function combination. In the table below, each S_{Nj} value is labeled by its concept number and the function in question; for example, the first concept's S_N representation for *Sort Aluminum (AL)* is $S_{A1\text{-}AL}$. The procedure outlined in 5.3.1 is then used to determine the ranks of each combination in order to calculate the function creativity weights for the full CCA analysis.

Table 5.1: Sample S_{Nj} values for the first seven concepts used in the revised metrics calculations example

	Concept						
FUNCTION	A1	A2	A3	A4	A5	A6	A7
Sort Aluminum	$S_{A1\text{-}AL}$	$S_{A2\text{-}AL}$	$S_{A3\text{-}AL}$	$S_{A4\text{-}AL}$	$S_{A5\text{-}AL}$	$S_{A6\text{-}AL}$	$S_{A7\text{-}AL}$
Sort Tin	$S_{A1\text{-}tin}$	$S_{A2\text{-}tin}$	$S_{A3\text{-}tin}$	$S_{A4\text{-}tin}$	$S_{A5\text{-}tin}$	$S_{A6\text{-}tin}$	$S_{A7\text{-}tin}$
Sort Plastic	$S_{A1\text{-}plast}$	$S_{A2\text{-}plast}$	$S_{A3\text{-}plast}$	$S_{A4\text{-}plast}$	$S_{A5\text{-}plast}$	$S_{A6\text{-}plast}$	$S_{A7\text{-}plast}$
Sort Glass	$S_{A1\text{-}glass}$	$S_{A2\text{-}glass}$	$S_{A3\text{-}glass}$	$S_{A4\text{-}glass}$	$S_{A5\text{-}glass}$	$S_{A6\text{-}glass}$	$S_{A7\text{-}glass}$
Outer Structure	$S_{A1\text{-}outer}$	$S_{A2\text{-}outer}$	$S_{A3\text{-}outer}$	$S_{A4\text{-}outer}$	$S_{A5\text{-}outer}$	$S_{A6\text{-}outer}$	$S_{A7\text{-}outer}$
Inner Structure	$S_{A1\text{-}inner}$	$S_{A2\text{-}inner}$	$S_{A3\text{-}inner}$	$S_{A4\text{-}inner}$	$S_{A5\text{-}inner}$	$S_{A6\text{-}inner}$	$S_{A7\text{-}inner}$
Order of Sort	$S_{A1\text{-}order}$	$S_{A2\text{-}order}$	$S_{A3\text{-}order}$	$S_{A4\text{-}order}$	$S_{A5\text{-}order}$	$S_{A6\text{-}order}$	$S_{A7\text{-}order}$

In order to calculate the effect of the combination between *Sort AL* and *Sort Tin*, it is essentially the summation of the products of each concepts $S_{N(Sort\ AL)}$ and $S_{N(SortTin)}$. Thus the calculation would become:

$$y_{SortAL-SortTin} = (S_{A1-SortAL} * S_{A1-SortTin}) + (S_{A2-SortAL} * S_{A2-SortTin}) + \ldots + (S_{A29-SortAL} * S_{A29-SortTin})$$

Once all y_k values are calculated, they are ranked in descending order such that the highest y_k gets a rank of 1 and the lowest value will get a rank equal to g (total number of possible combinations of functions). The calculations for Study Two are presented in Table 5.2 in order to demonstrate how to use the y_k values to calculate the f_j values.

Note that in Table 5.2, the highest y_k value is y_{21}=2301 for *Outer Structure* and *Order of Sort* and is thus given the rank d_l=1, while the lowest scoring function combination is y_{12}=841 for *Sort Tin* and *Sort Glass*. The above ranks (d_l values) are used to calculate the individual function weights by first determining the highest rank each of the functions embodies, summarized in Table 5.3 for Study Two, along with the calculated f_j values using Equation 11. As an example, in Table 5.2, the highest scoring function combination that includes *Sort Plastic* is y_{18} which was ranked d_5=5, thus $d_{h(SortPlastic)}$=5. To calculate $f_{SortPlastic}$, $d_{h(SortPlastic)}$ is divided by the total sum of all ranks ($\sum d_l$=40, shown in Table 5.3) to get $f_{SortPlastic}$ = 0.125.

Table 5.2: Calculated Pairwise Combination Effects for Study Two

k	Function Combination	Combination Effect - y_k	Rank of y_k – d_l
1	Sort AL – Sort Tin	1495	13^{th}
2	Sort Tin – Sort Plastic	1371	15th
3	Sort Plastic – Sort Glass	1054	19th
4	Sort Glass – Outer Structure	1157	17th
5	Outer Structure – Inner Structure	1986	6th
6	Inner Structure – Order of Sort	2112	4th
7	Sort AL – Sort Plastic	1933	9th
8	Sort AL – Sort Glass	1146	18th
9	Sort AL – Outer Structure	2131	3rd
10	Sort AL – Inner Structure	1940	8th
11	Sort AL – Order of Sort	2255	2nd
12	Sort Tin – Sort Glass	841	21st
13	Sort Tin – Outer Structure	1527	12th
14	Sort Tin – Inner Structure	1408	14th
15	Sort Tin – Order of Sort	1625	11th
16	Sort Plastic – Outer Structure	1968	7th
17	Sort Plastic – Inner Structure	1796	10th
18	Sort Plastic – Order of Sort	2082	5th
19	Sort Glass – Inner Structure	1030	20th
20	Sort Glass – Order of Sort	1233	16th
21	Outer Structure – Order of Sort	2301	1st

Table 5.3: Highest ranks (d_h values) for each function in Study Two used to calculate f_j for Pairwise Combinations

Function	d_h	f_j
Sort AL	2	0.05
Sort tin	11	0.275
Sort plastic	5	0.125
Sort Glass	16	0.4
Outer Structure	1	0.025
Inner Structure	4	0.1
Order of Sort	1	0.025
Sum Total of Ranks:	40	

Note that this method of calculating the function creativity weights places higher weight to those functions that exhibit lower creativity totals in the function combination scores. This rewards those functions that are harder to generate creative component solutions for, such as *Sort Glass* (only seven possible component solutions were generated in the 29 concepts) versus *Sort AL* (11 possible component solutions were used in the dataset).

5.3.1.2 Triple Function Combinations

Equation 9 is adapted for combination effects of three functions for creativity to the following equation:

Triple Combination Effect $$y_k = \sum_{p=1}^{n} \left(\prod_{i=1}^{3} v_{ip} \right) \quad (13)$$

Similar to the calculations presented in the previous subsection, combination effects of three functions are calculated for all possible combinations of functions. For Study Two, this equates to 35 possible y_k values. The calculations for the combinations and rankings are presented in Table 5.4 for Study Two with each function abbreviated as follows: *Sort AL* = A, *Sort Tin* = T, *Sort Plastic* = P, *Sort Glass* = G, *Outer Structure* = O, *Inner Structure* = I, and *Order of Sort* = R.

The values and ranks presented in Table 5.4 are then used to calculate the function creativity weights for the triple combinations in Table 5.5, similar to how the pairwise function creativity weights were calculated. For example, *Sort Tin* is not present until the 11^{th} highest scoring function combination, y_{24}, thus $d_{h(SortTin)} = 11$.

Table 5.4: Calculated Triple Combination Effects for Study Two

k	Function Combination	Combination Effect - y_k	Rank of y_k – d_l
1	A T P	11687	19th
2	A T G	7226	33rd
3	A T O	12992	13th
4	A T I	11892	18th
5	A T R	13768	12th
6	A P G	9135	27th
7	A P O	16823	7th
8	A P I	15229	10th
9	A P R	17744	5th
10	A G O	9993	23rd
11	A G I	8834	29th
12	A G R	10625	22nd
13	A O I	16828	6th
14	A O R	19571	1st
15	A I R	17822	4th
16	T P G	6637	34th
17	T P O	11897	17th
18	T P I	10899	20th
19	T P R	12615	15th
20	T G O	7401	32nd
21	T G I	6558	35th
22	T G R	7809	31st
23	T O I	12155	16th
24	T O R	14055	11th
25	T I R	12961	14th
26	P G O	9179	26th
27	P G I	8116	30th
28	P G R	9758	24th
29	P O I	15565	9th
30	P O R	18057	3rd
31	P I R	16481	8th
32	G O I	8948	28th
33	G O R	10721	21st
34	G I R	9552	25th
35	O I R	18237	2nd

Table 5.5: Highest ranks (d_h values) for each function in Study Two used to calculate f_j for Triple combinations

Function	d_h	f_j
Sort AL	1	0.025
Sort tin	11	0.275
Sort plastic	3	0.075
Sort Glass	21	0.525
Outer Structure	1	0.025
Inner Structure	2	0.05
Order of Sort	1	0.025
Sum Total of Ranks:	40	

5.4 REVISED METRICS VERSUS OLD DATA RESULTS

The following section presents analysis of the original calculated creativity scores versus the new variations of the CCA method, divided by Study One and Two. Study Two is presented first as it is used in the example calculations in the previous section and was the first analysis conducted to provide the motivation to looking deeper into the revisions at both the Novelty and Quality levels.

5.4.1 Study Two Revision Results

The revised method of calculating the f_j values allows representation within the weights for the disparity between scores. For example, the function *Sort Glass* is not present in high scoring pairwise function combinations until the 16th ranked combination (d_{16}), while *Sort AL* was in the second highest scoring pairwise function combination (d_2). For comparison purposes, the results also include a simple 1,2,3… rating that does not represent gaps in the rankings, but are based on the same d_h values. Table 5.6 presents the results of using a simple rating system given the calculations with the pairwise and triple function combinations for Study Two.

Table 5.6: Results for simple rankings in Function Creativity Weights in Study Two

	Pairwise d_h	Pairwise f_j	Triple d_h	Triple f_j
Sort AL	3	0.107	3	0.107
Sort tin	6	0.214	6	0.214
Sort plastic	5	0.179	5	0.179
Sort Glass	7	0.250	7	0.250
Outer Structure	2	0.071	2	0.071
Inner Structure	4	0.143	4	0.143
Order of Sort	1	0.036	1	0.036

Note that, since the simple rankings for the pairwise and triple combinations are the same, the following results and graphs present only one dataset for both analyses.

The first comparison of results is of all the function weights in order to easily interpret where the largest changes are in the results. Figure 5.1 is the difference in function weights for the three new calculated function weights along with the original weights. Note that the function weights for the revisions using a simple ranking system are labeled in the following figures as "Simple 1-7 Ranking", indicating that there were seven functions being ranked.

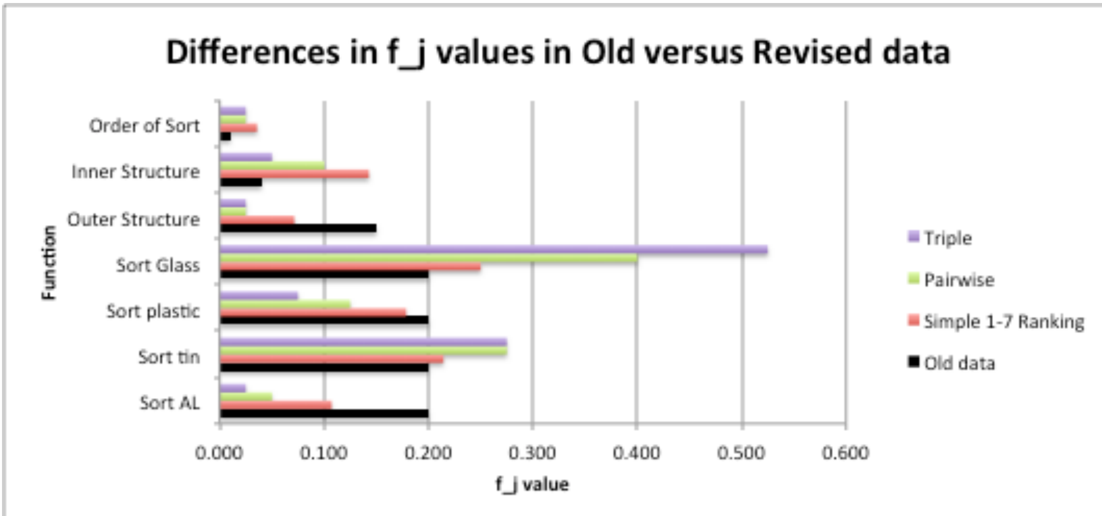

Figure 5.1: Differences in function weights for Study Two revisions

The new function weights are used to calculate three new datasets for the Automated Waste Sorter creativity analysis and compared to the previous data. To best represent the data, the results in Figures 5.2 and 5.3 are sorted by the old data in ascending order. Figure 5.2 presents the old data versus the triple function combinations, pairwise function combinations, and using the simple rankings for both revised datasets.

The comparison in Figure 5.2 shows an interesting trend in the way the revised function weights affect the concept creativity scores. Using the function combination effects to calculate the creativity scores shows starker differences between concepts compared to the old calculated data. Furthermore, the Pairwise and Triple function combinations provide the most contrast between concepts, which can be argued as a positive outcome of the revisions. This prevents concepts being rewarded for only one or two high individual function creativity outliers. This analysis rewards those concepts that have high creativity in multiple functions.

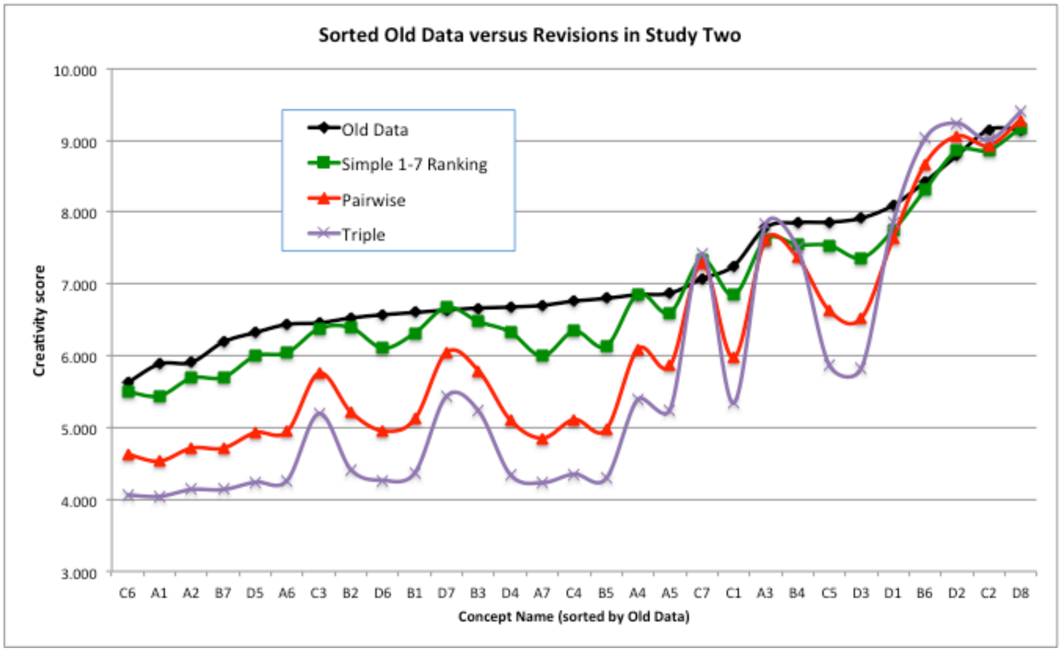

Figure 5.2: Study Two previous data sorted in ascending order versus revisions

Figure 5.3 compares the results of the revisions to the Judges' scorings out of a scale of ten as well as the MPCA data (a creativity method discussed in Section 5.2.2.3). This figure shows some similar trends in data compared to Figure 5.2, but not as clear as the previous data comparison. For example, the highs and lows for the revised data is consistent in both figures, but the revised data is lower than the old data in Figure 5.2 while there is no such trend in Figure 5.3.

Each of the datasets were then analyzed using a paired nonparametric test to determine which methods differed statistically. Table 5.7 presents the results of Wilcoxon Signed Rank analyses of the method comparisons for the Study Two data.

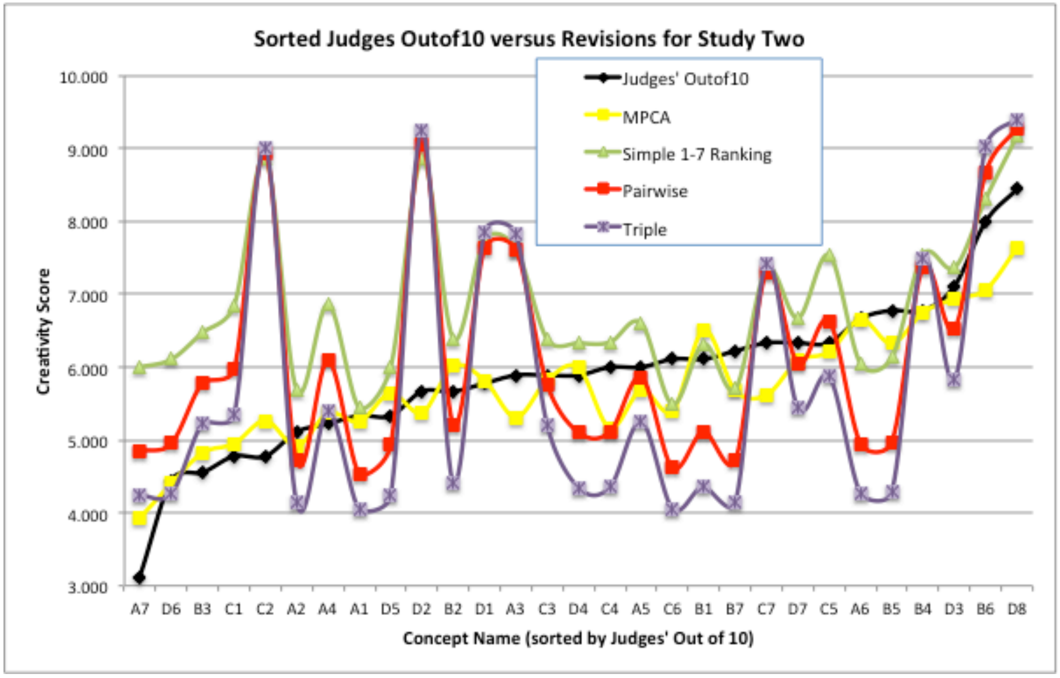

Figure 5.3: Judges' Out of Ten ratings sorted in ascending order versus revised data for Study Two

Table 5.7: Study Two Paired Nonparametric Statistical Results

Compared Datasets		**p-value**	**Result**
Old Data	Triple	.000	Statistically Different
Old Data	Simple Rank	.000	Statistically Different
Old Data	Pairwise	.000	Statistically Different
Old Data	Judges	.000	Statistically Different
Old Data	MPCA	.000	Statistically Different
Judges	MPCA	*.114*	*No Statistical Difference*
Judges	Pairwise	*.469*	*No Statistical Difference*
Judges	Triple	*.309*	*No Statistical Difference*
Judges	Simple Rank	.000	Statistically Different
Pairwise	Triple	.000	Statistically Different
Pairwise	Simple Rank	.000	Statistically Different
Pairwise	MPCA	*.239*	*No Statistical Difference*
Triple	Simple Rank	.000	Statistically Different
Triple	MPCA	*.642*	*No Statistical Difference*
MPCA	Simple Rank	.000	Statistically Different

The statistical results provide insight into which datasets tend to differ from all other datasets. The old method of setting the function weights is statistically different from all other methods, whereas the Judges ratings using a scale of 0-10 and the MPCA method of creativity analysis do not differ statistically from any of the other methods. This result provides evidence that the pairwise and triple combination calculations are on par with those done by multiple judges. As the CCA method does not require extra time or manpower to calculate creativity scores, this is validation that the CCA method can be used in place of judges when analyzing creativity of concepts.

Further analysis of the data included cluster analysis of the creativity calculations to provide a methods standpoint towards the practical implications of the variations. Cluster analysis provides organization for the observed data into homogeneous classes. Ward's method using squared Euclidean distance is the most efficient and generally accepted method to determine the number of clusters for a given data set. From there, the k-means clustering method is used to determine which cluster each data point belongs to. Table 5.8 presents the results of clustering the data into two groups.

Table 5.8: Study Two Cluster Analysis Results using Two Clusters

Case	2 Clusters
OldData	1
Pairwise	1
Simple Rank	1
Triple	1
Judges	2
MPCA	2

The two methods that require judges are grouped into one cluster, while all other methods are in a separate cluster. Further evidence of the distinct differences in the datasets can be found in Table 5.9, which shows that a three cluster approach groups the methods that use judges together as before, but also clusters the pairwise and triple combination variations of creativity calculations together.

The results of the revised Study Two data show enough evidence that the function combinations have a distinct effect on the outcome of the CCA method. This was motivation for assessing the Study One data using the revised metrics as well.

Table 5.9: Study Two Cluster Analysis Results using Three Clusters

Case	3 Clusters
OldData	1
Pairwise	2
Simple Rank	1
Triple	2
Judges	3
MPCA	3

5.4.2 Study One Revised Metrics Data Analysis

Study One analyzed 28 designs for a Mars Rover rock collector challenge for both Novelty and Quality in the CCA methodology. The following section is divided into these two categories to analyze the revisions to the Study One data.

5.4.2.1 Study One Revised Data Analysis for Novelty Criteria

The following abbreviations are used in the tables for this section: *Mobility* = M, *Over barrier* = O, *Pick up Rocks* = P, *Store Rocks* = S, *Drop Rocks* = D, and *Controller* = C. Table 5.10 presents the combination effects and ranks of the Novelty data for pairwise function combinations.

Table 5.10: Study One Pairwise combination results for Novelty

k	Function Combination	Combination Effect - y_k	Rank of $y_k - d_l$
1	MO	581.378	13th
2	MP	498.469	15th
3	MS	501.148	14th
4	MD	586.735	12th
5	MC	605.230	11th
6	OP	1307.908	10th
7	OS	1340.179	9th
8	OD	1596.556	6th
9	OC	1582.781	7th
10	PS	1352.423	8th
11	PD	1608.036	4th
12	PC	1598.852	5th
13	SD	1645.026	2nd
14	SC	1624.490	3rd
15	DC	1943.240	1st

Table 5.11 presents the calculations for triple function combinations for the Novelty Study One data, including the combination effects, y_k, and d_l rankings.

Table 5.11: Study One Triple combination results for Novelty

k	Function Combination	Combination Effect - y_k	Rank of y_k – d_l
1	MOP	4028	19th
2	MOS	4050	18th
3	MOD	4721	13th
4	MOC	4889	12th
5	MPS	3480	20th
6	MPD	4064	17th
7	MPC	4180	15th
8	MSD	4120	16th
9	MSC	4193	14th
10	MDC	4918	11th
11	OPS	8998	10th
12	OPD	10570	8th
13	OPC	10469	9th
14	OSD	11339	5th
15	OSC	11136	7th
16	ODC	13298	3rd
17	PSD	11410	4th
18	PSC	11237	6th
19	PDC	13388	2nd
20	SDC	13662	1st

Using the data presented in Tables 5.10 and 5.11, the function creativity weights are calculated and presented in Table 5.12, along with the simple 1,2,3,… rankings presented in Table 5.13, for Study One Novelty data analysis.

Table 5.12: Highest ranks (d_h values) for each function in Study One used to calculate f_j in Pairwise and Triple combinations for Novelty

	Pairwise d_h	Pairwise f_j	Triple d_h	Triple f_j
Mobility	11	0.440	11	0.579
Over barrier	6	0.240	3	0.158
Pick up rocks	4	0.160	2	0.105
Store rocks	2	0.080	1	0.053
Drop rocks	1	0.040	1	0.053
Controller	1	0.040	1	0.053

Note that, since the simple rankings for the pairwise and triple combinations are the same for the Novelty results, the following results and graphs present only one dataset for both analyses, labeled “Simple 1-6 Ranking”. Figure 5.4 depicts the differences in function creativity weights in comparison to the old weights that were generated based on user preference of importance for each function.

Table 5.13: Results for simple rankings in function creativity weights in Study One for Novelty

	Pairwise d_h	Pairwise f_j	Triple d_h	Triple f_j
Mobility	6	0.286	6	0.286
Over barrier	5	0.238	5	0.238
Pick up rocks	4	0.190	4	0.190
Store rocks	3	0.143	3	0.143
Drop rocks	1	0.048	1	0.048
Controller	2	0.095	2	0.095

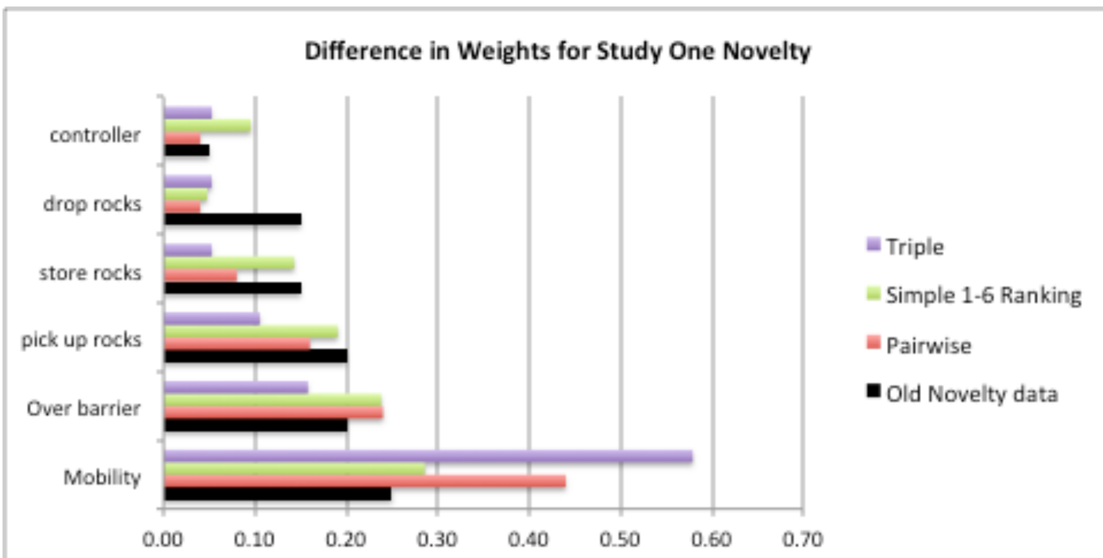

Figure 5.4: Difference in function creativity weights in Study One for Novelty

The new calculated function weights are used to generate datasets for analysis of how the Novelty criteria are affected by both the Pairwise and Triple combination effects, shown in Figure 5.5 below.

Figure 5.5 depicts the first group of datasets that show very definite trends in creativity levels across all of the concepts. However, note that the triple function combination results once again have the highest level of difference between the old data set and the revisions and provide starker differences between the low scoring and high scoring concepts.

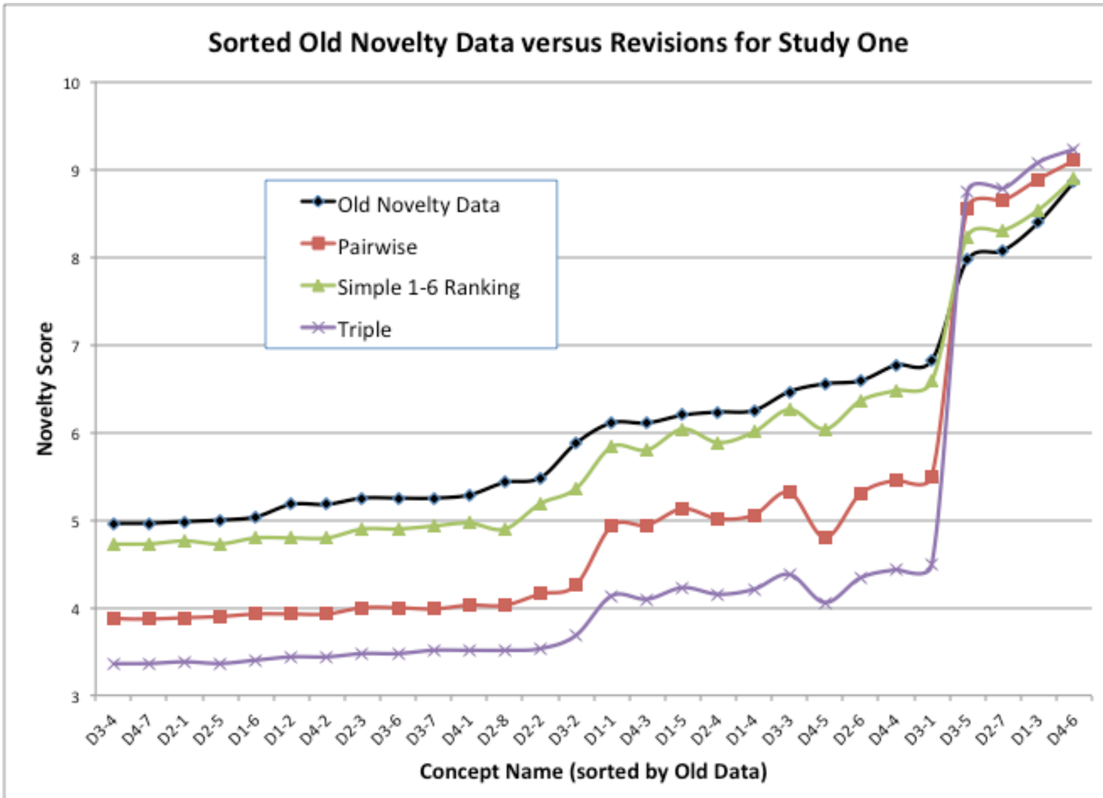

Figure 5.5: Study One previous Novelty data sorted in ascending order versus revisions

Analysis of the datasets using the Wilcoxon Signed Rank test shows that all the methods of calculating creativity scores are statistically different from one another. This is consistent with the results of Study Two.

Table 5.14: Study One Novelty Nonparametric Statistical Results

Compared Datasets		p-value	Result
Old Novelty	Pairwise	.000	Statistically Different
Old Novelty	Triple	.000	Statistically Different
Old Novelty	Simple Rank	.000	Statistically Different
Simple Rank	Pairwise	.000	Statistically Different
Simple Rank	Triple	.000	Statistically Different
Pairwise	Triple	.000	Statistically Different

Cluster analysis of the data confirms the conclusion that the pairwise and triple combination variations of calculating the CCA scores are statistically different from the old method.

Table 5.15: Study One Novelty Cluster Analysis Results using Two Clusters

Case	2 Clusters
OldNovelty	1
Pairwise	2
SimpleRank	1
Triple	2

5.4.2.2 Study One Revised Data Analysis for Quality Criteria

The following abbreviations are used in the tables for this section: *Weight* = W, *Milliamp Hours* = H, # *Switches* = S, # *Parts* = P, and # *Manufactured parts* = M. The analysis of Quality scores with the revised metrics had similar trends to the Study Two data, in that the revisions do not follow any trends with the old calculated data.

Table 5.16 presents the combination effects and rankings for the Study One Quality data using pairwise analysis.

Table 5.16: Study One Pairwise combination results for Quality

k	Function Combination	Combination Effect - y_k	Rank of $y_k - d_l$
1	WH	1438.265	6th
2	WS	1250.617	10th
3	WM	1504.887	4th
4	WP	1489.939	5th
5	HS	1288.965	9th
6	HM	1548.223	2nd
7	HP	1540.145	3rd
8	SM	1429.132	7th
9	SP	1365.122	8th
10	MP	1670.143	1st

Table 5.17 details the triple function combinations for the Quality criteria of Study One and the results of the combination effects calculations used to generate the new functions weights.

Table 5.17: Study One Triple Combination Results for Quality

k	Function Combination	Combination Effect - y_k	Rank of $y_k - d_l$
1	WHS	9602.136	10th
2	WHM	11346.164	4th
3	WHP	11577.428	3rd
4	WSM	9985.264	9th
5	WSP	9991.414	8th
6	WMP	11958.922	2nd
7	HSM	10147.559	6th
8	HSP	10141.379	7th
9	HMP	12255.992	1st
10	SMP	10941.948	5th

The data presented in the previous two tables is used in the same fashion as the Study Two data in Section 5.4.2.1 to calculate the new function creativity weights presented in Tables 5.18 and 5.19 for the revision rankings and simple rankings, respectively.

Table 5.18: Highest ranks (d_h values) for each function in Study One used to calculate f_j in Pairwise and Triple combinations for Quality

	Pairwise d_h	Pairwise f_j	Triple d_h	Triple f_j
weight	4	0.267	2	0.200
milliamp hrs.	2	0.133	1	0.100
# switches	7	0.467	5	0.500
# materials	1	0.067	1	0.100
# manuf. Parts	1	0.067	1	0.100

Table 5.19: Results for simple rankings in function creativity weights in Study One for Quality

	Pairwise d_h	Pairwise f_j	Triple d_h	Triple f_j
weight	4	0.267	4	0.267
milliamp hrs.	3	0.200	3	0.200
# switches	5	0.333	5	0.333
# materials	1	0.067	2	0.133
# manuf. Parts	2	0.133	1	0.067

Note that the Study One Quality simple rankings are the only set of simple rankings that do not match exactly between the pairwise and triple function combinations. Thus the following two figures present both datasets separately, labeled “Pairwise Simple Ranking” and

"Triple Simple Ranking", respectively. The f_j values in Tables 5.18 and 5.19 are depicted for ease of reference in the figure below.

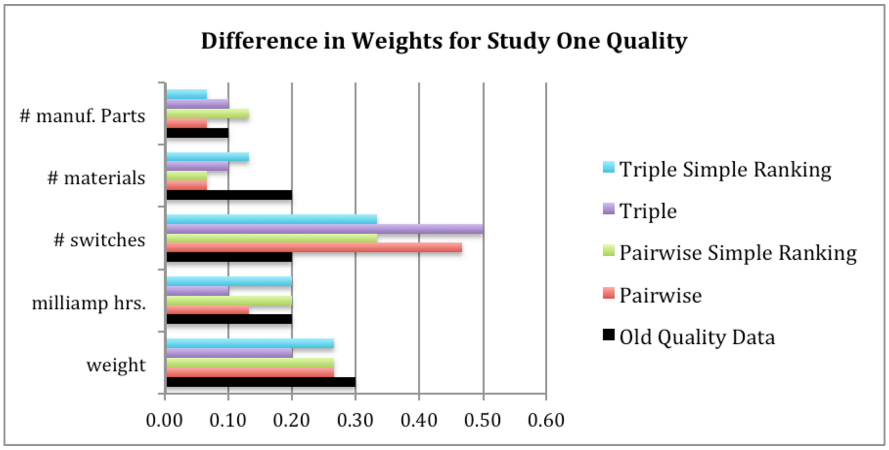

Figure 5.6: Difference in function creativity weights in Study One for Quality

Using the new function creativity weights in Figure 5.6, the Quality data for Study One are recalculated and shown in Figure 5.7 below.

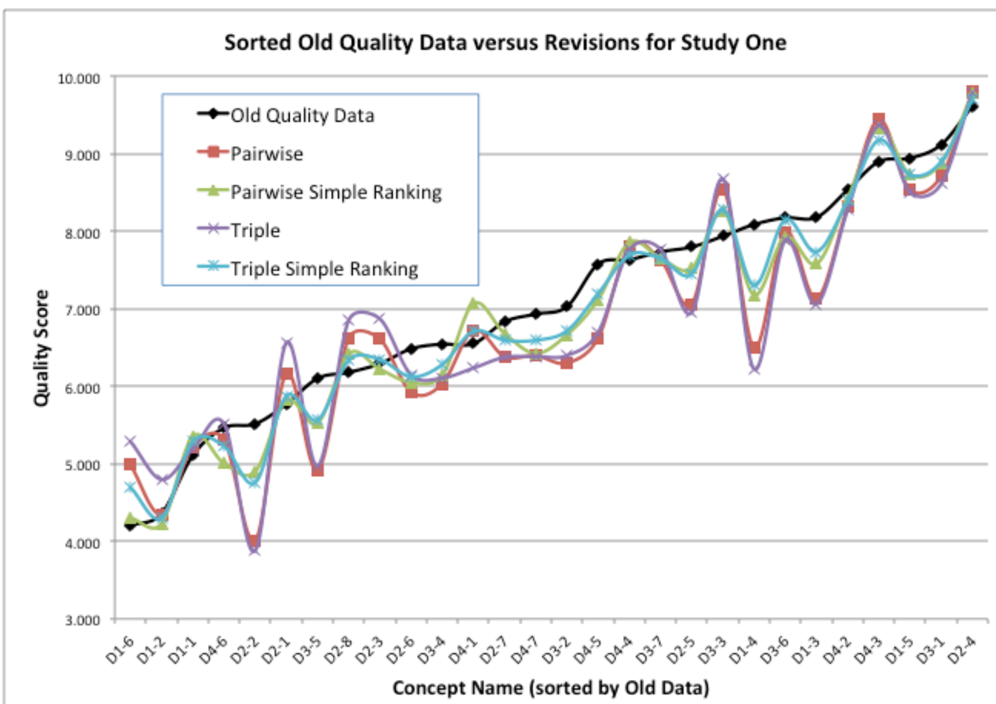

Figure 5.7: Study One previous Quality data sorted in ascending order versus Revisions

This figure shows that the trends in datasets are similar to those found in the Study Two data for the revised calculations.

Table 5.20 presents the statistical comparison results of the datasets using the Wilcoxon Signed Rank test. The comparisons show that the only statistically different sets are between the Old Quality Data and both the pairwise and triple combination analyses. This correlates with the results shown in Figure 5.7.

Table 5.20: Study One Quality Nonparametric Statistical Results

Compared Datasets		p-value	Result
Old Quality	Simple Pair	.052	No statistical difference
Old Quality	Pairwise	*.031*	*Statistically Different*
Old Quality	Simple Triple	.158	No statistical difference
Old Quality	Triple	*.036*	*Statistically Different*
Simple Pair	Simple Triple	.387	No statistical difference
Simple Pair	Pairwise	.111	No statistical difference
Simple Pair	Triple	.127	No statistical difference
Simple Triple	Pairwise	.356	No statistical difference
Simple Triple	Triple	.339	No statistical difference
Pairwise	Triple	.387	No statistical difference

The cluster analysis results are similar to the Novelty and Study Two results in that the pairwise and triple combination calculations are grouped into their own homogeneous class, as shown in Table 5.21.

Table 5.21: Study One Quality Cluster Analysis Results using Two Clusters

Case	2 Clusters
OldQuality	1
Pairwise	2
SimplePair	1
Triple	2
SimpleTriple	1

5.5 CONCLUSIONS

5.5.1 Summary of Results

Analysis of the results presented in Section 5.4 provide some interesting insight into the effects of function combinations in the creativity assessment.

As Study Two was used in the example calculations that explained the revisions to the CCA, the results of the analysis for Study Two were presented first. The trend in the revised data using pairwise and triple combination effects versus the old data showed that the creativity scores for the revised datasets were lower overall with more noticeable differentials in the concepts. The triple function combinations had the greatest affect on the creativity score results versus the old data. The comparison of the revised data to the judges' scorings showed even higher contrast in scores from the old data, particularly in the outlying creativity scores in the triple function combination calculations.

The results of the Study One revisions were not as consistent as Study Two. Particularly, the trends between the old data and the revisions were not as constant between Novelty and Quality. There was a unique trend in the Novelty data between the old data and the pairwise and triple function combination results. All the data sets had the exact same trendlines, but, as with Study Two, the creativity scores decreased with the pairwise function combination results and further decreased with the triple function combination results. The Quality data did not show the same trend as Novelty in all the datasets, but had similar results to Study Two in the contrast effects on the outliers from the pairwise and triple function combination results.

5.5.2 The Revised Comparative Creativity Assessment Method

This chapter presented a revision to the Comparative Creativity Assessment (CCA) method that reduces the subjectivity of the function weights by including combination effects of multiple functions in the design problem. Analysis of the revised metrics versus the old data presented in previous publications (Oman and Tumer 2009; Oman and Tumer 2010; Oman, Tumer et al. 2012) for both Study One and Study Two show that there is validity to including the combination effects of two or three functions. The complete method is presented as the following:

Novelty: $$M_N = \sum_{j=1}^{m} f_j S_{Nj} \quad (1)$$

$$S_{Nj} = \frac{T_j - R_j}{T_j} \times 10 \quad (2)$$

Quality: $$M_Q = \sum_{j=1}^{m} f_j S_{Qj} \quad (3)$$

$$S_{Qj} = 1 + (A_j - x_j) * (10-1) / (A_j - B_j) \quad (4)$$

CCA: $$C = W_N M_N + W_Q M_Q \quad (5)$$

where $$W_N + W_Q = 1 \quad (6)$$

and $$\sum_{j=1}^{m} f_j = 1 \quad (7)$$

Combination Effect $$y_k = \sum_{p=1}^{n} \left(\prod_{i=1}^{m} v_{ip} \right) \quad (9)$$

where $$k = 1 \ldots g \quad (10)$$

Function weight $$f_j = \frac{d_h}{\sum_{l=1}^{m} d_l} \quad (15)$$

where the design variables are:

T_j = number of total ideas produced for criteria j in Novelty
f_j = weight of importance of criteria j in all equations
m = total number of criteria in evaluation
R_j = number of similar solutions in T_j to criteria j being evaluated in Novelty
A_j = maximum value for criteria j in set of results
B_j = minimum value for criteria j in set of results
x_j = value for criteria j of design being evaluated
S_{Qj} = score of quality for criteria j in Quality
S_{Nj} = score of novelty for criteria j in Novelty
W_N = weight of importance for Novelty (W_N in real set [0,1])

W_Q = weight of importance for Quality (W_Q in real set [0,1])
M_N = creativity score for Novelty of the design
M_Q = creativity score for Quality of the design
C = Creativity score
y_k = combination effect of combination k
g = total number of possible m-function combinations
n = number of concepts in evaluation
m = number of subfunctions in function combination considered
v_{ip} = the S_{Nj} or S_{Qj} corresponding to the ith subfunction in the pth product
d_l = rank of y_k, such that l =1,2,3, …
d_h = lowest d_l value with function j represented in function combination k
For example: $y_{20} > y_4 > y_{16} > \ldots$ then $y_{20} \rightarrow$ ranked d_1=1, $y_4 \rightarrow$ ranked d_2=2, etc.

5.6 FUTURE CCA METRIC REVISIONS

By adapting the equation presented in the Section 5.2.2 of this chapter, the CCA method can include combination effects between functions into the calculation of individual concept creativity scores. This revision to the method rewards those individual concepts that have high novelty and quality values (S_{Nj} and S_{Qj}) for all the functions found to have high innovative properties when grouped together (i.e., combination effects between the functions).

In Study Two, the seven functions produce 21 possible pairwise combinations and 35 possible triple combinations. The large amount of possible combinations can become an issue if all calculations are done manually using a spreadsheet with greater amounts of functions. For example, if a design problem contained 17 functions, the analysis would have 136 pairwise comparisons and 680 triple function combinations to calculate. Future work will automate this calculation process to make such calculations possible in conjunction with the full CCA method. Ongoing work will encode these creativity metrics into a multi-agent coordination framework that would work towards learning through difference rewards to output the most creativity ideas out of a set (Rebhuhn, Gilchrist et al. 2012).

Lastly, future investigation will examine how to reward individual concepts that exhibit component combination interactions that have been documented as creative. For example, the Oliso Smart Iron has a foot assembly that lifts it off garments for burn prevention. In a coffee maker, the burn prevention function may be present, but using the components from the foot assembly in burn prevention in a coffee maker may be deemed as a new, creative solution. Future work will determine how to evaluate component combinations that are deemed creative and reward those concepts that exhibit the entirety of the component assembly in its problem solution.

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Chapter 6: Lessons Learned from Engineering Creativity Design Experiments

6.1 INTRODUCTION

Lessons learned from the studies conducted in this research provide insight into experimental design and setup in engineering, which can be used to develop key characteristics to design problem and creativity experiment formulation outlined in Future Work of this chapter. Some information from the previous chapters is repeated in this section in order to reiterate certain points for further explanation.

6.2 BACKGROUND

The literature regarding problem formulation in design focuses on several specific issues. For example, Linsey, et al. discuss how the complexity of the problem affects student perception of functional modeling (Linsey, Viswanathan et al. 2010). Moor and Drake address how project management during the design process affects engineering projects (Moor and Drake 2001). Lyons and Young present an interesting approach to student learning and design by forcing students to design their own experiments, thus teaching design of experiments (DOE) through hands-on problem solving (Lyons and Young 2001). Atman et al. examine the differences between using student and expert engineering experience during concept generation in order to better understand efficient characteristics in engineering design processes (Atman, Adams et al. 2007).

Two methodology studies present interactive computer solutions to produce more efficient design problems. Russo and Birolini focus on how to reformulate an already existing design problem (Russo and Birolini 2011) while Dinar et al. discuss how to formally represent the design problem that aides designers in the conceptual design stage for novice and expert users (Dinar, Shah et al. 2011).

Rodriguez et al. provide the most unique study regarding design problem formulation and creativity (Rodriguez, Mendoza et al. 2011). They present recommendations for designers through the entire conceptual design process that may aid creativity in the hypothesis generation, response variables, experiment factors, type of experiment, and the execution of said experiment. This study provides a broad perspective on the entire DOE aspect, but specifically presents six factors of the "ideation task" that pertain to the design problem formulation. The factors were identified through previous literature that outlined creativity experiments. These six factors (along with which original sources they were identified in) are: fertility (number of ideas) (Dorst and Cross 2001; Chiu and Shu 2008), domain (necessary knowledge) (Knoop 1997; Atman, Deibel et al. 2009), complexity (Court 1998; Shah 1998; Kim, Kim et al. 2005; Robertson and Radcliffe 2006; Smith, Troy et al. 2006; Tate, Agarwal et al. 2009), engagement (incentive or motivation for participants) (Robertson and Radcliffe 2006; Chiu and Shu 2008), ambiguity (level of constraints) (Rodriguez, Mendoza et al. 2011), and level of detail (Kim, Kim et al. 2005; Srinivasan and Charkrabarti 2010).

What the Rodriguez et al. study provides are recommendations that are not necessarily specific to increasing or aiding creativity in the design of experiment. The study looks at a much broader perspective of design experiment formulation based on the study of eleven previous published papers (cited in the previous paragraph). The Rodriguez et al. study is also limited to examining the planning and execution of concept generation studies and does not look further into concept evaluation.

6.3 LESSONS LEARNED FROM RESEARCH PRESENTED HEREIN

The experiments discussed in this section include the ASME Mars Rover and Automated Waste Sorter challenges, the RIP versus MEMIC test case of a toy hovercraft, and two experimental runs for students to design an automated tennis ball collector.

6.3.1 Lessons from CCA and MPCA experiments

The implementation of the CCA in Study One and both the CCA and MPCA in Study Two has taught some important lessons regarding the evaluation of concept designs. These two studies have shown that metrics can be applied to a set of designs to assess the level of creativity of possible designs. In the early stages of design, engineers and designers can use these metrics to determine which ideas may be the most beneficial for their problem statement by driving towards innovative products.

Much can be done to improve future use of the creativity assessment techniques to aid designers in the creativity evaluation process. First and foremost, the more controls in an experiment of this nature, the better. Using latent data on class competitions is a good starting point in the development of creativity assessment methods, but the conclusions drawn directly from the data are not very robust. The design and implementation of a controlled experiment is necessary as a final validation of the CCA and MPCA. The designs evaluated in this study were created based on overly-constrained ASME design competition rules and regulations, thus somewhat hindering the inclusion of creative solutions. The creativity in the solution sets was very similar and extremely innovative designs were few and far between. Further studies using the creativity analysis methods should be unconstrained, conceptual experiments. This will allow designers further room to delve outside the box. The evaluation of concepts is extremely important for engineers in order to move forward in the design process.

Another point to change in future experiments is varying the delivery of information to the judges, while keeping the information the exact same. This could include changing the order that the judges rate the devices and changing the way the data is presented for each device. This would prevent trends in which judges tend to learn as they go, thus the last ratings may be more consistent than the first few.

Furthermore, the way in which data was given to the judges must be taken into consideration. The first attempt at asking judges to rate the devices using the MPCA and an out of ten ranking failed. The first set of judges did not have enough time or a welcoming environment to efficiently rate all the devices. The second group of judges had controlled information, allowing them to create comparisons based on device functions and structure, however, they were unable to see the real products like the first group did.

The major downfall to the judging panels is that the pictures and physical appearance may have produced product appeal biases that skewed that data. Although the two scoring sets from the judges were statistically similar, they were well below the scores of the CCA. This could be explained by the fact that some judges may have used just the look of the devices to rate them on creativity instead of taking into account the uniqueness and originality they displayed in accomplishing the competition requirements. The judges' ratings for both the MPCA and the Out of Ten scores were based on rating the entire project concepts as a whole whereas the CCA broke down the projects into the feature level.

A prime example of this is Device 7 (see Figure 6.1), which had a unique way of sorting the aluminum and used an outer structure that no other team used. However, it simply looked like a box made of peg board, thus the judges could easily give it a low creativity score based on the outward appearance and apparent quality of the device. This fact would explain the lack of correlation between the CCA and the Judges' scorings, but further data and analysis would be necessary to fully attribute it to the low correlation coefficient. Limitations placed on the design teams (such as time, budget, and team member capabilities) contributed to the lack of implementation of their creative ideas.

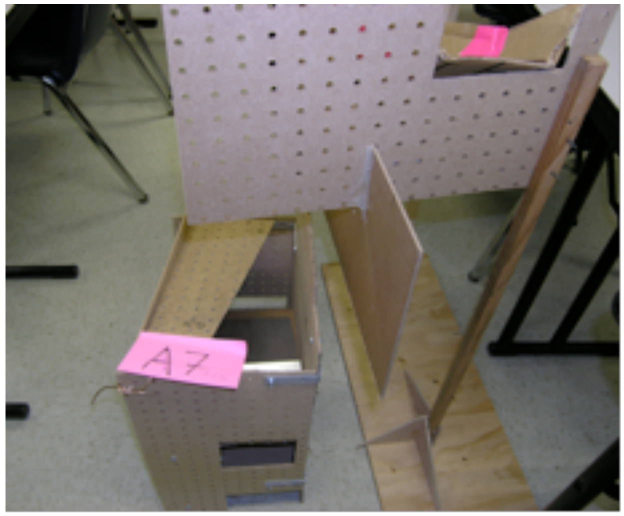

Figure 6.1: Device 7 from the automated waste sorter experiment as an example of how appearance can produce biases

Lastly, the information presented to the judges and used to calculate the CCA scores was gathered using the teams' class documentation, which was widely inconsistent. Some teams provided great detail into the make-up and operation of their device, while others did not even explain how the device worked. In preparation for a creativity analysis such as this, each team must be questioned or surveyed for relevant information regarding all aspects of their device beforehand. Because each team presented their device's information differently, the interpretation of said data was not consistent. This inconsistency could also explain the lack of correlation between the CCA results and the Judges' scorings.

6.3.2 Lessons from RIP validation experiment

As the RIP validation experiment was conducted after the initial studies for the CCA and MPCA development, the setup and data were more efficient and beneficial. However, there were still several observations to be made and lessons learned from the RIP validation that are discussed in this section. The major observations from the two runs of the Tennis Ball Collector experiment include how background methodology is taught prior to the experiment and how the experiment subjects (students in these instances) retain instructions.

The main difference between Experiment run #1 and Experiment run #2 of the Tennis Ball Collector experiment was how the information was taught to the class beforehand, which was proven in the statistical analysis of the data. In Experiment run #1, less emphasis was placed on how to create and interpret functional models by presenting it in one 50-minute lecture the day before the experiment. In Experiment run #2, functional modeling was taught in two 50-minute lectures one week before the experiment and a homework assignment included generating functional models for their class project. It was not foreseen in the first run of the experiment that interpreting the functional model of the experiment design problem would be crucial to the creativity results as shown in the statistical analysis of the data.

Furthermore, when designing experiments that involve students, it should be taken into account that a certain amount of the concept results will have to be thrown out due to participants not following the directions or instructions provided to them. Several instructions for the experiment were repeated verbally and in writing in their problem packets, but were still not followed by all students when creating concepts for the design problem. For example, the most reoccurring problem with student concepts were those that only presented component solutions to a fraction of the 15 functions involved in the Tennis Ball collector design problem. It was repeatedly mentioned to the students that only *complete* designs that satisfied all functions could be considered, yet dozens of potential designs had to be excluded from the data sets.

Lastly, an interesting observation from the statistical analysis regarding the lab times is that the time of day that the experiment is administered had no affect on the level of creativity of the students. This was contrary to initial impressions that most would think college students are less likely to be creative early in the morning or right after lunch.

6.4 FUTURE WORK: CREATIVITY EXPERIMENTS GUIDELINES

Lessons learned from the experiments conducted for this dissertation, along with information gathered across different domains in experimental setup, will provide key characteristics in design problems whose aim is to test design methodologies. By providing requirements for the development of creative design problems, the experimental design itself can provide greater resolution with creativity for the output.

These observations, combined with those found by Rodriguez et al discussed in Section 6.2 (Rodriguez, Mendoza et al. 2011), can lead to the development of characteristics for design problem formulation in creativity experiments,. These characteristics can then be combined with the concept evaluation observations (such as needing clear concept documentation) to provide guidelines for fostering creativity in conceptual design.

Characteristics include: use an unconstrained, conceptual design problem that is open-ended for interpretation by the designer; properly motivate the student participants; ensure concept information is properly documented; and provide an environment that allows for a large quantity of idea to be produced. Further research will be conducted to expand on these characteristics based on previous studies conducted in the mechanical engineering design theory and methodology field.

The motivation to structuring design problem formulation characteristics is best summarized in a study conducted by Barth et al., who examined 71 publications in the *Research in Engineering Design* journal over the past five years. This study concluded that this field of design is very diverse and the multidisciplinary nature of the experiments makes it difficult to categorize and compare results and validation experiments. The authors hope that their results will aid in a common methodology to, "improve the quality of research in engineering design (Barth, Caillaud et al. 2011)."

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Chapter 7: Conclusion

7.1 SUMMARY

The two research questions addressed in this dissertation were: (1) can creativity be assessed in the concept evaluation phase of engineering design through the use of specifically tailored creativity assessment equations, and (2) can creativity be fostered and increased in concept generation through the use of archived innovative information drawn from previously market-tested innovative products? These questions were answered through the development of the Comparative Creativity Assessment (CCA) method and the Repository of Innovative Products (RIP). The revision of specific aspects of the CCA yielded a more robust method of creativity evaluation that has little to no human subjectivity and includes combination effects between functions.

Chapter 3 presents and discusses the analysis of concepts generated during two mechanical engineering design course projects by means of creativity assessment methods. First a survey of creativity assessment methods is presented and summarized, which provides a unique opportunity to compare and contrast analysis methods for personality types, product creativity, and the creativity of groups of ideas. This survey contributed to the motivation behind the creation of the Comparative Creativity Assessment (CCA) and Multi-Point Creativity Assessment (MPCA) methods. The creation of the MPCA in conjunction with the CCA allowed for statistical analysis of the validity of these methods in analyzing creativity in design. Although there was limited statistical correlation between the judges' scorings of creativity and the CCA scores, this study provides valuable insight into the design of creativity assessment methods and experimental design. It can be argued that the statistical correlation between the judges' ratings and the CCA method is expected and encouraged as it shows that the CCA method puts more emphasis on the theory of the concept and less on the embodiment or appearance of the designs themselves.

Chapter 4 then uses the creativity assessment methods to explore whether archived innovation information can be used to foster and/or increase creativity. The method outlined in Chapter 4 is conducted in two parts: first, innovative products are compared to ordinary products in order to isolate innovative functions and components, and, second, those innovative components and functions are used to generate an innovative concept to demonstrate the utility of implementing the Repository of Innovative Products (RIP) into the Design Repository (DR). During the course of the Part I, it was discovered that innovation maps to clusters of functions within products, what is called an innovative function cluster. Using these innovative function clusters, the functional model for the design problem could be developed. Components housed in the RIP were then taken into consideration to generate a proposed concept for a toy hovercraft design problem. By analyzing the innovative products at the functional level, it was concluded that innovation metrics should be applied to the product components instead of the entire product in order to be applicable to automated concept generation tools.

Initial results based on Part II of Chapter 4 provide support that computer-directed innovation is possible using the data collection method from Part I for the entire Design Repository. Analysis of the 25 automatically generated concepts using the Design Repository against the proposed RIP hand-generated concepts shows that the RIP concept and the "Least Common Configuration" of the automatically generated concepts proved to be the most innovative solutions to the design problem. Further analysis on the student design experiment yielded statistical information on the utility of the proposed RIP method. Results from the Tennis Ball Collector design problem proved that the RIP method produced concepts that were as creative as those developed using a previously established, proven method of creative concept generation.

Chapter 5 presents revisions to the creativity assessment methods developed in Chapter 3 in order to reduce the subjectivity of the function weights in the analysis. The new method to calculate the function weights utilizes information regarding the combination effects of multiple functions to determine the level of creativity for each function. This in turn reduces the subjectivity of setting the weights of each function based on the evaluator's opinion on function importance, which was an issue that was identified in Chapter 3. The revisions show that using triple function combinations provide the most significant result differentials in the data to better highlight those designs that contain the highest levels of creativity over multiple functions. More importantly, the results of the multiple revision results show that the combinations of functions in a design problem can and do affect the overall level of creativity of designs.

Finally, Chapter 6 provided Lessons learned from the experiments ran for the CCA and RIP development, which were valuable insight into design problem formulation in experiments.

In summary, the two research questions of this research are satisfied through the propose guidelines for fostering creativity and innovation in conceptual design by the development of the Repository of Innovative Products used during concept generation and then evaluation through the use of the Comparative Creativity Assessment. These guidelines provide a unique understanding of the development of creativity through conceptual design in engineering.

7.2 FUTURE WORK AND END GOAL

7.2.2 Future Work Towards an Innovative Engineering Framework

A key future investigation will examine how to reward individual concepts within a data set that exhibit certain component combination interactions that have been documented as creative. For example, the Oliso Smart Iron has a foot assembly that lifts it off garments for burn prevention. In a coffee maker, the burn prevention function may already present, but using the components from the foot assembly in burn prevention in a coffee maker may be deemed creative. Future work will determine how to evaluate component combinations that are deemed creative and reward those concepts that exhibit the entirety of the assembly in its solution to a different problem statement.

To enhance the overall framework, future work will implement a method to incorporate function combinations in the functional model development stage of concept design. As it has been found that the combinations of multiple functions is a factor in the level of creativity and innovation in designs and products, further analysis will determine not only which individual functions contributed to market-tested innovative products, but how the leading and proceeding functions should be incorporated as well. All functional models of innovative products featured in Chapter 3 and additional products from those innovative lists will be analyzed for the innovative functions included in the Function-Component Matrices (FCMs) along with the accompanying functions attached in the models. These sets of function combinations will be stored in another repository to be used when designers are generating a functional model for the design problem being inputted into the Design Repository concept design framework. This will prompt users to include functions within their models that they normally would not have considered in the design process.

Future analysis will set up this functional model repository and test it on undergraduate and graduate level engineering courses similar to the experiments described herein to determine the utility of such a repository.

7.2.3 The Future Framework for Innovative Engineering

This research moves towards a framework for creative engineering concept design through the generation and evaluation stages. The Repository of Innovative Products (RIP) can be combined with the Comparative Creativity Assessment (CCA) method within the Design Repository (DR) to provide engineering students and industry professionals alike with the tools needed to increase their creative output in concept design. The initial steps to a multiagent framework for this work have already begun by Rebhuhn, et al (Rebhuhn, Gilchrist et al. 2012). This method will give designers the option to use the Design Repository to generate inspirational output from the RIP and automatically evaluate those ideas using the revised CCA method.

This will provide a more comprehensive framework of concept design that begins with the representation of the design problem using functional modeling, continue with concept generation that encourages creativity through previous innovative solutions, and ends with automated concept evaluation of those concepts based on comparative creativity. This is illustrated in Figure 7.1 (a reiteration of Figure 1.1 in the Introduction), in which a designer would use the Design Repository to guide them through the entire concept design process.

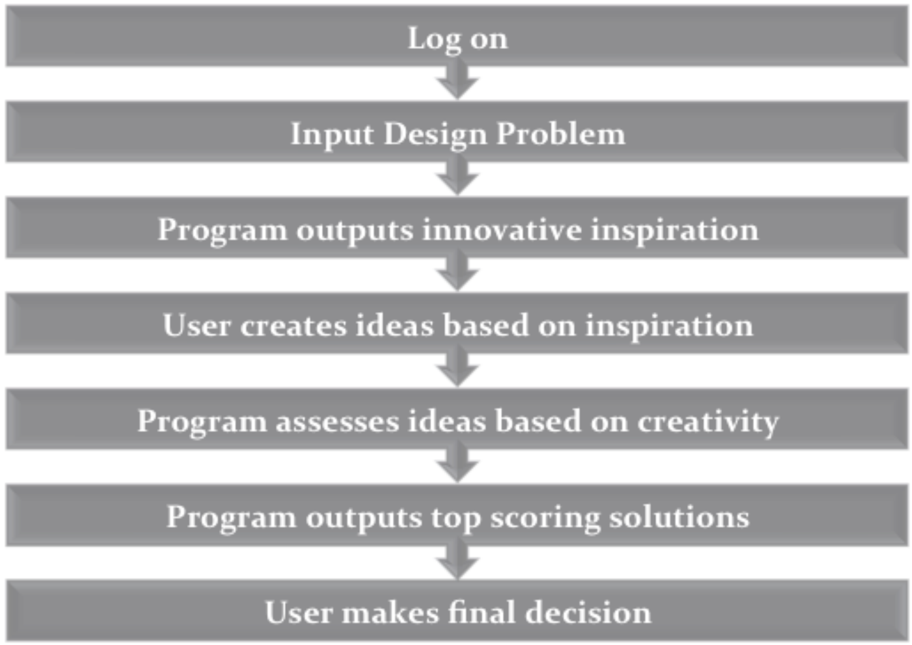

Figure 7.1: Future functionality of Design Repository utilizing RIP inspiration and CCA evaluation method

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