Establishing Functional Concepts Vital for Design by Analogy

Megan Tomko
Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA, USA

Briana Lucero, Cameron Turner
Department of Mechanical Engineering,
Colorado School of Mines,
Golden, CO, USA

Julie Linsey
Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA, USA
julie.linsey@me.gatech.edu

***Abstract*— Student designers and professionals alike have difficulty accessing appropriate analogies for design problems. Recognizing the advantages of Design-by-Analogy (DbA), the Design-Analogy Performance Parameter System (D-APPS) tool was developed to include a library of analogy entries and a matching algorithm. These components are combined into the Design Repository & Analogy Computation via Unit-Language Analysis (DRACULA) software package that maps functions across domains in order to present analogies to designers as initiated through engineering performance metrics and critical functions. Most tools developed for DbA emphasize the searching by function feature. Since analogies are based on more than function, DRACULA incorporates both performance and function for the user to identify relevant analogous solutions. Prior to exposing engineering students to this tool, we investigated their ability to use analogies when crossing domains. During this process, we identified three function concepts to be vital for students to effectively use analogies across domains: reoccurring functions, critical functions, and mapping functions. The results establish a better understanding of the information that students utilize in order to formulate appropriate and creative analogous design solutions.**

Keywords*— design-by-analogy, engineering education, functional modelling, mapping functions

I. Introduction

Through academic efforts, engineering curriculum aims to prepare students with a developed and extensive skillset in order to provide them with the means to successfully implement their knowledge in innovative and real-world applications. However, the challenge arises for the need to equip these engineers-in-training with the ability to understand both concept and application. Analogical reasoning or Design-by-Analogy (DbA) presents this opportunity for growth within the engineering domain. Amidst the complexity among the engineering domains, Design-by-Analogy offers the prospect of alleviating the barriers and potential design fixations associated with crossing domains.

In designers' attempts to tackle engineering problems, plausible solutions can be discarded or remain untouched early in the design process. During these early stages, designers can access multiple tools that can aid in concept development and idea generation. Of the many tools that are available for designers to use, functional modelling is one that allows designers to decompose a design problem into specific functionality as per a generalized taxonomy, the functional basis [1]. This generalizable decomposition introduces and pinpoints areas of innovation. It is in these areas of functional innovation that the Design-Analogy Performance Parameter System (D-APPS) tool can offer potential analogies. Integrating the D-APPS tool with the Design Repository & Analogy Computation via Unit-Language Analysis (DRACULA) software package seeks to provide analogies of similar functionality to design engineers and to employ the use of engineering performance metrics in a quantified manner. DRACULA consists of a repository, a matching algorithm, and an interface that returns alternative solutions.

Through the initial research in developing DRACULA, three function concepts were identified: reoccurring functions, critical functions, and mapping functions. For the purposes of the paper, functions are active verbs denoting an operation in a design process. The reoccurring functions are the functions that are commonly utilized throughout the various domains. Critical functions are the functions that are crucial for solving a specified design problem and defining the functionality of the product. Mapping functions are the functions that are favorable for determining appropriate analogies when crossing domains. Prior studies sought to validate the existence of reoccurring and critical functions [2-4]. During these studies, the concept of mapping functions surfaced. The process and initial findings regarding mapping functions are presented in this paper. It is important to note that these three function concepts are not mutually exclusive. There is overlap between them. This overlap introduces opportunities in building up the DRACULA repository in such a way that magnifies the potential for students to employ analogies across domains while reducing the potential for design fixation.

II. BACKGROUND

A. Design by Analogy (DbA)

To alleviate the effects of design fixation for students, analogies can offer alternative solutions to a design problem. When solving design problems, analogies provide engineers with latent analogical solutions based on a linguistic or visual portrayal of the design problem and description. Visual analogies are also useful in increasing the innovation of the design solution for both novice and expert engineers [5]. However, experimental results show that experts employ more analogies than novices [6].

Further experimentation has focused on using analogies as a means of improving design innovations [7-9]. In seeking innovative design solutions, human reasoning utilizes analogies through adhering to the design process, where the student polls their memory for source analogues. The student designer searches his or her memory and finds analogies that are comparable to the original problem. The connection between the design problem and the analogue can be established based upon experiences and memories. The final step is to develop the final design solutions using all of the analogical inputs.

To use analogical inputs in the design process, a repository of knowledge is required. Unfortunately, student and novice engineers do not have as robust of a repository as experienced engineers have due to an expert's wealth of experience that comes through practice. However, novice engineers are more willing to utilize previously employed technologies or solutions in their designs [5]. Because novice engineers do not always realize analogies to their fullest extent, they only partially reap the benefits proffered by abstraction.

B. Functional Modeling

Innovation can be engendered by functional modelling where a product is broken down into sets of functions that comprise the final tangible solution. When approached from a systems (top-level hierarchical) methodology, the sequential grouping of requirements for certain functions or subsystems (lower-level hierarchical) can lead to the same final functionality simply encased in a different form. In particular, function structures allow for the functional representation of a product using the system concept, as demonstrated through individual function boxes and flows. Function structures allow for a level of abstraction to be incorporated into the product design. Pictorially, the function and flow combinations allow for a form-independent solution that meets the design requirements. While the design progresses, the form becomes more function-dependent, and student designers can establish the specific nuances of the product in greater detail [10].

The function structure methodology requires breaking the functionality of the product into individual purposes or sub-functions. Graphically, the individual purposes are functional boxes with flows as both input and output arrows. Each flow is a material, energy, or signal that becomes pertinent to the operation of the box as derivative-notation, in a mathematical sense.

1) Functional Basis

Otto and Wood [11] proposed a defined taxonomy that can be used across multiple engineering disciplines and applications. This taxonomy was developed and refined in an attempt to aid functional modelling methods by utilizing a generic level of specificity and synonyms, also known as functional basis [1]. In this functional basis, the verb-object combination correlates to the function-flow relationship of the individual purposes. This vocabulary can be used in conjunction with the function box diagram aforementioned.

Within functional basis, functions are verbs that necessitate a specified action at a certain point in the requirement sequence. Consequently, the functions are formulated and generalized into a hierarchy of eight classes: channel, support, connect, branch, provision, control magnitude, convert, and signal. More specific functions result from the further decomposition of these eight classes. On the other hand, flows are the noun or form that coincides with this verb. Flow taxonomies can be broken down into three levels of general abstraction: material, energy, and signal as mentioned previously. As with the functions, greater levels of specific abstraction are the result of the decomposition of these three flows.

C. Functional Classification

Through the contributions of several universities, a design repository has been initiated as the basis for this work. The synthesis of the function structures in the repository led to the concept of various function classifications external to the class structure devised by Hirtz et al. [1]. This research broke down the functional modelling utilizing functions and flow based upon functionality. This functionality was derived from specific design problems possessing the potential to provide analogies for the same functions and not just linguistic similarity. The critical functions, reoccurring functions, and mapping functions are all subsets of the functions. As such, the relationship between these three function concepts is demonstrated in Figure I. The repository for providing analogies will be populated from the intersection of the critical and reoccurring functions.

1) Reoccuring Functions

Reoccurring functions are those functions that are most commonly used to model design problems in and among multiple domains. The reoccurring functions are domain specific and do not traverse boundaries as per analogical mapping. These functions are the most frequently represented functions and do not hold any specificity to the design problem. When solving design problems, student designers will more frequently use these functions to decompose the given problem, regardless of the domain for which the students are solving the problem in. For example, a student might decompose the design of a pulley system to include the function and flow combination of "import energy". This same combination of "import energy" can be utilized in efforts to decompose the design of a lamp. The pulley is in the mechanical domain whereas the lamp is in the electrical domain. Although the pulley and lamp are in different domains, the function "import" can be commonly incorporated into the functional decomposition of each product.

2) Critical Functions

Although reoccurring functions are commonly used in functional decomposition, this general subset of functions is not necessarily vital to the product's performance. Critical functions are those functions whose performance directly relates to a Key Performance Parameter (KPP) or over-arching purpose of the product or system as a whole. These functions are crucial in decomposing the product into appropriate subsystems that still successfully represent the overall system. The premise behind this concept is that not all functions hold the same level of importance in satisfying the KPPs. The KPPs are problem specific and are akin to the over-arching system-level black box model in functional modelling. Though critical functions can be made from reoccurring functions or mapping functions, critical functions are not explicitly defined by either reoccurring or mapping functions. Instead, the critical functions are problem specific and are the corner stone for this research.

III. Mapping Functions

Design-by-Analogy promotes promote design creativity and innovation [12, 13]. Innovations are either implicitly or explicitly considered when recognizing analogies. A formal definition of mapping functions is proffered as:

Mapping functions are the general subset of functions that are most conducive for successfully mapping analogies across domains in a specific design problem as laid out by functional modeling.

The differences and similarities between critical functions and mapping functions must carefully be addressed. Mapping functions behave differently in their use and purpose. Regarding domains, mapping functions act across domains in order to provide analogies which thereby indicates their lack of domain specificity. These functions illustrate the similarity between the original inspiring analogue and the analogous solution. On the contrary, critical functions are essential to the development and use of a product. Despite this difference, a mapping function can be a critical function for solving the design problem, as demonstrated in the overlapping region in Figure I. Therefore, for a given design problem, a mapping function may or may not be a critical function, and a critical function may or may not be a mapping function. The advent of mapping functions originates from the results of the following empirical pilot study and product study.

A. Empirical Product Study

This research corresponds with the study run by Ngo et al. [2] who conducted a pilot study to investigate patterns that designers use when mapping out functions for design analogies. Because of the coalescence between mapping functions and the study run by Ngo et al. [2], it is important to evaluate wherein lies the extraction of mapping functions through process that Ngo et al. follows. The process for the pilot study investigation follows that of an empirical product study, as shown in Figure II. By utilizing an empirical study, the research sought to investigate the claim that inventors will focus on certain critical function to the design problem when developing analogies. Investigating this, the study aimed to compare the critical functions of a product to the critical function of the product's respective source analogy, as pertaining to the black-box functional models. Results from the pilot study instigated further experimentation in a full-scale product study, which will be addressed later in this paper. When viewing the outcomes of both studies, the analysis suggested the presence of mapping functions in design.

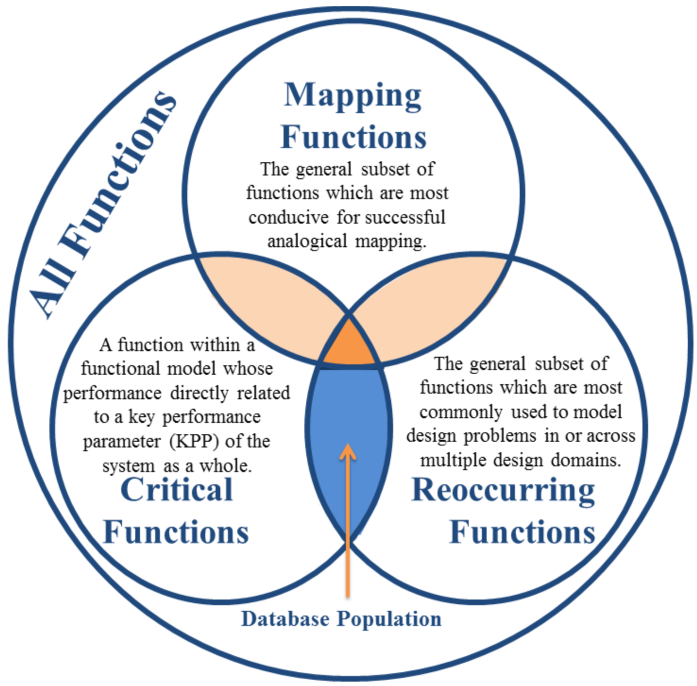

Figure I Design space for functions that stem from functional modeling.

1) Example Collection and Screening

Prior to the pilot study commencing, the researchers searched for already existing products that were inspired by analogy. After searching through a wide range of sources, a commercial product collection was compiled to include 77 product examples. These examples were screened to ensure they were in fact inspired by analogy; as such, this resulted in removing 20 examples from the collection in order to give a total of 57 product examples that would be presented to the participants of this study. A more descriptive account on the specifics of the screening process can be found in Ngo et al.'s work [2].

2) Classification

While the pilot study primarily sought to investigate the claim that inventors focus on particular critical functions, 5 classification variables were applied to the design processes that are utilized when creating the analogy-inspired products [2]. A classification variable is a variable that depends on features of the given product, the inspiring analogy, or the design process to characterize the examples provided. The 5 classification variables used are as follows:

1. Critical Functionality and Performance:

   Recalling that a critical function corresponds to the purpose of the system, the method for identifying the critical function originates from the method demonstrated by Otto et al. [11] with the Functional Basis. However, the detection of critical functions was discerned by Lucero et al. [3] as being both problem and domain specific. For each critical function, we needed to identify the system's complementary solution and performance effects. In other words, the critical function is the need, the system's solution is how the system solves that need, and the system's performance effect is the how the system's performance changes (i.e. durability, simplicity, maneuverability).

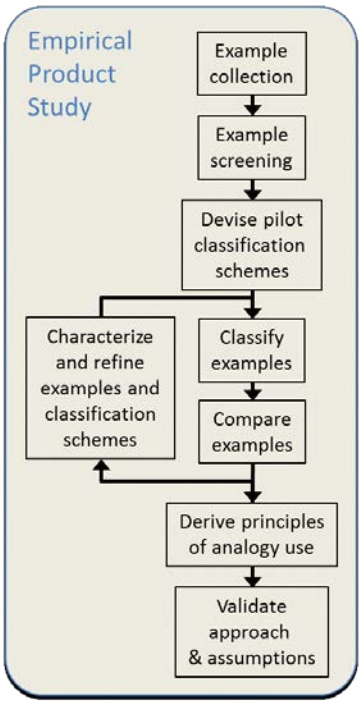

FIGURE II THE EMPIRICAL PRODUCT STUDY METHOD USED FOR PRODUCT EXAMPLES INSPIRED BY ANALOGY AS PRESENTED BY [2].

2. Main Benefit of Analogy Usage:

In design-by-analogy, the analogs inspire innovation. The main benefit of analogy usage establishes the primary contribution that an analogy inspires in an innovative product. There remain three benefits for design-by-analogy:

- Function-benefit: The analog inspires a new way of accomplishing a task.
- Performance-benefit: The analog inspires a better way of accomplishing a task.
- User Interaction-benefit: The analog inspires a new way of user interaction for accomplishing a task.

3. Analogy Difference Level:

Although the analogy inspires changes in the product's design, recognizable differences exist between the analogy and the product. Based on a low, medium, and high relation, these differences occur in the following areas:

- Critical Function: The product or analog's main purpose or function.
- Construction: The product or analog's physical configuration: material and geometry.
- Operating Environment: The product or analog's surrounding environment and conditions.

The low, medium, and high scale derives from counting the number of areas that the analogy and the product are different. When the difference is in 1 area, we assign the variable to have low-difference. With difference in 2 areas or significant difference in 1 area, we designate a medium-difference to the variable. As such, a high-difference occurs when there is difference between the product and analogy in 3 areas or significant difference in 2 areas.

4. Inventor's Primary Field of Work:

Recording the inventor's main area of work aimed to determine if their primary field of work impacted their analogy usage causing cross work domain differences to occur. The primary work fields were given as:

- Academic: This includes professors and students.
- Commercial: This includes companies and entrepreneurs.
- Military: This includes government affiliated laboratory researchers.

5. Analogy Origin and Driving Approach

During the design process, the context for how and why the analogy is used pertains to the driving approach. Analogies are not arbitrary used when mapping functions, but rather can be applied in two potential manners.

- Solution-driven approach: The designer understands a system or phenomena that can be used as an analogy, recognizes a design problem, and identifies the analogy to be the solution to the design problem.
- Problem-driven approach: The designer recognizes a design problem, identifies a system or phenomena to be used as an analogy the solution to the design problem, and fully understands the analogy being used.

3) *Mapping Functions in the Pilot Study's Results*

In order to analyze the analogy and product features, Ngo et al. [2] counted the number of examples regarding the criteria for each categorical variable, summarized this information into a contingency table as found in Table I, and recognized existing patterns in the data. Of the patterns found through the analysis, two patterns insinuate and validate the existence of mapping functions.

1. Critical Functions: Typically, inventors duplicate one or two of the analogue system's critical functions into their products.
2. Driving Approaches: The identifiable driving approach used for analogy mapping impacts how the analogy is incorporated into the design process.

TABLE I CLASSIFICATION SUMMARY OF THE PILOT STUDY [2].

Classification variables and labels	# of examples
Critical Function Matching	
Identical - One critical function	17
Identical - Two critical functions	4
Different - Inverted	1
Different - Other	2
Total	**24**
Analogy Benefit	
Function	30
Performance	24
Interaction	3
Total	**57**
Analogy Difference Level	
Level 1 – Low-difference	47
Level 2 – Medium-difference	9
Level 3 – High-difference	1
Total	**57**
Inventors' Field of Work	
Academic	32
Commercial	24
Military Research	1
Total	**57**
Driving Approach to Analogy Mapping	
Solution-driven	9
Problem-driven	4
Total	**13**

4) *Critical Functions*

Of the 24 varying analogy examples, results demonstrated 28 identifiable product and analogue critical functions pairs. For the 25 identical critical function matching pairs, we realized that there are not only critical functions, but also functions that allow for analogue mapping to occur. Since critical functions cannot be mapped across domains, these limitations on critical functions imply that certain functions exist that surpass such limitations. As such, the presence of functions capable of being mapped between domains signifies that mapping functions are a valid conjecture.

Since the results suggest that inventors directly transfer critical functions from analogies to products, further speculation insists upon the existence of mapping functions. To address these phenomena, we reviewed the latter portion of the content of the pilot study and designed a study to include human participation for data analysis

5) *Driving Approach*

From the pilot study, we re-examined the design process associated with the 13 products that had originally been investigated in efforts to determine the approach that inventors took for analogy mapping. The results of this effort can be found in Table II. As demonstrated, the solution-driven approach outnumbers that of the problem-driven approach by 9 products to 4 products. Additional results from this study indicate that: academic inventors gravitate towards solution-driven approaches whereas commercial inventors remain balanced in their approaches; problem-driven approaches tend to produce less performance beneficial analogies than function beneficial analogies whereas solution-driven approaches maintain a balance for analogy benefits; the analogy difference level does not depend on the driving approach that the inventor takes [2]. In the follow-up study performed by Ngo et al. [14], the inventor's occupation presented no correlation to the approach taken.

This analysis indicates the difference in the driving approaches influences the design process and the success of the design. In design-by-analogy, inventors travel down different avenues in their pursuit for innovation and design fabrication. In one path, the inventor already has inherent knowledge of a system or phenomena and applies their knowledge by means of an analogy in order to formulate a solution to a design problem; otherwise, this is known as a solution-driven approach. For the alternative pathway, the inventor knows of a design problem and seeks the solution through researching and applying potential analogies. This correlates to the problem-driven approach. Both approaches require mapping between domains.

TABLE II DRIVING APPROACHES VS. OTHER CHARACTERISTICS [2, 14].

	Field of Work		
Driving Approach	Academic	Commercial	Military
Solution-driven	5	4	
Problem-driven	1	3	
	Analogy Benefit		
Driving Approach	Function	Performance	User Interaction
Solution-driven	5	4	
Problem-driven	3	1	
	Analogy Difference Level		
Driving Approach	1- Low	2- Medium	3- High
Solution-driven	6	3	
Problem-driven	3	1	

In each approach, mapping functions initiate the response of the inventor. For the solution-driven approach, the inventor recognizes how certain functions within a system can be applied as functions in solving a design problem. These specific functions (aka mapping functions) allow the designer to acknowledge the similar functionalities between the product and analogue domains. As with the problem-driven approach, the inventor pursues a solution to a design problem. In their pursuit, they search to match functions of the desired product to that of an applicable analogy. Once again, the inventor heavily relies on the ability to map functions between domains. Evidently, mapping functions are essential for the inventor's ability to successfully implement analogical mapping. The mapping functions lead the designer to recognize inherent similarities between a product and an analogy.

6) Follow-up Study

In a follow-up study, Ngo et al. [14] compiled a collection of 70 products inspired by analogies for a larger cross-sectional empirical product study and analysis. In this study, two additional classification variables were incorporated for measuring the benefits in using analogies in design: additional function and improved performance. Additional function refers to a supplementary capability that arises in the participant's analogous product and not in the original functions associated with other existing products [15]. Moreover, improved performance signifies the analogy-inspired product's ability to exceed the initial functions of similar contemporary products. Integrating these variables into the analysis, subsequent results revealed that 90% of the analogy inspired products demonstrated improved performance in shared functions and 21% utilized additional functions when compared to similar products that did not utilize design-by-analogy.

We hypothesize that a majority of student designers who use analogies in analogous mapping will produce products with improved performance. However, designers will likely refrain from instituting additional functions to their innovative product. Nevertheless, during this process of mapping across domains, these results suggest that the student designer seeks to identify certain mapping functions which will not only allow them to develop an analogy-inspired design but also a product with enhanced-performance. In utilizing mapping functions, inventors have the ability to match functions across domains while producing more successful products.

IV. Study

A classroom study was performed to investigate the use and identification of mapping functions by engineering students. Mechanical engineering undergraduate students in a design course at Clemson University participated in the study. In this one semester course, students were trained in the engineering design process outlined by Otto and Wood, and also taught the functional basis for functional modeling [11].

A. Method

A specific in-class assignment was employed for use in understanding how students use mapping functions in the design process. Students were each provided with a function structure for a fruit/vegetable peeler as seen in Figure III for problem contextualization. The customer needs for the peeler product included a portable device that shields the operator from potential harm during use. Students were given different functions and a single flow type for their assignment. They were asked to provide analogies for the same action of the function on the flow. The assignment asked for any action that performed the same function to the listed flow. Directions for the assignment were given to the students as: *"You have been given three functions and a single flow type. You are to provide analogies for the same action of the function and flow. Provide any action that can do the same function to listed flow. For example, the "Guide energy" function can be analogous to trees sucking up water through capillary action. You may use analogies from any other domain and can use your phones or other devices to look up analogies."*

The students were each provided with a table template of paired "function + flows", an "analogy" column and a "rationale" column. Students were verbally instructed that this was to be an individual assignment to be completed without the use of external sources such as mobile devices or books. The instructor emphasized the desire to have as much creativity in the responses as possible by encouraging open-ended responses. Students were told there were no "correct" answers and their assignment would be graded as a participation credit.

B. Results

Provided with the given design problem, students' responses were categorized by function and analogy in order to determine their ability to produce analogies when provided with a function. Looking at the four potential functions that the students were asked to identify analogies for, convert, dissipate, position, and regulate, demonstrate relative equality in initiating analogies within the students' responses. As shown in Table III, the students who were able to create an analogy for convert was 76%, for dissipate was 64%, for position was 61%, and for regulate was 72%. This demonstrates that 24-39% of the students were not able to successfully generate analogies using the provided functions. Students and novices clearly require more support for generating analogies. Through additional analysis, the number of ideas generated was compared with the number of analogies produced, as demonstrated in Table IV. This shows that of the ideas generated for the convert, dissipate, position, and regulate functions 69%, 55%, 51%, and 64%, respectively, were analogies. Once again, the ideas generated that were not analogies ranged from 31-49% for the provided functions. This demonstrates the students' ability to utilize mapping functions when using analogies to cross domains.

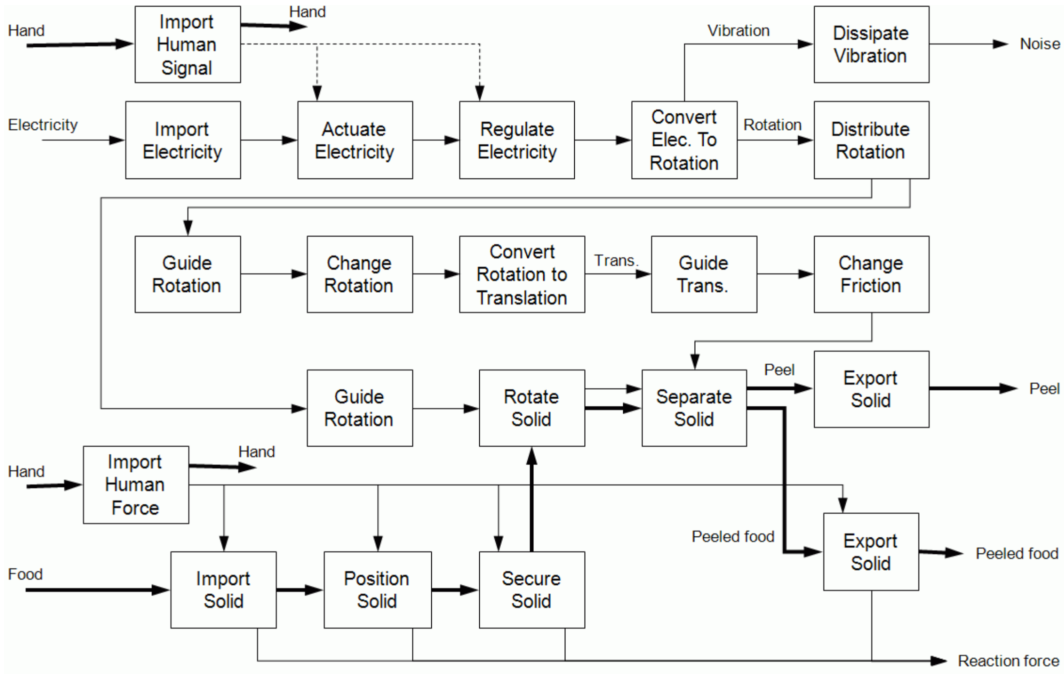

FIGURE III FUNCTION STRUCTURE FOR FRUIT/VEGETABLE PEELER FOR STUDENT ASSIGNMENT [11].

TABLE III NUMBER OF STUDENTS WHO WERE ABLE TO CREATE ANALOGIES.

Function	# of Students Who Created an Analogy	Total # of Students	% of Students Who Created an Analogy
Convert Energy	34	45	76%
Dissipate Energy	30	47	64%
Position Solid	27	44	61%
Regulate Energy	34	47	72%

TABLE IV NUMBER OF ANALOGIES FROM IDEAS GENERATED.

Function	# of Ideas Generated	# of Analogies	% of Analogies to Idea Generated
Convert Energy	80	56	70%
Dissipate Energy	77	42	55%
Position Solid	84	43	51%
Regulate Energy	84	54	64%

V. CONCLUSION

This research seeks to abate the effects of design fixations on engineering design problems when plausible solutions have been discarded too early in the design process or have yet to be found. By using functional modelling to decompose a design problem into specific functionality with a generalized taxonomy, certain areas of innovation can be pinpointed. These areas demonstrate the potential for student designers to more successfully utilize analogies across domains in order to create innovative and plausible designs.

When it comes to utilizing analogies across domains, mapping functions are the general subset of functions which are most conducive for successful analogical mapping. The mapping functions are an area of continued investigation at this time. Identified during the critical function study of Lucero et al. [3] and Ngo et al. [14], these specific sets of functions have the potential to provide more analogous solutions than those of just the critical functions or the reoccurring functions.

The research herein identified the mapping functions as retaining function, performance or user-interaction benefits between the analogue and product. The benefits of these functions then are based upon the product critical functions, the construction, and the operating environment. The approach of the mapping functions to generate analogies is based upon either a solution or a problem approach, similar to a forward or reverse methodology. To further validate the findings, additional studies are currently in the works and will be published.

ACKNOWLEDGMENT

Support for this work was provided by the National Science Foundation Award No. CMMI-1304383 and CMMI-1234859. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. The authors would also like to thank Dr. Joshua Summers at Clemson for assisting with data collection. This work is derived from the dissertation of Briana Lucero [4].

REFERENCES

[1] J. Hirtz, R. B. Stone, D. A. McAdams, S. Szykman, and K. L. Wood, "A functional basis for engineering design: reconciling and evolving previous efforts," *Research in engineering Design*, vol. 13, pp. 65-82, 2002.

[2] P. Ngo, V. Viswanathan, C. J. Turner, and J. Linsey, "Initial Steps Toward an Analogy Retrieval Tool Based on Performance Specification," in *ASME 2013 International Design Engineering*

Technical Conferences and Computers and Information in Engineering Conference, 2013, pp. V02AT02A070-V02AT02A070.

[3]B. Lucero, V. K. Viswanathan, J. S. Linsey, and C. J. Turner, "Identifying Critical Functions for Use Across Engineering Design Domains," *Journal of Mechanical Design*, vol. 136, Dec 2014.

[4]B. Lucero, "Design Analogy Performance Parameter System (D-APPS)," unpublished thesis Colorado School of Mines, 2014.

[5]H. Casakin and G. Goldschmidt, "Expertise and the use of visual analogy: Implications for design education," *Design Studies,* vol. 20, pp. 153-175, 1999.

[6]L. J. Ball, T. C. Ormerod, and N. J. Morley, "Spontaneous analogising in engineering design: a comparative analysis of experts and novices," *Design Studies,* vol. 25, pp. 495-508, 2004.

[7]J. S. Linsey, A. B. Markman, and K. L. Wood, "Design by Analogy: A Study of the WordTree Method for Problem Re-Representation," *Journal of Mechanical Design,* vol. 134, Apr 2012.

[8]J. S. Linsey, I. Tseng, K. Fu, J. Cagan, K. L. Wood, and C. Schunn, "A Study of Design Fixation, Its Mitigation and Perception in Engineering Design Faculty," *Journal of Mechanical Design,* vol. 132, Apr 2010.

[9]R. L. Marsh, J. D. Landau, and J. L. Hicks, "How examples may (and may not) constrain creativity," *Memory & cognition,* vol. 24, pp. 669-680, 1996.

[10]G. Pahl, W. Beitz, J. Feldhusen, and K.-H. Grote, *Engineering design: a systematic approach* vol. 157: Springer, 2007.

[11]K. N. Otto and K. L. Wood, *Product design : techniques in reverse engineering and new product development*. Upper Saddle River, NJ: Prentice Hall, 2001.

[12]B. T. Christensen and C. D. Schunn, "The relationship of analogical distance to analogical function and preinventive structure: The case of engineering design," *Memory & cognition,* vol. 35, pp. 29-38, 2007.

[13]P. Leclercq and A. Heylighen, "5. 8 analogies per hour," 2002, pp. 285-304.

[14]P. Ngo, C. J. Turner, and J. S. Linsey, "Identifying Trends in Analogy Usage for Innovation: A Cross-Sectional Product Study," *Journal of Mechanical Design,* vol. 136, Nov 2014.

[15]M. N. Saunders, C. C. Seepersad, and K. Holtta-Otto, "The Characteristics of Innovative, Mechanical Products," *Journal of Mechanical Design,* vol. 133, Feb 2011.