Functional Representations in Conceptual Design: A First Study in Experimental Design and Evaluation

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Abstract

Functional modeling is an abstraction technique intended to help engineering designers perform conceptual design. Functions are constructs that describe a transformation between an input flow and an output flow. A primary characteristic of functions is their independence from the physical aspects of a device or artifact. In this sense, functions are form independent and deliberately lack reference to geometry that would otherwise describe how a design solution is physically instantiated. This form independence is generally thought to facilitate designer thinking and reasoning about designs in a manner that benefits designer performance. The purpose of this work is to develop an experimental method with metrics to examine the effects of functional modeling on designer performance in a controlled setting and to test the hypothesis that functional modeling has a positive impact on designer performance.

Our approach is to test the effectiveness of concept generation by measuring a carefully selected set of parameters. The values of these parameters are determined from the results of a controlled conceptual design exercise. This approach effectively circumvents the need to perform protocol analyses of the engineers. Instead, the results of an experimental design task such as a set of concept sketches and descriptions are used as a data source. Recent work in the design research community has provided examples of how to relate empirical results of this form to underlying performance parameters of interest. Outcomes of this research are an improved experimental technique, a refined set of metrics, and an improved understanding of the manner and degree to which functional modeling supports conceptual design practice and design education. This study shows that functional modeling, for the experimental parameters and design problem selected, is indistinguishable from the experimental control and does not inhibit the idea generation process. While this result is incomplete to address the hypothesis, important contributions of the study include a development and investigation of general experimental metrics, a greater understanding of how to design and structure concept generation experiments, and the need to empower participants with either inventive functions or with a full-fledged functional methodology.

Keywords: functional modeling, design method effectiveness, empirical design study, conceptual design, concept generation

1. Introduction

The activities involved with design are skills that must be developed and nurtured with practice and repetition. Expert level design skills emerge after many such repetitions that occur as a result of activities on-the-job or closely related experiences. Concept generation is one particular engineering design skill emphasized in engineering curricula. Engineering students are taught many techniques that offer a structured approach to conceptual design. Examples include both individual and team based creativity-enhancing methods such as brainstorming, mind-mapping, or 6-3-5. Due to time constraints, students often have minimal practice with methods taught in the classroom for the purpose of skill development. An important and unresolved question is how much impact these design methods have on designer performance in light of the fact that practice is minimal.

In this work, we examine how the use of functional modeling during conceptual design impacts student designer performance. We define designer performance as the overall effectiveness and efficiency with which students complete a conceptual design activity. Although this view of performance includes a great number of metrics and variables, this work accounts for a reduced set of factors that describe the output of a design activity (in contrast to a protocol study, directly accounting designer actions such as decision events). Here we choose to measure the: (1) quantity of ideas, (2) technical feasibility, and (3) novelty. The research objective is to experimentally measure the impact of functional modeling methods upon conceptual design performance by senior engineering students. An empirical study is conducted in a controlled setting to meet this objective in which the *experimental group* ("functions group") is cued to use functional modeling, and the *control group* is not cued to use any specified technique. The hypothesis of this work is that functional modeling is expected to result in overall improvements in designer effectiveness and efficiency.

Here we briefly review functional modeling and refer the reader to design texts such as Pahl and Beitz[1] or Otto and Wood[2] for greater detail. The particular vocabulary for the functional modeling language used in this work was developed by researchers from University of Missouri-Rolla, University of Texas-Austin, and National Institute of Standards and Technology. This line of work has resulted in the development of a standard vocabulary for describing the functionality of systems in the electro-mechanical domain. This effort has culminated in a functional basis language that includes a set of terms that span the space of all functions and all flows in this domain.[3] Here "function" refers to a transformation operation from input flow to output flow. Functions are used in verb-object format. For example, a motor "converts electrical energy to mechanical energy." Tables 1 and 2 show a portion of the functional basis. Using this functional vocabulary, device functions can be defined for a given system using a functional model.

Table 1: Function examples from the functional basis[3]

Class	Function
Branch	Separate
	Distribute
Channel	Import
	Export
	Transfer
	Guide
Connect	Couple
	Mix
Control Magnitude	Actuate
	Regulate
	Change
	Stop
Convert	Convert
Provision	Store
	Supply
Signal	Sense
	Indicate
	Process
Support	Stabilize
	Secure
	Position

Table 2: Flow examples from the functional basis[3]

Class	Flow
	Human
	Gas
	Liquid
	Solid
	Plasma
	Mixture
Signal	Status
	Control
	Human
	Mechanical
	Acoustic
	Pneumatic
	Biological
	Radioactive/Nuclear
	Chemical
	Thermal
	Electrical
	Electromagnetic
	Hydraulic
	Magnetic

Using the language of the functional basis, designers can describe a system using a connected set of functions and flows. An example of a functional model for a subsystem of an extraterrestrial probe is shown in Figure 1 (from collaborative research endeavors with NASA-Ames Research Center). Functional models can be implemented as catalysts during conceptual design to promote creative generation of concepts. This work aims at experimentally determining how well functional modeling supports this design task.

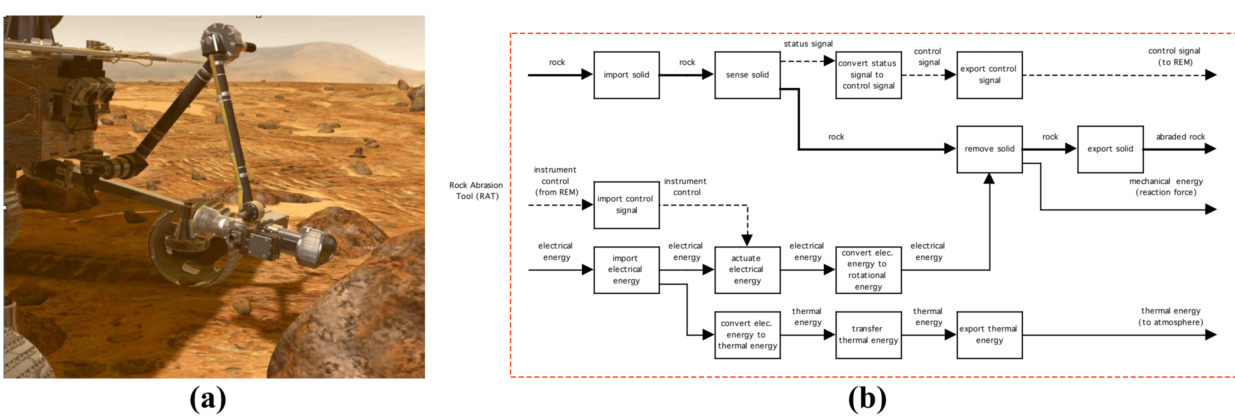

Figure 1: (a) NASA Martian space probe
(b) Functional model of space probe robotic arm rock abrasion tool

2. Experimental Method

To evaluate the effects of using functional modeling during conceptual design, two experimental sessions were conducted in a lecture hall. The sessions used two different design problems and were held sequentially. Participants were randomly assigned to one of two conditions represented by a control group (no specified concept generation technique was given) and an experimental group, referred to in this paper as the "functions group", that was told to use a functional modeling approach. The sessions were conducted near the end of a semester following a series of lectures on functional decomposition and various techniques for idea generation.

2.1 Participants

The participants included fifty-four students from a senior design methods course at The University of Texas at Austin. The participants received extra credit for their participation based on the number, quality, novelty, and variety of solutions they developed but all participants received substantial credit. The participants were told their extra credit would be based on the quality and quantity of their solutions.

2.2 Description of the Design Problems

The design problems for the experiment were derived to address needs of traditionally underserved communities, such as persons with physical disabilities. Motivation has been shown to have a strong influence on the idea generation process.[4] For this reason, real-world problems were chosen to provide additional motivation for the participants and to provide the possibility their efforts could be put to good use. The participants were informed that their solutions might be given to design teams for further development.

The first session's design problem was based on a problem from ThinkCycle.[5] ThinkCycle is a web site facilitating distributed design collaboration to meet the needs of underserved communities. The "design challenge" selected from ThinkCycle is the inadequacy of hot water, heating, and electricity to meet the needs of students residing in dormitories at universities in Southern China. One specific problem created by the lack of access to electricity and/or hot water is less sanitary dish washing. A related problem exists in many parts of the world where bathrooms do not have running water available for hand washing. These difficulties served as the basis of a design problem formulated for this work to develop a sink for a college-style dorm room. Many students participating in the study have lived with the inconvenience of limited access to a community sink a far distance from their dorm room. These experiences made the problem easy for the students to understand and relate to, and yet they were unfamiliar with satisfactory solutions to the problem and thus free from the danger of fixating on existing solutions during concept generation.

The problem description requested the participants to design a portable dorm room device for hand washing, dish washing, and teeth brushing (Table 3). It briefly described the corresponding real-world problems and explained the reason for posing the problem as designing a device for a dorm room. The statement included the following customer needs: easy for hand washing, convenient and sanitary for dish washing, convenient for teeth brushing, and easily portable. Participants in the experimental "functions" group were given a starting point defined by a set of basic functions. These basic functions included the following: contain the water, heat the water, dispense water to object, and dispose of or store the dirty water.

Table 3: Design problem #1 – "Dorm room washing device"

Design Problem	Design a portable device for a dorm room to allow you to wash your hands, your dishes, and brush your teeth in your dorm room. Your dorm room does not have a sink.
Customer Needs	1. Easy to wash your hands 2. Convenient and sanitary to wash dishes 3. Convenient to brush your teeth 4. Easily portable
Functions *Test Group Only	1. Contain water 2. Heat the water 3. Dispense water to object 4. Dispose of, or store the dirty water

The design problem for the second session was a device enabling children with very limited motor skills to create art (Table 4). This problem resulted from discussions with teachers at a local school for children with disabilities. The problem statement included a brief description with a picture of a switch frequently used for this type of application to give the participants an idea of the motor skill level the children have. Participants were also given the customer needs of: easy to operate, easy to clean-up, and easy to create art with limited motor skills. Participants in the experimental "functions" group were given the basic functions of: the device must contain, position, and dispense an art medium along with holding a paper in place.

Table 4: Design problem #2 – "Art enabling device"

Design Problem	A device needs to be designed to allow children with severe physical disabilities to create art projects. The children have very limited motor skills. They cannot hold items such as a paint brush. The device needs to be actuated by simple electrical devices such as the large switch shown on the left. Teachers will set-up the device for the students to use. The device must be safe and easy to use. 
Customer Needs	1. Easy to create art with very limited motor skills 2. Very easy to operate 3. Simple operation with the push of large buttons or other simple devices 4. The art medium (e.g. paint, glue, glitter, and/or markers) device should not make a large mess and needs to be easy to clean-up
Functions *Test Group Only	1. Contain art medium such as paint, glue, glitter, and/or markers 2. Position the art medium over the paper 3. Dispense the art medium onto the paper 4. Hold paper in place

2.3 Procedure

Participants began the exercise with no initial information regarding the particulars of the design problems. All participants received blank sheets of 8 ½" by 11"paper and were then given sheets with the description of the problem and instructions for the design exercise. Participants were seated every other seat to provide adequate space for drawing and to prevent participants from inadvertently gaining ideas by seeing each other's work. Participants had 45 minutes to complete the activity.

The participants were randomly assigned to either the control group or the functions group based on the set of instructions they received. Participants in the experimental "functions" group were given the set of functions for customer needs and the additional guideline to generate ideas by focusing on finding solutions to the functions stated. The instruction sheets for all participants, both the experimental and control groups, included a description of the problem, a set of rules to follow, and a set of customer needs. The instructions were partially based on the basic brainstorming rules[6] of seeking a large quantity of ideas along with encouraging "wild" (uncommon) and diverse ideas. The instructions also indicated that the students should solve the design problem by writing down their solutions with words and/or pictures, the solutions could meet one or all the customer needs, and the goal was to maximize the quality, quantity, novelty, and variety of the solutions.

3. Metrics for Evaluation

A number of different metrics have been used to evaluate idea generation techniques including quantity of ideas, number of good idea, practicality, novelty, and variety. Commonly used metrics are the quantity of non-redundant ideas and a quality rating.[7] An early study on the use of brainstorming for engineering problems included the metrics of quantity of ideas, technical feasibility, effectiveness, and cleverness.[8] A more recent study by Van der Lugt[9] used a technique called linkography[10, 11] which uses connections (links) between ideas as the base measure. Linkography can be used to evaluate how well participants build off each other's ideas and the types of modifications made to previous ideas. Shah et al.[12] developed a set of metrics for the evaluation of engineering ideas including quantity, quality, novelty, and variety of ideas.

Three metrics were chosen for evaluation in this study: quantity of ideas, feasibility, and novelty. Building from the procedure developed by Shah et al.[12] where each problem is broken down functionally to measure quantity of ideas and then rated for the novelty, quality, and variety of ideas, the quantity of ideas was measured. The definition of what constitutes an idea was defined as a solution that meets a primary product function of the functional basis. This provided a consistent level of detail and good inter-rater agreement. Two raters, who were blind to the conditions of the experiment and the hypothesis, independently counted the number of ideas based on a standard procedure. Full evaluation, including technical feasibility and novelty, is in progress although preliminary results are presented in this work. Preliminary novelty scores were completed by one of the authors. The inter-rater agreement for quantity was 78% for a sample of the second session's data. For novelty and technical feasibility, raters will be considered to be in agreement if they are within one point of each other. This method for inter-rater agreement has been used previously.[13, 14, 15]

A critical definition for this process is what constitutes a single idea since two of the metrics are measured at the single idea level. Is a single idea a component, a single noun phrase, an item that meets any function, or something else? This question is particularly difficult when the data is in the form of sketches because sketches frequently contain many vague details. Most sketches contain a number of identifiable individual components along with a number of other details (Figure 2). Ideally a procedure for counting ideas would not depend on the functions chosen or would be based on a standardized basis of functions that describe engineering products at a set level of detail. Shah et al.[12] based the definition of an idea on meeting a key function from the product's function structure. Shah et al.[12] used guidelines provided by Pahl and Beitz[1] to express the design problem as subfunctions.

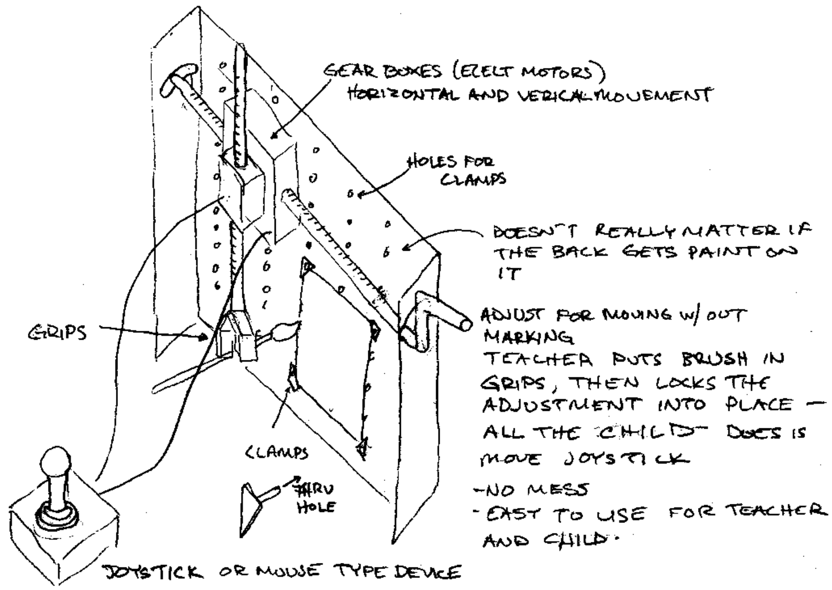

Figure 2: An example of a sketch containing a number of identifiable components and other details

The method for measuring the quantity of ideas given by Shah et al.[12] is a good starting point but is not completely adequate because this method does not implicitly provide a standardized level of detail in the functions. Different idea generation techniques may tend to produce ideas at various levels of abstraction. Functional decomposition is likely to cause a focus towards less abstract, very specific solutions. Other idea generation techniques, such as the use of physical effects or analogy to biological systems, may produce more abstract concepts that must be refined later in the process. Thus care must be taken in defining the metrics in order not to bias the results. The definition used for this study was an idea meets at least one product function as expressed by the functional basis.[2, 3, 16, 17, 18]

The counting of ideas based on product function provides a good initial step for measuring the number of ideas but does not address all issues. A summary of the procedural counting rules is given in Table 5. A remaining issue is whether only primary or secondary level functionality should be included. In the data, very few secondary support functions were identified by the judges and therefore the choice was made to include secondary functions in the quantity of ideas. A second difficulty occurred with components that meet more than one function. For example, a paint gun serves the functions of energizing and guiding the paint. Each component was counted as only one idea even when it met more than one function. This choice was made because it provided greater consistency between raters since there is less room for different interpretations of the intended function of a component. A third rule was the case when the only change between ideas was that previous ideas were combined. For this case, it was not counted as an additional idea. Occasionally a fourth issue occurred when both a category and specific subordinates were listed. In this case, the category was not counted but the subordinates were. If only a category was listed then it was counted. The last guideline for quantity measurement was when the same component was used to meet the same function in multiple places it was not counted as an additional idea.

Table 5: Quantity counting rules summary

1.	Each idea must meet one of the functions in the functional basis
2.	An idea can meet either a primary or secondary function
3.	Each idea or component counts as only one idea even if it solves more than one function
4.	Combinations of previous solutions do not count as ideas
5.	Categories only count as ideas when no subordinates are given
6.	A component being used in multiple places counts as one idea

After the quantity of ideas was counted, each individual idea from the quantity metric was then given a technical feasibility rating (Table 6). Example data with feasibility ratings is shown in Figure 3.

Table 6: Technical feasibility scale (for concept elements)

Score	Description
1	Not feasible or not useful for solving the given problem
2	May be possible but would require significant research and development time
3	Requires some development or research but it is probably possible
4	Used in other application but needs some minor changes
5	Very feasible (it is a common solution), and would definitely work

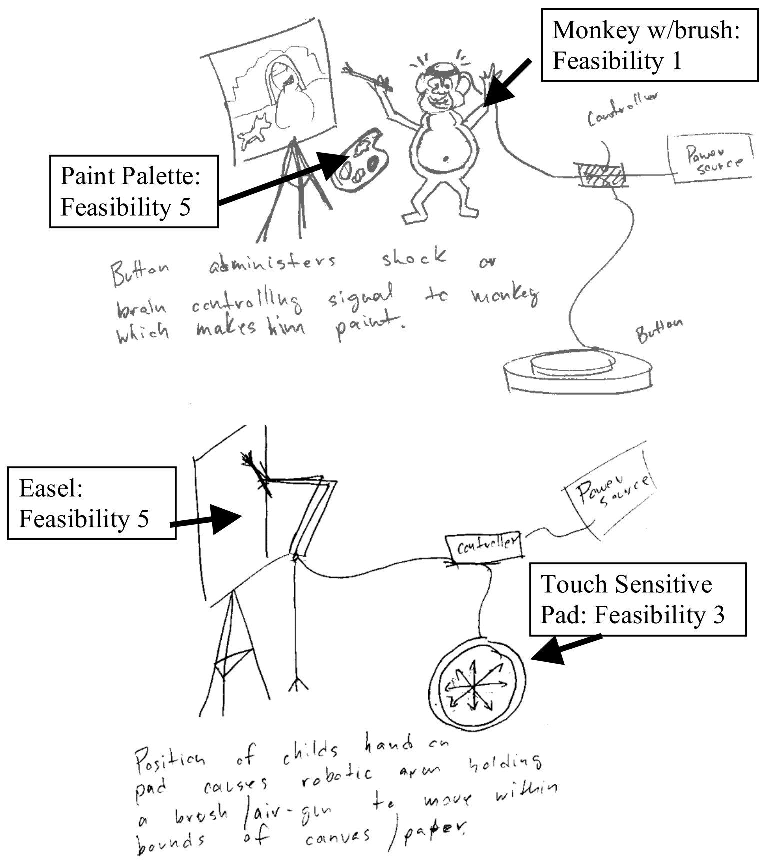

Figure 3: Example data with technical feasibility ratings

Each design concept rather than individual ideas was rated for novelty (Table 7). A concept was defined by a separation existing between groups of ideas. This separation was usually in the form of being on a different page, separated by a line, identified with a new number, or separated by white space.

Table 7: Novelty scale (for a design concept)

Score	Description
1	Not an unusual solution, a very common solution
2	Common solution for very similar problems
3	Occasionally used for related problems
4	Rarely used
5	Very unusual

4. Preliminary Results

Preliminary results for quantity and novelty have been completed for the data from the second design problem, the "art enabling device." One participant's data was thrown out because he quit about half way through the session. Quantity results were completed by two evaluators who were blind to the conditions and hypothesis of the experiment. One evaluator measured quantity for half of the "art enabling device" results while the other evaluator completed about ten percent of this problem's results. Novelty was scored for all data from the "art enabling device" by one of the authors. Below we provide example results for one participant to illustrate our methodology, followed by aggregate results for all data counted.

4.1 Example Results for One Participant

A complete set of data from one participant and the resulting quantity, novelty, and technical feasibility scores are shown in Figures 4 and 5, and Tables 8, 9 and 10. Like most participants,

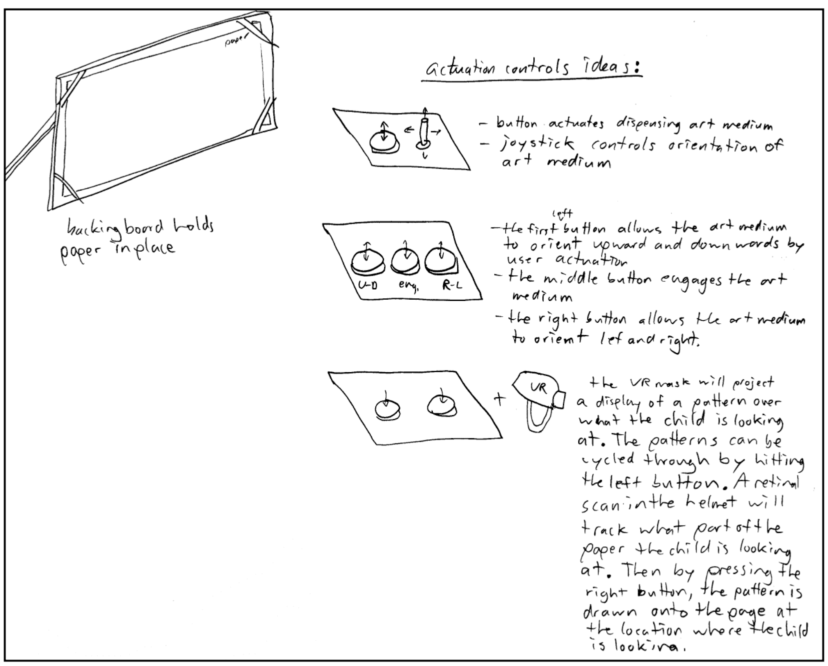

Figure 4: Data from participant #1, page one

this person incorporated the switch given in the problem statement into his concepts. This participant tended to use sketches less than many of the other participants. When participants gave long written descriptions, the description usually did not contain a large quantity of ideas, which is suggestive of the importance of sketching or other graphical techniques in concept generation. The sample of data from this participant illustrates the level of detail found in the data and shows how this particular sample measures in terms of quantity, feasibility, and novelty.

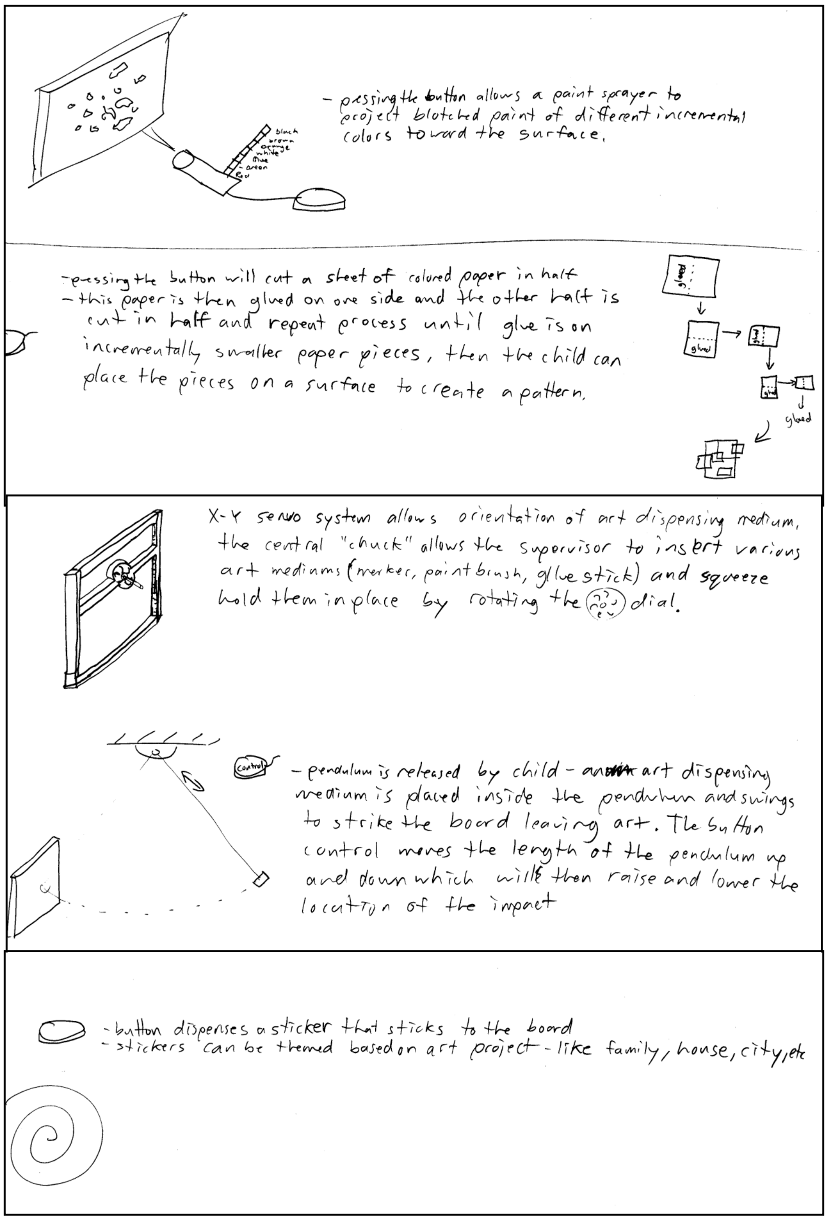

Figure 5: Data from participant #1, pages two, three, and four

Table 8: Quantity of ideas - participant #1 summary

Functions	Summary of ideas for each function	# of unique solutions
[Signal] – from user		
Import on/off	button	1
Import position	joystick, *button*, retinal scan	2
Import medium choice	*button*, virtual reality helmet	1
[Energy] - main		
Guide	pendulum pivot	1
Energize art medium	paint sprayer, pendulum potential energy	2
[Material]		
Store medium	tube w/ color segments, central chuck	2
Guide medium	X-Y servo, pendulum	2
Store paper	vertical board, support leg	2
Total Quantity of Ideas		**13**

Table 9: The technical feasibility of each unique idea for participant #1

Functions	Solution	Feasibility	Solution	Feasibility
[Signal] – from user				
Import on/off	button	5		
Import position	joystick	4	retinal scan	2
Import medium choice	virtual reality helmet	2		
[Energy] - main				
Guide	pendulum pivot	5		
Energize art medium	paint sprayer	5	pendulum potential energy	5
[Material]				
Store medium	central chuck	4	tube w/ color segments	4
Guide medium	X-Y servo	5	pendulum	4
Store paper	vertical board	5	support leg	5

Table 10: The novelty scores of each concept for participant #1

Concept Number	Novelty Score
1	1
2	1
3	1
4	2
5	2
6	3
7	2
8	4
9	2
Avg. Novelty Score (per Concept)	**2**
# of concepts >=3	2
# of concepts >=4	1

4.2 Summary of the Preliminary Results

The preliminary results for the "art enabling device" produced some unexpected results that seem to reject, in part, the hypothesis. The quantity of ideas generated using functional modeling was not different from the control group (Table 11). One explanation is the particular design problem is relatively easy to break-down and therefore the participants in the functions group did not have an advantage. Participants in both groups were familiar with functional modeling but only the functions group was given a set of functions and told to focus on them.

Table 11: Quantity of ideas - preliminary results

	Ave. Quantity of Ideas	Standard Deviation of Quantity	Sample Size
Control Group	19.0	8.6	5
Functions Group	19.7	5.8	7

The preliminary novelty data indicates the average novelty score per concept was not statistically different, but the participants in the control group produced 71% of the concepts in the top half (>=4) of the novelty scale (Table 13). These results show that functional modeling warrants further investigation, especially the variety and novelty of functional descriptions given to the participants. The results also show that a staged approach to concept generation may be needed at different levels of problem and functional descriptions.

Table 12: Novelty of ideas (total concept) - preliminary results

	Avg. Novelty	Standard Deviation of Ave. Novelty	Sample Size
Control Group	2.22	0.23	11
Functions Group	2.16	0.43	13

Table 13: Novelty - number of high scoring concepts

	Concepts w/ Novelty Scores >=3	Concepts w/ Novelty Scores >=4
Control Group	26	5
Functions Group	23	2
Total	***49***	***7***

5. Discussion of the Results

The preliminary results from the experiment are interesting and intriguing. While, at the very least, the control group could not be distinguished from the experimental group (indicating hypothesis rejection), the quantitative and anecdotal data gives us tremendous insights into concept generation experiments in engineering. These insights range from the type of experimental problem chosen to the level of function description and the development of appropriate experimental metrics.

The problems chosen for this experiment motivated the participants and were sound choices in terms of complexity and real-world character. These problems, however, were straight-forward for the participants to decompose into functions, and therefore did not provide a robust test of functional modeling. In addition, the way this experiment was set-up, the complete functional modeling methodology was not used. More control was needed since participants in both groups were familiar with the technique and therefore participants in the control group could have also used functional modeling. For these reasons no difference between the control and the experimental group may have been observed.

A relevant consideration is the notion that persons under time pressure or other significant stress do not rise to the occasion but rather sink to the level of their training. In this case, the implication is that the participants did not possess sufficiently well developed functional modeling skills to ultimately exceed the conceptual design performance levels of their peers who used no mandated technique. Inadequacies in functional modeling skill may actually burden the designer if mandated to use functional representations. Additional experiments with highly skilled functional modelers or the removal of time constraints can clarify the utility of function based representations in the context of conceptual design. The results of this work suggest that design theory researchers should continue to develop and advance functional modeling techniques in order to improve the viability of such methods in undergraduate curricula.

Research results also suggest the need for an improved focus on the choice of the design problem. For our study, the problem states that the device is for "… children with severe physical disabilities … [with] very limited motor skills … [such that they] cannot hold items such as a paint brush." However, a significant number of concepts disregarded this information, resulting in infeasible concepts for meeting the customer needs. This result may imply that students were unfamiliar enough with physical disabilities that they had trouble connecting with the problem statement, and quickly forgot the customer they were generating concepts for. In fairness to the students, an emphasis was placed on quantity of ideas along with the spirit that "crazy ideas are good" (because they can lead to further innovation). An open question is do diverse ("crazy') ideas actually lead to innovation and feasible concepts or is the suspension of judgment the key to the success of techniques that emphasize diversity.

The current novelty scale does not adequately capture the range of novelty seen in the concepts. Our current procedure of measuring novelty only at the concept level is not adequate. Novelty must be measured at both the concept and the functional level, because important novelty at one level is not necessarily reflected at the other. A particular solution to a single function can be novel without producing a novel concept, and conversely a novel arrangement of low-novelty functional solutions can result in a concept with high novelty. A revision of the novelty scale and procedure is anticipated. A deeper understanding of what is meant by novelty is needed.

6. Conclusions and Future Work

This paper provides an important initial starting point for understanding the effects of functional modeling on the design process. An experiment was preformed to evaluate the impact of functional modeling on conceptual design performance. A set of metrics for the evaluation of functional modeling in the conceptual idea generation phase was chosen and refined. The metrics proposed in this paper are technical feasibility, novelty, and quantity of ideas. A set of procedural guidelines for these metrics was developed and implemented. Preliminary results were produced and evaluated. This preliminary evaluation of functional analysis shows that the participants produced a rich set of ideas and that provided functional descriptions did not help or hurt the idea generation process. A careful study of the preliminary results shows the results are rooted in the simplistic functional descriptions provided, the common functional modeling training of the participants, and the straight-forward nature of the problems that were easily decomposable into basic functions. This conclusion, while not desired, provides key insights into how to develop more complete and robust future experiments.

Future work will include a more precise definition of what constitutes a single idea, consideration of additional metrics, and additional experiments to adequately measure the method of functional analysis. Currently, the definition of an idea does not include items such as the type of material to be used, overall product layout, and industrial design aspects such as aesthetics. The procedural rules for the measurement of quantity will be improved to provide a higher level of inter-rater agreement. The current procedure provides an adequate level of agreement but a better set of rules is preferred. Additional metrics to be considered include the level of abstraction, cost feasibility, and customer needs satisfaction. Clearly, functional modeling may have effects not captured by the current set of metrics or this experiment. Future experiments will include participants who are not familiar with functional modeling and will use design problems where functional descriptions include alternative sets of functions and the inclusion of novel or non-obvious basic functions.

Acknowledgements

The authors would like to thank Rebecca Lee for her assistance with the development of the device for a dorm room problem and Jeremy Murphy for acting as the second evaluator. Rebecca Lee's work was a part of her participation in Graduates Linking with Undergraduates in Engineering (GLUE) at the University of Texas. The authors also thank the support provided from the Cullen Endowed Professorship in Engineering, The University of Texas at Austin.

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