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# ASSESSING DESIGN METHODS FOR FUNCTIONAL REPRESENTATION AND CONCEPT GENERATION: STRATEGIES AND PRELIMINARY RESULTS

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## ABSTRACT
To support collaborative conceptual design, methods for functional representation and concept generation are essential. Many methods have been proposed following various design theories, but little assessment has been done to compare methods or provide guidance for choosing appropriate methods. In particular, the context considered is entrepreneurial engineering design in which support is needed for individuals—many with non-technical backgrounds—to define, assess, and develop their ideas, thus involving a combination of individual and collaborative work. Seven methods for functional representation and six methods for enhancing creativity during conceptual design were considered. A proposed set of criteria was defined for evaluation of the methods, and the methods were applied to a common set of design problems and compared and contrasted. Additionally, experimental design procedures for individual and group design tasks and samples of training materials are presented. An initial set of interviews and experiments were conducted to assess designers' perceptions, learning, and skills in using the different methods. Preliminary results of the on-going experiments, conclusions, and future work are described.

*Keywords: Functional representation, Creativity, Conceptual design, Assessment*

## 1 INTRODUCTION
Conceptual design is the earliest stage of the design process in which major decisions are made about the principal technical solution of the design [1, 2]. The decisions made during this stage have significant influence on outcomes of the design such as cost, performance, reliability, etc. of a product [3]. Conceptual design in a collaborative environment brings diverse groups of designers and stakeholders together, and functional models play an important role in collaborative, conceptual design. While designing a concept, functions of the product are defined and represented, and functional models allow design information to be abstracted at the functional level, thus providing a focus for conceptual design activities. Creativity is a mental process involving the generation of new ideas or concepts, or new associations between existing ideas or concepts [4]. It can support collaborative, conceptual design with additional, new, and divergent ideas.

Many design models or methods to improve the functional representation and creative thinking of designers have been proposed, but there has not been much research assessing the relative usefulness of the methods. The validation or assessment of design methods is important for both the continuing advancement of design theory and the professional practice of engineering. Researchers in design theory require validation processes to guide the development and evaluation of new methods. Professional practitioners need validation processes to determine which methods to employ, as well as when and how to employ them [5]. Without evaluation and feedback on design methods, engineering design lacks a sufficient scientific foundation and makes design practice to be guided by specialized empiricism, intuition, and experience [6].

The goal of this paper is to propose a strategy to assess those methods for functional representation and creative thinking of designers. This kind of research, called "research in design thinking," has several research methods, such as interviews with designers, observations and case studies, protocol studies, controlled tests, simulation trials, reflection, and theorizing [7-9]. This work uses a combination of interviews, observations, and case studies.

Section 2 of the paper presents the background and motivation of the work. Section 3 of this paper gives a brief introduction of the selected, representative design methods used for representing functional descriptions (7 methods) and creative thinking in conceptual design (6 methods). Section 4 presents a detailed view of the experimental design and procedures for assessing those methods. Section 5 gives the preliminary results of the experiments that are in process and discussion, and the last section is the conclusion and future work.

# 2 BACKGROUND AND MOTIVATION

## 2.1 The Future of Mass Innovation

For sustained economic development and industrial competitiveness, participation in innovation activities needs to be broadened. Considering the integration of engineering design with innovation, the future of the innovation process should provide opportunities for individuals—especially expanding opportunities for additional individuals with or without engineering and scientific backgrounds—to participate in the genesis and realization of novel products and services. Ideas for novel products can arise from disparate sources: medical devices and surgical tools from a pathologist, sustainable building equipment from a rancher/contractor [10], automotive power train components from machinist [11], and so on.

The design research community can help move society beyond mass production and mass customization into a new paradigm of **mass innovation**. Mass innovation can be defined as expanding and diffusing engineering activity to the lowest possible level through connecting individual inventors and entrepreneurs—who do not have engineering backgrounds—with the engineering tools and services needed to realize their novel design concepts. They should be able to communicate with engineering service providers and access available tools to state, test, analyze, and develop their ideas. When this vision is realized, individuals will be able to leverage globalization and cyberinfrastructure to draw upon the latest scientific and technological advances in developing their ideas.

The first step in the mass innovation process is for a prospective inventor or innovator to describe the intended functionality of the product, device, service, etc. All invention is the result of perceived shortcomings in existing products [12]. An individual or small number of users have recognized a need before the general public, and they stand to benefit from resolving the shortcomings of the existing design or system [13, 14]. Once a person forms an idea, a set of computer tools should be available to state their idea formally, to assess the originality of the idea, to locate available technological solutions, and to quantify its prospects to have an innovative impact. This involves checking whether the idea represented by its intended functionality and the choice of design solution already exists and if not, whether is possible to be realized. After the originality and feasibility of the idea are validated, the next step in the process involves the inventor communicating the idea to others. Engineering analysis can be accomplished through a variety of means, depending on the nature and complexity of the project: doing the analysis oneself, automated analysis with software, using virtual reality and other computer-aided engineering tools, outsourcing the analysis to domestic or overseas engineers, or collaboration with academic or industrial partners. Once the design and engineering analysis have been conducted, a prototype can be created through several possible methods: rapid prototyping, outsourcing, etc. Within a short time—a few weeks or days—an idea should go from germination to tangible implementation. The inventor can then use the tangible device for experimental validation, robust design, etc.

Additional steps in the entrepreneurial process to be considered include the development of business plans and strategy, quantifying the financial prospects of the design, raising capital, etc. as well as the need for protecting intellectual property and intellectual capital. These steps can be tied to existing architectural frameworks for modeling operational, functional, node connectivity, and other business and strategic aspects of a new design in creating a cyberinfrastructure. Many of the pieces needed for future entrepreneurial engineering already exist, and others are in development. The piece that needs the most work is the first—the cyber-tools for modeling, communicating, testing, and refining of an idea to predict its innovative potential. This work is motivated by the search for the best means for non-technical individuals to formulate and develop their inventive or innovative ideas.

## 2.2 Assessing Design Methods and Tools

Recent research in engineering design has started with a "functional basis" for representing engineering designs [15-18], yet this is only one of many approaches to modeling function that have been proposed. A rigorous assessment needs to be made of different methods for capturing design functionality from the cognitive standpoint of entrepreneurs or designers.

It is important to understand formal methods used for representing functions during problem formulation. These methods describe a system's functions and how they interact. They are intended to facilitate communication among designers and stakeholders and to support the development of innovative and collaborative designs. Problem formulation has been observed to be the most difficult task in design [19], and it is critical because designed systems and artifacts will fail if problem formulation never stabilizes or is based upon incorrect premises.

This work seeks to establish a means to evaluate various formal methods for representing functions during problem formulation and concept generation in engineering design. [20, 21] The goal is to facilitate communication and establish a complete and correct set of functions in collaborative, creative design. A method needs to be created to evaluate the approaches. As Frey and Dym have said, "If the engineering profession does choose to extend an objective concept of validation to design methods and tools, it will need a supporting set of practices and standards for the provision of evidence" [5].

## 3 DESIGN METHODS CONSIDERED

### 3.1 Methodologies for Representing Functionality

Functional requirements represent what a product or system must do independently of possible technical solutions [19]. An effective and efficient representation of functions is very important to facilitate collaborative, creative, and innovative design. It also provides domain independence so as to allow transdisciplinary design and analysis [22]. Various methods have been proposed for representing functions [23, 24]: functional basis [15-18], black box, function means tree [1, 25-28] (compare with [29] and [19, 30]), enhanced function means tree, function—behavior—structure [31-34], functional evolution process, structured analysis and design technique (SADT/IDEF0) [35-38], and so on. Each of the functional models captures a different set of information, and each has its own advantages and limitations. In this paper, seven kinds of functional representational methodologies were selected for evaluation. Other standard diagrams of systems that could be considered include UML (or SysML) but were not considered in this study. Reviews of functional modeling can be found in [39, 40].

#### *A. Functional Basis*

The functional basis of design accurately specifies various flows (of materials, energy, and signals) through a design using a vocabulary of standardized flows that can be broken down into flow classes, basic and sub basic flows and complements [15-18], as shown in the example in Figure 1. The representation of flow describes physical information about transformations within a product's technical system. Functional representation based on the functional basis of design consists of the following three steps [15, 41, 42]: 1. generate a black box model, 2 create function chains for each input flow (express sub-functions using the common functional basis and order function chains with respect to time), and 3. aggregate function chains into a functional model.

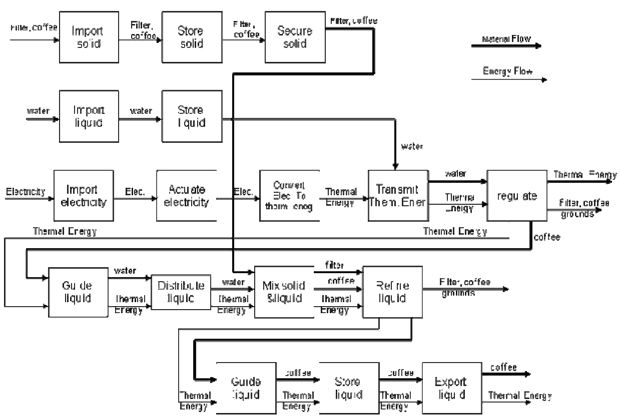


*Figure 1. Functional basis model for a coffee maker [20]*

#### *B. Black-Box Method*

The design process begins with defining the function of a product from the specifications provided. Then the functions are divided into sub-functions, sub-functions into sub-sub-functions, and so on, until the level in which physical behaviors to perform each sub-functions are achieved. A design artifact can be considered as a transformer that takes in a set of inputs–namely, energy, material, information, and forces/moments & displacements, shown in Figure 2—and transforms them into a set of desired outputs. Information is gathered about the necessary inputs by asking questions on the inputs and outputs: What type of energy is required? How much? What materials are required? [43]

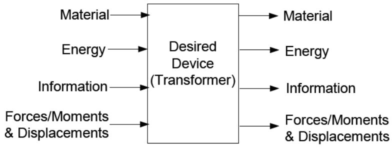


*Figure 2. Black Box Approach [43]*

***C. Function Means Tree***

The function means tree represents each hierarchical level of design with independent functions as seen in Figure 3. A function means tree gives an overall view of the functions and possible solutions of a system [27]. Initially, in a function means tree, the main function is defined for which a solution is needed. Then, the second level represents the possible means/solutions for the main function. Successive levels list possible solutions for the prior sub-functions and sub-functions for prior solutions. The process continues by dividing the sub-solutions into sub-sub-functions and so on until the designer is satisfied with the decomposition.

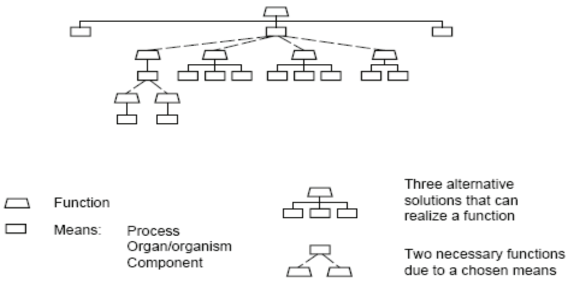


*Figure 3. Function Means Tree [44]*

***D. Enhanced Function Means Tree***

The enhanced function means tree gives more details of design decisions than can be included in a function means tree [44]. An enhanced function means tree consists of three different objects: functional requirements (FR), means (DP), and constraints (C), shown in Figure 4 [45]. The modeling procedure starts with the overall functional requirement (FR) and constraint (C) at the highest hierarchical level. The decomposition of the design proceeds similar to that for the function means tree, but also includes constraints on sub-solutions as well additional types of relationships.

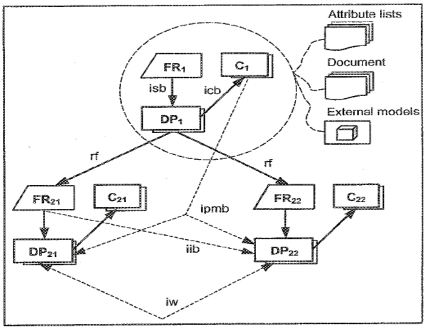


*Figure 4. Enhanced Function Means Tree [45]*

### *E. Functional Evolution Process (FEP)*

In this method a functional representation is defined using structure and behavior FBS (Function-Behavior-Structure) modeling [33, 34, 46]. Then, the FBS is used in a design process in which functions are gradually evolved using the Functional Evolution Process (FEP) [47]. In FEP the model of a design object is evolved through three steps: 1. function description, 2. function actualization, and 3. function evaluation [48]. Based on the structure of the function, there are three kinds of relations among functions that represent a part of functional evolution: decompose, be-caused-by, be reinforced by.

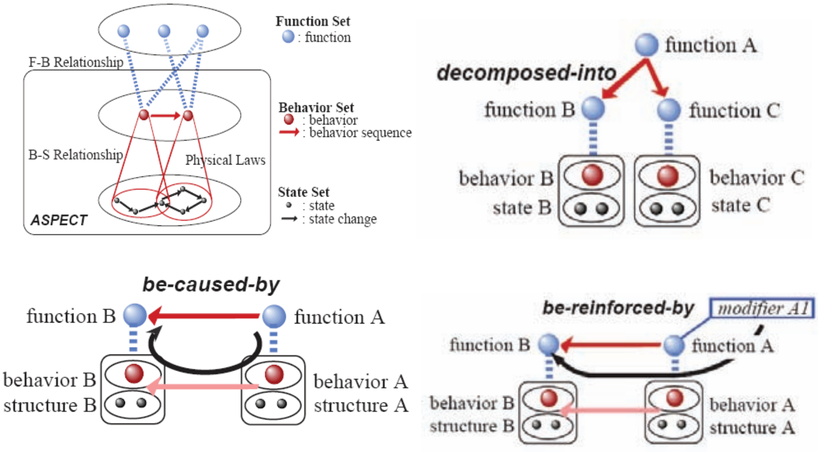


*Figure 5. Functional Evolution Relations [47]*

### *F. SADT/IDEFØ*

SADT/IDEF0 is an activity-modeling methodology used to provide a structured representation of the functions performed by a product, system, or organization [35]. IDEFØ is based on the Structured Analysis and Design Technique (SADT), a graphical approach to system description [36, 37]. The IDEFØ notation consists of boxes that represent activities in the system and arrows that represent the interfaces between the activities consisting of inputs, outputs, mechanisms, and controls.

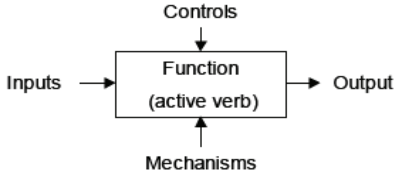


*Figure 6. Basic elements of SADT/IDEFØ modeling [36]*

### *G. Schemebuilder*

The initial step in Schemebuilder is the creation of a generalized function means tree [49]. Scheme builder is based on the bond graph formalism to represent a function. The bond graph technique is used to represent a system as a composition of components, such as transformers, sources, and gyrators. The use of bond graph reasoning provides a unique set of rules for the decomposition of energetic systems.

## 3.2 Methods for Improving Creativity in Conceptual Design

Several traditional and novel design methods were selected for the study: concept mapping, affinity diagrams, morphological charts, TRIZ, biomimetic design, and function means trees.

***A. Concept Mapping***

A concept map is a diagram that shows the relationships among concepts. They are graphical tools for organizing and representing knowledge. They include concepts, usually enclosed in circles or boxes of some type, and relationships between concepts indicated by lines linking concepts [50] with labels which can be words or symbols, such as "gives rise to", "results in", "+" or "%". Figure 7 gives an example of a concept map showing key ideas and principles.

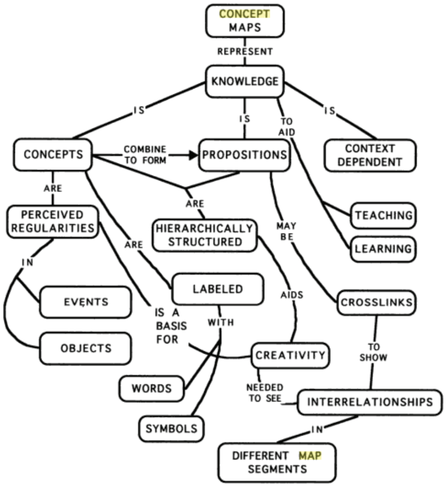


*Figure 7. a concept map showing key ideas and principles exhibited in a concept map [51]*

***B. Affinity Diagrams***

An affinity diagram maps issues and insights across all customers into a hierarchical diagram to reveal the scope of the problem [52]. An affinity diagram is a tool that gathers large amounts of language data (ideas, opinions, issues, etc.) and organizes it into groupings based on the natural relationship between each item. It is largely a creative rather than a logical process. The following steps are used for creating an affinity diagram: 1. generate a list of ideas, and post the ideas on a wall, or a table in a random manner (see Figure 9-a), 2. sort the ideas into related groups which are placed at the wall in columns (see Figure 9-b), 3. create header cards for the groups, which capture the essential link among the ideas in the group (see Figure 9-c), and 4. continue placing header and superheader cards above the groups of ideas, 5. review and document the finished affinity diagram. (see Figure 8)

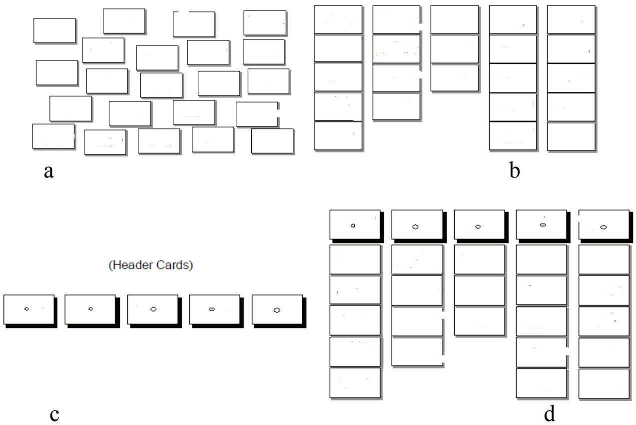


*Figure 8. Example figures for describing the steps for creating an Affinity Diagram*

### *C. Morphological Charts*

A morphological chart is a visual way to capture the necessary product functionality and describe alternative embodiments to fulfill a device's functions [53]. For each element of product function, there may be a number of possible solutions. The chart provides a structure for considering alternative combinations in concept generation and can help the team generate a complete range of alternative design solutions. However, note that morphological charts only illustrate aspects of a design, but do not directly refer to whole, distinct design concepts The steps in following the morphological approach are 1. list product functions that are essential to the product, 2. list the possible 'means' for each function, 3. draw up a chart containing all possible sub-solutions, then 4. chart functions and means and explore combinations. An example of a morphological chart is given below in Figure 9.

### *D. TRIZ*

TRIZ is the Russian acronym for the theory of inventive problem solving that originated from extensive studies of patent and technical information. Studies of patent collections by Altshuller, the founder of TRIZ, indicated that only one per cent of solutions were truly pioneering inventions: the rest represented the use of previously known ideas and concepts, although perhaps in a novel discipline [17, 54].

TRIZ methodology includes analytical tools for problem formulation and knowledge-base tools for system modification. The analytical tools include the algorithm for inventive problem solving (ARIZ), substance-field (su-field) analysis, contradiction analysis, and required function analysis and are used for problem formulation, analysis, and transformation. The knowledge-base tools include 40 Inventive Principles, 76 Standard Solutions, and a database of physical effects. These tools have been developed based on an accumulation of innovation experience and a vast collection of patents [54]. Following the theory, designers need to an abstract model using the analytical tools for the design problem, then go to the knowledge base tools to look for solutions, and finally map the abstract solution to their specific problem.

### *E. Biomimetic design*

Biomimetic design was inspired by the motivation to follow nature through learning and imitation. Biomimetic design (also known as bionics, biognosis, biomimicry) is a design that, fully or partially, imitates or evokes some biological phenomenon [55]. There are many inventions and applications based on biomimetic design. For example, the Wright brothers got their inspiration for the first aircraft steering mechanisms from birds, or the total drag of the aircraft can be reduced by drag reducing micro-riblets as found on the scales of shark skin, etc. The natural world has provided human beings with optimal solutions to their problems, and biomimetic design is the best means in realizing these.

### *F. Function Means Tree*

Function means trees have already been introduced in Section 3.1; however, since the creation of the function means tree involves the detailed decomposition of both functions and means, it can be used as an aid for concept development.

## 4 EXPERIMENTAL DESIGN

In this work, the authors constructed an experiment to assess the seven methods for functional representation and six methods for enhancing creativity during conceptual design with three stages:

1. Applying the selected methods to a same product or problem to create training material for subjects of the experiments and make a first level comparison.
2. Design a questionnaire for interviews about methods for functional representation to be conducted wigh individual participants for a qualitative comparison.
3. Design a well-structured experiment to assess methods for enhancing creativity with subjects formed in groups for a high quality comparison.

### 4.1 Stage I

In this stage, the seven different functional representation methodologies were applied to represent the functions of one daily used product, a coffee maker, to give the authors a first view at the influence of using different methodologies. The same procedure was done for the six methods for enhancing creativity, applying them to generate concepts of the coffee maker design. Also during this stage, the authors produced training materials for each method by recording and analyzing the process of application, which could be used in the following stages to train the subjects.

## 4.2 Stage II

In this stage, a short interview was conducted to test different functional representation methodologies, and and a set of criteria for evaluating the interview results was created.

The subjects included university faculty members, graduate students, and expert designers working at a Fortune 500 company. Following are the interview procedures:

1. Different methodologies for representing functions were explained to the subjects.
2. The subjects were asked to represent functions of products using the discussed methodologies.
3. Questions were asked to them relevant to the criteria selected for evaluation of different methodologies, including "How much time was required for you to understand this methodology?" "For representing functions which method would be easiest to use?" and "What difficulties did you meet while representing functions?"
4. Answers to the questions were documented maintaining anonymity of the subjects.

Several criteria were established for evaluating functional representation methodologies:

1. Subjects disciplines: The functional model should be able to represent functions covering various disciplines such as mechanical, computer, electrical, chemical etc.
2. Time: Time required for representing functions using the methodology.
3. Time to learn the method: Time required for learning the method, in order to use it. Need to consider whether the method is easy and convenient to use or not.
4. Completeness of information produced: The method considered should be complete; it should be able to represent all the functions (details) of the product (information for multiple disciplines).
5. Communication accuracy: The method should be easy to interpret and convey all the details (functions) accurately about a product to designers and stakeholders.
6. Software support: Is software support available for representing the selected model?

Then, the authors analyzed the records of the interview based on the criteria above.

## 4.3 Stage III

In this stage, a well-structured experiment was designed to assessing the six selected methods for enhancing creativity. the methods are concept mapping (c), affinity diagrams (a), morphological charts (m), function means tree (f), biomimetic (b), and TRIZ (t). Additionally control groups were assigned that were neither taught nor used a particular method during the session.

The authors recruited about 80 subjects consisted of undergraduate students, graduate students, and members of the Amarillo Inventors' Association. With the guidance of the training material, the subjects were asked to represent the same design problem using different methodologies, which will give insight on how those methodologies affect their creativity.

### *4.3.1 Procedures*

1. The subjects are divided into 3 sections: (a) graduate students section, (b) undergraduate students section, and (c) Amarillo inventors section. Each section is divided into 7 groups, 3-5 people per group, and the experiment is done with each section one by one. The experiments for sections (a) and (b) have been carried out, and those for group (c) are on-going.
2. All of the groups are distributed with respect to the experiment task and methods.
3. Each group subjects works in two parts. For each part, the groups are given instruction materials for one method or serve as a control group. After finishing working on part 1, the group secretaries turn in the discussion results. Then the subjects of each group will be given instruction materials for another method, and that is the part 2. Table 1 shows a sample of the arrangement. each group will be allowed to work on each part for 35 minutes. the methods are concept mapping (c), affinity diagrams (a), morphological charts (m), function means tree (f), biomimetic (b), TRIZ (t), and control (n/a). the design process of section (b) was also videotaped in order to maintain a comprehensive record for research analysis of group interaction.

*Table 1. Distribution of groups and methods for stage III*

| | G1 | G2 | G3 | G4 | G5 | G6 | G7 |
|---|---|---|---|---|---|---|---|
| Part1 | B | T | C | A | M | N/A | N/A |
| Part2 | F | B | T | C | A | M | F |

### *4.3.1 Criteria of evaluation*

Creativity is a mental process involving the generation of new ideas or concepts, or new associations of the creative mind between existing ideas or concepts [4]. It is mysterious and hard to measure. Historically

researchers have defined creativity in terms of several features, which, of primary importance are fluency, flexibility, and originality. More recently, some researchers have asserted that creativity should also be defined in terms of usefulness, which reflects the practicality of a given set of ideas. Fluency refers to the number of ideas; flexibility reflects the number of different conceptual categories represented in a given set of ideas or the number of ideological shifts in thinking, in other words, diversity of ideas; originality indicates the novelty or rarity of each idea.
So in this paper, the definition of creativity above will be used as the evaluation standard for the experiment:

1. Fluency: the number of ideas produced in the experiment task.
2. Flexibility: the number of different disciplines of the ideas covered in the experiment task.
3. Originality: the number of the novelty or rarity of ideas.
4. Ratio of Usefulness: improvement of the design goal or requirements compared with existing designs.

### *4.3.2 Evaluators*

In this experiment, three experts of the design field will invited as the evaluator. They will be provided with the evaluation standards for assessing. For section b) which is videotaped, the evaluators will do evaluation on both the materials written by the subjects and the videos record all of their activities.

## 5. RESULTS

The first and second stages of the experiment have been completed. The third stage is in process. Therefore, in this paper, results of the first two stages will be exhibited and discussed.

1. For the first stage, the authors applied the selected thirteen methods to coffee maker design and created training material for the followed experiments. Since the limited length of the paper, only the material of morphological charts is exhibited as a sample.

A brief overview is used as the first paragraph, followed by the example design process to explain the steps to implement this method:

1) List product functions. See the ‘Functions’ column on the example figure, Figure 9. The functions should be generated at an appropriate level and be essential to the product.
2) List the possible 'means' for each function. See the ‘Options’ column on the example figure. For each function, list the ‘means’ or possible solutions by which it might be achieved: Think about new ideas, as well as known solutions or components and where possible ideas should be expressed visually as well as in words.
3) Chart functions and means & explore combinations. See the lines on the example figure.

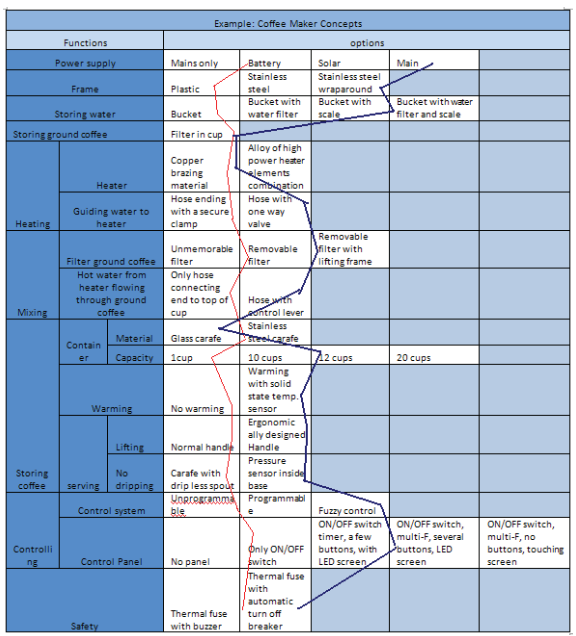


*Figure 9. Sample Morphological Chart of Coffee Maker*

For the second stage, the answers of the participants of the interview were evaluated by using the criteria. 1) **Disciplines:** The function means tree, enhanced function means tree, and functional evolution process seems general and are able to represent multiple disciplines. Schemebuilder is mostly suitable for electronic and mechanical components, and it will be difficult to represent functions of products which cannot be represented as power or energy flow. Functional basis can also represent functions of mechanical and electromechanical components appropriately. Black box approach has difficulty in representing functions of a component that does not transform something from I/P to O/P. IDEFØ can represent decisions, actions, and activities of an organization or system. Among all the approaches considered black box approach seems to be the weakest in its original form; 2)**Time required for learning the method:** Black box approach and function means tree take least time to understand. Schemebuilder take the most time to learn; 3) **Time required for representing functions:** black box approach and functions means tree take least time. Functional basis and functional evolution process require more time; 4) **Completeness of information:** enhanced function means tree, IDEFØ, and functional evolution process represent most of the information about a product. Function means tree and functional evolution process have a good way of representing constraints of a product, which is important for achieving a good practically feasible design. Functional basis is useful to represent abstract and incomplete information during the conceptual stage of the design process; 5) **Communication accuracy:** Functions represented by function means tree and function evolution process are easiest to interpret. Function means tree, and function evolution process models functional requirements and design parameters together which improves communication between different stakeholders. The design parameters and constraints of Enhanced function means tree interact with each other, lending dependency to the system. It helps in communicating and tracking the effects of changing one parameter on other associated parameters. Functional basis has a standard set of words for representing and decomposing functions which makes it easier to communicate between stakeholders and to come up with repeatable functional representation of a product. As IDEFØ model also shows information about controls and mechanisms with the functions at the same time, it helps for understanding and communicating functional information more clearly. 6) **Software support:** Most of the interviewees said software support will be helpful in representing functions of a product. The software support should also allow stakeholders geographically located in different locations to document and represent functions effectively.

## 6 CONCLUSION AND FUTURE WORK

In this paper, a well-structured experiment was designed with sets of evaluation standards to assess the methodologies selected for improving functional representation and creative thinking in collaborative conceptual design respectively. The results gained from the completed two stages indicate that the method of assessment designed in this paper is working well so far. The authors can also say that when assessing different design methods, good training materials are needed and making sure that representing the same design problem with different methodologies gives clear insight on how those methodologies affect the conceptual design of subjects.

The future work will implement the experiment of the third stage: Making evaluation of the design methods to provide support for increasing creativity of problem formulation and design concepts, facilitating communication among designers and stakeholders, developing collaborative software tools for design, and expanding design tasks to larger, more complex problems.

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