A Framework for Holistic Ideation in Conceptual Design

Based On Experiential Methods

by

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ABSTRACT

The main objective of this project was to create a framework for holistic ideation and research about the technical issues involved in creating a holistic approach. Towards that goal, we explored different components of ideation (both logical and intuitive), characterized ideation states, and found new ideation blocks with strategies used to overcome them. One of the major contributions of this research is the method by which easy traversal between different ideation methods with different components were facilitated, to support both creativity and functional quality. Another important part of the framework is the sensing of ideation states (blocks/ unfettered ideation) and investigation of matching ideation strategies most likely to facilitate progress. Some of the ideation methods embedded in the initial holistic test bed are Physical effects catalog, working principles catalog, TRIZ, Bio-TRIZ and Artifacts catalog. Repositories were created for each of those. This framework will also be used as a research tool to collect large amount of data from designers about their choice of ideation strategies used, and their effectiveness. Effective documentation of design ideation paths is also facilitated using this holistic approach.

A computer tool facilitating holistic ideation was developed. Case studies were run on different designers to document their ideation states and their choice of ideation strategies to come up with a good solution to solve the same design problem.

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DEDICATION

This thesis is dedicated to my mother Visalakshi and my father Mohan who worked so hard all their life to provide a good education for me, whose love and support will always be there for me anytime. I also dedicate this thesis to my dear sister Gayathri Mohan whose care and affection was always there when I needed them. Special thanks to my friends back in India Collins Rajendran, Venkateswaran Prasanna, G.M.Karthikeyan, Selvakumar, Senthil and Sriram Narasimhan. I would also like to thank my friends here in the U.S., Dr. Saravana Prakash, Kumaraguru Prabakar, Adithiya Sreenivasan, Srinath Balaji, Neelakantan Mani, Sreeram.R.C., Harikrishna Devaraj, Sarangarajan V. Iyengar and Christofer Jenkins who were always there to help me in the last 2 years.

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Chapter 1

PROBLEM DEFINITION

It is not unusual to see only a handful of people involved in conceptual design and this critical activity being typically conducted over a short period of time. On the other hand, detailed design may involve orders of magnitude more engineers and time. The reasons for this are that there is a lot of work needed to be done in the detailed design stage and there is also a lack of formal methods and design ideation tools for conceptual design. Experienced designers also tend to use the past solutions and design for a new design problem and patch or refine it to fit new set of requirements [1]. Time constraints, risk aversion and design fixation exacerbate this practice.

Computer tools for embodiment and detailed design (CAD) evolved rapidly in the past 30 years and now are pervasive throughout industry. However, they provide little or no support for the early stages of design where creativity is most needed. The primary focus of design researchers has been more on design automation, rather than support for enhancing human creativity. Fundamental understanding of design processes and human cognition are pre-requisites for future CAD tools for conceptual design. Some conceptual design tools present today follow a single approach to ideation. Conceptual design is not a monolithic process and many strategies are needed at different times i.e. a single approach is not sufficient. Ideation methods have been broadly classified into intuitive and logical methods. Since engineering design requires both creativity and functional quality, it is argued that strategies of both experiential methods and intuitive methods must be included. It is also not possible to employ all known ideation methods into a single research tool. Both intuitive and logical ideation methods have certain elements in them which promote ideation called as ideation strategies. In attempts to understand these ideation strategies, some researchers have employed protocol studies. It is estimated that it generally takes 40 hours to analyze 1 hour of data, and hence this method is considered to be very difficult. Therefore, there is need to create a time efficient research method/ tool that would enable collecting and analyzing massive amounts of data related to creativity in design.

In systematic conceptual design, [2] there are several steps such as function decomposition, idea generation, idea evaluation and creation of solution principles.

Thus a complete design ideation tool should support at least the following functions:

a. Functional decomposition
b. Sub solution generation
c. Solution combinations
d. Solution evaluation
e. Documentation

In the coming sections, we will see in detail about the steps involved in conceptual design, how ideation states are sensed, different ideation methods used and how a holistic ideation test bed with all these characteristics is built. Also, at this point we need to emphasize that this holistic ideation test bed will not be a design automation tool or has the capability to build an integrated CAD model. This will just be a test bed which can sense ideation states and suggest appropriate ideation methods present in the test bed and also facilitate effective documentation of information related to creativity.

Chapter 2

BACKGROUND

2.1 ENGINEERING DESIGN

To begin with, let us discuss what engineering design is and what the steps involved in it are and the importance of conceptual design.

Engineering design is a multi-step process to create a product for a set of requirements. This multi-step process can be listed as follows [2]:

a. Task clarification and planning
b. Conceptual design
c. Embodiment design
d. Detailed design
e. Production

2.1.1 Planning and Task Clarification

This is the initial stage in product design where the task is given to the product development from the marketing team. The requirements imposed can be based on either customer requirements or just to make some improvement on an existing product. So when the task comes from the marketing department, all the tasks need to be clarified and requirements should be analyzed in detail. Also, the objectives and constraints for the product design should be defined precisely here. At the end of this stage, a list of requirements is created and this list prevails as a reference for the conceptual design and subsequent phases of product design. This list gets updated with the design process.

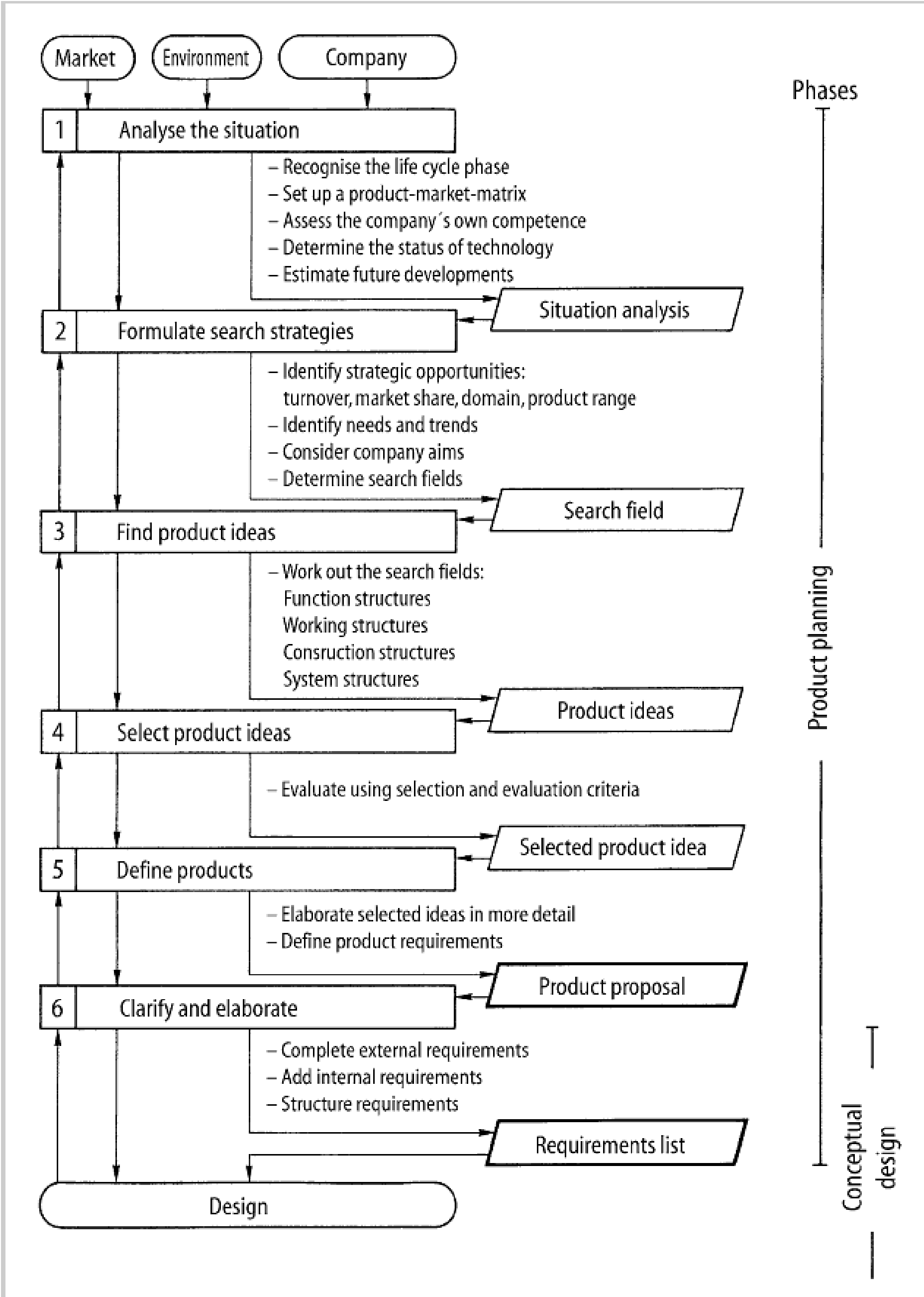


Figure 1. Planning and design process [2]

2.1.2 Conceptual Design

Design process explained in this section is based on systematic design of Pahl and Beitz [2]. In actual practice, the conceptual design process is totally different. It changes with respect to problem novelty, complexity, uncertainty, experience of designer, available sources etc. Hence, systematic design explained here cannot be wholly applied for novel and evolutionary designs. Hence, certain additions/changes need to be made to make it more suitable to current conceptual design practice. The main change needed in systematic design process to make it suitable to novel/evolutionary design is the addition of different ideation strategies.

Once the requirements are clearly defined in the planning stage, they should be transformed in appropriate functions. Thus, with the help of these requirements, function decomposition is made and a function tree is built. This function tree can be either sequential or hierarchical. An example of a sequential function structure from Pahl and Beitz [2] is shown below.

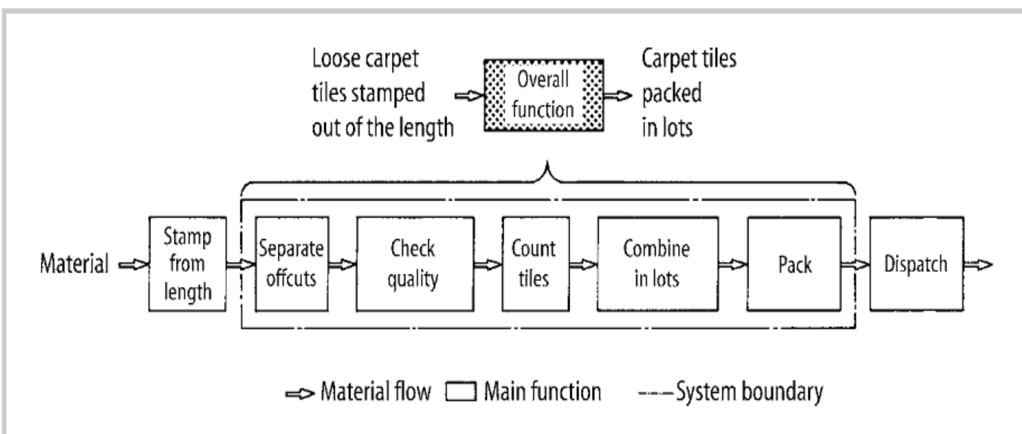


Figure 2. Function structure for Carpet tiles packaging [2]

After the creation of function structure, for each of these functions, appropriate working principles are searched for and those working principles are combined to form a working structure. Ultimately, at the end of a conceptual design process, the designer gets a principle solution (concept) with the help of different working structures. Mostly, a working structure cannot be assessed until it is transformed into a more concrete representation. This involves material selection, dimensional layout, and analyzing technical feasibility. More details on steps involved in conceptual design process is shown in the next section and importantly, none of those steps should be skipped if the most promising principle solution is to be found. A successful design depends mostly on the decisions taken and solution principles generated in conceptual design stage and it is very much difficult to make changes in later stages during embodiment or detailed design if there are any shortcomings. This does not ensure that there will be no problem arising in the detailed design stage if an effective conceptual design process is done. An effective conceptual design process is a process where more time is spent and more options are explored using divergent thinking.

At the end of this conceptual design process, a set of solution principles are obtained. Now, they need to be evaluated and inappropriate solution principles are eliminated. Once a finalized set of solution principles are obtained, we move on to a more concrete level of embodiment design.

2.1.3 Embodiment Design

The concepts produced in the conceptual design process are transformed into construction structures and layouts are generated for several variants generated in conceptual design.

Once sufficient numbers of layouts are generated, they are analyzed to check whether they satisfy the technical and economic criteria. Embodiment stage has a higher information level compared to conceptual design stage. At the end of the embodiment design stage, one promising layout is selected and more ideas are incorporated on it and essential features from other layouts can also be imposed thereby creating a best layout. Only after all the functional, strength, spatial, compatibility and financial checks are done on this definitive layout, the designer can proceed to the detailed design stage.

2.1.4 Detailed Design

As it is mentioned in Pahl and Beitz [2], this is the phase of the design process in which forms, dimensions and other geometrical properties are defined, materials are specified, production possibilities are analyzed and all the documentation and production documents are produced. The detailed design stage results in the specification of information in the form of product documentation. The detailed design process nowadays has become so proficient with the rise of CAD modeling tools where most of the details can be specified and documented.

Thus, we now know about the several stages of engineering design process and how much they are important. As we can see, the conceptual design process is the most important stage since most of the key decisions are taken at this stage and it affects the whole process. This explains the importance of conceptual design and the importance of need for an effective conceptual design tool which will help the designer in generating effective and efficient solution principles.

In the coming sections, we will see in more detail about the steps involved in conceptual design stage and several ideation methods and strategies that are used for idea generation in conceptual design process.

2.2 CONCEPTUAL DESIGN

2.2.1 Steps in Conceptual Design

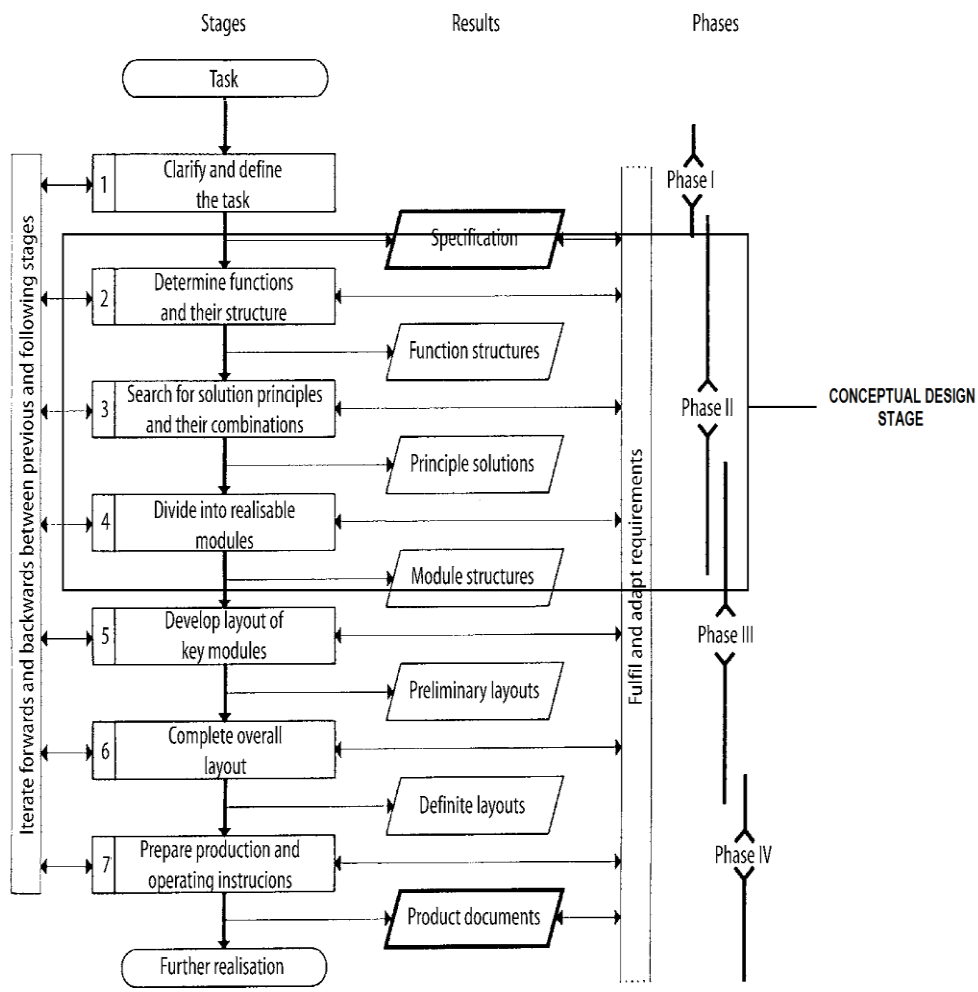


Figure 3. Steps in engineering design [2]

The early phase of engineering design deals with conceptual design. The Phase II of the diagram shown in Fig.3 corresponds to the stage of conceptual design which is followed by embodiment design and detailed design. Systematic conceptual design and present day conceptual design practice have certain differences. A clear illustration of the steps involved in systematic conceptual design is shown in the following Figure 4.

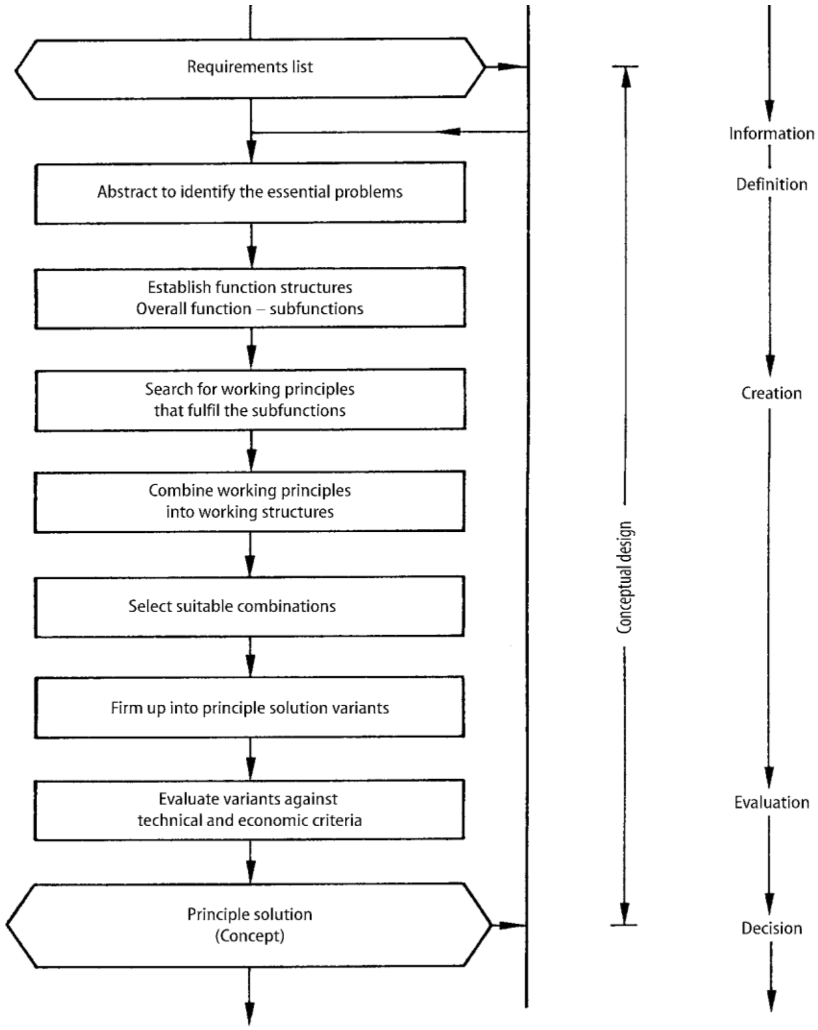


Figure 4. Steps involved in conceptual design [2]

In Fig.4 it is shown that after creating a function structure, the next step is to search for working principles that fulfills the sub-functions. This is not the case in present day's design process. It is not guaranteed that he will always find a working principle for each of this sub-function. Also, the designer might have different needs like need for a novel solution or he might be working on an evolutionary design and he need not necessarily search for working principles. He can use different methods to come up with a desired principal solution. These different methods that help him to generate ideas/solution principles are called as idea generation methods. These ideation methods need to be added to the systematic flow to make it more befitting to today's design processes.

2.2.2 Different Ideation Methods – Intuitive and Logical

Design creativity mainly deals with divergent thinking which helps in creation of several design alternatives where novelty and functional quality are also considered to be important. Intuitive methods work by stimulating the unconscious thought process of human mind. The outcome is rather unpredictable, yet they may aid in coming up with a novel solution. Logical or experiential methods involve step by step problem analysis, decomposition and direct usage of catalogued solutions (charts, tables and databases) based on the science and engineering principles and past experience.

Intuitive methods have been sub-classified into five categories: [3, 4] Freeform, Brain-writing, facilitator controlled, re-framing and idea morphing. The most well-known of free form ideation in this group is Brain-storming [5] and its many variations (PMI [6], K-J [7]). The claimed benefit is that one must suspend judgment in order to produce a large number of ideas regardless of quality. There were some disadvantages in this method since a few individuals dominate the session and a few participants are hesitant to impart their ideas. Therefore another type of intuitive method was developed in which the participants collaborate indirectly. Examples of these are Method 6-3-5[8], Gallery method [9], and C-Sketch [10]. Also, reformulation of a problem may lead to a new solution and a few techniques like using of alternative words for key functions [11] and use of analogies and metaphors can be used to reformulate. Analogies play an important part in Synectics [12]. Checklists [5] and action verbs [7] (e.g. invert, enlarge, and rotate) can systematically support idea morphing.

Logical methods can be classified into four categories: History based, Generalized principles, Idea morphing and factorization. Success in using logical methods is dependent not only on the technical expertise of the individuals but also the quality/ quantity of the information in catalog or database. History based methods involve the use of past solutions that have been catalogued and archived in some form of database. The German school has produced catalogs of both physical effects and solution principles corresponding to a variety of mechanical functions [13, 14]. Also there is a function to artifact catalog developed by the Oregon state university [15] which helps in searching for artifacts based on the flow variables and function verb. Case based design systems [16, 17] are supported by computer tools for classifying and searching past designs that have been archived and indexed in a database [18]. From the described methods, we can see that most of them use the past design cases and past solutions and hence, the chances of finding a novel solution are slight and these methods cannot be used for devices/objects that do not already exists. On the other hand, if certain aspects are modified to be expressed in generalized ways, there are greater probabilities of getting a novel design. TRIZ [19] is another logical ideation method (with some intuitive strategies) which falls under the conflict resolution principles. In this method, the designer needs to find and classify a technical contradiction and find a TRIZ recommended principle that has been used in similar situation but perhaps in another application or domain. Another important method is searching for working principles from function suggested in the VDI 2222 [14] which may lead to logical embodiment of a device. When the designer cannot find a related working principle, he needs to go one step further to the fundamental level i.e. physical effects level [13]. Morphological charts [20] are used for generating solutions for sub-functions and then randomly connecting different solutions to get a novel principle solution. This classification of ideation methods has been described in Fig.5.

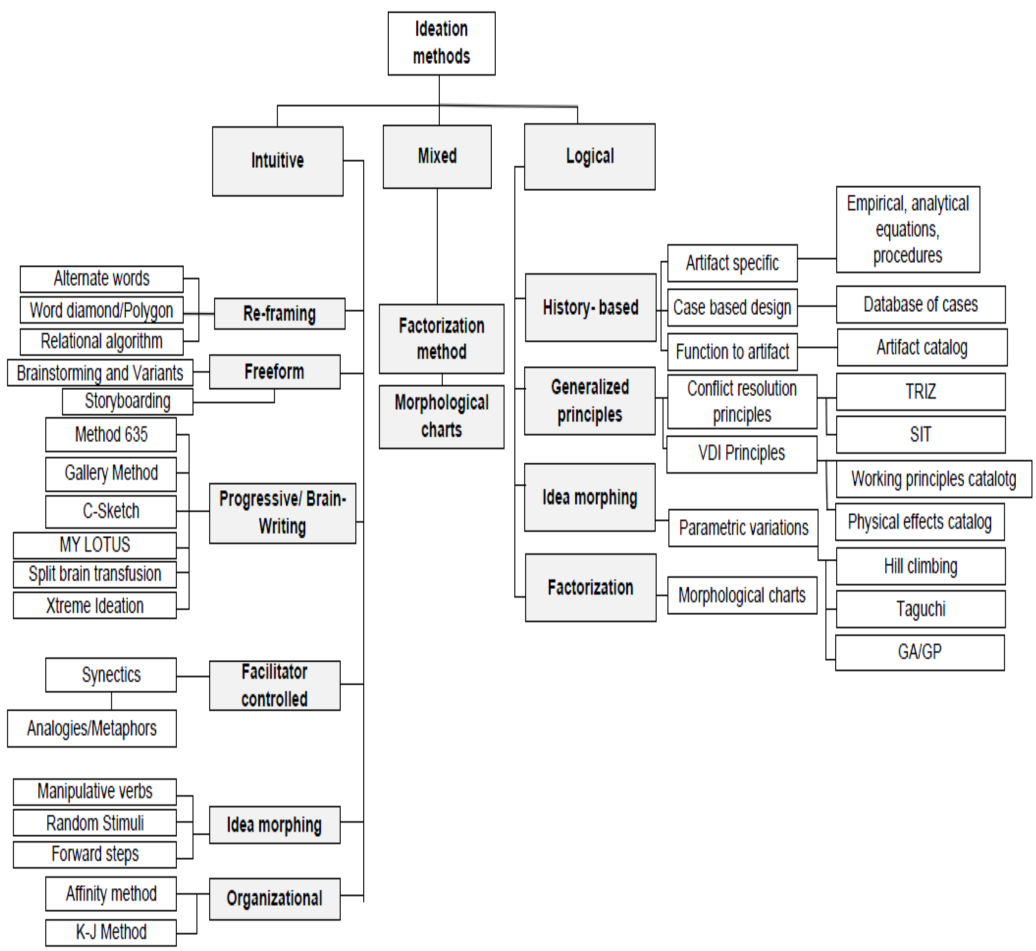


Figure 5. Examples of ideation methods [3]

2.2.3 Current Conceptual Design Tools

Presently there are many conceptual design tools that are used for ideation. For creating an effective conceptual design tool, we must first get a fundamental understanding of design process and have a clear insight about human cognition. Many of the conceptual design tools present right now (for example TRIZ [19], OSU design repository [15], Dane [21], Innovation workbench [22], Thoughtoffice [23] etc.), they all follow a single approach for ideation. Conceptual design is certainly not a monolithic process and different strategies are needed at different times during the conceptual design process. A single approach will hence be not effective. Engineering design also requires both creativity and functional quality and hence, strategies of both intuitive and logical ideation methods should be used to create a proper conceptual design tool. These shortcomings in present conceptual design tools were the main inspiration for this project.

2.2.4 Ideation Strategies

There are some creative cognition components in each ideation methods which help in promoting creativity or to overcome hurdles while solving a design problem. Those components which promote ideation and help the designer to come up with a desired solution are called ideation strategies.

2.2.4.1 Literature Review

Koestler’s Bisociation Theory [24], Wallas Model [26], and Chance-Configuration Theory [27] relate cognitive structures and processes to various aspects of creative activities. The Roadmap Theory [26] explains creativity through basic cognitive structures and processes. The Computational Model of Scientific Insight [27] is based on reasoning by analogy mental models. The Geneplore model [28] divides creative mental processes into Generative and Exploratory. Human Problem Solving (HPS) defines a problem as the presence of a gap, a discrepancy between the existing state and a goal state; a gap that is not readily bridged because of barriers or constraints [29-31]. It also deals with problems classification based on how much structured the problem is, complexity, and domain specificity. HPS is very different for well-structured problems than for ill-defined problems. For the former, various types of schema based theories have been proposed [30, 31]; Analogical reasoning needed to retrieve scripts.

Extensive studies had already been done on incubation, example exposure, analogical reasoning and provocative stimuli. Fixation in design is a persistent block that prevents discovery of a solution, whereas incubation is the surprising way solutions come to mind after a break from a problem. Fixation corresponds to dead-end branching; incubation allows escape from dead-ends. Smith and Blankenship [32] conducted sets of experiments that not only demonstrated reliable incubation in problem solving, but they showed that the effects occur predictably when initially induced fixation effects weakened over time. Jansson [33] studied design students and professional designers discovering fixation from example exposure (termed Conformity Effects in ideation). Finke, et al., [28] developed the Mental Ruts hypothesis and Roadmap theory of idea generation. Effects of fixation in brainstorming groups were empirically studied and reported by Dennehy [34]. Akin & Akin [35] showed through experiments how a change of frame of reference is essential to get a sudden mental insight leading to the solution of a problem. Visser [36], Cross [37], Poze [38], Gordon [39] demonstrated usefulness of analogies in design and the emergence of a novel concept as a bridging process that involves analogy and combination (synthesis). Theorists have emphasized the role of analogy in creative thinking [40, 41]. For example, Roy [42] had described several cases of designers using analogies from another field to invent new inventive product during the development of first cyclone vacuum cleaner. Recent empirical studies by Wood et al [43] and Schunn et al [44] found analogies were used both for identifying problems and solving them. Schunn found equal use of domain-specific and cross-domain analogies. Ekvall [45] verified significant improvement in real life problem-solving when analogical thinking processes are used along with deferred judgment procedures. Parnes studied processes for new connections via analogies and incubation [46]. The use of design catalogs and CBD can be viewed as context specific example exposure. Verstijnen [47] studied effects of restructuring and combining. Restructuring is aided by sketching (flexible representation). Tovey[48] describes several case-studies to emphasize the importance of visual thinking and drawings in the design process. Contextual Fluctuation Theory [49] states that mental states bias coding of stimuli, memories and ideas Design problems may be cognitively represented differently in differing mental contexts, which can be influenced by interruptions, context shifting, and reference frame shifting. Several research on time and cost constraints were also done by Finke et al. [28]. Also, at present stage of research in conceptual design, the importance of function based design is widely realized. In Oregon State University, they realized the same importance and developed a function based usage of TRIZ [50]. Biology based design tools are also being developed such as DANe [51], Analogic retrieval and Biomimetic catalogs of OSU [52] and BioTRIZ of Vincent et al [53].

From the literature review, we can see that there are several components of creativity that promotes ideation. Finding and analyzing these creativity promoters will be useful in knowing more about different ideation methods and also we will know about how they can be inculcated to the designer. Some of the creativity components that were found in past research [54] and some which were found in the recent research [55] are given as a list below.

Suspend judgment: A designer can suspend his judgment by not prematurely taking a decision about his ideas. This is done by reducing the character of being judgmental. By suspending judgment, the designer would not lose any of his past ideas and he won't reject any alternatives which might be helpful in future. This ideation strategy helps very much in expanding and exploring the design space.

Emphasize quantity: By emphasizing quantity of ideas more, no ideas will be rejected at the early stage of idea generation thereby helping the designer in having a large number of design alternatives at the end of ideation process since not much emphasize would be given for novelty and quality.

Shift frame of reference: A designer might focus only on a particular area and he might generate same kind of ideas again and again. This is because, the ideation space of the designer is very narrow and he is not exploring the design space. In order to explore and expand his design space, he can change his frame of reference so that he can explore unseen areas and find a totally different idea from his previous ones.

Use of analogies and metaphors: Analogies and metaphors are supposed to fuel up a person's creativity. Analogies from another field will help in coming up with new inventive designs. There are several past researches which explain about the usage of analogies to enhance creativity as discussed in the literature review.

Apply provocative stimuli: Provocative stimuli can be provided by things around a person, namely pictures, sounds or videos. Stimuli can also come from another designer's idea. Giving a stimulus to a designer helps him to overcome fixation when he is not able to generate any useful ideas.

Making random connections: Random connections between different concepts and solution principles can be used to get a novel and different concept which has features from all the individual concepts.

Incubation: When a designer is fixated (mental saturation or tired), he can take a break i.e. staying away from problem for some time. By doing this, he allows his subconscious mind to think about the problem while he is taking a break. This ideation strategy is not a part of any ideation method and is only employed only when the designer has a fixation.

Breaking rules/ suspending constraints: By having constraints, a designer restricts himself to a very narrow design space. Breaking these rules and constraints helps him to expand and explore the design space and come up with different solution which might be novel (since he suspended his constraints and considered the problem to be very abstract).

Abstraction of problem: A problem can be abstracted by using different words to describe the problem thereby removing constraints that were initially imposed. Using of common/abstract words makes a designer think in a different perspective.

Imposing fictitious constraints: During a design process, some constraints are imposed without a designer's knowledge which reduces his design space. Fictitious constraints are generally used to increase the functional quality of the design.

Removing fictitious constraints: A designer might impose some constraints which were not originally imposed. These constraints might be applied by the designer to improve the functional quality of the design but it might actually hinder him from thinking in a divergent manner thereby making him generate less novel ideas.

Using sketches/ graphical representation: As we know, pictures are worth a thousand words. When pictures or sketches are used, it conveys the ideas more easily and there is much scope for improvement. A lot of functional features can be explained in a picture easily which might be difficult to represent by text.

Example exposure: Related examples can be provided to a designer to easily come up with a solution from the stimulus given by an example. Examples are an integral part of many ideation methods. Of course, since the ideas are based on some example solutions, the novelty of the ideas is believed to be generally low.

2.2.5 Ideation Strategies Embedded In Different Ideation Methods

As we have seen in the previous section, ideation strategies are an integral constituent of ideation methods. In Table.1, the ideation strategies which are embedded in several ideation methods are shown clearly.

Table 1. Ideation strategies in several ideation methods

IDEATION "mini" STRATEGY	***Embedded in method***
Suspend judgment	Brainstorming, K-J, PMI
emphasize quantity over quality	Brainstorming, 635
emphasize quantity over variety	Brainstorming, 635
Shift frame of reference	Alternate Words, Action verbs, Physical effects database/ WP database
Use analogies and metaphors	Synectics
Apply provocative stimuli	C-Sketch, Gallery, 635, Brainstorming, Artifact catalogs
Make random connections between sub solutions	Morph charts
Incubate (use SC thinking)	Used whenever fixation is identified except for fixed time methods (C-sketch, Gallery,635)
break rules; suspend constraints	Synectics
abstract the problem	Alternate words, hypernyms
impose fictitious constraints	Relational algorithm
remove fictitious constraints	Artifact catalogs (based on functional decomposition)
look at an example solution	Database of cases, TRIZ, component catalogs

As we can see in the table, premature judgment of ideas is not done in ideation methods like Brainstorming and K-J. Similarly in those methods, there is more emphasize on quantity of ideas that are generated and relatively lesser importance is given to novelty and quality. Using of different words or verbs has the ability to change frame of reference. The most abstract level of representation of ideas corresponds to physical effects as we can see in the genealogy tree of abstraction [57]. Also, looking at a different working principle helps to change frame of reference. Synectics [12] uses analogies to help designer get creative ideas. Stimulus is provided by many ideation methods where stimulus comes from pictures, sketches or other's ideas. Abstraction of problem can be done using alternate words or by using Hypernyms. Examples are provided in logical ideation methods like artifacts catalog, case catalogs and TRIZ.

Chapter 3

HOLISTIC IDEATION – OVERVIEW

3.1 NEED FOR HOLISTIC IDEATION

Synectics [12] is an old idea generation technique found by Bill Gordon where he found that, a person goes through several different phases in creative problem solving and thus the strategy needed to move forward varies as one navigates through the design space. Trained individuals are needed to supervise the idea generation process in Synectics. Unlike brainstorming, there is a facilitator and a client; the rest of the group is in a supporting role to help the client. The group varies its direction as needed (idea generation, analogies, evaluation etc.). The job of the facilitator is to determine the current cognitive state of the group and suggest a tactic that in his experience would be most effective to make progress towards a solution. The main principle in which Synectics works is that, it realizes creative ideation as not a monolithic process and hence, different strategies were used at different times. The inspiration for this holistic ideation tool comes from Synectics but we will encompass many ideation strategies (wider than synectics).

Hence, the main objectives of this study can be listed as follows:

a. Facilitation of both intuitive and logical ideation strategies since both functional quality and creativity are important for engineering design.

b. Characterization of ideation state of designer should also be made possible. Appropriate ideation methods will be suggested based on the characterization.

c. Collect research data related to creativity and effectiveness of ideation strategies

At this point, it is important to emphasize that we are not providing a prescriptive method to carry out ideation process. We are only making a variety of ideation strategies/methods available to the designer which can be used as desired. The designer has his freedom of choosing other ideation methods which are not suggested after characterizing his ideation state.

3.2 PROPOSED FRAMEWORK FOR HOLISTIC IDEATION

3.2.1 Pre-Ideation, Ideation and Post-Ideation Stages

Ideation process of a designer can be classified into three:

a. Pre-ideation stage
b. Ideation stage
c. Post-ideation stage

The first step in a conceptual design process is the creation of a function structure. Hence, the pre-ideation stage comprises of these initial stages of conceptual design where a function structure is created from the set of requirements.

Once the function structure is developed, the next step is to generate ideas for each of those functions. The ideation strategy to be used by the designer will be based on the characterization of his ideation state which should be monitored at regular intervals. With the help of ideation strategies suggested, a set of ideas will be generated. This idea generation process corresponds to the ideation stage.

Ideation stage and ideation state has totally different meanings and should not be confused with one another.

While the designer generates his ideas, he also evaluates those ideas and if he finds them appropriate to the function that he is working on, he documents those ideas (good ideas to the morph chart). The evaluation done in the holistic ideation framework is done wholly by the designer himself and is not automated. The evaluation will be based on the four effectiveness metrics: Quantity, Quality, Novelty and variety defined by Shah et al. [57]. Evaluation and documentation are key processes involved in post ideation stage and it occurs simultaneously with the ideation stage and does not happen separately. If satisfactory ideas are generated for a particular function, information about the effectiveness of ideation strategies is also collected. This pre-ideation, ideation and post ideation process repeats for all the functions defined in the function structure. These processes are illustrated in Section 3.2.2 in a holistic ideation framework.

3.2.2. Holistic Ideation Framework

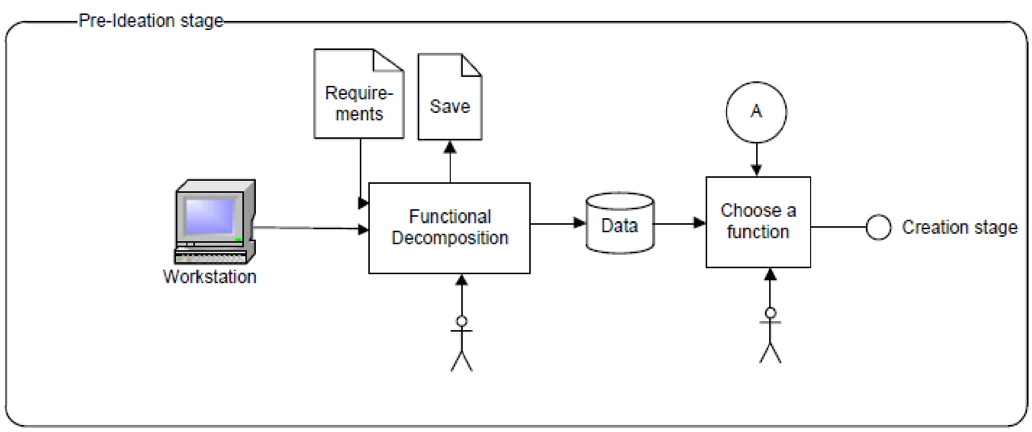


Figure 6. Pre-ideation stage in conceptual design

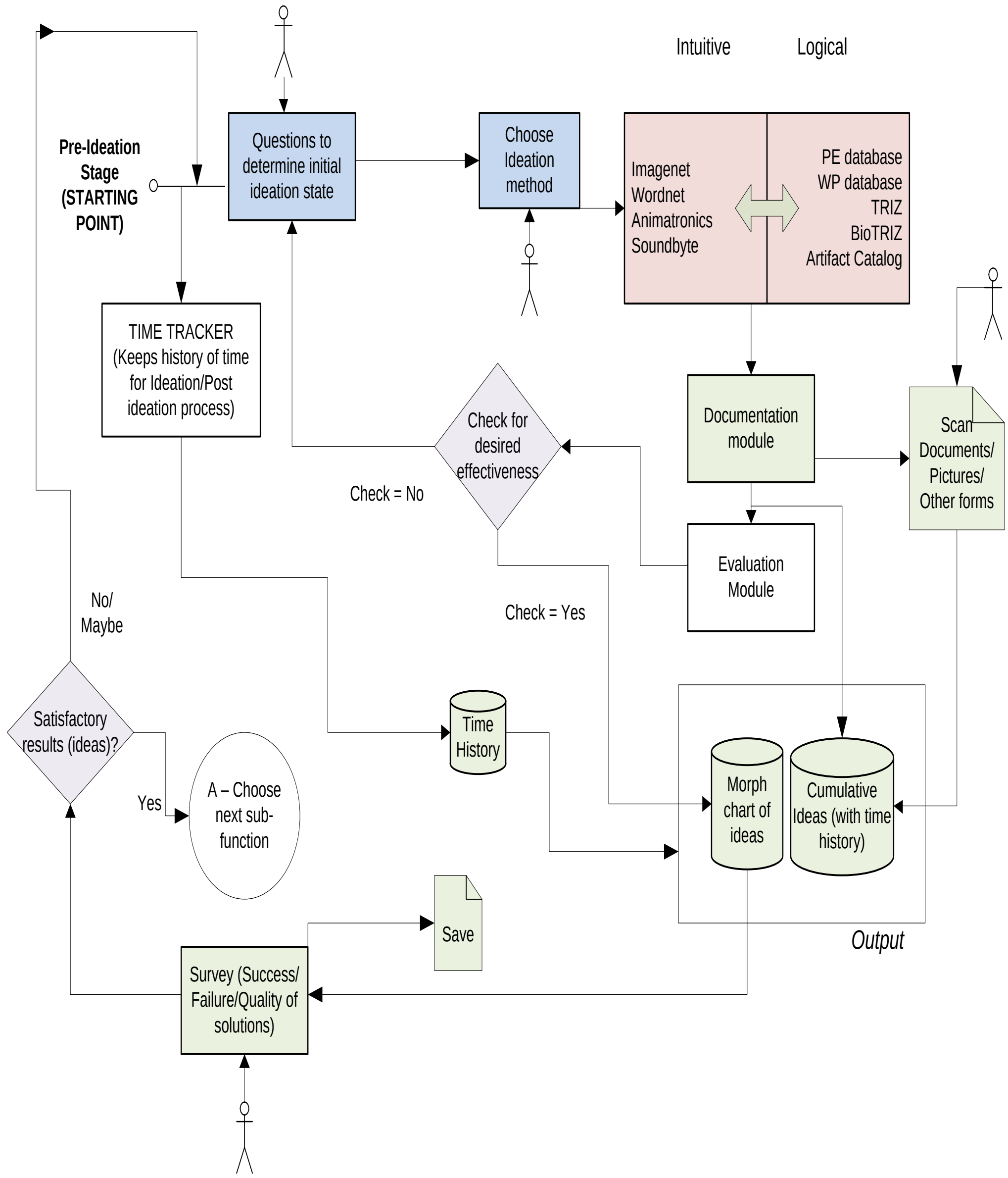


Figure 7. Ideation and post-ideation stages in conceptual design

In previous sections, we presented different ideation methods and ideation strategies embedded in them. In the coming sections, we will discuss about different ideation states of a designer, how they are sensed and also about different ideation methods embedded in holistic ideation framework.

3.3 IDEATION BLOCKS

When solving a design problem, a designer may run into an impasse at various times until he gets to an acceptable solution. These impasses are called as creativity blocks [55, 56]. These blocks need to be identified in order to characterize the ideation state of a designer. In the Synectics method, there is an experienced facilitator who monitors the idea generation process and advises the group with tactics that would overcome their mental blocks. In order to monitor these ideation blocks, we must first know in detail about each ideation blocks and how they are characterized and what ideation strategies can be used to overcome those ideation blocks.

3.4 REMEDIES FOR IDEATION BLOCKS

For all ideation blocks, there are some strategies that can be used as remedy. These remedies are the ideation strategies (unblocking strategies) that we saw in previous chapter. Hence, we need to map these ideation blocks to ideation strategies. Several ideation blocks have been identified in the past research [55], several ideation blocks have been found in our recent research and several ideation blocks are expected to be found with the use of holistic ideation.

Table 2. List of ideation blocks and unblocking strategies

IDEATION BLOCKS	UNBLOCKING IDEATION STRATEGIES
Difficulty understanding the problem	Flexible problem representation, Use of analogies and metaphors,Reframe problem
Unmanageable complexity	Work on a higher problem,Break rules,

	Decomposition
Design fixation	Provocative stimuli (Random/focused),Random connections,Forced connections, Incubation
Pre-mature judgment	Suspend judgment, Emphasize Quantity over Quality
Fictitious constraints	Break rules,Work on a higher problem
Impasse due to lack of data	Return to problem formulation
Too many ideas	Categorical organization, Dissect/Intersect
Functional coupling	Decomposition, reframing
Lack of domain expertise	Use experential catalogs
Tight grip on technical requirements	Change frame of reference, Use of analogies and metaphors, solve fictitious problems
Rigid problem representation	Use sketches and graphical representation
Conflicting requirements that appear to be physically impossible	Break rules, Reframe problem
Bias towards past design	Provocative stimuli (Random/focused),Change frame of reference
Unable to find fundementally different ideas	Change frame of reference,Emphasis on variety, suspend judgment
Difficulty identifying critical technical issues	ARIZ/TRIZ principle
Mental saturation, bored or tired	Incubation
Lack of motivation	Generate alternatives anyways for its own sake, solve fictitious problem
Inability to find new solution paths	Change frame of reference,Forced connections,Random connections,Incubation,PE and biomemic catalogs, analogies

3.5 CONNECTION BETWEEN IDEATION BLOCKS, IDEATION STRATEGIES AND IDEATION METHODS

Now we have a relation between ideation blocks, their remedies and ideation methods in which these remedies are embedded. Fig.8 illustrates their relations. Our next discussion will be about how the ideation states of the designer be found and how appropriate ideation methods will be suggested according to their ideation states.

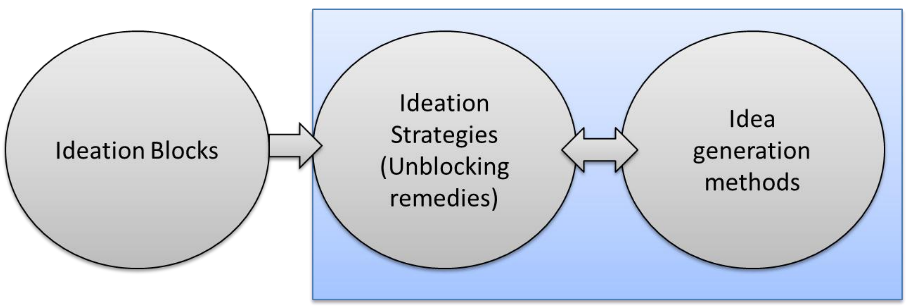


Figure 8. Connections between strategies, blocks and methods

3.6 SENSING IDEATION BLOCKS

As we know, a problem and solution co-evolves [56] and they do not evolve separately one after another. Hence we need to consider the characteristics of both problem and outcomes along with characteristics of process to characterize ideation state of a designer (Table.3). Characteristics of problem can be defined by its novelty (how new the problem is for the designer), uncertainty (how uncertain is the problem for the designer), complexity (how complex the problem is for the designer). All the problem measures are personnel (changes for different designers), they are not absolute measures. Also, the problem measures can be in the context of the whole problem or function-by-function. It depends on the level of abstraction that the designer is working on. Characteristics of process are defined by time (in minutes). Characteristics of outcomes are defined by the effectiveness measures [54, 58] for ideation generation found in past research: Quantity, Quality, Novelty and Variety. Fig.9 shows about the values that these characterization measures can take.

Table 3. Characterization measures to define ideation state

Problem measures	**Process measures**	**Outcome measures**
Novelty	Time	Quantity
Complexity		Quality
Uncertainty		Novelty
		Variety

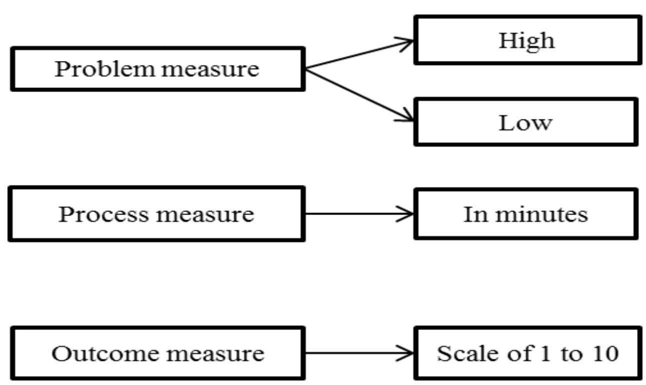


Figure 9. Values for characterization measures

As shown in Fig.9, the problem measures take the value of high or low. The process measure of time is classified into high, low, medium based on the number of minutes spent in the idea generation cycle. Since outcome measures are rated on a scale of 1 to 10, ratings less than 5 are considered to be less and ratings more than 5 are considered to be high. For different combinations of values for these characterization measures, there is an ideation block which corresponds to it. For the ideation blocks that we have defined in this section, we have mapped different combinations of characterization measures. The list of ideation blocks and corresponding values of characterization measures are shown in the table below. Certain ideation blocks might be similar to other ideation blocks (just one or two measures will vary – for example 'Lack of domain expertise' and 'Difficulty in understanding critical technical issues' are similar because some outcome measures in both blocks can take any value either high or low). Otherwise, all the ideation blocks are mostly independent of each other.

Table 4. Characterization measures for ideation blocks

	Characterization							
	Problem			**Process**	**Outcomes**			
Blocking Phenomena	***Nvlty***	***Cmplx***	***Uncrt***	***Time***	***Qty***	***Qlty***	***Nvlty***	***Var***
Difficulty understanding the problem	↑	↑	↑	↓	↓	↓	↓	↓
Unmanageable complexity	–	↑	–	↓	↓	–	–	–
Design fixation	–	–	↓	↑	↓	–	↓	↓
Pre-mature judgment	–	–	–	↓	↓	↑	–	↓
Fictitious constraints	↓	↑	↑	–	↓	–	↓	↓

Impasse due to lack of data	↑	–	↑	↓	↓	↓	–	↓
Too many ideas	↓	↓	↓	↑	↑	↓	↓	↓
Functional coupling	–	↑	–	↓	–	–	–	–
Lack of domain expertise	↑	–	↑	↓	↓	↓	–	–
Tight grip on technical requirements	↑	↑	–	–	↓	↑	↓	↓
Rigid problem representation	–	–	–	↓	↓	–	↓	↓
Conflicting requirements that appear to be physically impossible	–	↑	–	–	↓	↓	↑	–
Bias towards past design	↓	↑	–	↓	↓	↑	↓	↓
Unable to find fundamentally different ideas	↑	↑	↓	↓	–	–	–	↓
Difficulty identifying critical technical issues	↑	–	↑	↓	–	↓	↓	–
Mental saturation, bored or tired	–	–	–	↑	↓	↓	–	↓
Lack of motivation	–	↑	–	↓	↓	–	↓	↓
Inability to find new solution paths	↑	↑	–	↑	–	–	↓	↓

3.7 UNFETTERED IDEATION

In our previous research and discussions, we only discussed about determining ‘ideation blocks’ from the set of characterization measures. But, these same characterization measures can also be used for finding progress in ideation process. The designer need not actually always have some blocks or hurdles; he can also be going on the right direction. We call this position of designer in ideation space is called as 'Unfettered Ideation'. There can also be certain ideation states in between these two extremes of ideation blocks and unfettered ideation. A designer can also encounter multiple ideation blocks at the same time. We expect to find a lot more of those while we conduct the experiments.

Examples of Unfettered Ideation: Unfettered ideation may be thought as the opposite of ideation blocks. Some examples of unfettered ideation are: Proper understanding of problem, No design fixation, high domain expertise, no grip on technical requirements, not related to past designs, flexible problem representation, finding fundamentally different ideas, proper understanding of critical technical issues, highly motivated and ability to find new solution paths.

3.8 CHARACTERIZATION MEASURES FOR UNFETTERED IDEATION

Table 5. Characterization measures for unfettered ideation

Unfettered Ideation	**Characterization**							
	Problem			**Process**	**Outcomes**			
	Nvlty	***Cmplx***	***Uncrt***	***Time***	***Qty***	***Qlty***	***Nvlty***	***Var***
Good Understanding of Problem	↓	↓	↓	↓	↑	↑	↑	↑
Ability to manage complexity	–	↓	–	↓	↑	–	–	–

No fixation	–	–	↑	↑	↑	–	↑	↑
Late Judgment	–	–	–	↑	↑	↓	–	↑
Not imposing any fictitious constraints	↑	↓	↓	–	↑	–	↑	↑
Proper availability of data	↓	–	↓	↓	↑	↑	–	↑
Not too many ideas	↑	↑	↑	↑	↓	–	–	↓
High domain expertise	↓	–	↓	↓	↑	↑	–	–
Not worried about Technical requirements	↓	↓	–	–	↑	↓	↑	↑
Flexible problem representation	–	–	–	–	↑	–	↑	↑
Resolving conflicting requirements	–	↓	–	–	↑	↑	–	–
No similarity to previous design	↑	↓	–	↓	↑	↓	↑	↑
Able to find fundamentally different ideas	↓	↓	↑	↑	–	–	–	↑
Easily identifying critical technical issues	↓	–	↓	↓	–	↑	↑	–
Not mentally saturated or bored	–	–	–	↑	↑	↑	–	–
Highly motivated	–	↓	↓	↓	↑	–	↑	↑
Able to find new solution paths	↓	↓	–	↑	–	–	↑	↑

In this section, we saw about an introduction to holistic ideation, its importance, ideation states of a designer, ideation blocks, their remedies, unfettered ideation and characterization measures to define ideation states.

Chapter 4

EMBEDDED IDEATION METHODS IN HOLISTIC IDEATION FRAMEWORK

4.1 KEY CONSTITUENTS OF HOLISTIC IDEATION

As we have discussed in Section 1, a proper holistic ideation tool should possess all the features of characterizing ideation states, facilitate functional decomposition, have enough ideation methods embedded to aid the designer and also provide facility for documentation and easy seamless navigation between different ideation methods. In this chapter, we will discuss in detail about the experiential ideation methods that had been used in holistic ideation. Functional decomposition is one kind of systematic method used in early stages of conceptual design and hence, it is listed along with experiential methods (Functional decomposition is NOT an ideation method). We will also have an overview about the intuitive ideation strategies that had been used since they are an integral part of holistic ideation too.

4.2 IDEATION METHODS USED IN HOLISTIC IDEATION

4.2.1 Intuitive Ideation Methods

There is a set of intuitive ideation strategies that will be used in our holistic ideation. We identified the most common ideation strategies from the ideation methods discussed in section 2 and we found ‘provocative stimuli’ and ‘reframing of problem’ to be the most prominent ideation strategies embedded in different ideation methods. Stimuli are provided by graphical objects like Pictures and animations while sounds can also provide provocative stimuli. There are sources like Imagenet [59] which can be used as a source of stimuli. For reframing of the problem, sources like wordnet [60] can be used. We won't see in detail about the intuitive ideation strategies since it is still a work in progress.

4.2.2 Functional Decomposition

Functional model may be considered as a framework for design activities. The main feature of a functional model is that it converts customer requirements into engineering requirements. Solutions are found for functions initially defined and the functional model is iteratively refined. Continuation of this iterative process through a product design cycle insures that customer needs are inherently designed into a product with a defined relation between function, behavior and component. Functional decomposition is based on a Function design framework [61] which is used for generation of hierarchical models of function, process and environment.

The function design framework first proposed in [61] integrates functional modeling based on functional basis [63, 62] with process modeling to provide a unified modeling architecture. There are other functional decomposition techniques defined in terms of binary logic by Rodenacker [64], in terms of general applicability by Roth [65], and in terms of physics developed in University of Pisa [66]. Certain terminologies which are used for defining hierarchical functional models are:

a. Functional modeling: 'What' a product must do.
b. Process modeling: Actions involved to perform the function

c. System: Combinations of artifacts and actions which performs the function
d. Flow: Energy, material or signal which interacts with the product. They are denoted by nouns [62]
e. Boundary: An outer limit within which the flows exist
f. Function: Description of the function, how input flow is transformed to output flow. They are generally denoted by an action verb.
g. Process: The sum of defined events that occur with respect to the product as a whole and aim to meet a particular aim.
h. Environment: System surroundings, interactions and operations

The step by step process for generating a functional model using a function design framework is shown below:

1. Identify the boundaries of the environment in which the system is being designed to operate. Once the customer needs are identified, the boundaries should be specified.
2. Identify the process boundaries, modeled as events, which define the operational aspects of the system. All flows required by the process originate from within the environment. At the environmental and process level, the system being designed exists as a flow between events within the process.
3. Identify the physical boundaries of system. As flows were defined in environment and process level, flows are modeled for system level too.

4. Decompose the process into event and configuration models and system into functional models until the desired level of fidelity is reached. The functions can be decomposed till the most abstract level.

Generation of these functional models in some graphical modeling application is much pain and there was a need to create an application purely to build functional models. Combining the needs for a functional modeler and function ontology defined in reconciled functional basis [62], a functional modeler was created by Oregon State University [67] called FunctionCAD. Functional requirements can be represented in terms of key variables and these variables are transformed into flow variables (energy, material and signal) of the function ontology. There is also a function set in the RFB used to describe the actions on flow (user defined words are also allowed). RFB was developed as a combination of functional basis and NIST function ontology [68]. RFB is widely used in several researches on conceptual design around the world and it is a widely accepted ontology by several design research groups and that was one of the important reasons for us to choose RFB even though we were looking for a generic representation of functions (more abstract), which is difficult to develop in such a short time. Some limitations of FunctionCAD are lesser varieties of shapes to diagrammatically represent functions and inability to represent AND/OR functional trees.

Hence, FunctionCAD was the best option available to solve the purpose of function modeling in holistic ideation. Energy is always a product of a flow variable and an effort variable. But the flow variables in RFB do not have these analogies associated with the energy flows. Hence, we plan to add those analogies to FunctionCAD in the future.

Example from the functional basis is shown in Fig.10. The whole table is given in the appendix.

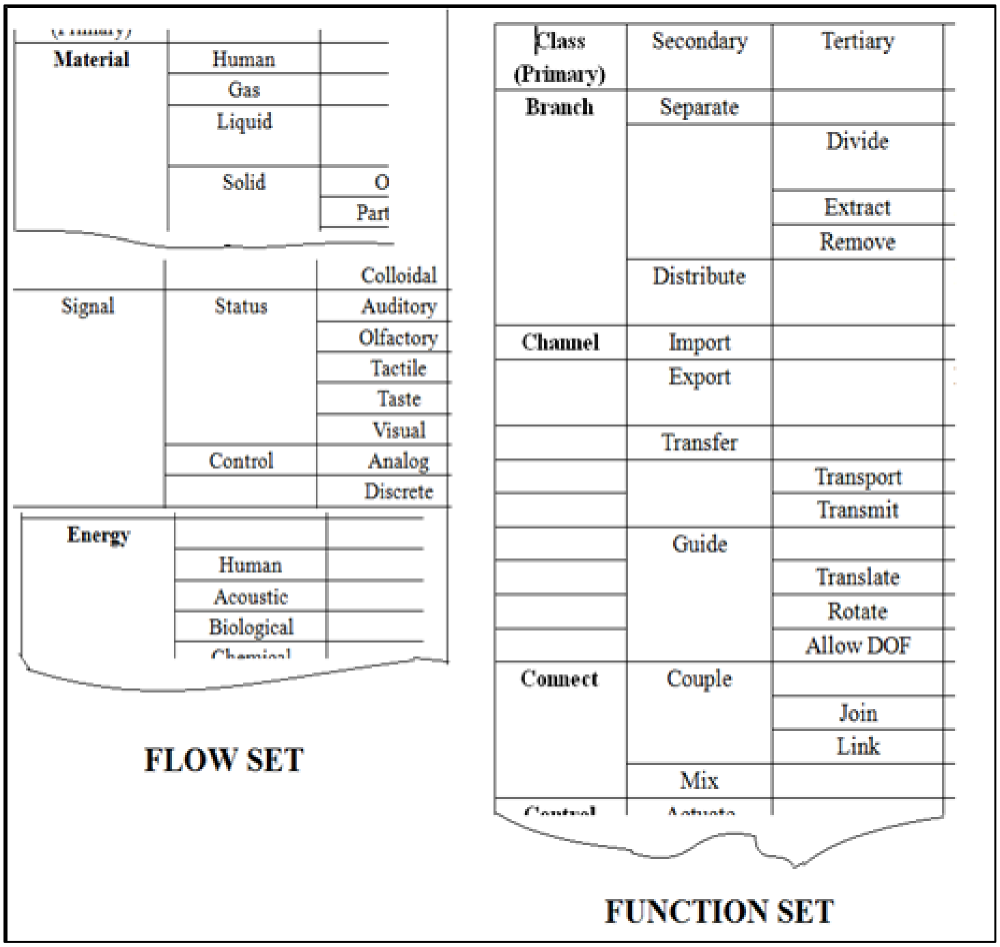


Figure 10. Function and flow set of reconciled functional basis

4.2.3 Physical Effects

We saw about the decomposition of functions based on function set and flow set as described in reconciled functional basis. Knowledge representation can be defined at 3 levels, namely the function, behavior and structure levels.

Function decomposition corresponds to the function level. Physical effects and working principles together define a behavior. We will see each of those one by one.

There are certain physical laws which govern the physical quantities involved in a process. These laws govern the flow variables/ physical variables. The most abstract level of representation is the physical effects as we can see in the genealogy tree defined by Shah et al. [58]. Ideas and concepts generated at physical effects level has a high variety i.e. fundamentally very different. Hence, if the designer needs to explore different places in his design space, he can opt to go to a fundamental level of physical effects. Rodenacker [64] and Koller [69] in particular have collated these effects. We, from different sources like Koller, Wolfram and VDI guidelines have created a set of physical effects ranging in different areas like mechanical, electrical, thermal and fluid.

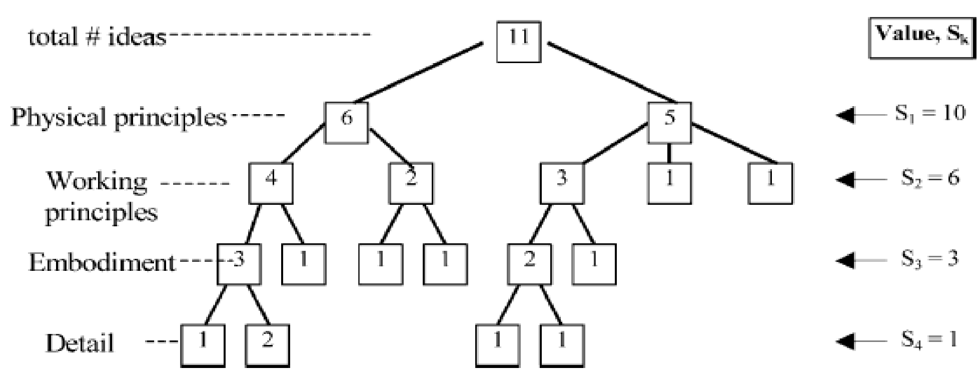


Figure 11. Genealogy tree [58] with variety scores

For achieving a particular function, not one physical effect will be enough. Most of the times, combinations of physical effects are needed to fulfill the function. An example from our Physical catalog is shown in the following figure, and in the next figure we show how physical effects are related to flow variables of function ontology.

2. **Angular acceleration**

Rate of change of angular velocity wrt time. Also, for constant torque exerted by a body, there will be a constant angular acceleration

EQUATION:
α = dw/dt
α = d^2(theta)/dt^2
τ = I * α

PARAMETERS:
w -Angular Velocity
alpha - Angular acceleration
t -Time
theta - Angular displacement
I - Moment of inertia
tou -Total Torque

Law: Newton's law of motion
Medium: Any

10. **ELECTROLYSIS:**

Method of using a direct electric (DC) to drive an otherwise non-spontaneous chemical reaction

EQUATION: $m = k \cdot q$

PARAMETERS:
m- Quantity of elements separated by passing electric current
q – electric charge

Law: Law of electrolysis

Medium: Solids and Liquids

Figure 12. Example from our physical effects catalog

		Energy									
		Human	Acoustic	Biological	Chemical	Electrical	ctromagne	Hydraulic	Magnetic	Mechanical-rot	Mechanical
43	Thermal conduction										
44	Thermal radiation			•							
45	Thermal convection										
46	Thermionic emmision										
47	Absorption				•						
48	Thermal dissociation										
49	Combustion		•		•					•	•
50	Thermo diffusion				•						

Figure 13. Mapping physical effects to flow variables

4.2.4 Working Principles

When certain geometric and material characteristics are given for a physical effect, a working principle is obtained. The working principle is in a much lesser level of abstraction when compared to physical effects. A function is fulfilled by the physical effect, realized by a working geometry i.e. arrangement of working surfaces and choice of working motions [2].

As is described in the text written by Pahl and Beitz, working surfaces can be determined by type, shape, position and size. Working motion can be type (translation or rotation), nature (regular or not), direction and magnitude. These details are not sufficient to determine a working principle and hence material properties are also attributed. To satisfy an overall function, a combination of working principles realized for different sub-functions need to be used. VDI 2222 calls this a combination of principles. This combination of several working principles results in a working structure. Thus, a principle solution is obtained from a working principle through a combination of principles which is called a working structure. However, if the designer is happy with the working structures obtained, he should not accept that as an end point.

In our holistic ideation, we have created a working principle catalog from a set of working principles described in VDI 2222 [14] and Pahl and Beitz [2]. Also certain important working principles were also added other than those listed in VDI 2222. Since working principle is more detailed than physical effect, certain details like graphical representation and material properties need to be attributed. Also bio-inspired design is the next big thing in the area of conceptual design. To contribute towards that, our working principles catalog has a biological example for each of the working principles defined. A behavior cannot be modeled just by using a physical effect. Physical effects are very much abstract and it needs some more details to make it 'behave' in a certain way. Hence, a combination of physical effects and working principles need to be used to describe the behavior of a system. Behavioral models (Modelica models [70]) will be attributed to the working principles in the future works in holistic ideation. Some examples from our working principle catalog are shown in Fig.14.

#	Working principle name (from VDI 2222 and Pahl&Beitz)	Description	Components (Specific ex.)	PE involved	Materials
3	Electrostriction	Changing the shape of a non conducting object by application of electric field	Lead magnesium niobate applications - Sonar	Di-electric Electric current (minimum)	Dielectric materials
4	Magnetostriction	Changing the shape of a ferromagnetic object by application of magnetic field	Magnetostrictive actuators, transducers	Eddy current	Ferro-magnetic materials

Key Phy Variable	Geo ation (Picture fro hl and Beitz)	Bio example (Ref: Biology reference, Asknature, Water Encyclopedia)	Functions
Electrostrictive coefft Electric field		http://asknature.org/strategy/c8d9568dc1047944da961716c47e6ec	Electrical to mechanical
Magnetrostrictive coeff Magnetic field		http://asknature.org/strategy/486222a04a1d8feee28f5794fd081c8	Magnetic to mechanical

Figure 14. Example from our working principles catalog

4.2.5 TRIZ

The theory of Inventive Problem Solving (Russian Acronym: TRIZ) was developed by Altshuller in the 1940s. He wanted to create a pattern, a set of solutions, which can be used for any creative problem solving and in doing so dispelled myths of the day that invention was random and possible by only a few persons. An exhaustive search of more than 200,000 patents was done by him and his colleagues. It was found that many inventions were characterized simply by the application of principles to solve contradictions among technical characteristics. Once this pattern was recognized, both the characteristics found in the patents as well as the principles employed in their solutions were identified and then distilled into a reasonably comprehensive set of 39 characteristics/features and 40 principles. The list of principles and characteristics are shown in Table.6. A partial TRIZ matrix is shown in Fig.15.

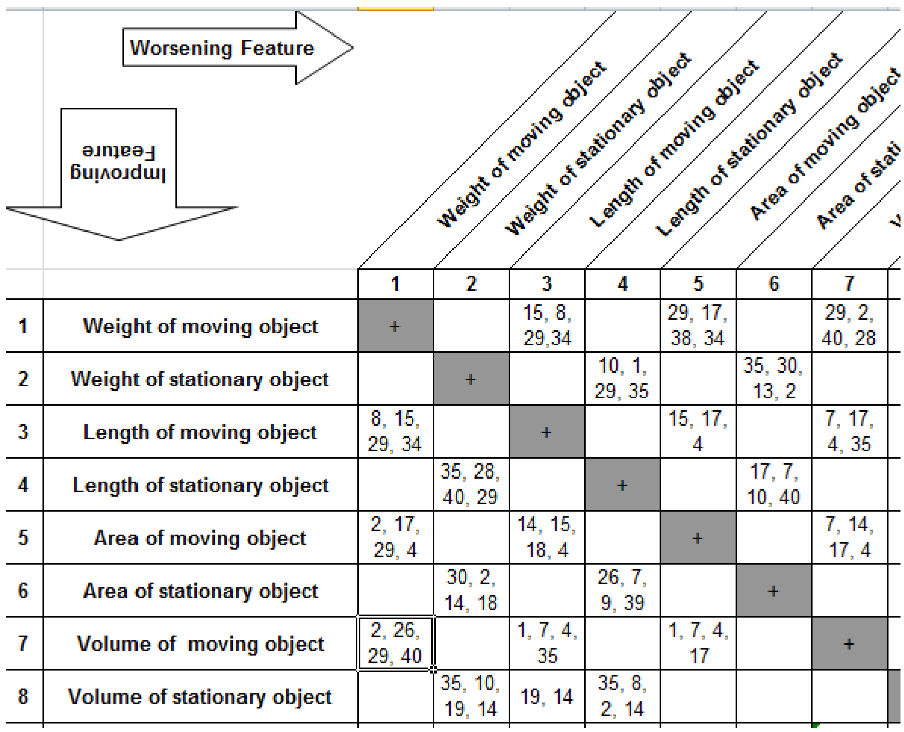


Figure 15. Partial screen shot of TRIZ matrix.

Table 6. Principles and improvising/worsening characteristics in TRIZ

PRINCIPLES	Improving/worsening Features
1. Divide and Conquer	1: Weight of moving object
2. Extract as needed	2: Weight of stationary
3. Local Quality	3: Length of moving object
4. Asymmetry	4: Length of stationary
5. Consolidate	5: Area of moving object
6. Increase Universality	6: Area of stationary
7. Nesting	7: Volume of moving object
8. Use counterweight	8: Volume of stationary

9. A priori counter action	9: Speed
10. Pre-emptive action	10: Force (Intensity)
11. Compensation in advance	11: Stress or pressure
12. Equipotentiality	12: Shape
13. Reverse action	13: Stability of the object
14. Change form	14: Strength
15. Increase degree of flexibility	15: Durability of moving obj.
16. Excessive or deficient action	16: Durability of non moving obj.
17. Change dimension	17: Temperature
18. Use Mechanical vibration, Oscillation	18: Illumination intensity
19. Periodic action	19: Use of energy by moving
20. Steady Useful actions	20: Use of energy by stationary
21. Speed up	21: Power
22. Turn a minus into Plus	22: Loss of Energy
23. Use Feedback	23: Loss of substance
24. Use Mediation	24: Loss of Information
25. Generate Self service	25: Loss of Time
26. Copying	26: Quantity of substance/the
27. Make disposable	27: Reliability
28. Replace Mechanical system	28: Measurement accuracy
29. Use Pneumatics and hydraulics	29: Manufacturing precision
30. Flexible shells and thin films	30: Object-affected harmful
31. Porous materials	31: Object-generated harmful
32. Color changes	32: Ease of manufacture
33. Homogeneity	33: Ease of operation
34. Rejection and Regeneration	34: Ease of repair
35. Transform parameters	35: Adaptability or versatility
36. Use phase Transformations	36: Device complexity
37. Thermal expansions	37: Difficulty of detecting
38. Accelerate Oxidation	38: Extent of automation
39. Inert environment	39: Productivity
40. Composite materials	

Perhaps the greatest contribution made by Altshuller was the connection of these two data sets. Based on information from the patents, he linked the principles to contradictions between technical characteristics using a matrix named “TRIZ Contradiction Matrix”. In this 39x39 matrix technical characteristics are listed on both the vertical and horizontal axes while the principles that may be used to address such contradictions are found in the associated cell. A subset of the matrix is shown in Fig.15. TRIZ design methods treat design as an inventive problem. In this light, there are three core steps to applying the TRIZ method. First, the designer should decompose the system, analyzing each component and determining the system’s characteristics thereby finding the contradictions and defining the improving and worsening features. For example, one might wish to increase the strength of a component without changing the weight. Finally, the contradictions stated in step two might be resolved using the contradiction matrix and appropriate principles would be suggested. Further examples of a TRIZ solution may be found in “40 Principles; TRIZ Keys to Technical Innovation” [19].

While the TRIZ methodology involves many higher-level tools such as ARIZ (Algorithm of Inventive Problem Solving) and Substance Field Analysis, arguably the most accessible and frequently used contribution from TRIZ is the Contradiction Matrix. This matrix may be used to solve a wide variety of conflicts found in design problems in many different domains. Each design method seeks to introduce the designer to information from previously successful designs, mined through empirical analysis of design data from a variety of sources. The expectation is that novel ideas may be generated introducing high quality and proven “out of the box” concepts and hence we decided to use TRIZ as a part of holistic ideation.

4.2.6 Bio-TRIZ

Biologically inspired design is an important and growing movement in design. The movement is driven in part by the need for environmentally sustainable development, and partly by the recognition that nature can be a powerful source of inspiration for technological innovations. Given a target design problem, finding relevant biological systems to emulate is one of the key initial steps in the practice of biologically inspired design. But if engineers are limited in their knowledge of biology, this step also constitutes one of the biggest hurdles of biologically inspired design practice. When engineers cannot rely on their prior knowledge, they often turn to online information environments such as the World Wide Web to seek bio-inspiration. However, the task of seeking bio-inspiration in online information environments poses its own set of challenges like unstructured and non-semantic way of representation which might lead to unwanted solutions and results. We researched many Bio-inspired design like DANe [21], Analogic retrieval and Biomimetic catalogs of OSU [52].

We wanted to utilize a bio-inspired design method that can be included in our holistic ideation. The design tools mentioned above have their own limitations like poor information, non-semantic representations and not much data on effectiveness or applicability had been reached about them at this stage of research. So, we decided to use Bio-TRIZ which is based on biological phenomena attributed to the characteristics described in TRIZ. Vincent et al [53] analyzed a total of 2500 conflicts and their resolutions in biology, sorted by levels of complexity. However, that is just 1/10th of the data compared to the actual TRIZ. Bogatyreva et al [71] followed the principle of “Things do things somewhere”. This established six fields of operations in which all actions with any object can be executed: ‘Things’ (substance, structure) includes hierarchically structured systems, that is the progression subsystem – system – super system; ‘do things’ (requiring energy and information) implies that energy needs to be regulated; ‘somewhere’ (space and time). These six operational fields reorganize and condense the TRIZ classification of both the features used to generate the conflicts and the inventive principles. This more general TRIZ matrix (which they named PRIZM – Pravila Reshenija Izobretatel’skih Modernizirovannye – translated as ‘The rules of inventive problem solving, Modernized’) was populated with relevant inventive principles (IPs) taken from original matrix. This PRIZM matrix is shown in Fig.16.

Operation fields that should be improved	Operation fields that cause problems					
	Substance	Structure	Time	Space	Energy/Field	Information/ Regulation
Substance	6, 10, 26, 27, 31, 40,	27	3, 27, 38	14, 15, 29, 40,	10, 12, 18, 19, 31	3, 15, 22, 27, 29
Structure	15	18, 26	27, 28	1, 13	19, 36	1, 23, 24
Time	3, 38	4, 28	10, 20, 38	5, 14, 30, 34	19, 35, 36, 38	22, 24, 28, 34
Space	8, 14, 15, 29, 39, 40	1, 30	4, 14	4, 5, 7, 8, 9, 14, 17	6, 8, 15, 36, 37	1, 15, 16, 17, 30
Energy/Field	8, 9, 18, 19, 31, 36, 37, 38	32	6, 19, 35, 36, 37	12,15, 19, 30, 36, 37, 38	14, 19, 21, 25 36, 37, 38	2, 19, 22
Information/ Regulation	3, 11, 22, 25, 28, 35,	30	9, 22, 25, 28, 34	1, 4, 16, 17, 39	2, 6, 19, 22, 32	2, 11, 12, 21, 22, 23, 27, 33, 34,

Figure 16. TRIZ PRIZM

From the PRIZM matrix, BioTRIZ was developed where the IPs of TRIZ were put into a new order that more closely reflects the biological route to the resolutions of conflicts. Even for similar problems, the inventive principles that nature and technology use to solve problems can be totally different. In Vincent et al [53], there is a detailed description of how the improving and worsening parameters were mapped to these six fields. Also, they had given biological examples for each of these inventive principles which are proved to be very effective for biologically inspired design. The BioTRIZ matrix is shown in Fig.17. The detailed TRIZ/Bio-TRIZ matrices and biological examples of Bio-TRIZ given are given in the appendix for reference.

Operation fields that should be improved	Operation fields that cause problems					
	Substance	Structure	Time	Space	Energy/Field	Information/ Regulation
Substance	13, 31, 15, 17, 20, 40	1, 2, 3, 15, 24, 26	15, 19, 27, 29, 30	15, 31, 1, 5, 13	3, 6, 9, 25, 31, 35	3, 25, 26
Structure	1, 10, 15, 19	1, 15, 19 24, 34	1, 2, 4	10	1, 2, 4	1, 3, 4, 15, 19, 24, 25, 35
Time	1, 3, 15, 20, 25, 38	1, 2, 3, 4, 6, 15, 17, 19	2, 3, 11, 20, 26	1, 2, 3, 4, 7, 38	3, 9, 15, 20, 22, 25	1, 2, 3, 10, 19, 23
Space	3, 14, 15, 25	2, 3, 4, 5, 10, 15, 19	1, 19, 29	4, 5, 14, 17, 36	1, 3, 4, 15, 19	3, 15, 21, 24
Energy/Field	1, 3, 13, 14, 17, 25, 31	1, 3, 5, 6, 25, 35, 36, 40	3, 10, 23, 25, 35	1, 3, 4, 15, 25	3, 5, 9, 22, 25, 32, 37	1, 3, 4, 15, 16, 25
Information/ Regulation	1, 6, 22	1, 3, 6, 18, 22, 24, 32, 34, 40	2, 3, 9, 17, 22	3, 20, 22, 25, 33	1, 3, 6, 22, 32	3, 10, 16, 23, 25

Figure 17. Bio-TRIZ matrix

4.2.7 Artifacts Catalog

Extensive research had been going on in UMR/Oregon State University since 1999 in the area of development of artifacts catalog. Initially the work was just based on dismantling of objects and documenting different objects, bill of materials etc. This was done as a part of a design course and to make it contributing to the conceptual design research, they started exploring the functions each of the components can perform. In the later years, function structures were developed for each component and other attributes were constituted to the artifacts. The function it performs, the failure modes, performance characteristics, material, parent and child components etc. were some of the useful information attributed to the artifacts. A detailed information diagram of that design repository is shown in Fig.18. The shaded circles imply property of higher importance whereas the un-shaded circles represent additional details.

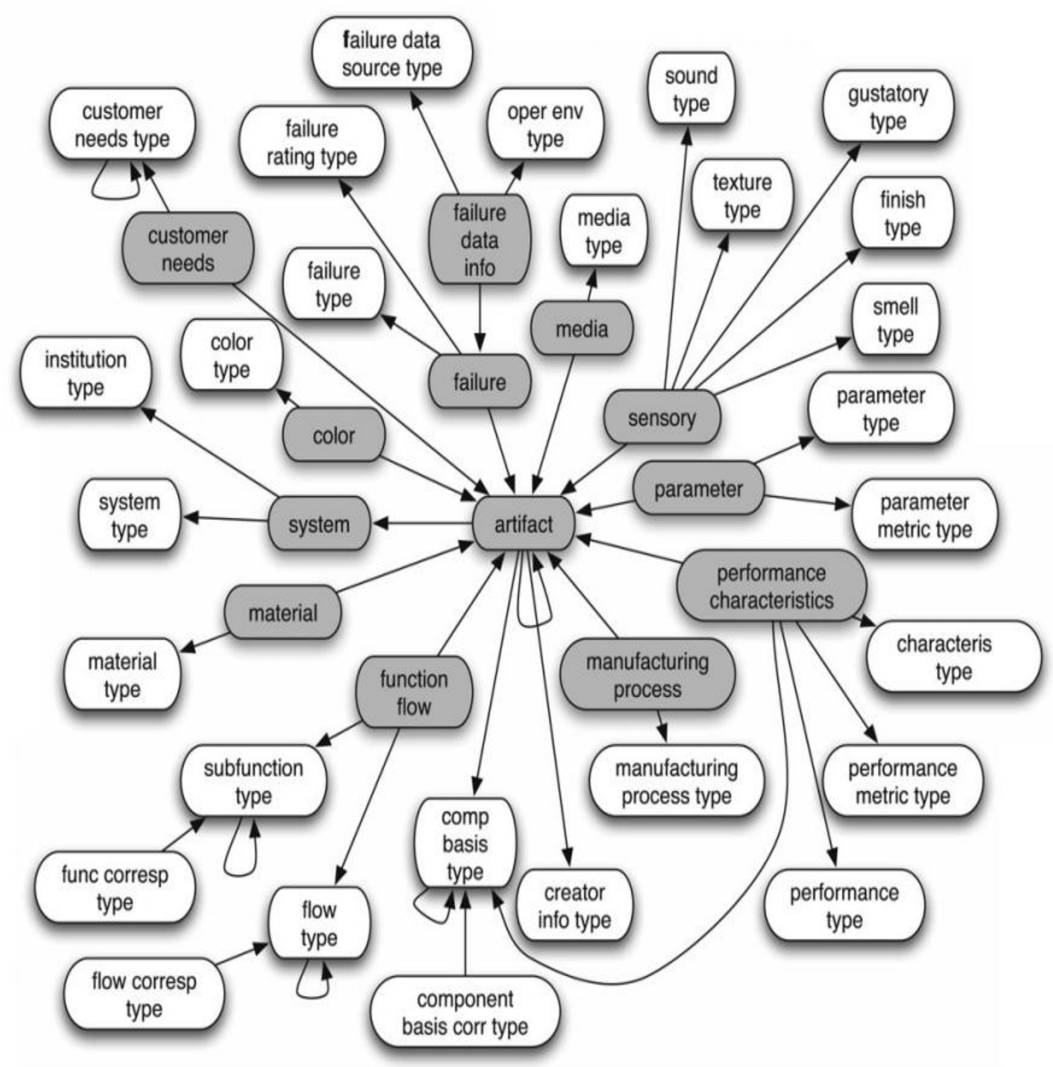


Figure 18. OSU design repository [15]

This function artifact catalog with its present capability, allow designers to search for artifacts according to functions. Since their catalog is huge with almost 5600 artifacts till date, we decided to utilize this useful resource. However, the information for many artifacts is incomplete. Some artifacts do not have failure information while some do not have information about physical parameters involved. The functional description is the only data which is complete for the whole set.

In this section, we saw in detail about all the experiential methods that we had used in out holistic ideation. In the next section we will see about the database schema for these methods and how they are connected and implemented as a computer tool.

CHAPTER 5

HOLISTIC IDEATION ARCHITECTURE

5.1 REPRESENTATION FOR IDEATION METHODS

5.1.1 PHYSICAL EFFECTS

In the previous chapter, description about physical effects was given. In this chapter, we will discuss about how the ideation methods are represented and what are the entities present in each of their representation. The following sections of this chapter will have details about relation between entities and finally an overall architecture for holistic ideation.

The entities in physical effects are:

a. Name

b. Description

c. Physical equations (E.g. F = m*a)

d. Physical variables (E.g. ‘F – Force’, ‘m – mass’)

e. Medium of occurrence (E.g. Solid, Liquid, Gas)

f. Physical law involved (E.g. Newton’s law of motion, Amonton’s law)

5.1.2 WORKING PRINCIPLES

Working principles have several entities some of which are similar to the entities in physical effects. They are:

a. Name

b. Description

c. Physical effects involved

d. Related physical variables

e. Materials (E.g. Steel alloy, Cast iron etc.)
f. Graphical representation
g. Functions it can fulfill (E.g. Mechanical energy to Electrical energy)
h. Biological example (E.g. Translocation in plants is an example for 'Flow of liquid')

5.1.3 TRIZ/ Bio-TRIZ

TRIZ is an ideation method which is fundamentally different from physical effects and working principles. The entities involved in TRIZ are:

a. Improving feature (E.g. Strength, Reliability etc.)
b. Worsening feature (E.g. Weight, Area etc.)
c. Inventive principle (E.g. Segmentation, Asymmetry etc.)

5.1.4 ARTIFACTS

The entities involved in the description of artifacts are:

a. Name
b. Description
c. Related functions
d. Parent/Child artifact
e. Failure (mode,type) – (E.g. Ductile fracture, wear etc.)
f. Color
g. Physical variables (In OSU design repository, it is mostly dimensions/weight)

5.1.5 FUNCTIONS

Functional description does not come under ideation methods. Functional decomposition is a systematic method to build function structures. Since it is systematic and it is an integral part of holistic ideation, we discuss about its description too.

a. Input/output flow variable (E.g. Mechanical energy, Solid material etc.)
b. Function verb (E.g. Divide, convert, expand etc.)

Flow variables are energy, material or signal which flows between artifacts. Function verb are description of actions that are done on the flow variables. There is a list of functional verbs and flow variables (Reconciled functional basis) which is given in the Appendix.

5.2. NEED FOR INTEGRATION AND TECHNICAL ISSUES

As it was discussed in the previous chapters, the main intent of this research is to build a holistic approach for conceptual design. Holistic approach provides the designer with different ideation strategies that he could use at different times. Hence, when the designer is working using a certain ideation strategy and he wants to switch to another ideation strategy, he needs to traverse seamlessly and be able to look at information related to what he saw before. He can also look at other information using various search strategies. But holistic ideation approach shows him first the information which is related to the information he looked at the previous ideation strategy. Hence, there is a need for strong integration between ideation strategies in order to provide seamless traversal.

There are also several technical issues involved in development of this holistic approach. As it is discussed in first section of this chapter, different ideation strategies/methods are described using different representations. Since the representations and vocabularies are different, it is very difficult to integrate them using a common relation. Different ideation methods also involve different processes. For example, physical effects, working principles and artifacts are just catalogs which can be queried. On the other hand, TRIZ is a different ideation method where the designer needs to define the technical contradictions and look at inventive principles. Also, TRIZ deals with improving and worsening features and does not deal with physics, whereas physical effects and working principles mainly deal with physics. Hence, we can observe that representations of different ideation strategies are completely different and also the processes are different.

Hence, there was a need for deep understanding of different representations and a common connection was needed to be found to facilitate the integration. On further research, it was found that physical parameters/variables were an integral part of physical effects and working principles. Also, in artifacts, physical variables are the flow variables that flow in and out of the components. Hence, artifacts were attributed with physical variables. The most difficult part in integration was connecting TRIZ to other ideation methods because both its representation and process is totally different from other methods. On deeper analysis of TRIZ method, it was found that improving and worsening features of

TRIZ can be related to one or more physical variables. Similarly each physical variable can correspond to one or more TRIZ parameter (E.g. 'sigma – Stress' is related to 'Stress/Pressure', 'Strength' and 'Reliability'). More details about relationships between ideation methods are explained in the following section.

5.3 RELATIONSHIPS

Details about representation of information in ideation methods and technical issues in integrating different strategies were discussed in last section. This section discusses about the relationship between different ideation strategies which is one of the main contributions of this research. The first part of this section discusses about how each ideation strategy is connected to functional definition, and how ideation methods are inter-related between one another is discussed in later part of this section.

5.3.1 Functions to Physical effects

Functions are defined using flow variables and functional verbs. Related research are being done in TU Munich [72] which is based on creation of bond graphs based on functional flow variables and physical equations. For now, we take the simple path of relating flow variables to the physical variables of the physical effects catalog. Physical effects are a very abstract form of representation and we had related functions to physical effects through flow variables of function ontology. As a step towards that, we first classify the physical variables as Energy, material and signal. Further classification is done using the flow set of the reconciled functional basis. Each flow variable has several physical variable associated with it. Based on the relations between the flow variables and the physical variables, functions and physical effects were mapped.

Energy is a product of force and effort, e.g. “Affinity” is effort analogy and “reaction rate” is flow analogy for “Chemical Energy”. Flow and effort analogies are expected to be added to the functional basis used in FunctionCAD. These flow and effort parameters are physical variables themselves and can be mapped directly. Other flow variables from primary, secondary and tertiary in functional flow set are mapped to one or more physical variables. The E-R diagram for relation between functions and physical effects are shown below.

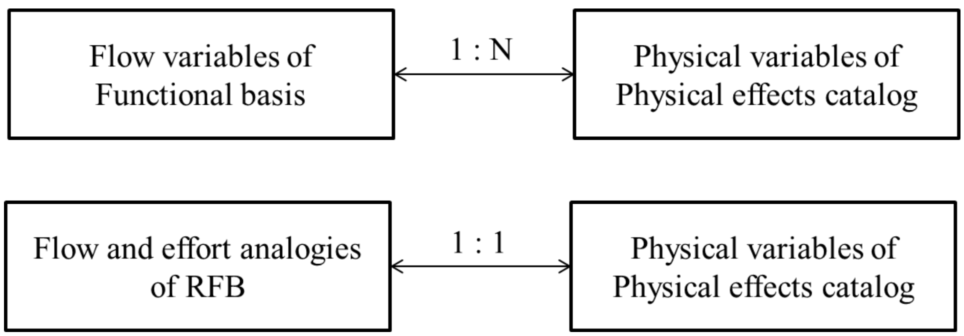


Figure 19. Relation between function definition and Physical effects

5.3.2 Function to TRIZ/ BioTRIZ

As explained in the literature review, the design team in Oregon State University had developed the function based TRIZ. They explored the flow variables of functional basis and variables involved in TRIZ principles. Extensive research was done on examples and principles in TRIZ and they were mapped to Functional verb – Flow variables combination of RFB. A function based TRIZ matrix was created as a result which is shown in the following Table.7.

Also, we already saw that the flow variables of function definition are mapped to the physical variables. We had also mapped the physical variables to the improving and worsening parameters of TRIZ. Hence, the 39 characteristics in TRIZ are related to one or more physical variables. The relationships table is shown in the appendix. This physical variable based relation will be useful for relating TRIZ to other ideation methods. To connect TRIZ to function definition, function based TRIZ is used. The Bio-TRIZ was developed as a result of analysis on several biological phenomena and further research needs to be done to map them to the physical variables thereby relating them to the functions. Also, the inventive principles of TRIZ can be thought as working principles obtained when there is a contradiction between two physical variables.

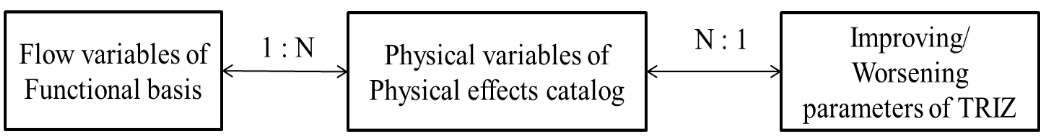


Figure 20. Relating flow variables to TRIZ with physical variables

Table 7. Function based TRIZ [50]

		Material	Energy	Signal
Branch	Separate	1, 2, 15, 27, 30, 40	1, 2	1, 2
	Distribute	3, 24	3, 11	3, 24
Channel	Import	39[1]	8[2], 37[3]	
	Export	2, 27, 34	2	2
	Transfer	10, 24, 34		24
	Guide	12, 15, 17	13	
Connect	Couple	6, 7, 8, 24, 39	6	6, 8, 24
	Mix	5, 33, 39, 40	5	5,
Control Magnitude	Actuate		9[4], 15, 18[4]	4, 15, 26[5]
	Regulate	16, 20, 21	16, 19[4], 20[4], 21, 38	16, 19, 20, 21
	Change	4,14, 31, 32, 33, 34, 35, 36[6], 38, 39[1]	9, 13, 20, 35, 37, 38	10, 32[5], 35
	Stop	11		15
Convert		17, 22, 29[7], 36	14[8], 19, 22, 28[9], 37	22
Provision	Store	5, 7, 10, 25, 26	9, 10, 25	
	Supply	10, 11, 24, 39	10	10
Signal	Sense	23	23	11, 15
	Indicate			23, 32
	Process			23
Support	Stabilize	7		
	Secure	5, 7		5, 7
	Position	5, 10, 12, 13, 17, 18	5	5, 10, 13

5.3.3 Function to artifacts mapping

The artifact catalog of Design engineering lab of OSU has a list of artifacts with details about related functions, failure modes and key physical variables. They already have almost 5616 artifacts which are exhaustive and each one of those has one or more functions associated with it. Since this list is vast, we are using this in our holistic ideation too.

5.3.4 Function to working principles

As we have seen before, working principle has related physical variables associated with it. Also, the flow variables of functions are related to the physical variables. Hence physical variables are a bridge between functions and working principles. The following Fig.21 explains the relationship between functions and working principles.

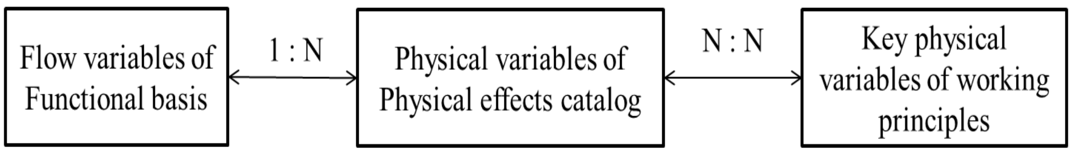


Figure 21. Relating function definition to working principles with physical variables

5.3.5 Relationship between ideation methods

As we have explained in this section,

i. Physical variables are an integral part of Physical effects
ii. Working principles are attributed with related physical variables
iii. Artifacts catalogs have key physical variables too
iv. TRIZ improving and worsening parameters are related to one or more physical variables.

As we can see, physical variables prevail to be the common connection between all the ideation methods and hence, physical variable is the primary key in our holistic ideation framework. If we take a look on higher scale, physical parameters are not only a part of every ideation methods used in holistic ideation but also they prevail to be a part of function, behavior and structure. That is also one of the main reason that we decided to have physical variables as a key connection between all ideation methods and function definition. Based on these variables, the traversal is facilitated seamlessly.

In last section, we discussed about the entities in different ideation methods and relationships between one another. The next section discusses an overall class diagram for holistic ideation.

5.4 CLASS DIAGRAM

Class diagram shown in Fig.22, shows the inter-relation between each ideation method.

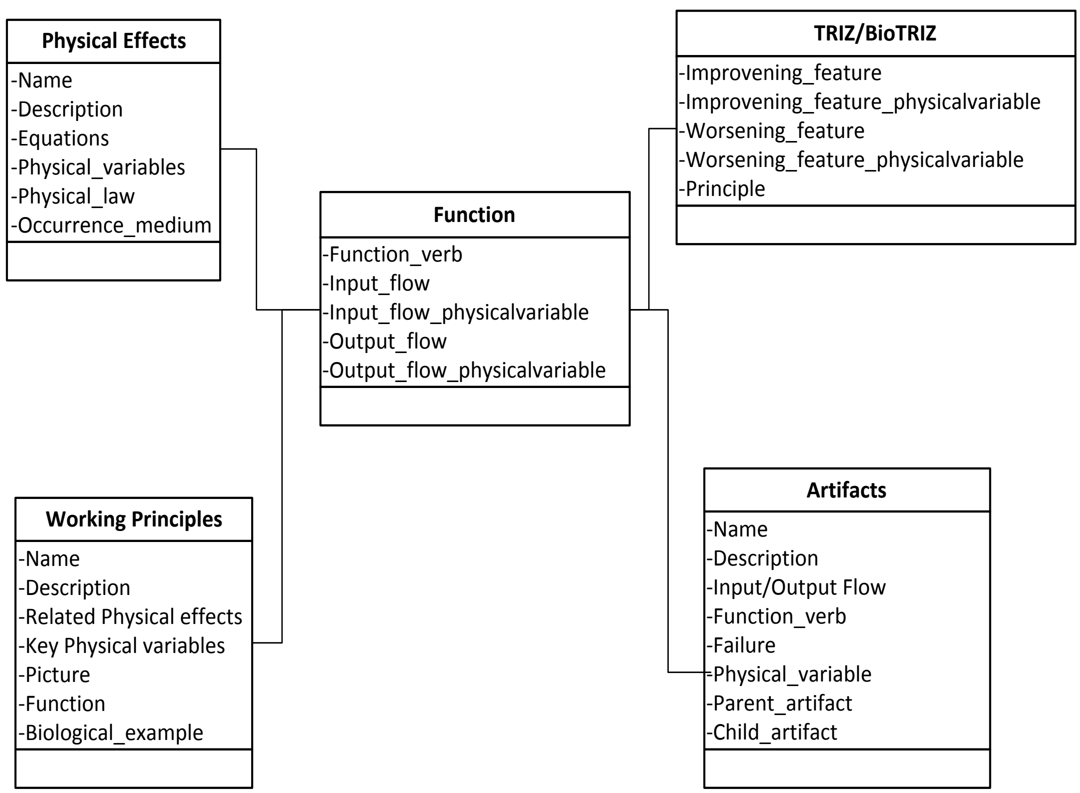


Figure 22. Class diagram for Holistic ideation with experiential methods

The class diagram shown in the above figure illustrates the structure of holistic ideation system with classes associated with them and their attributes. It also explains about the interaction between different sub-systems in holistic ideation. The energy, material and signal flow are transformed into relevant physical variables and they flow through different ideation methods in holistic ideation. It's also clear from this class diagram that physical variables are an integral part of all the ideation methods. Functional flow variables are related to one or more physical variables and same is the case for TRIZ improving/worsening parameters. Between ideation methods, there is always a 1:1 relationship between connecting physical variables based on the variable which the designer is interested in. For addition of new data into the repositories, the developer just needs to add an entry in the relations table to create the relationships. The relations are not made automatic (if the physical variable is already present in the database).

CHAPTER 6

HOLISTIC IDEATION IMPLEMENTATION

6.1 DATABASE SCHEMAS

We will discuss about the computer implementation for each of the experiential ideation methods in this chapter. The repositories play a vital role in holistic ideation and studying their schema is hence very important. Relationship diagrams from each of our design repositories are shown in this section. The first we look at will be the physical effects database schema. As we have discussed before, Physical effects are represented using a name, description, related physical equations, related physical parameters and occurrence medium. Database schema for the physical effects database is shown below in Fig.23. In this database schema, we can see additional details like 'field' which corresponds to 'mechanical', 'electrical' or 'thermal/fluid'. The 'flow' and 'flow_pe' tables show the relation between the flow variables and the physical variables of the physical effects. In later part of this chapter, we will see the UI for PE search tool.

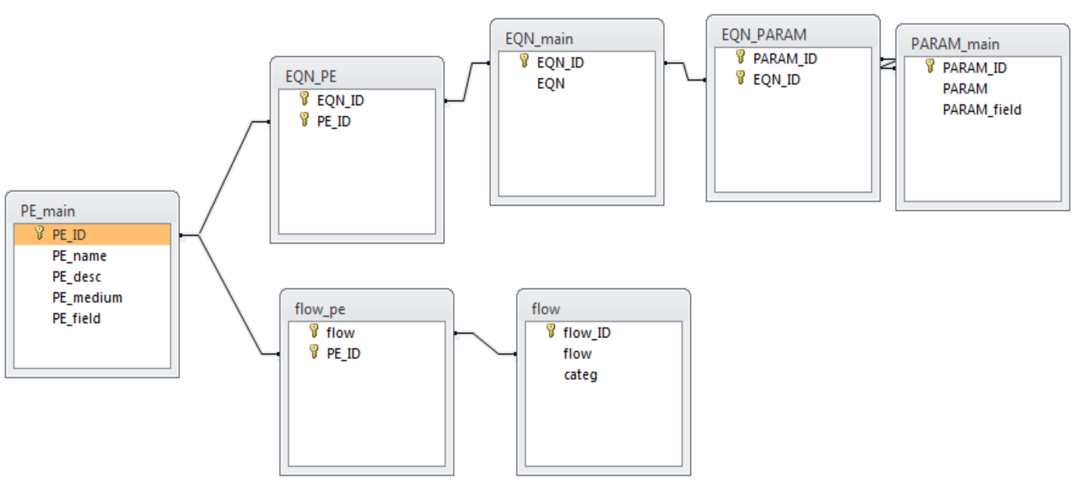


Figure 23. Database schema for physical effects database

The next experiential database that we will look at will be the working principles database. As we have seen in the last section, a working principle is defined using a name, description, related physical effects/variables, intended functions, graphical representation and biological examples. The following Fig.24 shows the database schema for WP. In later part of this chapter, we will see the UI for WP search tool.

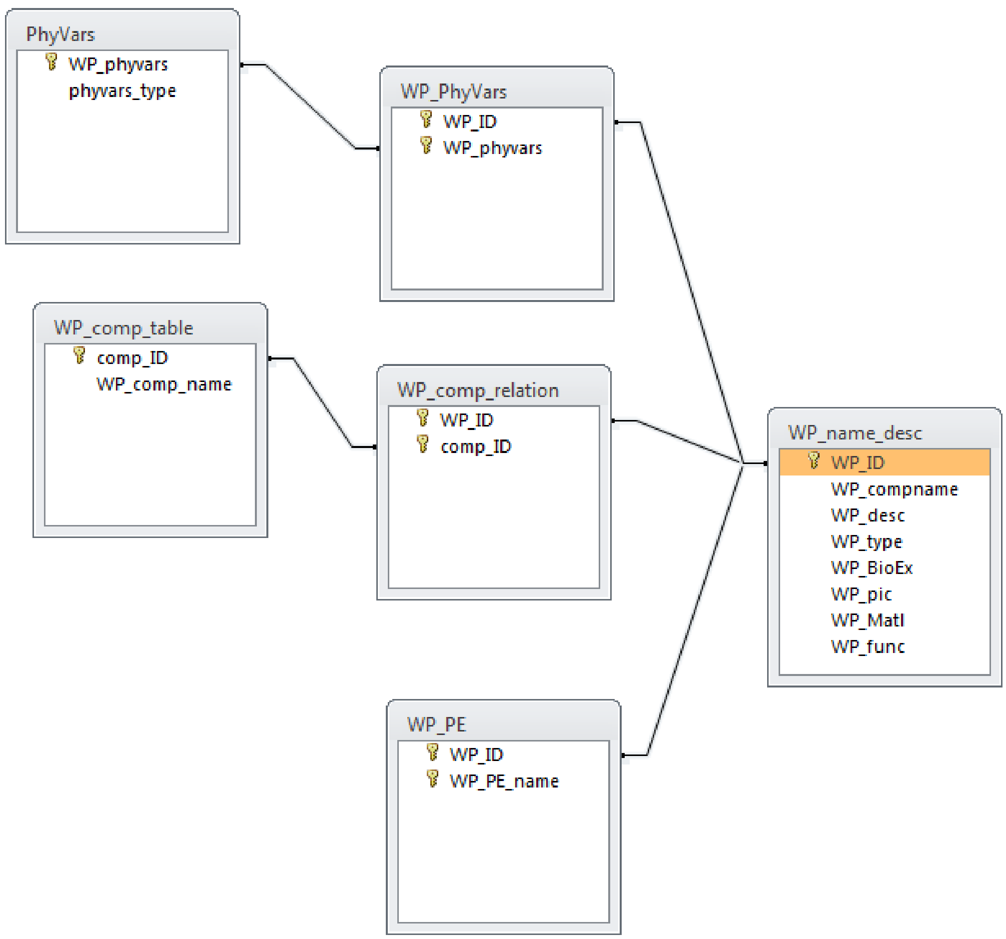


Figure 24. Database schema for working principles database

The next experiential ideation method that we will discuss is TRIZ and BioTRIZ. As we discussed in previous section, based on the contradicting parameters and the TRIZ/BioTRIZ matrix, appropriate principles will be suggested. The database schema shown in Fig.25 illustrates the structure of the database and also about how function based TRIZ is incorporated into the database. In the later part of this section, TRIZ workbench UI will be explained.

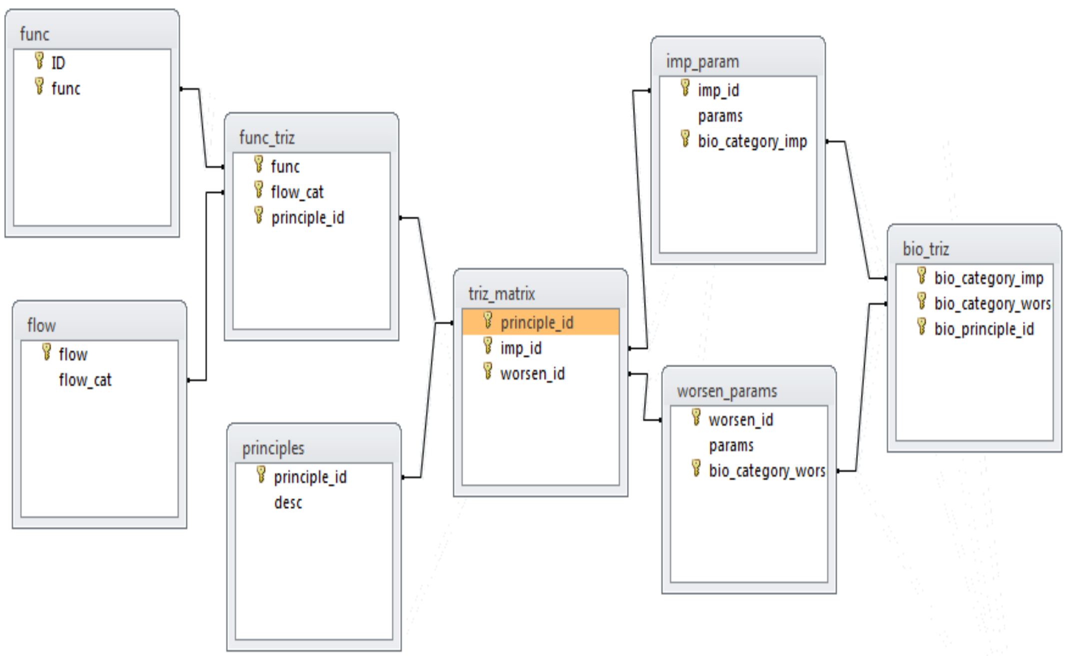


Figure 25. Database schema for TRIZ/BioTRIZ and function based TRIZ

The next experiential ideation method that we will see will be the artifacts catalog. In the previous section, we discussed about how artifacts are defined. The following figure shows the design repository schema taken from the work of Robert Stone et al. [15].

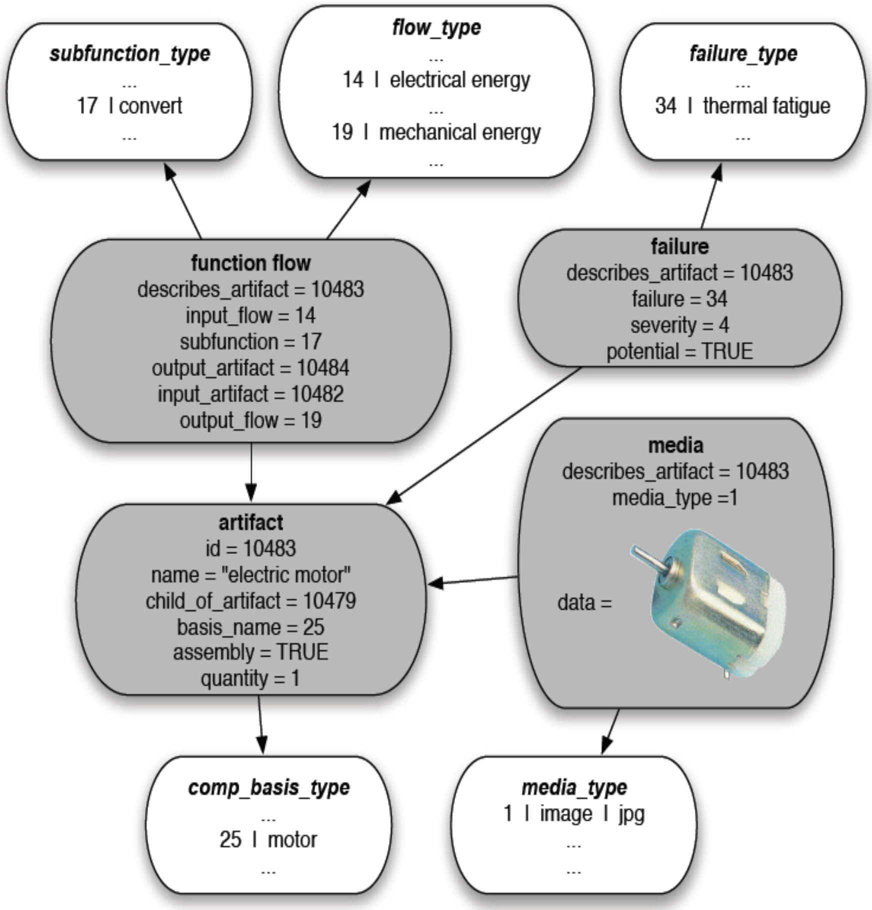


Figure 26. Database schema for Oregon State University Design repository

6.2 UI DEVELOPMENT FOR LOGICAL IDEATION TOOLS

A complete holistic ideation test bed should facilitate functional decomposition, ideation, documentation and navigation between ideation methods as we have discussed before. Hence, we need to develop UI for the following set of computer tools to facilitate holistic ideation:

1 Function decomposition tool

2. Ideation state characterization tool
3. Ideation tools (ideation methods)
4. Textual and graphical documentation tool
5. Survey tool

6.2.1 Function decomposition tool

FunctionCAD from Oregon State University is a tool used for visual representation of functional models and we use the same tool in our holistic ideation test bed. We decided on using FunctionCAD because, it already possesses the modeling tools for drawing the function structure based on the reconciled functional basis (RFB) which we had planned to use. The function structure here will be saved as a "fcad" file. FunctionCAD is the key part of pre-ideation stage in our holistic ideation framework. A screenshot of function structure drawn using FunctionCAD is shown in Fig.27.

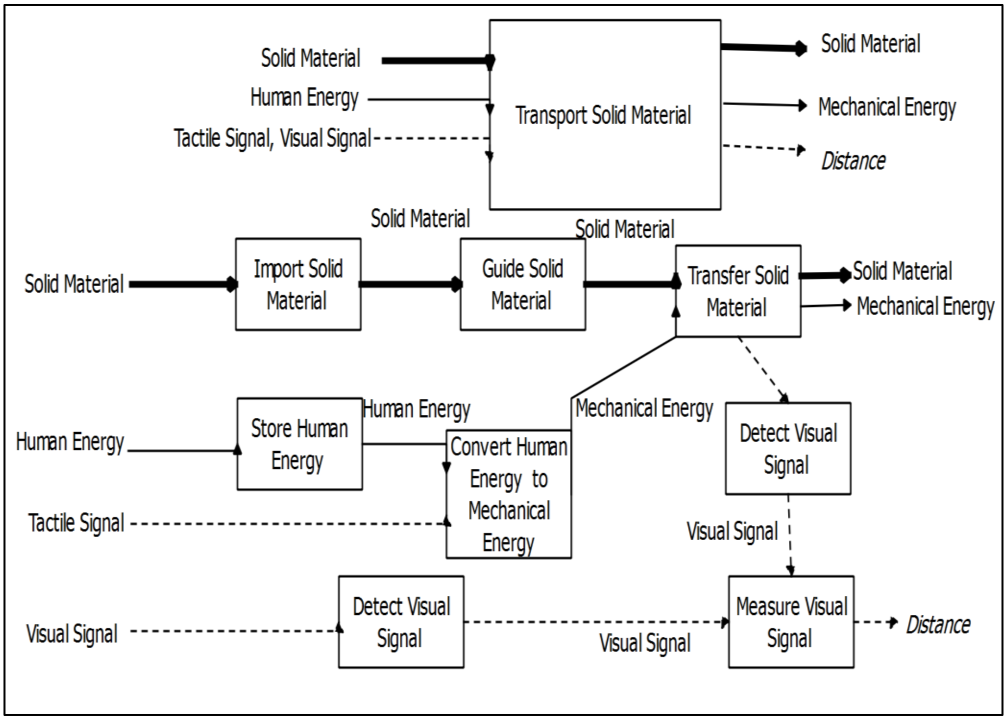


Figure 27. Example of function structure drawn using FunctionCAD

6.2.2 Ideation state characterization tool

For the characterization of ideation states, the UI had been developed which can take several values for the indicator measures as discussed in chapter 3. When the values are entered for the characterization measures, corresponding blocks are found and appropriate ideation methods are suggested based on the blocks. If there was no block found, he is allowed to choose any of the ideation method present in the test bed and he is allowed to give a short explanation about his ideation block in the final survey where we get details about his ideation state. If the selected ideation strategy was effective, he would document it along with details about his ideation state. Hence, it can be seen that blocks and tackles are a stationary point. As more and more data are collected, we will be able to improve the system. The UI for ideation characterization is shown below.

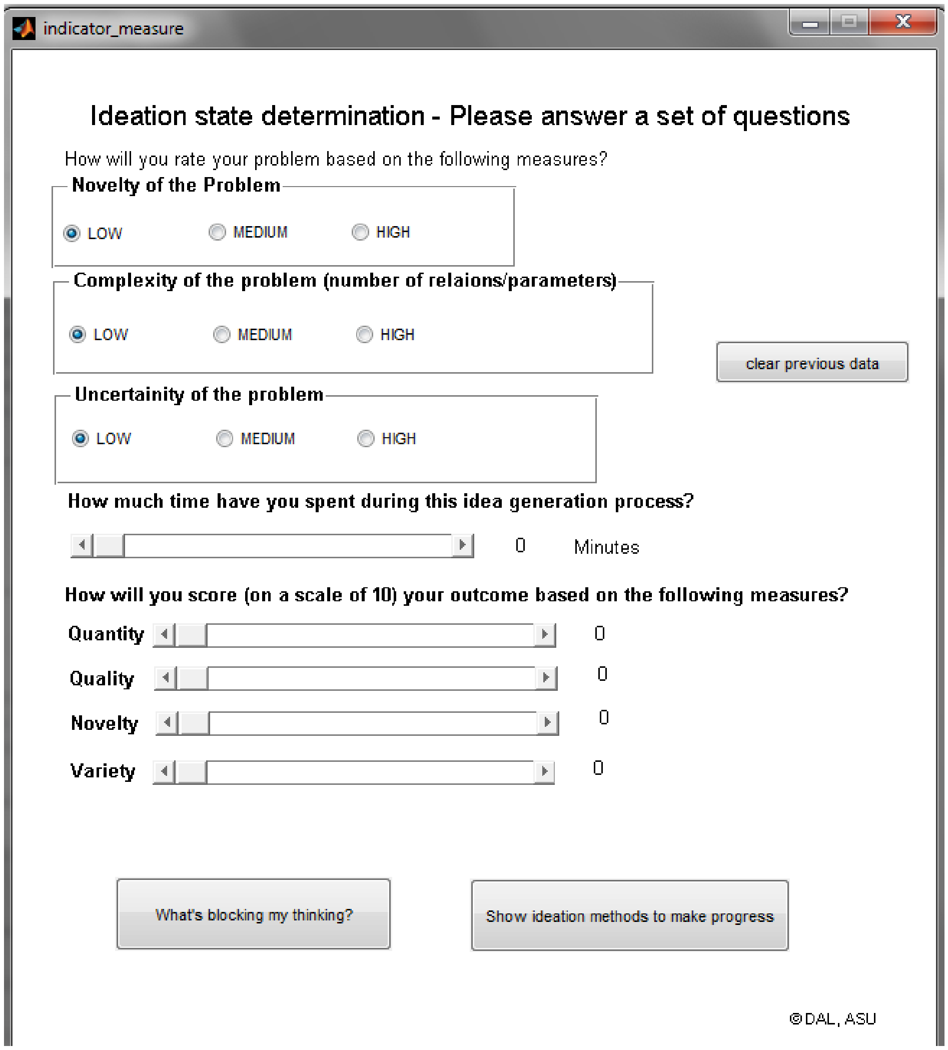


Figure 28. Ideation characterization tool

6.2.3 Idea generation tools

The physical effects database can be searched through the physical effect's name, physical parameter or function. The following snapshot shows the UI for physical effects search tool.

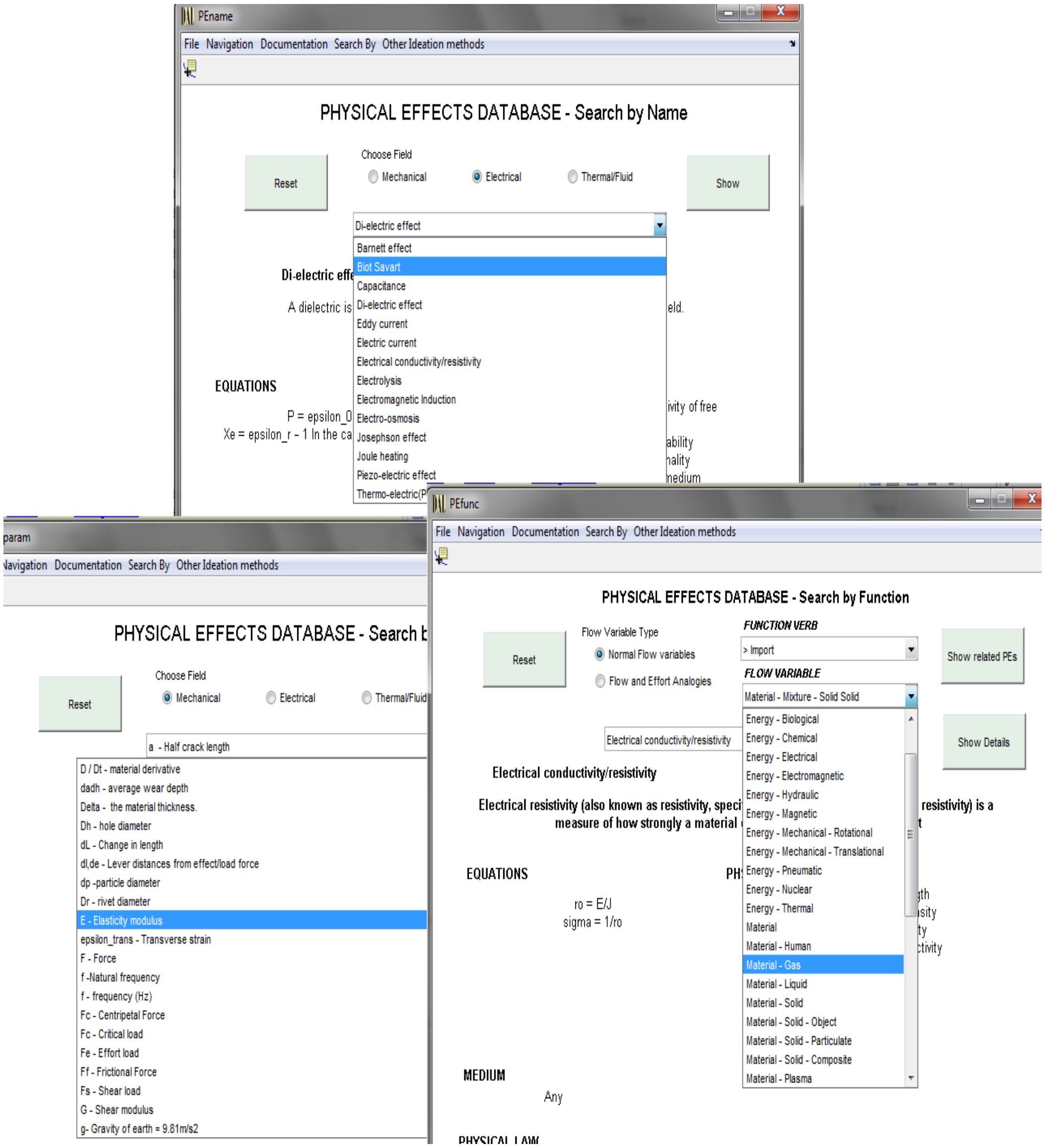


Figure 29. Physical effects search by name (top), by physical variables (left) and by function (right)

Also, the working principles can be searched with respect to name, physical variables and function. The following snapshot shows the UI for working principles search tool.

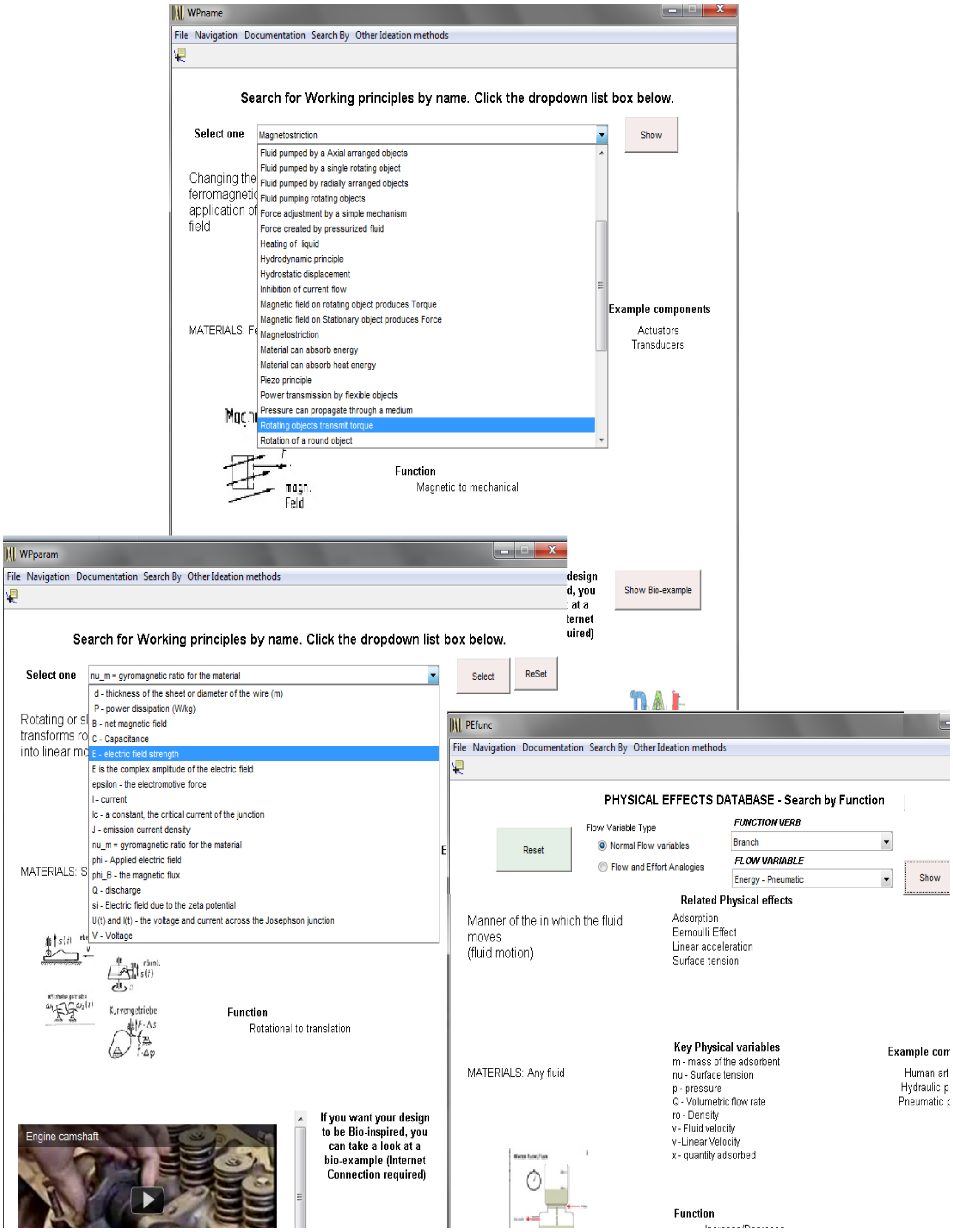


Figure 30. Working principles search by name (top), by physical parameters (left) and functions (right)

TRIZ/BioTRIZ had been implemented based on the database schema described in earlier part of this chapter. Also, function based TRIZ is implemented as shown in the following Fig.31.

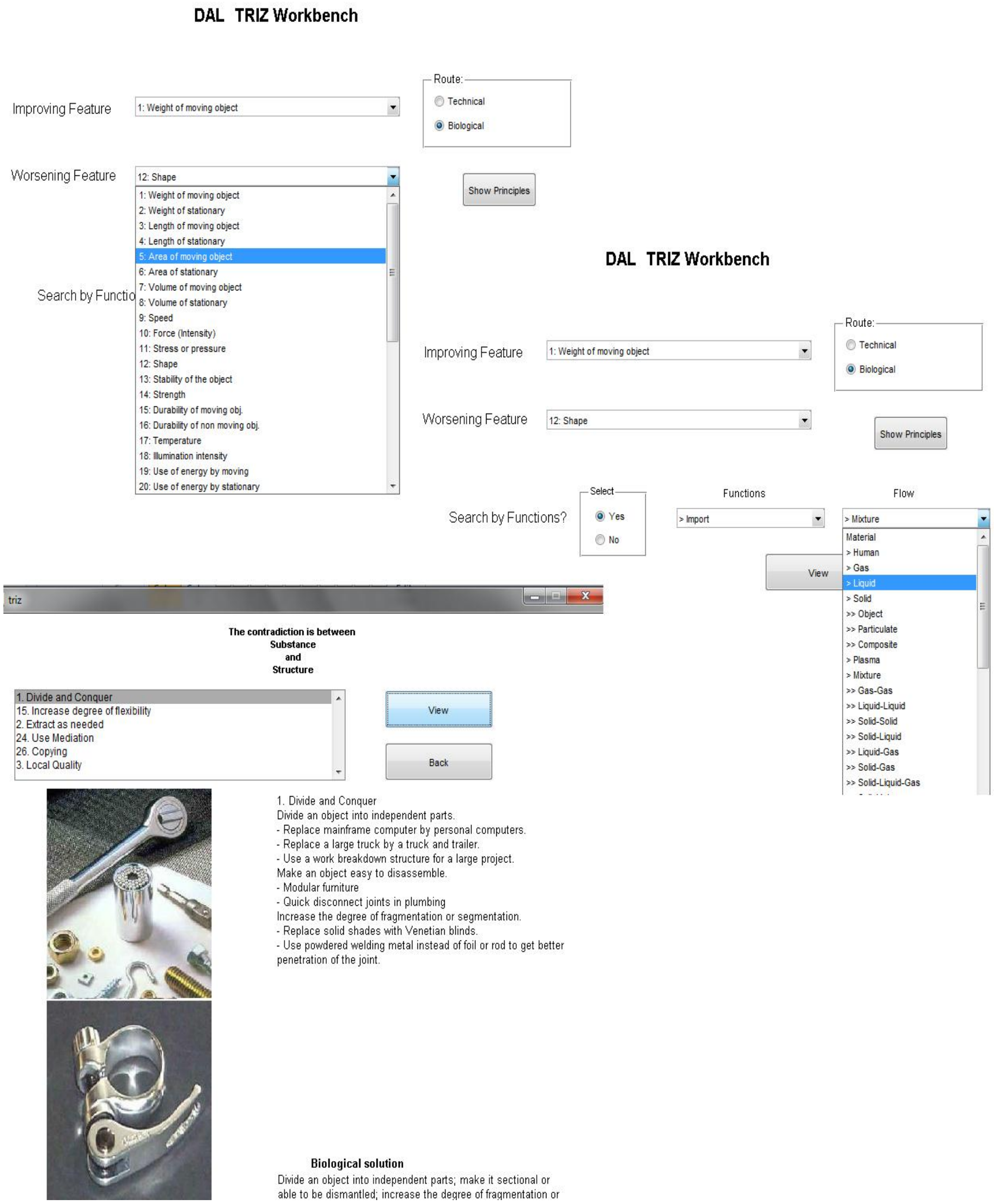
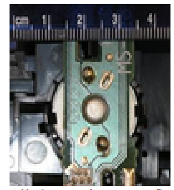


Figure 31. TRIZ normal search (top), search by function (right) and example window (bottom)

Artifact search can be done based on names and based on functions. The UI for artifact search tool is shown below in Fig.32.

Artifact Name	**door motor**
Sub Artifact Of	cd cover
Quantity	1
Description	motor that opens and closes cd drawer
Artifact Color(s)	not specified
Component Naming	electric motor

Artifact Photo



click on image for full size

Input Artifact	Input Flow	Subfunction	Output Flow	Active Flow	Output Artifact
green circuit board	electrical	convert	mechanical	active	cd cover
Supporting Functions					
green circuit board	solid	couple	solid	active	internal

Physical Parameters

mass	25.0	grams
radius	12.0	mm
height	20.0	mm

Manufacturing Process

material [metal]

no process specified

Failure Information

Failure Mode	Severity	Potential	Occurrences	Sample Size	Failure Rate
high cycle fatigue	0	potential	0	0	0.0

Artifact Entry Information:

manufacturer:	empty
trademark:	empty
release date:	2000-01-01
upload date:	2010-05-26
modification date:	2006-06-09

Figure 32. Artifact search tool

6.2.4 Documentation

Idea generation tools were discussed in the previous sections. Once ideas are generated, it is necessary to document those. In our present holistic ideation tool, we had facilitated textual and graphical documentation. Textual documentation can be made in a text pad and graphical documentation can be done in an in-built graphical editor. The graphical editor is a simple sketching tool in which the designer can sketch in different colors and save in JPG, PNG or BMP format, according to his need. In the future, tablet PCs can be integrated with our tool so that sketching can be made easier.

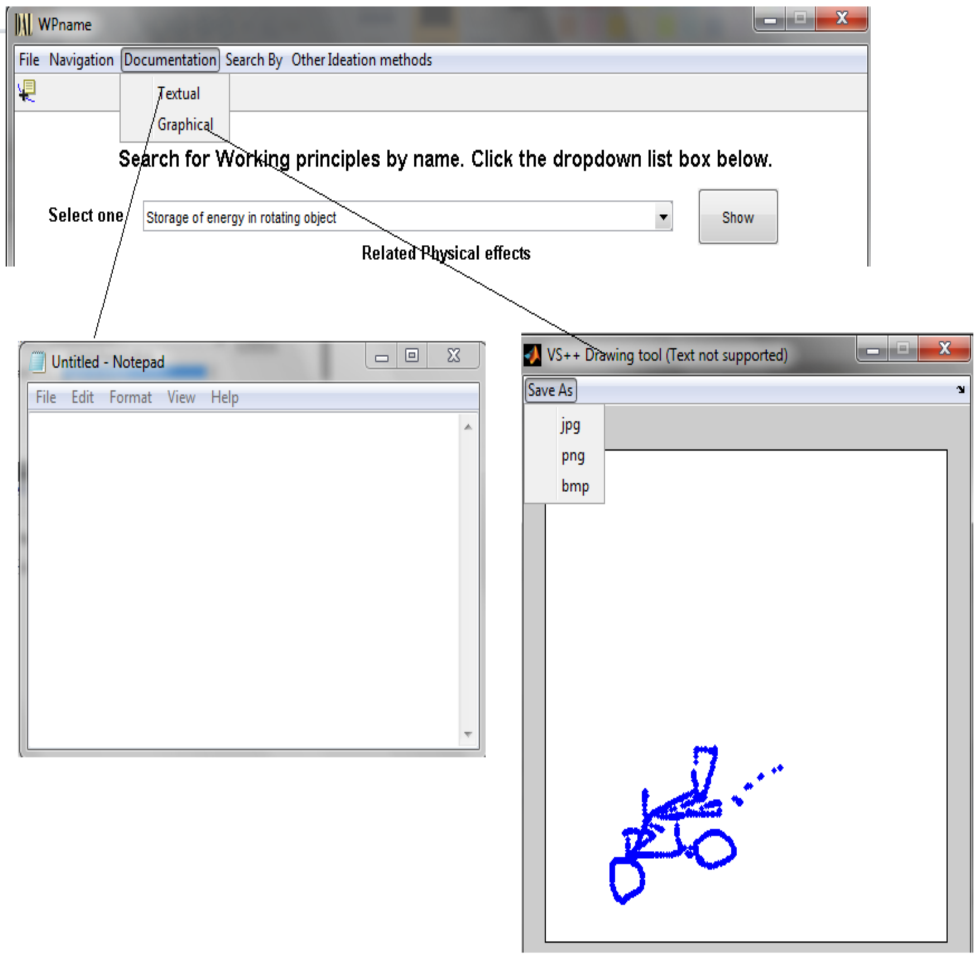


Figure 33. Textual and graphical documentation

6.2.5 Survey tool

This survey tool is used to collect information about how well the designer's functions were satisfied and also some details about the effectiveness of ideation strategy used. The designer can also describe his state of mind in this UI (if the ideation block found did not match to his mindset).

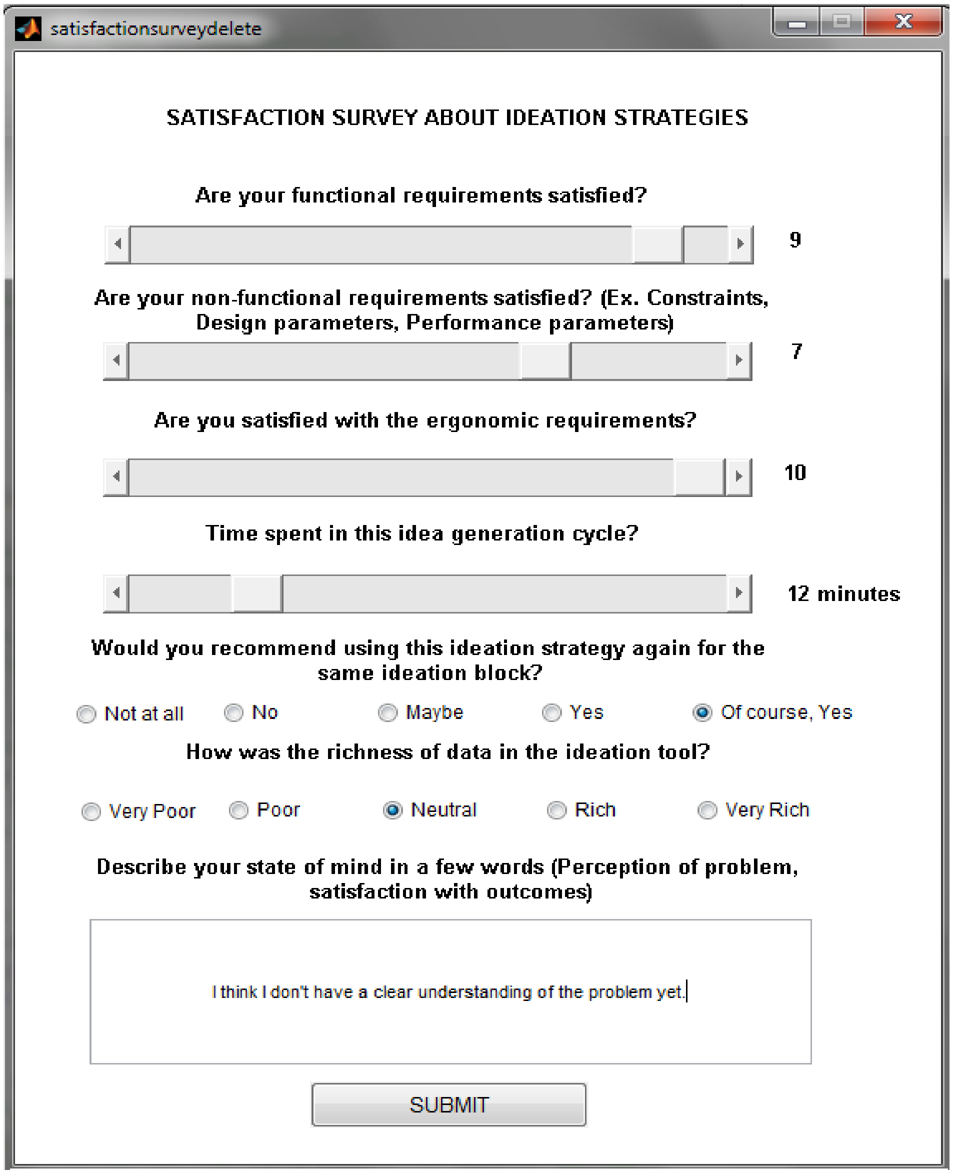


Figure 34. Satisfaction survey to collect details about effectiveness of ideation strategies

Chapter 7

USER STUDIES/RESULTS

7.1 DESIGN IDEATION PATHS

Holistic ideation is a method which facilitates mix and match of ideation methods and also effective documentation of data related to ideation and creativity. Our primary goal is to analyze and research on areas which is not feasible with the data obtained with protocol studies due to time and human constraints. Our main motivation here is that how effective will the data obtained from holistic ideation be and how they can be used for exploring different areas of research related to design ideation. Certain ideation strategy might be useful for one designer while it was not effective for another. This might be because of the knowledge/background of the designer or maybe due to the richness of information in the search tool. Different designers will have different ideation states during problem solving and they might find different strategies to be effective in different situations. Hence, different designers take different routes to come up with effective solutions for a problem. These different paths that the designer takes are called as design ideation paths. Effectiveness and usefulness of design ideation paths is an area which had not been explored before, and we believe, with the information we will obtain related to creativity and ideation, some initial observations can be made about design ideation paths and its effectiveness.

Usage of a sequence of ideation strategies will be useful when compared to another sequence. In our past research and also presently, we only discuss about how individual are strategies helpful in overcoming blocks. But, we had not discussed about the combinations of ideation strategies that can be used and the sequence in which they are to be used. Only from a framework like Holistic ideation, we can explore this area.

Documentation of ideation paths is a new area of research and we do not have much insight about it presently. The following sections in this chapter will just discuss about some initial guidelines for future research on ideation paths. Concrete results or conclusions cannot be reached at this point of research.

7.2 USE OF HOLISTIC IDEATION TO EXPLORE IDEATION PATHS

Since holistic ideation has the capability to sense the ideation state of a designer and also has the capability to guide him to different logical and intuitive ideation strategies, we believe holistic ideation is a good platform to check the effectiveness of design ideation paths. An example ideation path obtained from the usage of holistic ideation is illustrated in Fig.35. The starting point one of the functions from function structure. Once the function is selected, the next stage is to characterize ideation state and use appropriate ideation methods until satisfying solution(s) are obtained after which the designer moves on to the next function after a small survey. The flow can be clearly seen in the case study in last section of this chapter.

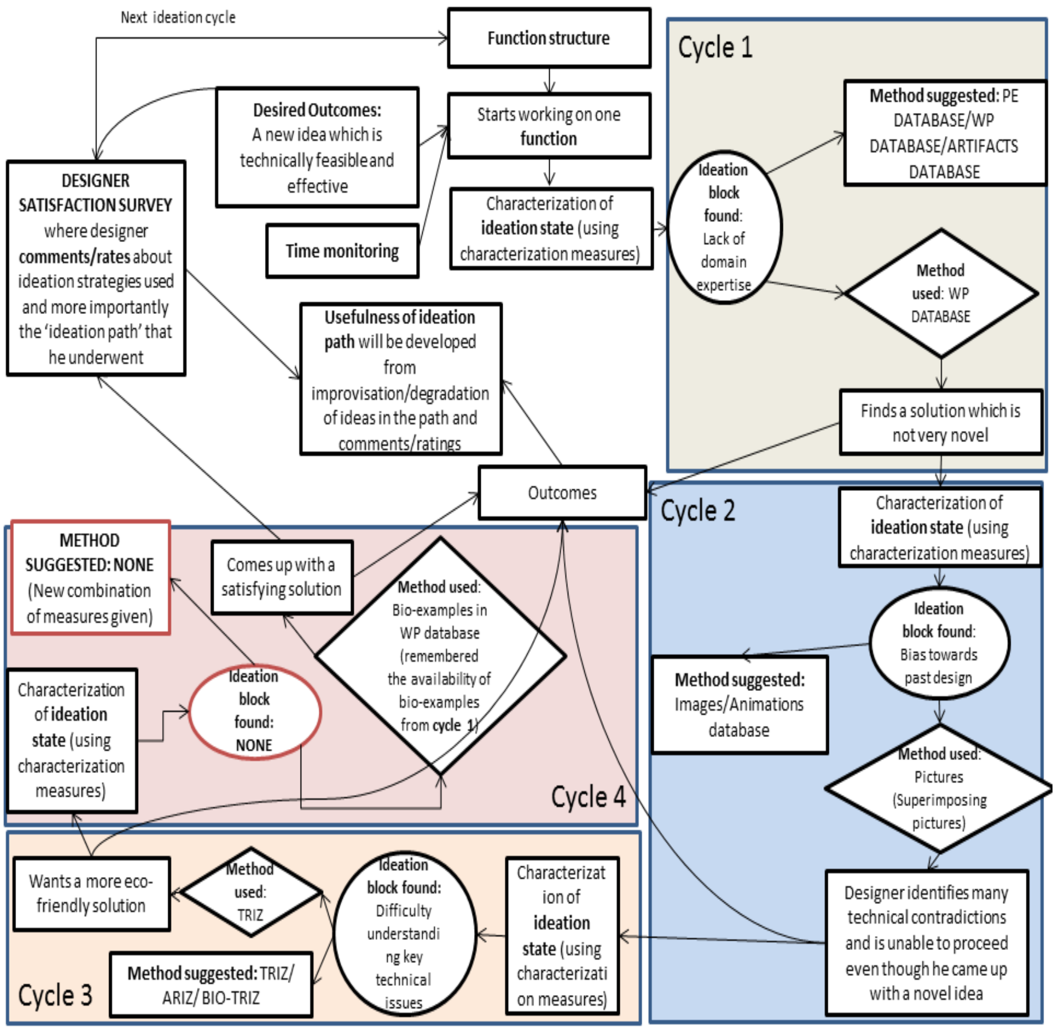


Figure 35. Example design ideation path (for one function)

Based on the idea generation cycles seen in the figure, we can define the content of ideation paths, its structure/representation, documentation and visualization. Also, we will discuss about how it can be used for future research.

7.2.1 Contents of Ideation paths

Ideation paths will be documented all through the idea generation process using holistic ideation. The contents of design ideation paths will consist of:

a. Intended function

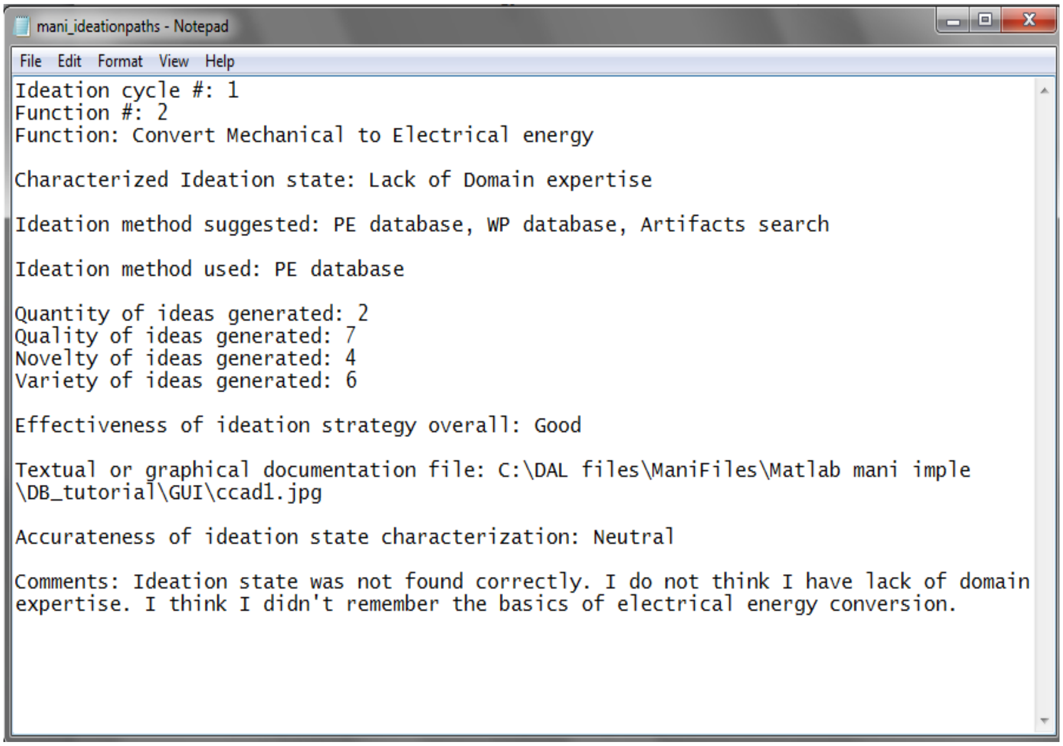
b. Characterized ideation state
c. Ideation strategies suggested and Ideation strategies used
d. Effectiveness of ideation strategies
e. Accurateness of characterization of ideation state
f. A short description of his/her ideation state

7.2.2 Structure of Ideation paths

The documentation of ideation paths should be structured in such a way that it should be easy to interpret and understandable. The ideation paths in holistic ideation framework will be documented as a text file so that querying/accessing can be easily done using file reading/writing. The structure of ideation path should have all the contents described above. It should also have additional details about the function number, ideation cycle number etc. which will be useful for knowing about number of cycles taken for a particular function.

Function number: The designer might work on multiple functions for a given design problem. Hence, his functions are numbered to make it more searchable and structured.

Ideation cycle number: For a given function, the designer might use multiple ideation strategies to come up with a satisfying solution. He might go through different number of ideation cycles and it is good to number those. The number of cycles can be related to effectiveness of ideation strategies in the future work.



mani_ideationpaths - Notepad

File Edit Format View Help

Ideation cycle #: 1
Function #: 2
Function: Convert Mechanical to Electrical energy

Characterized Ideation state: Lack of Domain expertise

Ideation method suggested: PE database, WP database, Artifacts search

Ideation method used: PE database

Quantity of ideas generated: 2
Quality of ideas generated: 7
Novelty of ideas generated: 4
Variety of ideas generated: 6

Effectiveness of ideation strategy overall: Good

Textual or graphical documentation file: C:\DAL files\ManiFiles\Matlab mani imple \DB_tutorial\GUI\ccad1.jpg

Accurateness of ideation state characterization: Neutral

Comments: Ideation state was not found correctly. I do not think I have lack of domain expertise. I think I didn't remember the basics of electrical energy conversion.

Figure 36. Structure of ideation path

Function: After creating the function structure for the problem, the designer works on one particular function. The function which he is working on is also documented. Certain ideation path might be effective for certain functions and hence we document that.

Characterized ideation state: The characterized ideation state of the designer is also documented. It might be an ideation block or unfettered ideation.

Ideation method suggested/used: Based on the characterization of ideation states, the holistic ideation framework suggests a set of ideation methods. The designer might use one of those or he can use an ideation strategy other than what was there on the list. Hence, to know information about highly/least used ideation methods suggested, we record this data.

Outcomes: The quantity, quality, variety and novelty of ideas are recorded to know about how strategies/paths affect the outcomes.

Effectiveness of ideation strategies: Effectiveness of ideation strategies are recorded in the satisfaction survey at the end of each ideation cycle. It can take the values of ‘very bad’, ‘bad’, ‘neutral’, ‘good’ and ‘very good’.

Accurateness of ideation state characterization: The ideation state characterization might not be always correct initially. If the designer has an ideation block which different from what the software sensed, it is recorded using the comments section in the satisfaction survey. This measure can take values of ‘very bad’, ‘bad’, ‘neutral’, ‘good’ and ‘very good’.

File path: The file paths where the ideas are documented are recorded too, as a reference for the designer, in case he wants to access it later.

7.2.3 Documentation

The ideation cycle number, function details, ideation state characterization details, and outcomes are recorded using the mouse clicks on buttons. Each click is logged as text file in a structure described above. Information about effectiveness of strategies and comments about ideation states are recorded from the satisfaction survey at the end of each ideation cycle. All the information are recorded as log text file.

7.2.4 Visualization

Ideation paths can be effectively visualized using flow charts. The visualization is similar to the example ideation path described in the beginning of this section. The visualization has details only about the function, ideation state, ideation methods suggested/used and their effectiveness.

7.3 QUERYING THE DOCUMENTATION

The information from the holistic ideation documentation can be queried using:

a. Function (refer effective ideation path)
b. Ideation strategy (to know what was the next/previous strategy that was used)
c. Ideation block (what strategy resolved the block)
d. Outcomes (strategies to obtain required outcomes. E.g. High quality or high novelty)

7.4 EMBEDDING DESIGN IDEATION PATHS AS A PROCESS MEASURE TO CHARACTERIZE IDEATION STATE

From the information we collect during documentation of ideation states, we will also learn about the common ideation blocks encountered during certain ideation paths. Based on this information, we can map possible ideation blocks to a certain ideation path. Finding ideation state based on path will not be a good conclusion with the information we have about ideation states presently. We must run exhaustive number of experiments to map a set of ideation blocks precisely to a design ideation path which will be an important part of our future work.

7.5 CASE STUDY

To understand in more detail and get more insight about different ideation paths that designer take, we did a series of experiments with fellow designers from Design Automation Lab who were also enrolled in Advanced Product design course. The choice of participants was made such that they have some preliminary knowledge about conceptual design and different ideation strategies. Each designer was given with the same design problem and was asked to solve it using different ideation strategies/methods provided by holistic ideation tool (also their own knowledge). They were also asked to characterize their ideation state and take a short survey at regular intervals during the ideation process (mostly when switching between ideation methods).

The problem defined was to design a PORTABLE POWER RAMP which could transfer/transmit objects in and out of any vehicle (car/truck/bus). The power ramp should be light, strong and portable with less power consumption. Also, the objects which are transferred in and out of vehicles should be secure and safe so that it would not fall off. Before the designers started using the holistic ideation tool, they were given a 20 minutes tutorial followed by initial instructions. The designers were allowed to ask questions so that they are clear about the UI and capabilities of the tool before they even looked at the problem. The time provided for this ideation experiment was 40 minutes. Since using FunctionCAD needs a bit of training, the designers were also given the choice of documenting their functional structure in paper. The functional flow set and functional verb set of reconciled functional basis were given as handouts for each designer.

In the following pages, we will discuss about different ideation strategies/paths used by the designer, new cognitive states that were found and some overall comments about the software.

Case study 1:

The design process started with documentation of user information and building of function structure for the given problem. Designer 1 created a detailed function structure by hand and tried to solve more than one function at a time. After creating an initial set of ideas, designer wanted to characterize his ideation state. The designer gave in values for characterization measures (problem novelty = medium, problem complexity = medium, uncertainty = low, time = less, Quantity = 1, Quality = 1, Novelty = 2, Variety = 1) and the ideation block found was "Rigid problem representation". There were many methods suggested to overcome that ideation block such as C-sketch, gallery method and storyboarding. But unfortunately, none of those are available as computer application. Hence he was allowed to choose an ideation method of his choice and he opted to look for working principles by searching through functions. Designer started his search with "Transfer solid object" and looked at several related working principles. Once he finished using working principles, he was allowed to take a short survey where he answered questions about effectiveness of strategy and richness of information provided. After the short survey, he again characterized his ideation state (problem novelty = medium, problem complexity = medium, uncertainty =

low, time = less, Quantity = 2, Quality = 3, Novelty = 3, Variety = 2) and unfortunately there was no ideation state mapped to that combination of characterization measures and there was no ideation method suggested. Hence, designer made his own decision and decided to use function based TRIZ. The functions searched were “Convert electrical” and “transfer solid object”, and from the search results, the designer was exposed to various kinds of stimuli. Another set of ideas were generated and again he decided to characterize his ideation state. After giving in the measures, the ideation block found again was “Rigid problem representation” and the designer decided to look at working principles again since he felt it was useful during his initial ideation cycle. Some functions that he searched for were “Actuate electrical”, “convert mechanical”, “increase mechanical” and “decrease mechanical –translation”. After using the working principles search, the designer took again the short survey and again characterized his ideation state (problem novelty = low, problem complexity = medium, uncertainty = low, time = less, Quantity = 3, Quality = 4, Novelty = 2, Variety = 5). One observation we could understand here is, as the designer looked at different working principles, the novelty of the problem had decreased. And for this combination of characterization measures, there were no ideation state mapped and hence he decided to use artifacts search. Some functions that were searched in this tool were “solid-transfer-solid”, “electrical-store-electrical”, “solid-support-solid” and “mechanical-decrease-mechanical”.

After the time given was over, the designer was allowed to complete his sketches and label them properly for 2 minutes so that it would be easy to understand.

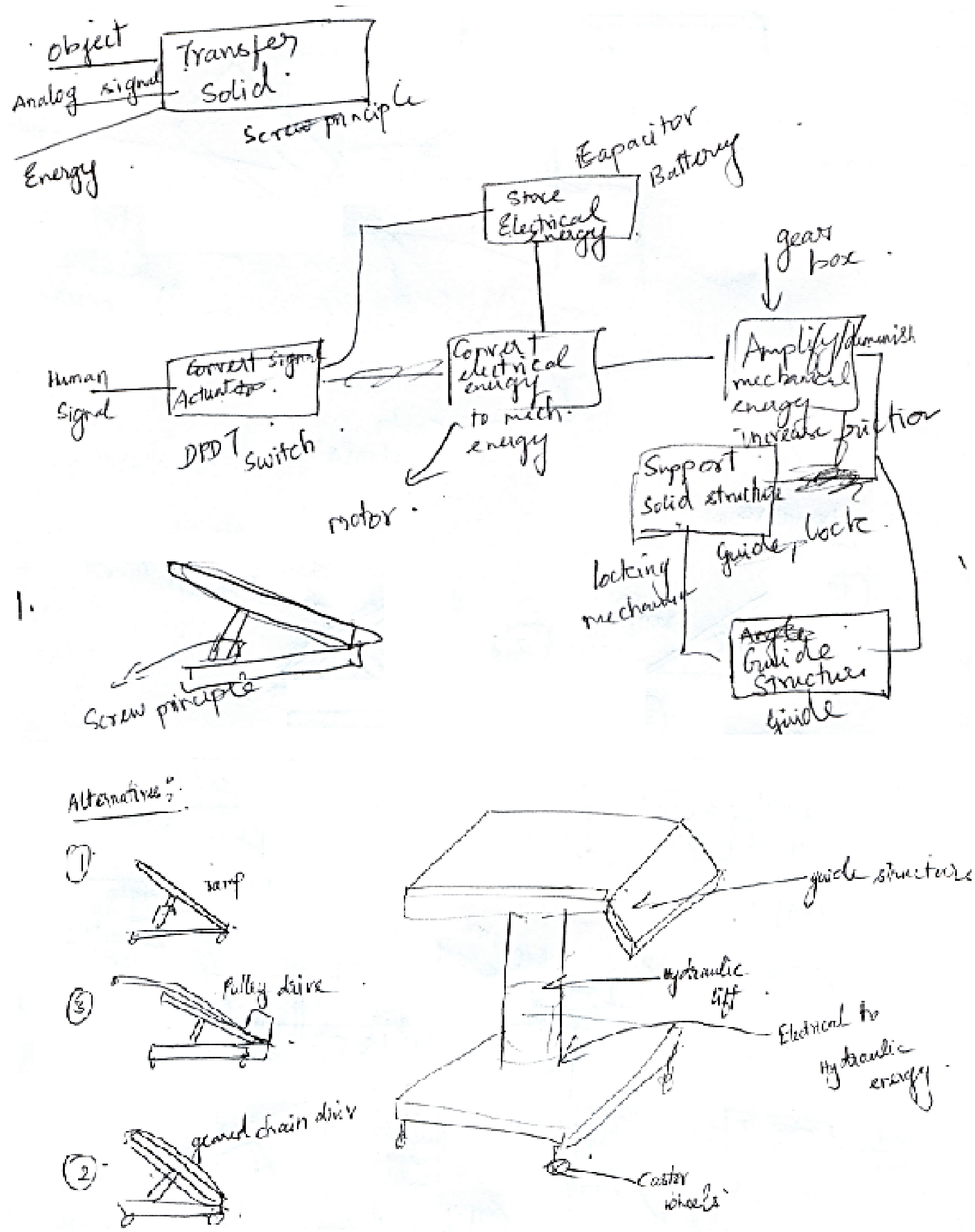
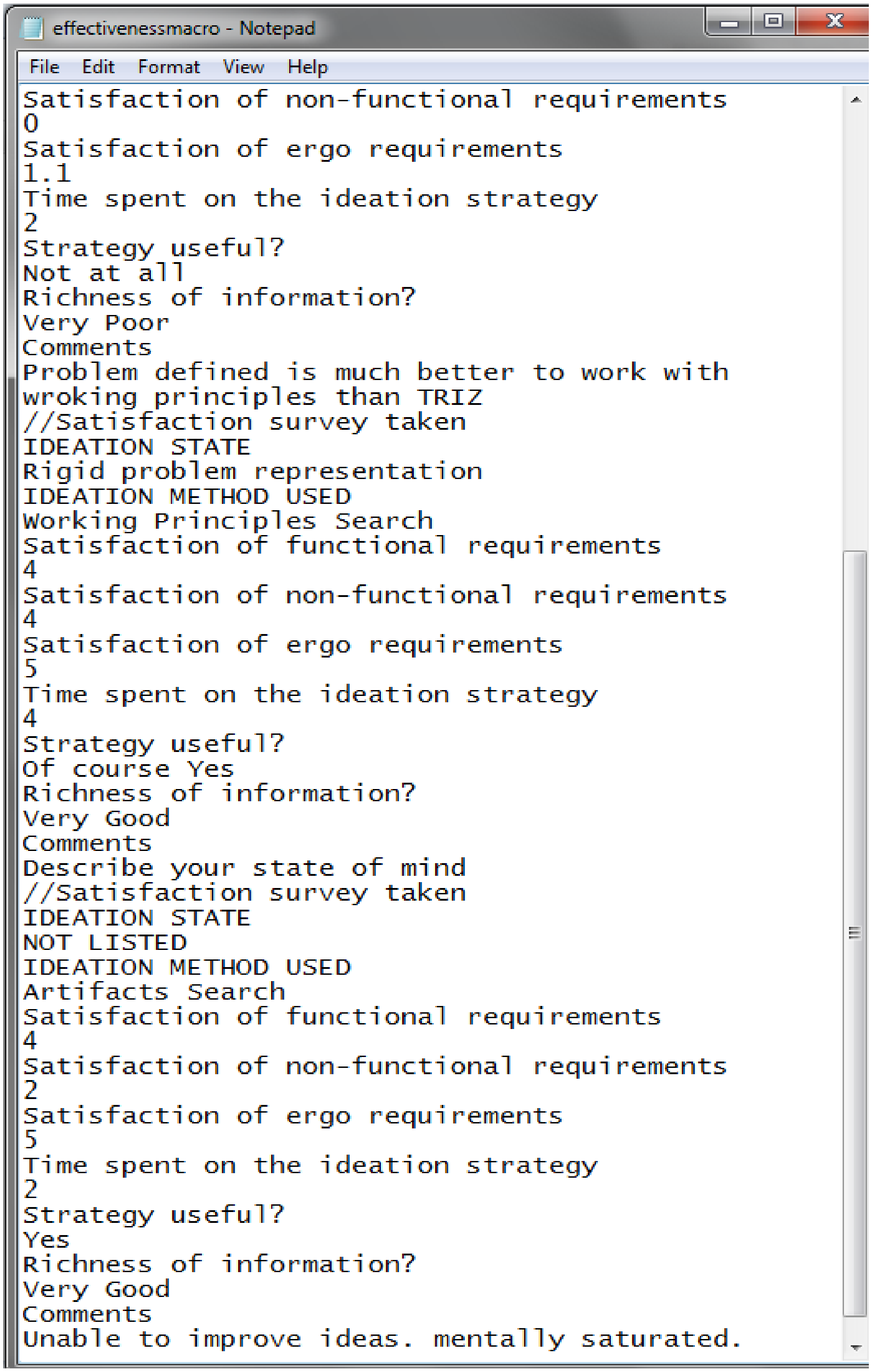


Figure 37. Designs created (Designer 2)



```
effectivenessmacro - Notepad
File Edit Format View Help
Satisfaction of non-functional requirements
0
Satisfaction of ergo requirements
1.1
Time spent on the ideation strategy
2
Strategy useful?
Not at all
Richness of information?
Very Poor
Comments
Problem defined is much better to work with
wroking principles than TRIZ
//Satisfaction survey taken
IDEATION STATE
Rigid problem representation
IDEATION METHOD USED
Working Principles Search
Satisfaction of functional requirements
4
Satisfaction of non-functional requirements
4
Satisfaction of ergo requirements
5
Time spent on the ideation strategy
4
Strategy useful?
Of course Yes
Richness of information?
Very Good
Comments
Describe your state of mind
//Satisfaction survey taken
IDEATION STATE
NOT LISTED
IDEATION METHOD USED
Artifacts Search
Satisfaction of functional requirements
4
Satisfaction of non-functional requirements
2
Satisfaction of ergo requirements
5
Time spent on the ideation strategy
2
Strategy useful?
Yes
Richness of information?
Very Good
Comments
Unable to improve ideas. mentally saturated.
```

Figure 38. Satisfaction survey snapshot

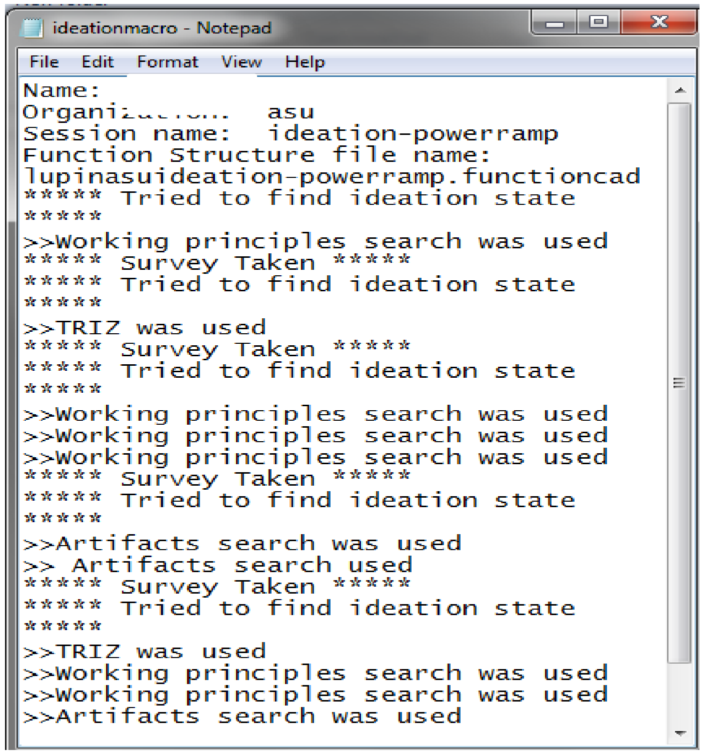


Figure 39. Ideation macro snapshot

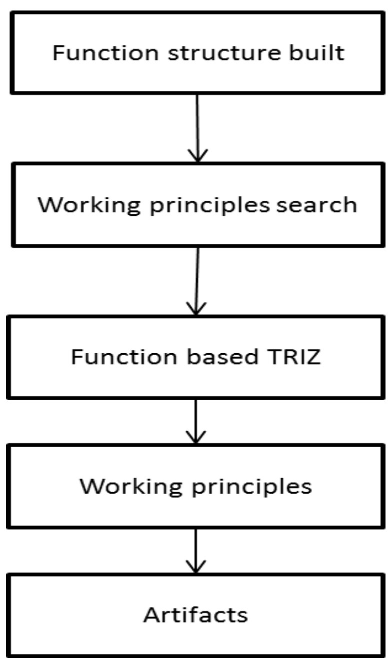


Figure 40. Graphical representation of sequence of ideation strategies

At the end of ideation process, few questions were asked to the designer to know more about his comfort level with the software and about suggestions which could improve the tool. Some comments and suggestions are listed below:

a. Did not want to travel using physical variables because the designer thought it would narrow his results and block his creativity.

b. Designers do not deal with one function at a time. Searching for multiple functions could be a possible future work.

c. If a list of ideation methods is given in a particular order in the main window of holistic ideation, people will tend to use them in a particular sequence (as shown to them) and it might lead them to taking a wrong path. Thus, user experience research needs to be done to know more about it.

d. Designer felt that it would be difficult to develop ideas from physical effects since he thought it would be hard for him to comprehend different effects and develop ideas from those.

e. Designer also felt that it would be easier if FunctionCAD had the capability to write down artifacts or other ideas beside functions so that it would be easier to follow.

Case study 2

The design process started with documentation of user information and building of function structure. After creating an initial set of ideas, designer wanted to characterize his ideation state. He gave in values for characterization measures (problem novelty = medium, problem complexity = low, uncertainty =

medium, time = less, Quantity = 1, Quality = 5, Novelty = 2, Variety = 1) and there was no ideation state found and there was no ideation method suggested. The designer decided to use physical effects search and tried to look at different functions. After a certain time, the designer was not able to generate enough ideas and decided to switch over to a different method. He again characterized his ideation state (problem novelty = low, problem complexity = low, uncertainty = medium, time = less, Quantity = 0, Quality = 0, Novelty = 0, Variety = 0) and the ideation block found was "Rigid problem representation". The method suggested for this ideation block was not available as computer application and hence the designer had to make his decision and choose an ideation strategy on his own. The designer decided to look at working principles (search by functions) and he searched for functions like "transport solid" and "secure solid" and even looked at biological examples given for each working principle. After that, he took the short survey but skipped the characterization of his ideation state. The designer decided to use function based TRIZ and he looked for similar functions again and generated only a few ideas, which was followed by a short survey again. The designer then decided to characterize his ideation state (problem novelty = medium, problem complexity = medium, uncertainty = medium, time = less, Quantity = 1, Quality =1, Novelty = 1, Variety = 0). From the characterization of his ideation state, we could understand that, the complexity of the problem had increased as he solves it. For this combination of characterization measures, there were no ideation methods suggested (no ideation state found) and hence the designer made his own decision to use working principle search. Functions like “transport solid object” were searched for and appropriate results were referred. The designs, survey results and ideation paths are shown in the following figures.

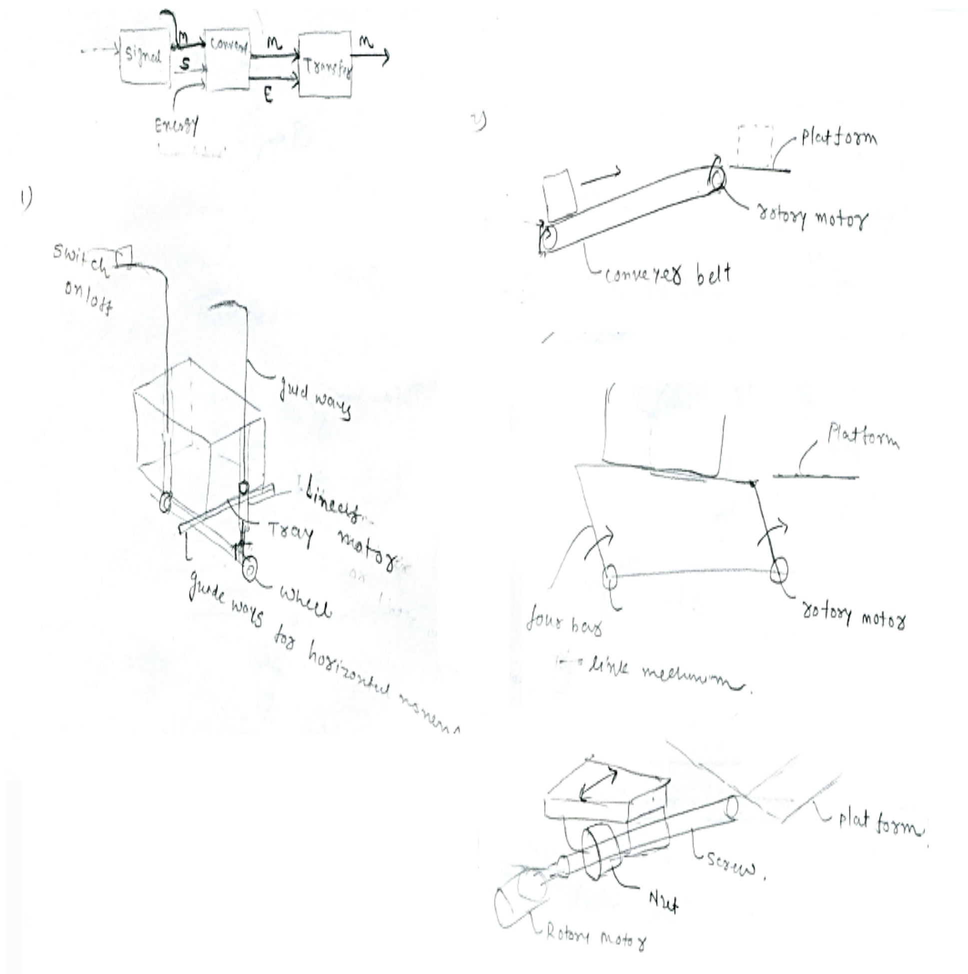
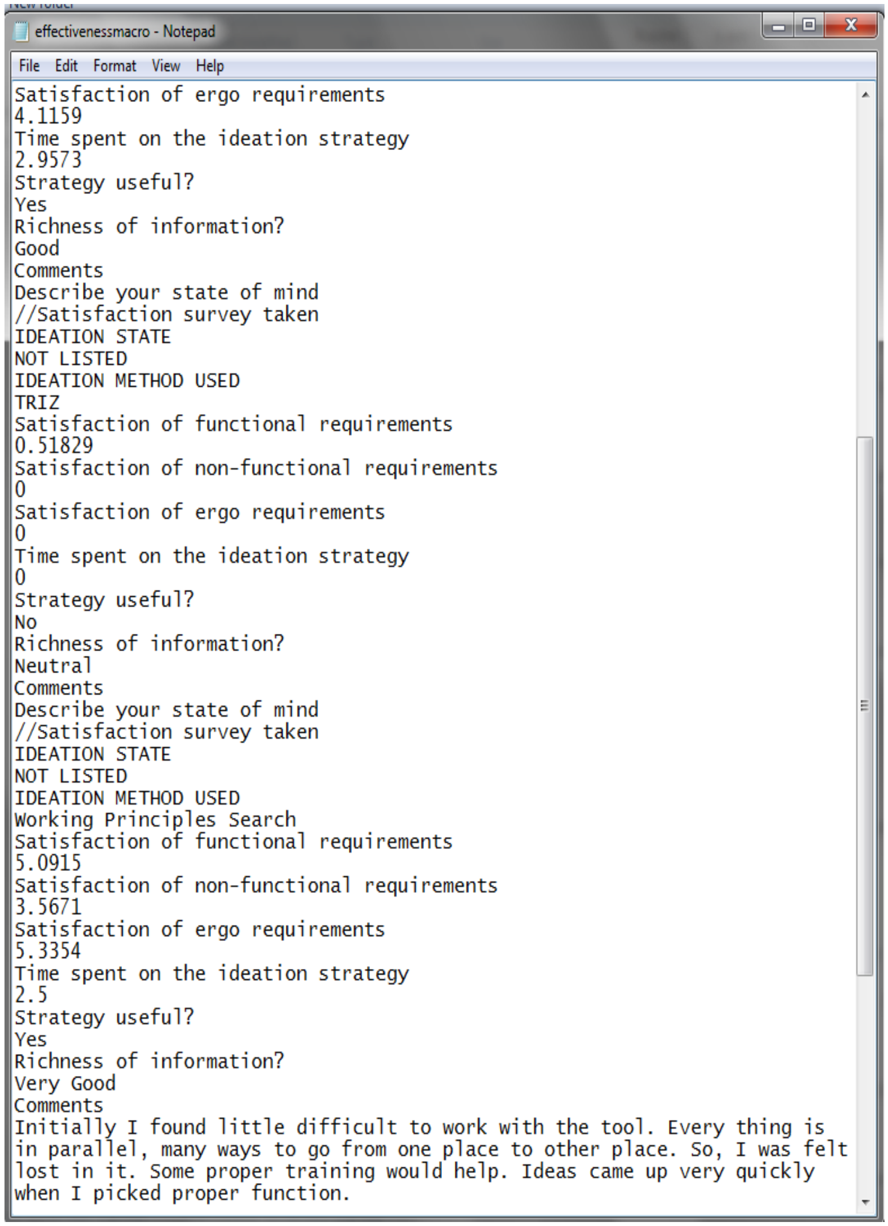


Figure 41. Designs created (Designer 2)


effectivenessmacro - Notepad
File Edit Format View Help

Satisfaction of ergo requirements
4.1159
Time spent on the ideation strategy
2.9573
Strategy useful?
Yes
Richness of information?
Good
Comments
Describe your state of mind
//Satisfaction survey taken
IDEATION STATE
NOT LISTED
IDEATION METHOD USED
TRIZ
Satisfaction of functional requirements
0.51829
Satisfaction of non-functional requirements
0
Satisfaction of ergo requirements
0
Time spent on the ideation strategy
0
Strategy useful?
No
Richness of information?
Neutral
Comments
Describe your state of mind
//Satisfaction survey taken
IDEATION STATE
NOT LISTED
IDEATION METHOD USED
Working Principles Search
Satisfaction of functional requirements
5.0915
Satisfaction of non-functional requirements
3.5671
Satisfaction of ergo requirements
5.3354
Time spent on the ideation strategy
2.5
Strategy useful?
Yes
Richness of information?
Very Good
Comments
Initially I found little difficult to work with the tool. Every thing is in parallel, many ways to go from one place to other place. So, I was felt lost in it. Some proper training would help. Ideas came up very quickly when I picked proper function.

Figure 42. Satisfaction survey snapshot

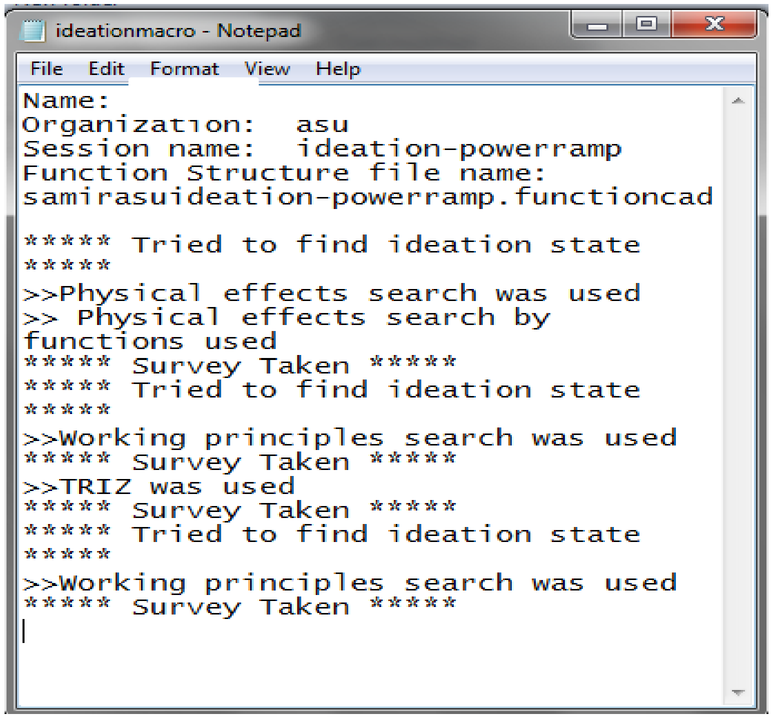


Figure 43. Ideation macro snapshot

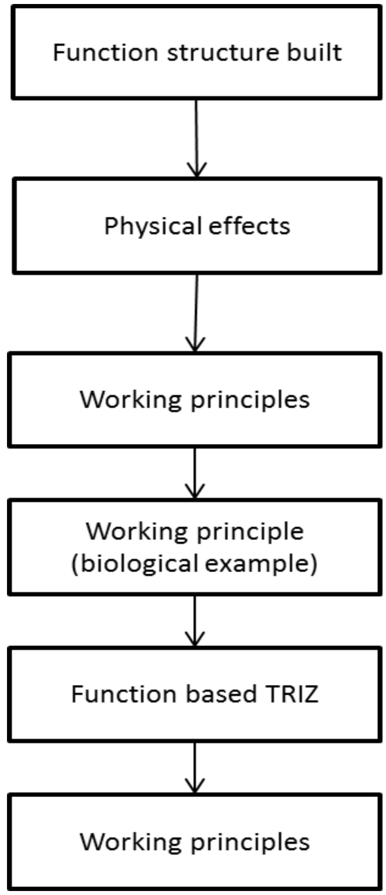


Figure 44. Graphical representation of ideation path

During the final comments/suggestions session, there were a few areas that the designer felt that could be improved:

a. The functional verb/flow variables list was too long and difficult to search. The designer felt it would be better if the functions were shown at primary, secondary and tertiary levels.
b. Designer used the ideation methods in the same order as displayed in holistic ideation window. This user experience factor, hugely affected the designer's ideation path.

c. Designer felt he would have done better if he was given a detailed formal training with different tools in holistic ideation before the design process.

Case study 3

The design process started with documentation of user information and building of function structure. After creating an initial set of ideas, the designer wanted to characterize his ideation state. The designer then gave in values for characterization measures (problem novelty = low, problem complexity = medium, uncertainty = low, time = less, Quantity = 4, Quality = 4, Novelty = 1, Variety = 3) and there was no ideation state found and there was no ideation method suggested. Even though the designer had only a few ideas, he decided to start with BioTRIZ. The designer was not able to determine contradicting features and hence he started using function based TRIZ. The designer did not consider the time constraint and spent a whole lot of time browsing function based TRIZ thereby generating little or no ideas. The designer also did not want to characterize his ideation state, and he wanted to again use BioTRIZ where he gave in contradicting features as "improve use of energy by moving object" and "worsen weight". The designer looked at a few inventive principles that would solve the contradicting features and generated a few ideas. After using BioTRIZ, the designer chose to look at physical effects and started searching by functions. Once again, the designer spent a lot of time exploring one single strategy and got lost inside it looking at a lot of information (related and unrelated). In the last few minutes, he decided to look at artifacts and for the artifacts that the designer chose, there were no images available. Even though there were not much ideas generated during this ideation experiment, we learnt a lot of things out of it. Some of them are:

a. Designer wanted stimulus from pictures and was looking for analogy all through the process which our present system could not provide. In short, the designer needed intuitive strategies. This one case study is a good example of the importance of intuitive strategies in a holistic framework.

b. Designer did not want to characterize his ideation state because he wanted to spend time to look at more information.

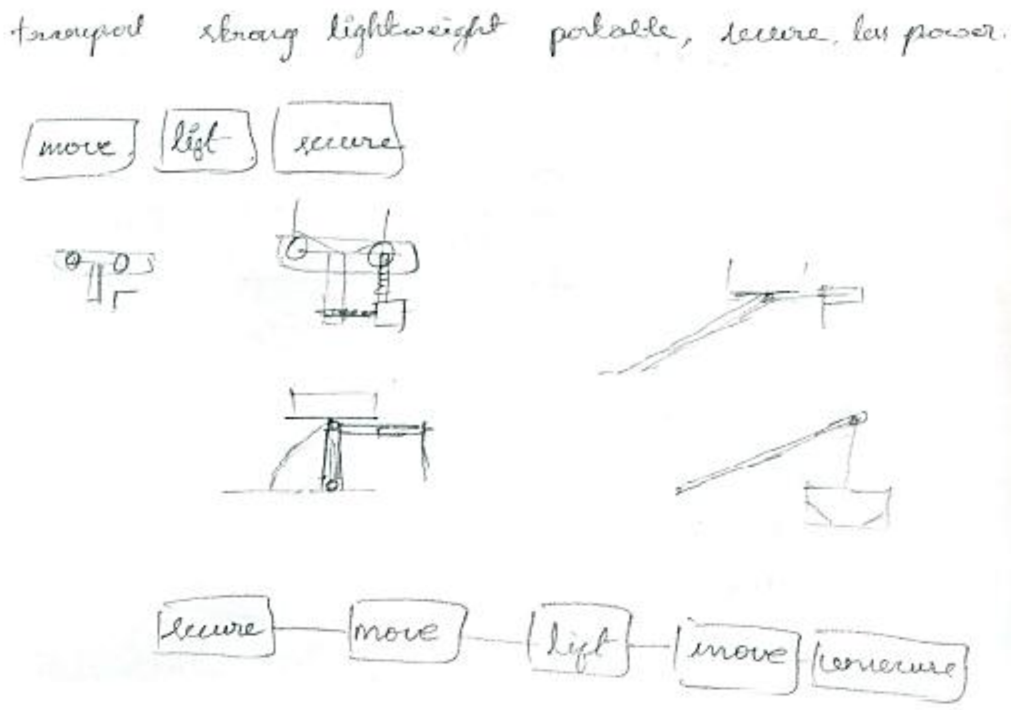
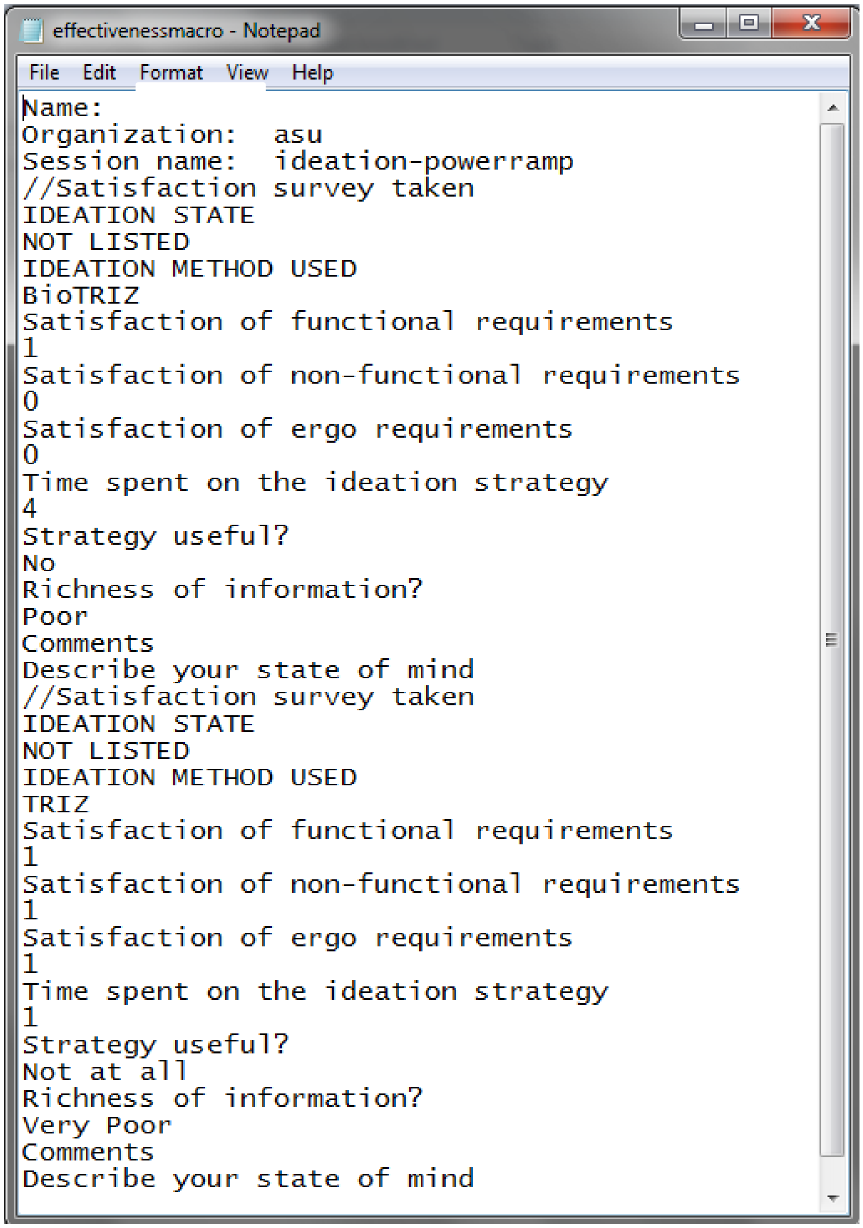


Figure 45. Designs created (Designer 3)



effectivenessmacro - Notepad

File Edit Format View Help

```
Name:
Organization:  asu
Session name:  ideation-powerramp
//Satisfaction survey taken
IDEATION STATE
NOT LISTED
IDEATION METHOD USED
BioTRIZ
Satisfaction of functional requirements
1
Satisfaction of non-functional requirements
0
Satisfaction of ergo requirements
0
Time spent on the ideation strategy
4
Strategy useful?
No
Richness of information?
Poor
Comments
Describe your state of mind
//Satisfaction survey taken
IDEATION STATE
NOT LISTED
IDEATION METHOD USED
TRIZ
Satisfaction of functional requirements
1
Satisfaction of non-functional requirements
1
Satisfaction of ergo requirements
1
Time spent on the ideation strategy
1
Strategy useful?
Not at all
Richness of information?
Very Poor
Comments
Describe your state of mind
```

Figure 46. Satisfaction survey snapshot

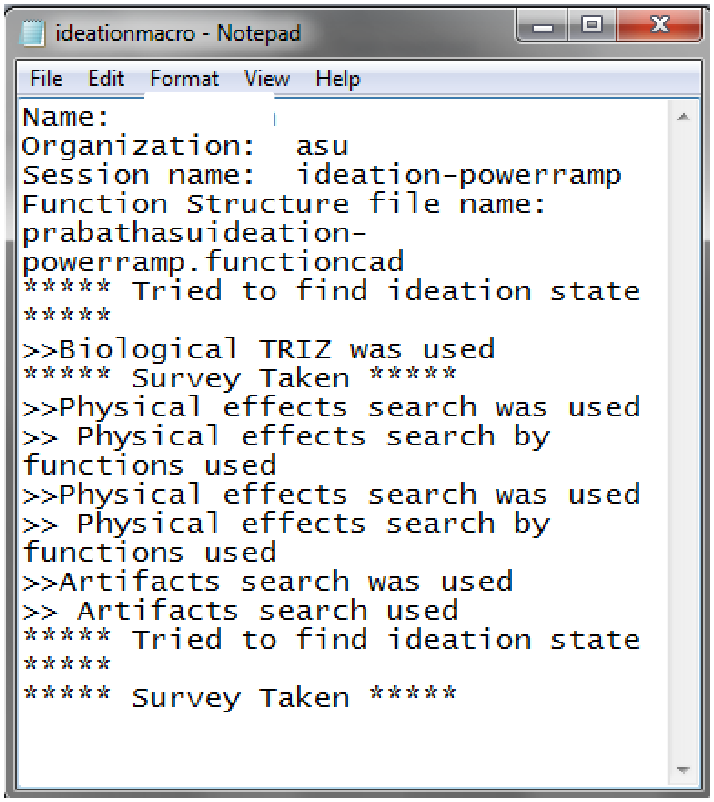


Figure 47. Ideation macro snapshot

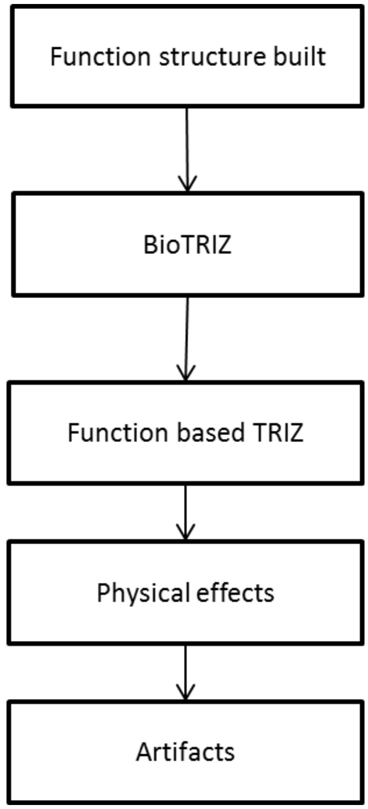


Figure 48. Graphical representation of ideation path

Case study 4

The design process started with documentation of user information and building of function structure. After creating an initial set of ideas, the designer wanted to characterize his ideation state. The designer then gave in values for characterization measures (problem novelty = low, problem complexity = low, uncertainty = low, time = less, Quantity = 5, Quality = 5, Novelty = 3, Variety = 3) and there was no ideation state found and there was no ideation method suggested. The designer decided to choose artifacts search and looked at different artifacts by searching through functions. In this experiment, the designer came up with a lot of initial designs even before using an ideation method which are shown in the following figure. Again after generating a few ideas, the designer gave values for characterization measures and the ideation block found was “difficulty in understanding critical technical issues”. Ideation method suggested for the block was TRIZ and BioTRIZ. The designer chose function based TRIZ and again started generating ideas. For the rest of time, the designer chose artifacts search again and browsed through all the components and looked for related artifacts and possible stimuli that could be helpful. Some comments and suggestions that the designer gave as input are listed as follows:

a. Designer should be allowed to take the survey at the end. If the survey is given in between, the designer might lose focus and would not be able to generate effective ideas.
b. During the first ideation cycle, the designer did not find any result for the function search (in artifacts repository). When no results showed up, the designer lost faith in the tool and decided to work on her own.
c. Also, the designer did not want to look at physical effects and working principles because he felt that an engineer knows all the physical effects and possible working principles and they would not want to see them.
d. The designer felt that the time given for the design problem was very low. Also, the designer felt that a proper formal training needed to be given to all the designers before they are allowed to use the holistic ideation tool.

The ideas, ideation paths and survey results of this designer are shown in the following figures.

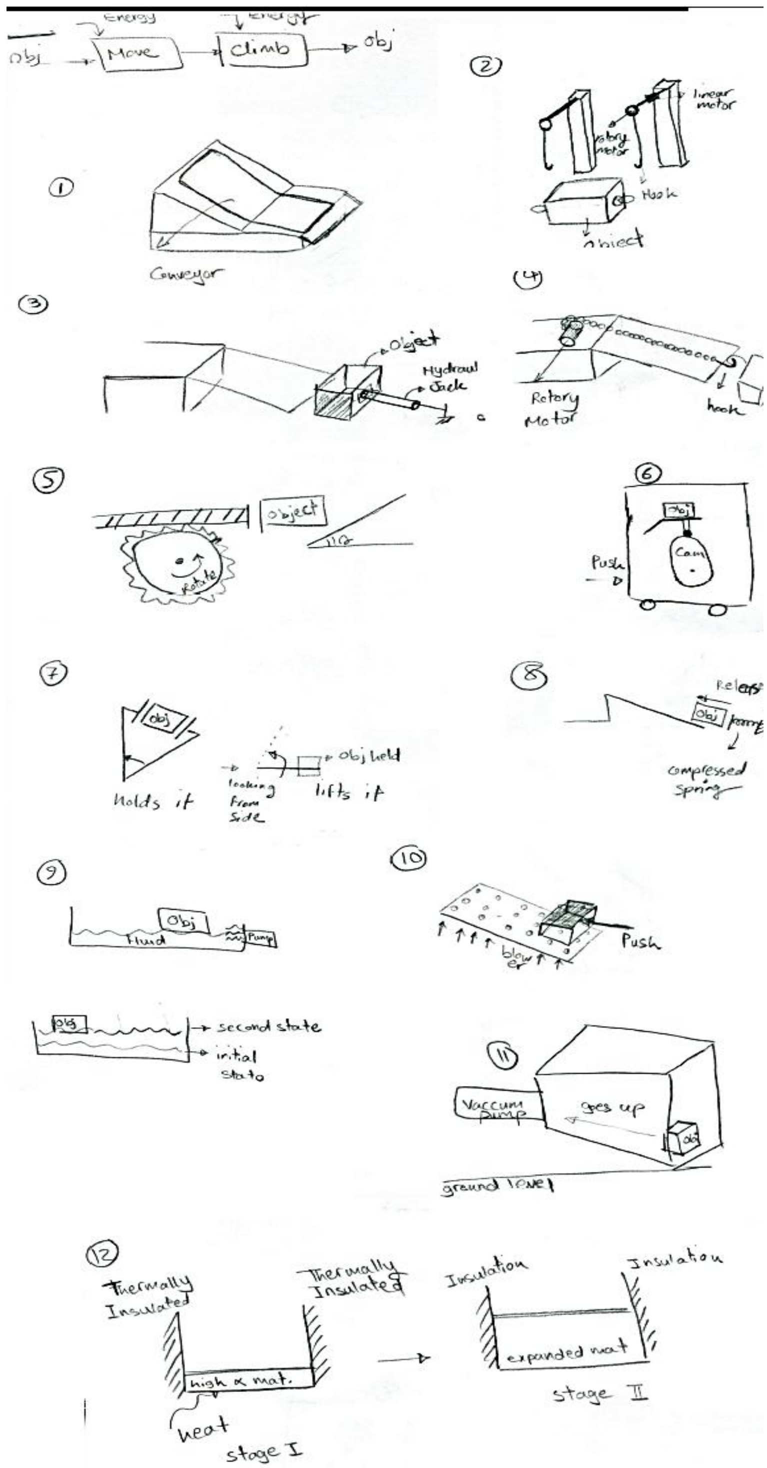
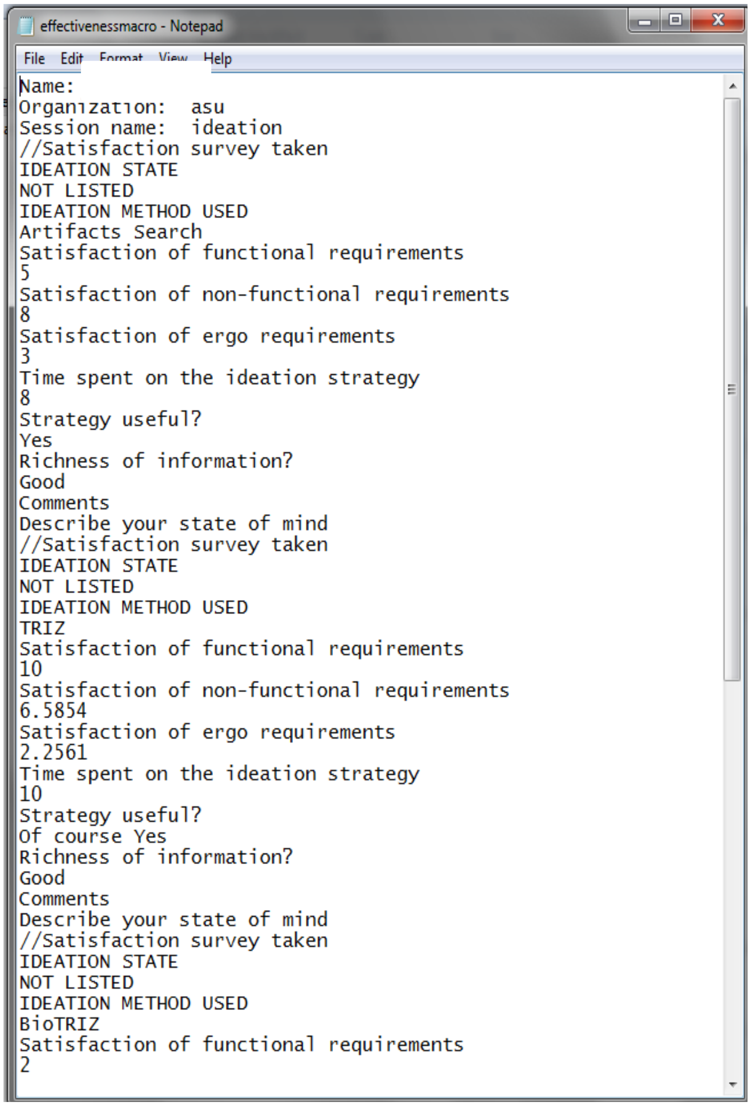


Figure 49. Designs created (Designer 4)



Name:
Organization: asu
Session name: ideation
//Satisfaction survey taken
IDEATION STATE
NOT LISTED
IDEATION METHOD USED
Artifacts Search
Satisfaction of functional requirements
5
Satisfaction of non-functional requirements
8
Satisfaction of ergo requirements
3
Time spent on the ideation strategy
8
Strategy useful?
Yes
Richness of information?
Good
Comments
Describe your state of mind
//Satisfaction survey taken
IDEATION STATE
NOT LISTED
IDEATION METHOD USED
TRIZ
Satisfaction of functional requirements
10
Satisfaction of non-functional requirements
6.5854
Satisfaction of ergo requirements
2.2561
Time spent on the ideation strategy
10
Strategy useful?
Of course Yes
Richness of information?
Good
Comments
Describe your state of mind
//Satisfaction survey taken
IDEATION STATE
NOT LISTED
IDEATION METHOD USED
BioTRIZ
Satisfaction of functional requirements
2

Figure 50. Satisfaction survey snapshot

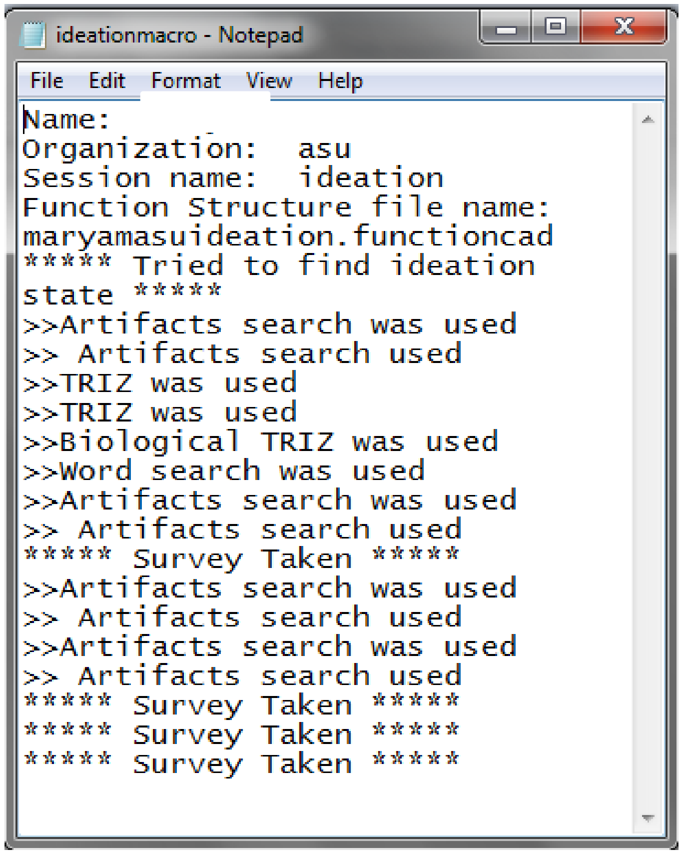


Figure 51. Ideation macro snapshot

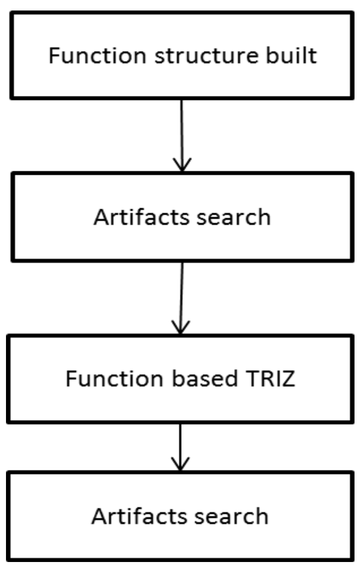


Figure 52. Graphical representation of ideation path

7.5.1 Findings from case study

Most of the time, the ideation state was not found by the system and the designer was allowed to choose any of the ideation methods present in the framework. Different designers had different choices of ideation strategies and their outcomes were also different. From start till end of their ideation processes, the sequence of strategies used were completely different the other three designers which could be seen from the figures shown in this section.

Also, there were a few cognitive states identified from the comments of the designer:

a. Losing hope initially due to time constraint
b. Losing belief in ideation method when no result is shown, thereby starting to work on own without aid of any method
c. Characterization of ideation state and surveys can be termed under ideation blocks. This is because, the designer needs to evaluate their ideas in order to complete the survey and characterize ideation states. This clearly contradicts the ideation strategy of suspending judgment.
d. Experienced designers do not want to look at physical effects or working principles since they feel they already know those.

Chapter 8

CONCLUSIONS AND FUTURE WORK

The main objective of this Thesis was to investigate the technical issues involved in developing a holistic approach for conceptual design. Different ideation methods/strategies have different kinds of representation. Integrating those methods and providing easy traversal between them was certainly not an easy task. A common connection between all strategies was needed to be found and extensive research was done on each one of those methods, and physical variables/parameters were found as the key for traversal. Having physical variables connecting different ideation methods has its own advantages. For example, information can be searched in all our experiential methods using physical variables which make all our strategies “physics based” which is a very important contribution towards systematic engineering design. Other important contributions of this research were characterization of ideation states, mapping ideation states to appropriate strategies and effective documentation of ideation paths. Even though the test bed initially consists of four logical methods and two intuitive strategies, we believe the results that we will obtain from the documentation will give us valuable insight into the effectiveness of the strategies used in those methods. Also, with the use of this framework, there is a vast scope for future work and also has a very good scope for expansion like mentioned in the following paragraphs.

8.1 EXPLORATION OF IDEATION STATES

As the holistic ideation test bed is used intensively, more ideation states will be found and based on surveys and documentation obtained from the designer, we can also find the remedial strategies for those ideation blocks. Not only ideation blocks which hinder ideation will be found, also cognitive processes which promote ideation will be found.

8.2 ADDITION OF NEW IDEATION STRATEGIES

Our initial test bed only has 4 logical ideation methods and 2 intuitive ideation strategies. In the future, more ideation methods/ strategies will be added. This is because; the designer should have a diverse choice of ideation tools to use and should be able to overcome any kind of ideation blocks. To make the new ideation strategies compatible with holistic ideation framework, indexing them with physical variables would be the best method to integrate them easily. For example, case catalogs can be added (cases can be attributed with physical variables) or pictures/sounds can be attributed with related physical variables/physical effects. For ideation strategy that cannot be indexed with physical variables, new method of representation can be devised. Also, collaborative environment could be developed to facilitate group based idea generation and expanded review teams where ideas are evaluated by other people.

8.3 WEB BASED HOLISTIC IDEATION TEST BED

Our short term goal after creating this initial test bed is to host this test bed online so that we can get a lot of designers around the country to use it. When more people use this test bed, we can collect more data related to creativity. Also when it is hosted on the web, only the documentation about ideation states and creativity will be available to us. The ideas and designs generated by the designer will not be available to us, since they are intellectual property of the user and we need to give the designers that privacy so that many designers will start using the holistic ideation tool.

8.4 EVOLUTION OF IDEATION STATES

The ideation state of a designer evolves in time and it can be monitored using plot based evaluation. The outcomes of the ideas are plotted against time/idea generation cycle so that we can get an idea about how his creativity improves or degrades over time. This kind of plot based evaluation will be helpful in identifying creative leaps [73] and creative dips. This is based on the well-known belief that the most creative idea occurs at one instant, known as creative leap.

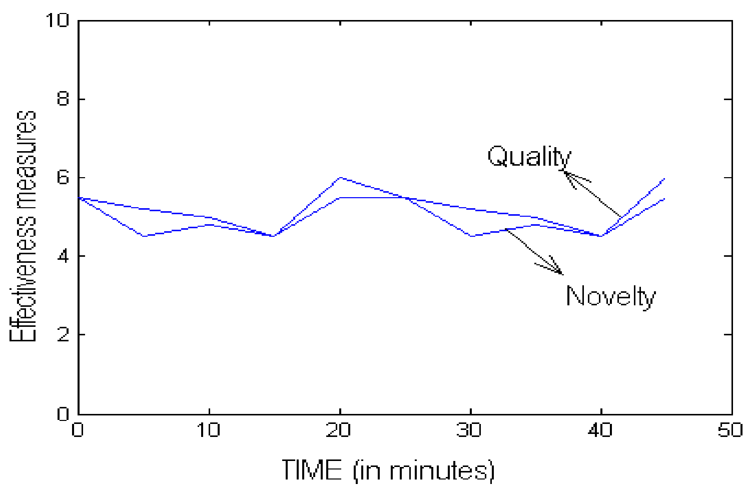


Figure 53. Plot based evaluation to monitor evolution of ideation states

8.5 MAPPING IDEATION PATHS TO IDEATION BLOCKS

From the user studies, we will obtain some details about the design ideation paths that the designer takes to achieve his functional and non-functional requirements. As we mentioned before, design ideation paths will be added as a process measure. Based on the initial ideation state of the designer and the desired requirements, ideation paths will be mapped to the ideation states. In the future, according to the ideation state determined, appropriate ideation paths will be suggested to the designer to make progress.

8.6 USER EXPERIENCE RESEARCH ON HOLISTIC IDEATION TOOL

User experience research based on usability engineering and interaction design principles will be done on the holistic ideation test bed. Reliability, learnability, navigation capability, aesthetics value etc. will be explored. There are some common UX research tools like UserZoom and Keynote which can be used to test the user experience. It provides several plots for several measures, and also has capability to create heat maps (monitor places of maximum clicks). These graphical outputs will be very useful in learning the usability of our holistic ideation test bed.

REFERENCES

[1] Ullman D.G., The mechanical design process, Mc Graw Hill, 2010

[2] Pahl G. and Beitz W., “Engineering Design: - A systematic approach”, Springer, 1996

[3] Shah,J.J., “The Science and Art of design ideation”, Tutorial notes, Arizona State University, 2009

[4] Shah,J.J., Kulkarni,S.V., Vargas-Hernandez, N., “Evaluation of idea generation methods for conceptual design: Effectiveness metrics and design of experiments”, Journal of mechanical design, 2000, Vol 122, 377-384

[5] Osborn A., “Applied Imagination”, Scribners, NY, 1979

[6] DeBono E., “The Five Day Thinking Course”, Penguin Books, 1967

[7] Niemark E., “Adventures in Thinking”, Harcourt, Orlando, 1987

[8] Rohrbach G., “Kreativ nach Regeln - Method 635, eine new Technik zim Lösen von Problemen”, Absatzwirtschaft 12, 1969.

[9] Hellfritz H., “Innovation via Gallerie methode”, Königstein/Ts: Eigenverlag, 1978.

[10] Shah, J. J., Vargas-Hernandez N., Summers, J. D., Kulkarni, S., 2001, “Evaluation of Collaborative Sketching as an Idea Generation Technique for Engineering Design”, Journal of Creative Behavior, Vol. 35, No. 3, pp.1-31.

[11] Weaver J, Kuhr R, Wang D, Crawford R, Wood K, Jensen, Linsey J, “Increasing Innovation In Multi-Function Systems: Evaluation of Two Ideation Methods For Design” , ASME DETC 2009.

[12] Gordon W., “Synectics”, Harper & Row, NY 1961

[13] Roth, K., 2000, Konstruieren Mit Konstruktionskatalogen:Band 1: Konstruktionslehre, Springer, Berlin

[14] Konstruktionsmethodik/ 1 VDI-Handbuch Konstruktion. 2222,1, Methodisches Entwickeln von Losungsprinzipien, 1997

[15] Bohm,M., Stone,RB., Simpson,TW., Steva,ED., Introduction of a data schema to support design repository, Computer aided design, Vol 40, Issue 7, July 2008

[16] Maher, M. L., Balachandran, M. B., and Zhang, D. M., 1995, "*Case-Based* Reasoning *in Design",* Lawrence Erlbaum Associates, Mahwah, NJ

[17] Kolodner J, "Case based reasoning", Morgan-Kaufman, 1993.

[18] Duffy A, Smith J, Duffy S, "Design re-use research: a computational perspective", Eng Design Conference, Brunel Univ, UK, 1998.

[19] Altshuller G, "40 Principles: TRIZ keys to technical innovation", Tech Innov Center, 2001

[20] Zwicky P., "Discovery, Invention, Research through Morphological Analysis", McMillan, NY, 1969

[21] Swaroop Vattam, Bryan Wiltgen, Michael Helms, Ashok Goel & Jeannette Yen. DANE: Fostering Creativity in and through Biologically Inspired Design. In Proc. First International Conference on Design Creativity, Kobe, Japan, November 2010.

[22] Innovation workbench – Ideation international Inc. (http://www.ideationtriz.com/new/iwb.asp)

[23] Thoughtoffice (http://www.thoughtrod.com/)

[24] Koestler, A., "The Art of Creation", Hutchinson and Co., London, 1964.

[25] Wallas, G., "The Art of Thought", Harcourt, New York, 1926.

[26] Smith, S. M.,"Creative Cognition: Demystifying Creativity," in C. N. Hedley et al., eds., Thinking and literacy – the mind at work, Lawrence Erlbaum Associates, Hillsdale, NJ, 1995

[27] Langley, P., and Jones, R., "Computational model of scientific insight," in R. J. Sternberg, ed., The nature of creativity – contemporary psychological perspectives, Cambridge Univ Press, NY, 1988

[28] Finke, R., Ward, T., and Smith, S., Creative Cognition: Theory, Research, & Applications, MIT Press, 1992.

[29] Newell & Simon H, Human problem solving, Prentice-Hall, 1972.

[30] Marshall S, Schemas in problem solving, Cambridge Univ Press, 1985.

[31] Jonassen D, Towards a design theory of problem solving, Humanities, Soc Sci & Law, 48(4), December 2000 .

[32] Smith, S. M. and Blankenship, S. E., "Incubation effects", Bulletin of the Psychonomic Society, 27, 311-314, 1989

[33] Jansson, D. G., and Smith, S. M., “Design Fixation,” Design Studies, Vol. 12, pp. 3-11, 1991

[34] Dennehy, E.B., Bulow, P., Wong, F., Smith, S.M., and Aronoff, J.B.. A test of cognitive fixation in brainstorming groups. Paper presented at the meeting of the Eastern Psychological Association, Boston, MA, April, 1992.

[35] Akin, O., and Akin, C., “Frames of reference in architectural design: analyzing the hyperacclamation (A-h-a-!),” Design Studies, Vol. 17, No. 4, pp. 341-361, 1996.

[36] Visser W., “Use of analogical relationships between design problem-solution representations: exploitation at the action-execution and action-management levels of the activity”, Studia Psychologica, v34, n4/5, pp. 351-357, 1992

[37] Cross, Descriptive model of creative design, : application to an example Design studies 1997, Elsevier

[38] Poze, T., “Analogical connections – the essence of creativity”, *Journal of creative behavior,* 17(4), pp. 240

[39] Gordon W., “Synectics”, Harper & Row, NY 1961

[40] Sternberg, R., Intelligence, information processing and analogical reasoning, Erlbaum, 1977

[41] Polya, G., How to solve it, Princeton University Press, Princeton, NJ, 1945

[42] Dreistadt Roy, An Analysis of the use of analogies and metaphors in science, American Psychological association, 1968.

[43] Linsey, J., Murphy, J., Markman, A., Wood, K.L., & Kortoglu, T. Representing Analogies: Increasing the Probability of Innovation, ASME DTM, Philadelphia, PA, September 10-13, 2006.

[44] Christensen, B. T., & Schunn, C. D. The relationship of analogical distance to analogical function and pre-inventive structure: The case of engineering design. Memory & Cognition, 35(1), 29-38, 2007

[45] Ekvall, G., and Parnes, S. J., Creative problem solving methods in product development – a second experiment, The Swedish Council for management and work life issues, Stockholm, Sweden, 1984

[46] Parnes, S. J., “Visioneering – state of the art,” Journal of Creative Behavior, Vol. 21, No. 4, pp. 283-299, 1987

[47] Verstijnen, I., Van Leeuwen, C., Goldschmidt, G., Hamel, R., and Hennessey, J., Sketching and Creative Discovery, Design Studies, Vol. 19, No. 4, pp. 519-46, 1998

[48] Tovey,M., Sketching, concept development and automotive design, Design studies 2003, Vol. 24, Issue 2, Publisher: Elsevier, Pages 135-153

[49] Estes, W. K. Statistical theory of spontaneous recovery and regression. Psychological Review.

[50] Nix, AA,. Sherrett,B., Stone,RB., A function based approach to TRIZ, IDETC/CIE 2011, Washington D.C., USA

[51] Vattam,S., Wiltgen,B, Helms,B., Goel,A., Yen,J., Dane: Fostering creativity in and through biologically inspired design, ICDC 2010, Kobe, Japan, pp 115-122

[52] Nagel,R., Tinsley,A., Midha,P., McAdams,D., Stone,R., and Shu,L., Exploring the use of functional models in biomimetic conceptual design, Journal of mechanical design, Dec 2008, Vol 130, Issue 12, 122102

[53] Vincent,JFV., Bogatyreva,OA., Bogatyreva, NR., Bowyer,A., Pahl,AK., Bio-mimetics: Its practice and theory, J.R.Soc. Interface (2006) 3, 471-82

[54] Shah, J.J., “Experimental investigation of progressive idea generation techniques in engineering design”, DETC DTM conference, 1998

[55] Mohan,M., Chen,Y., Shah,J., Towards a framework for holistic ideation in conceptual design, IDETC/CIE 2011, Washington D.C.

[56] Dorst,K., Cross,N., Creativity in the design process: co-evolution of problem solition, Design Studies, Vol.22 No.5, pp 425-437, 2001

[57] Vargas-Hernandez, N., Shah,J.J., Smith,S., “Cognitive models of design ideation”, ASME DTM conference, Las Vegas, September 2007

[58] Shah, J. J., Smith, S. M., Vargas-Hernandez, N., “Metrics for Measuring Ideation Effectiveness”, Design Studies, vol. 24, no. 2, pp. 111-134, 2003.

[59] Image net - http://www.image-net.org/

[60] Word net - http://wordnetweb.princeton.edu/

[61] Nagel,R., Perry, Stone,RB., FunctionCAD: A functional modeling application based on function design framework, IDETC/CIE 2009, San Diego, California USA

[62] Stone,R., Szykman, Wood,K., McAdams (2001) , “Evolving a functional basis for engineering design”, Proceedings of DETC01, 2001 ASME Design Engineering Technical Conferences, September 9-12, 2001 Pittsburgh, PA

[63] Stone, R. and Wood, K. (2000), “Development of a Functional Basis for Design”, Journal of Mechanical Design, 122(4):359-370.

[64] Rodenacker, W.G.: Methodisches Konstruieren. Konstruktionsbucher, Bd. 27. Berlin: Springer 1970, 2. Aufl. 1976, 3. Aufl. 1984, 4. Aufl. 1991.

[65] Roth, K.: Konstruieren mit Konstruktionskatalogen. 3. Auflage, Band I: Konstruktionslehre. Berlin: Springer 2000. Band II: Konstruktionskataloge. Berlin: Springer 2001. Band III: Verbindungen und Verschlusse, Losungsfindung. Berlin: Springer 1996.

[66] Andrea Bonaccorsi, Riccardo Apreda and Gualtiero Fantoni, “A theory of the constituent elements of functions, ICED 2009, Stanford University, CA, USA

[67] Functional modeling Software ‘FunctionCAD’, http://designengineeringlab.org/FunctionCAD/, Design engineering lab, Oregon State University

[68] Szykman, S., J. W. Racz and R. D. Sriram (1999a), “The Representation of Function in Computer-based Design,” Proceedings of the 1999 ASME Design Engineering Technical Conferences (11th International Conference on Design Theory and Methodology), Paper No. DETC99/DTM-8742, Las Vegas, NV, September

[69] Koller,R., VDI –Ber., 219 (1974), pp. 25-34

[70] Elmquist,H., B. Bachmann, F. Boudaud, J. Broenink, D. Brück, T. Ernst, R. Franke, P. Fritzson, A.Jeandel, P. Grozman, K. Juslin, D. Kågedahl, M. Klose, N. Loubere, S. E. Mattsson, P.Mostermann, H. Nilsson, M. Otter, P. Sahlin, A. Schneider, H. Tummescheit, H.Vangheluwe Modelica – A unified object oriented language for physical systems modeling, tutorial and rationale, V1.3, December 15, 1999

[71] Bogatyreva,NR., Bogatyreva,OA, TRIZ evolution trends in biological and technological design strategies, 19th CIRP design conference, Cranfield University, March 2009, pp 293.

[72] Helms,B., Schultheib,H., Shea,K., Automated assignment of physical effects to functions using ports based on bond graphs, IDETC/CIE 2011, Washington D.C., USA

[73] Nigel Cross, “Designerly Way of knowing”, Springer First edition, April 2006

APPENDIX A

LIST OF PHYSICAL EFFECTS

MECHANICAL:	ELECTRICAL:	THERMAL & FLUID
1. Adhesion	1. Biot Savart	1. Thermal conduction
2. Angular acceleration	2. Di-electric effect	2. Thermal radiation
3. Bend	3. Electro-osmosis	3. Thermal convection
4. Centripetal Acceleration	4. Electro-magnetic induction	4. Thermionic Emission
5. Collision	5. Electric Current	5. Absorption
6. Coriolis acceleration	6. Eddy current	6. Thermal dissociation
7. Dynamic/Kinetic Friction	7. Joule heating	7. Combustion
8. Elastic instability	8. Thermo-electric(Peltier) effect	8. Thermo-diffusion
9. Form closure	9. Electrical conductivity/resistivity	9. Capillary effect
10. Gravitation effect	10. Electrolysis	10. Evaporation
11. Heat strain	11. Josephson effect	11. Sublimation
12. Impact	12. Barnett effect	12. Diffusion
13. Lever effect	13. Piezo-electric effect	13. Adsorption
14. Linear Acceleration	14. Capacitance	14. Crystallization
15. Linear Momentum		15. Effusion
16. Mass Inertia		16. Permeation
17. Material join		17. Volumetric Flow
18. Mechanical Resonance		18. Bernoulli effect
19. Poisson effect		
20. Spring Effect - Linear		
21. Static Friction		
22. Surface tension		
23. Torsion		
24. Torsional spring effect		
25. Wedge effect		

APPENDIX B

LIST OF WORKING PRINCIPLES

S.No	Working principle
1	Magnetic field on rotating object produces Torque
2	Magnetic field on Stationary object produces Force
3	Electrostriction
4	Magnetostriction
5	Piezo principle
6	Storage of charge
7	Creation of Magnetic field
8	Chemical energy used to store charge
9	Current conduction of a semi conductor
10	Inhibition of current flow
11	Hydrostatic displacement
12	Hydrodynamic principle
13	Screw principle
14	Rotation of a round object
15	Rotation of an eccentric round object
16	Simple mechanism converts linear to rotary motion
17	Combined transmission
18	Sudden adjustment
19	Force adjustment by a simple mechanism
20	Power transmission by flexible objects
21	Force created by pressurized fluid
22	Screw principle (Fluid)
23	Fluid pumping rotating objects
24	Fluid pumped by a single rotating object
25	Fluid pumped by a Axial arranged objects

S.No	Working principle
26	Fluid pumped by radially arranged objects
27	Storage of energy in rotating object
28	Translation
29	Storage of energy by virtue of position
30	Deformation (material)
31	Rotating objects transmit torque
32	Rubbing an object with other inhibits motion
33	Flow can be controlled by valves
34	Wedging principle
35	Pressure can propagate through a medium
36	Flow of liquid
37	Material can absorb energy
38	Material can absorb heat energy
39	Heating of liquid
40	Super heating
41	A rotating object rolls on an inclined plane
42	None

APPENDIX C

RECONCILED FUNCTION BASIS

FUNCTION SET

Class (Primary)	Secondary	Tertiary	Correspondents
Branch	Separate		Isolate, sever, disjoin
		Divide	Detach, isolate, release, sort, split, disconnect, subtract
		Extract	Refine, filter, purify, percolate, strain, clear
		Remove	Cut, drill, lathe, polish, sand
	Distribute		Diffuse, dispel, disperse, dissipate, diverge, scatter
Channel	Import		Form entrance, allow, input, capture
	Export		Dispose, eject, emit, empty, remove, destroy, eliminate
	Transfer		Carry, deliver
		Transport	Advance, lift, move
		Transmit	Conduct, convey
	Guide		Direct, shift, steer, straighten, switch
		Translate	Move, relocate
		Rotate	Spin
		Allow DOF	Constrain, unfasten, unlock
Connect	Couple		Associate, connect
		Join	Assemble, fasten
		Link	Attach
	Mix		Add, blend, coalesce, combine, pack
Control Magnitude	Actuate		Enable, initiate, start, turn-on
	Regulate		Control, equalize, limit, maintain
		Increase	Allow, open
		Decrease	Close, delay, interrupt
	Change		Adjust, modulate, clear, demodulate, invert, normalize, rectify, reset, scale,

			vary, modify
		Increment	Amplify, enhance, magnify, multiply
		Decrement	Attenuate, dampen, reduce
		Shape	Compact, compass, crush, pierce, deform, form
		Condition	Prepare, adapt, treat
	Stop		End, halt, pause, interrupt, restrain
		Prevent	Disable, turn-off
		Inhibit	Shield, insulate, protect, resist
Convert	Convert		Condense, create, decode, differentiate, digitize, encode, evaporate, generate, integrate, liquefy, process, solidify, transform
Provision	Store		Accumulate
		Contain	Capture, enclose
		Collect	Absorb, consume, fill, reserve
	Supply		Provide, replenish, retrieve
Signal	Sense		Feel, determine
		Detect	Discern, perceive, recognize
		Measure	Identify, locate
	Indicate		Announce, show, denote, record, register
		Track	Mark, time
		Display	Emit, expose, select
	Process		Compare, calculate, check
Support	Stabilize		Steady
	Secure		Constrain, hold, place, fix
	Position		Align, locate, orient
Overall increasing degree of specification			

FLOW SET

Class (Primary)	Secondary	Tertiary	Correspondents	
Material	Human		Hand, foot, head	
	Gas		Homogeneous	
	Liquid		Incompressible, compressible, homogeneous	
	Solid	Object	Rigid-body, elastic-body, widget	
		Particulate		
		Composite		
	Plasma			
	Mixture	Gas-Gas		
		Liquid-Liquid		
		Solid-Solid	Aggregate	
		Solid-Liquid		
		Liquid-Gas		
		Solid-Gas		
		Solid-Liquid-Gas		
		Colloidal	Aerosol	
Signal	Status	Auditory	Tone, word	
		Olfactory		
		Tactile	Temperature, pressure, roughness	
		Taste		
		Visual	Position, displacement	
	Control	Analog	Oscillatory	
		Discrete	Binary	
Energy			***Effort analogy***	***Flow analogy***

	Human		Force	Velocity
	Acoustic		Pressure	Particle velocity
	Biological		Pressure	Volumetric flow
	Chemical		Affinity	Reaction rate
	Electrical		Emf	Current
	Electromagnetic	Optical	Intensity	Velocity
		Solar	Intensity	Velocity
	Hydraulic		Pressure	Volumetric flow
	Magnetic		Mmf	Magnetic flux rate
	Mechanical	Rotational	Torque	Angular velocity
		Translational	Force	Linear velocity
	Pneumatic		Pressure	Mass flow
	Radioactive/ Nuclear		Intensity	Decay rate
	Thermal		Temperature	Heat flow
Overall increasing degree of specification				