Cascading Evolutionary Morphological Charts

for Holistic Ideation Framework

by

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ABSTRACT

The main objective of this project was to create a framework for holistic ideation and investigate the technical issues involved in its implementation. In previous research, logical ideation methods were explored, ideation states were identified, and tentative set of ideation blocks with strategies were incorporated in an interactive software testbed. As a subsequent study, in this research, intuitive methods and their strategies were investigated and characterized, a framework to organize the components of ideation (both logical and intuitive) was devised, and different ideation methods were implemented based on the framework. One of the major contributions of this research is the method by which information passes between different ideation methods. Another important part of the research is that a framework to organize ideas found by different methods. The intuitive ideation strategies added to the holistic test bed are reframing, restructuring, random connection, force connection, and analogical reasoning. A computer tool facilitating holistic ideation was developed. This framework can also be used as a research tool to collect large amounts of data from designers about their choice of ideation strategies, and assessment of their effectiveness.

DEDICATION

Dedicated to my father MintangChen, mother YumeiQi, sister Chen Chen, and girlfriend Sijing Xin; whose love and support made me strong and made the foundation from which I can pursue my dreams. Special mention to my kind friends Shuai Wang and Han Bao; as well as friends back home Jiapeng Li, and Jianhong Zhu whom I can always count for support.

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# CHAPTER 1

## PROBLEM STATEMENT

In product design and development, the greatest opportunity for creativity and innovation is in early stages when key choices are made in conceptual design. However, it is not unusual to see only a handful of people involved in conceptual design and this critical activity is typically being conducted over a short period of time. On the other hand, detailed design may involve significantly more engineers and time. One reason is that there is a lack of formal methods and tools for design ideation. Computer tools for embodiment and detailed design (CAD) evolved rapidly in the past 30 years and are now pervasive throughout industry. However, these tools provide little support for early stages of design where creativity is most needed.

There is often a tendency, particularly by experienced designers, to use past solutions and adapt them to new requirements even when the requirements are significantly different. Many engineers consider the search for alternatives as a wasteful effort; as soon as they find one potentially feasible design the motivation to look for more alternatives is lost. This is particularly true when there are tight schedules and budget constraints. Another problem is that during the design, under certain understanding of the design space and one's current location in that space (ideation state), designers might encounter some mental blocks (ideation block). In order to overcome these mental blocks, certain cognitive mechanisms that are believed to intrinsically promote ideation (ideation strategies) are

necessary. It is hardly possible that a single strategy works for all kinds of situations. However, many conceptual design tools are based on a single approach to ideation, such as function-component catalogs, case based reasoning, and TRIZ, etc.

For all the above reasons, a holistic ideation research was devised to guide designers through different stages of ideation to produce creative designs in a time efficient manner. Towards this goal, the components of ideation (both logical and intuitive) were investigated; twenty one of ideation states have been characterized; ideation blocks and strategies used to overcome these blocks were found and summarized. A computer aided framework which is based on logical methods was also implemented. One of the major contributions of this research is the method by which the logical and intuitive ideation methods are interlaced together. This is very important in engineering design as it involves both creativity and functional quality. Such a strategy inverts the present approach of using a single ideation strategy for reaching a creative solution for a design problem. Another important part of the framework is the identification of creativity blocks and suggestions of appropriate ideation strategies to overcome them. This framework also supports a collection of large amount of data from the designer about the ideation strategy used, usefulness of the strategies, and also their effectiveness.

The initial ideation framework was designed and implemented in previous research in Design Automation Lab [1]. However, there are some shortcomings in the previous framework:

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1. Every design has to begin with a function decomposition, which focuses a function based approach to ideation that is somewhat restrictive.

2. There is no formal framework to organize all the ideas explored.

3. The previous framework is heavily dependent on logical methods; more intuitive methods with ideation strategies are needed.

In order to enhance novelty and variety of solutions, the option of using any morphology such as features, requirements, and materials (not only function) should be implemented. This would bring flexibility to the design, which allows the designer to decompose the problems in any forms of tasks. Through a new framework, designers could freely explore appropriate ideation methods for the problem and ideation state. This thesis also demonstrates the addition of intuitive methods. When more methods are added to the system, an effective way of inter-connecting them with the modules already present needs to be developed.

# CHAPTER 2

# BACKGROUND

## 2.1 Conceptual Design

The design process typically consists of several stages: pre-design (market studies, customer survey, identification of opportunities, competitive benchmarking), problem definition (design objectives, Tech specifications, QFD), conceptual design (data collection, research, functional synthesis, concept generation, concept evaluation, selection), embodiment design (product architecture; sizing critical components, material selection, geometric & parametric design, engineering analyses; trade-off studies, economic analysis; optimization), detail design (detailed layout, CAD models, eng. drawings, tolerance analysis, DfX), prototyping & testing. The majority of the cost of a new product design is committed at the conceptual design stage [2], because the decisions made at early stage have a significant influence on factors such as cost, performance, reliability, safety and environmental impact of a final product. The process of Conceptual Design is to generate design alternatives or Design Concepts and to evaluate them at a high level to determine their feasibility and fitness. More importantly, a good detailed design cannot come from a poorly conceived design concept [3].

However, knowledge of all the design requirements and constraints during this early phase of design is usually imprecise, approximate or unknown. This

project aims to understand the ideation process with the additional goal to develop computer tools for supporting conceptual design.

## 2.2 Engineering creativity

Neimark defines technological and scientific problem solving as creativity in a "narrow sense" [4].It is generating alternative solutions and ideas to technical problems. Creativity is defined in terms of breaking free of fictitious barriers and constraints. Technological creativity lies at the intersection of novelty, functionality and feasibility. Generally, designers define creativity in terms of novel combinations of old ideas. The novel combinations must be valuable in some way. They concern original ideas [5] that not only did not happen before, but also—in a sense to be clarified below—could not have happened before. So, in order to achieve a creative and novel design, it is crucial to try to generate as many novel solutions as possible during conceptual design.

## 2.3 Holistic Ideation

Many design researchers have proposed one-dimensional approach for design ideation, such as C-Sketch, TRIZ, Function-artifact morphology, and Morphological Charts. Similarly, most of the existing ideation tools for conceptual design support just one approach for ideation. For example, Design Repository [6] supports function based artifacts, DANE [7] supports the use of analogies between nature and engineering. However, the reality is that due to the variation in design problems, artifact domains, and designer expertise, a single

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approach and tool is not likely to fit every scenario. Also, the designer's ideation state continually changes which requires change in ideation strategies.

More than half a century ago, Bill Gordon, the founder of Journal of Creative Behavior, recognized that one goes through many different phases in creative problem solving; the strategy needed to move forward varies as one navigates the problem space. This is the very basis of the patented Synectics method. The name Synectics comes from the Greek and means "the joining together of different and apparently irrelevant elements. However, the method was developed 50 years ago, so it takes no advantage of information technologies, such as the Internet, computer assisted learning and searchable knowledge in data and knowledge bases. Following the spirit of Synectics, a holistic approach [1] was proposed to allow designers to use any combination of ideation methods and their ideation strategies to overcome creativity blocks encountered at different steps.

### 2.4 Ideation states

The term "ideation state" refers to the designer's current understanding of the design place and their current location in that space [1]. Examples include but are not limited to, the source of the difficulty (designer, problem, resource..), the nature of the problem (technical, physical, economic), and the complexity of the problem (variables and relations involved; degree of coupling).Ideation strategies are defined as cognitive mechanisms believed to intrinsically promote ideation or to help designers overcome mental blocks. The strength of the holistic approach is that it recognizes ideation stages at different times, and helps to solve the design

creativity blocks through different ideation methods (strategies). Clearly, the holistic approach is not one-dimensional but rather is multi-dimensional.

## 2.5 Intuitive & Logical methods

Intuitive ideation methods have been developed in order to remove perceived barriers to divergent thinking and increase the chances for conditions believed to be promoters of creativity. Time constraints are not important in these methods and they do not guarantee a solution, but rather depend on chance. Success is dependent entirely on human creativity and stimuli from interaction between people in groups. Logical and experiential methods involve step-by-step problem analysis, decomposition, and direct use of catalogued solutions (charts, tables, databases) based on science and engineering principles and past experience. Success is dependent not only on technical expertise of the individuals, but also the quality/quantity of information in catalogs, charts, and other databases.

There is no unique way of classifying intuitive methods. As shown in Figure 1, they are cataloged into six categories: Reframing, Freeform, Progressive/Brain writing, Facilitated, Idea Morphing and Organizational. Categories of the major logical methods are also shown in the Figure 1. Logical methods differ from each other in the type of archived knowledge or databases used.

Empirical analytical equations and procedures

Database of cases

Artifact catalogs

TRIZ

SIT

Working principles catalog

Physical effects catalog

Hill-Climbing

Taguchi

GA/GP

Artifact specific

Case based design

Function-to-artifact

Conflict resolution principles

VDI systematic synthesis principles

Parametric variation

Logical/Experiential

History Based

Heuristic Principle

First principle

Idea morphing

Mix

Factorization methods

Morphological Chart

DANE

Asknature

BioTRIZ

Biomicry

Intuitive

Reframing

Freeform

Progressive/ Brainwriting

Facilitated

Idea Morphing

Organizational

Provocative stimuli

Alternative words

Word Diamond/polygon

Relational Algorithm

WordNet

Brain Storming

Storyboarding

Method 635/SIL

Collaborative sketching

Gallery method

My lotus

Split Brain Transfusion

Xtreme Ideation

Attribute analogy chains

Synectic

Analogies/ Metaphors

Manipulative verbs

Random stimuli

Deliberate connection

Forward steps

Affinity method

K-J method

External information

ImageNet

Figure 1: Ideation methods Classification [1]

# CHAPTER 3

## HOLISTIC IDEATION TOOL REVIEW

### 3.1 Overview

The overarching objective of the project was to research the technical issues involved in creating a holistic approach and creating a computer aided framework for holistic ideation. Towards this goal, a computer tool facilitating holistic ideation was developed. This framework is designed as a research tool to collect data from designers, including their choice of ideation strategies used and their effectiveness. In this chapter I will review the previous state of DAL's holistic ideation tool in the following subsections:

1. Ideation methods implemented in previous framework.

2. Characterization of ideation states of designers and associated ideation blocks.

3. Unblocking operations with potential for overcoming ideation blocks.

4. Integration framework for relating the requirements, functions, intuitive ideation entities and logical ideation entities.

5. Computer implementation of holistic ideation based on the above framework.

### 3.2 ideation methods

Both logical and intuitive methods were analyzed with respect to the ideation strategies embedded in them. In this section, the previously implemented ideation methods are reviewed. These methods include Function CAD, Physical Effect

catalog, Working Principle catalog, TRIZ, Bio-TRIZ, and Artifacts Catalog. It can be seen from this list that the previous version of holistic ideation test platform was based on experiential methods.

### 3.2.1 Function decomposition

A function is defined as the intended input/output relationship of a system which performs a certain task [2]. Functional decomposition refers to the process of breaking down a functional relationship into its constituent parts. In this way, the original function can be reconstructed (recomposed).

The result of decomposing is a structured representation of the functions, their hierarchy and temporal relations. Functions are defined by an action and an object. Many ontologies exist for functions. Functions are modeled in term of an input and an output flow (energy, material, signal). FunctionCAD [8] is an interactive functional modeler created by Oregon State University. It uses the Function Basis ontology [9, 10]. There are types of flows (energy, material, signal) which can be conceptually represented. Flow is modeled in terms of key variables related to energy, material and signal. The user constructs a flow chart and specifies function types through pull down menu which was from RFB (reconciled functional basis). RFB was developed as a combination of functional basis and NIST function ontology [10].

The initial implementation of the ideation tool uses FunctionCAD to decompose the problem. One of the advantages of implementing FunctionCAD is

that the common functions are pre-defined from Function Basis ontology. It is up to the designer to select the functions and flows from the pre-loaded list.

### 3.2.2 Physical effect catalog

Designed artifacts exploit various physical effects (mechanical, thermal, biological, electronic) to achieve particular functions. Many such effects have been identified and formulated. Corresponding to a variety of mechanical functions, flow variables and physical parameters, researchers have produced catalogues of physical effects. Physical effects (PE) can be cataloged in basis form or combination with same embodiment. Physical effect forms behavior with working principle (WP). Working principle will be discussed in next section.

In the previous version of Holistic Ideation tool, a physical effect catalog is included. PEs were defined in forms of name, equation, parameters, laws, medium, domains and descriptions. There are 60 physical effects, 206 parameters, and 96 equations. Ideas and concepts generated at the physical effects level are highly varied. Therefore, the designer can explore different places in his design space by going to a fundamental level of physical effects. An example from our Physical Effect catalog is shown in the Figure 2. It shows two physical effect cases, angular acceleration and electrolysis.

### 2. **Angular acceleration**

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

EQUATION:
$\alpha = dw/dt$
$\alpha = d^2(theta)/dt^2$
$\tau = I * \alpha$

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 n

EQUATION: $m = k \cdot q$

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

Figure 2. Examples of physical effect

The basic usage of PE is to provide abstract or case based information to designers. Usually, the use of physical effect follows function decomposition, but the catalog does not contain any link to function. The connection has to be made by the designers. For achieving a particular function, one physical effect or combinations of physical effects may be needed to fulfill the function. The integration of physical effects database by DAL brings flexibility into the performance of framework. As we can see, the form of physical effect is constructed by physical law, physical equations, physical parameters, medium, domain, and description. There are two major advantages to the integration implemented by DAL. First, the use of a starting point adds flexibility. As discussed above, the content included in each physical effect is equation, parameters, laws, medium, domains and descriptions; any of them could be the starting points and the breakthrough points to other databases (i.e. working

principle database). Second, some elements in physical effects may be shared, for example, the parameter "force" is associated with both Newton's law and angular acceleration. By sharing common medium (such as parameters, equations), the links between physical effects are easy to establish, which provides the support for tracking the information from one physical effect to related ones.

### 3.2.3 Working principle catalog

Physical effects are mainly about physical laws ("what it is"), while working principle focuses on geometric and material characteristics ("how to do it"). As Pahl and Beitz [2] described, 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 fully determine a working principle and hence material properties are also needed.

Past DAL projects created a working principle catalog from a set of working principles (WP) described in VDI 2222 [11] and Pahl and Beitz [1]. In the previous version of Holistic Ideation tool, a working principle catalog is included. WPs were defined in forms of name, description, component, corresponding physical effect, materials, key physical variable, and geometry. Similar to physical effect, by sharing the common medium (such having same parameters), the working principle can be linked. A combination of physical effects and working principles are required to describe the behavior of a system.

### 3.2.4 Artifact catalog

Extensive research has been going on in UMR/Oregon State University since 1999 in the area of development of artifacts catalog. The tool they developed is Design Repository [6], which has been included in the previous Holistic Ideation tool. Initially, the artifacts catalog was done as a part of a design course in order to make contribution to the conceptual design research. Function structures were developed for each component and other attributes were constituted to the artifacts. Figure 3 is the interface of the Design Repository. In Design Repository, each artifact is defined by input flow, output flow, output artifact, input artifact, support function and sub-function. This function artifact catalog allows designers to search for artifacts according to functions. There are 5,600 artifacts in the database.



Figure 3. The interface of the Design Repository [6]

### 3.2.5 TRIZ

The theory of Inventive Problem Solving (TRIZ [12]) was developed by Altshuller in the 1940s. In TRIZ, a pattern which can be used for any creative problem solving was developed. Certain aspects of design are modified and expressed in generalized ways; hence, there are probabilities of getting a novel design by the use of generalized principles. TRIZ is a logical ideation method 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. A partial TRIZ matrix is shown in Figure 4. By using the TRIZ matrix, principles are suggested according to technical contradiction. Table 1 shows parts of list of principles and characteristics. With the help of TRIZ, the designers could certainly learn from past experience, and then provide the future design's development by transferring our thinking patterns.

Figure 4. Partial of TRIZ matrix

Table 1. Parts of 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 |

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### 3.2.6 Bio-TRIZ

In order to enable designers to implement natural principles for innovative design and technology, TRIZ could be used as the bridge between biology and engineering. This is the main idea behind Bio-TRIZ. Vincent and Bogatyreva [13] established six fields of operation for the purpose of capability of comparing parameters from technological and biological domains. These six operational fields (substance, structure, energy, information, space and time) re-organize and condense the TRIZ classification (Contradiction Matrix) both of the features used to generate the conflict statements and the Inventive Principles. This more general TRIZ matrix is used to place 40 principles of TRIZ into a new order, which could reflect the biological route through TRIZ conflicts. This new matrix is named BioTRIZ matrix. BioTRIZ reflects both logical methods and intuitive methods by tracking past design experience though particular conflicts and seeking bio-inspiration (i.e. analogy). By using BioTRIZ, for particular pairs of conflicts, comparison of the types of solutions in technology and biology is possible. Table 2 provides more detail on the placing of the 40 principles of TRIZ.

Table  2. Six fields of operation matrix [14]

| 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 |

### 3.3 Ideation blocks and unblocking operations

When solving a design problem, the designer may face an impasse at various times due to various reasons. These impasses are called as creativity blocks [1, 15]. In the classical synectics method, there is an experienced facilitator who monitors the designers' idea generation process and suggests ideation methods which has ideation strategies to overcome their mental blocks. Table 3 provides some of the ideation methods and certain cognitive mechanisms embedded in them.

Table 3. Ideation strategies and corresponding ideation methods [1]

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

In the past research, some ideation blocks have been identified and characterized. For example, one blocking phenomenon is Design Fixation. The uncertainty of the problem is very less, after spending a lot of time in the problem, the designer comes up with less number of ideas which are not novel. Ideation strategies are used to overcome creativity blocks. The list of ideation blocks, corresponding values of characterization measures and unblocking operations are shown in the Table 4. The ideation blocks are mostly independent of each other. For indicators in Table 4, symbol↑ means high and symbol ↓ means low. The indicators with ideation states will be discussed in next section.

Table 4.Part of Blocking Phenomena, Tentative Characterization & Unblocking Operations [1]

| Blocking Phenomena | Tentative Characterization | | | | | | | | | Unblocking operations |
|---|---|---|---|---|---|---|---|---|---|---|
| | Problem | | | Process | | Outcomes | | | | |
| | Nvlty | Cmplx | Uncrt | Time | Path* | Qty | Qlty | Nvlty | Var | |
| Difficulty understanding the problem | ↑ | ↑ | ↑ | ↓ | | ↓ | ↓ | ↓ | ↓ | Flexible problem representation, Use of analogies and metaphors ,Reframe problem |
| Unable to prioritize | ↑ | ↑ | ↑ | ↓ | | | | | | TBD |
| Unmanageable complexity | – | ↑ | – | ↓ | | ↓ | – | – | – | Work on a higher problem, Break rules, Decomposition |
| Design fixation | – | – | ↓ | ↑ | | ↓ | – | ↓ | ↓ | Provocative stimuli (Random/focused), Random connections, Forced connections, Incubation |

### 3.4 Characterization of ideation states

In this project, an ideation state is defined as the current understanding of the design space and one's current location in that space [1]. It is characterized by the current focus of the problem solver, the factors that are blocking creativity, the level of satisfaction/dissatisfaction with ideas generated, and the types of problem (novelty, complexity, uncertainty). Ideation states were characterized with the use of a set of indicators. As shown in Table 5, these indicators are classified into problem related, process related, and outcome related. This process of finding the position of the designer in the design space is called characterization of the ideation state.

Table 5: indicators of ideation states

| Problem | | | Process | | Outcome based | | | |
|---------|------------|-------------|------|------|----------|---------|---------|---------|
| novelty | complexity | uncertainty | time | path | quantity | quality | novelty | variety |

### 3.5 Organizational framework for holistic ideation

How the ideation methods are represented and what are the entities present in each of their representation will be discussed in this section. The following subsections will provide details about the relation between entities, and then an overall architecture for holistic ideation will be presented. Table 6 presents the entities in each of representation of ideation methods.

Table 6. Entities of ideation methods in previous holistic ideation tool

| Physical effect | 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) |
| Working Principle | 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') |
| TRIZ/BioTRIZ | a. Improving feature (E.g. Strength, Reliability etc.) |
| | b. Worsening feature (E.g. Weight, Area etc.) |
| | c. Inventive principle (E.g. Segmentation, Asymmetry etc.) |
| Artifacts | 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) |
| Functions | a. Input/output flow variable (E.g. Mechanical energy, Solid material etc.) |
| | b. Function verb (E.g. Divide, convert, expand etc.) |

During the design, the designer may need to switch to another ideation strategy when he/she is working with a certain ideation strategy. In order to provide seamless traversal among ideation methods, strong integration between ideation strategies is required. In the previous 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. 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').

### 3.5.1 Function to physical effect

Through flow variables of function ontology, functions were related to physical effects. As a step towards that, the physical variables can be classified as Energy, Material and Signal. As shown in Figure 5, each flow variable has several physical variables associated with it. Based on the relations between the flow variables and the physical variables, functions and physical effects were mapped.
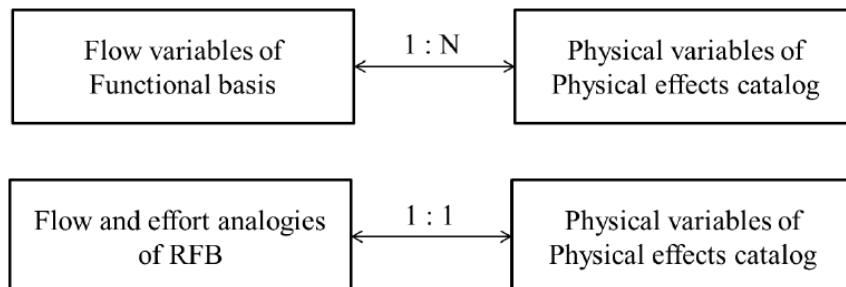


Figure 5. Relation between function definition and Physical effects

### 3.5.2 Function to TRIZ

The design team in Oregon State University had developed the function based TRIZ [16]. They explored the flow variables of functional basis and variables involved in TRIZ principles. Figure 6 indicates that TRIZ principles were mapped to Functional verbs. Moreover, the physical effects and parameters had also been mapped to the improving and worsening parameters of TRIZ through flow variables. The 39 characteristics in TRIZ are related to one or more physical effects and parameters. And the flow variables of function definition are mapped to the physical effects and parameters.



Figure 6. Relating flow variables to TRIZ with physical effects and parameters

### 3.5.3 Function to artifact

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. The list was used in holistic ideation tool for mapping function to artifacts.

### 3.5.4 Function to working principle

Working principle has related physical variables associated with it. Moreover, the flow variables of functions are related to the physical variables. Hence, physical variables can form the bridge between functions and working principles. Figure 7 explains the relationship between functions and working principles.
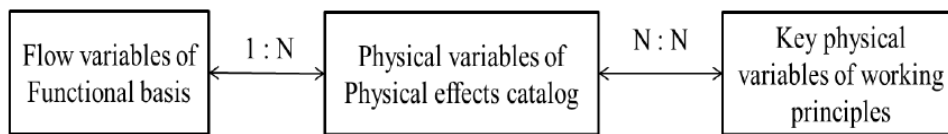


Figure 7. Relating function to working principles with physical variables

### 3.5.5 Class diagram

Figure 8 is the class diagram which illustrates the structure of the holistic ideation system and how different classes associate with each other in addition to their attributes.

**Physical Effects**

-Name
-Description
-Equations
-Physical_variables
-Physical_law
-Occurrence_medium

**TRIZ/BioTRIZ**

-Improvening_feature
-Improvening_feature_physicalvariable
-Worsening_feature
-Worsening_feature_physicalvariable
-Principle

**Function**

-Function_verb
-Input_flow
-Input_flow_physicalvariable
-Output_flow
-Output_flow_physicalvariable

**Working Principles**

-Name
-Description
-Related Physical effects
-Key Physical variables
-Picture
-Function
-Biological_example

**Artifacts**

-Name
-Description
-Input/Output Flow
-Function_verb
-Failure
-Physical_variable
-Parent_artifact
-Child_artifact

Figure 8. Class diagram for Holistic ideation with experiential methods

Moreover, the class diagram 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. Between ideation methods, there is a relationship which is somehow connecting to physical variables of certain physical effect.

## 3.6 Pre-ideation, ideation & post-ideation stages

The ideation design is organized into three major stages: pre-ideation stage, ideation stage, and post-ideation stage. The pre-ideation stage comprises of the initial stages of conceptual design, and by the end of the pre-ideation stage, a tasks list or tasks structure of the design problem is created from the set of requirements. Once the tasks are developed, the user can move to the ideation stage, which facilitates idea generation for each function. The designer can choose

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from a variety of ideation strategies based on his needs and preferences. In post ideation, the evaluation of the solutions is done based on the four effectiveness metrics: quantity, quality, novelty, and variety defined by Shah et al.[17]. Moreover, by these indicators, the evolution of ideation states can be monitored. From the measures of the outcomes, a plot can be generated for effectiveness measures versus time/phase number. In this preliminary research, the evaluation is done by the designer himself and values are assigned by him for each effectiveness measure with the help of the metrics. When the plot is steadily increasing, there is no problem and the designer can stick to the strategy he was using. When there is a large change in the gradient of the curve, the phase or time is noted and the designer may be asked to take a different strategy (or the same path if he is making progress).

Both the ideation and post-ideation processes occur simultaneously and not one after other. So while generating ideas and solutions, the designer can document those ideas. This pre-ideation, ideation, and post ideation process repeats until all the tasks are solved. Figure 9 illustrates the overview and the general process of pre-ideation stage, ideation stage, and post-ideation stage.
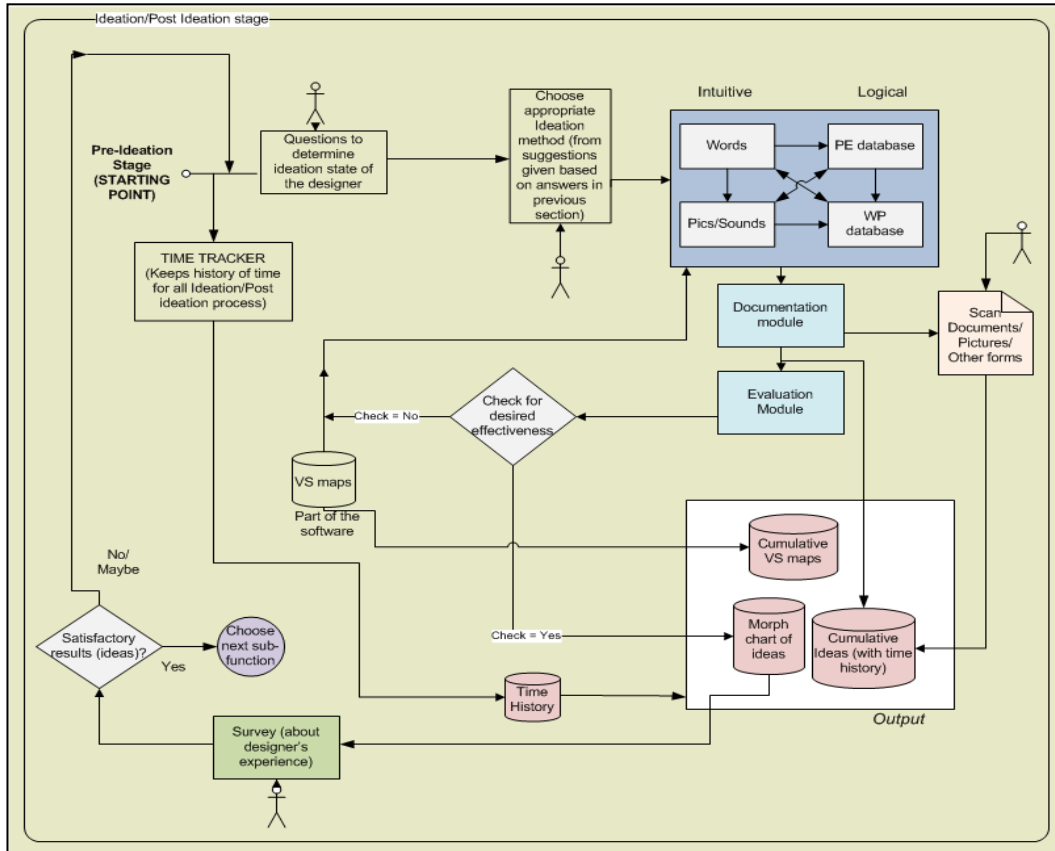
Figure 9. Framework of previous holistic ideation test bed

## 3.7 Implementation of holistic ideation

Computer implementation for each of the experiential ideation methods will be reviews in this section. The repositories play a vital role hence studying their schema is very important. Relationship diagrams from each of design repositories are shown in this section.

### 3.7.1 Repositories schema

Database schema for the physical effects database is shown in Figure10. Figure 11 shows the database schema for WP. Figure 12 is the database schema

for TRIZ/BioTRIZ and function based TRIZ.Figure 13 is thedatabase schema for

Oregon State University Design repository.
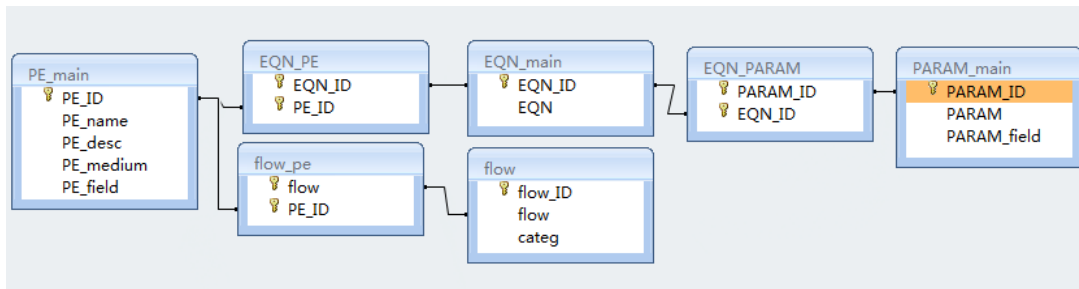


Figure 10. Database schema for physical effects database
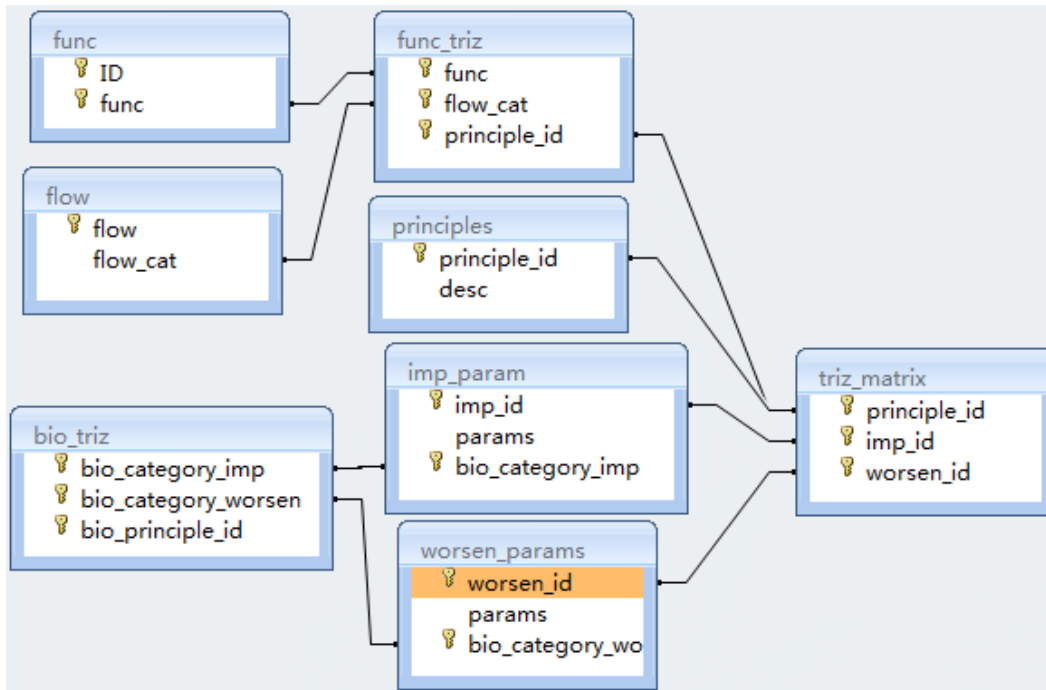


Figure 11. Database schema for TRIZ/BioTRIZ and function based TRIZ
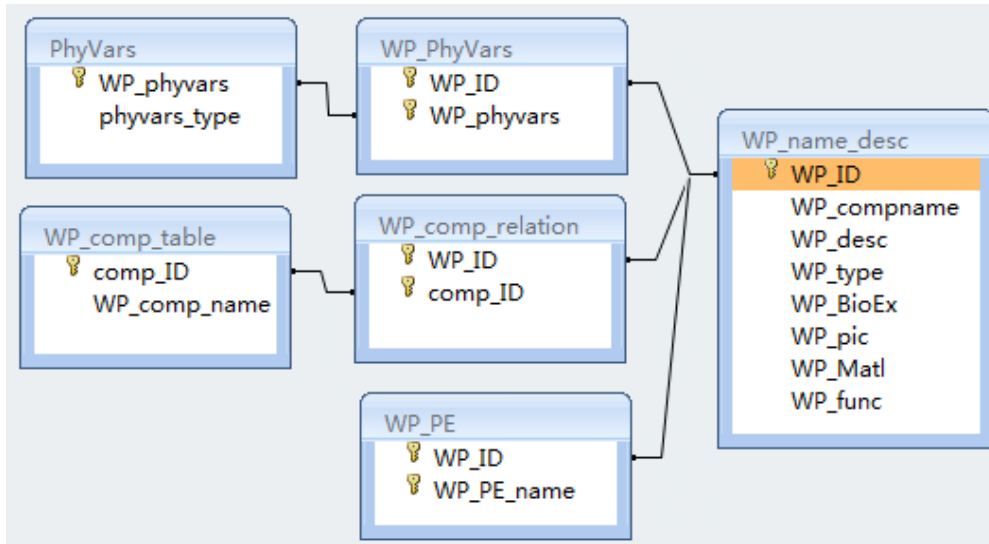
Figure 12. Database schema for working principles database
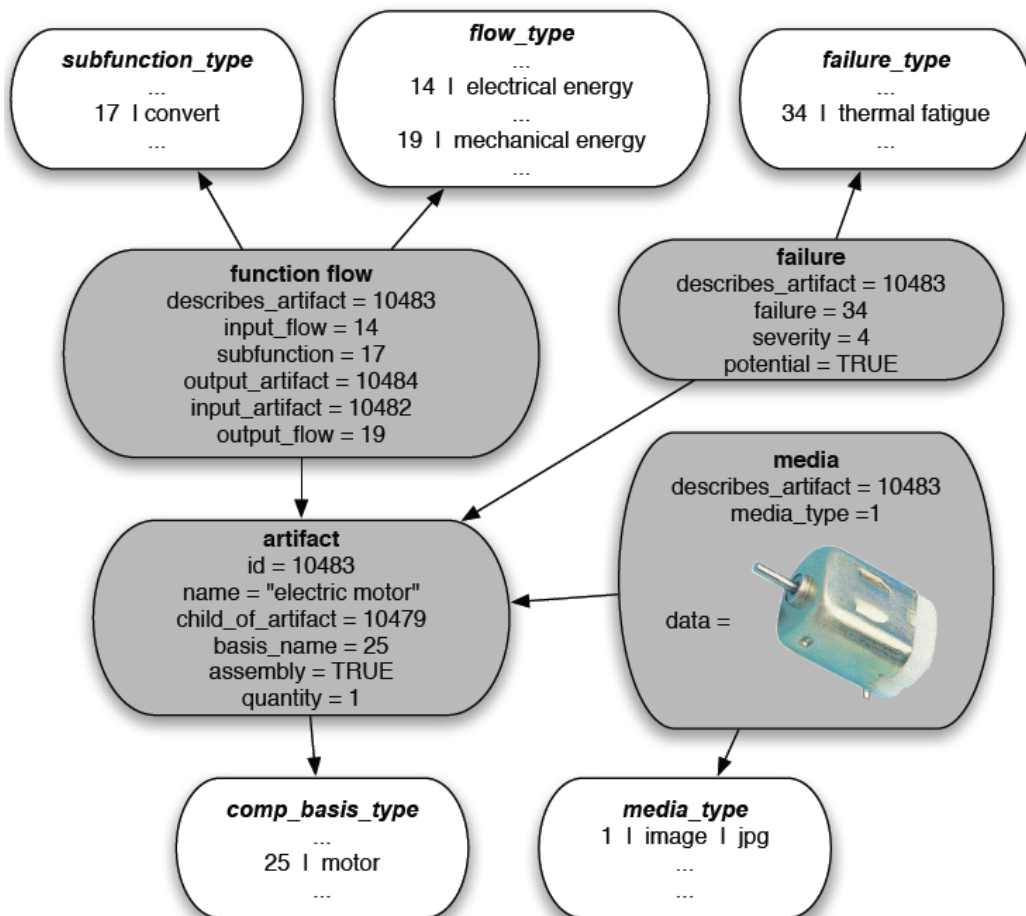


Figure 13. Database schema for Oregon State University Design repository

### 3.7.2 Ideation state characterization tool

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, the designer 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. Figure 14 is the user interface for ideation state characterization.



Figure 14. Ideation characterization tool

### 3.7.3 Ideation generate tools

The physical effects database can be searched through the physical effect's name, physical parameter or function. The working principles can be searched with respect to name, physical variables, and function. TRIZ/BioTRIZ had been implemented based on the database schema described in Figure 15. Figure 16 is the user interface for physical effect.
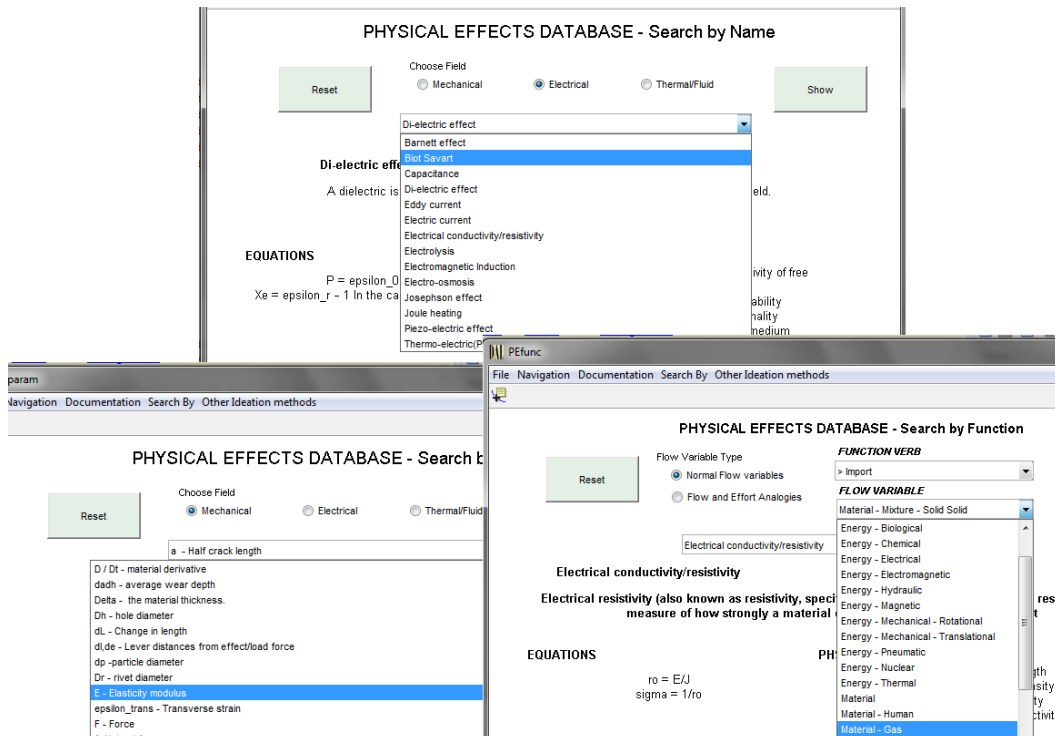


Figure 15. Physical effects search by name (top), by physical variables (left) and by function (right)

### 3.7.4 Documentation & survey tools

Once ideas are generated they must be documented. As shown in Figure 16, textual documentation can be made in a text pad and graphical documentation can be done in an in-built graphical editor.

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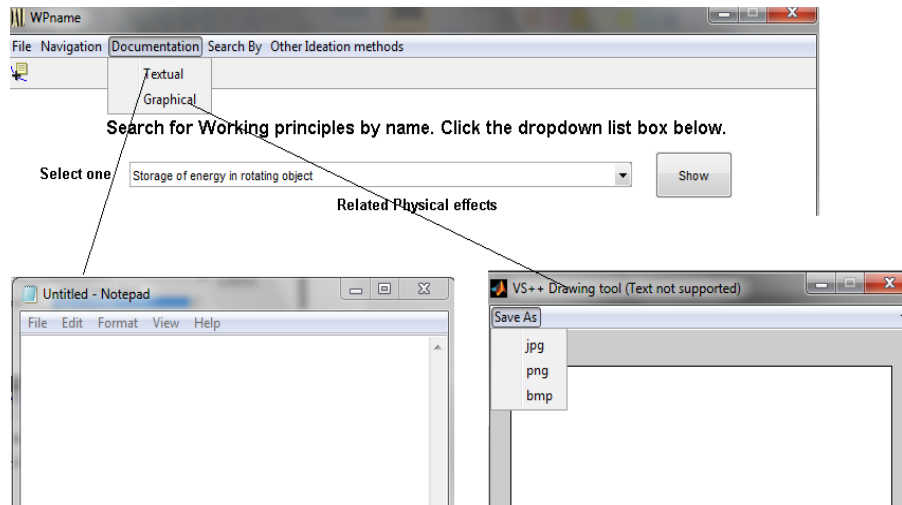
Figure 16. Textual and graphical documentation

A 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 user interface of survey tool is in Figure 17.



Figure 17. Satisfaction survey to collect details about effectiveness of ideation strategies

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**3.8 Summary and New tasks**

This chapter reviewed the preview version of the Holistic Ideation tool. The shortcomings can be divided into three aspects:

1. Every design has to begin with a function decomposition, which focuses a function based approach to ideation that is somewhat restrictive.

2. There is no formal framework to organize all the ideas explored.

3. The previous framework is heavily dependent on logical methods, more intuitive methods with ideation strategies are needed.

Design ideation based on logical methods is supported by technical data, such as physical effect catalog and artifacts database. However, design based on intuitive methods is mainly dependent on the processes which the designers go through. The main challenge for my thesis is to facilitate the cognitive processes. The rest of the thesis will present additional work in following order:

1. The implementation of new ideation methods (mainly intuitive methods).

2. Finding a suitable framework to organize ideation methods.

3. Not only beginning with functions, but generating the flexibility of ideation paths.

# CHAPTER 4

## INTUITIVE IDEATION STRATEGIES

One of the major tasks of this thesis is the addition of intuitive ideation strategies and their integration with the experimental strategies already in place. So, in this chapter, some of the intuitive strategies that are implemented in holistic ideation will be introduced including: Reframing, Analogical reasoning, Restructuring, Random connection and deliberate connection.

### 4.1 Reframing

In design thinking, one strategy to find new solutions is to change problem formulations. Both reframing and restructuring are changes in design problem formulation. Reframing may involve change in functions, objectives, specification and constraints. Restructuring involves changing the relationships between problem definition components (e.g. function structure). In order to fully understand reframing, it is necessary to explain the concept of a frame; which is not unique to design theory. Initially, the concept of framing was constructed in artificial intelligence [18, 19]. In design theory, it is based on reflective practice [20, 21, 22]. In engineering design, a frame could be viewed as a combination of three things: a certain perception of a problem or situation, the adoption of a terminology, and a way of reasoning that allows the designer to think and develop a set of possible actions [23].

"Reframing" can be seen as a change in problem formulation. Once a situation is experienced by considering it outside its original frame, changing the

viewpoint could be involved in the reframing. In other words, reframing is the situation in a different frame which could fit the primary situation equally well or even better, thereby altering its partial or entire meaning [24].The new frame "re-embeds" a product, system, or service in a new (and not necessarily logical) context, allowing the designer to explore associations and hidden links to and from the center of focus [25].

### 4.1.1 Reframing & Creativity

Reframing has been shown to be one of the ways of bringing creativity to design for the generation of novel ideas for product design. Gardner stated that, "invention is putting a couple of old things in a new relation, so what there should be done is to discover." [26] This example indicates that reframing could lead to creativity. In design, it is true that designers tend to reframe the issues before making the designs in a way which would make the problem an appropriate solution. The theoretical viewpoint of Crovitz is that the basic feature of all possible solutions to a problem is that the set of all possible actions that might mediate between the given and the desired solution [27]. Schön [28] used the word 'surprise' in his theory of creative design, where it has the crucial role of being the power source that leads to framing and reframing. Surprise is what keeps a designer away from routine behavior. The 'surprising' parts of a problem or solution drive the originality streak in a design project [29].

The power of reframing is that it forces one to incite one's creative and innovative thinking to achieve breakthrough solutions. One case that shows the

effect of reframing would be Paton& Dorst's study. It shows the clear difference between typical and innovative projects, as being whether the project could be reframed during briefing [30]. Duncker and Crovitz did some actual problem-solving by reframing [31] such as the X-ray problem, the clock problem, the river problem, the hanging-ropes problem and many more. Duncker & Crovitz's cases illustrate that reframing could lead to technically "good", novel, and plausible solutions. Another researcher Rainer Fischbach [32] gave several examples about the effect of reframing and he stated that contrary to the suppositions underlying the traditional design methods, most of the engineering problems don't have a unique formulation.

### 4.1.2 Use of reframing in holistic ideation

For experienced designers, the significant barriers to reframing are: fixation by the client on their initial idea for the project, a problem-solving mental model of design, and resistance to design paths. A significant way in which designers reframe a situation is abstracting from a client's currently held frame, so that new frames can be communicated and adopted [33]. In order to implement reframing, one must take what appears to be a difficult situation and find something positive to make out of it. One should put a different frame (perspective) on the situation which he/she is facing, looking for other ways to view the design problem. In short, reframing is formulating a problem in a new way or to identifying a new problem.

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After thinking about the possible ways of how the ideation tool could facilitate reframing, the Holistic Ideation tool is proposed that it should support the synonymy or antonymic changing by internal and/or external databases. It also should have the capability of reframing the meaning of the object which contains more information than a single word, such as sentence. I decided that it could be done by some existing tools and ideation methods, including Wordnet, Relational-algorithm, Word diamond, and Manipulative verbs. WordNet resembles a thesaurus, in which semantically similar words share a stem with the same meaning. It supports reframing of words based on the meanings of words. Relational-algorithm inserts one "relation" word into a problem statement to reframe a new perspective of the problem. Word Diamond could achieve reframing by generating ideas by combining words in the problem statement in different ways.

**4.2 Restructuring**

Restructuring is the transformation from one representational form to another at the same relative abstraction level, while preserving the subject system's external behavior (functionality and semantics) [34]. Generally, restructuring is such a process that it will recognize the application of similar transformations and then recasts the objects in the form of reshaping models, design plans, and requirements structures. As discussed in last section, the difference between reframing and restructuring is that restructuring involves changing the

relationship between problem define components (e.g. function structure), and reframing involves change in functions, objectives, specification and constraints.

### 4.2.1 Problem restructuring & creativity

A significant amount of research has shown that the creative potential of design exists with problem restructuring and the creative potential is increasing with the growing of problem restructuring. Some studies ([35], [36]) indicated that in order to be productive in engineering problem solving, one of the actions is to involve restructuring the problem in problem solving process. Wertheimer [37] applied productive thinking to problem solving. He claimed that productive thinking would lead the designer and solver to restructure problems in ways that make the problem easier for them to seek appropriate solutions. Great creative potential exists within problem restructuring, which is consistent with productive thinking.

### 4.2.2 Use of restructuring in holistic ideation

When a design engineer is using an ideation method to generate solutions and integrate concepts it would be useful to be aware of how different representations of the design problems impact the exploration of the design space and the quality of the solutions developed. Restructuring of problem representation would bring some effect on the ideation methods, because different representations would input different factors and parameters. Restructuring of problem representation will be integrated and implemented with the framework of my holistic ideation tool.

Specifically, restructuring in holistic ideation is the transformation between morphology list and morphology structure. Morphology list and morphology structure are come from problem decomposition and they are similar, in which they are both form-neutral representations of a product and describe the problems. The primary differences between a morphology list and morphology structure are: (1) a morphology structure is a graphical representation, whereas the morphology list is a textual representation and (2) the morphology structure explicitly captures topological connectivity between the sub-problems, whereas morphology lists can only imply order. The holistic tool should support the restructuring between morphology list and morphology tree.

## 4.3 Analogical reasoning

Generally, analogical reasoning is a cognitive process of transferring information or meaning from a particular subject (the analogue or source) to another particular subject (the target). In a narrower sense, the fundamental properties of analogical reasoning are the relational similarity and structural similarity. In one domain, analogical reasoning maps the causal structure between the source objects (i.e. products, designs) to the target design problem which is being solved. Enabled by a supporting system of relations or representations of situations, analogical reasoning is the mapping of knowledge from one situation to another [38].

### 4.3.1 Two theories of Analogy

Both psychology and computer science are concerned with structure mapping theory which was framed by Gentner in 1983 [39]. Structure mapping theory indicates that mapping or alignment of the elements of source and target forms the foundation for analogy. The mapping takes place between objects, between relations of objects, and between relations of relations. Analogy is viewed as a structure-preserving process.

Within structure mapping theory, Keith Holyoak and Paul Thagard [40] developed their multi-constraint theory. Depending on structural consistency, semantic similarity and purpose, they defined the "coherence" of an analogy. At any level of abstraction, similarity requires that the mapping connects similar elements and relations between source and target. Similarity would be maximal under two conditions: when there are identical relations and when connected elements have many identical attributes. An analogy achieves its purpose as it helps solve the problem by the "coherence."

### 4.3.2 Analogy in engineering design

Undoubtedly, analogical reasoning is one of the most important ideation methods in the field of engineering design. By transporting knowledge from the source domain, the design problem is analogous to another familiar design in source domain, which would enable the designer to reach a better understanding of the design domain or design problem . One possible example is Holyoak's

research [40], under the aid of similarity, they demonstrated that analogy can help people to solve a difficult problem in engineering design.

In fact, among many design projects, the objective is to find parts or entire of a product, of which the partial or whole functions are given as functional analogies. The new designed products are filled to the brim with functional analogies.

The field of biomimetics investigates mapping natural phenomenon to engineering design. Biologically inspired design carries out cross-domain analogies from biological systems to problems in engineering and other design domains [41, 42]. From bio-inspired clothing to bio-mimetic robots, analogical reasoning has led to many innovative designs [43, 44, 45]. Srinivasarao & Padilla [46] claim that bio-analogy can help develop new materials such as iridescent surfaces for computer screens). Among the 66% of projects studied by Vattam [47], bio-analogy based design included compound analogies, in which new design targets were composed of the results of multiple cross-domain analogies. Figure 18 is an example of bio-design.
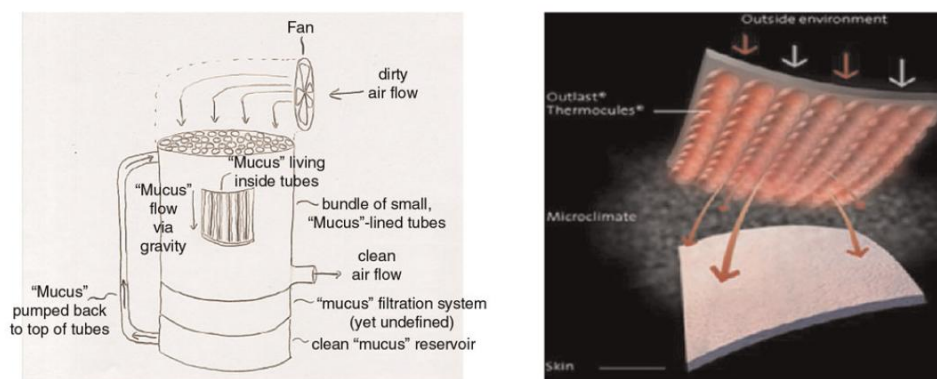


Figure 18. A bio-analogy design case

### 4.3.3 Analogical reasoning in holistic ideation

In holistic ideation, analogy will be implemented based on both logical and intuitive methods. In chapter 3, we reviewed Function Basis ontology, Physical Effect catalog, Working Principle catalog, Design Repository, and the ways of how different entities (i.e. PE, WP) associate with each other in addition to their attributes. Based on that, analogical reasoning can achieved. For example, if the user wants to find analogical reasoning for a specific design component, he/she could track the information in physical effect data base and working principle data base, find the abstraction information and knowledge, then look for another component which has the similar behavior. Similarly, he/she could go higher level by functions and look at other components which involve the same or related functions. The mediums for analogical reasoning could be abstraction information, source and target domain information, design prototypes information, design patterns, design concepts, and consistency identical attributes isomorphism.Moreover, for implementing bio-analogical reasoning, some external ideation methods and tools could be included, such as Asknature and DANE.

### 4.4 Random & deliberate connections between solutions elements

One of the main aims of holistic ideation framework is to widen the search for a possible new solution. One possibility is to explore the solutions space by combining of the elements of existing solutions randomly or deliberately. Random connection is to associate one concept/object/idea/solution with another

one, even if there is no mechanism between them at all. This connection could be conceptual, geometrical or topological. Deliberate connection is to link two concepts/objects/ideas/solutions together by careful selection rather than randomly. In this section, the two ideation strategies will be discussed together.

### 4.4.1 Random & deliberate connection and creativity

Random connections are used to break designers out of the fixated response by stimulating divergent thinking ([48],[49]). The purpose of the random and deliberate connections is to facilitate the thought of possible relations between two unrelated concepts to generate new ideas. Random connection and deliberate connection are techniques for finding commonalities between two or more seemingly unrelated concepts or items, to generate creativity which relies on random combination or designers' own talent. In this process, by making the association between concepts/objects/ideas/solutions, the designer could discover how thinking about the attributes and descriptors of seemingly unrelated objects and images for aims of opening mind to new and unexpected ideas. Association works because the mind makes a natural connection between two concepts by forcing together of two seemingly unrelated concepts. The Random connection and deliberate connection techniques can be used to generate "hybrid" ideas. For examples: the invention of rollerblade is one of the "hybrid" ideas. It is apparent that some designer conceptually linked a pair of roller and ice skates and in-turn invented a new product. The Swiss army knife is another example, but here the different parts are implemented, conceptually and physically.

### 4.4.2 Random &deliberate connection in holistic ideation

In order to implement random & deliberate connection, the holistic ideation tool should provide following capability. It would allow the designer sub-divide a problem into smaller sub problems or aspects. After generating sub solutions for each sub problems, the designer should able to combine sub-solutions randomly or at will to synthesis full solutions. Moreover, the system should allow the designer take one aspect of component of an existing solution and combine it with another aspect/attribute/component of another solution to create new concepts/ideas/solutions.

One of the most important advantages of random connection is to avoid the pre-judgment. Sometimes, designers make the decision too early, as a result, potential novel solutions may be get filtered. By selecting sub-solutions randomly to form principle designs, no judgment is undertaken at all. During the design process, it does not matter whether the designers accept the randomly generated design or not, the designs will be stored for later consideration and review. Furthermore, with help of a computer aided tool, the selected, used or potential combinations are recorded clearly.

### 4.5 Provocative stimuli

Provocative stimuli are any external stimuli to the designers that provide for a change of reference ([50],[51]). They may be the information and knowledge in any form, such function, behavior or component. Both textual information and

graphical information could be the provocative stimuli. Provocative stimuli may be derived from the exchange of ideas between designers.

### 4.5.1 Provocative stimuli and engineering creativity

Provocative stimuli allow designers to combine multiple concepts in unexpected ways. Also, it was found that while many design modifications were misinterpreted from the original intent, the misinterpretations served as launching pads for new design solutions [52]. Research on the components of C-Sketch was conducted at the DAL [53]. With the help of provocative stimuli which embedded in C-Sketch, designers combined two or more concepts in unexpected ways develop new concepts. By looking at the sketches from the previous designer provide, the designer was excited by provocative stimuli. These provocative stimuli presented the designers with new solution directions and new frames of reference from the previous designers. And in DeBono [50] and Osborn's [51] researches, there was evidence that provocative stimuli aid idea generation.

### 4.5.2 Provocative stimuli in holistic ideation

In holistic ideation tool, provocative stimuli could be implemented by unexpected information, such as design knowledge (e.g. parameters, equations, functions) from existing components and design, graphical information from external database. In order to enable provocative stimuli, the framework could easily transform knowledge among different domain and from different levels (function, behavior, component). Moreover, the system should be able to provide the designer the option to put an emphasis on the solutions quantity rather than the

quality. And in order to facilitate thinking about a problem differently, it should provide flexible representations of not only problems but also solutions, such as sketch and text.

# CHAPTER 5

## HOLISTIC IDEATION ARCHITECTURE

One major task of this research is to find an appropriate or effective framework to organize ideas and navigate ideation methods. This framework is supposed to have the following capabilities:

1. Navigating through different ideation methods.

2. Navigating and relating ideas generated.

3. Giving the designers maximum freedom to decompose and formulate the design problem.

4. Generating solutions in any way the designer likes, such as text and graph.

5. Allowing multiple framing to co-exist.

In this chapter, the framework will be introduced first, then how to use the framework to operate both intuitive methods and logical methods should be discussed. Moreover, the methodologies of implementing ideation methods together are also covered in this chapter.

### 5.1 Organizational framework

In this section, I will introduce an existing framework—morphological chart which can form the foundation of organizing both intuitive and logical ideation methods.

### 5.1.1 Morphological chart

The term morphology comes from ancient Greek (morphe) and means shape or form. The general definition of morphology is "the study of form or pattern", i.e. the shape and arrangement of parts of an object, and how these "conform" to create a whole. The "objects" in question can be physical objects (e.g. an organism, a geography or an ecology), social objects (an organization or other social system) or mental objects (e.g. linguistic forms, concepts or systems of ideas). Today, morphology is associated with a number of scientific disciplines in which formal structure is a central issue. In biology, it deals with the form and structure of organisms; in geology it concerns the characteristics, configuration and evolution of rocks and land forms.

In engineering design, morphological charts were first used by Zwicky[54].It consists of decomposing a problem into sub-problems for design ideation, generating all solutions to each sub problems independently and then combining the sub-solutions randomly and to obtain complete solutions. The chart has rows to represent each sub-problem and in each row there are one set of sub-solutions (one or more) to that problem. Thus (i, j) in the chart is the jth sub-solution to the ith sub-problem. Candidate complete solution is the union of one sub-solution from each row. Of course, if combinations are made at random, some union solutions may be incompatible and will be discarded.

Function decomposition could be the starting point but design attributes and requirements could also be used for problem decomposition. The various

functions, sub-functions, features or requirements of a product can be established through a pre-analysis. Possible solutions/means/ideas are listed corresponding to their features/(sub)function. The solutions are usually concrete and specific; some of them could be specified to a category (i.e. parameter). These solutions could be known ones that come from existing solutions such as analogous products; meanwhile, other solutions could also be novel ones which are generated during the design process. Figure 19 shows part of a morphological chart, sub-functions are listed in columns and solutions are listed in rows. The design problem is to design a manned transport. The listed sub-functions include "human power", "stearing", "transmition", "surprise", "learning effect", "acceleration" and so on.
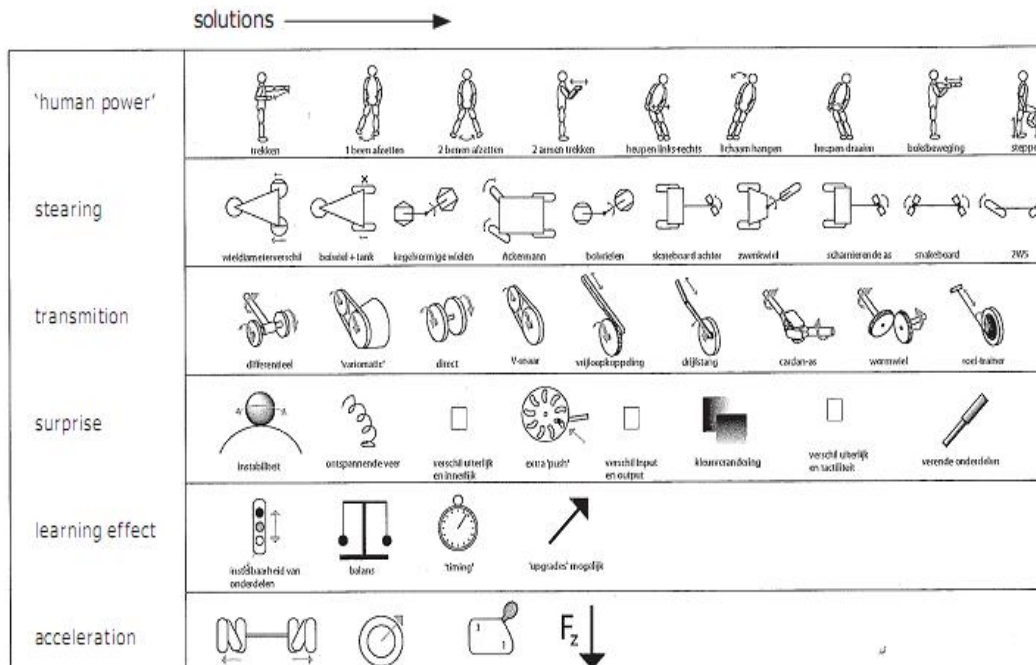


Figure 19. One example of morphological chart

(http://www.wikid.eu/index.php/Morphological_chart)

The main aim of the morphological chart is to widen the search for possible new solution based on the combination of the solutions. The morphological method is an evolutionary method: sub-problems and sub-solutions evolve in parallel until the final morphological chart is made.

In a formed morphological chart, the number of possible configurations is the product of the number of solutions under each feature (i.e. sub-functions). However, only trying to examine or read all possible configurations would take a good deal of time and effort. For example, in Figure 19, the morphological chart contains $9*10*9*8*4*4=103680$ possible configurations. A computer tool can facilitate tracking the combinations. With the help of computer, there could be a step in the analysis-synthesis process to reduce the total set of possible configurations in the total problem space, for generating a smaller set of configurations.

Before going to the specific design of the holistic ideation framework, we first summarize the enhancements which are needed to be implemented for morphological chart:

1. Any of the sub-problems can be further decomposed, generating a morphological chart of its own (This can be called cascading morphological chart).

2. Sub-solutions can be generated by the designer either with any ideation aids or auto generated provocative stimuli and example exposure or on his own.

3. The sub-problems represent a particular framing and the candidates represent a structure. Reframing and restructuring can be facilitated by morphological charts. Rows can be reformulated using different function or attributes for reframing. And if the morphological chart could be arranged and modified, it amounts to restructuring (This could be called evolutionary morphological chart).

### 5.1.2 Cascading evolutionary morphological charts

In order to match the requirements of the framework, the traditional morphological chart need to be modified. Here, the modified morphological chart is called Cascading Evolutionary Morphological Charts (CEMC). "Cascading" indicates that it could support further decomposition of the design problem and "Evolutionary" indicates the reframing and restructuring would be embedded in the modified morphological charts, in which sub-problems and sub-solutions evolve in parallel until the final chart is made. Cascading Evolutionary Morphological charts can be used as an organizational framework for holistic ideation for following reasons:

1. They allow complex problems to be decomposed into sub-problems that are more likely to be solved.

2. The cascading morphological structure is not solely created for functions. The flexibility of the tool allows the discovery of other ideation paths involving various aspects of the design as feature, material, requirement and so on.

3. Any of the sub-problems can be further decomposed, generating a morphological chart of its own.

4. It is a good framework to organize lots of ideation methods (intuitive and logical). There has been no previous attempts in organizing the extensive number of ideation methods under one application tool.

5. Sub-solutions can be generated by the designer with or without any ideation aids.

6. Any combination of ideation methods can be used for sub-solutions.

7. Sub-solutions are documented and organized structurally.

8. The designers can make deliberate or random connections between sub-solutions.

9. Combination can be tracked, evaluated and documented.

10. The designer can navigate back to sub-solutions or combinations, modify, add, delete them.

The Cascading Evolutionary Morphological Charts and how to implement other ideation methods together will be introduced mainly in terms of ideation strategies in following order:

1. Multilayer problem decomposition (cascading)

2. Reframing

3. Restructuring

4. Cross relating with logical ideation methods (Provocative stimuli)

5. Analogical reasoning

6. Rancom and deliberate connections

## 5.2 Multilayer problem decomposition

As Figure 20 shows, the morphological chart consists of two parts. The left part contains sub problems which are features, (sub)functions, requirements or anything could achieve the target design. The right side is the (sub) solutions for each feature (function, requirement or anything) in a row. We can say that the left part is the problem space and right part is the solution space.
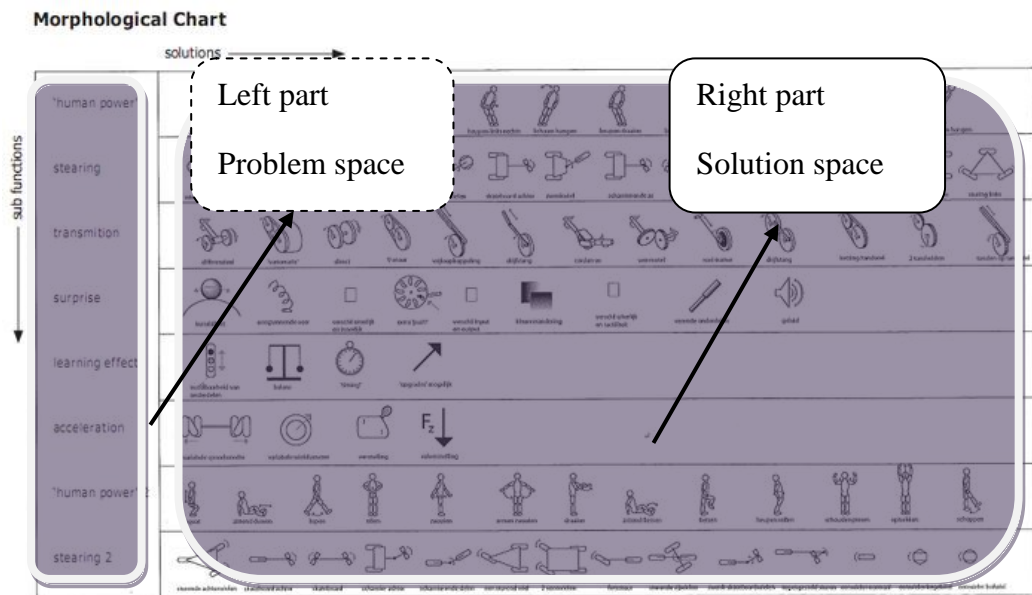


Figure 20. Problem space and solution space

In classical morphological charts, the first step is to formulate the design problem through problem decomposition in a single chart. Unlike Version 1 of holistic ideation where decomposition was purely function based, the new framework allows the designer to choose any basis for decomposition, not only by functions, but also features, requirements, etc. of the design target. The various

functions, sub-functions, features, requirements, morphology, or properties of a new design could be established through a pre-analysis.

Compared with the classical morphological chart, one of the new features of CEMC is the cascading property where further decomposition of any (sub) problem is allowed. In cascading morphological chart of holistic ideation project, a series (hierarchy) of morphological charts can be spawned off from any sub problem in the base morphological chart. Based on one sub-problem of the original tasks, a new morphology list or morphology structure could be explored and the user can create a new CEMC based on that. Figure 21 is one example of problem decomposition of a CEMC a specific design problem:"Design a mechanical device to collect samples of water from fresh water lakes. After release, the device must not be attached to the boat and must descend to within 10 m of an easily adjustable predetermined depth. It must return to the surface with a 0.5 liter sample of water from that depth and then float on the surface until picked up."
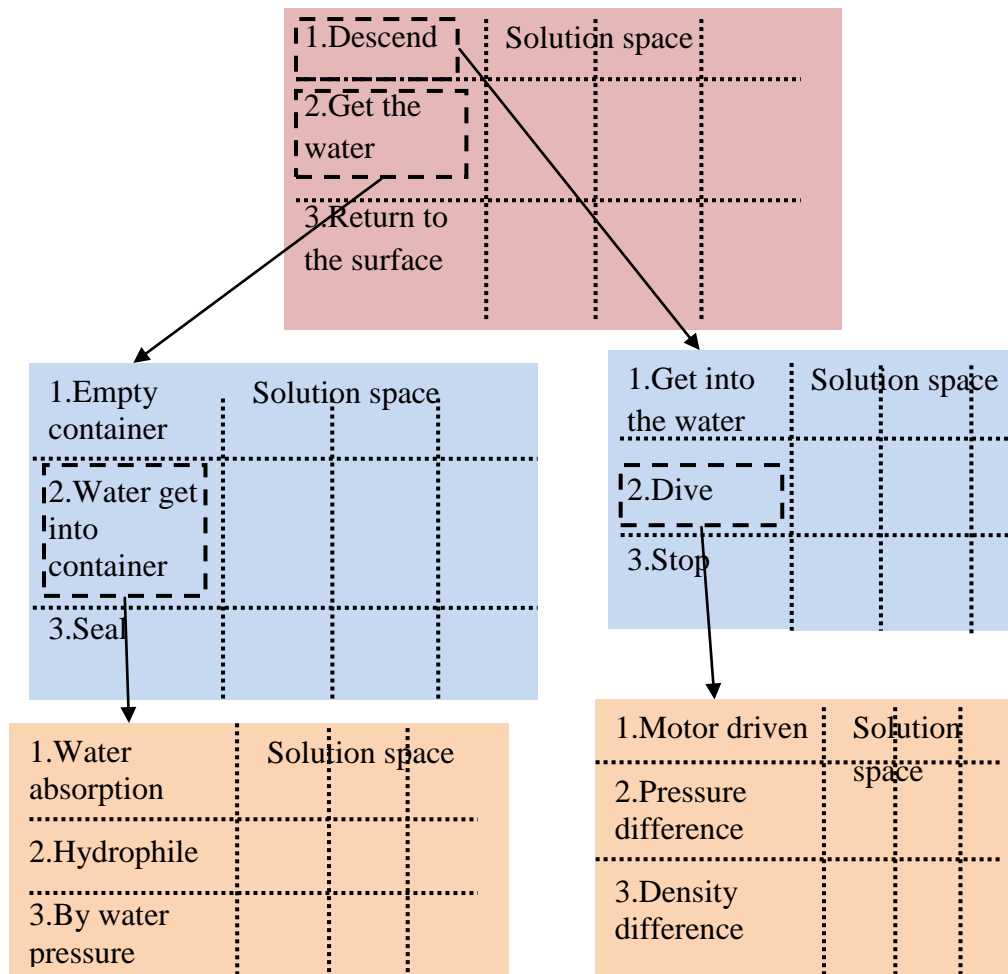
Figure 21. Multilayer problem decomposition of CEMC

As shown in Figure 21, in initial Cascading Evolutionary Morphological Chart, sub-problems (Descend and Get the water) are decomposed into two sets of sub-problems and form second level CEMC. In the second level CEMC, sub-problems could be further decomposed into third level CEMC.

### 5.3 Reframing

Common ways for reframing are use of words. In holistic ideation, in order to achieve reframing, these methods have been implemented as described below.

#### 5.3.1 Reframing by meaning

Superficially, WordNet (http://wordnet.princeton.edu/wordnet/) resembles a thesaurus, in which it groups words together based on the meanings of words. However, there are some important distinctions from traditional thesauruses. WordNet labels the semantic relations among words, whereas the collection of words in a thesaurus does not follow any explicit pattern other than meaning similarity. WordNet consists of four sub-nets: nouns, verbs, adjectives, and adverbs. Table 7 provides statistics on WordNet.

Table 7. WordNet 3.0 database statistics

|           | Unique Strings | Synsets | Word-Sense Pairs |
|-----------|----------------|---------|------------------|
| Noun      | 117798         | 82115   | 146312           |
| Verb      | 11529          | 13767   | 25047            |
| Adjective | 21479          | 18156   | 30002            |
| Adverb    | 4481           | 3621    | 5580             |
| Totals    | 155287         | 117659  | 206941           |

The main feature of WordNet is connecting words from the same part of speech. In WordNet, semantically similar words share a stem with the same meaning, for instance: observe (verb), observant (adjective) observation, observatory (nouns). In many of the noun-verb pairs the semantic role of the noun with respect to the verb has been specified: {sleeper, sleeping_car} is the location

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for {sleep} and {painter}is the agent of {paint}, while {painting, picture} is its result.

Reframing would work as long as there is a text that can be used as the basis for searching equivalent information. As Figure 22 indicates, all the information at solution space can be the input of reframing to seek alternative description of problems or sub problems.



Figure 22. Reframing by WordNet

For the reason of increasing the strength of reframing, the information space could be enlarged by importing extra information such as information for describing a single topic/feature/function, information for describing single solution. Due to different amount of information contained in the reframing, the effect of it would make a large difference. For example, the reframing alternates of a single word may be as same as the reframing alternates of a word of a

sentence; however, the outcomes are located in totally different levels. Single word reframing would lead to a beginning of some certain solutions or even abstraction of some mature idea, while sentence reframing may directly obtain a solution which contains completed design which is almost impossible for single word reframing. However, it is not possible to provide a quick answer to the question of whether it is better to reframe a single word or the reframing of a word in a sentence.

### 5.3.2 Relational-Algorithm

The basic idea behind the Relational-Algorithm is to take two parts of the problem and insert one "relation" word to reframe a new perspective of the problem. In Table 8, forty two words are presented; these words are a possible set of basic English words that can lead to the wildest stretch of imagination. The holistic ideation framework can support Relational-Algorithm in problem space, because in problem space the information space would be enlarged by importing extra text for describing single topic/feature/function. The designer will be provided the list of forty two words. Since there are problem statements in solution space too, the system also provides the option to use Relational-Algorithm in solution space.

Table 8. The 42 relation in relational-algorithm [31]

| Above | Among | By | Near | Toward | Upon | Without |
|---|---|---|---|---|---|---|
| About | Because | Beyond | Into | Over | Up | |
| Across | Behind | Down | In | Through | When | |
| After | Below | From | Off | Throughout | While | |
| Against | Beneath | During | On | Till | Within | |
| Along | Between | Except | Opposite | Under | With | |

### 5.3.3 Reframing by Word Diamond

The Word Diamond technique originally was developed as a simple combination procedure using elements of problem statements. Instead of using alternative word meanings, Word Diamond generates problem statements by combining words in random order. Figure 23 shows an example: design a robot which can collect more golf balls than the opponents. Key words are balls, attack, store, grab, device, opponent and defend. These words are linked as a diamond, then words are picked randomly and put in a random order. The new generated problem statements may lead the designer to new directions. In holistic ideation, word diamond can be used in problem space of CEMC to lead the designers to seek different aspects of problems.
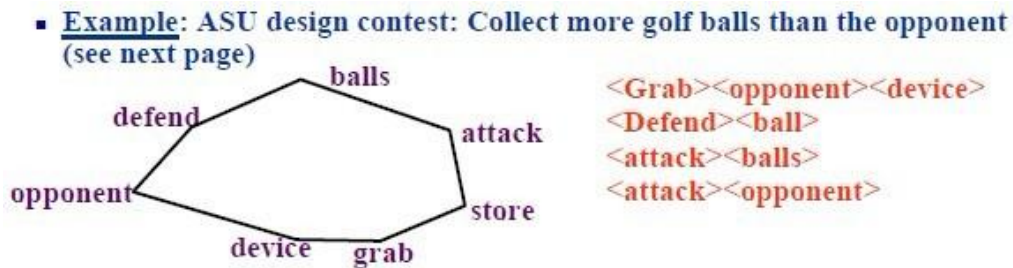


Figure 23. One example of Word Diamond

### 5.4 Restructuring

In order to use problem restructuring for creativity generation, the cascading morphological chart should first present some structures, and then restructures them. One possible way of starting a cascading morphological chart is problem decomposition. In this section, the restructuring with problem representation would be presented. To be specific, the restructuring is the interaction between

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morphology list and morphology tree, in other words the restructuring of morphology structures (both morphology list and morphology tree are morphology structures). In restructuring, a morphology list is generated first and then in a hierarchy interface, the user could move each (sub) problems around and define the relation or link between them to generate a morphology tree. Because in the CEMC, the features, requirements, morphology, and properties could be the rows, so in the morphology tree as shown in Figure 24, relations and function flow can be defined.
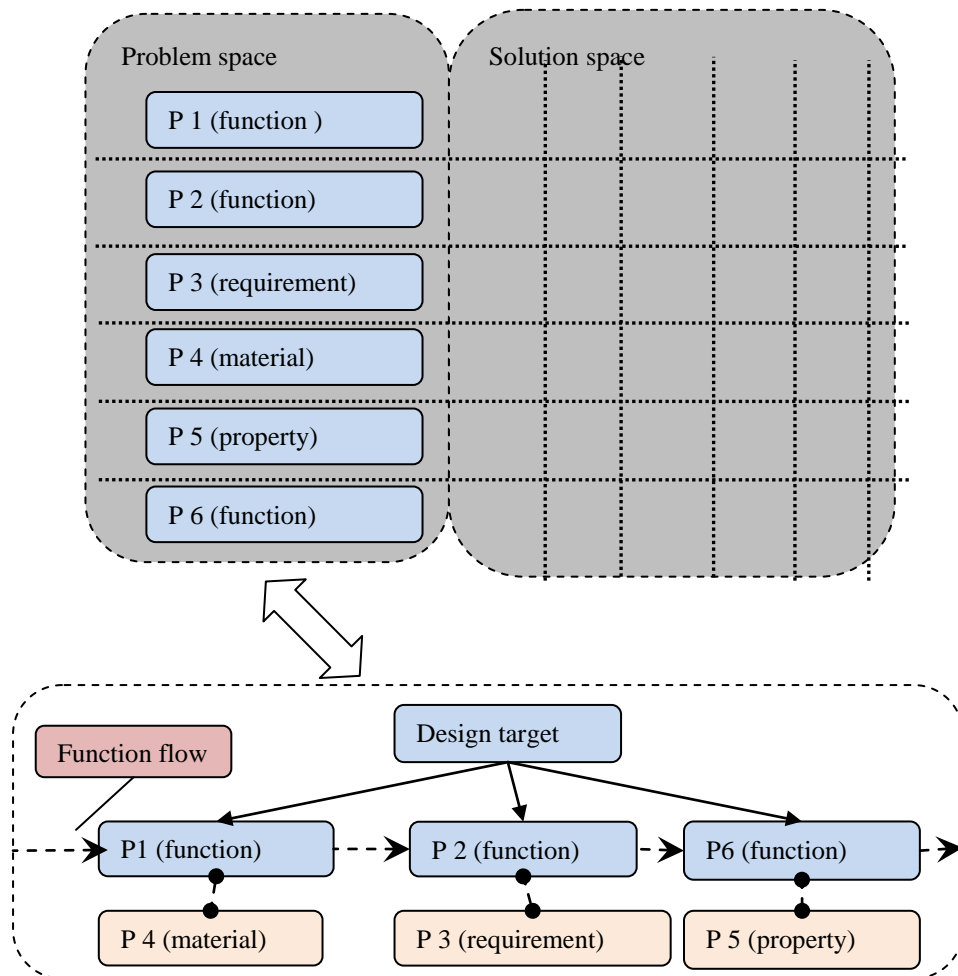


Figure 24. Restructuring between morphology structures

Additionally, within the function structure, one function could be replaced by another function and sets of (sub) functions are equivalent with other sets of (sub) functions, it can be called "OR" relation. With further problem decomposition, restructuring could be implemented by morphology trees from different problem decomposition. CEMC provides the option that the user can replace any (sub) problem with another one, user also can replace any sets of (sub) problem with another sets freely. As indicating in Figure 25, sub-problem F1 can be further decompose in different way, thus different morphology trees were created.
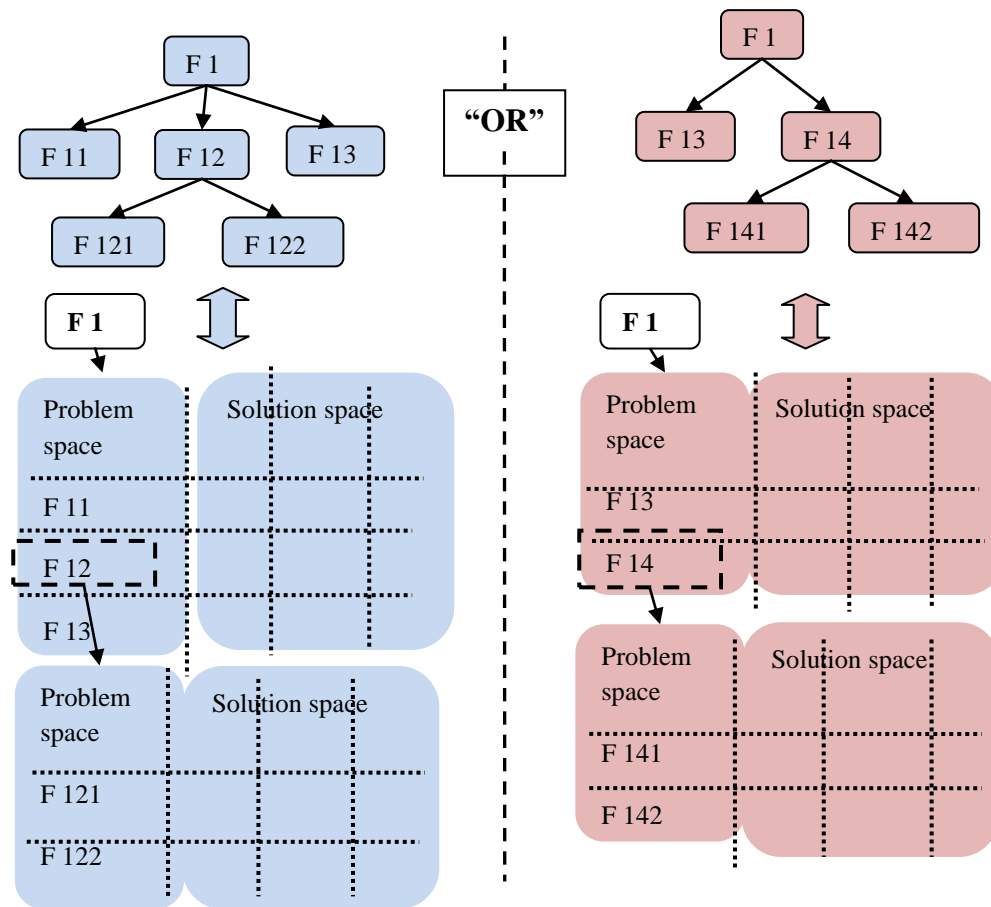


Figure 25: "OR" relations in restructuring

### 5.5 Cross relating with logical ideation methods

In the current stage of the holistic ideation project, the interaction between intuitive and logical ideation methods is the essence of the holistic ideation framework. In this section, an approach of embedding logical ideation methods with cascading morphological chart will be introduced to link logical and intuitive ideation methods.

### 5.5.1 "parameters"& three spaces

In cascading morphological chart, we provide designers the option to seek the elements which are essential to all solutions corresponding to (sub) features. The elements could be called "parameters". Thus, possible realizations, which is called "component," could be cataloged in relation to every "parameter."The parameters are independent and abstract. Those parameters are identified by focusing on the commonalities of components. They can be described as the characteristics which a product should have, thus indicating what the product should be. Among each row of cascading morphological charts, possible components are listed on the basis of their topics.

In holistic ideation, the "parameters" could be any information of physical effect database and working principle database. As Figure26, every solution is assigned to three spaces. Existing logical ideation tools are implemented in three spaces.
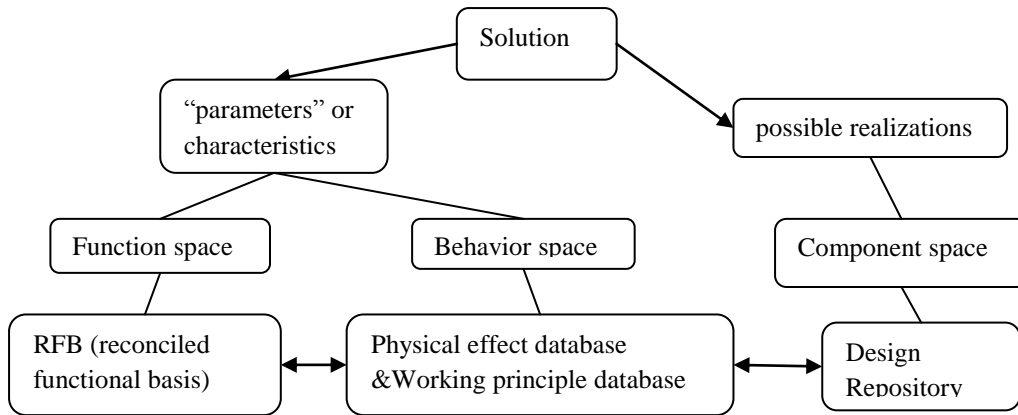
Figure 26. Three spaces for single solution

The three spaces have all the identities of the previous logical ideation frame, but are not constrained to it. First, the content in function space is more than functions; it is a conception, construct, an abstract or general idea inferred or derived from specific instances. It could be anything relative to the existing function, a noun or even a name.

Behavior space includes information such as physical effect and working principle. Physical effect is coded as PE name, PE description (keywords), PE medium, PE field, PE equation and PE parameter. Working principle is coded as WP name, WP component name, WP description (keywords), WP function, WP flow, WP material, WP Phy name, WP type (field), WP Bio-example. Behavior space is the connection between the function space and the component space.

In mechanical design, components refer to some technical artifacts or some parts which have certain usage and can generally be classified into certain categories. The OSU Design Repository is the database of known artifacts and included in our tool. In Design Repository every artifact is defined by input

artifact, input flow, sub-function, output flow, active flow, output artifact, and supporting functions. All the artifacts could be searched by these items.

### 5.5.2 Cross relating mediums

As shown in Figure 27, a dynamic system is implemented, where the user is able to cross relate function space, behavior space and component space.
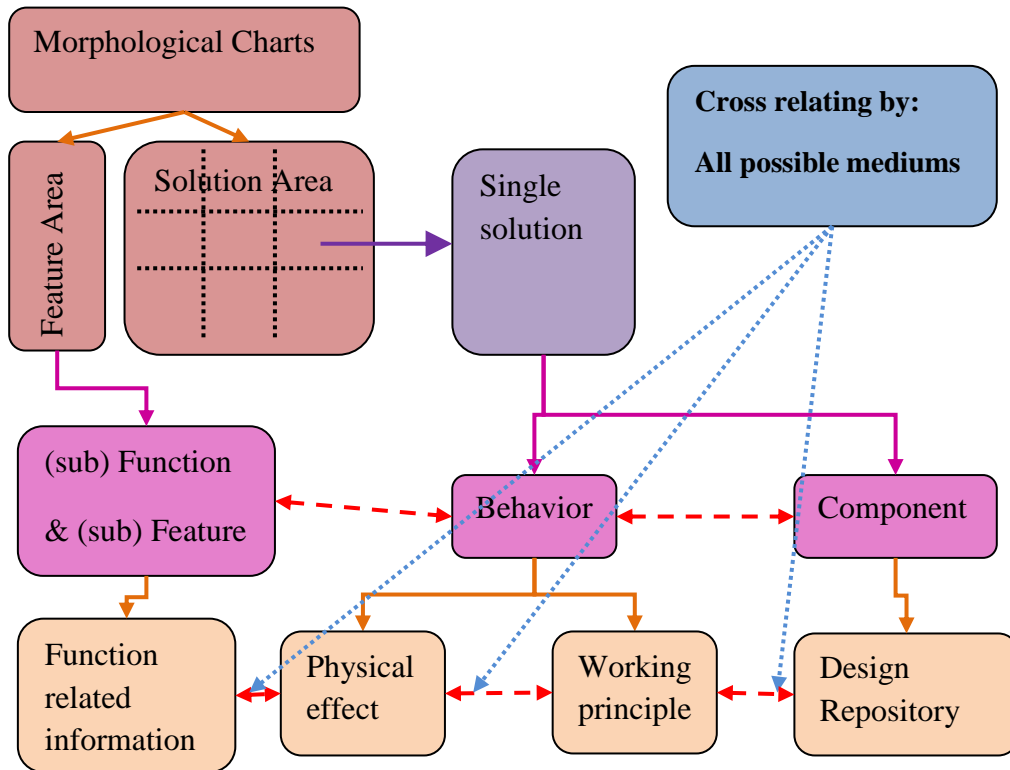


Figure 27. Function-behavior-component structure and the corresponding tools

For each aspects (function, behavior, component), certain data bases are assigned for the purpose of expanding the solution space. Figure 28shows the detail of cross linking mediums with cascading morphological chart. The cross-indexes are physical effect (PE) name, PE field, PE medium, PE parameter, PE

equation, working principle (WP) name, WP field, WP flow, WP parameter, WP bio-example, WP component, WP function, input flow, output flow, input artifact, output artifact, supporting functions, and sub-function.
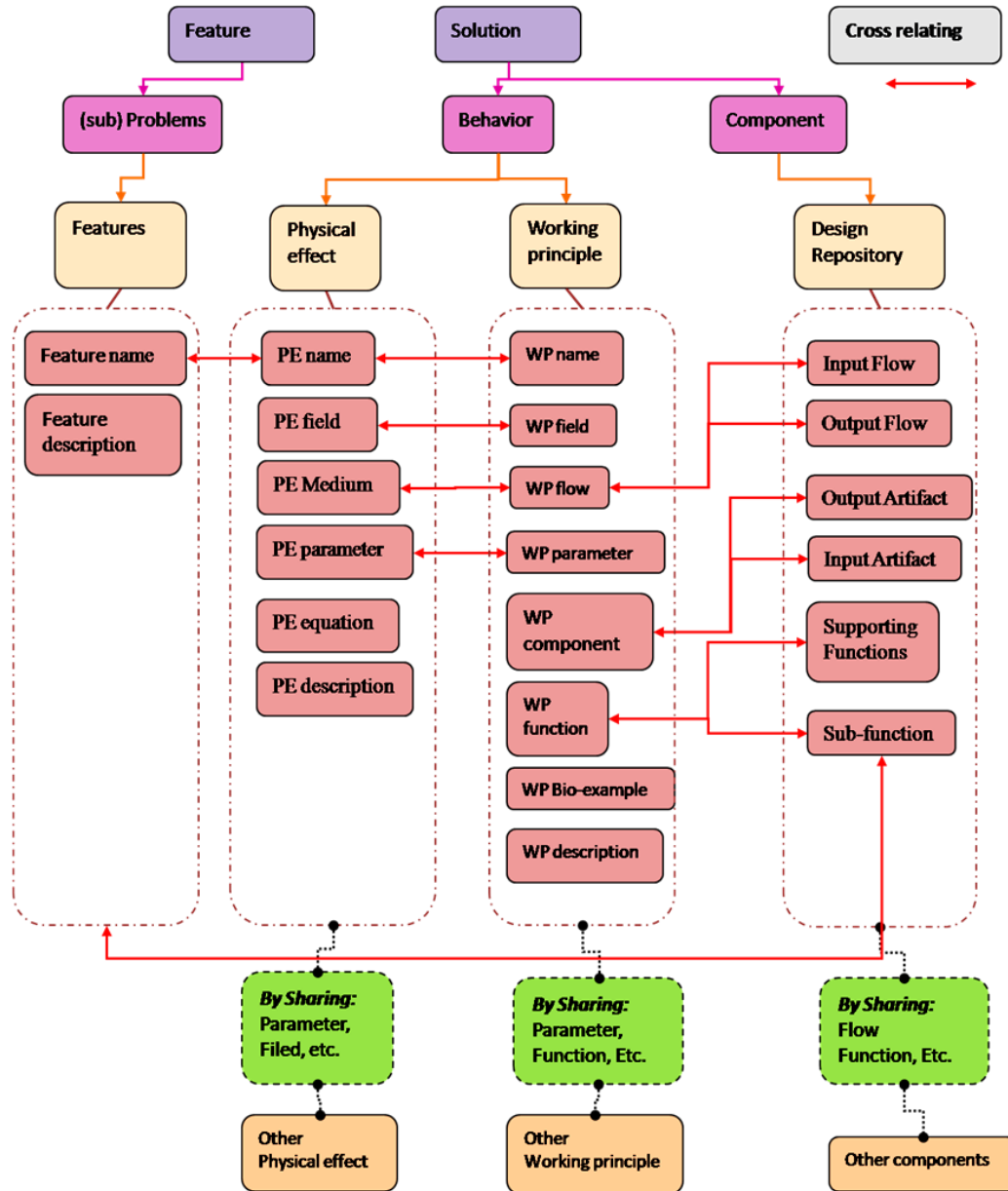


Figure 28. Cross relating in holistic ideation

### 5.5.3 Provocative stimuli

Design fixation can be overcome by timely interaction in the form of a solution hint. The method designed to incorporate provocative stimuli and experiences is explained in the remainder of this section. The designer can go through an initial problem formulation and idea generation, with or without any of the embedded methods. At any time that designers feel the need, they can ask the system to auto-generate hints in the form of PEs, WPs or components. These hints could include pictures to enhance the effect of provocative stimuli. Association indicates across different spaces can be used based on his own terms from his own solutions.

Figure 29 shows the tracking / cross relating paths among three spaces to get new information. Here the tracking indicates the process of cross relating two entities (parameters, design, or knowledge) by some mediums. These mediums are the sharing information among the two entities. The medium could be any information stored in our databases (e.g. functions, physical effect equations, etc.). In the Figure 29, ① is tracking from physical effect to working principle,② is tracking from working principle to design repository; ③ and ④ are the tracking within design repository;⑤ and⑥ are the tracking within working principle; ⑦ and⑧ are the tracking within working principle;⑨ is tracking from design repository to working principle; ⑩ is tracking from working principle to physical effect.
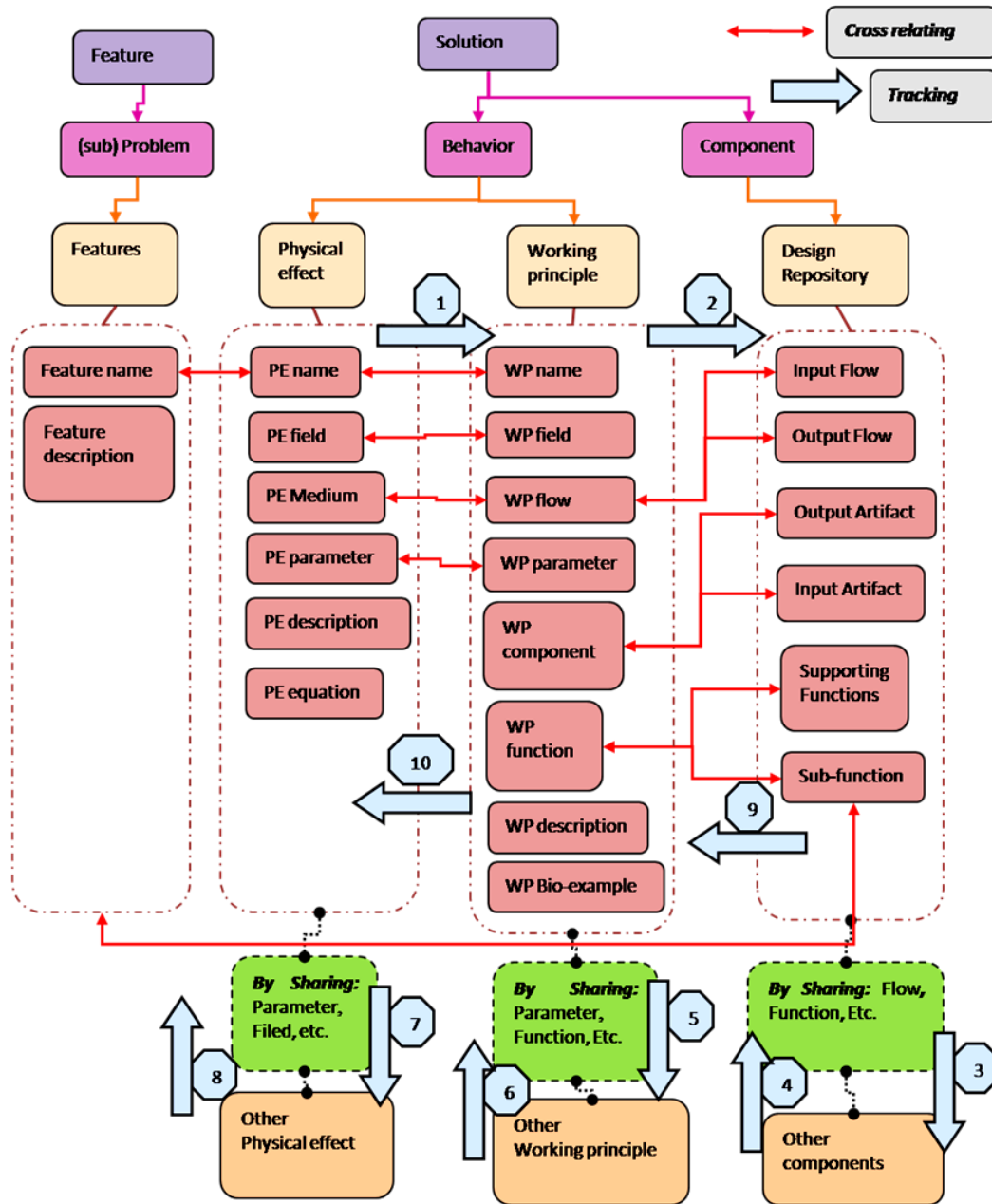
Figure 29. Possible tracking / cross relating paths

As Figure 29 indicates, the designer could track to a working principle from physical effect by physical effect name, field, flow, and parameter. The tracking could be done by one of the mediums, some of them or all of them.

If the tracking process is ① and the tracking medium is only "physical name", it could be predicted that several working principles which are related to this physical effect would be taken out. In the other way, however, if the tracking is through three or even four different items (name, flow, parameters, etc.), the results will turn out in a small region, maybe only one working principle would be tracked. By increasing the number and the types of the medium, the tracking results could be made increasingly narrower.

The links between working principle and Design Repository can be established through the following items: flow (input flow or output flow), components (input artifact or output artifact), and functions (sub-function or supporting function).

One time tracking is defined as single tracking between two different catalogs, and several single tracking could form a completed tracking path, the number of tracking times is fully depend on the designer. For instance, in Figure 29, one tracking path could be ① + ② + ③ + ④ + ⑨ +⑩, which is composed of tracking process as①,②,③,④,⑨, and ⑩.

In the tracking path, the existence of two different tracking types support the variety of the tracking results: 1. one is about the sequence and order of the models (PE, WP and DR). For instance, the overall path could be① + ② + ③ + ④ + ⑨ +⑩ or ① + ②+⑨+⑩+ ⑦ + ⑧. Although tracking path is consisted of same tracking number, the sequence and order could be different; 2. the other is about the mediums of links. For example, in tracking number ①, the medium

could be physical effect name, or field, or flow, or parameter, or both flow and parameter, or all of them. Those two kinds of varieties provide countless possibilities for importing new information.

One example of a tracking path is shown in Figure 29, considering the beginning point is the physical effect name of one physical effect. The goal is to get some new design, new ideas and new information. Then the tracking path could be:① + ② + ③ + ④ + ⑨ +⑩ or ① + ②+⑨+⑩+ ⑦ + ⑧ or ⑦ + ⑧.All of them begin with a physical effect and end with another physical effect by tracking. Additionally, even in the same path, say within ① + ② + ③ + ④ + ⑨ + ⑩, the mediums could be various. So, for path① + ② + ③ + ④ + ⑨ +⑩, it could be: (①)PE field to WP field + (②)WP flow to input flow + (③ and ④)existing component function to other components function + (⑨)supporting function (other component) to WP function + (⑩)WP parameter to PE parameter, or alternate can be (①)PE medium to WP flow + (②)WP function to sub-function + (③ and ④)existing component flow to other components flow + (⑨)input artifact to WP component name + (⑩)WP field to PE field. For both paths, at the end, another physical effect is found leading to importing new information and knowledge. The two different types of tracking variety would lead to a possibility of generating creative (novelty and variety) idea or solution.

### 5.5.4 Tracking distance

For the tracking path in the holistic ideation project, if the tracking path length is relatively small, the relation between reference object and target object is defined as close; on the other hand, if the length is large, the relation is defined as far. When the distance is relatively small, the stimuli is found in the same or similar domain, while large distance will generate the stimuli from a different domain. It is hypothesized that smaller conceptual distance is more relevant and generally leads to higher fitness; however larger distance may lead to higher novelty and variety.

In holistic ideation tool, the tracking distance could be identified with the help of conceptual distance between two concepts or objects. The conceptual distance can be measured by the knowledge/information/conceptual density. Large common knowledge/information/concept between two concepts/objects indicates close, on the other hand, small common knowledge / information / conceptual indicates that the two concepts/objects are conceptually far. The distance of two concepts/objects is not depended on the number of sharing information, but depended on the depth/level of the common information. For example, between two designs, if their functions, physical effects and working principles are the same, but the material or size is different, these two designs are close to each other. If their functions, physical effects are different, then the two designs are conceptually far away. In holistic ideation databases, reconciled functional basis, physical effect databases, working principle databases and

artifacts databases are implemented. These databases can provide the entities to determine the tracking distance. In the tracking/cross relating, function difference indicates very far relation; PE name, WP name or fields difference indicates far relation; PE parameter, PE description keywords, WP flow, WP parameters, or WP description keywords  difference indicates medium relation; only property difference (e.g. material, input artifacts, output artifacts) indicates close relation. For example, if the physical effects and functions of two concepts/objects are different, these two concepts/objects are conceptually far. And if the only difference between two concepts/objects is the input artifacts and material, these two are close.

Another way of determining the tracking distance is based on the length of tracking path. Every physical effect, working principle and artifact is defined by entities, such as name, parameter, equation, functions and keywords in description. During the tracking, any of these entities could be the node, the distance is quantified by the number of the nodes from the starting point. For example, in Figure 30, the starting point is linked to several physical effects, working principles or artifacts (red circle), then every red cycle can have nodes (such parameter, keyword), from those nodes, other physical effects, working principle and artifacts are linked. As Figure 30 shown, the information and knowledge (physical effect, working principle, artifact) in red cycle 1 and red cycle 2 are relatively close to the starting point, on the other hand, the information of red cycle 3 and red cycle 3 are relatively far away from the original information.
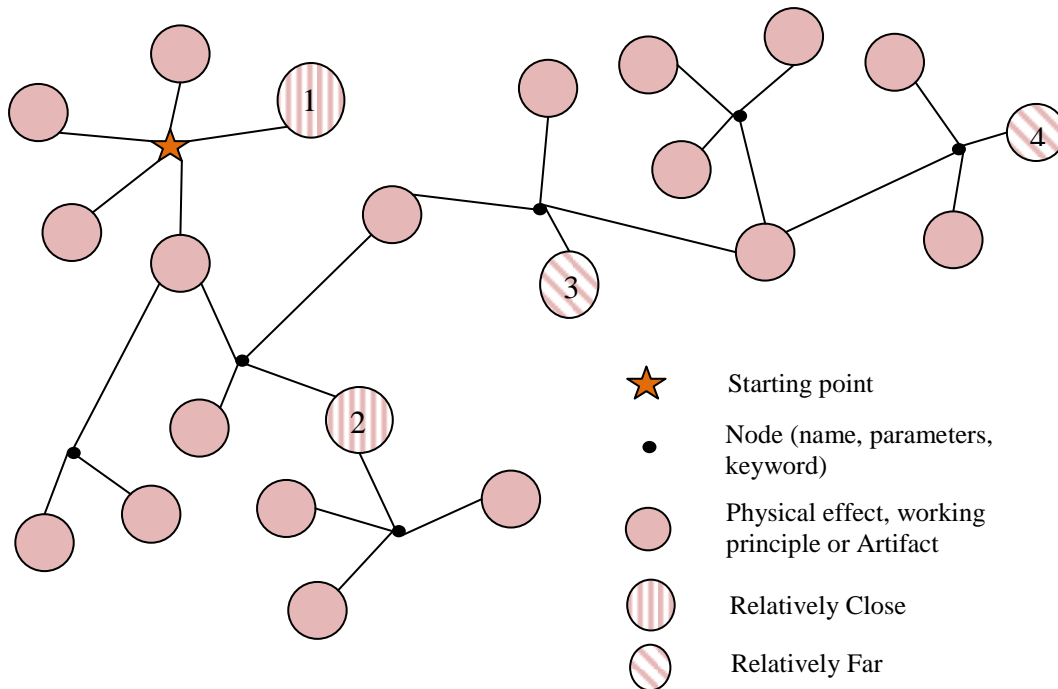
Figure 30. Tracking distance

The tracking relation supports the different stimuli: knowledge which is close to original field and knowledge which has no interaction with original field. The relation gradually changes based on the length of tracking path. Small tracking distance indicates close knowledge, while large tracking distance gives random-like results. In holistic ideation, the mapping in Figure 30 is dynamic. When the user try to track new information from the starting point, the system could randomly pick the nodes (parameters, keywords, equations) and generate new map automatically. For the same original starting point and same number of the nodes, the user might get totally different information. The dynamic mapping extends the design space widely.

Tracking distance could support future experiments whose aim is to investigate the connection between novelty (creativity) and distance of

information stimuli. It is predicted that when the tracking end objects are from unrelated fields, the possibility of increasing novelty and creativity generation is higher. To validate this prediction it would be necessary to conduct experiment studies in the future.

## 5.6 Analogical reasoning

Analogical reasoning requires abstraction and pattern matching. It can achieve the form-function relationship by finding a source domain and its hierarchy. In detail, this process is done by looking for targets among sources, in which the abstraction (function, behavior or related knowledge) of one target element is identical to the abstraction (function, behavior or related knowledge) of another target element in the same or different domains. Working with appropriate ideation methods and tools, the tracking system described in last section could support analogical reasoning in a sense. In this section, analogical reasoning in different domains would be discussed.

### 5.6.1 Analogical reasoning with TRIZ

The general way of generating ideas by using TRIZ is to abstract the contradiction from the design problem, use TRIZ Improving and Worsening parameters to identify the TRIZ principles, and then apply the principles to the specific problem for ideas. Therefore, TRIZ is analogical reasoning in physical domain.

In previous research, the physical variables for the Improving and Worsening parameters of TRIZ had been mapped. Hence, the thirty nine characteristics in

TRIZ are related to one or more physical variables in physical effect database. Based on that, analogical reasoning with TRIZ could be constructed. In Figure 31, the beginning points of analogical reasoning can be any point among the problem space and solution space. Through physical effect parameters, the improving and worsening parameters of TRIZ are presented to the designer, and then TRIZ 40 principles can be used to solve the problems.
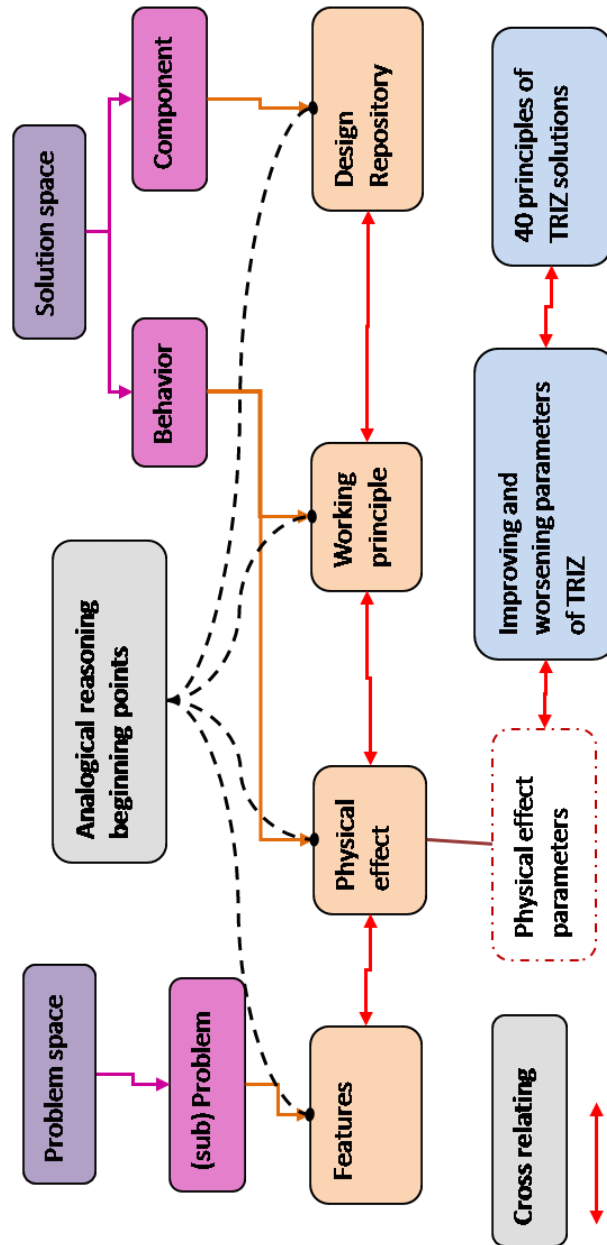


Figure 31. Analogical reasoning with TRIZ

### 5.6.2 Bio-analogical reasoning

Usually, the beginning point of bio-analogy is highly abstracted, may be from functions or abstracted requirements. In holistic ideation tool, the tracking points for bio-analogy could be any information among the problem space and solution space. With the help of physical effect data base, working principle data base and Design Repository, bio-analogy ideation tools could be implemented with Cascading Evolutional Morphological Charts by cross linking the commonalities.

DANE (Design by Analogy to Nature Engine) was developed at the Design Intelligence Lab at the Georgia Institute of Technology. The classification in DANE is mainly based on cases by function name, verb that characterizes the function, subject of the verbs, object(s) of the verbs, preposition condition, adverb condition and etc. In Figure 32, there are multi-links from physical effect, working principle, design repository to DANE, which provides the possibility for the tracking from information of holistic ideation tools and databases to the information of the bio-design tool DANE.
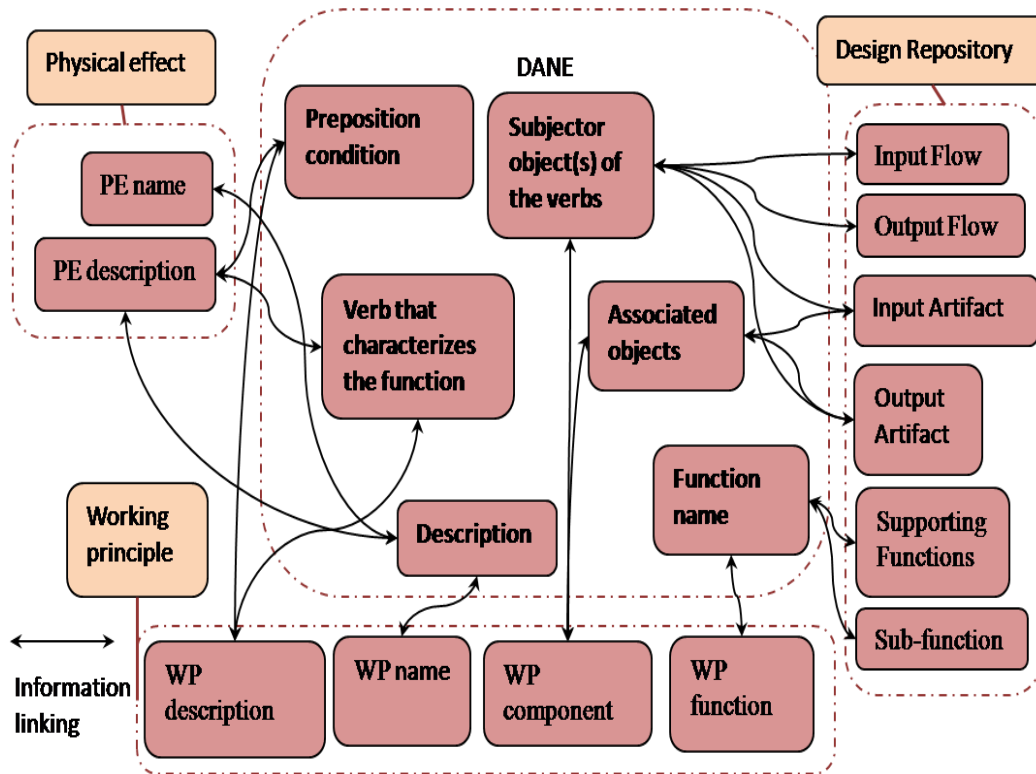
Figure 32. Tracking mediums between DANE and other tools

AskNature is a website in which biology cases can be related with engineering design. The idea behind AskNature is the online inspiration source for the biomimicry community, which could help designers to find planet-friendly solutions. The cases in AskNature are mainly defined by the function, requirements, subjects, and objects. Thus, at any point in the holistic ideation frame, the user is allowed to go to the bio-analogy tools for design inspiration. Figure 33 shows the possible links between physical effect, working principle, design repository, and AskNature, which provides the possibility of the tracking from physical effect, working principle and design repository to AskNature. Similar to DANE, AskNature can be tracked and viewed at any design point.

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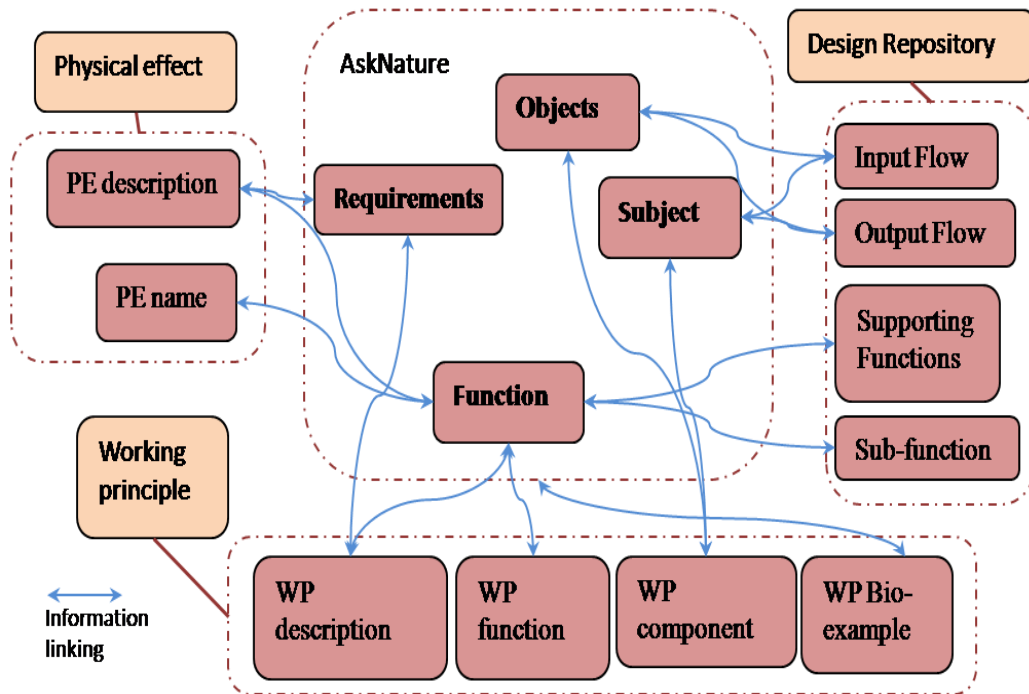
Figure 33. Tracking mediums between Asknature and other tools

### 5.6.3 Analogy and tracking distance

As we discussed, the implementation of the tracking distance supports the different provocative stimuli: knowledge which is close to original field, and knowledge which has no interaction with original field. By working with tracking path length, analogy could be given based on the tracking distance. In order to generate novelty and variety, large tracking distance could be done before taking analogical reasoning. For relevant design and higher fitness, small tracking distance should be taken. Similarly in the case of bio-analogical reasoning, based on the tracking distance, bio-cases which are totally out of original field could be assigned for novel solutions and bio-cases which are close to the design field could be given for existing designs or ideas.

## 5.7 Force connection & Random connection

Usually, across the solution field in the cascading morphological chart, the number of possible combination is numerous, and includes not only existing and conventional solutions but also completely novel solutions. As one of the most important ways of finding these novel solutions, the cascading morphological chart encourages the users to identify novel combinations of elements, ideas or solutions by using random connection and force connection.

In the holistic ideation framework, CEMC provides the user to combine existing solution/ideas together to make a complete solution though random combination. For each (sub) feature, corresponding solutions are presented in the row, the system then selects one particular solution from first row randomly, one solution from second row randomly, and so on. Finally, all of the randomly selected solutions are combined conceptually together. Moreover, the computer aided tools should enumerate the existing combination and then propose user random connections automatically.

For achieving the realization of force connection, the system should be able to show the user all the features and corresponding solutions by listing all of the features in one column and present solutions correspond to the features in rows. When the chart is completed, the user could select the solutions deliberately and combine them together to generate complete solutions.

# CHAPTER 6

## COMPUTER IMPLEMENTATION

One of the major objectives of this research is to facilitate idea generation in engineering design by implementing both intuitive and logical ideation methods. In order to achieve the task mentioned above, a computer aided holistic ideation tool was developed. This software primarily has two parts: the front-end User Interface (UI) and back end database. The architecture of the software is presented in Figure 34. The architecture indicates the general process of making a Cascading Evolutionary Morphological Charts: 1. Problem decomposition; 2. Creating morphology list and morphology structure (reframing and restructuring of the organized problem form is possible at any time); 3. Generating ideas or solutions by using ideation methods; 4. Composing the sub-solutions into complete solution; 5. Store the Plausible complete solutions.

Figure 34. The architecture of the software

**6.1 Database schemas**

In the cross relating intuitive and logical ideation methods, repositories play a crucial role. In Figure 35, relationship diagrams from each of our design repositories are shown. Database "WP_name_desc" contains the information of working principles, database "PE_main" contains the information of physical effects. Databases "PE-main" and "WP_name_desc" is related by mapping WP_ID to PE_name. Working principles (database "WP_name_desc") are related to the components (database "WP_comp_table") by mapping WP_ID to comp_ID. Functions in RFB (database "func") are related to working principle (database "WP_comp_table") through mapping both working principles and functions to flow (database "flow"). As the data schemas displays, physical effect database, working principle database and RFB are related together. The system supports the cross relating by keywords and parameters, and will be discussed in next section.
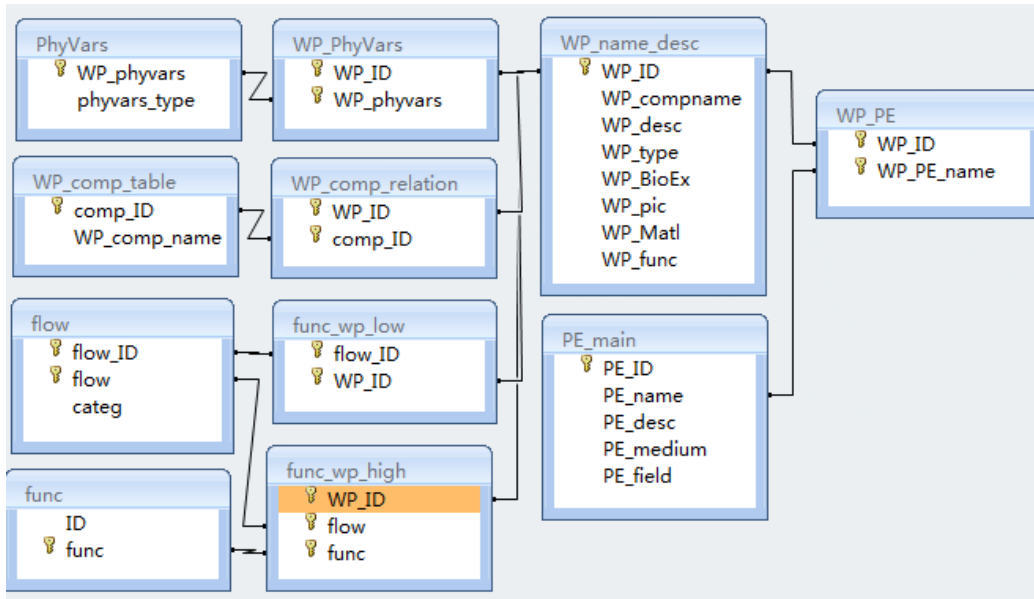


Figure 35. Database schema for cross relating repositories

In holistic ideation tool, the information of the sub-problems and sub-solutions are stored in the databases shown in Figure 36. Problem information is stored in the forms of sub-problem name, the name of the design, and short description. Sub-solution information is stored as sub-problem name, information types (text or graph), information content (words or pictures address). Complete solutions are defined as the combination of sub-solutions.
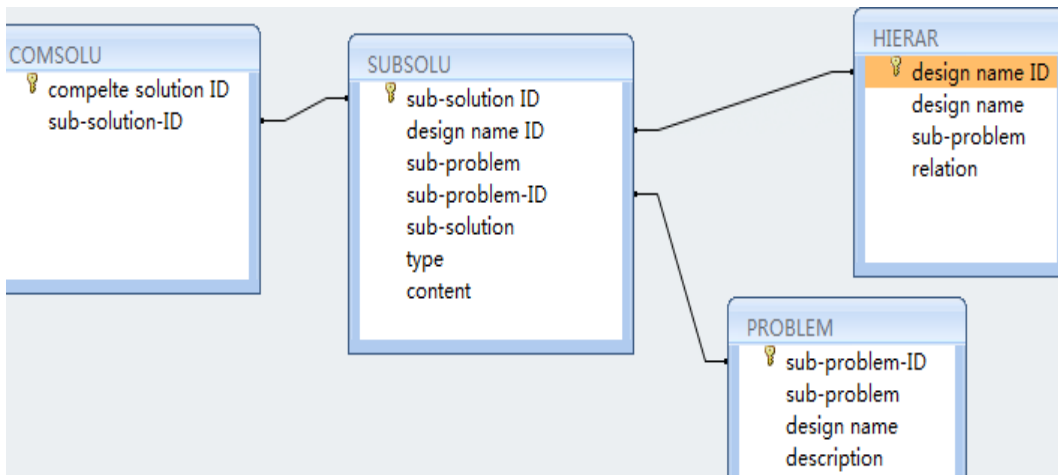


Figure 36. Data schemas of the information stored in holistic ideation tool

## 6.2 User Interface development

The developed UI of computer tools to facilitate holistic ideation is presented in the sequence of design process, and the sections are divided based on ideation methods, including problem decomposition, reframing, restructuring, provocative stimuli, analogical reasoning, and random and force connection.

### 6.2.1 Problem decomposition

The main interface of CEMC is divided into two different parts: topic area (morphology list) and solution area. In holistic ideation framework, even during

problem decomposition, other intuitive methods are available for using at anytime without losing any design data. As Figure 37 shows, the morphology list allows the user to specify and update the name of the (sub) feature and short description. The features don't have to be functions, any text which describes the problem clearly can be used. Each (sub) feature has a row to list the solutions horizontally. There is no limit of the number of the (sub) features and solutions. The UI could be extruded by the user and maximum size depends on the resolution of the computer. The information of sub-problem and sub-solutions is stored in the databases automatically. When the user opens the same design in the future, all the information will be presented.

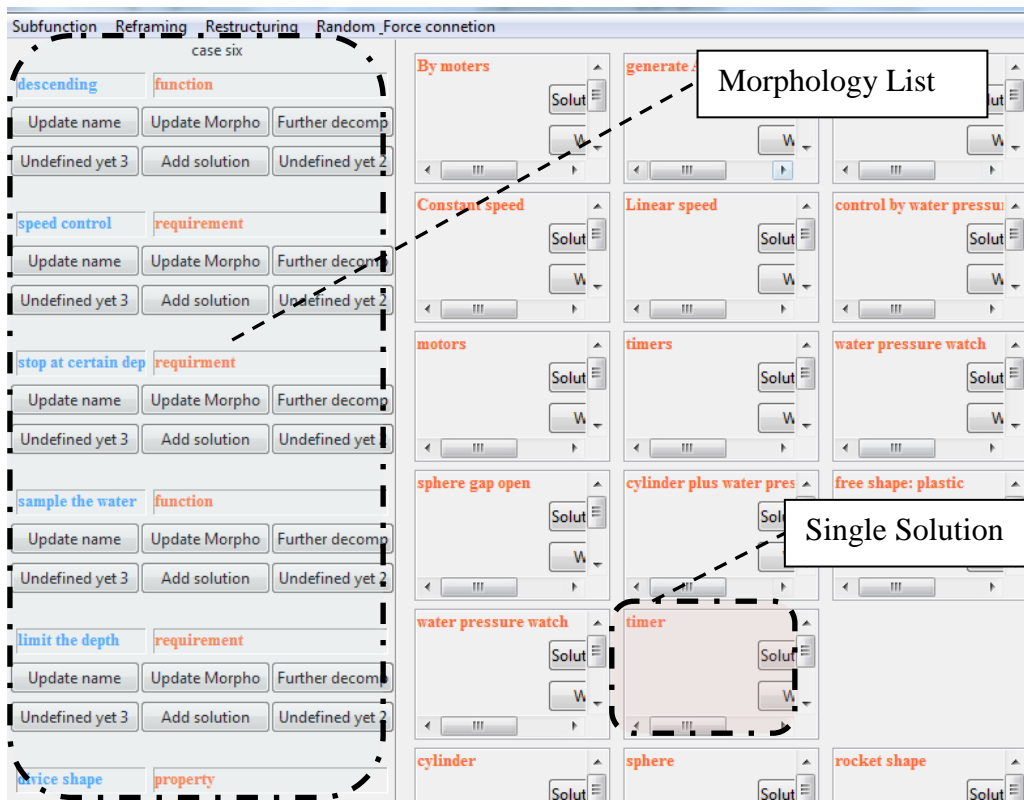Figure 37. Morphological Chart User Interface of the holistic ideation

The query of creating a morphological chart is following:

1. Problem decomposition (this step is done in pre-analysis);

2. Create a sub problem in the UI—create a space in database for this sub problem;

3. Give/update the name of the sub problem—write/update the name of the sub problem into the database;

4. Give/update the short description of the sub problem—write/update the short description of the sub problem into the database;

5. Repeat step 2 to step 4 at any time for completion of the sub problems;

6. Further problem decomposition for certain sub problem—create space for new sub-Cascading Evolutional Morphological Chart;

7. Add sub solution for selected sub problem—create space in database for this sub solution, including text and pictures;

8. Give/update the short description of the sub solution—write/update the name of the sub solution into the database;

9. Repeat step 7 to step 8 at any time for alternative sub solutions for the sub problem;

### 6.2.2 Reframing

In WordNet, Synsets are interlinked by means of conceptual-semantic and lexical relations. The resulting network of meaningfully related words and concepts can be navigated with the browser. For example, in Figure 38, under the top toolbar "reframing", the button of opening WordNet is available. In the "filter"

reframing, when we consider the "filter" as a function, the output are "filtrate", "separate out", "filter out", which are all function. Some functions are followed by behavior explanation, such as "filter out (remove by passing through a filter)".
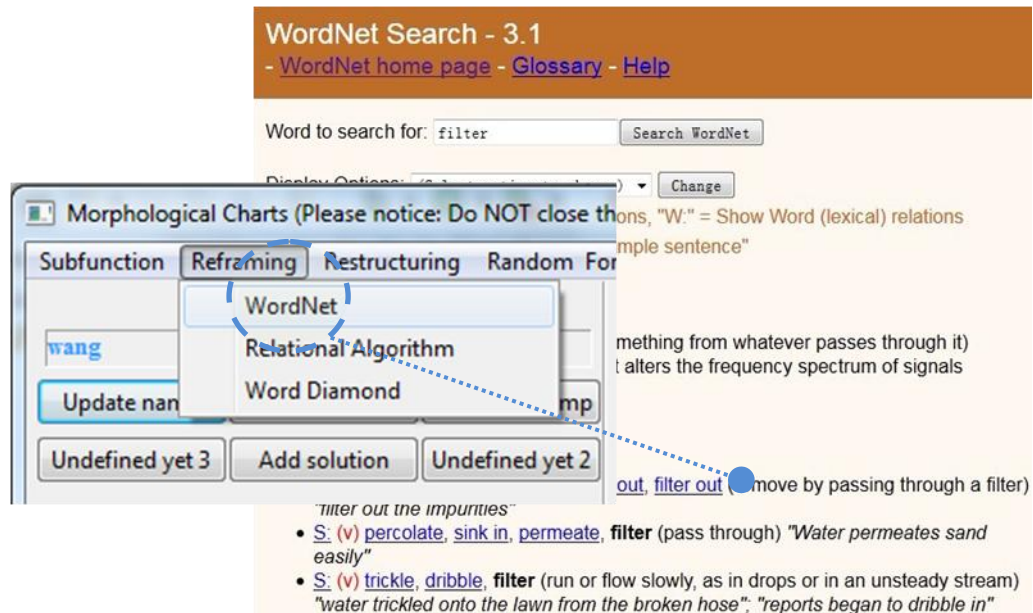


Figure 38. Reframing by WordNet

As shown in Figure 39, holistic ideation framework supports the Relational-Algorithm, in which the designer is provided the list of forty two words. What is more, sketches and pictures are attached with words to generate stimuli for the reframing of the design problems. These pictures are pre-selected and attached with certain words.  Currently, images in ImageNet are only about nouns. In the future, when there are images about preposition conjunction and verbs, the forty two words of Relational-Algorithm can be represented by the images in ImageNet.

The query of using Relational Algorithm is following:

1. The system loads a problem statement—the problem statement is temporarily stored in EMS memory of the local PC;

2. Get one word from the list of forty two words of Relational Algorithm—the system gets and lists the forty two words from the database. One of them is selected by the user or random picked by the system;

3. New problem statements are generated and showed to the user. All the problem statements are temporarily stored in EMS memory of the local PC;

4. Repeat step 1 to 3;
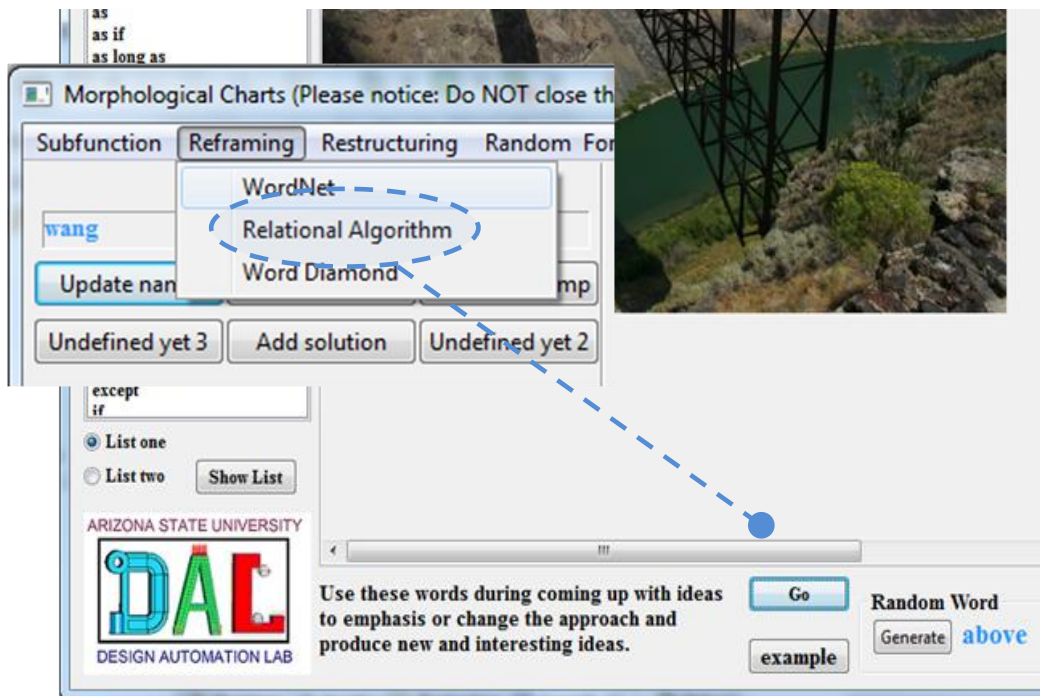


Figure 39. Relational-Algorithm in holistic ideation framework

The logic behind the implementation of Word Diamond for the purpose of reframing was explained in section 5.3.3. As shown in Figure 40, the designer first specifies how many words would be included. After inputting words, the

system uses random number of words and put them in a random order to generate

problem statements, some of which may be meaningful, some are not.



Figure 40. Word Diamond in holistic ideation framework

The query for using Word Diamond is following:

1. The user inputs several keywords into the system—these keywords are

   temporarily stored in EMS memory of the local PC;

2. The system randomly gets words from the keywords and put them in a

   random order for new problem statements;

3. New problem statements are generated and showed to the user, all the

   problem statements are temporarily stored in EMS memory of the local PC;

4. Repeat step 1 to 3;

### 6.2.3 Restructuring with function representation

The holistic ideation framework provides restructuring between morphology

list and morphology tree. Figure 41 shows morphology list from the program.

Figure 42 shows the index of morphology tree. By clicking the buttons "update

name" and "update morpho", the information of the sub problem in the database is updated. Button "further decomp" is used to further decompose the sub problem. In the database, all the information in the index is written or rewritten immediately.
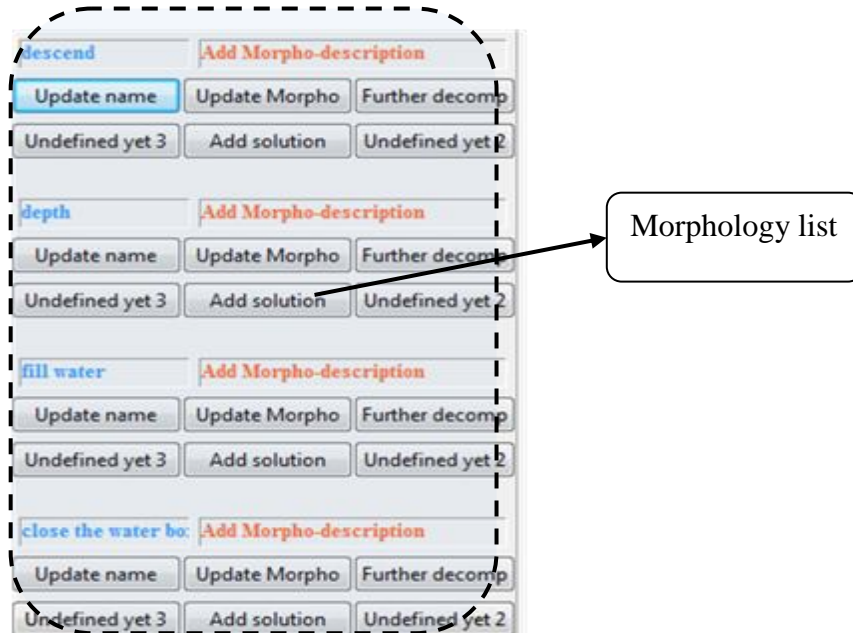


Figure 41. Morphology list in holistic ideation
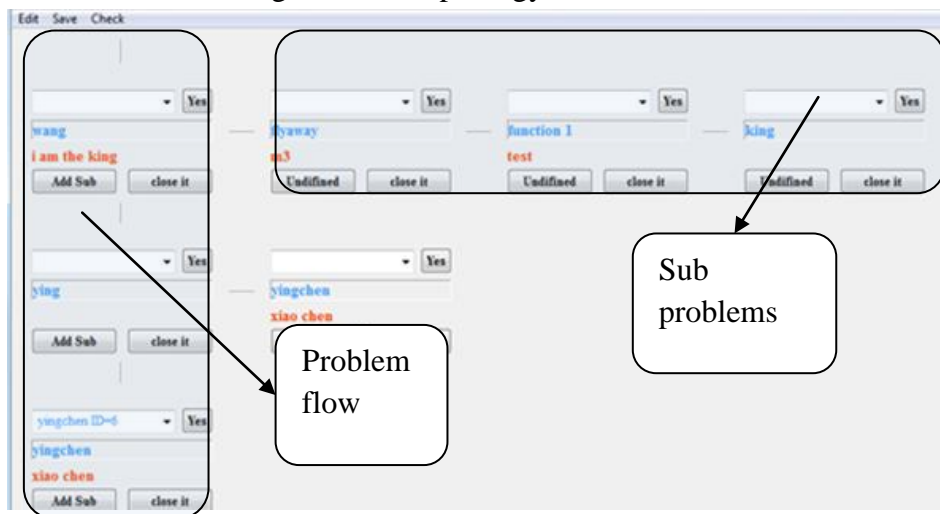


Figure 42. Morphology Tree in holistic ideation framework

Restructuring between morphology list and morphology tree is shown in Figure 43. The information of morphological list is stored in the database. During the constructing of morphology tree, the system provides the option of choosing sub-problems which are listed in morphology list. The existing features are automatically updated in the database of morphology tree.



Figure 43. Restructuring between morphology list and morphology tree

The query of restructuring is following:

1. Open the interface of restructuring—the system reads the databases and pulls out the name and description of the sub problems;

2. Select one sub problem and place it into the index of morphological tree—the system presents the name and description of the selected sub problem;

3. Repeat step 1 and 2 until the morphological tree is formed;

### 6.2.4 Provocative stimuli

For each solution, the user can document one sketch, multiple images and text at any time as shown in Figure 44. One sketch is allowed to be assigned for each solution and the user can use any sketch tools as long as pictures are formatted in file types, such as jpg, png, gif. Moreover, the framework provides the option to attach multiple images. All the images are attached on the canvas which can be added by clicking the button "Add image canvas". By clicking "sketch", the user can sketch by using the sketch tool implemented. All the images attached with solutions are copy and stored in the database, so when the user try to open previous projects, the images will still be presented. ImageNet is an online image database for the pictures. Figure 45 shows ImageNet via the holistic ideation framework. In ImageNet, each node of the hierarchy is depicted by hundreds and thousands of images. By this hierarchy, one advantage is that the pictures are well organized and users can view related pictures of each node. Currently they have an average of over five hundred images per node. Figure 46 is an example of searching pictures by ImageNet.
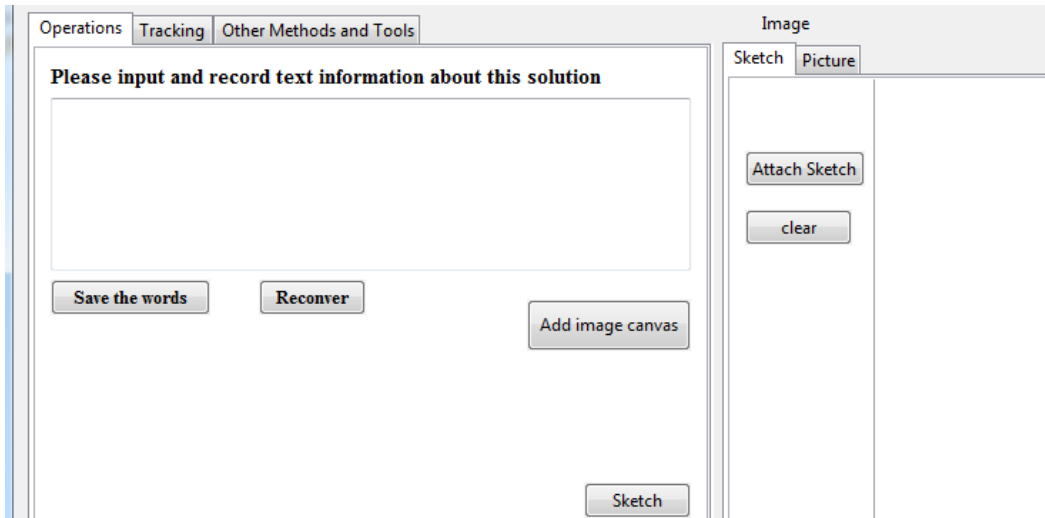
Figure 44. User Interface for documenting each solution



Figure 45. ImageNet in Holistic Ideation Framework



Figure 46. One example of ImageNet

As discussed in the previous chapter, the physical effect database and the working principle database are implemented for modeling the behavior of artifacts while the design repository contains artifacts. All of these support logical ideation. Intuitive and logical ideation methods are inter-related as shown in Figure 47. By performing some backend tracking among databases through keywords or mediums, the holistic ideation framework gives the user physical effect, working principle, or components information for certain stimuli, which depends on the information stored in the databases. For example, in Figure 47, the user used physical effect parameter "contact area" for provocative stimuli, the outcome is information about a physical effect "Wear", because "contact area" is one of the physical effect parameters of physical effect "Wear". The presented information includes name, medium, equations, parameters, description and related PE or WK. The user can choose the relation distance by moving the toolbar "Relation-Level". Outcome information that is far away from the original information can be obtained by moving the toolbar to the right.
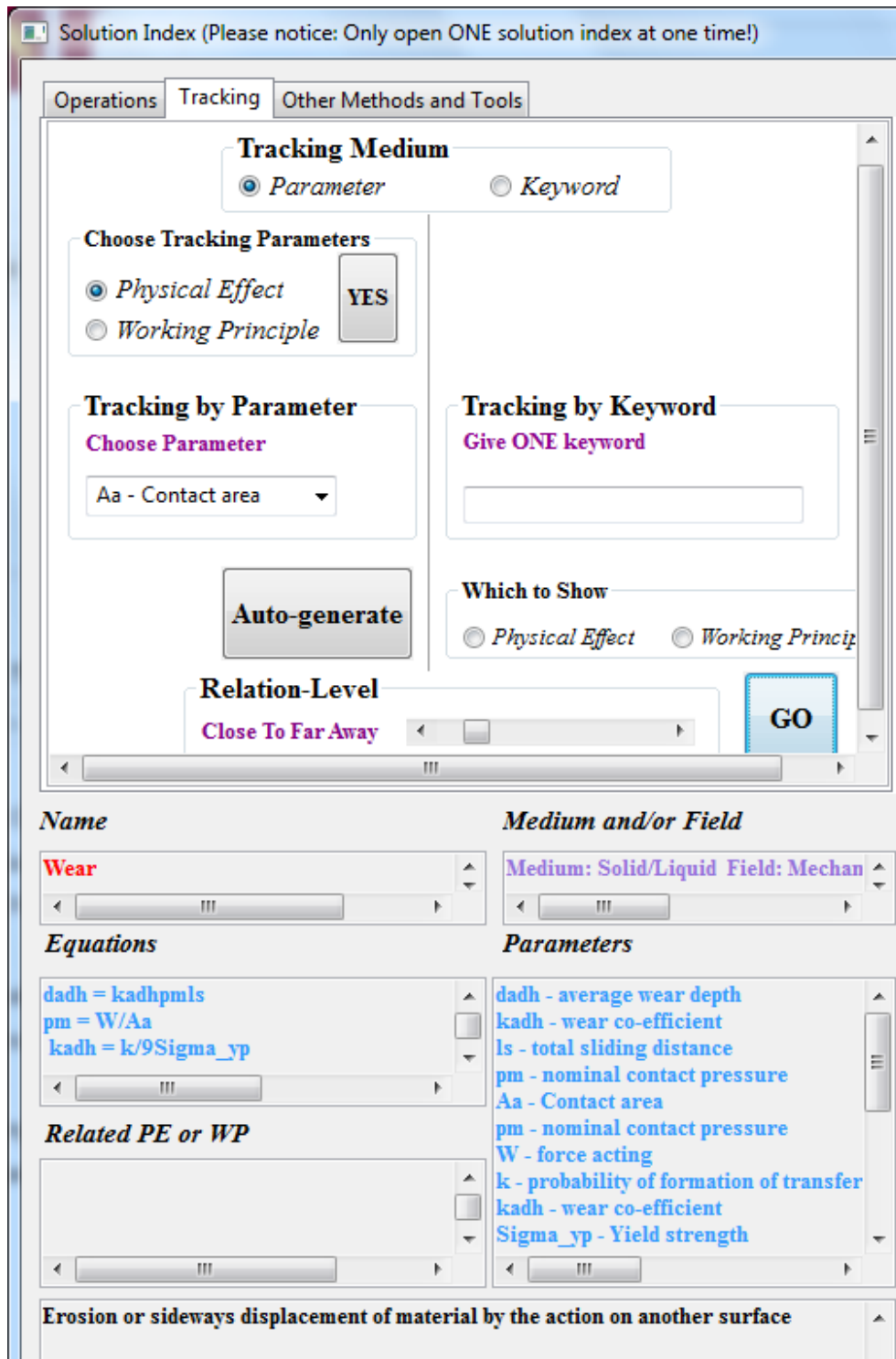
Figure 47. Cross relating between intuitive and logical methods

The query of auto-cross relating is following:

1. The systems reads the input information and checks whether it is a random cross relating (selected by the user);

2. If it is a random cross-relating, the system would present some random information and knowledge from the databases;

3. If it is not a random cross-relating: the system reads the text information (input by the user) of the sub solution and its sub problem, and then the system selects keywords randomly from the text information;

4. The systems reads the relationship level which specified by the user (level 1 to level 9);

5. According to the relationship level, the systems determines the entities and their identification (relationship 1-2 indicates functions, physical effects and working principles same, others different; relationship 3-6 indicates that functions different but physical effects or working principles same, relationship 7-9 indicates that functions, physical effects and working principle different);

6. The system takes keywords into the database and tracks to some information and knowledge.

7. Based on the relationship, the system selects the information and presents the information and knowledge to the user;

8. Repeat step 1 to 7 for auto-cross relating;

### 6.2.5 Analogical reasoning

By working with the physical effect and working principle databases, and the Design Repository, analogical reasoning is implemented in the holistic ideation tool. Figure 48 and Figure 49 show the analogical reasoning in physical domain. The keywords and selected parameters will be taken in into the physical effects and working principle databases. After the cross relating tracking described in section 5.5.4, the user interface shows the information from databases which may lead to analogical reasoning.



Figure 48. Information from physical effect and working principle

| Artifact Name | door motor | Artifact Photo |
|---|---|---|
| Sub Artifact Of | cd cover | |
| Quantity | 1 | |
| Description | motor that opens and closes cd drawer | |
| Artifact Color(s) | not specified | |
| Component Naming | electric motor | click on image for full size |

Figure 49. One example from design repository through tracking

In the holistic ideation tool, the bio-analogy tools DANE and AskNature are implemented. By using the sharing keywords (e.g. functions, subjects, objects, verbs), the cases in DANE and Asknature can be searched. For example, the user may be interested in some verbs (e.g. accelerate), these verbs may be from physicals effects, working principles, or any information during the design process. He/she can take the verbs to Asknature to search bio-cases for analogical reasoning in bio domain (case: "Wing structure allows rapid acceleration: dragonfly").

The query of analogical reasoning is following (the interface of analogical reasoning is the same UI with cross relating):

1. Instead of getting the keywords automatically, the user selects the inter medium of the cross relating. The medium can be physical effect parameters, working principles parameters or the input keywords by the user;

2. After the system gets the selected parameter (physical effect or working principle) or the input keyword, the medium is taken into the data base.

3. The systems reads the relationship level which specified by the user (level 1 to level 9);

4. According to the relationship level, the systems determines the entities and their identification (relationship 1-2 indicates functions, physical effects and working principles same, others different; relationship 3-6 indicates that functions different but physical effects or working principles same, relationship 7-9 indicates that functions, physical effects and working principle different);

5. The system takes keywords into the database and tracks to some information and knowledge.

6. Based on the relationship, the system selects the information and presents the information and knowledge to the user;

7. Repeat step 3 to step 6 for analogical reasoning in physical domain;

8.  The user can takes keywords of presented information to bio-databases for analogical reasoning in bio domain.

9. Repeat step 1 to step 8 for analogical reasoning in bio domain.
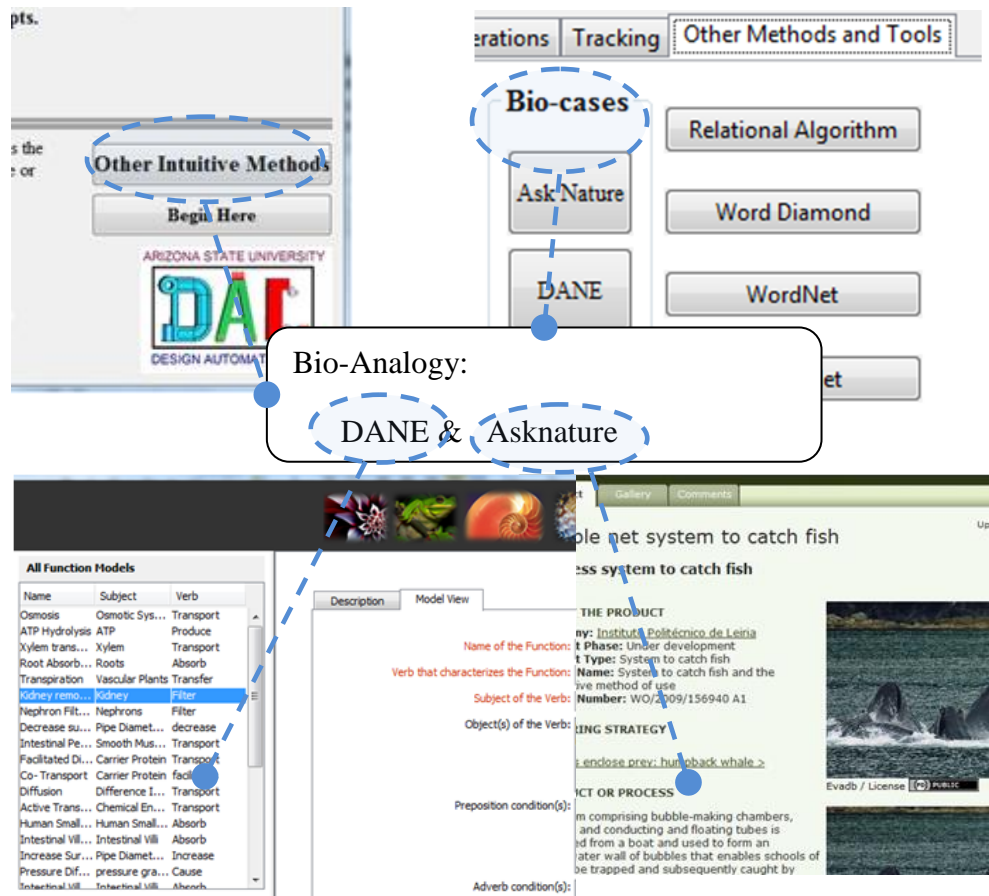
Figure 50. Bio-analogy in Holistic Ideation

### 6.2.6 Random & forced connection

Sub solutions can be combined to produce overall solutions by either the user picking one sub solution from each sub problem (forced connection) or let the system select at random. The random and forced connection user interface is shown in Figure 51 and Figure 52. The holistic ideation framework support both random combination solutions and deliberate combination solutions.
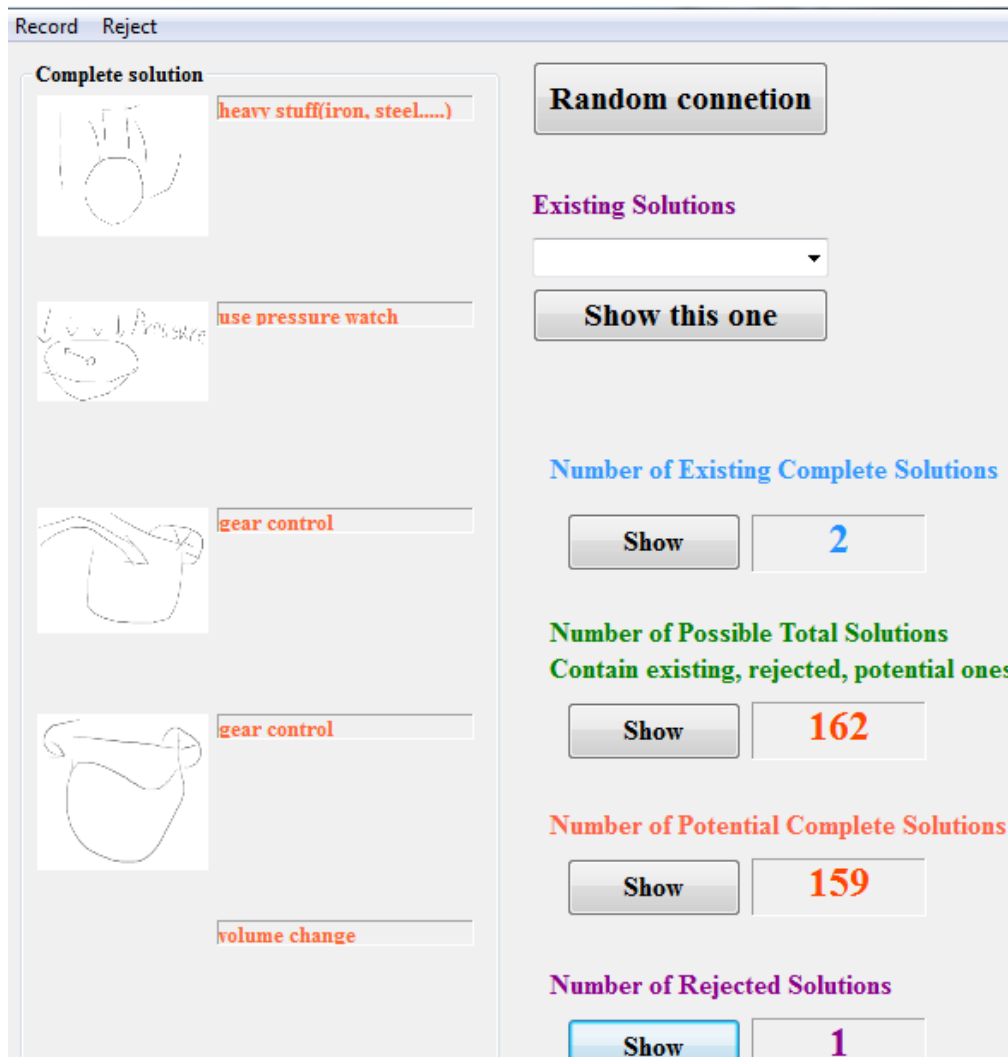
Figure 51. Random Connection User Interface

In Figure 51, the randomly generated complete solution is listed on the left. By clicking the button "Random connection", the system goes into the database and randomly selects sub-solutions from each sub problem. These selected sub solutions are listed in the order corresponding to the sub-problems. Moreover, the system can present statistics information on the right of the interface, including the number of existing complete solutions, the number of potential complete

solutions (difference value between recorded solutions and products of sub-solutions of each sub problem), and the number of rejected complete solutions. By clicking "recording" button, the user can record the complete solution, while "reject" button is used to record the rejected solutions.

The query of random connection is following:

1. The system reads the recorded sub solutions under the same sub problem from the database and randomly picks one of them;

2. The system presents the selected sub solution;

3. Repeat step 1 and 2 for all the sub problems;

4. The user chooses to record the generated complete solution or reject it—the system records the series of the solution and marks it in the database. If it is recorded, the solution is marked by a solution name inputted by user; if it is rejected, the solution is marked as "rejected".

5. Repeat step 1 to 4 for random connections.
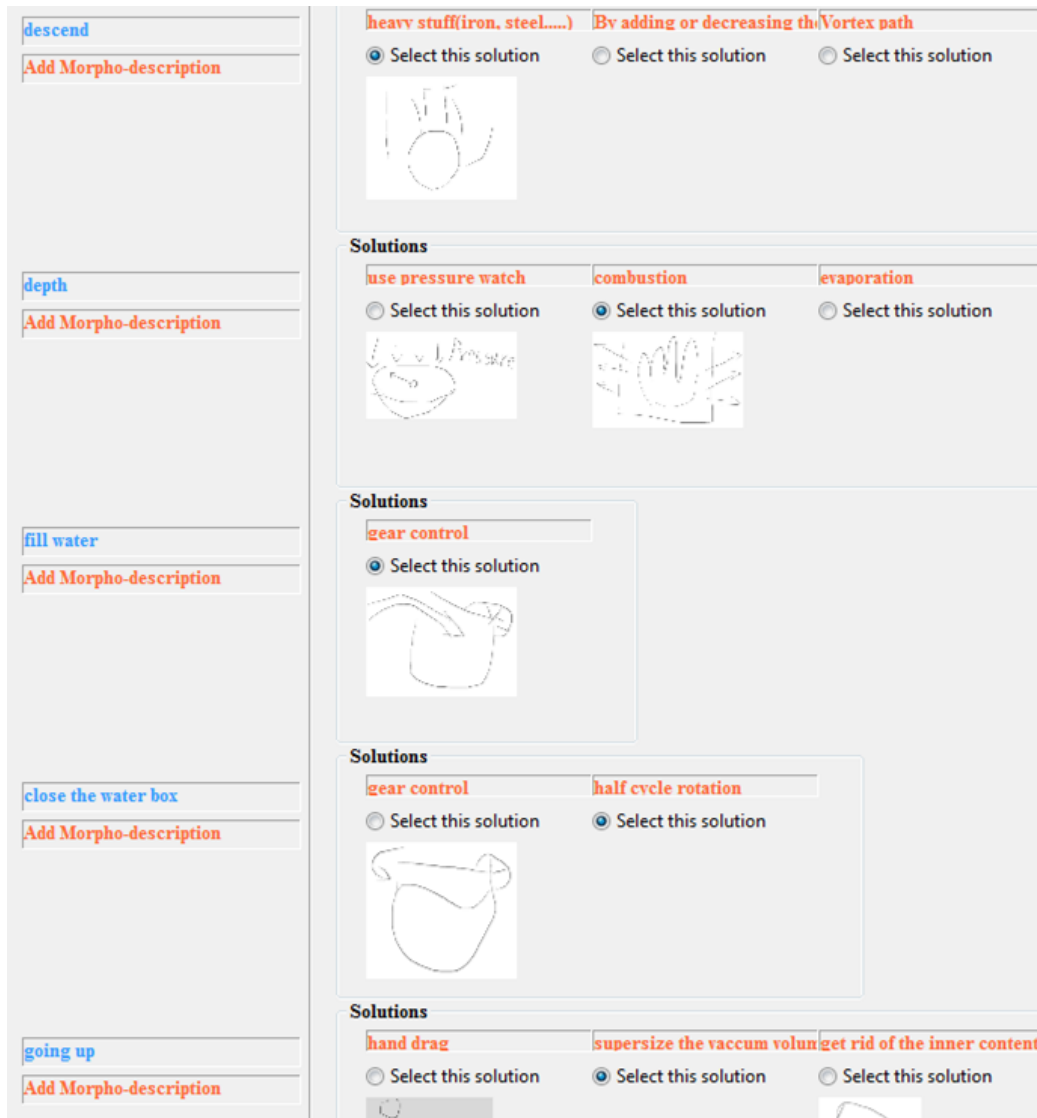
Figure 52. Deliberate Connection User Interface

The user can decide when to move to deliberate connection. In another words, when the user feel that there are enough sub solutions of sub-problems, he/she can begin to generate complete solutions deliberately. The user interface of deliberate connection just looks like the morphological chart interface—morphology list is on left side and the corresponding solutions are listed on the

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right side. The designer could select solutions from each row and then combine them into the final design.

In this chapter, the computer implementation of holistic ideation is presented, including: database schemas, problem decomposition, reframing, restructuring, provocative stimuli, analogical reasoning, random connection and deliberate connection. Figure 53 shows the distribution of ideation methods in preview and current holistic ideation tool. The implementation of logical methods was done in preview work and intuitive methods are implemented in current research.
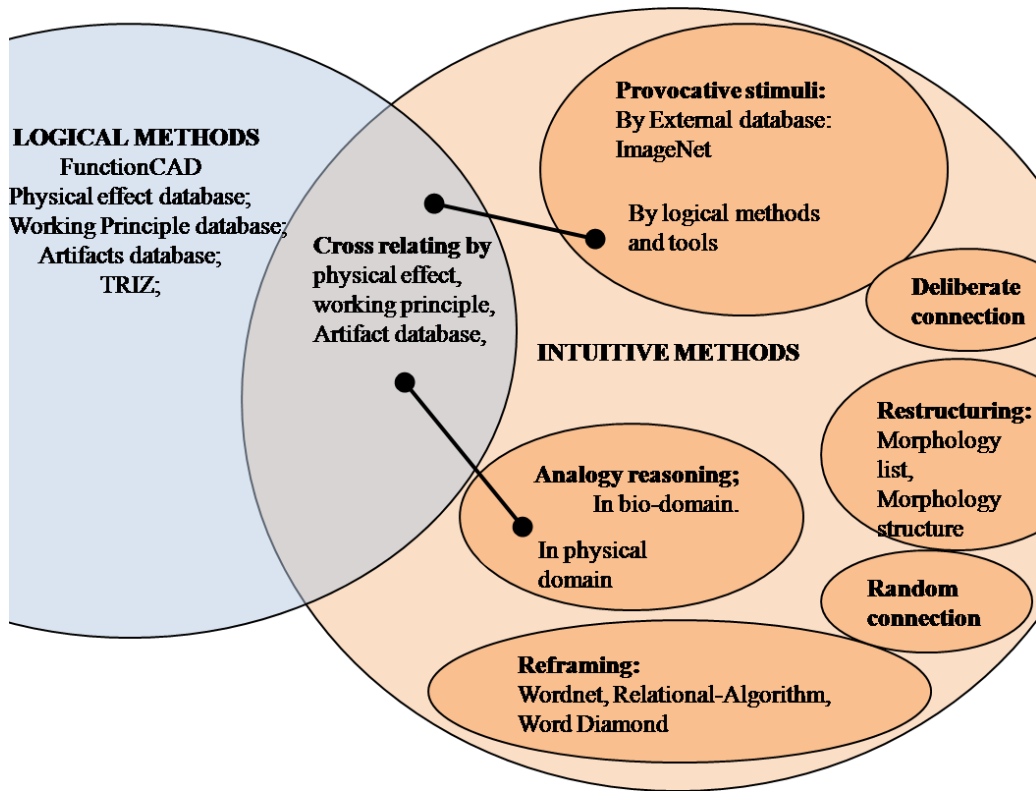


Figure 53. Implementation of ideation methods

# CHAPTER 7

# USER STUDIES

Holistic ideation is a method of combing different ideation methods (both logical and intuitive) to facilitate the user in overcoming ideation blocks. Based on the implementation framework and tools used, a certain ideation strategy might have a particular effect in idea generation. In order to gauge the effectiveness of the ideation methods used in the holistic ideation tool, user studies were conducted. The cross relating of intuitive and logical methods is an area which had not been explored before, and with the information we will obtain related to creativity and ideation, some initial observations can be made to holistic ideation tool and its effectiveness.

## 7.1 Case study

A cursory evaluation of the Testbed was done by graduate students in the Design Automation Lab. The participants had basic knowledge about conceptual design, different ideation strategies and ideation methods. The same design problem was given to all the designers, and the designers were required to solve the design problem with the help of different ideation strategies/methods provided by holistic ideation tool. No specific previous flow was specified for the sequence of using ideation methods.

Four designers were given the problem to design a mechanical device to be used from a rowboat to collect samples of water from freshwater lakes (e.g. Lake Tahoe) at known depths down to a maximum of 500 m. After release, the device

must not be attached to the boat and must descend to within ten meters of an easily adjustable predetermined depth. It must return to the surface with a 0.5 liter sample of water from that depth and then float on the surface until picked up. The device should be reliable, easy to use, reusable, and inexpensive. Two other designers were asked to design an adjustable television screen which could let the viewer see the television from different angles and positions. The designers were asked to design a television screen which could let the viewer continue watching television without stopping their current work.

After initial instructions, a 20 minutes tutorial was given to them to get familiar with the holistic ideation tool. The designers were allowed to ask questions about the UI and capabilities of the tool. There was no strict control of time for this ideation experiment. The designers were given 30 to 45 minutes to solve the design problem and they can stop at any time they want as long as they are satisfied with the solutions. After the design, there was a debrief session to find out the sequence of ideation methods/strategies used by designers and the designers were asked about the comfort level with the software, comments and suggestions which could improve the tool. In the following pages, different ideation strategies/paths used by the designers and some overall comments about the software will be discussed.

### 7.1.1 Water sampler case study

The first designer for the water sampling problem decided to begin with hand-written morphology list (shown in Figure 54) and then constructed the list

with holistic ideation tool (shown in Figure 55). In the morphology list, the type of the feature only included function. After finishing the list, the user went to WordNet (searching keyword "heavy") and Relational-Algorithm (generated new statement: "water go depth") for reframing, no new design direction or ideas came out. When the user was solving a feature and generating solutions, he used cross relating between intuitive methods and logical methods. The user first tried to use keywords "control" & "rotation" for information tracking but no new ideas were generated. Then he used physical effect parameter "pressure" and working principle parameter "vapor pressure" for the tracking. One new idea "use pressure watch to measure depth" was found, however this new idea was for another sub-function. When generating ideas for the last sub-function feature, the user went to bio-analogy (searching keyword "volume"). In AskNature, the user found an idea (bio-case "swimming efficiently: sharks" indicates solution "control the depth of diving by volume of air") for the previous sub-function. The user was then satisfied with his solutions and was finished using the tool.
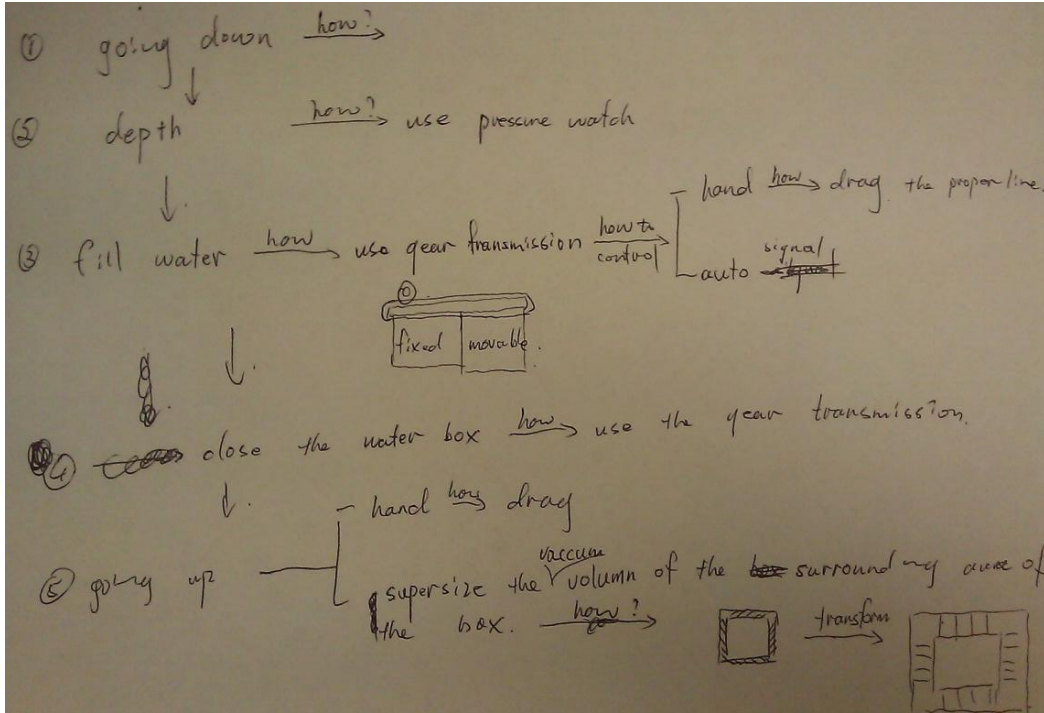
Figure 54. Problem decomposition of study one



Figure 55. Morphology list and solutions of study one

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The Graphical representation of sequence of steps used by designer one is shown in Figure 56.
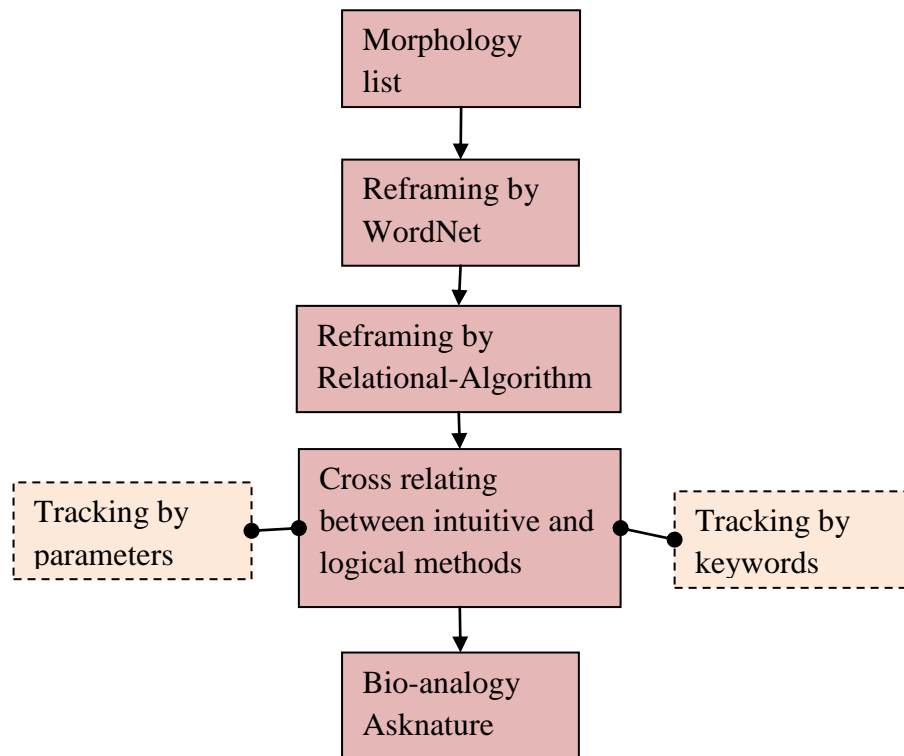


Figure 56. Graphical representation of sequence of ideation strategies of designer one

At the end of ideation process, a few questions were asked of the designer to know more about his comfort level with the software. And the designer was asked about suggestions which could improve the tool. The designer was satisfied with the solutions generated during the design. Some comments and suggestions are listed below

1. Reframing was not very useful after the morphology list was done. Because the overall idea has already been fixed.

2. Provocative stimuli of cross relating and Bio-analogy were useful for generating novel solutions. However, those generated ideas could be the solutions for any sub-problems in the design.

3. If there was a guided pre-analysis provide by the system before the problem decomposition, the design process would be faster.

The second designer of water sampling problem used a morphology tree as the starting point. Then he restructured the morphology list from the morphology tree. Relations between the sub-functions were defined to determine the function flow. The user went to WordNet for reframing (searching keyword "descend") but no new sub-problem came out. By using keywords for physical effect tracking (parameters "fluid velocity", "volumetric flow rate"), the user generated some solutions (e.g. "volume change to provide the buoyant force") and several extra functions (e.g. "close the water container") were added. By searching functions, the user went to the Design Repository to look at some existing components and found that two components ("piston", "brake") matched his ideas. After recording these ideas, the user went to bio-analogy (searching keyword "cylinder" & "water") and found out one idea ("Vortex path") for the first sub-function. Again, the user went to information tracking by working principle parameter ("force"), one solution ("half cycle rotation") was generated and added. Finally, the user went to random connection for complete solutions.

The sequence of major steps for designer two is shown in Figure 57.
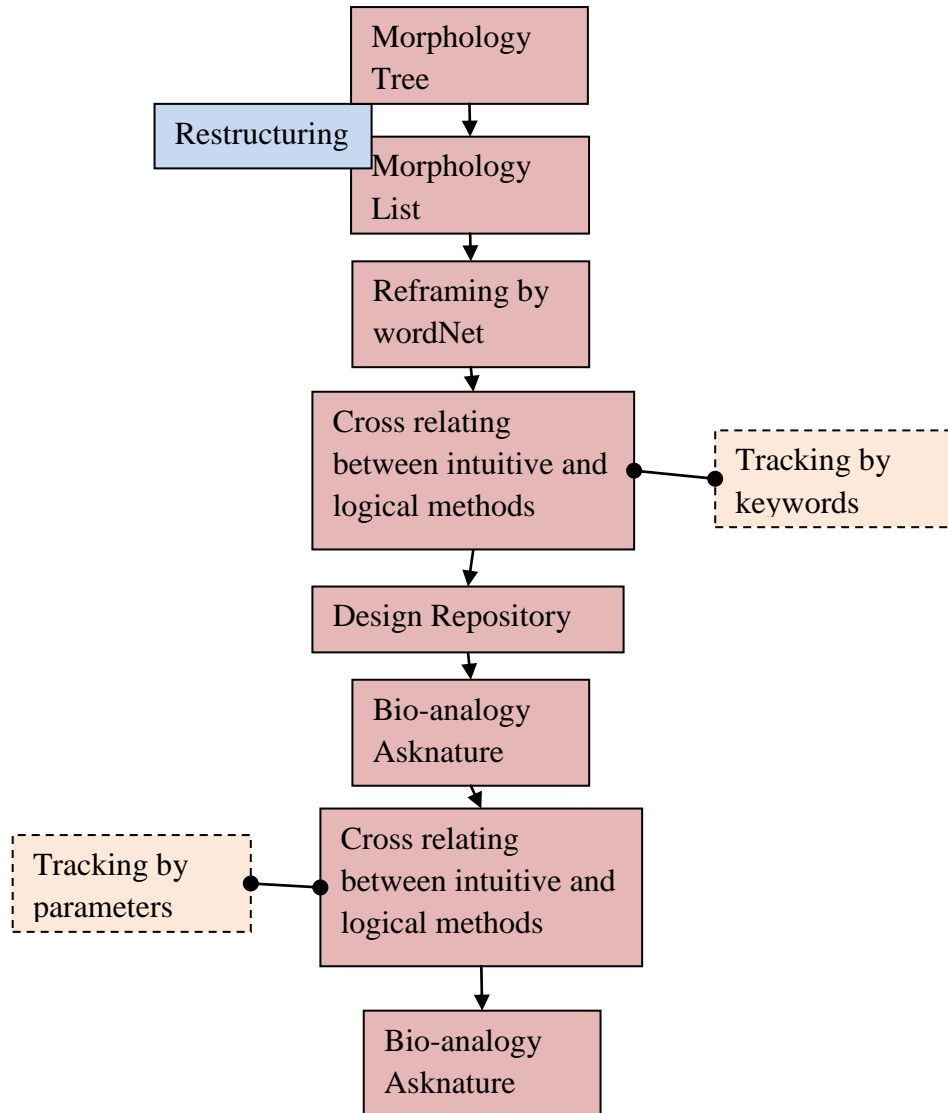
Figure 57. Graphical representation of sequence of ideation strategies of designer
two

In the debrief section, the designer was satisfied with the solutions generated
during the design. Some comments and suggestions were given:

1. Restructuring between morphology list and morphology tree make the
   design tasks much clearer;

2. The information tracking system should be divided into three aspects: function tracking shows function information, behavior tracking shows behavior information, and component tracking shows components information.

3. Information tracking is useful and it would be better if function information, behavior information and component information could be showed at the same time.

The third user of water sampling problem used a hand written morphology tree as the starting point. In the morphology tree, only functions were listed. Then he restructured the morphology tree into a morphology list. During this restructuring process, the user input several solutions for each sub-problem. The user went to WordNet for reframing (searching keyword "fill") but the sub-problems remain. By using physical effect parameter "pressure" and keyword "buoyancy" for physical effects tracking, the user generated some solutions (e.g. "combustion for power to go up", "evaporation for ascending"). By viewing some component cases in ImageNet (searching keyword "cylinder"), the user got the solution "needle cylinder". Then the user continued to search existing components pictures in ImageNet (e.g. searching keywords "vacuum", "tube", "air pump"). After generating and recording some ideas, the user went to bio-analogy (searching keyword "squid") and inspired by one bio-case "siphon directs underwater movement: octopus". Again, the user went to ImageNet and searched

the keyword "octopus" and "movement" for ideas generation. Finally, the user went to deliberate connection and run several times to generate the complete solutions.



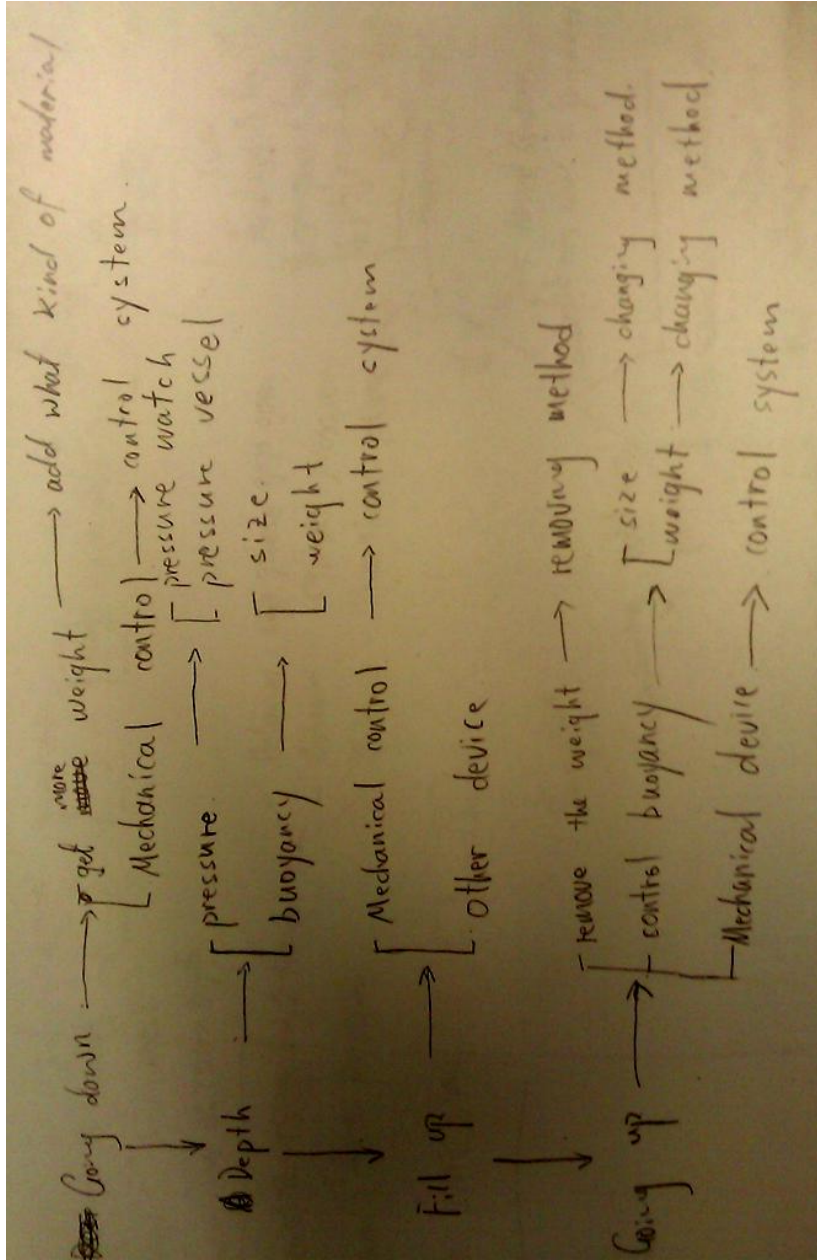Figure 58 . Morphology tree of study three

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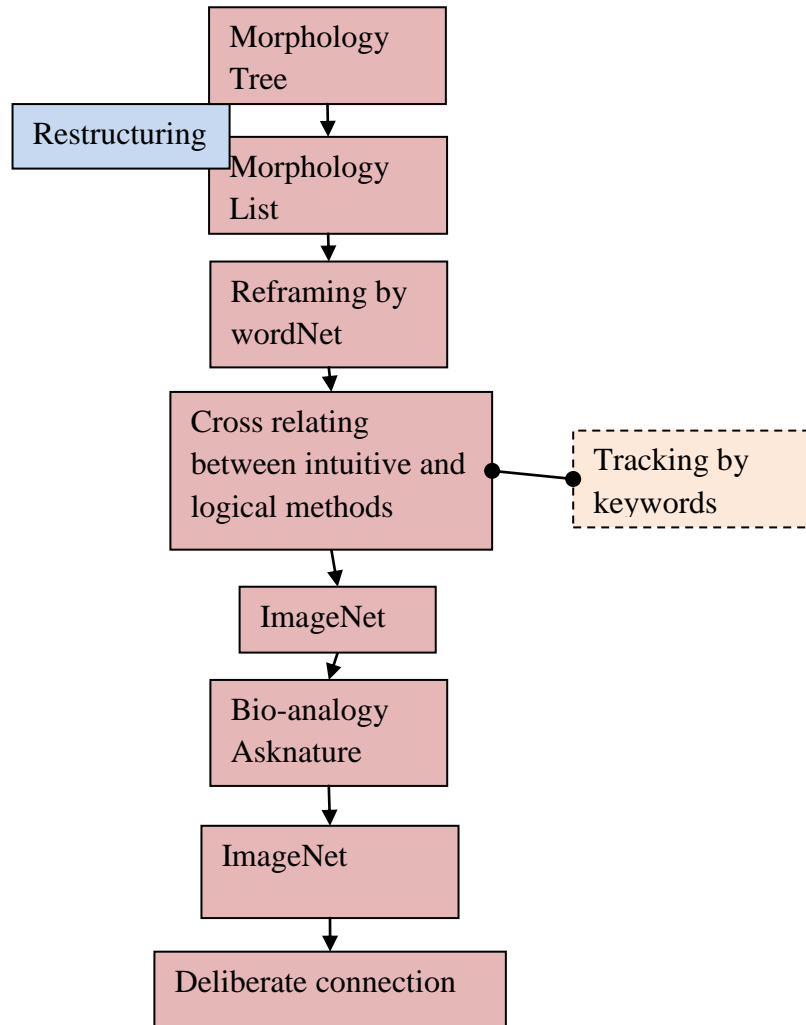The Graphical representation of major steps taken by designer three is shown in Figure 59.



Figure 59. Graphical representation of sequence of ideation strategies of study three

In the debrief section, the designer was satisfied with the solutions generated during the design. The comments and suggestions from designer three are as follow:

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1. Reframing is not useful after the overview of the design problem has already been structured by the designer;

2. Analogy is very useful when there are some pictures of some existing components;

3. High level provocative stimuli with animation would be better for users to generate solutions and ideas. For information of behavior level, animation is better in helping novelty than physical equations;

The fourth designer of water sampling problem decided to start with a morphology list with hand writing and then restructured this list into morphology tree. During the restructuring, the relationships between sub-problems were identified and some other requirements and properties were added. Then the morphology list was updated. In the morphology list, the type of the features included function, requirements and properties. During the restructuring, the user went to WordNet (searching keyword "buoyancy") for reframing and added one more requirements to the problem ("speed control"). When generating solutions, the user used cross relation by physical effect parameters "specific density", but didn't recognize new design direction. Then the user used working principle parameter "displacement" for tracking, the displayed information was "force adjustment by a simple mechanism", from this the user generated the solution of "using motors". When generating ideas for another sub-feature, the user went to bio-analogy (searching keyword "ascent"). In AskNature, one bio-case "Xylem

conduits transport water: plants" provided the provocative stimuli to the user to generate the idea "transporting water by syphonage". After several in the random connection, the user was satisfied with these complete solutions and stopped generating more alternatives.



Figure 60. Morphology list and solutions of study four

The Graphical representation of sequence of using different ideation strategies is showing in Figure 61.

Figure 61. Graphical representation of sequence of ideation strategies of study four

In the debrief section, a few questions were asked of the designer to know more about his comfort level with the software. The designer was satisfied with the software and the solutions. Some comments and suggestions are listed below

1. Restructuring can help designer to find out potential requirements and properties of the design problem;

2. In the provocative stimuli of cross relating of logical database, it will be better to present relative information automatically, such as list all the working principles which are related to certain parameters .

3.  Construct the morphological chart in 3-D, which means present the morphology tree in 2-D and list the solutions of each feature in the third dimension.

### 7.1.2 Adjustable TV case study

After reviewing the structure of CEMC, the first designer for adjustable TV screen problem decided to start with problem decomposition with hand writing. Instead of a morphology list, the user first created a morphology structure (shown in Figure 62) and restructured the problem structure into a morphology list. There were "OR" relations in the problem structure, which means certain features could be replaced by other features. In the morphology list, the types of the feature included functions, requirements and properties of the design. while converting of problem structure to a morphology list, the user found that some items in problem structure could be directly used as solutions. When the user was solving a feature and generating solutions, the user used cross relating with logical methods for provocative stimuli. The user first tried to use physical effect tracking; however, the user didn't find any related parameters to start the tracking. Next, he went to tracking through keyword 'linear" and working principle "power transmission by flexible objects" displayed. When generating ideas for another feature, the user went to bio-analogy. In AskNature, the user searched the database by keyword "chain", found some ideas; however, these ideas were identical to his original ideas and no value was added. After that, the user went to reframing by WordNet

(searching by "eye") and found some information matching his solutions. After generating sub-solutions, the user ran random connection several times.
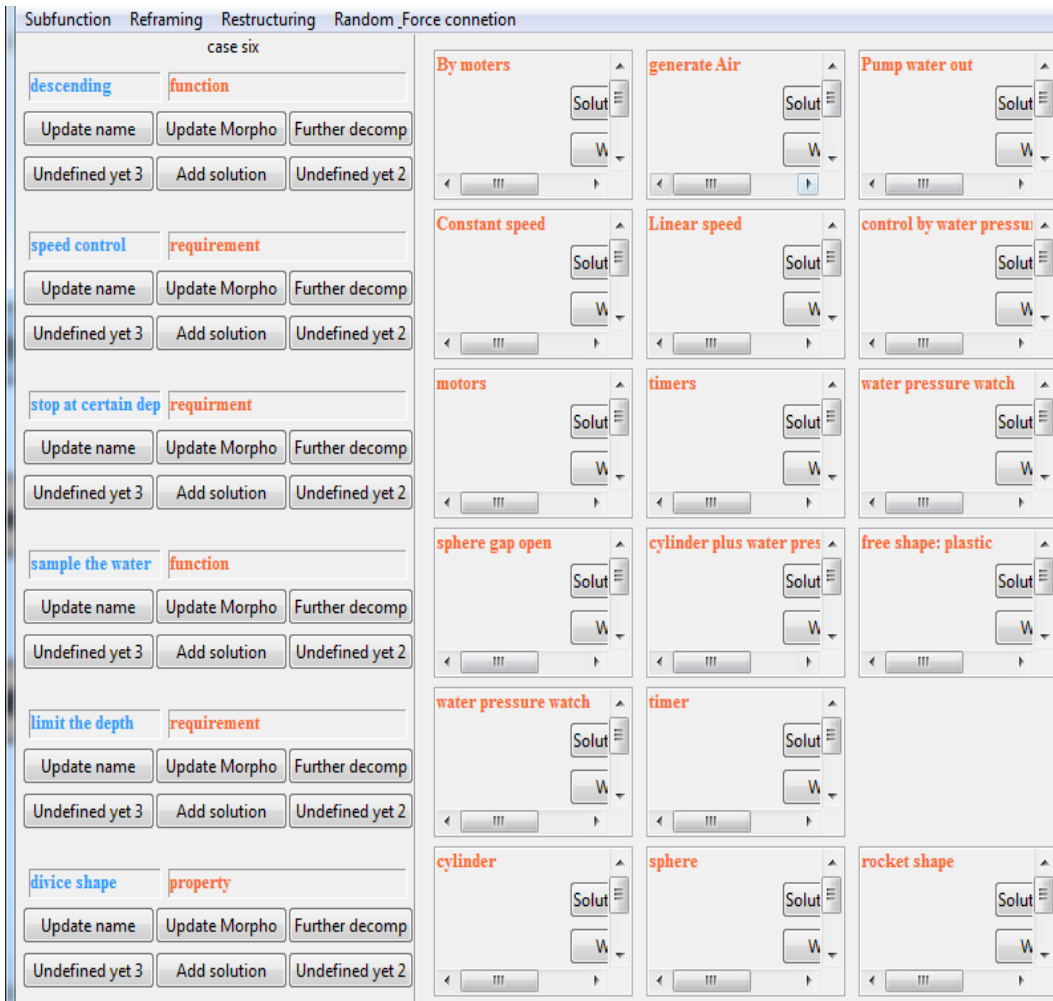


Figure 62. Problem decomposition of study five

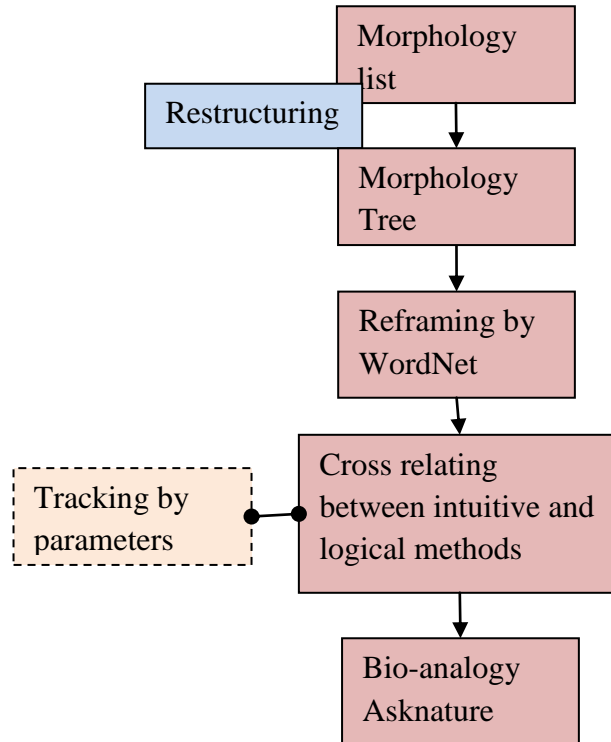The Graphical representation of sequence of using different ideation strategies is showing in Figure 63.

Figure 63. Graphical representation of sequence of ideation strategies of study five

In the debrief section after the design, the designer was satisfied with the solutions generated during the design. Some of his comments and suggestions are listed below

1. It would be better if the hierarchy of problem decomposition could be converted into morphology list automatically.

2. Tracking through keywords is easier than tracking by selecting physical effect parameters and working principle parameters,because tracking by keyword does not require design discipline and experience.

3. It is good to use tracking in different levels, for instance in holistic ideation, tracking among AskNature is specific while tracking in function-behavior-component is abstract.

4. In the reframing by WordNet, it is a constraint that the user is only allowed to use one word for exploring.

The second designer for adjustable TV screen problem used a morphology list as the starting point. Then he restructured the morphology list into a morphology structure. In the morphology list, most of the features are components and requirements, such as screen, orientation and location. When the user was solving a feature and generating solutions, the user went to WordNet for reframing (searching keyword "rotate") and generated several novel solutions (solutions "ball joint", "two 2-D rotational joint") according his own judgment. After that the user went to Word Diamond and Relational-Algorithm for reframing. By using Relational-Algorithm, the user generated problem statements ("implement location change", "implement orientation") which belonged to another feature. Then when generating ideas for another feature, the user tried to use physical effect parameters ("Angular acceleration") for information tracking. After seeing some information ("Centripetal Acceleration") which came from tracking in the holistic ideation database, the user generated and recorded some ideas. Then, the user went to bio-analogy. In AskNature, the subject searched through keyword "rotate" for some cases ("Concentrated solar plant", "sycamore,

ceiling fan"), which were reviewed but did not provide any additional benefit. After generating solutions (Figure 64 shows some of the solutions), the user went to random connection of holistic ideation tool and ran several times.
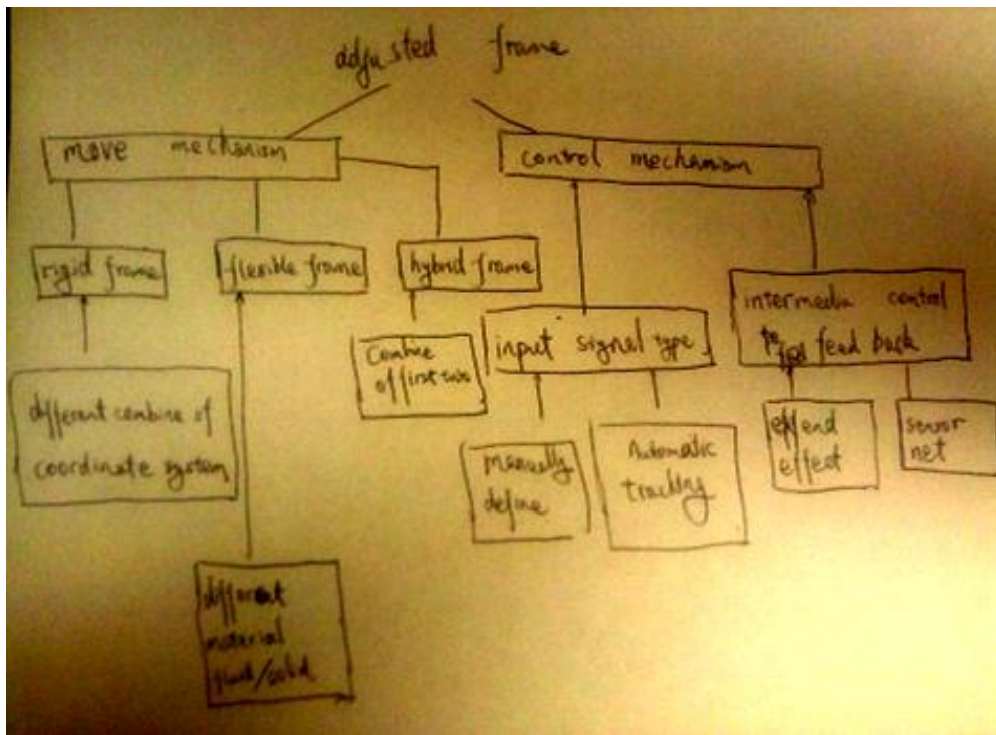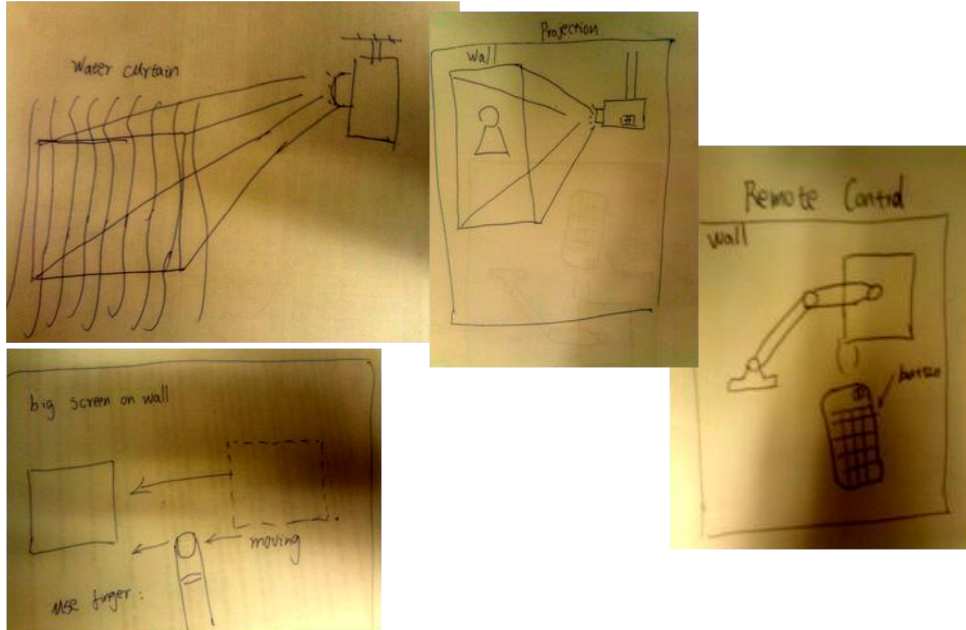


Figure 64. Some solutions of study six

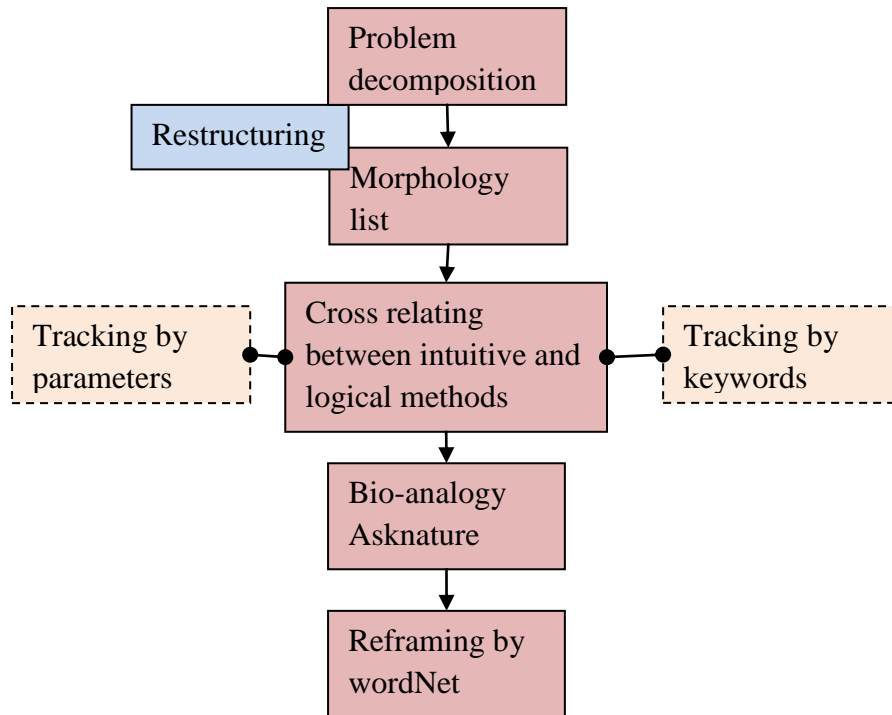The Graphical representation of sequence of using different ideation strategies is showing in Figure 65.
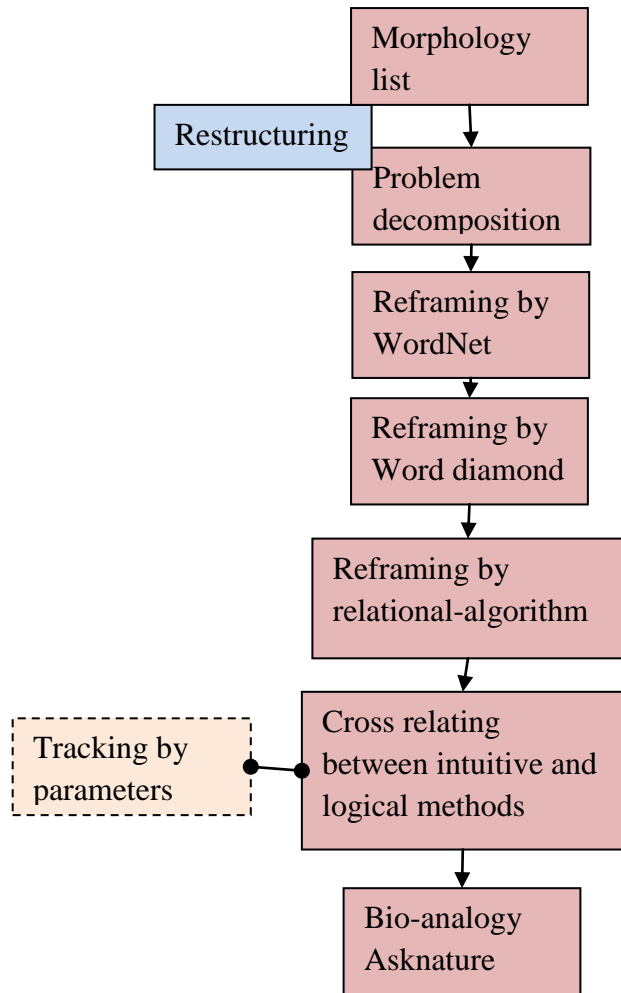
Figure 65. Graphical representation of sequence of ideation strategies of study six

The designer was satisfied with the solutions generated during the design. Some comments and suggestions were given during the final comments/suggestions session:

1. Reframing by Word Diamond was not helpful. Because all the words were known, some random combinations of the words are meaningless and some random combinations are even not feasible.

2. Reframing by WordNet is too logical, more divergent factors need to be included.

3. Reframing by Relation-Algorithm would stop user current train of thought, and force user to think other topics.

**7.2 Findings from case study**

Based all the above cases, the observation can be categorized into following aspects: ideations methods and cognitive states. For the ideation methods/strategies,

1. Problem decomposition is the starting point of the design.

2. Restructuring can make the design problem clear, including show the relation between two sub problems.

3. Different designers had different choices of problem decomposition-morphology list or morphology tree. Their outcomes were also different: people who use morphology list tend to use specific components to be the features in morphology list, while people who used morphology tree generated related properties (e.g. requirements) in the structure.

4. In the case study, reframing by Relational-Algorithm and Word Diamond didn't lead to many new design directions.

5. Provocative stimuli and analogical reasoning stimulated the designers for generating new solutions and these new solutions may belong to any of the sub problems.

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

1. Designer who does not know logical databases well tend to skip the logical ideation method, instead, he prefers to use keywords.

2. When using intuitive ideation methods, people tend to seek information which is not close to the design field.

3. People tend to use the tools which are flexible and dynamic.

4. The users tend to stop seeking for more alternatives when satisfied solutions were generated.

Based on these observations, I suggest following improvements and changes:

1. A guided pre-analysis can be implemented. The system could try to provide some background knowledge related to the design problem.

2. For the cross related tracking, three aspects (function, behavior and component) can be shown together. Moreover, detail information and knowledge should be presented for the information of physical effect and working principle, such as physical effect parameters.

3. Animation can be added as alternative form of provocative stimuli.

4. Cascading Evolutional Morphological Charts should be extended into 3-D. Morphological tree can be in 2-D and sub-solutions for each sub problem are in the third dimension.

# CHAPTER 8

## CONCLUSION AND FUTURE WORK

The main objective of this thesis was to investigate the technical issues involved in developing a holistic approach for conceptual design. Based on previous research, additional intuitive ideation strategies and methods were investigated and added, including reframing, analogy, random & force connection, and restructuring. Currently, the available tools implemented in holistic ideation are following:1.Function CAD application; 2. Repository entry application; 3.Ask-nature; 4.Morphological Charts; 5.Physical Effect; 6.Working Principle; 7.Wordnet; 8.Imagenet; 9.Conjunction database; 10.Verb database; 11.BioTRIZ; 12.DANE (Design by Analogy to Nature Engine); 13.TRIZ. A framework was found and modified for integrating those methods. In order to establish connection between all strategies (both intuitive and logical), traversal between intuitive and logical methods was defined. Another important contribution of this research is the importing of flexibility. At any point, user could use any combination of ideation methods without losing data. Moreover, the starting point is not limited to functions any more. Features, requirements, material and even components could be the starting point of CEMC. Also, with the use of this framework, there is a vast scope for future work.

### 8.1 Web-based holistic ideation

A radical paradigm shift is needed to collect massive amounts of data from diverse set of users over an extended period of time to truly get into deeper issues and solution strategies employed by real designers instead of timed experiments on exercise given to undergraduate students. We propose to establish a web enabled Holistic Ideation Testbed online and to automatically collect used data in a structured way suitable for data mining later.

### 8.2 Experiments for Ideation paths

Our "hidden" agenda for this service is to capture ideation mechanisms and paths followed by different users. Ideation paths could be understood as the order and combination of ideation methods or ideation strategies. Studying ideation paths in conceptual design has not been previously explored and researched in a formal manner. Once a web-based Holistic Ideation framework is implemented it will be possible to get a large number of users to test it. Several experiments can be designed to find and summarize the ideation paths.

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