Designing Product Forms Inspired by Nature – A Design Science Approach

A thesis submitted in partial fulfilment of the requirements of the degree of

Doctor of Philosophy

in

Design

By

Shiv Kumar Verma

Under supervision of

Prof. Ravi Mokashi Punekar

Department of Design

Indian Institute of Technology Guwahati

India

September 2020

Declaration

It is certified that the work contained in this thesis entitled "Designing Product Forms Inspired by Nature – A Design Science Approach" has been carried out by me, a student in the Department of Design, Indian Institute of Technology Guwahati under the guidance of Prof. Ravi Mokashi Punekar for the award of Doctor of Philosophy and that this work has not been submitted elsewhere for a degree.

Shiv Kumar Verma
Department of Design
Indian Institute of Technology Guwahati
Assam, India 781039

Date: 28-09-20

Certificate

The research work presented in this thesis entitled "Designing Product Forms Inspired by Nature – A Design Science Approach" has been carried out under my supervision and is a bonafide work of Mr. Shiv Kumar Verma. This work submitted for the degree of Doctor of Philosophy is original and has not been submitted for any other degree or diploma to this institute or to any other institute or university. He has also fulfilled all the requirements including mandatory course work as per the rules and regulations for the award of the degree of Doctor of Philosophy of Indian Institute of Technology Guwahati.

Ravi Mokashi Punekar
Professor
Department of Design
Indian Institute of Technology Guwahati
Assam, India 781039

This thesis is dedicated to my parents Mrs. Nirmala Verma & Mr. Chandra Prakash Verma and my sisters Dr. Kavita Verma and Dr. Ritu Verma.

Acknowledgements

I wish to express sincere appreciation to Professor Ravi Mokashi Punekar for his guidance, insight, and practical advice in the preparation of this thesis. His positive attitude, calm nature, and in-depth knowledge makes him a wonderful supervisor and mentor to work with.

I would like to thank my Doctoral Committee members, Associate Professor. Sougata Karmakar (Chairman), Associate Professor. Pratul Chandra Kalita (Member), Assistant Professor. Debayan Dhar (Member) and Professor P.A.S Krishna (Member) for their constructive and critical comments during my research.

I must thank Dr. Avinash Shende, Associate Professor, IDC School of Design, IIT Bombay for his participation as a product expert. I would also like to thank M.Des students: Niharika, Kritika, Kshipra, Rijas, Faris, Darpan, Phaneendra, Abijit, Shyam, Sarath, Ajinkya and Tarun for their participation in my study.

I thank all the faculty members and fellow research scholars at the Department of Design, IIT Guwahati for their support during my entire Ph.D.

A special thanks to my friends Susmita, Pranav, Sachin, Angelus, Ravi, Tony, Raman, Ashish, Jyotirmoy, and Saurabh for their support and encouragement. I thank Nilakshi, Venkatesh, Sai, Bighna, Chiripriya, Indresh, Aditi, Pranjal, Priya Ma'am, Anushmita, Umme for all the interaction and discussions on various topics during my Ph.D.

I express my deep appreciation to my family for their indispensable support during the period of my Ph.D.

Abstract

The author uses the phrase "we" to present arguments in the thesis because the analysis and synthesis of the investigation was executed jointly by the author and his guide.

Taking inspiration from nature is seen to be a very innovative, creative, and novel approach to design products. Human-beings are seen to be practicing this since the stone age — Cavemen observed the teeth of carnivores to build weapons; The Chinese invented silk nearly 3000 years ago; Leonardo da Vinci designed the flying machine inspired from the wings of bats in 1488; Wright brothers made the first successful airplane inspired by large birds in 1903; while George de Mestral, drawing inspiration from burrs, invented the Velcro in 1948.

People from different professions have developed various methods and tools for drawing inspiration from nature in their line of work and practice. To begin with, we examined the literature on methods and processes followed by two professional groups for our primary research: Researchers/Scientists/Engineers who have developed systematic methods in studying principles and phenomenon in nature; and Designers/Architects/Painters/Artists who seem to prefer and follow more intuitive methods. This approach of designers is often criticized by scientists and engineers for being 'non-scientific'. Motivated by such criticisms, the current research explores the possibility of examining a systematic design approach in the process of generating nature-inspired product forms that will be useful for designers in their understanding and professional practice.

The research work covered in this thesis is presented under the following chapter heads:

Chapter 1: Introduction – A review on Nature Inspired Design

This chapter undertakes a literature review on terms, methods, and tools related to nature inspired design as broadly developed by the following two professional groups viz. Researchers/Scientists/Engineers and Designers/Architects/Painters/Artists respectively. It also discusses the limitation of these methods and a few criticisms on the latter's approach to design nature-inspired product forms.

Chapter 2: Research Design

In this chapter we present the research questions formulated based on the literature review and outline the aim of our research by examining design science, and outline the research framework adopted following Nigel Cross taxonomy. We outline four experimental studies for this research.

Chapter 3: Experimental Studies in Processes, Products, and People

This chapter elaborates in detail each of the four studies of our research framework following Nigel Cross taxonomy. These include:

- Study 1 – Study of Processes and Methods.
    - The study is a comparative study of ten methods selected after conducting a systematic literature review by exploring fifteen design journals, six design conference proceedings and various other resources like books, websites, and blogs.
- Study 2 – Study of Products.
    - The study is a three-dimensional visual analysis of thirty nature inspired product forms conducted to identify perceptual similarities between product form and natural inspirational form.
- Study (3a) on People – Study on approaches followed by professional designers.
    - The study attempts to understand the design approach of five internationally acclaimed industrial designers: Owen Jones, Christopher Dresser, Arthur Heygate Mackmurdo, Luigi Colani, and Ross Lovegrove.
- Study (3b) on People – Study on approaches followed by design students.
    - The experiment was conducted to understand the design thinking process adopted by 12 master's design students (9 male+3 female) during an exercise of designing nature-inspired product form.

The findings and results of each of the four studies are summarised at the end of each study. It may be noted that the outcome of each study contributes and is drawn into the consequent study undertaken, to draw cumulative inferences and insight that impinge upon our understanding of consideration and factors that contribute to an understanding of the design thinking process underlying nature inspired product form generation processes. Such an approach gives us multiple perspectives and, in the process, enriching a holistic understanding drawn from an understanding of processes involved; their reflection in the different product designed; and design thinking processes followed by people engaged in the creation and generation of such nature inspired product forms.

Chapter 4: Discussions

In this chapter, we consolidate our findings obtained from the above four studies into a framework. Each dimension of the framework and its influence on the form generation process is discussed in detail. The chapter also proposes and outlines a generative tool developed based on the proposed framework that can help systematize the form generation process.

Chapter 5: Reflections on the Research Outcome

In this chapter, taking an overall view of our research we reflect upon our insights gained from our study and discuss our understanding of two critical observations on our research and its outcomes:

- The hidden science/s behind the nature-inspired form generation process – This section compares the findings from the study (3a) with the four stages of Goethean phenomenological method and discusses similarities between them. Based on these findings, it argues that there is perhaps an underlying science behind the nature-inspired form generation process.
- Design and Science relationships that exist in our research – This section draws upon various design and science co-relations that exist in our research. Based on the definition of scientific design, design science, and science of design defined by Nigel Cross, we argue how the three can practically co-exist in design research of this nature.

Chapter 6: Conclusions

In conclusion, this chapter summarises the six key contributions of the research that add up and contribute to new knowledge and insights to the design research domain of nature inspired design. It also discusses some of the limitations of the study and outlines future scope that can be explored in subsequent research work.

Table of Content

Contents

List of Figures

List of Tables

Glossary of Terminology

Dominant form – It is the largest form in a three-dimensional composition and has strongest character. Due to its structural importance, this form holds an interesting position in the composition and influence other parts (Koler, 1994).

Form generation/Form-making/Form giving – A special class of design problems and an intellectual exercise that involves a mix of rigorous analysis and creative problem solving. It also explores the synergic partnership between form innovations and conscious expression of meaning and is another perspective in product semantic (Athavankar, 2009).

Hierarchy of order – In a composition or asymmetrical organization of three-dimensional forms there exist a hierarchy among the sub-forms. This hierarchy is decided by observing visual qualities based on three features: Dominant form, Subdominant form, and Subordinate form (Koler, 1994).

Subdominant form – It is the smaller form compared to the dominant form in a three-dimensional composition and has strong character. This form also has a structural importance and holds an interesting position in the composition. It is influenced by dominant form (Koler, 1994).

Subordinate form – It is the smallest form in the three-dimensional composition and has a character which is complementary to the dominant and subdominant form. It is influenced by both dominant and subdominant form (Koler, 1994).

Three-dimensional visual analysis – Is a process of 'thinking with eyes' to translate an inner vision into concrete experiences. It is a framework developed by Prof. Cheryl Akner Koler that shows how form may be created, influenced, and perceived in a structured manner (Koler, 1994).

Chapter 1

Introduction – A review on Nature Inspired Design

1.1 Introduction

Studying nature, its various manifestations in terms of principles, phenomenon, and occurrences has been a source of wonder and fascination for mankind since time immemorial. It has drawn the attention of various professionals including artists, scientists, social scientists, and designers in equal measure. Taking inspiration from nature continues to be a very innovative, creative, and novel approach to design products. Human beings are seen to be practicing it since the Stone Age. One can cite a number of innovations inspired by nature—caveman made weapons by observing the teeth of carnivores and the Chinese invented artificial silk 3000 years ago. In 1488 Leonardo da Vinci designed a flying machine inspired from the wings of bats. Wright brothers in 1903, made the first successful airplane inspired by large birds, and Velcro invented by George de Mestral in 1948 was inspired by the burrs.

Various perspectives, approaches, and methods have evolved over time in studying nature among these professional communities. Two broad approaches are witnessed. Systematic design methods follow the scientific approach which is more function oriented. It attempts to understand the principle behind occurrence in a natural phenomenon. On the other hand, designers also seem to follow a more intuitive approach in the conceptualization of the product form when dealing with the creation of products that involve both function and aesthetics. Those designers' who focus on the creation and generation of product form, based on intuition, are often criticized by scientists and engineers for being 'non-scientific' in their approach since they argue that the process is not verifiable.

In this chapter, we review some of the important published literature on systematic design methods undertaken by researchers and the methods followed by industrial designers for nature-inspired design. This closer and in-depth analysis will help to understand the creative task of form generation. Such a review will help to understand the developments in the processes in nature-inspired form generation and to see if they inherently confirm to a verifiable rigor following a design science approach that is made explicit. If they can be, then how can one identify the different visual attributes that constitute such transformations that are reflected in the product form to achieve aesthetically acceptable nature-inspired forms.

In the following sections terms, methods, and approaches adopted by professional groups such as scientists, engineers, and designers are discussed. This will be followed by a discussion of their limitations, criticisms of designers' approach, and the few studies that not only defend such criticism but also provide a new vision to work in the less explored areas of form and emotion of nature-inspired products.

1.2 Literature review

The literature review was conducted in two stages. The first stage review was done to get an overview of nature-inspired design. 'Nature-inspired design' and 'nature-inspired design process' were two keywords used during the search for the articles on ScienceDirect search engine and Google Scholar search engine. The second stage review was more focused on nature, design, and product forms. Fifteen design journals, six design conference proceedings (Table 1.1), and various other resources like books, websites, and blogs were explored with keywords like 'nature-inspired product forms', 'nature and product semantics' and 'nature-inspired form generation process'.

Table 1.1 List of journals and conference proceedings explored during the literature review.

Journals	Conference proceedings
Design Studies	Conference on Design and Semantics of Form and Movement
International Journal of Design	
Design Issues	Design & Nature , International Conference on Comparing Design in Nature with Science and Engineering
The Design Journal	
International Journal of Design and Nature & Ecodynamics	
International Journal of Design Creativity and Innovation	Design Research Society International Conference
Journal of Design Research	
Design Science , An International Journal	International Conference on Research into Design
International Journal of Design Sciences and Technology	
International Journal of Technology and Design Education	International Conference on Design Creativity
Journal of Learning Design	
International Journal of Art and Design Education	International Association of Societies of Design Research
Online Journal of Art and Design	
Art and Design Review	
Journal of Design History	

We summarize the key findings from our literature review below.

1.2.1 On developments in nature-inspired design and their associated terminologies

The study of nature-inspired innovation has led to the emergence of new definition of terms among various professional groups over time. In 1960, the term 'Bionic' was coined by Jack E. Steele as the science of constructing systems with some functions copied from nature (Vincent et al., 2006) (Gleich et al., 2010). Today Bionics has been applied in replicating real organs in the design of medical prostheses. In 1969 Otto Schmitt introduced the term 'Biomimetic' as the study of biological mechanisms, structures, and materials to produce products artificially (Vincent et al., 2006) (Gleich et al., 2010). In 1997 Janine Benyus in her book 'Biomimicry: Innovation inspired by nature' popularized the term 'Biomimicry' as "*new science that studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems*" (Benyus, 1997). While, "*Biologically inspired design is the use of designs found in nature for analogy and inspiration in designing technological systems*" (Goel et al., 2013). Even in art, the term 'Biomorphism' refers to an art movement having its roots associated with Surrealism and Art Nouveau. The word 'biomorphic' is commonly used for abstract, free form and organic shapes used in arts and design (Wood, 2007). Painters, poets and musicians seem to be inspired from nature for their art. Scientist, engineers and industrial designers too, take their inspiration from nature. Luigi Colani is famous for his 'biodynamic forms' and Ross Lovegrove is known for his 'organic design'. Both seem to draw inspiration for design from nature. Terms may be different, but broadly they have a common focus of being 'Inspired by Nature'.

From these developments, one can see the keen engagements by different professional communities in contributing to the study of nature from different perspectives and the nuanced terms, definitions and processes that have emerged in their development/s. Two broad approaches are seen viz. more formal and systematic methods preferred by the scientific community who have developed their own set of tools for study and the other being the 'designer/s' method that is more intuitive in nature engaged for the purpose of creation of novel man-made forms.

1.2.2 Systematic methods and tools for nature-inspired design

Researchers have developed a few systematic methods for the process of extracting principles in nature and converting them into tangible products. These systematic methods outline the different stages that need to be followed to develop a product. Systematic methods follow two broad approaches in nature-inspired design (Table 1.2).

Table 1.2 Systematic methods for nature-inspired design

First approach	Second approach
Top-down process (Speck & Speck, 2008)	Bottom-up process (Speck & Speck, 2008)
Problem-driven biologically inspired design process (Helms et al., 2009)	Solution-driven biologically inspired design process (Helms et al., 2009)
Biomimetic by analogy (Gebeshuber & Drack, 2008)	Biomimetic by induction (Gebeshuber & Drack, 2008)
Challenge to biology (Baumeister, 2011)	Biology to design (Baumeister, 2011)

In the first approach, the researchers' start from a problem statement and tend to search for the relevant biological analogy to get a solution. The *Top-down process* – is specifically developed for biomimetic innovations and improvements in the existing technical product. In the first step of the process, the technical problems are clearly defined with their boundary conditions. In the second stage, biologists search for biological analogies to solve those problems. Appropriate principles are identified in the third stage and these principles are detached from the biological model and investigated experimentally in the fourth stage. In the final stage, the concept is prototyped and checked for final feasibility (Figure 1.1).

While in the *Problem-driven biologically inspired design process* – the process starts with concurrently identifying a problem and defining that problem as a function in the first stage itself. In the second stage, the designer has to 'biologize' the problem by reframing the problem in biological terms. Then biological solution search is carried out using the following four strategies/techniques viz. change constraint; champion adapters; variation within a solution family; and multi-functionality. In the next step, after understanding the in-depth interaction of various components of the complex system using functional decomposition studied in step 1, a biological solution is defined. Following this stage, the important principles are extracted after removing structural and environmental constraints. The last and final step is principle application where the principle is translated from one domain to another (Figure 1.2).

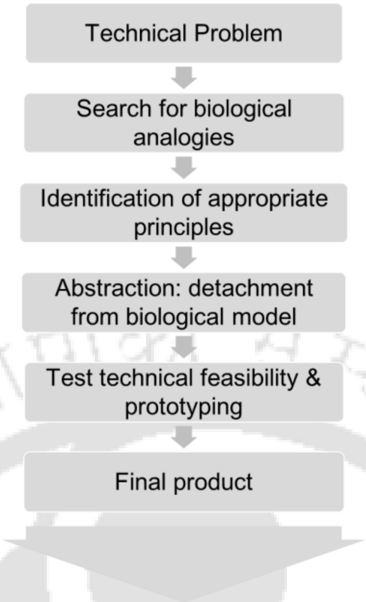


Figure 1.1 Stages of 'top-down process'

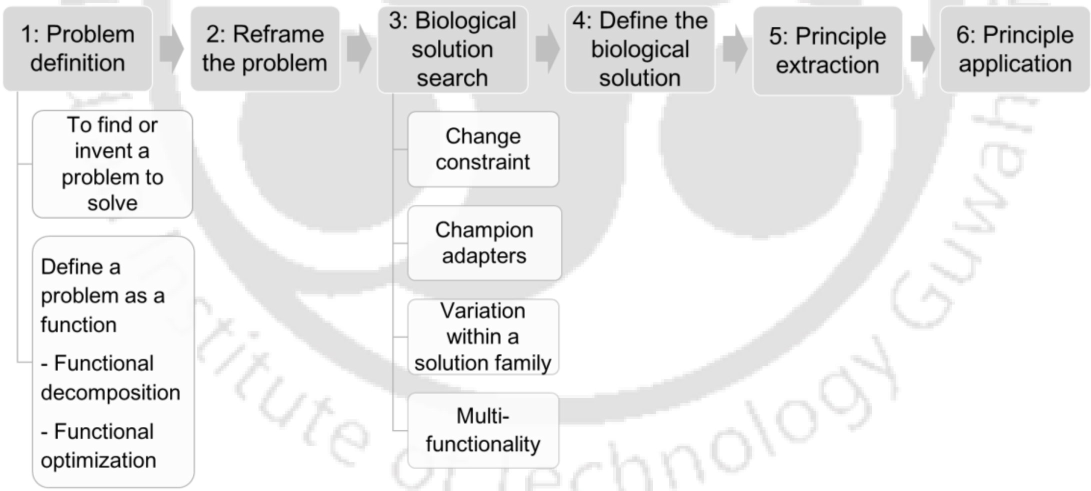


Figure 1.2 Stages of 'Problem-driven biologically inspired design process'

In the *Biomimetics by analogy* approach – the process starts with defining a problem originating from engineering. In the second step, the analogous problems are searched in nature. During the final stage, the examples in nature are analysed and the results of the analysis are used to find solutions to the engineering problem identified in the first stage (Figure 1.3).

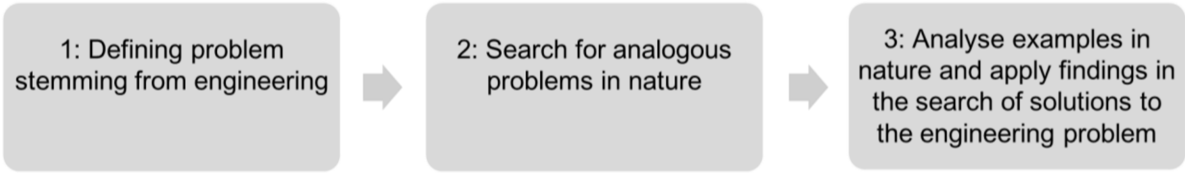


Figure 1.3 Stages of 'Biomimetics by analogy' design process

When we consider *Challenge to biology* approach – the first step in the process is to 'identify' and this includes developing the design brief that clarifies human need/problems to be solved. The next step is to 'interpret'. This is about translating design briefs into biological terms and defining parameters. Then we approach the 'discover' stage where we identify the biological model that meets the design brief. The next step is to 'abstract', which includes the identification of patterns and creating taxonomies. This is followed by the final two steps viz. 'emulate', where the practical solutions are developed based on the biological model and the last step is 'evaluate' in which the solutions are reviewed against life's principle (Figure 1.4).

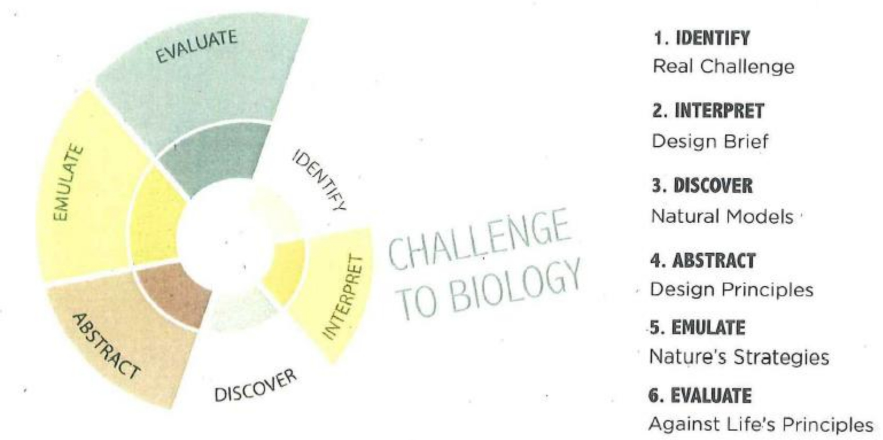


Figure 1.4 Stages of 'challenge to biology' design process

In contrast to the methods described above, in the second approach researchers have a biological phenomenon in their mind and that leads them to search for its application in the man-made world. We outline below some of the methods under this approach.

The *bottom-up process* is for new biomimetic projects based on biological research. In the first step of the process, the biomechanics and functional morphology of the biological model is analysed. During the second stage, the researcher tries to understand the underlying principles of structure, shapes, and the form of a biological model through quantitative analysis. This observed principle is separated from the biological model during abstraction. In the technical implementation stage, the early prototypes are made in the laboratory followed by large scale industry production (Figure 1.5).

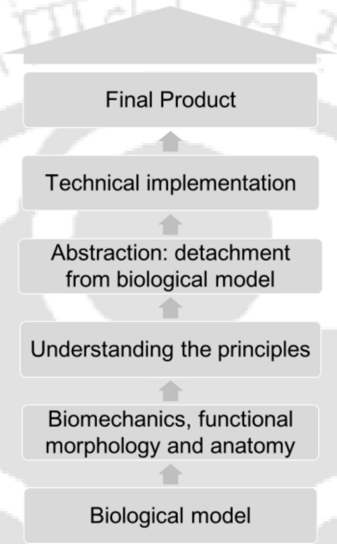


Figure 1.5 Stages of 'Bottom-up process'

Solution-driven biologically inspired design process – This 7-stage process, starts with the biological solution identification where the designers have a particular biological solution in their mind. The 2nd-stage is defining the biological solution, which includes an understanding of how the biological source is solving that problem. In step 3, the behaviour and principles of the biological source that solves the problem are extracted. Step 4, is reframing the solution where the designer is forced to think about how the achieved biological function is helpful to humans. Step 5, is problem search - the designer finds the human problems that match the solution. The next step of problem definition includes defining the constraints. The final step is the principle application where the principle is applied to solve the problem (Figure 1.6).

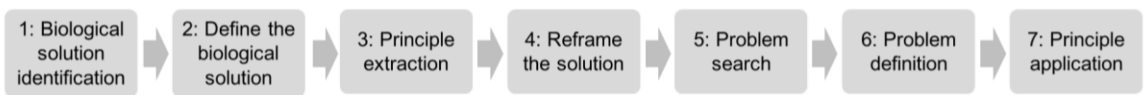


Figure 1.6 Stages of 'Solution-driven biologically inspired design process'

Biomimetics by induction – The process is initiated with the fundamental biological research without focusing on any specific application. In the second stage, the principle behind the natural phenomena is abstracted and translated into non-specific language. During the final stage, technological applications are developed (Figure 1.7).

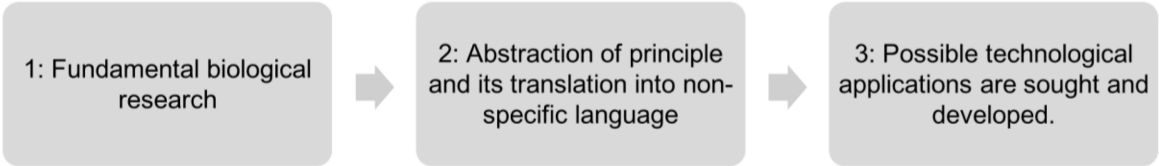


Figure 1.7 Stages of 'Biomimetics by induction' design process

Biology to design – The first step of the process involves discovering the biological model that meets the design brief. The next step is to 'abstract', where champions are selected with the most relevant strategies. The third stage is brainstorming with biologists and specialists in the field. The next stage is to 'emulate', where ideas and solutions are developed based on the biological model. The last step is 'evaluate', in which solutions are reviewed against life's principle (Figure 1.8).

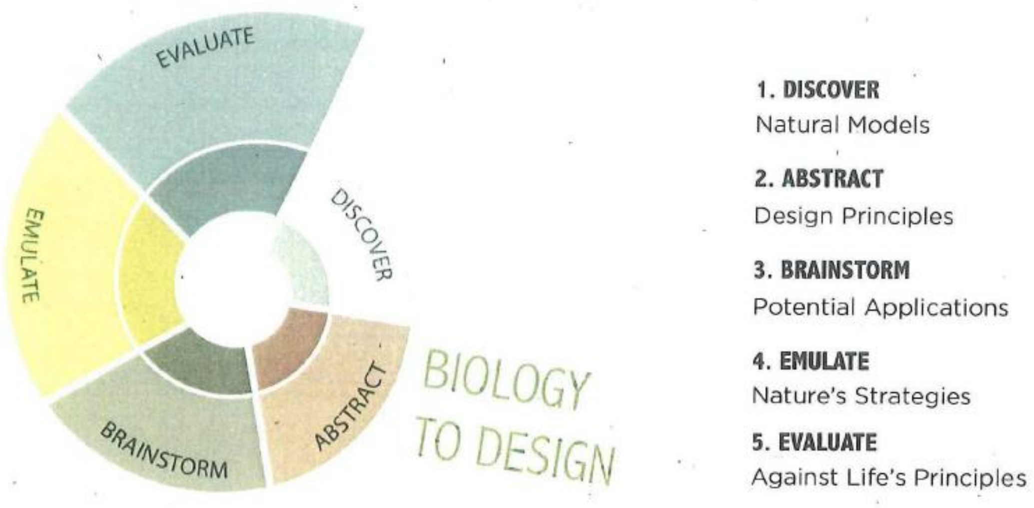


Figure 1.8 Stages of 'Biology to design' design process

In addition to the above broad approaches, there are specific methods like – BioGen, a methodology for biomimetic design concept generation developed to solve problems of architecture, but can be used by other disciplines other than architecture (Badarnah & Kadri, 2015). Junior & Guanabara (2005) proposed a methodology based on bionics research to design new products. Product Design from Nature (PDN) methodology is an integration of three approaches viz. reverse engineering, 3D geometrical computation, and inspiration from a designer sketch of a biological system (Wen et al., 2008). Lenau (2009) in a study explored the successful use of biomimetic design methodology for engineering design. Researchers from different scientific fields developed these approaches. They outlined the methods in general terms to make them suitable for end-users with varied educational backgrounds.

Biomimetic involves the transfer of information from the biological domain to other domains like engineering, material science, etc. Many computational tools and databases have been developed to make easy retrieval of this biological information and help designers in the ideation phase (Kaiser et al., 2012) (Fu et al., 2014) (Glier et al., 2011) (Helms et al., 2016). Some of the tools developed include:

- IDEA-INSPIRE is a computational tool based on SAPPhIRE model of causality. The biological and engineering analogies can be retrieved from the database based on the description of problem in terms of constructs of SAPPhIRE model (Chakrabarti et al., 2005).
- Design by Analogy to Nature Engine (DANE) is based on the Structure Behavior Function (SBF) model. It helps user to understand the SBF relationship between biological system and engineering system. The user can construct new SBF model and can add it to the library (Vattam et al., 2010).
- 'Ask nature' is a database based on biomimicry taxonomy that allows user to search information on biological phenomena and biomimetic products (http://www.asknature.org/. Visited on 23 Sept 2015)

Modified biological information and keeping the database up-to-date manually are few disadvantages of these databases (Kaiser et al., 2013). Ideation in biomimetic is a knowledge based ideation that demands a large repository of biological knowledge for creative thinking and should always stay updated. Vandevenne (2013) employed scalable web crawling approach to continuously develop and update the database based on biological strategies. 'Biologue' is an online citation cataloging system based on the concept of social semantic web that helps in building the database and keeping it up-to-date (Vattam & Goel, 2011). 'BIOscrabble' uses PubMed, which is a meta-database, allowing users to search large updated biological research articles (Kaiser et al., 2012) (Helms et al., 2016) (Kaiser et al., 2013).

Paper based and computer aided catalogues were also developed that contains biological principles and corresponding technical functions. Researchers have also developed certain engineering to biology translation tools to link engineering and biological terminologies (Kaiser et al., 2012) (Helms et al., 2016). BioTRIZ was developed on the basis of inventive principles of TRIZ. It is based on the analysis of 500 biological phenomena with 270 functions forming 2500 contradictions. Unlike TRIZ having 39 by 39 contradiction matrix, BioTRIZ uses 6 by 6 contradiction matrix (Vincent et al., 2006). Considering the drawbacks in terms of cost and availability of these tools, the biomimicry card deck was developed for novice designers that helps them to enlarge the solution space for solving problem through biomimicry (Volstad & Boks, 2012). Biomimicry Innovation Tool (BIT) uses the idea of Problem Based Learning (PBL) Method, innovation and biomimicry to solve technical ergonomics design problems (Lynch-caris, 2012). There are Nature Inspired Design (NID) strategies which include Biomimicry, Cradle to Cradle, Ecodesign and Natural Capitalism to apply principles of nature in a holistic way focusing on the system rather than developing a product (De Pauw et al., 2014) (De Pauw et al., 2010).

1.2.3 Limitations of systematic methods

Although systematic methods are useful for designers and engineers, they have certain limitations too. It is identified by researchers in their studies that there are learnability issues of these tools among professional designers and design students. Fu et al. (2014) in their study found that learning to use these tools/methods is different from conventional design methods and tends to increase the cognitive load on designers. A study by Glier et al. (2011) indicates that it is difficult to train students in this field because biomimetic is still in the developing phase and is not included in the academic curriculum. Hsiao & Chou (2007) during their research found that the existing tools and methodologies are insufficient to train students in organic form transformation and abstract associative thinking. Researches also indicate the reasons why designers and industries do not use these methods to design their products commercially. In the comparative analysis of five bio-inspired design methods by Versos & Coelho (2011) it was found that the methods failed to deliver a communication effective product. Jorgensen et al. (2013) found that current methods deal with only functionality and not the aesthetics of a designed product, which later became the base for the development of their design methodology focused on aesthetics. Kennedy (2014), through a case study in his research, explains that current methods and tools are focused on generating concepts and are insufficient in transforming concepts into the implementable solutions. Fu et al. (2014) identified that most of the tools/methods are part of academic projects and are not easily accessible to designers. A study by Volstad & Boks (2012) indicates that the tools are still in the developing phase, which makes it difficult to predict their usability and are too costly for small design studios to afford.

1.2.4 Designers' approach to nature-inspired design

Visual interaction is the first interaction of a user with a product. This focus on the visual appeal of a product is one of the reasons why designers lay emphasis upon product form. Design schools and practicing Designers have developed their own methods that focus upon the generation of form and aesthetics of a product. However, there is limited published literature available on training industrial designers in designing products that draw inspiration from nature. The designers' approach to design nature-inspired products focusing on styling and aesthetics starts with visual thinking. From the limited literature available, we find few researchers who have mentioned designers' approach that starts with observation of natural systems to identify form elements. Wen et al. (2008) describe 'Art and Design method' in which a designer observes a natural object to identify form elements and creates a conceptual design in the form of 2D sketch which can be scanned and used further to produce CAD models. Hsiao & Chou (2007) outline a proposal in which the process of transforming an organism form into a product form involves a concept transformation stage. This is further divided into two sub-stages viz. utilizing the concept of product semantics and morphology analysis. These authors developed a Diagram for Biomimetic Product Design (DBPD), which guides students in observing, extracting, and transforming the biological features of natural objects. At the Technical University of Denmark (DTU), they have adopted and followed a process outlined in their 'Applied aesthetics in biomimetic design—a guide'. In their approach, they propose seven methods in taking inspiration from nature's aesthetic attributes in a methodical way that can be used individually or as complementing each other (Jorgensen et al., 2013). The study by Huang & Li (2014) employs a method in which students first identify the objective pattern in nature which are responsible for aesthetic experience. After analysing these aesthetic patterns, 2D and 3D compositions are developed based on aesthetic principles like unity, harmony, proportions, balance, rhythm, symmetry, repetition etc.

1.2.5 Limitations of designers' methods

Industrial designers are often faced with the challenges of dealing with complexities in visualizing and transforming organic/nature-inspired forms that will appeal to the customer's psychological needs but are also easy to manufacture. Due to the complexities of natural forms designers often face a problem in analysing and extracting the design elements for product form (Hsiao & Chou, 2007). Designers' approach in designing such product form are more often based on experience and intuition. It, therefore, makes it difficult to design a product that exactly meets customer psychological needs (Tovey, 1997) (Hsiao & Wang, 1998) (Tovey, 1994). According to Kamehkhosh et al. (2010)

"designers usually reduce complex forms to their basic geometries and proportions, in order to find orders in their complexity and to harmonize them with their design paradigms...".

They believe that this common vision to nature "...deprive us from perceiving its reality". Maintaining a balance between natural form and abstractive form is a challenge for both novice as well as professional designers. Literature suggests that the degree of abstraction of a bios form is an important factor in consumer pleasure. It is found that less abstractive bios form result in a higher pleasure response than those with more abstractive form (Wu & Chang, 2007).

1.2.6 Criticism of designers' methods

The two approaches that emerge in following the various methods that are adopted by the scientific community and the Design community are broadly – the Systematic approach and the Designer approach respectively. It is evident that the Scientific community approaches methods that are purely function-oriented, while industrial designers engage with both function and aesthetics of a product. Both communities work under different environments and constraints in studying nature-inspired design. The former approach it with a more rigorous scientific temper that is subject to verification of their processes. On the other hand, the designer's approach form generation and nature-inspired design that is more intuition-based. Their approaches and their corresponding outcomes often face criticism for following an unsystematic approach. These criticisms are focused mainly on product form and aesthetics. Some of the often-heard critical comments on biomimetics include:

- *"Imitating or being inspired by natural-looking forms, textures and colors alone is not biomimetics; it has to have some biology in it. This means that to be truly biomimetic, a design should in some way be informed by nature's science, not just its look"* (El-Zeiny, 2012).
- *"Morphology and form are most common traits to be transferred from natural systems into architecture. However, such traits seldom retain any function of the imitated natural systems, and therefore hardly represent a successful biomimetic design"* (Badarnah & Kadri, 2015).
- *"We emphasize that it is the transfer of function from biology to the machine that allows biomimetics to test hypotheses from the biological sciences; otherwise, there is a danger of merely blind copying or mimicry of design principles with no further insight into the living system"* (Lepora et. al, 2013).

On the other hand, the importance of product aesthetics is evident from the literature of emotional and pleasurable products. Success stories of products like Juicy Salif lemon squeezer, Volkswagen Beetle, Diatom chair, TY NANT water bottle shows that the psychological aspects behind product aesthetics and its effect on product usability can't be ignored. Therefore, the design research community should reflect upon such criticisms. There seems sufficient evidence from our literature review that there is a need for introspection among designers' to find approaches in product form generation processes that are made more evident; and ones that can follow stages that are more systematised in their generation. An attempt should be made in making these stages more transparent and perhaps verifiable if possible.

1.2.7 Researches/Studies that support designers' methods

Having considered the above aspects, we also see evidence, through case examples, that are in favour of the designers' methods that counter the above criticisms.

Natural forms have always been a source of inspiration in developing new products by industrial designers (Podborschi & Vaculenco, 2004). For example, the Automotive industries, encourage the use of the animal form for styling because of optimized mechanical performance and wide appeal of the vehicle (Burgess & King, 2004). Understanding the semantic and emotional responses related to animal inspiration can help designers develop highly expressive design solutions (Kim et al., 2011). It is reported that products with bios form evoke the higher intensity of consumer pleasure and emotional responses than those without bios form (Wu & Chang, 2007) (Chang & Wu, 2007). Nature is a rich source of analogies and metaphors. Exposure to biological examples during the design process helps in increasing the novelty and variety of ideas generated (Wilson et al., 2010). Designers use metaphors in their designs to make products more communicative and expressive, both functionally as well as aesthetically (Hekkert & Cila, 2015).

Edward O. Wilson in his book 'Biophilia' argues that there is a bond between humans and nature. He defines Biophilia as "The innate tendency to focus on life and lifelike processes" (Wilson, 1984). The biophilic design is an application of biophilia concept in built environments. Biophilic design uses natural elements as the design inspiration in the built environment (Kellert et al., 2008). Many pieces of research have reported on the positive effects of the natural environment and its features on human health and psychological comfort (Kaplan & Kaplan, 1989) (Ulrich et al., 1991) (Parsons, 1991) (Gillis & Gatersleben, 2015).

All these studies explain the importance of nature in industrial design and justify in equal measure, the designers' approach in designing creative products inspired by nature.

1.2.8 Insights from literature review

In summary, nature is a great source of inspiration for both form and function. For an industrial designer, it is very important to study and extract the underlying principles of form and function, as per the demand of the design project. A study of nature-inspired design is all about the abstraction of the principles in nature. It could be the abstraction of a functional principle or the abstraction of a natural form to evoke certain emotions, but both kinds of abstraction require the understanding of the underlying principle existing in nature. From the literature review, we have examined the systematic methods undertaken by researchers and the methods followed by industrial designers for nature-inspired design. The results of the review indicate from an industrial design perspective, the strengths of both systematic methods and designers' method and also the nuanced differences in their emphasis and approach. Systematic methods are necessary as they help to increase the overall number of ideas generated. The products produced by such methods are more sustainable than the products available in markets. On the other hand, designers' methods result in the design of products that are relatively more communicative and expressive both functionally as well as aesthetically. These methods are necessary for semantic shape coding and symbolic association. The review also supports the position that the existing research approach lay more focus upon functional aspects.

It is evident from the available literature that the principles in nature are understood only in terms of functionality and areas which deals with the form and emotions are still left unexplored with the exception of a few studies (Wu & Chang, 2007) (Kim et al., 2011) (Chakrabarti & Gupta, 2007). A domain that deals with the form and emotion in the generation of expressive and communicative product forms extend sufficient scope for the research on the design of nature-inspired products from an industrial design perspective. This forms the basis for developing a work plan for research for this doctoral thesis.

Chapter 2

Research Design

2.1 Introduction

In a review of published literature in the previous chapter, we were able to identify many systematic methods that have pre-defined stages to be followed during the design process. One of the important features of these systematic methods is the quantitative experimental investigation of the observed principles in nature which gives a scientific and verifiable rigour to these methods. On the other hand, when we studied designers' approach of nature-inspired design focused on form generation, we found that their approach is intuitive, unsystematic and involves identification of form elements that are abstracted in later stages. As this approach of the designer is very individualistic there are no pre-defined stages of the form generation process that can be supported by some systematic studies. What principles they observe in natural form and how do they use these principles to generate a product form often remain unanswered. This also makes it difficult for novice designers to learn this process as it may vary from designer to designer. This premise sets the basis to establish the scope of inquiry for this design research.

There has been a strong concern among design researchers to establish relationships between design and science since the 1920's. Therefore, we would like to make our position very clear on such aspects. In this research we are not attempting 'scientism', rather we are more focused on an inquiry into the designerly ways of knowing, thinking, and acting.

We believe that a rigorous investigation of this phenomena of 'taking inspiration from nature to develop product forms' can help us to understand if there is indeed an underlying science behind such a form generation process. In this chapter, we will formulate our research questions and outline a research framework that will guide us through our designerly inquiry. The outcome of the study should help to outline approaches that can assist design educators in developing design curriculum on form studies and guide professional practicing designers in the design of nature-inspired product forms.

2.2 Research questions

The systematic way of design that brings a scientific rigour to the design process is a basis of the criticism of designers' approach that we have covered under chapter 1, section 1.2.6. We established that designers seem to follow very few systematic methods/tools during the form generation process and the principles that they extract from nature are supported by very few verifiable scientific studies. Therefore, the current research work intends to explore the possibilities of systematic design research and systematic design practice for the process of generating nature-inspired product forms.

Specifically, in this research we seek to address the following two research questions:

- Can there be a systematic approach to inquire into the process of generating nature-inspired product forms?
- Can the process of generating a nature-inspired product form be systematized?

2.3 Design science and the Aim of research

Reflecting upon the above two research questions, our search on systematic design led us to a secondary search for existing published literature on Design Science. For the purpose of this research, we analysed various definitions of design science.

Design science is about investigating a design process and making it more systematic. Johannesson and Perjons have defined design science as *"The scientific study and creation of artefacts as they are developed and used by people with the goal of solving practical problems of general interest"* (Johannesson and Perjons, 2014). Nigel Cross has defined it as *"an explicitly organized, rational and wholly systematic approach to design; not just the utilization of scientific knowledge of artefacts, but design in some sense a scientific activity itself"* (Cross, 2006). According to Hubka and Eder, *"The term design science is to be understood as a system of logically related knowledge, which should contain and organize the complete knowledge about and for designing"* (Hubka and Eder, 1996). Gregory explained it as *"Design science is* *concerned with the study, investigation, and accumulation of knowledge about the design process and its constituent operations. It aims to collect, organize and improve those aspects of thought and information which are available concerning design and to specify and carry out research in those areas of design which are likely to be of value to practical designers and design organizations"* (Gregory, 1966).

From these various definitions, design science can be summarised to be an 'investigation and accumulation of knowledge about the design processes'. Further we can also say that it is also a 'systematic approach to design'.

Following these definitions and directions established in Design Science, **this research aims to study, investigate, and accumulate knowledge about the process of designing nature-inspired product forms.**

2.4 Formulation of the research framework and objectives

The phenomena of generating nature-inspired product form is very complex. It has three crucial elements:

1. The 'Designer' who designs a product form and his designerly way of thinking.
2. The 'Design Process' that is followed to design a product form.
3. The 'Designed Product' which is a final three-dimensional form.

The knowledge about this phenomenon is not limited to the process only, rather it is embedded and can be processed in all the above three aspects equally. A designer collects various types of information about natural form like visual and semantics. Then the designer synthesizes this information during the design process. Finally, this information is coded into a three-dimensional product form. Therefore, to accumulate knowledge about this phenomena one must study this phenomenon of form generation from all these three aspects.

So far the act of creating nature-inspired product forms in design is considered more artistic. This domain of design was never supported by systematic scientific studies, but in this research, we are exploring it through a scientific lens. There has been a long discussion on 'science' and 'design'. How design is different from science and how in some aspects it is similar. Nigel Cross has covered many of these aspects in his book 'Designerly Ways of Knowing'. He considers design as a discipline in itself and suggests that to establish it as a separate discipline different from science and arts/humanities, it must have a strong foundation of research. For this, he suggests that design researchers must borrow and apply research methods from science, arts, or humanities whenever required to match their rigour and in the process build their own intellectual culture. This argument has been the source of inspiration for this research. We want to explore this phenomenon of form generation among designers in a 'designerly' way rather than following purely a 'scientific' or 'artistic' approach. We specifically focus upon nature as the source of inspiration in product form generation as the emphasis of our research.

In the same book, Nigel Cross suggests that design research has to engage with the development, articulation, and communication of design knowledge that is embedded in three sources: People, Processes, and Products. It is therefore pertinent to investigate three aspects – the human ability to design; the processes and techniques that aid the designers; and the study of form and configuration of the products (Cross, 2006).

Based on people, processes and products, Nigel Cross categorises his taxonomy under three categories:

- design epistemology – study of designerly ways of knowing
- design praxiology – study of the practices and processes of design
- design phenomenology – study of the form and configuration of artefacts

In setting workable objectives that will help us to address the aim of addressing our research questions, we found in Nigel Cross taxonomy a suitable framework. It was appropriate in considering various perspectives for exploring different ways to investigate and accumulate design knowledge to study nature-inspired product form generation process. It fulfils our requirement to study three crucial elements of the phenomena.

This taxonomy proposed by Nigel Cross forms the framework of inquiry for this research (Figure 2.1).

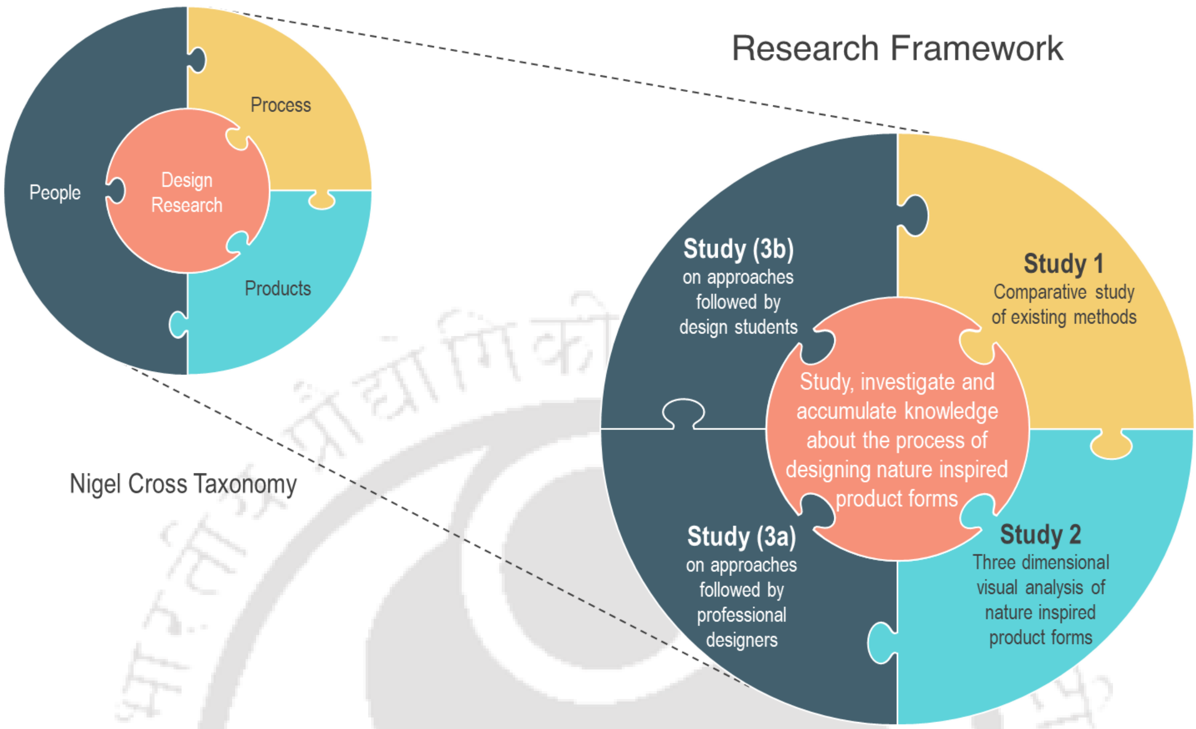


Figure 2.1 Research Framework adopted from Nigel Cross Taxonomy

Following the above framework, for our research, we planned and outlined the following four specific studies of inquiry viz.

- **Study 1 – Study of Processes and Methods:** This study examines the methods proposed by researchers, designers, and design educators to design nature-inspired product forms.
- **Study 2 – Study of Products:** It undertakes a three-dimensional visual analysis of product form of a selected range of products that are inspired by nature.
- **Study (3a) on People – Study on approaches followed by professional designers:** It examines the approaches followed by professional designers to design nature-inspired product forms.
- **Study (3b) on People – Study on approaches followed by design students:** This study involves an experiment conducted with design students to record and study the process of product form development that is inspired

by nature. It formed part of a live experiment engaging student designers to participate in an experiment in nature-inspired form generation. Analysis of their form generation process aimed to understand their approach and design thinking process in the form generation exercise. The outcome of this experiment aimed to find how it could influence and contribute to formulating the pedagogic process in form generation.

For the purpose of this research, we divided our Study on People into two different studies: Study (3a) on Professional Designers and Study (3b) on Design Students. Many studies in the literature have explained certain patterns in design cognition of professional designers and design students e.g. preference for inspirational sources during the ideation phase (Gonçalves et al., 2014), behavioral differences in the use of analogies (Jia et al., 2020) (Casakin & Goldschmidt, 1999) (Fu et al., 2014), analysis of problem statement (Mathias, 1993), the difference in visual behaviour in seeing shapes in design (Liu, 1995) etc. These studies indicate the difference in the approaches adopted by expert and novice designers to solve design problems. This supports the need to conduct different studies to understand the creative activity of designing nature-inspired product forms by design students and professional designers. The findings from these studies will not be used for any comparative analysis between professional designers and design students. These findings will contribute to a pool of knowledge that we aim for.

Based on these four studies we formulated four objectives to achieve our aim of the research. These four objectives are:

Objective 1: To perform a comparative study of the ten methods/tools used for the development of nature-inspired product forms and identify their strengths and limitations.

Objective 2: To conduct a three-dimensional visual analysis of selected products to identify perceptual similarities between product form and natural inspirational form.

Objective 3: To understand the design approach of five well-known designers and identify the various factors that they considered in their design process to generate forms inspired by nature.

Objective 4: To study the design approach of design students and identify various factors that are engaged in their thinking during the process of generation of product forms inspired by nature.

The research outcomes of design science are the artefacts like physical products, drawings, blueprints or they could take the form of knowledge e.g. guidelines, constructs, models, methods, and instantiations (Johannesson & Perjons, 2014) (Borek et al., 2012). The four objectives of the research will help us to gather tacit knowledge from all the above three sources. The insights drawn from these experiments can be used in the development of multiple outcomes. We expect that the outcome of our design research based on the approach of design science may lead to some systematic method, model, frameworks, or guideline for the process of designing nature-inspired product forms.

This forms the basis for the four experiments that are planned and conducted in the following chapter. The experiments are sequential and the findings of one contribute to assimilate, include and build upon in the next experiment. The findings could help draw certain patterns that could reflect a holistic perspective on the designerly way of thinking in the form generation process.

Chapter 3

Experimental Studies in Processes, Products and People

3.1 Introduction

As outlined in Chapter 2, the studies undertaken in this chapter form the four principal research studies of our research. It is based on the framework of inquiry outlined by Nigel Cross that cover three main perspectives viz. study 1 of processes and methods; study 2 – a study and analysis of products and study 3 that comprises of two aspects of the study of people viz. that of leading professional designers and their processes in the design of nature-inspired products and an experiment with an identified group of students tasked with the assignment of the generation of product forms inspired from nature in designing a scent bottle.

The planning of these four studies is undertaken in a sequence. The analysis and the findings therein of each study are summarized at the end of each study. The findings of each contribute and find reflection in the next study that follows. At the end of all the studies, a multi-perspective understanding is sought by drawing a holistic understanding of the methods and processes and the parameters of visual design that contribute to the creative act of generation of product forms inspired by nature.

Such an overview forms the basis in proposing a framework for the form generation process.

In the sections to follow we outline the details of each study.

3.2 Study 1 – Study of Processes and Methods

Drawing from multiple sources of literature, partly referred to in Chapter 1 earlier, we have identified ten methods/tools developed by researchers and design schools for generating product forms inspired by nature (Table 3.1).

3.2.1 Objectives of study 1

The objectives of this study are to perform a comparative study of the ten methods/tools used for the development of nature-inspired product forms and identify their strengths and limitations.

3.2.2 Methods and tools for generating product forms inspired by nature

During our initial literature review covered in chapter 1 on nature-inspired design we found only four methods focused on form generation. These methods are: (1) Product Design from Nature (PDN), (2) Generative product design, (3) Diagram for Biomimetic Product Design (DBPD), (4) Applied aesthetics in biomimetic design – a guide. With our secondary search focused only on 'methods and tools to design product forms inspired by nature' we found six more methods: (5) Elements of Form IV – Course series by Alexander Bosnjak, (6) Abstraction in form generation, (7) Designing with analogy, (8) Abstraction of animal, bird or insect (D'source course), (9) Form generation through styling cue synthesis, (10) Product metaphors. A total of ten methods/tools were studied in detail for this study.

These methods/tools consist of different stages that need to be followed during the form generation process.

Product Design from Nature (PDN) (Wen et al., 2008) and Generative Product Design (Huang and Li, 2014) are the methods based on CAD application. These methods involve the integration of new technologies like 3D scanning, generative modelling, and rapid prototyping.

In design education, there are some methods developed to aid novice designers in ideating new product forms. Diagram for Biomimetic Product Design (DBPD) is a nine-step process in which product semantics is the main approach in conceptual transformation (Hsiao and Chou, 2007). Applied Aesthetics in Biomimetic Design – a guide, is a work of Technical University of Denmark (DTU), which proposes seven methods that can be used individually or complement each other in taking inspiration from nature's aesthetic attributes in a methodical way (Jorgensen et al., 2013). Among the schools of Design in India, the processes followed include Elements of Form IV – Course series by Alexander Bosnjak (Bosnjak, 2007, IIT Guwahati), Abstraction in form generation (Sharma & Chakravarthy, 2009, IDC/IIT Bombay). Designing with analogy (Sinha and Chakravarthy, 2013) and 'Abstraction of animal, bird or insect', are research works and methods followed also at IDC, IIT Bombay (http://www.dsource.in/course/form/form-and-abstraction)

Other methods were not specifically developed to take inspiration from nature but they, however, have included natural objects as inspiration in their process. Form generation through styling cue synthesis, is a method in which the styling cues from two different objects are merged together and abstracted for a new product form (Teubner, 2008). Hekkert and Cila (2015) explain the process of applying metaphors to product forms to enhance the product experience. Table 3.1 summarizes these different methods and groups them into three broad types –

- CAD application based methods
- Design education-focused methods
- Methods not specific to nature-inspired design

3.2.3 Result of Study 1

From the study of the ten methods and their different stages for the form generation process, we noted the various stages of the process undertaken by each method. These stages were compiled in the form of a table for comparison of commonality and differences in approach among the ten methods followed (Table 3.1).

In this study of ten methods/tools, we identified the following five criteria/requirements as the key aspects in the process of designing:

(1) Integration of technology with the design process.
(2) Observation of principles in nature and their application in the form generation process.
(3) Use of product semantics.
(4) Focus on abstraction.
(5) Approaches to help generate more number of conceptual solutions.

following the concept of Pugh matrix/Decision matrix/Criteria-based matrix where certain criteria/requirements are formulated first and then each option/alternative is evaluated against those criteria, we evaluated selected ten methods against the above mentioned five criteria/requirements. Adopted from Pugh Matrix, we made a comparative study of ten methods against these five criteria/requirements to highlight the strengths and limitations of these methods as illustrated in Table 3.2 and discussed below.

(1) Integration of technology with the design process:

Only Product Design from Nature (PDN) and Generative Product Design integrate technology such as CAD-based applications like 3D scanning, generative modelling, and rapid prototyping into the design process (Method 1&2). While these applications are helpful in quick prototyping, they involve expensive 3D digitizing tools and require specialized knowledge to process their output data.

(2) Observation of principles in nature and their application in the form generation process:

Three methods in Table 3.2 involve the observation of principles in nature. The natural form is analysed in the second step of Generative Product Design (Method 2). The method includes the application of observed principles in the design process but is limited to the principles of aesthetic patterns only. The observed principles related to structure, geometry, proportion, etc. are recorded in the form of graphic images like photographs and diagrams (Method 5). However, the integration of information obtained by analysing natural form and development of three-dimensional form is not clear in this method. Abstraction of animal, bird or insect involves the observation of four principles on unity of rhythm, variety, balance and form found in nature and their application in design (Method 8).

Table 3.1 Methods for designing nature-inspired product form

Method No.	Methods	Stages in Form Generation										Type
1	Product Design from Nature (PDN) (Wen et al., 2008)	Capturing surface geometrical information	Building a 3D model	Manufacturing a prototype								CAD application based methods
2	Generative Product design (Huang and Li, 2014)	Identifying objective patterns in nature	Natural form analysis & development	Generative modeling								
3	Diagram for Biomimetic Product Design (DBPD) (Hsiao and Chou, 2007)	0. Describe organism name & photo (Text)	1. Explain the features of organism (Graphics)	2. Depict unique feature that most represent the organism (Graphics)	3. Depict other features (Behaviour, habitat) (Graphics)	4. Describe various features obtained in step 3 (Text)	5. Categorize the keywords selected from step 4 into Noun, Adjectives & Verbs (Text)	6. Illustrate the meaning of three types of keywords in step 5 (Graphics)	7. Reproduce the graphic & objects from step 6 in grid (Graphic) (Objects)	8. formulate several conceptual solutions using graphics form step 2 & step 7 (Sketches)	9. Produce a detailed model	Design education focused methods
4	Applied aesthetics in biomimetic design – a guide (Jorgensen, Kjeldsen and Lenau, 2013)	Nature as product	Action reaction	Split feeling	Impressions on the spot	Inspiration boards	Pattern of inspiration	Inspiration wheel				
5	Elements of Form IV – Course series by Alexander Bosnjak (Bosnjak, 2007)	Analysing inspiration	Recording Observations	Compilation of result	Evolving three-dimensional form							
6	Abstraction in form generation (Sharma & Chakravarthy, 2009)	Perception	Conception	Visualization								
7	Designing with analogy (Sinha and Chakravarthy, 2013)	Expression depiction	Take an analogy from nature and source visuals	Identify attributes of the source analogy	Representation of analogy to target plate design and its form							
8	Abstraction of animal, bird or insect (D' source course)	Generic study	Develop a concept	Choice of material	Analyze material use	Final abstraction						
9	Form generation through styling cue synthesis ((Teubner, 2008))	Understanding styling cues and visual language	Generating a configuration drawing	Choosing two objects	Analyzing and absorbing the styling cues	The Abstraction Scale	Applying the Process	The Final Synthesis				Methods not specific to nature-inspired design
10	Product metaphors (Hekkert and Cila, 2015)	Source selection	Metaphoric means									

Table 3.2 Comparison of ten methods based on five essential requirements.

Method No	Methods	1. Integration of technology with the design process	2. Observation of principles in nature and their application in the form generation process	3. Use of product semantics	4. Focus on abstraction	5. Help to generate more number of conceptual solutions
1	Product Design from Nature (PDN)	✓				
2	Generative Product design	✓	✓			
3	Diagram for Biomimetic Product Design (DBPD)			✓		✓
4	Applied aesthetics in biomimetic design – a guide			✓		✓
5	Elements of Form IV – Course series by Alexander Bosnjak		✓		✓	
6	Abstraction in form generation				✓	
7	Designing with analogy			✓		✓
8	Abstraction of animal, bird or insect (D'source course)		✓		✓	
9	Form generation through styling cue synthesis			✓	✓	✓
10	Product metaphors			✓		

(3) Use of product semantics:

Product semantics seeks to convey the meaning of product form. There are five methods in the list that involve the use of product semantics. In Diagram for Biomimetic Product Design, product semantics is the main approach in conceptual transformation (Method 3). Step 1 of Applied Aesthetics in Biomimetic Design – a guide, helps to transfer the qualities of natural elements into design expressions by analysing natural element as a product (Method 4). In Designing with Analogy, direct analogy in nature acts as a point of association and helps in the initial stage of idea generation (Method 7). Form generation through styling cue synthesis, involves the use of a cue chart that has a list of terms that represent elements of visual semantics (Method 9). Product Metaphors discusses eight metaphoric means or modes that a designer can use to transfer source cues to the target to enhance the product experience (Method 10). The method is more focused on the selection of source and transfer of source cues to the target but does not discuss the transfer of selected features into form during the form generation process.

(4) Focus on Abstraction:

In art, abstraction is the act of drawing out the essential qualities in a thing, a series of things or a situation (Hale, 1993). Designers try to achieve abstraction by removing extra visual cues from their designs instead of imitating exact natural form. Bosnjak makes use of photographic, allegorical, iconographic and diagrammatic representations to explore various possibilities for abstracting meaning and form (Method 5). Abstraction in form generation, is the adoption of Emiko Ohnuki's model with three levels of abstraction: perception, conception, and visualization, in which externalization happens at modified level 3 (Method 6). The authors explain the form generation process aided by abstraction involving four stages. In Stage 1 of the process, the number of ways to capture stimulus in its abstraction is not well defined. IDC School approaches abstraction considering the limitation of the medium/material (Method 8). Form generation through styling cue synthesis uses a scale between literal depictions to abstract interpretation (Method 9).

(5) Approaches to help generate more number of conceptual solutions:

Creativity is a very significant element of a design method. A good design method supports creative idea development and helps designers to generate a large number of conceptual solutions (Shah et al., 2003) (de Bono, 1992). Diagram for Biomimetic Product Design (Method 3) uses morphological analysis and Applied Aesthetics in Biomimetic Design – a guide involves the use of the inspiration wheel (Method 4). These are the only methods in the list that make use of ideation tools during form generation. Designing with Analogy uses analogy from nature as a catalyst to trigger multiple thoughts (Method 7). Form generation through styling cue synthesis merges the styling cues of two different objects to make a new one (Method 9). Both these methods also support the generation of alternative conceptual solutions, but they do not involve the use of any ideation tool.

In summary, drawing from a comparative study of the strengths and limitations of the ten different methods we can say that the evaluation indicates the adequacy of methods in relation to the above five requirements. It is evident that no single method meets all the requirements of the form generation process. This is a research gap that can be explored for the development of new ideation tools and generating a novel framework for methods that can comprehensively integrate the five identified requirements for the generation of product forms inspired by nature. Such a multi-perspective study also offers scope to examine findings from across the five identified requirements and help to theorize the phenomena, as one moves towards the development of tools and methods to help a designer in generating product forms inspired by nature.

3.3 Study 2 – Study of Products

Following the taxonomy proposed by Nigel Cross, in this study we undertake a three-dimensional visual analysis of product form of a selected range of products that are inspired by nature. We study these products as a basis for understanding the process of designing. We aim to understand the process of visual transformative adaptation from the source in nature to its visual manifestation in the designed artefact.

To build this understanding, we first consider three levels of biomimicry - mimicking of natural form, mimicking of natural process and mimicking of natural ecosystems (Baumeister et al., 2013). Mimicry of natural form is very often characterised by close resemblance or similarity between the source (natural inspirational form) and target (designed product form). We draw upon the research work undertaken by Cila et al. (2012) on analogy and metaphor in which, the role of similarity between source and target is discussed elaborately. In their study, they outline two types of similarity between source and target:

(1) Perceptual similarity - which is the physical resemblance between two objects. It includes appearance, movement, sound, and interaction pattern.
(2) Conceptual similarity - which represents the relation between two concepts. It includes function, working principle, emotions they evoke, and environment/context.

We focus on the perceptual similarity in nature-inspired products by examining visual elements and their attributes between the source in nature and their transformative adaptation in the designed artefact.

3.3.1 Objectives of study 2

The objectives of the study are to conduct a three-dimensional visual analysis of selected products to identify perceptual similarities between product form and natural inspirational form to help us understand a pattern in the usage of form attributes by designers to achieve perceptual similarity. The finding of this study is a form of knowledge embedded in the products that will contribute to the aim of this research.

3.3.2 Methodology

A sample size of thirty products that are inspired by natural forms were identified to collect data on the perceptual similarity between product form and their respective natural inspirational form.

A three-stage methodology was adopted for this study that is illustrated in Figure 3.1.

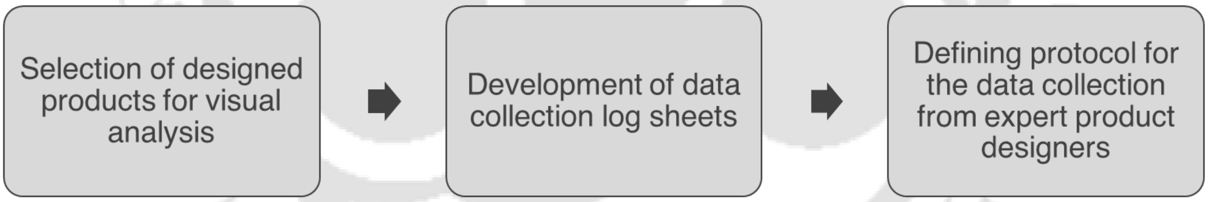


Figure 3.1 Methodology for three-dimensional visual analysis

Stage one is a product selection stage where images of nature-inspired product form and their respective natural inspirational form are collected. In the second stage, a data collection log sheet was developed to record responses of design experts during three-dimensional visual analysis. A protocol for the data collection was defined in the third stage to make the process of visual analysis more systematic.

Stage (1) Selection of designed products for visual analysis:

Stratified sampling of 30 nature-inspired products was undertaken based on the following two criteria:

i. Selected products are designed by leading designers/companies who are well known for designing nature-inspired products.
ii. The source of inspiration (in nature) for the selected products is clearly specified.

Following these two criteria, 15 products designed by professional Indian designers and 15 products designed by well-known professional international designers were selected. Table 3.3 shows a detailed list of all the products with their respective designers/companies. Visual plates juxtaposing the natural source with their product were prepared for the experiment (Figure 3.2).

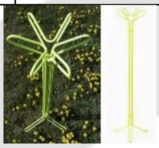
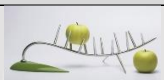
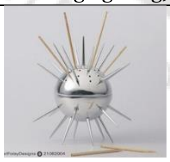
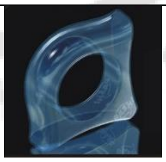
Stage (2) Development of data collection log sheets:

It was felt appropriate that a graphical means of collecting responses from experts be devised. The visual elements and their attributes of the product form and their sources in nature needed to be identified and assessed. This was derived by referring to Rowena Reed's methodology of 'structure of visual relationships' (Hannah, 2002); principles of three-dimensional visual analysis (Koler, 1994); methods of three-dimensional form analysis/manipulation (Young, 1985); and methods on using universal form and principles in design (Macnab, 2012).

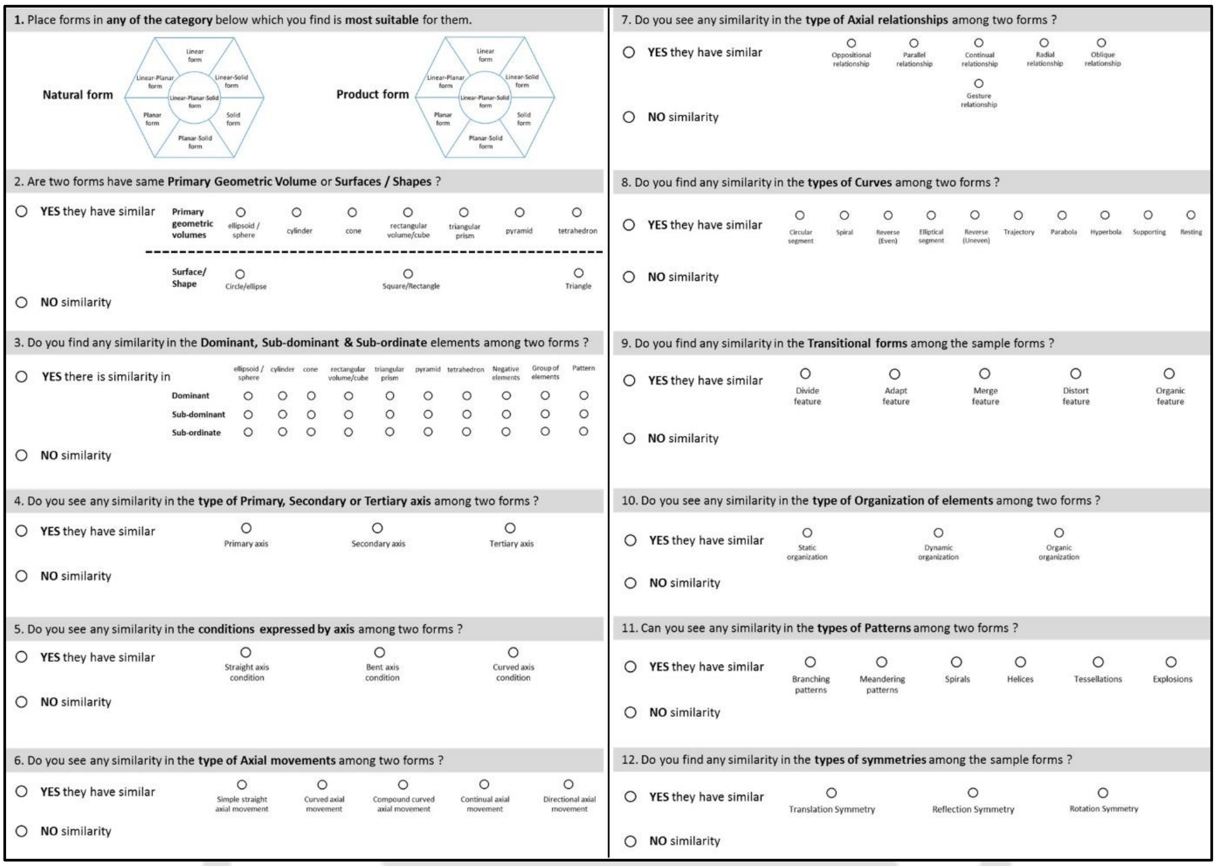
Graphical data collection log sheets were designed for the data collection on the perceptual similarity between product form and their respective natural inspirational form. These were based on collecting data for twelve form attributes: Form category, Primary Geometric Volumes & Surfaces, Hierarchy of order, Type of axis, Conditions expressed by axes, Types of axial movements, Types of axial relationships, Types of curves, Transitional forms features, Type of organization of elements, Type of symmetries and Type of patterns. The graphical log sheet (Figure 3.3) would guide the expert respondent to compare and enter their responses by studying visual plates containing the selection of three-dimensional product forms and their corresponding inspirational form in nature. Qualitative data was gathered in the form of texts and subsequently coded into numbers for further analysis.

Figure 3.2 Samples of the visual plates prepared for the experiment

Table 3.3 List of thirty nature-inspired products with their respective designers/company

Products designed by International Designers					
Designer/Company	Products				
Ross Lovegrove	 Diatom Chair	 Biophilia	 Agaricon	 Florensis	 Cosmic Leaf
Luigi Colani	 Anyfix	 Mega passenger	 Tea Service "Drop"	 Squirrel Colani Cup	 Canon Frog
Alessi	 Kastor	 Parrot	 Piccantino	 Juicy Salif	
James Irvine/Danese Milano			 Daisy (Coat Stand)		
Products Designed by Indian Designers					
Designer/Company	Products				
Neil Foley	 Jelly Fish (Floor standing lighting)	 Ant (Floor book holder)	 Twig (Fruit holder)	 Hammer head (Digital movie player)	 Slice (Fruit holder)
	 Urchin (Tooth pick holder)	 Raptor (Bicycle)	 Sting-ray (Watch packaging)	 Leaf (Mixer grinder)	 Butler's Mixer Grinder
			 Pure it		

Satish Gokhale	 Ground or Suspended lamp
Axiom Consulting	 Tiltr – Fitness Device
i2r Design	 Water Purifier inspired by apple
Onio Design	 Perfume Packaging inspired by lotus


1. Place forms in **any of the category** below which you find is **most suitable** for them.

Natural form — Linear form; Linear-Planar form; Linear-Solid form; Linear-Planar-Solid form; Planar form; Solid form; Planar-Solid form

Product form — Linear form; Linear-Planar form; Linear-Solid form; Linear-Planar-Solid form; Planar form; Solid form; Planar-Solid form

2. Are two forms have same **Primary Geometric Volume** or **Surfaces / Shapes** ?
- YES they have similar — Primary geometric volumes: ellipsoid / sphere; cylinder; cone; rectangular volume/cube; triangular prism; pyramid; tetrahedron — Surface/ Shape: Circle/ellipse; Square/Rectangle; Triangle
- NO similarity

3. Do you find any similarity in the **Dominant, Sub-dominant & Sub-ordinate** elements among two forms ?
- YES there is similarity in — ellipsoid / sphere; cylinder; cone; rectangular volume/cube; triangular prism; pyramid; tetrahedron; Negative elements; Group of elements; Pattern — Dominant; Sub-dominant; Sub-ordinate
- NO similarity

4. Do you see any similarity in the **type of Primary, Secondary or Tertiary axis** among two forms ?
- YES they have similar — Primary axis; Secondary axis; Tertiary axis
- NO similarity

5. Do you see any similarity in the **conditions expressed by axis** among two forms ?
- YES they have similar — Straight axis condition; Bent axis condition; Curved axis condition
- NO similarity

6. Do you see any similarity in the **type of Axial movements** among two forms ?
- YES they have similar — Simple straight axial movement; Curved axial movement; Compound curved axial movement; Continual axial movement; Directional axial movement
- NO similarity

7. Do you see any similarity in the **type of Axial relationships** among two forms ?
- YES they have similar — Oppositional relationship; Parallel relationship; Continual relationship; Radial relationship; Oblique relationship; Gesture relationship
- NO similarity

8. Do you find any similarity in the **types of Curves** among two forms ?
- YES they have similar — Circular segment; Spiral; Reverse (Even); Elliptical segment; Reverse (Uneven); Trajectory; Parabola; Hyperbola; Supporting; Resting
- NO similarity

9. Do you find any similarity in the **Transitional forms** among the sample forms ?
- YES they have similar — Divide feature; Adapt feature; Merge feature; Distort feature; Organic feature
- NO similarity

10. Do you see any similarity in the **type of Organization of elements** among two forms ?
- YES they have similar — Static organization; Dynamic organization; Organic organization
- NO similarity

11. Can you see any similarity in the **types of Patterns** among two forms ?
- YES they have similar — Branching patterns; Meandering patterns; Spirals; Helices; Tessellations; Explosions
- NO similarity

12. Do you find any similarity in the **types of symmetries** among the sample forms ?
- YES they have similar — Translation Symmetry; Reflection Symmetry; Rotation Symmetry
- NO similarity

Figure 3.3 Graphical data collection log sheet

Stage (3) Defining protocol for the data collection from expert product designers:

An experimental protocol makes a study more systematic and scientific. In a general protocol for qualitative studies, the data is either coded using new codes or it is coded using codes defined by previous theories. In case the data is coded by two or more coders then a reliability check is performed. If the agreement among the coders crosses an acceptable range, then they arbitrate the differences in their codes to reach a consensus otherwise they recode their data again.

In our study of three-dimensional visual analysis of product forms of nature-inspired products selected for this study, we have adopted a similar approach. We have defined a protocol of our experiment for data collection from expert product designers (Respondents/coders) that is explained schematically through a flow chart in Figure 3.4.

The visual analysis of any object can involve a high level of subjectivity and depends on an individual's perception. Therefore, to ensure the objectivity of the study, the experiment was conducted in two sessions with three respondents/coders with the following profile: Respondent A was a doctoral student who has a post-graduate degree in industrial design with nine months of experience on academic projects; Respondent B was an industrial designer and design educator having more than twenty years of experience in Industry and academics; Respondent C was an industrial designer and design educator with more than ten years of experience in designing products along with academic teaching experience.

- Discussion on visual analysis principles:

  A detailed discussion on principles of visual analysis was held before the experiment to bring three respondents on a common ground for analysis. They were introduced with the principles of visual analysis and the manner in which these were applied to nature-inspired product forms and their inspirational natural forms. The sample visual reference sheets used for discussion were not included in the experiment (Figure 3.5).

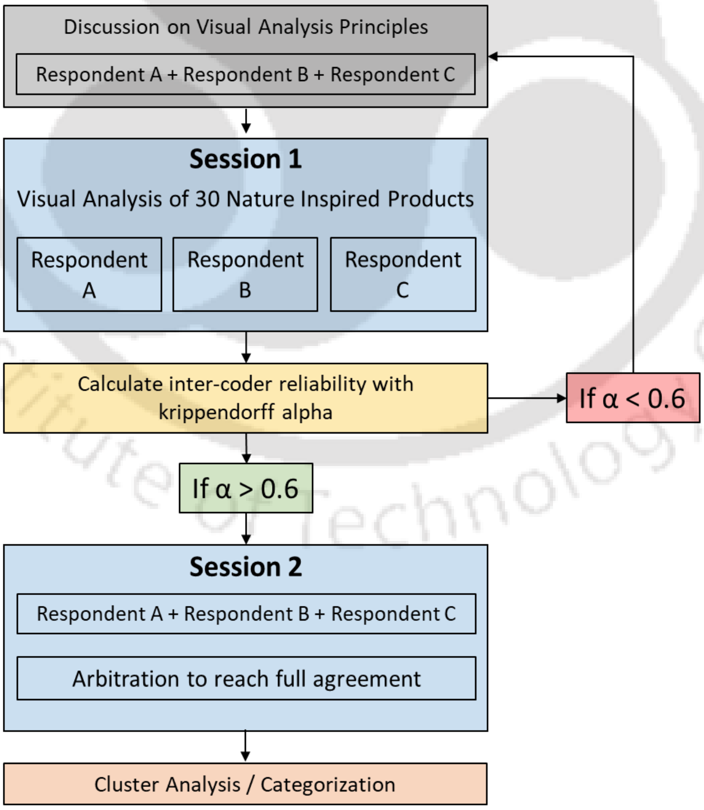


Figure 3.4 Experimental protocol for data collection

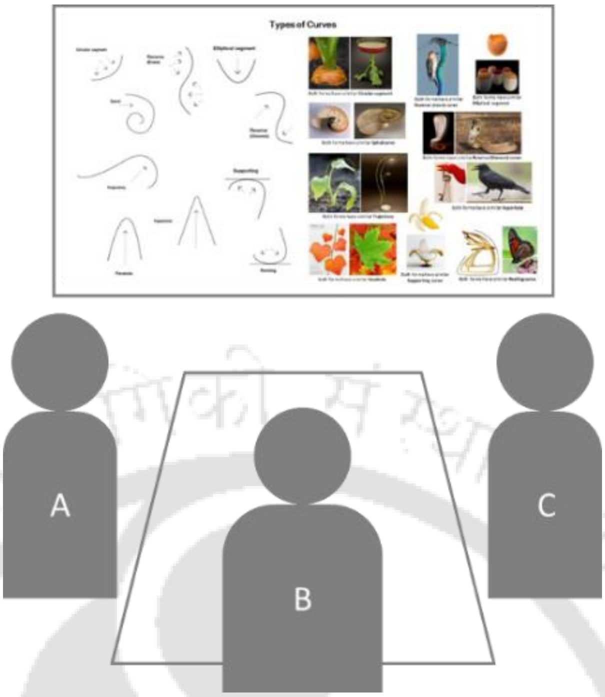


Figure 3.5 Illustration representing discussion on visual analysis principles

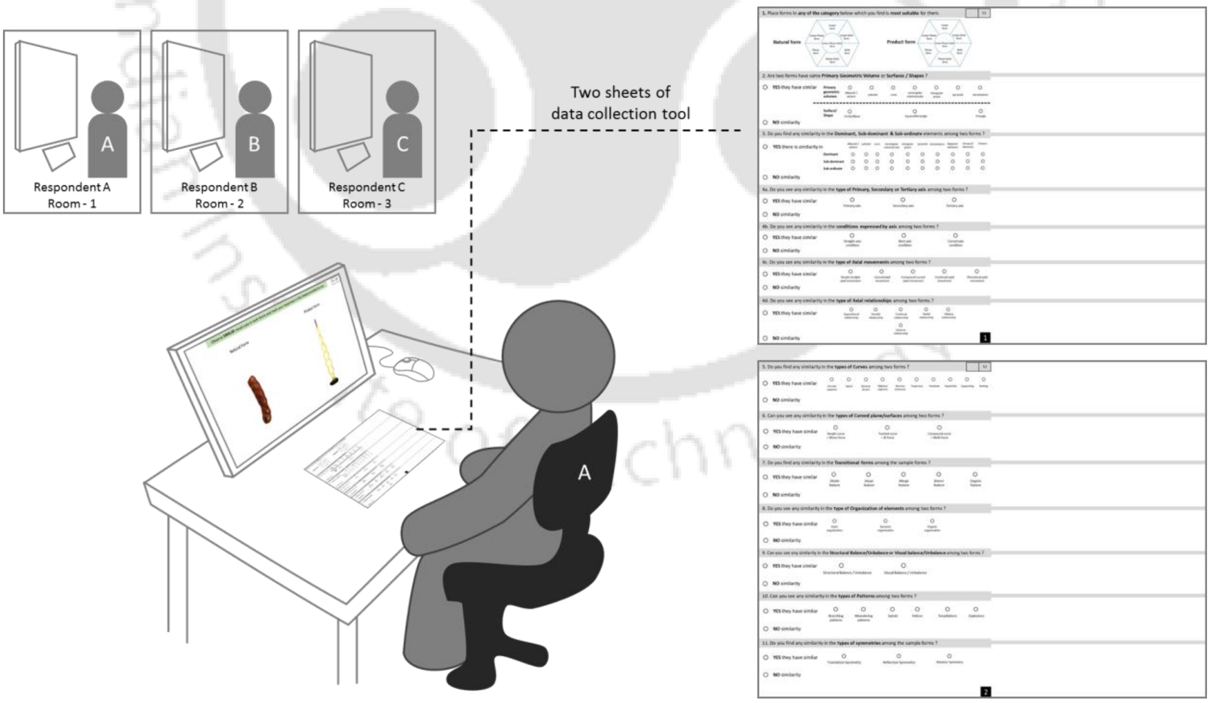


Figure 3.6 Illustration representing Session 1

- Session 1:

  In session 1, respondents performed the visual analysis individually and independently in different rooms. The experimental setup included a personal computer and data collection log sheets. The set of images containing both product and natural inspirational form were displayed to the respondents and they recorded their responses in the data collection log sheets (Figure 3.6).

- Calculating inter-coder reliability:

  The inter-coder reliability for 12 items of the data collection log sheet was checked using Krippendorff alpha (Hayes and Krippendorff, 2007) (Krippendorff, 2004). If the agreement was very low ($\alpha < 0.60$), then the respondents/coders were required to discuss the principles of visual analysis again and repeat session 1. If the value of alpha crossed the acceptable range ($\alpha > 0.60$), the respondents/coders could move to session 2. The values of Krippendorff alpha for twelve form attributes for the current experiment after session 1 are represented in Table 3.4.

Table 3.4 Value of Krippendorff's alpha for Respondent/Coder A, B & C after session 1

S.No	**Form attributes**	**Krippendorff's alpha For Respondent/Coder A, B & C**
1	Similarity in the ***form category***	.9304
2	Similarity in ***Primary Geometric Volumes*** or ***Surfaces / Shapes***	.8490
3	Similarity in ***Dominant, Sub-dominant*** and ***Sub-ordinate*** elements	.9027
4	Similarity in ***types of Axis***	.8024
5	Similarity in the ***conditions expressed by axes***	.7606
6	Similarity in ***types of Axial movements***	.8202
7	Similarity in ***types of Axial relationships***	.8909
8	Similarity in ***types of curves***	.6263
9	Similarity in the ***transitional forms features***	.7694
10	Similarity in the ***type of organization of elements*** existing in the form	.7200
11	Similarity in ***type of patterns***	.7567
12	Similarity in ***types of symmetries***	.6365

- Session 2:

  During session 2, respondents/coders checked and discussed all the differences in their data until they reached a consensus (Figure 3.7). Separate sheets were used to enter the consensus data during the arbitration process. Complete agreement is necessary for cluster analysis as the input data is in the binary form where ‘0’ indicates the absence of an attribute of similarity and ‘1’ indicates the presence of an attribute of similarity.

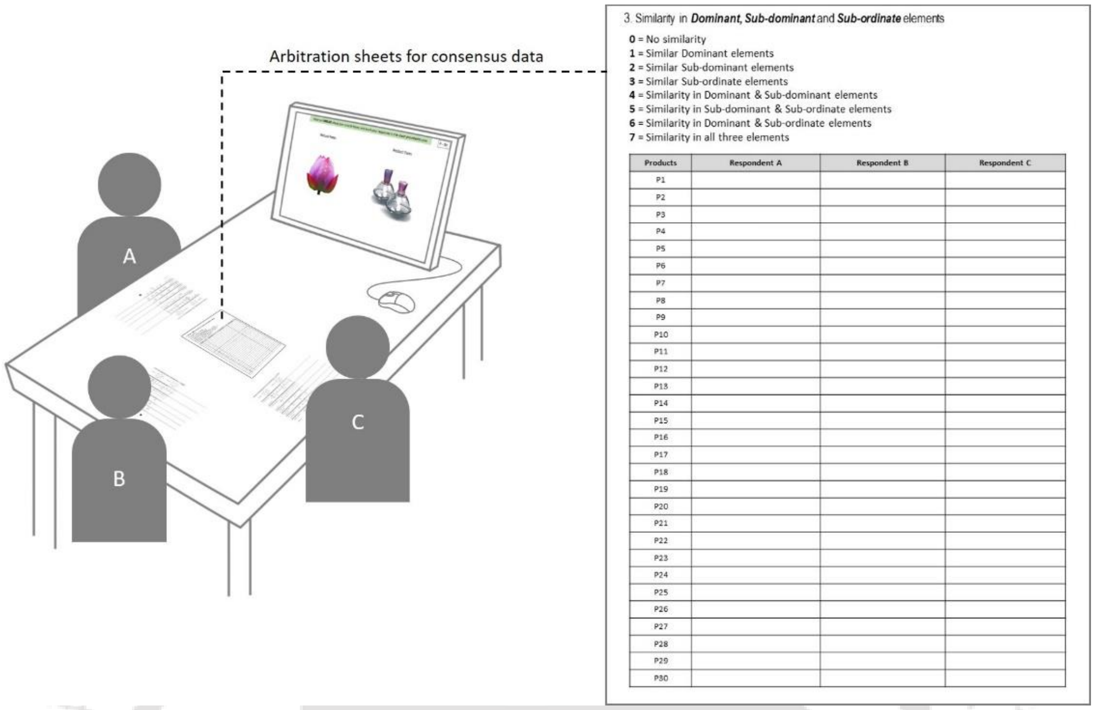


Figure 3.7 Illustration representing Session 2

- Cluster analysis / Categorisation:

  To observe and identify the patterns of similarity that exist in the product form and inspirational form, the Cluster analysis method seemed appropriate as it has widely been used by scientists in numerical taxonomy for classification in the biological domain. The data obtained after session 2 was used as an input for hierarchical cluster analysis and analysed using the SPSS statistical software package. For hierarchical cluster analysis, the average linkage method was used following simple matching binary measure to calculate the simple matching coefficient. The reason for using simple matching coefficient for analysis was that it makes use of negative matches as well as positive matches, unlike Jaccard coefficient which ignores negative matches (Romesburg, 1984).

  It was felt that both kinds of matches were significant - the features which are preferred most as well as the features which are least preferred by designers. After getting statistical results in the form of dendrograms (Figure 5) the cutting point for each case was decided based on the following criteria (Romesburg, 1984):

- The first one was to cut the tree at some point within a wide range of resemblance coefficient which indicates that clusters are well separated in attribute space.
- The second was, the tree should be cut to produce classes that are maximally related to other specific variables of interest.

Cluster analysis was performed only for those visual form attributes that have more than three attributes of similarity. If the attributes of similarity were less than three, then the products were grouped under those attributes of similarity.

Example - The cluster analysis result of similarity in the 'hierarchy of order' for thirty products reveal that there are four clusters when a cutting point is located at 7 scales as shown in Figure 3.8.

- Cluster 1: Cluster of products in which there is no similarity in the dominant, sub-dominant and sub-ordinate elements of the product and natural inspirational form.
- Cluster 2: This cluster consists of products that have similarity in dominant and sub-dominant elements of the product and natural inspirational form.
- Cluster 3: This cluster of products has similarity in dominant elements of the product and natural inspirational form.
- Cluster 4: This cluster consists of five small clusters: Cluster of products having similar sub-ordinate elements, a cluster of products having similarity in dominant & sub-ordinate elements, Cluster of products with all three elements similar, cluster of products having similarity in sub-dominant & sub-ordinate elements and a cluster of products having similar sub-dominant elements.

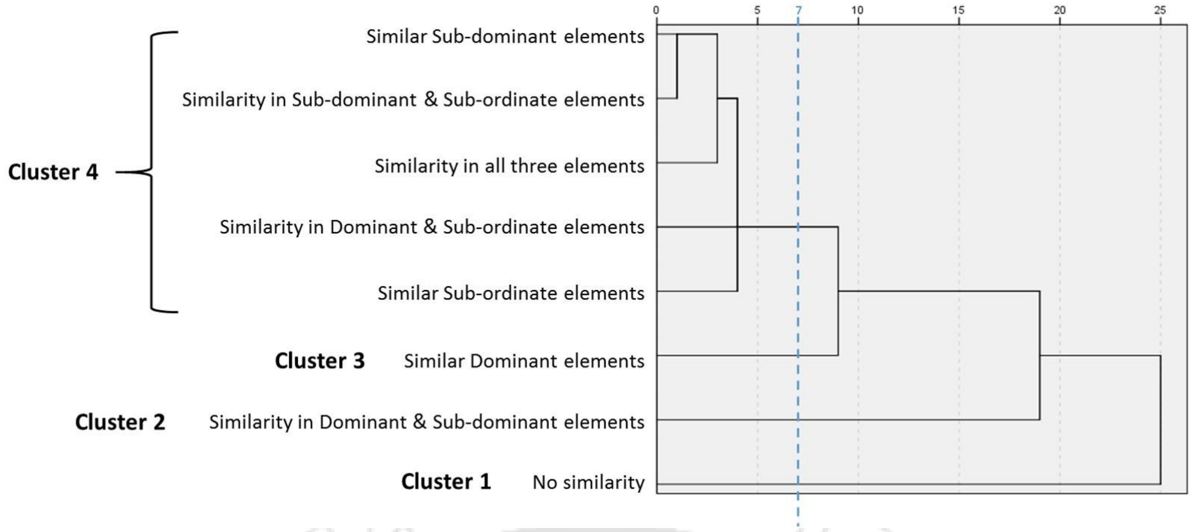
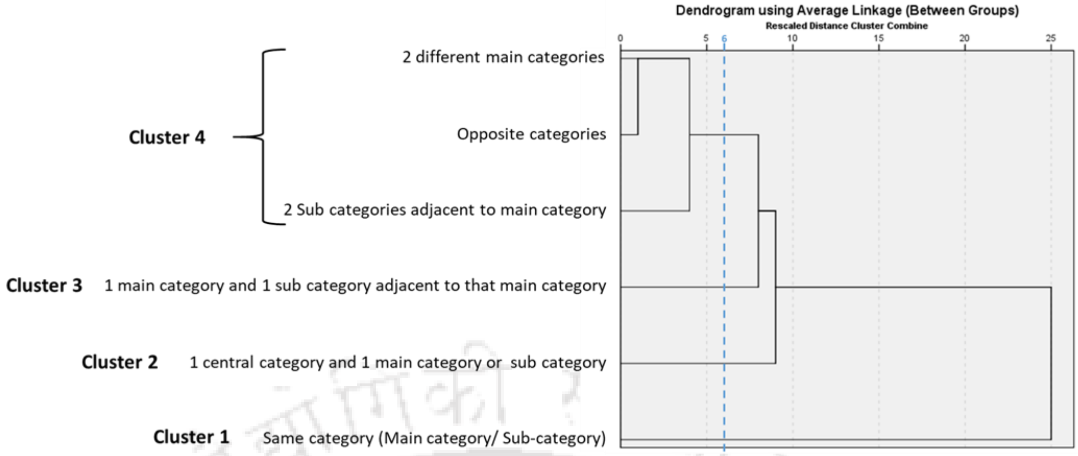


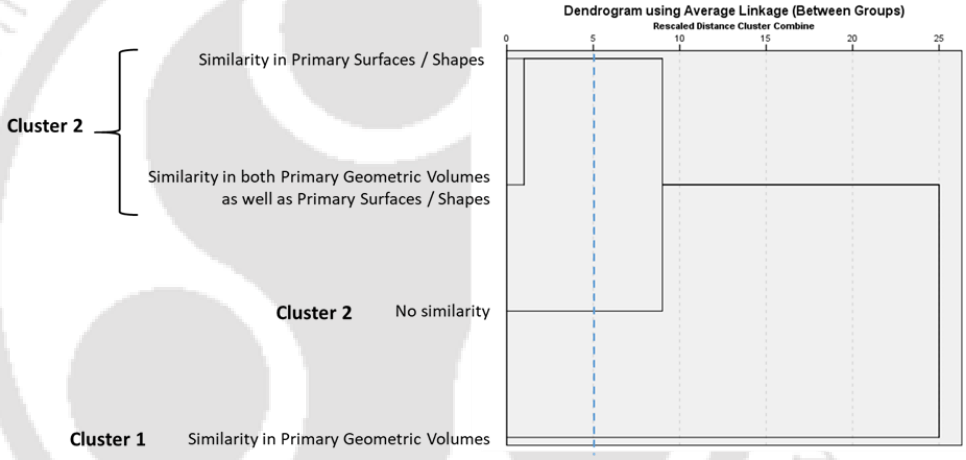
Figure 3.8 Dendrogram of similarity in the 'hierarchy of order' for thirty products.

The dendograms for ten form attributes are shown in Figure 3.9. As the attributes of similarity for '5 - Conditions expressed by axes' and '12 - Type of pattern' were less than three, therefore the products were grouped under those attributes of similarity.

1. Form categories



2. Primary Geometric Volumes & Surfaces



3. Hierarchy of order

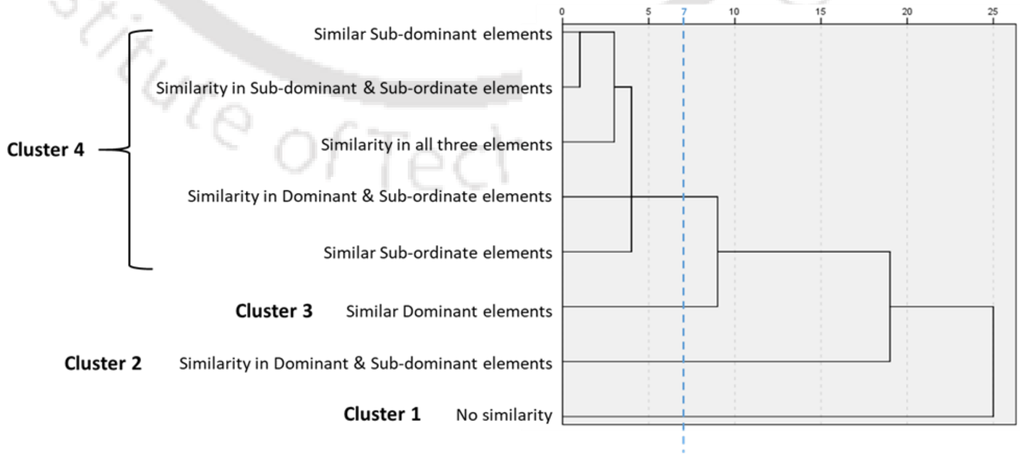
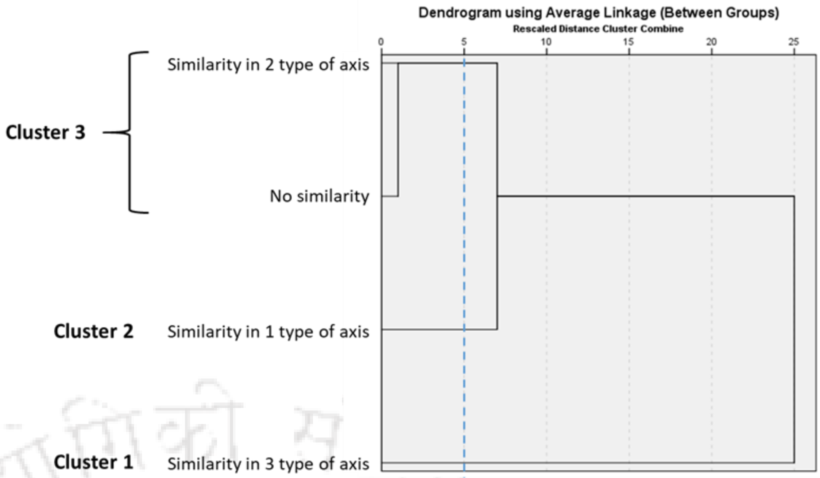
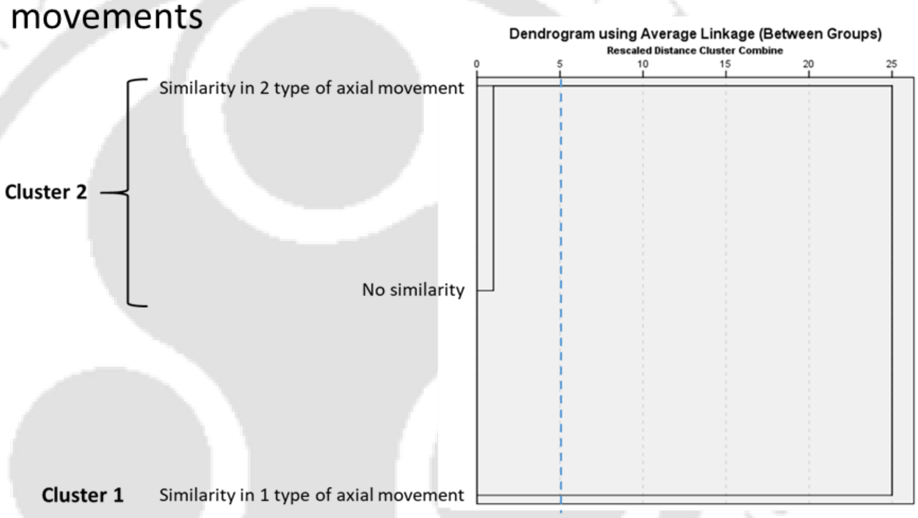


Figure 3.9 Dendrograms for ten form attributes

4. Type of axis



6. Types of axial movements



7. Types of axial relationships

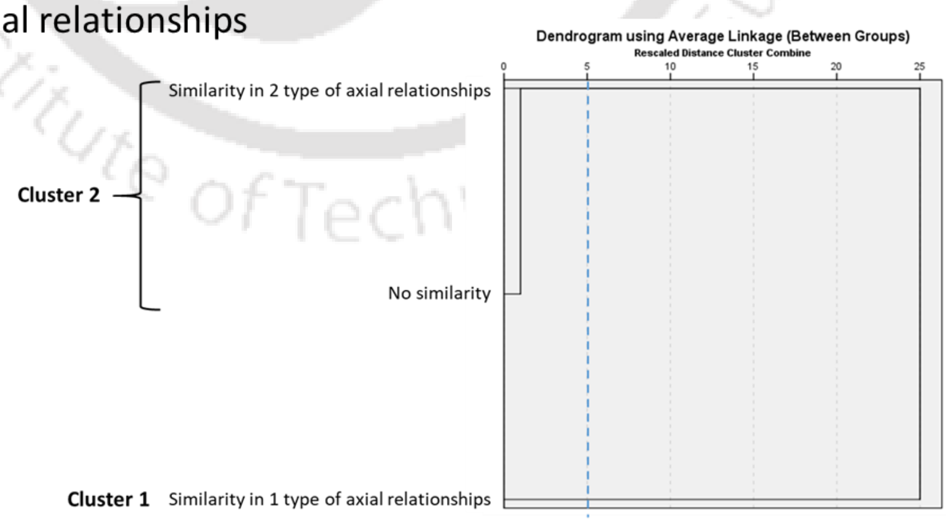
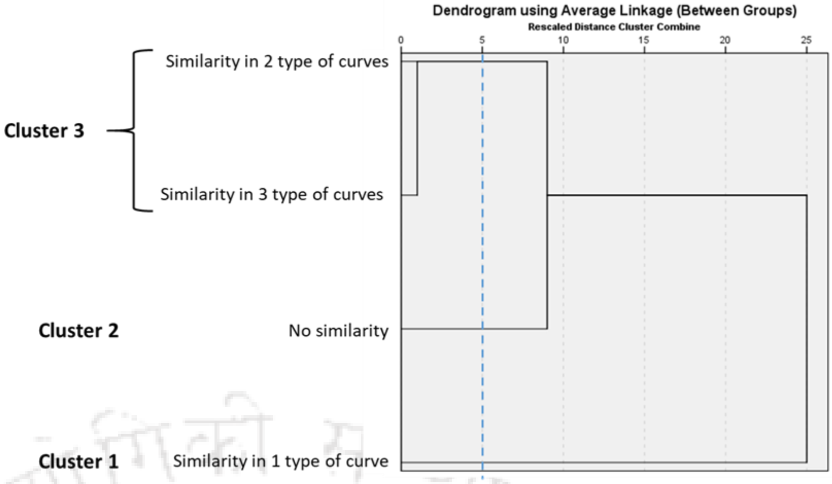
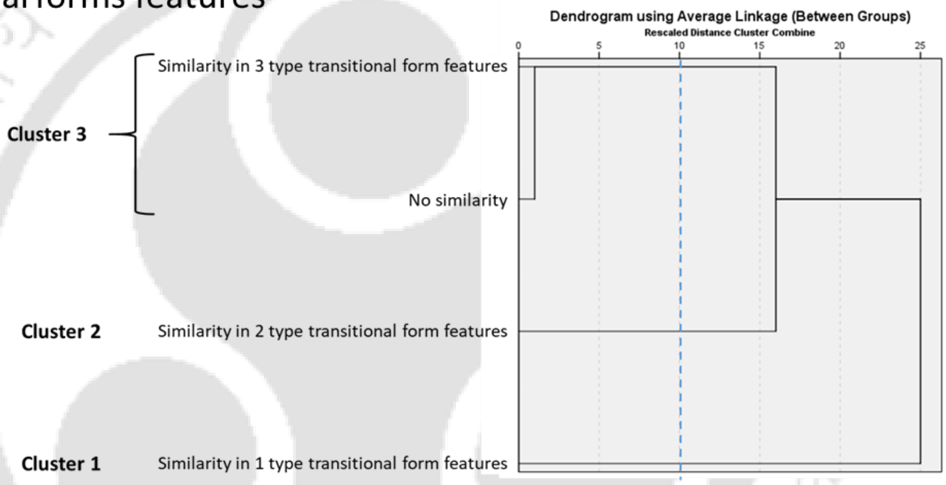


Figure 3.9 Dendrograms for ten form attributes (continued)

8. Types of curves



9. Transitional forms features



10. Type of organization of elements

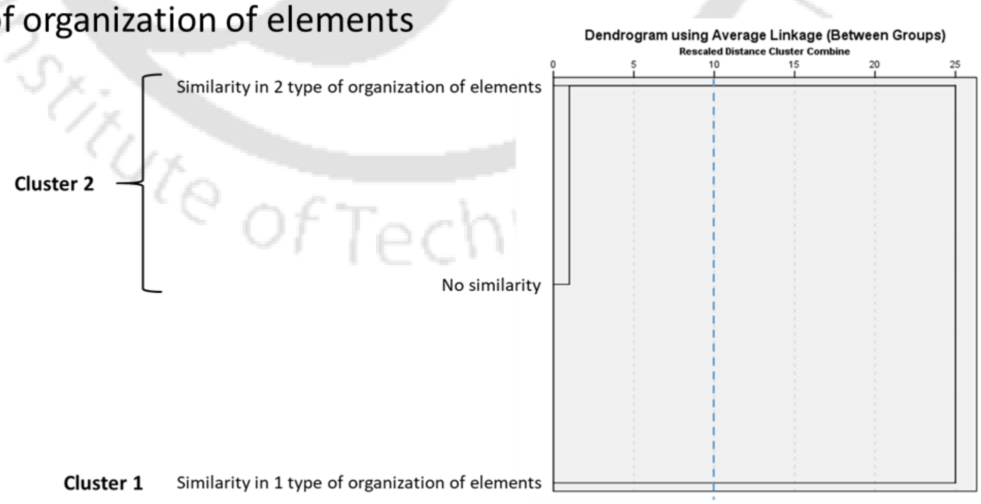


Figure 3.9 Dendrograms for ten form attributes (continued)

11. Type of Symmetries

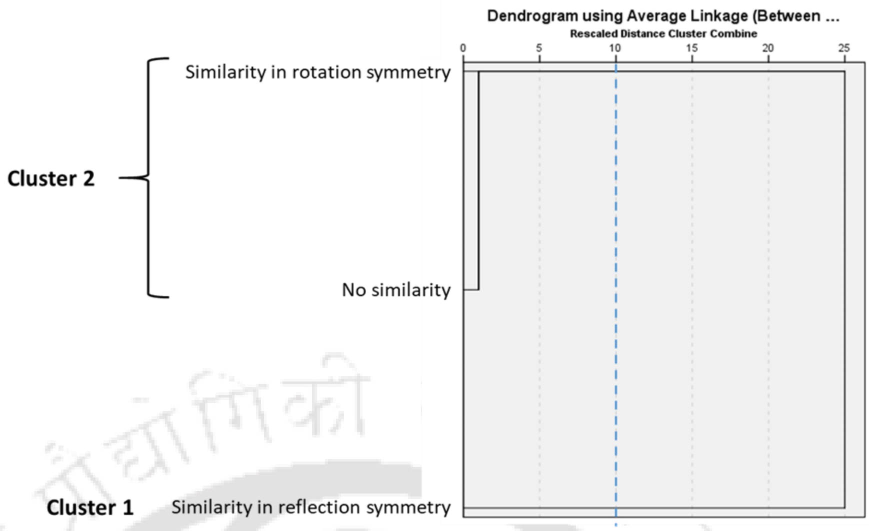


Figure 3.9 Dendrograms for ten form attributes (continued)

3.3.3 Results of Study 2

The visual analysis of thirty products for twelve form attributes indicates that similarity in certain visual cues and no similarity, both of them have emerged as major clusters/groups in analysed results (Table 3.5). All twelve form attributes have clusters/groups of similarity with the majority of the products falling in those clusters/groups e.g. form category - Cluster 1 and Primary Geometric Volumes & Surfaces – Cluster 1 & 3. These form attributes also have the clusters/groups of no similarity e.g. Hierarchy of order – Cluster 1 and Conditions expressed by axes – group 2.

This finding on similarity and no similarity in visual elements has important implications. It can be an important parameter in deciding upon the degree of resemblance and abstraction that designers are confronted with during the form generation process. We may consider similarity/more resemblance and No similarity/less resemblance/abstraction as the two extremes of a spectrum (Figure 3.10).

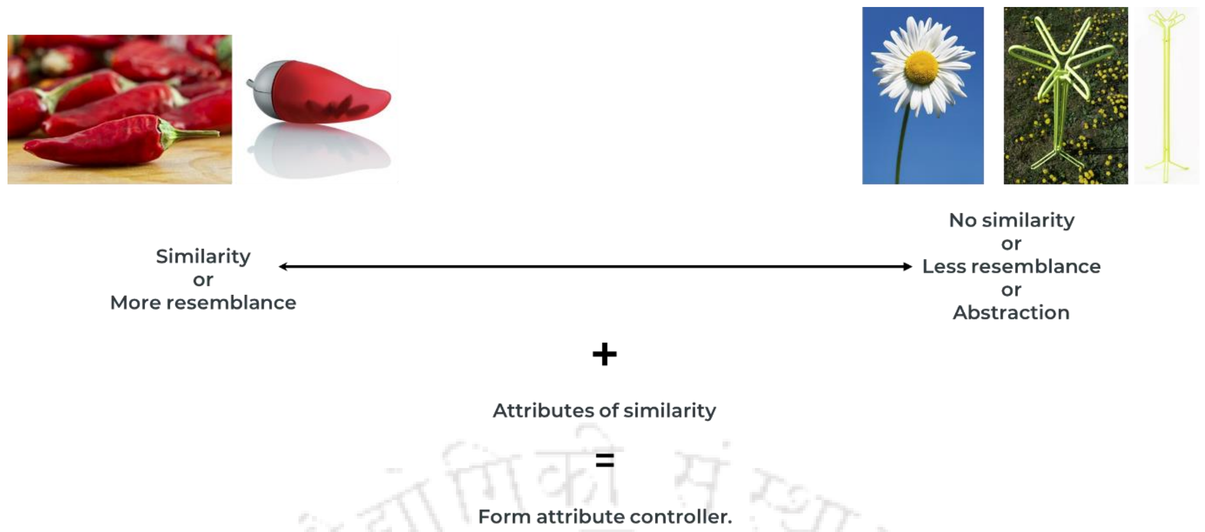


Figure 3.10 Spectrum of similarity and no similarity

This spectrum when merged with attributes of similarity, can help a designer to control abstraction in new designs through a form attribute controller (Figure 3.11). It can also result in generating a number of variations of design concepts following a generative approach of design. This study of analysing products inspired by nature has focused on the generation of the exterior form of the artefacts (Nature-inspired products). The outcome of our analysis has significantly helped to understand the relationship between perceptual similarity, form attributes, and abstraction in such products.

Table 3.5 Results of cluster analysis of thirty products

S.No	**Form Attributes**	**Number of Clusters/ Groups**	**Classified clusters and Groups**		**Number of products in each variable**
			Cluster/Group	**Attributes of similarity**	
1	Form category	4	Cluster 1	Both forms belong to the same form category	16
			Cluster 2	One form belongs to the central category and other belongs to main category or subcategory from the outer ring.	5
			Cluster 3	One form belongs to the main category & another one belongs to subcategory adjacent to main category	5

			Cluster 4	Both forms belong to two subcategories adjacent to main category.	3
				Two forms lie in opposite categories	1
				Both form belongs to two different main category	0
2	Primary Geometric Volumes & Surfaces	3	Cluster 1	Both forms have similar primary geometric volumes	18
			Cluster 2	No similarity of primary geometric volumes and surfaces in both forms	8
			Cluster 3	Both forms have similarity in primary geometric volumes as well as primary surfaces.	1
				Both forms have similar primary surfaces	3
3	Hierarchy of order	4	Cluster 1	No similarity in dominant, sub-dominant and sub-ordinate elements	10
			Cluster 2	Similarity in dominant & sub-dominant elements	8
			Cluster 3	Both forms have similar dominant elements	4
			Cluster 4	Both forms have similar sub-ordinate elements	2
				Similarity in Dominant & Sub-ordinate elements	2
				Both forms have similarity in all 3 elements (Dominant, Sub-dominant & Sub-ordinate)	2
				Similarity in Sub-dominant & Sub-ordinate elements	1
				Both forms have similar Sub-dominant elements	1
4	Type of axis	3	Cluster 1	Similarity in three types of axis exists in both forms	16
			Cluster 2	Similarity in one type of axis exists in both forms	7
			Cluster 3	No similarity in the type of axis among both forms	3

				Similarity in two types of axis exists in both forms	4
5	Conditions expressed by axes	2	Group 1	Both forms have a similarity in one type of condition expressed by axes.	20
			Group 2	No similarity in the type of conditions expressed by axes.	10
6	Types of axial movements	2	Cluster 1	Both forms have a similarity in one type of axial movements	16
			Cluster 2	No similarity in axial movements of forms	9
				Similarity in two types of axial movements	5
7	Types of axial relationships	2	Cluster 1	Both forms have a similarity in one type of axial relationship	17
			Cluster 2	No similarity in axial relationships among the two forms	7
				Similarity in two types of axial relationships between forms	6
8	Types of curves	3	Cluster 1	Both forms have a similarity in one type of curve	14
			Cluster 2	No similarity in the type of curves exist between forms	8
			Cluster 3	Similarity in three types of curves among forms	1
				Similarity in two types of curves in both forms	7
9	Transitional forms features	3	Cluster 1	Both forms have a similarity in one type of transitional form features	10
			Cluster 2	Both forms have a similarity in two types of transitional form features	9
			Cluster 3	No similarity in the type of transitional form features among two forms	9
				Similarity in three types of transitional form features	2
10	Type of organization of elements	2	Cluster 1	Similarity in one type of organization of elements	15
			Cluster 2	No similarity in the type of organization of elements	12

				Similarity in two types of organization of elements	3
11	Type of Symmetries	3	Cluster 1	Both forms have similar reflection symmetry	21
			Cluster 2	No similarity in the type of symmetries among two forms	5
				Similarity in rotation symmetry among two forms	4
12	Type of pattern	2	Group 1	Similarity in the type of patterns among two forms	10
			Group 2	Pattern doesn't exist	20

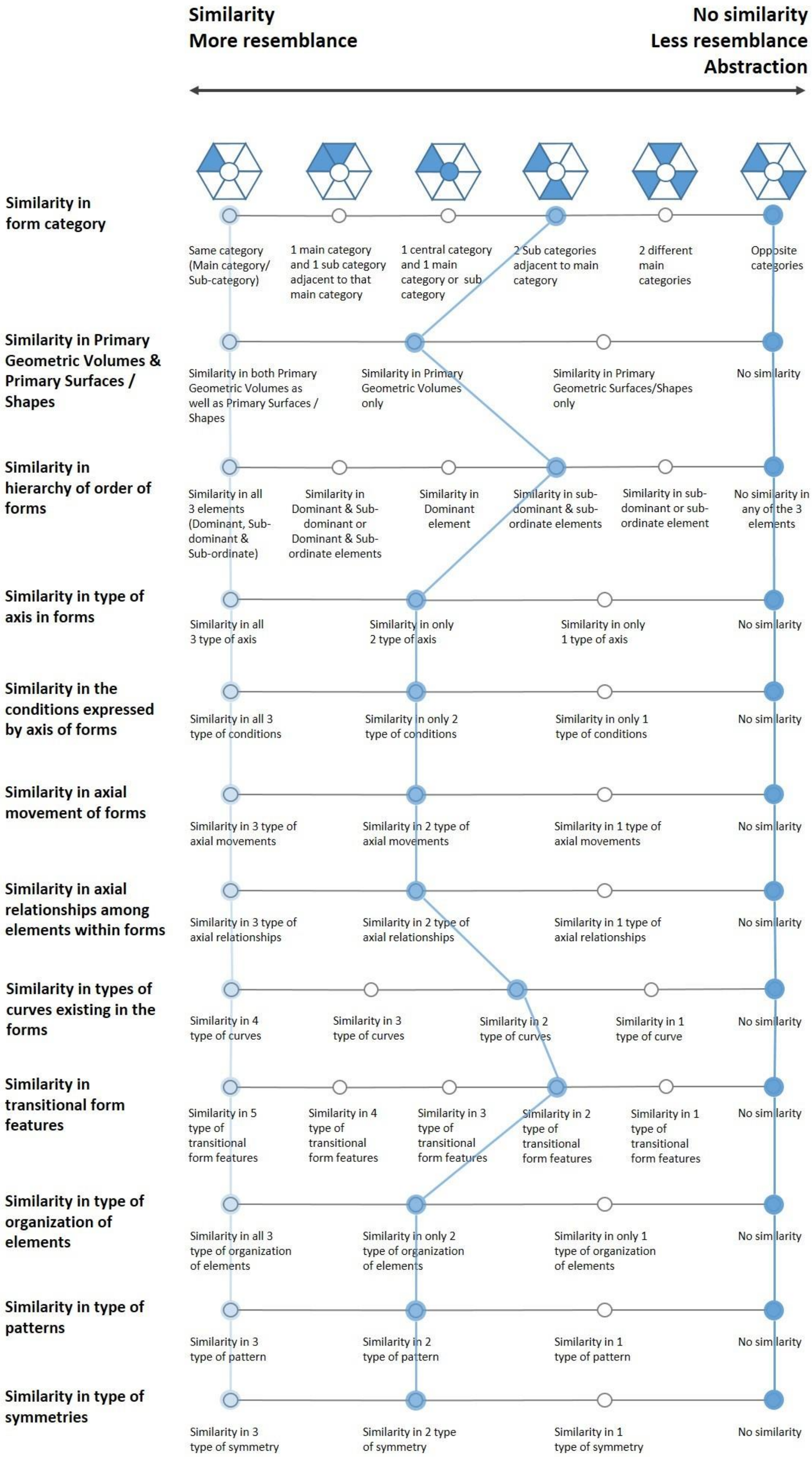


Figure 3.11 Proposed form attribute controller that can be used in a design tool

In our view, this kind of approach for three-dimensional visual analysis of nature-inspired product forms has not been attempted earlier. Hence, our experiment makes a novel attempt in developing a methodology that is more systematic. As is illustrated, it has perhaps made the process and manipulation of form generation more transparent. Thus, giving the designer insights and control in the generation of variations and transformation on the form in a more conscious and regulated manner. It contributes in presenting to the Design educators and practicing designers an approach in planning a more systematic approach in project assignments in product form generation inspired by nature.

The experiment in the study of products, is our second study that contributes in meeting the objective of this research.

3.4 Study (3a) on People – Study on approaches followed by professional designers

Continuing with the third aspect of Nigel Cross taxonomy as the framework for our research, in this section we focus upon people – more specifically the approaches followed by professional designers. In this study, we examine the approaches followed by some of the leading designers known for their unique professional work of nature-inspired product design. In their portfolio of professional work, are reflections of elements of nature as the source of inspiration. These are well-known designers of high repute. We source published resources, interviews, and journal interviews that are in the public domain to critically interpret their approach and thoughts on nature-inspired design. It is an attempt to understand their design thinking and inspiration of what and how they draw inspiration from nature to design these products. This part of the study constitutes the third aspect of our study - of people.

3.4.1 Objectives of study (3a)

The objectives of this study are to understand the design approach of five well-known designers and identify the various factors that they considered in their design process to generate forms inspired by nature. It makes an attempt in understanding Design thinking that has undergone into the generation of nature-inspired product form. The approach followed by these leading Designers in conceiving and transforming ideas from source into tangible product form. What may be the key underlying considerations in their processes in product form development.

3.4.2 Subjects (Professional Designers)

Five internationally acclaimed industrial designers were selected to benchmark excellence in Design for the current study. They were shortlisted based on their known works on nature-inspired design: Owen Jones, Christopher Dresser, Arthur Heygate Mackmurdo, Luigi Colani, and Ross Lovegrove.

3.4.3 Methodology

The study of existing literature that attempts to understand the approach of designers to design nature-inspired product forms is very limited and inadequate (Lutchmansingh, 1990) (Sala, 2007) (Chen & Sung, 2013), Further, published literature specifically on the design factors of such product forms is almost non-existent. However, a few researches are actively engaged in the area of forms and nature (Wong, 2010) (Burgess & King, 2004) (Irwin & Baxter, 2008).

Considering the limited available published studies that focus upon investigating the less explored area of understanding the design process of nature-inspired form generation, we had to examine different theoretical approaches that would help meet our research objective. Literature indicated that Grounded theory as a research methodology is best suited for the areas where no prior theory exists (Strauss & Corbin, 1998). Grounded theory is a qualitative strategy to derive a general, abstract theory of a process, action or interaction grounded in the data obtained from participants (Charmaz, 2006) (Strauss & Corbin, 1998).

For this experimental study, a methodology based on grounded theory was, therefore, adopted for the current study (Strauss, 1987) (Charmaz, 2006).

3.4.4 Data collection and analysis

Published literature suggests that documentary evidences and textual data are the research material that can provide significant information about human thoughts and human behavior (Denzin & Lincoln, 2000: 769). These research materials include memoirs, letters, diaries, newspapers, maps, photographs, paintings, etc. Investigators from different fields like social science, history, psychology, etc. use a different type of research material for their investigation e.g. ethnographers use data from field notes and interviews obtained from field observations (Strauss, 1987: 3). Researchers have used documentary and textual analysis in architectural research (Kellett, 1990) (Suwa & Tversky, 1997) (Wong, 2010), industrial design research (Lloyd & Snelders, 2003) (Blaich, 1989) & engineering design research (Lemons, Carberry, Swan, Rogers & Jarvin, 2010).

In the context of our study, we have used text material from books and research papers along with the transcripts of the interviews of designers as the main source of data for our analysis (Table 3.6). Our main consideration for the data collection was to search for the data which is a record of the designers own approach of design. This includes books published by designers or their interviews in audio or video format that explain their design discourse. We found books by Christopher Dresser and Owen Jones in which these designers have documented their design approach and design considerations. In case of Arthur Heygate Mackmurdo, we draw upon the research work by Lutchmansingh who investigated his design approach in detail. For Luigi Colani, we collected data from the two websites and a book. We used data from the interviews and ted talk for Ross Lovegrove. Figure 3.12 shows a few sample images of the work of these designers.

We followed Grounded theory as the basis for our analysis. Before starting the coding process, we sorted and organized the data based upon their type and source. After that a thorough reading was done through all the data to understand their overall meaning. Chunks and segments of the data that contain information about the design process were identified during this stage. During coding process, these chunks and segments of texts were coded following the grounded theory procedure proposed by Strauss and Corbin (Strauss & Corbin, 1998). The two stage-coding scheme was used to code the transcripts and textual data viz. open coding and axial coding (Strauss, 1987) (Strauss & Corbin, 1998). Open coding, the first stage of coding, was achieved by analysing a sentence, paragraph, and also perusing books as the data source and included simple and precise words that captured and condensed the meanings in the textual data. Open coding was done to create code that best fitted the data, which was achieved by staying close to the data during the coding process. The second stage of coding was axial coding, where codes obtained during open coding were categorized under core categories. During axial coding process, the codes that made most analytic sense were brought together around a core category to build a dense network of related codes. The entire coding process was done through a continuous comparison between data to data and data to codes (Strauss & Corbin, 1998) (Charmaz, 2006).

Table 3.6 Type of sources and their details

Designer	**Type of source**	**Detail about source (Name/URL)**	**In-text citation**
Owen Jones	Book	The grammar of ornament. Day and Son Limited, Lithographers to the queen, London (1856).	(Jones, 1856)
Christopher Dresser	Book	The art of decorative design. Day and Son, Lithographers to the queen, London, (1862).	(Dresser, 1862)
	Book	Studies in design. Cassell, Petter and Calpin, London (1876).	(Dresser, 1876)
Arthur Heygate Mackmurdo	Research Paper	Lutchmansingh, L. D.: Evolutionary Affinity in Arthur Mackmurdo's Botanical Design. De-sign Issues, 6(2), 51–57 (1990).	(Lutchmansingh, 1990)
Luigi Colani	Website	http://www.colani.ch	(Luigi Colani, 2007)
	Website	https://designmuseum.org/designers/luigi-colani	(The Design Museum, 2015)
	Book	The Fundamentals of Product Design. AVA Publishing, Switzerland (2009).	(Morris, 2009)
Ross Lovegrove	Ted talk	https://www.ted.com/talks/ross_lovegrove_shares_organic_designs	(Ross Lovegrove, 2005)
	Interview	https://www.youtube.com/watch?v=VebEnzMrAug	(Ross Lovegrove, 2010)
	Interview	https://www.youtube.com/watch?v=6epm8fkUwzw	(Ross Lovegrove, 2017)

Figure 3.12 Sample designs by the five designers

3.4.5 Results of Study (3a)

The text analysis extracted fifty-one coded concepts, grouped under fourteen core categories: *Inspiration, Observation, Necessary conditions, Laws in natural forms, Principles in natural forms, Manipulation in natural forms, Mental conceptions, Symbolism, Art, Pleasure and emotions, Modes of externalizing ideas, Transformative processes, Previous work, Design philosophy* (Figure 3.13). The core categories and the linked coded concepts were the design factors that influenced the work of five designers. All the core categories and coded concepts related to them were organized into a network diagram (Figure 3.13). This diagram is grounded in the words and text of designers under study as all the design factors were directly coded from the primary source of data.

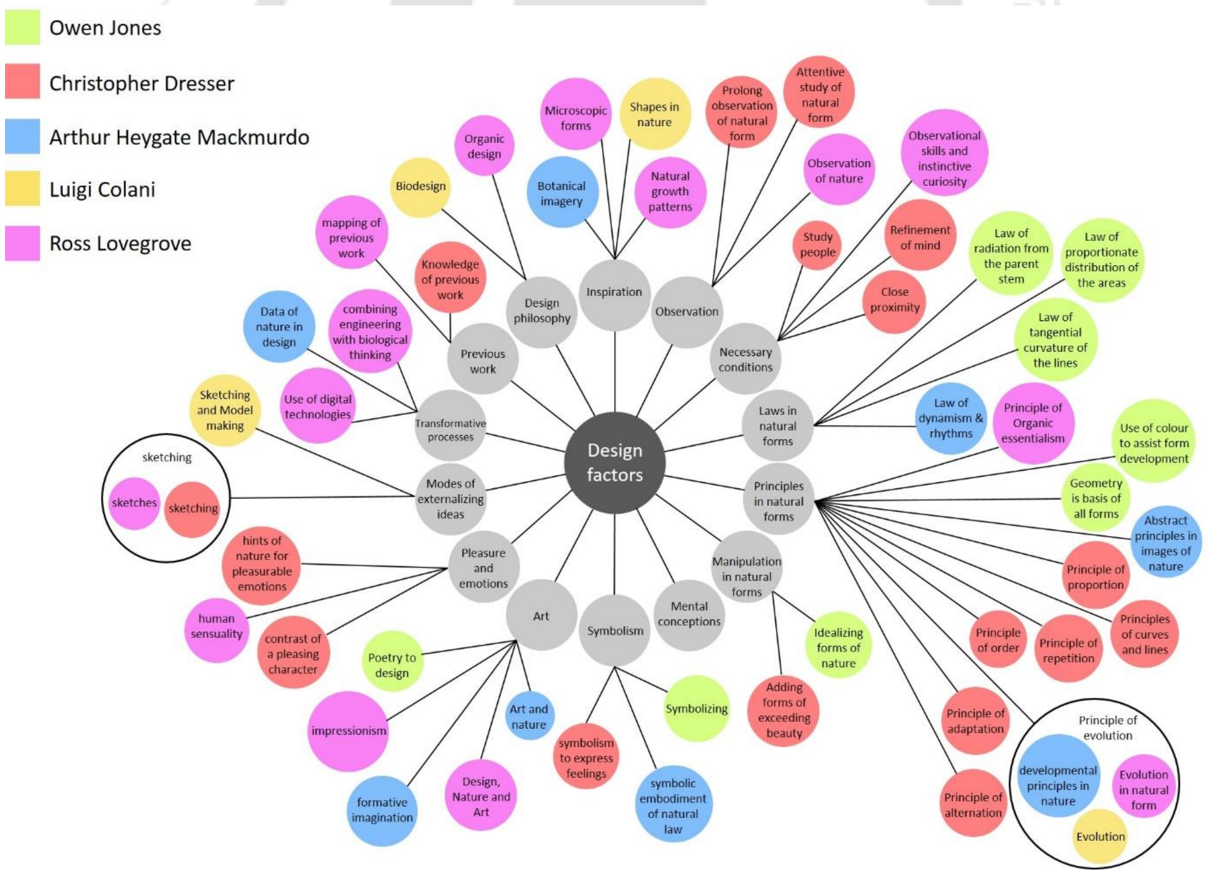


Figure 3.13 Design factors (Core categories & Coded concepts) identified from the text analysis of the five selected international designers

A detailed discussion of the fourteen core categories and their subcategories is as follows:

(1)Inspiration:

The core category indicates the type of inspiration from nature, which designers mostly preferred for their design work. Mackmurdo preferred the use of *Botanical imagery* for his designs; these are the images of natural environment like marine vegetation (Lutchmansingh, 1990). Ross Lovegrove (2005) explored *Microscopic forms* for his inspiration. These microscopic forms are the sources of new form elements as they are not visible to the naked eye but can be explored only using instruments like an electron microscope. He has also drawn inspiration from *Natural growth patterns* like fractals in nature (Ross Lovegrove, 2005). Luigi Colani looks for *Shapes in nature* to get inspiration. Products designed by him display a close resemblance with natural shapes and forms (Luigi Colani, 2007).

There seems an inherent wonder about order and harmony in the hidden and the unseen in nature. This seems to inspire these designers in understanding the underlying science and bringing this novelty into their design.

(2)Observation:

All the designers concur that observation of a natural form is necessary to collect visual information about that form. Ross Lovegrove (2010) mentions that his work is very much influenced by the *Observation of nature*. Christopher Dresser suggests that a *Prolong observation of natural form* is necessary to investigate and to understand its refined shapes. He also explains that this observation could be an *Attentive study of natural form* which involves the study of various parts and their orientation, shapes, lines, colours, contour in organs and sections of forms (Dresser, 1862).

(3)Necessary conditions:

These conditions support and help designers to understand nature and reflect it in their design work. Dresser proposes that being in *Close proximity* to a natural form helps to discover new forms within a single natural form. He states that to appreciate the delicacies of form and line, *Refinement of mind* is required. For this refinement, constant observation and investigation of natural forms is required. He also suggests that to design an ornament for the people, it is necessary that one should enter the spirit of ornament. For this, the student must *Study people*, their religion, habits, nature of their food and character of their climate, etc. (Dresser, 1862). Referring to the drawings of Leonardo da Vinci, Ross Lovegrove explains how good *Observational skills and Instinctive curiosity* work together to create amazing art (Ross Lovegrove, 2005).

(4)Laws in natural forms:

These are the underlying laws which we find everywhere in nature. For example, the laws on which leaves and flower grow. Owen Jones identifies some of these laws as:

- *Law of radiation from the parent stem* – "In surface decoration all lines should flow out of a parent stem. Every ornament, however distant, should be traced to its branch and roots".
- *Law of proportionate distribution of the areas* – "Areas in the leaf are so perfectly distributed that repose of the eye is maintained".
- *Law of tangential curvature of the lines* – "All junctions of curved lines with curved or of curved lines with straight should be tangential to each other" (Jones, 1856).

Mackmurdo's work was based on the *Law of dynamism & rhythms*, which is about the dynamic changes or rhythmic changes in the natural form in response to an external force of wind or water e.g. swaying of plants in air or water (Lutchmansingh, 1990).

(5)Principles in natural forms:

These principles are the guiding ideas that may help a designer to observe, study and understand the natural form or any natural phenomena.

Christopher Dresser explains some of these principles (Dresser, 1862):

- *Principle of order:* Various parts of a plant follows a principle of order during their development phase. This principle of order is a result of geometric arrangement that exists in these parts e.g. spiral leaf arrangement.
- *Principle of repetition:* Principle of repetition is an indication of plant growth. Repetition is further divided into four categories: Radiating repetition (in

flowers), Elongated repetition (in leaves), Extended repetition (growth of the plant in a divergent manner e.g. Parsnip flower), Repetition of a spot or a part.

- *Principle of alternation:* Alternation in botanical phraseology is referred to the arrangement of parts of the flower and distribution of leaves on a stem. In flowers, the principle of alternation governs the arrangement of four series of parts: first series (ring of outer green leaves), second series (ring of coloured leaves), third series (awl-shaped or thread-like members), and inner series (a central organ). These series are arranged in an alternate fashion, for example, third series parts do not fall over the second series parts but in the space between them, they alternate with them and also with inner series. In case of leaves, second leaf is situated at the opposite side of stem and when viewed from the top second pair falls between the spaces of units of first pair.
- *Principles of curves and lines:* There is beauty and power associated with curves and line. Beauty lies in the subtlety of a curve. Curves are full of energy and life. To capture that beauty of life, one must have energetic curves in design. If observed carefully one can easily spot curves like parabola, hyperbola, ellipse, catenary, involute, convolute and arc in nature. Among various curves that exist in nature, the line is found to be the most powerful in character. The line of life is a class of line, which expresses a strong vital power in nature. The direction of growth of leaf and buds are related to this line. The rule of tangential union, which states that the union of curves with curves, or curves with right lines must always grow place in a tangential manner.
- *Principle of proportion:* Proportion in nature is a harmonious relationship among several parts or to the whole organism. Proportions in nature are very pleasing and are of subtle character. Professor Adolf Zeising proposed the 'Golden cut' as a law prevailing in the entire universe.
- *Principle of adaptation:* Adaptation of plants to the surroundings is something that can be learned from nature and can be applied to the artefacts to make them adaptable to the conditions in which they will be used. The form of different parts of plants are in harmony with the surroundings and environmental conditions in which the plant exist. Similarly, objects are adapted to the purpose for which they are intended. For example, in nature plants that appear as horizontal objects have radiating structure and plants that

appear as vertical objects have a bi-symmetrical structure. In architecture, the same principles are applied to the floor-patterns and wall-decorations.

- Owen Jones explains two principles that he observed in natural forms. First one is related to the use of colour to assist form development and second one is on geometry as a basis of all forms (Jones, 1856).
    - *Use of colour to assist form development:* Use of different colours for the transition of form and also to make features of form distinct is something that can be used as the guiding inspiration of nature. Different colours separate different forms in an organism. Just like the natural law that exists in nature where we generally find primary colour on buds and flowers and the secondary colour on leaves and stalk.
    - *Geometry is the basis of all forms:* one can observe the symmetry and regularity in the natural forms like flowers when viewed in plan or elevation.
- *Abstract principles in images of nature:* Mackmurdo explains the abstract principles in images of nature as principles of irregularity, arbitrariness, and economy of form that exist in nature (Lutchmansingh, 1990).
- *Principle of Organic essentialism:* Ross Lovegrove defines the principle of organic essentialism as reducing a form to its minimum material mass, which means removal of the extra material from the form that is not required (Ross Lovegrove, 2005).
- *Principle of evolution:* Many designers have noticed the role of evolution in the development of natural forms. Mackmurdo explains that even for an artist it is necessary to understand the developmental principles in nature. These are the principle of organic evolution derived from the observation of natural phenomena (Lutchmansingh, 1990). Natural forms improve and evolve with time. The form of organisms is a result of millions of years of evolution, which are highly functional (Ross Lovegrove, 2005) (The Design Museum, 2015).

(6)Manipulation in natural forms:

Owen Jones suggests that for a good work of art the forms of nature must be *idealized* based on the observation of principles, which regulate the arrangement of forms in nature (Jones, 1856). Christopher Dresser also proposes that *adding forms of exceeding beauty* can modify natural forms.

These adaptations and modification of natural form may be used to enhance our pleasure (Dresser, 1862).

(7)Mental conceptions:

Mental conceptions related to natural forms is the embodiment of the idea or conception of natural form into the form of the existing object e.g. conception of blooming of flowers. This mental conception could be about orientation of parts, shapes of parts, colours, and details related to a particular form like character of line and order (Dresser, 1862).

(8)Symbolism:

Natural forms are very often used to *symbolize* something else in the man-made world like in ancient Egypt lotus was the symbol of power (Jones, 1856). Dresser used *symbolism* to *express feelings*. It is the way of expressing definite ideas through ornamental shapes making use of forms having acknowledged significance e.g. leaf-buds for spring, leafless branches for winter, and orange-blossoms for innocence (Dresser, 1862). Mackmurdo also advocates the *symbolic embodiment of natural law*. He describes the embodiment of natural law in the form is way to approach symbolic function of botanical design (Lutchmansingh, 1990).

(9)Art:

Designers have identified art as an important factor for nature-inspired designs. Mackmurdo explains the link between *art and nature* as work of art is similar to the work of nature. Design, as manifested in art, is work of human and plant is a work of nature. Primarily plant and human both are influenced by same 'nature' and therefore work of art is similar to work of nature. He also suggests that the independent role of *formative imagination* can help to avoid transcription of nature (Lutchmansingh, 1990). *Design, Nature, and Art* are the three things that significantly influence the work of Ross Lovegrove. He also supports the use of *impressionism* as an important art form for expressing ideas (Ross Lovegrove, 2005). Ornamentation is not different from the architectural member rather it forms a part of that member. This harmony between ornamentation and architectural elements adds *poetry to design* (Jones, 1856).

(10)Pleasure and emotions:

Christopher Dresser in his book discussed *hints of nature for pleasurable emotions*. He suggests that while following hints of nature with an inward instinct or passion one can design the forms, which yield pleasure to our mind. He also explains how the diversity of character in parts within a natural form gives rise to the production of a *contrast of a pleasing character* (Dresser, 1862). Ross Lovegrove believes that nature has a direct link with *human sensuality*. Organic design directly influences the human senses and their sense of relationship with things (Ross Lovegrove, 2005).

(11)Modes of externalizing ideas:

Designers mostly rely on two modes to externalize the ideas that they have in their mind: Sketching and Model making. Christopher Dresser suggests that *sketching* every stage of form development of the natural form can help the student to describe that natural form precisely with delicacy and feelings, which will further help the student to define the use of that form in ornament and its symbolic significance (Dresser, 1862). Ross Lovegrove (2010) *sketches* whatever he visualizes. In his design process, Colani develops his idea through *sketching and model making* (Luigi Colani, 2007).

(12)Transformative processes:

This factor includes the approaches followed by designers to transform their ideas into tangible designs. Mackmurdo's designs are the result of his unique design approach in which he combines the *data of nature* with the rules of abstraction and requirement of decorative design (Lutchmansingh, 1990). Ross Lovegrove employs *digital technologies* like parametric design software, 3D printers, and 3D scanners to reinvent his design process of form creation. When industrially manufactured products are subjected to biomorphic or organic design treatment, one has to search the creative solution within engineering constraints but in harmony with nature, He attempts to find such creative solutions by *combining engineering with biological thinking* (Ross Lovegrove, 2005).

(13)Previous work

Sometimes referring to previous work may help designers to overcome design fixations. Ross Lovegrove (2017) says the *mapping of previous work* helps to position himself and see the missing gap or new scope of work. Dresser has also many times referred his *previous work to gain knowledge* of what has already been done (Dresser, 1876).

(14)Design philosophy

With experience gained with time and years of design practice, designers have developed their own design philosophies. Famous for his philosophy of *Biodesign*, Luigi Colani has designed products that are characterized by round and organic forms inspired by nature (Morris, 2009). Ross Lovegrove is well known for his design philosophy of *Organic design*, based on his principle of organic essentialism (Ross Lovegrove, 2005).

To summarize, in the opinion of all these five leading designers, they agreed that nature is a great source for designers to draw their inspiration from. To be able to do so, there is a need to create an environment for their work that is in close proximity to nature. This will enable them to have an immersive experience of studying, observing and understanding the various principles, natural laws that can be used to draw into their design works. The designer has the creative freedom to firstly understand these aspects of nature and also to go beyond to add new dimensions of symbolism and meaning onto the products they design. This can be achieved by understanding the values, beliefs and practices of the society that they are designing for. All the designers agreed that translating such an understanding of laws and principles in nature will translate into good and aesthetically well designed products if they are able to incorporate these into their design by using the state–of-art knowledge and understanding of engineering principles.

The outcome of this study also brings out one more aspect that has implications on planning the structure of introducing a course in nature inspired design. The fourteen criteria outline an order that a design educator can follow in planning the course.

Appropriate assignments can be planned to include a keen study of nature inspired design projects.

This study formed our basis to undertake this next experiment of our study of people. We planned a design task in the study of the process of form generation of a scent bottle inspired by nature. This was undertaken with senior students of Design at our Design department. The study and its objects are presented in the next section to follow.

3.5 Study (3b) on People – Study on approaches followed by design students

In the previous study, we attempted to understand the approach of professional designers. However, there exists a difference in the design cognition of professional and novice designers. Therefore, to understand an alternative perspective on people and processes, we conducted an experiment to understand and interpret the design strategies and processes of senior design students who formed the subject for this study.

This study is more applied in nature. We introduced an assignment in design of a product – a perfume bottle, to senior students of Design at our Department of Design at IIT Guwahati. It aimed to see first-hand the process these young designers follow in design and to interpret the design thinking process they undergo by analysing their journey of developing their ideas. To gain insights of their thought processes of analysis, and transformation from mental ideas into tangible product forms by following a think-aloud process for our analysis in this experiment.

3.5.1 Objective of study (3b)

The objective is to study the design approach of design students and identify various factors that are engaged in their thinking during the process of generation of product forms inspired by nature.

3.5.2 Methodology

As outlined in the objective, the primary goal of this exploratory research is to understand the design thinking process adopted by design students during an exercise of designing nature-inspired product form. The inductive theory building approach of grounded theory makes it suitable to investigate the less researched subject of nature-inspired form generation for the current research (Strauss & Corbin, 1998).

Considering that for more than four decades, protocol analysis has been used in design research to understand design processes, we adopted the Protocol Analysis method for our study. It is a well-established technique used to study design processes and design cognition in various disciplines like Architecture, Industrial Design, Mechanical Engineering, Electronic Engineering, Software Design, and other domains (Cross, 2001)

Protocol analysis is the process of collecting verbal data from a subject who is performing a design task. There are three ways to collect this verbal data: Concurrent verbalization, Retrospective verbalization, and Introspective verbalization (Ericsson & Simon, 1993). While concurrent and retrospective verbalization methods yield the most faithful and detailed information about the problem-solving processes, concurrent protocol analysis is the most widely used method in the design domain (Ericsson & Simon, 1993; Chan, 2001). In concurrent protocol analysis subjects are instructed to think aloud while performing a design task and by doing so they are concurrently reporting the content of their short-term memory. These verbal reports help a researcher to get insights into how subjects develop solutions to that problem (Ericsson & Simon, 1993).

In this study, we adopted the method of concurrent protocol analysis to collect verbal data from a select group of design students participating in this experiment. Subsequently, our study employed the qualitative research methodology of grounded theory (Strauss, 1991) (Creswell, 2013) to analyse the data and find various factors responsible for the development of nature-inspired product form during their design process.

Design tasks

In the process of designing nature-inspired product forms, a designer more often, either uses physical three-dimensional natural form or searches for images in sources like books, internet etc. Therefore, in our experiment, we planned to include two tasks of developing the form of a perfume container that is inspired by nature as shown in Table 3.7.

The first task involved the use of two-dimensional representation (Images) drawn from nature while in the second task we introduced a Hibiscus flower as a three-dimensional source of inspiration from nature. The perfume container was selected to keep its functional requirement to a minimum and enable the participants to focus on developing the form of the container rather than attend to functional aspects, intended market, and other factors like brand identity and manufacturing process.

Table 3.7 Two design tasks for the experiment.

Task No.	Instructions given to the students
Task 1	Design a 50 ml perfume container taking inspiration from natural forms. You are permitted to use the internet to search for sources from nature for inspirations.
Task 2	Design a 50 ml perfume container taking inspiration from a Hibiscus flower provided to you.

Participants

Protocol analysis is expensive and requires a substantial amount of time (Ericsson & Smith, 1991). As a result, most of the studies require a small sample size. Purposeful sampling strategy was adopted for the current study (Creswell, 2007). We selected senior students from the Master of Design (M.Des) programme who had recently completed their academic course work at the time of this experiment. The knowledge of the structure of visual relationships (Hannah, 2002) and the principles of three-dimensional visual analysis (Koler, 1994) was the essential criteria for their selection. Participants included 12 senior master's students in industrial design (9 male+3 female). The age of subjects ranged from 23 to 28 years, the average age being 25.5 years. Deciding factors for the number of participants include: Detail in the collected data from each participant for each task and the saturation achieved during analysis.

It was also decided to include more number of participants if the saturation is not achieved with 12 participants.

Experimental set-up

The experiment was conducted in a closed room equipped with two video cameras to record all verbal data and sketching activities of each individual participant (Figure 3.14 a & b). A3 papers, pencils, eraser were provided to the participants along with a computer to access the internet for design Task 1 (Figure 3.14 c) and Hibiscus flower for design Task 2 (Figure 3.14 d).

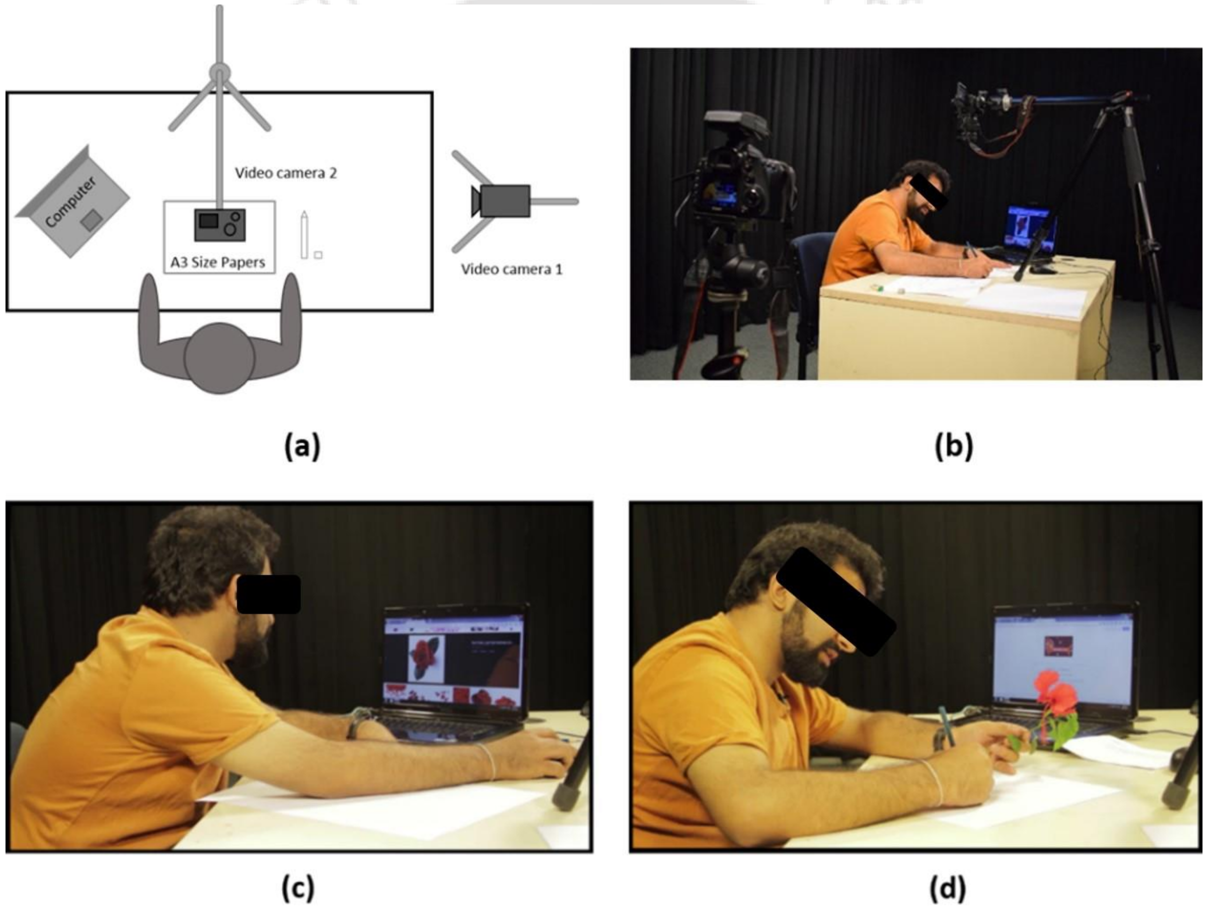
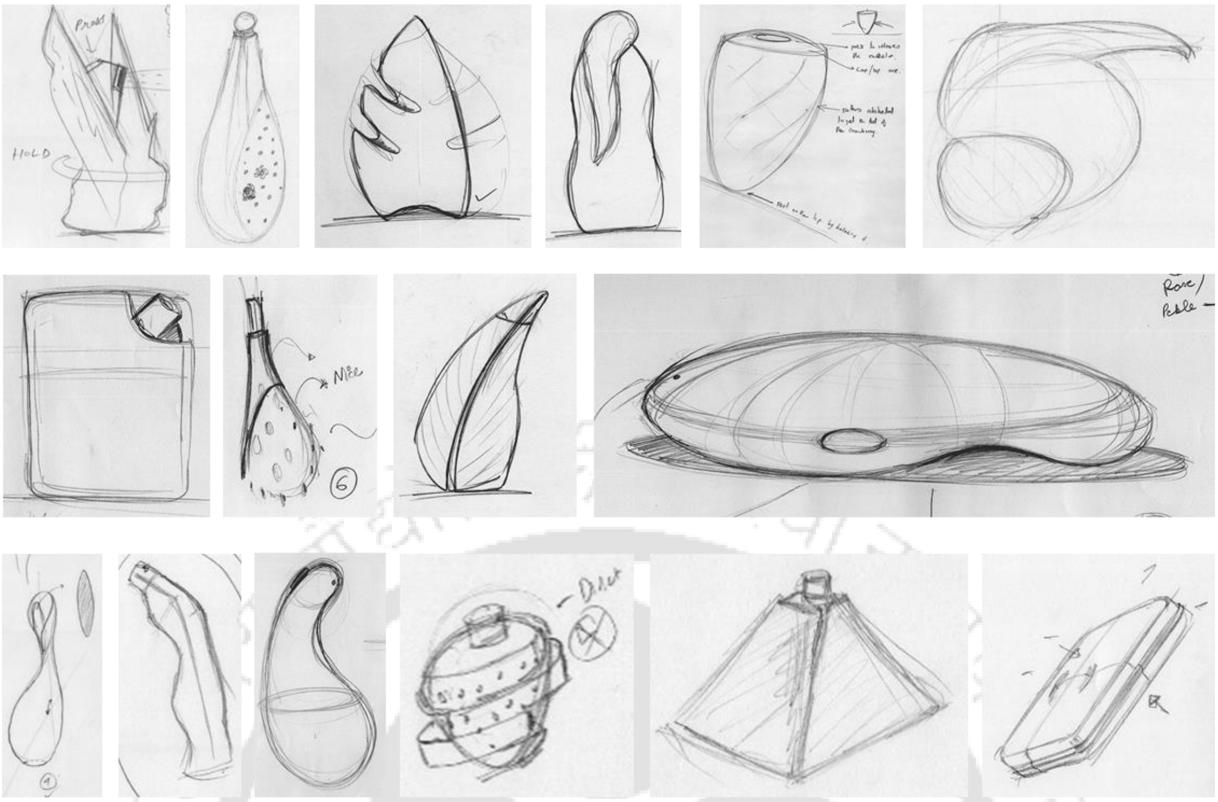


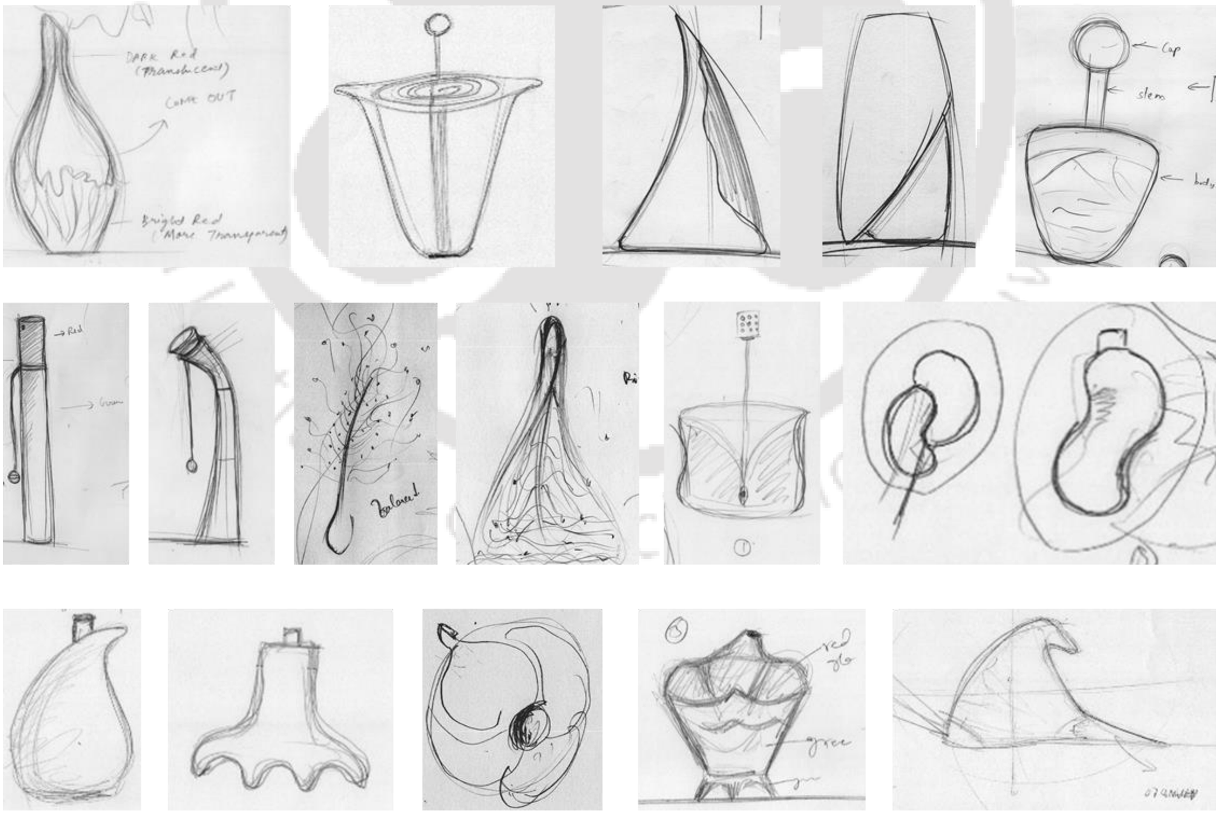
Figure 3.14 (a) & (b) Experimental set up for Verbal Protocol Analysis, (c) Design Task 1, and (d) Design Task 2.

Experimental procedure

A short think-aloud exercise was conducted before main experiment to make participants familiar with the think-aloud method. At the beginning of each task participants were given design brief as a written document. Participants performed both the tasks one after another. While working on the tasks, participants were asked to think-aloud. All the verbal data and sketching activities were recorded by the two video cameras. The participants were asked to generate as many concept as they can and they were free to submit the tasks whenever they feel out of ideas. The average time duration for Task 1 was 22 min 27 sec and for Task 2 was 14 min 13 sec. Sample sketches of the participants for Task 1 and Task 2 are shown in figure 3.15.



(a)



(b)

Figure 3.15 Sample sketches of the participants for (a) Task 1 and (b) Task 2.

Data collection and analysis

The transcribed texts with time stamping formed the main data for analysis but sketches also provided additional support (Figure 3.16). Three stage-coding scheme of grounded theory was used to code the transcribed data: open coding, axial coding and selective coding (Strauss, 1991) (figure 3.17 a).

Sub	Time (min)	Segments/episodes	Images	Open Coding	Axial Coding
M1	08:58 – 09:08	So this is a bottle and it has some step kind of thing step by step it is reducing the shape something		Reduction in shape	Manipulation
M1	09:09 – 09:46	So lets say this is the basic base and the next one will come inside of this form and next one is coming something like this and the top part something like this and			
M1	09:47 – 10:14	Any other interesting forms (image search)		Image search	Inspiration Search
M1	10:15 – 10:39	This another leaf you can see it has a small head kind of shape and it has cuts here one two three		Head kind of shape and cuts	Morphological Observation & illustration (inspiration)
M1	10:40 – 11:00	What about a perfume bottle it has a clearance at the centre (sketch)		Central clearance	Mapping (Form)
M1	11:01 – 11:07	I am not taking the other part I am just simply keeping it as plane		Selective area	Element Extraction Strategies (Cutting)
M1	11:08 – 11:19	And it has a curve here and this shape		Curves & Shape	Morphological Observation & illustration (Concept)
M1	11:20 – 11:33	So basically this kind of shape			
M1	11:34 – 11:57	(Image search)looking for other leaves		Image search	Inspiration Search (Specific category)
M1	11:58 – 12:09	Patterns of leaf (Image search)		Patterns of leaf	Inspiration Search (Specific category)
M1	12:10 – 12:56	Now I am changing something like patterns of leaf (Image search)			
M1	12:57 – 13:03	So just drawing I think this is not the original leafs			

Figure 3.16 Excerpt from the collected data

Open coding was the first stage of coding applied to the segments of the transcribed texts. Codes during open coding were generated by close inspection of each segment line-by-line or word-by-word while moving quickly through the data. These codes were kept simple and precise. To stay close to the data most of the codes during this stage were in vivo codes, which provided a useful analytical point of departure. In this stage, concepts are extracted from the texts to reach a conceptual level necessary for the theory development. These are called coded concepts.

The second stage of coding was axial coding, where we shift our focus from data to the coded concepts obtained after open coding. During this stage, the analysis was done around the axis of one category at a time to build a dense network of relationships around that axis. The codes generated in this stage help to synthesize and organize a large amount of data obtained after open coding. Codes obtained during this stage were called as main categories. Coding during this stage is conceptual where linkages between coded concepts and main categories were made. In some cases, we have also developed a third level of sub-categories due to the increased density of the codes.

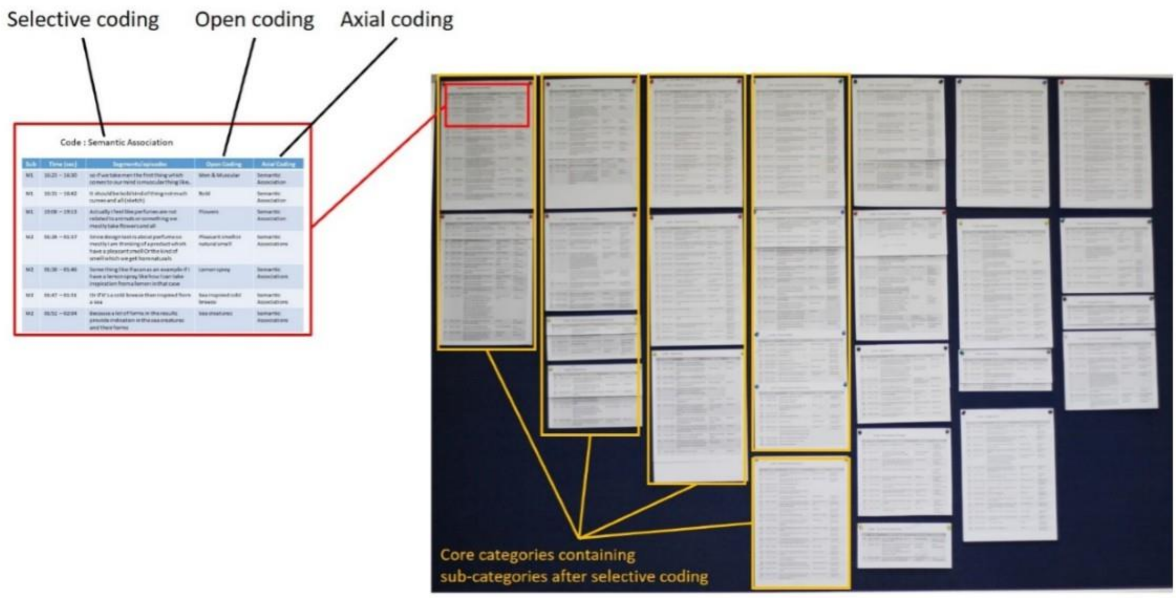
The third stage of coding was selective coding, which was done systematically to generate core categories. In this stage, all the coded concepts, main categories, and sub-categories were systematically linked with the core categories. These core categories formed the key factors, which are responsible for the designing of nature-inspired product form of the perfume bottle. The findings were first represented in the form of a network diagrams that later helped us to develop hierarchical diagrams (Figure 3.17 b).

The constant comparative method of data analysis was followed throughout the coding process. The coded concepts from both the tasks were collectively used to generate main categories, sub-categories and core categories. It was presumed that findings following this approach would later help in the development of an emergent theory/theoretical framework on nature-inspired product form generation.

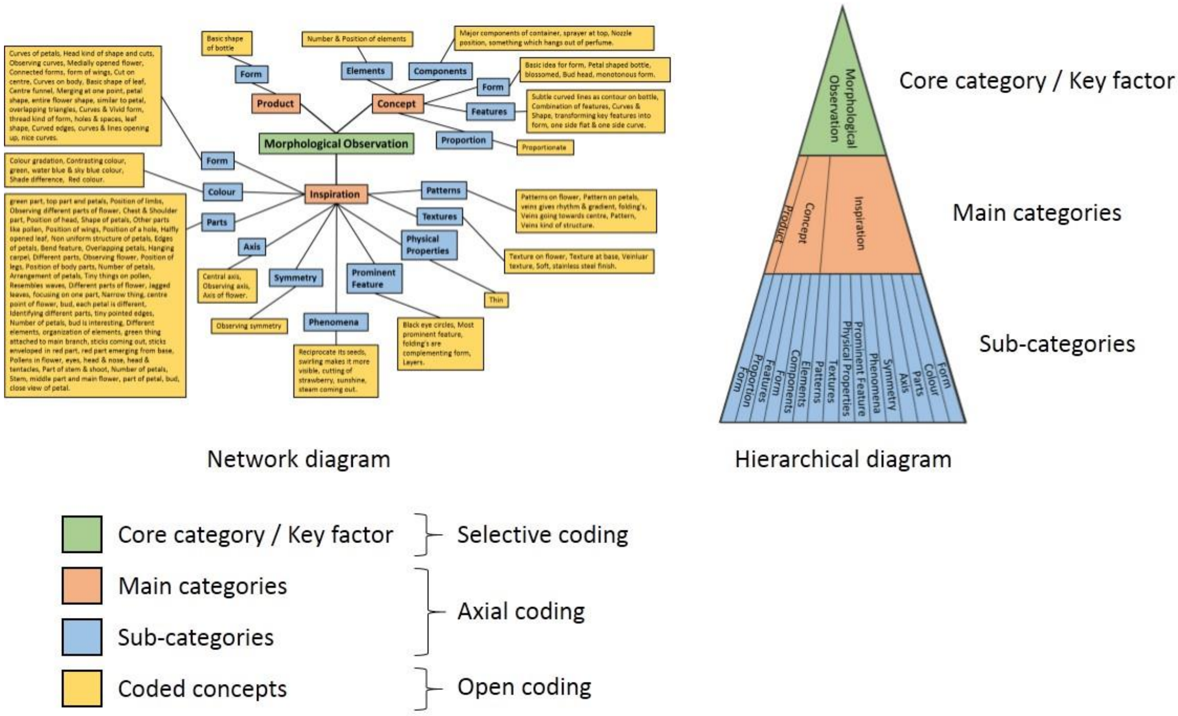
Note on reliability:

We did not perform any inter-rater analysis for the coding. The codes and categories in our study are grounded in the data obtained from the twelve participants. Due to its standardised format of analysis, the grounded theory does not require inter-rater reliability measurements (McDonald et al., 2019). The rigorous process involves constant comparative method of data analysis, followed by three stages of coding, and finally development of theory. Constant comparative analysis helps a researcher to refine theory at every stage of the process (Strauss and Corbin, 1998) (Creswell, 2013). For a grounded theorist, codes are one of the interim product and not final result that require testing. It is the process in addition to codes that generates a grounded theory (Grinter, 2010).

However, as per the demand of some journals we calculated intra-coder agreement for the collected data. The data was coded twice with a time gap of two months by a single coder. All the entered codes were compared with other codes of that category to check if they were related to each other or not. If a code did not fit into an existing category, it was moved to another category; or new category was created and data was recoded. The intra-coder agreement was 99.2% for two sessions of the coding with a time gap of two months.



(a)



(b)

Figure 3.17 (a) Three stage-coding scheme of transcribed text, (b) Network diagram and a Hierarchical diagram constructed after coding

3.5.3 Findings

The coded concepts obtained after open coding, main categories and subcategories after axial coding and core category after selective coding were first organized into network diagrams that later helped in the development of hierarchical diagrams. Eleven core categories emerged after analysis that were found most appropriate in terms of the form generation process. The theoretical saturation was achieved for the tenth participant where no new categories emerged relevant to the form generation process. However, data for the remaining two participants was also coded to confirm the saturation. After achieving saturation no more participants were included in the experiment.

The eleven core categories are the key factors that participants considered while designing nature-inspired product form. During axial coding, it was found that some codes could be further categorized into two levels of axial coding. The five key factors: *Inspiration, Morphological Observation, Strategies, Manipulation in Form* and *Possibilities* have two levels in axial coding. The other six key factors: *Semantic Associations, Experience, Elements Extraction, Mapping, Judgement* and *Triggers* have a single level of axial coding.

Findings of this study are covered under three sections:

- Section a: covers all the eleven key factors in detail with their respective network diagrams and hierarchical diagram.
- Section b: discuss the influence of these of eleven key factors on design process of design students.
- Section c: Explain the links between categories and overlapping key factors.

Section a: Eleven key factors

In the following sections, all the eleven key factors are discussed through their network diagrams and hierarchical diagrams.

1. Inspiration

Inspiration factor includes the actions of design students related to their search and selection of inspiration to start their new concept (see Figure 3.18 a). For task 1 subjects were, free to search their inspiration on the internet as well as seek for some inspiration in their mind (mental images). An excerpt of the transcript below explains these two approaches for inspiration search.

Table 3.8 Excerpt of the transcript

M1	01:59 – 02:08	I am looking for rose flowers
M7	14:51 – 15:28	I am just searching the word premium so let see what all images come
M2	03:21 – 03:37	So maybe as if now I am thinking about which fruit or which vegetable I need to be taking to give that flavor
F3	00:00 – 01:38	I will write down natural forms first – Flowers, Animals, Birds, Aquatic life, Mountains, Rivers, Tornado, Ocean ripples, Stones, Trees, Fruits…hmm…Ok

The text analysis extracted one hundred and eighteen coded concepts, which are grouped under two main categories *Search* and *Selection*. Coded concepts under *Search* and *Selection* are further divided into two sub-categories *External Stimuli (Internet)* and *Internal Stimuli (Mental Images)* (see Figure 3.18 a). While using *External Stimuli (Internet)* students browsed the internet for their inspiration and in the use of *Internal Stimuli (Mental Images)*, students are thinking of inspiration in their mind. *External Stimuli* of *Selection* category is again divided into two sub-categories *Internet* and *hibiscus flower*. The category *hibiscus flower* comprises of all the concepts related to the features of hibiscus flower that students had selected to use in their concepts. The key factor, main categories, and sub-categories are represented in a hierarchical diagram (see Figure 3.18 b).

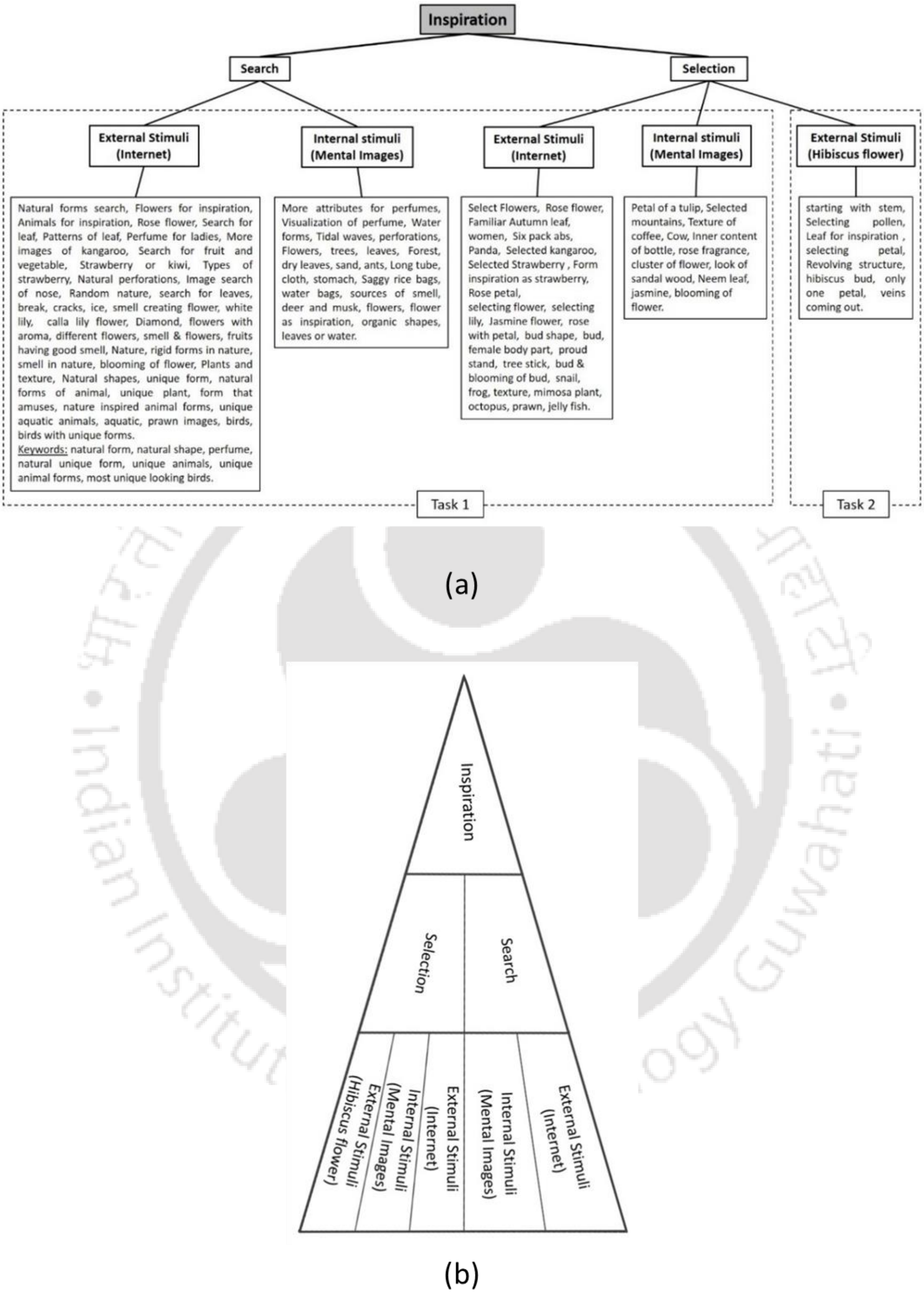
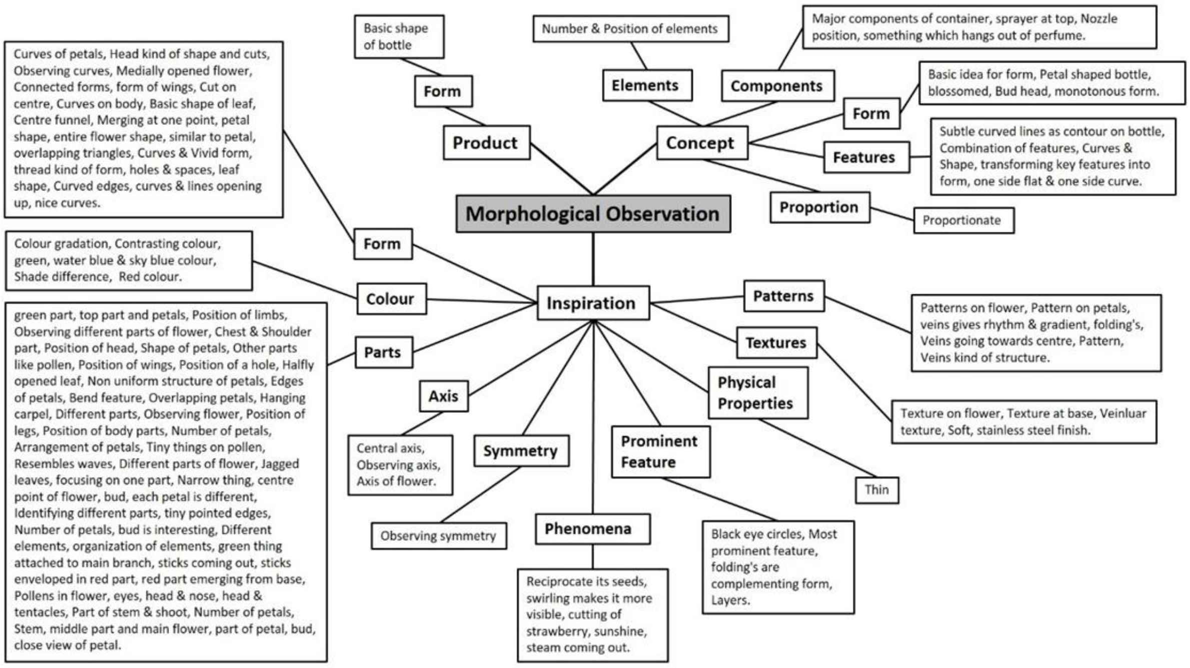


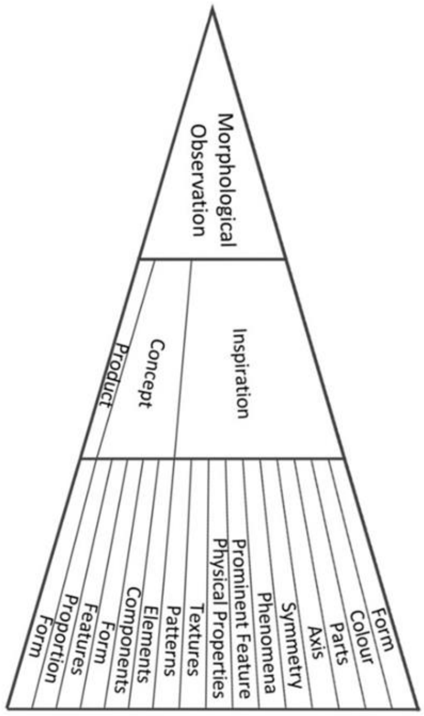
Figure 3.18 (a) Network diagram for Inspiration key factor, (b) Hierarchical diagram for Inspiration key factor.

2. Morphological observation

Morphological Observation is the key factor, which represents the approach of design students while observing the inspirational natural form, their developed concepts, and existing products. It is interesting to note that students not only observed the morphological features of inspiration, but they also observed morphological features of their developed concepts and existing products too. As a result, one hundred and twenty-three coded concepts under this factor are grouped into three main categories of *Inspiration, Concept*, and *Product* (see Figure 3.19 a). The highest number of coded concepts falls under *Inspiration* category, where students observed various Parts of the inspirational form along with *Form* features, *Colour, Axis, Symmetry, Phenomena, Prominent feature, Physical properties, Textures* and *Patterns* of inspirational form. The *Concept* category branches out into five sub-categories *Elements, Components, Form, Features,* and *Proportion* with coded concepts that students observed while developing their product concepts. The *Product* category has only one sub-category *Form*, where student observed the basic shape of the existing product. The hierarchical diagram illustrates the *Morphological Observation* key factor along with other main categories and sub-categories (see Figure 3.19 b).



(a)

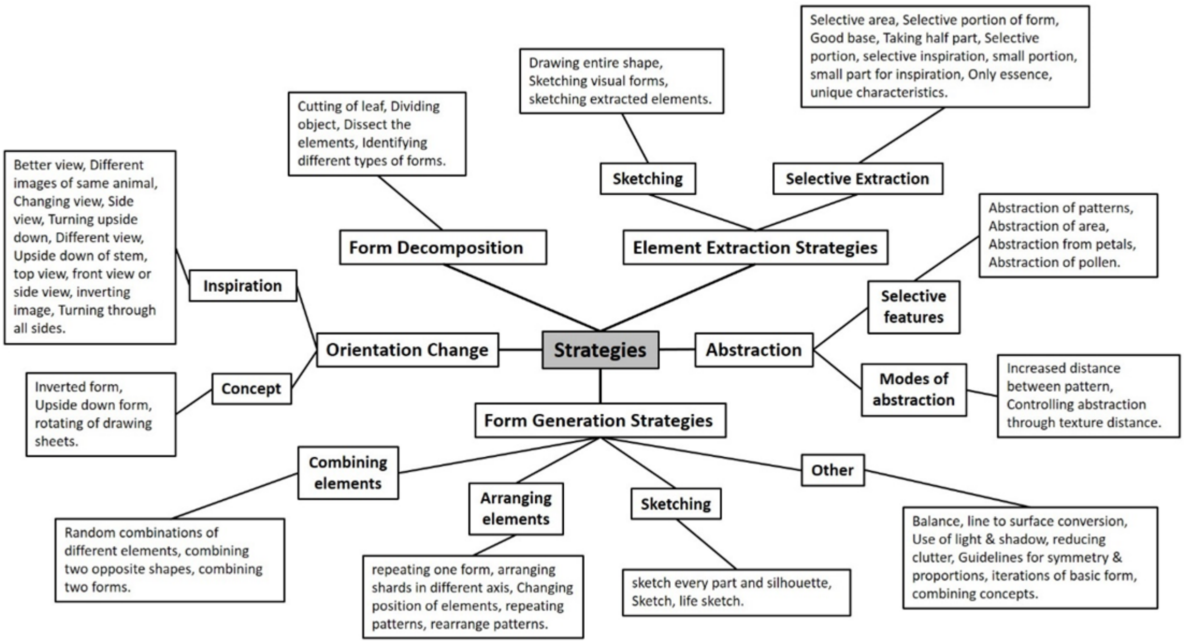


(b)

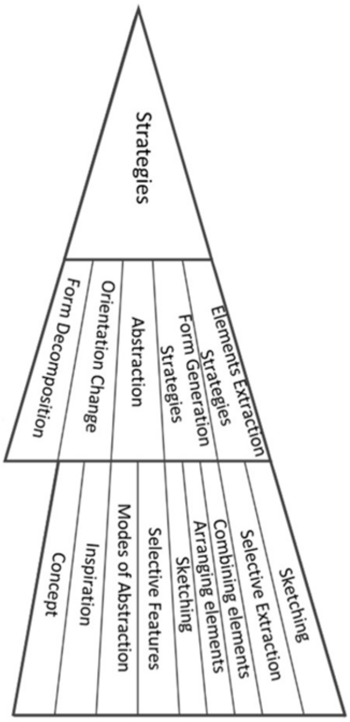
Figure 3.19 (a) Network diagram for Morphological Observation key factor, (b) Hierarchical diagram for Morphological Observation key factor.

3. Strategies

The key factor *Strategies* encompass various strategies used by design students during their design process. Forty-eight coded concepts are identified from the analysed text which are grouped under five main categories - *Elements extraction strategies, Form generation strategies, Abstraction, Orientation change,* and *Form decomposition* (see Figure 3.20 a). The main category *Element Extraction Strategies* includes coded concepts relating to extraction of form elements from the inspirational form through sketching form or shape and selective extraction of few elements or a small portion of the inspirational form. As a result, this category is further divided into two sub-categories *Sketching* and *Selective Extraction* (see Figure 3.20 b). *Form Generation Strategies* covers three sub-categories: *Combining elements*, *Arranging elements* and *Sketching*. The subcategory *Combining elements* covers all the concepts related to the combination of different forms or shapes. *Arranging elements* involves a change in the position of form elements, repeating them or rearranging them. The subcategory *Sketching* deals with the sketching of parts of the inspirational form and its silhouette. The main category *Orientation Change* includes coded concepts that indicate the change of the orientation of inspiration or concept. Therefore, this category is branched out into two sub-categories *Inspiration* and *Concept*. The main category *Abstraction* refers to the abstraction of elements of inspirational form done by students and is divided into two sub-categories *Selective features* and *Modes of abstraction*. The analysed text indicates that students have abstracted *Selective features* of the inspirational form like the abstraction of patterns, area or pollen, etc. Students have controlled the abstraction through changing texture distance as a *Mode of abstraction*. The fifth main category is *Form Decomposition* and coded concepts under this category represent various actions of cutting or dividing the inspirational form or identifying different types of forms within a single inspirational form. All the main categories, subcategories and their link with a key factor are represented through the hierarchical diagram (see Figure 3.20 b).



(a)

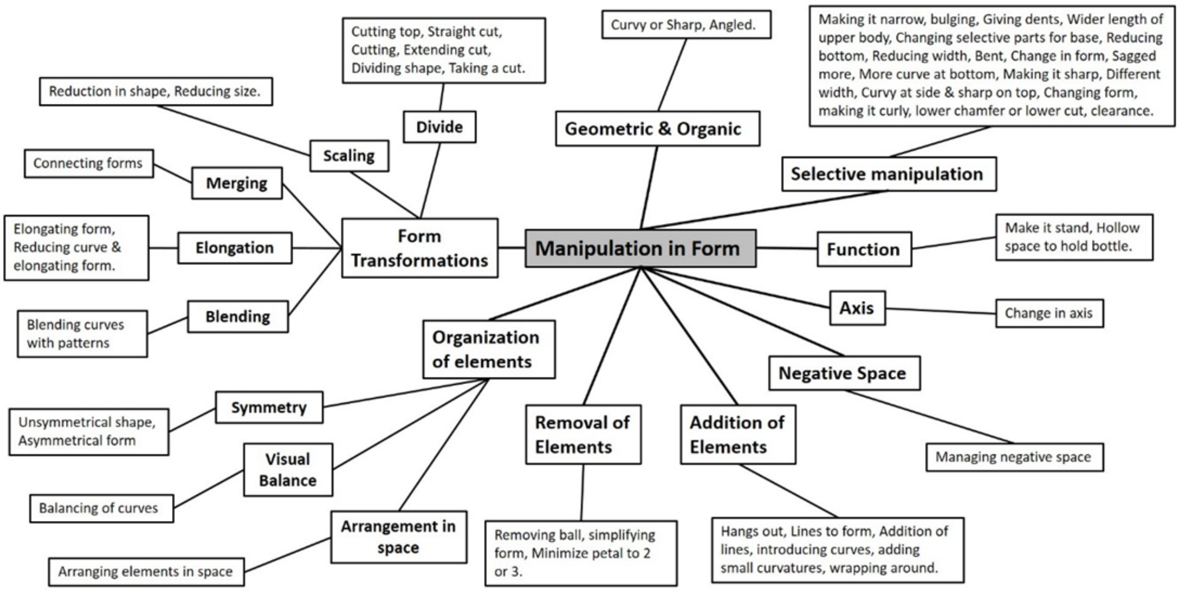


(b)

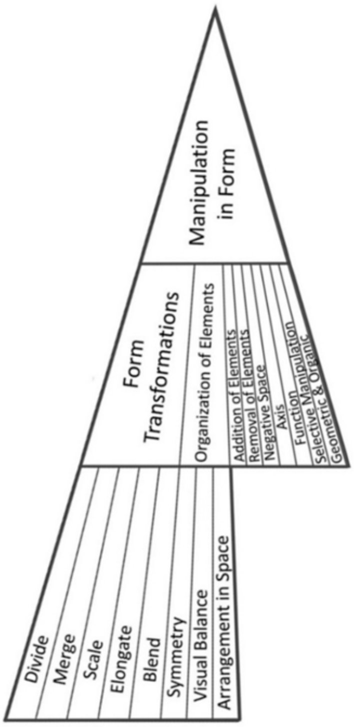
Figure 3.20 (a) Network diagram for Strategies key factor, (b) Hierarchical diagram for Strategies key factor.

4. Manipulation in form

Manipulation in Form is the key factor, which represents various manipulations performed by design students during their form generation process. Forty-nine coded concepts were extracted after analysing the text, which are further grouped under nine main categories: *Selective manipulation, Form Transformations, Organization of elements, Removal of elements, Addition of elements, Negative space, Axis, Function* and *Geometric & Organic* (see Figure 3.21 a). The category *Selective manipulation* contains the highest number of coded concepts and indicates a kind of manipulation where students have used selective features of concept form to manipulate. *Form Transformation* is the second major category that involves the manipulation of the complete form. It covers five subcategories: *Divide, Scaling, Merging, Elongation,* and *Blending*. The third major category is the *Organization of Elements* that involves the manipulation of form elements to obtain a good composition. Coded concepts under *Organization of Elements* are categorized under three sub-categories: *Symmetry, Visual Balance* and *Arrangement in Space* (see Figure 3.21 b). Two manipulation categories deal with *Addition of Elements* and *Removal of Elements* in the concept form. Manipulation with *Negative space*, manipulation in *Axis*, manipulation for some *Function* and manipulation between *Geometric & Organic* shapes are four categories that have very few coded concepts.



(a)



(b)

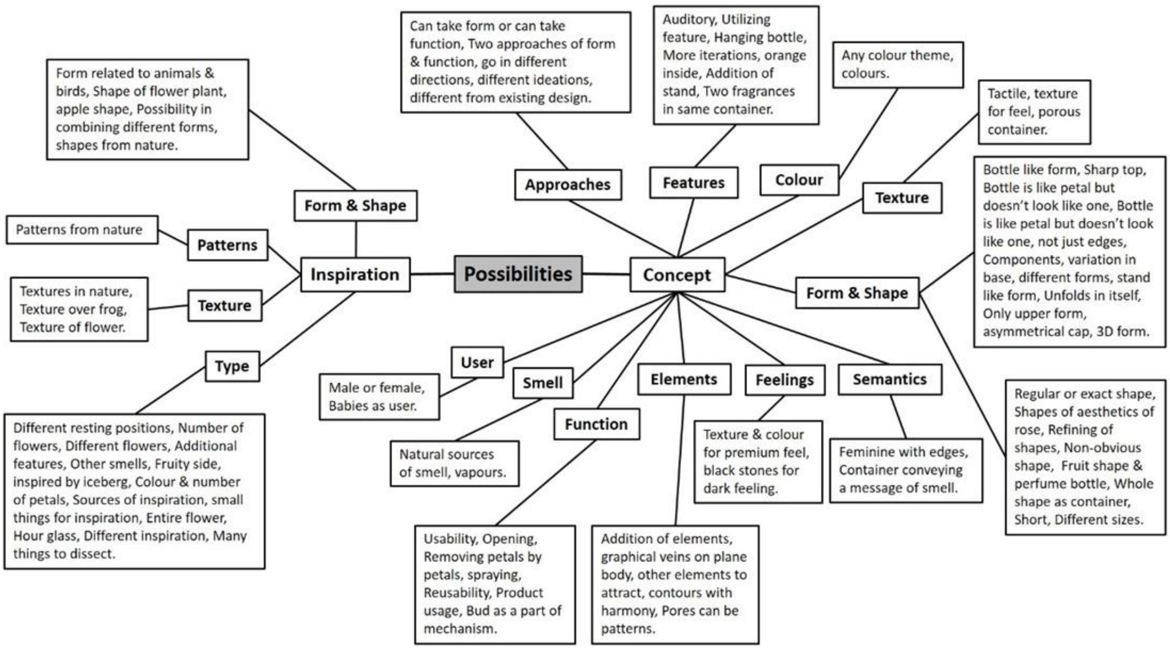
Figure 3.21 (a) Network diagram for Manipulation in form key factor, (b) Hierarchical diagram for Manipulation in form key factor.

5. Possibilities

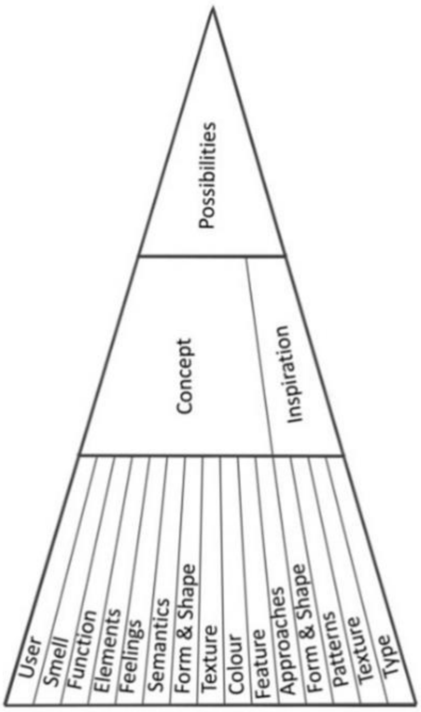
Possibilities factor represents all the possibilities that design students have explored during the design process. Eighty-one coded concepts identified from the analysed text are categorized under two main categories: *Concept* and *Inspiration* (see Figure 3.22 a). The main category *Concept* comprises of all the possibilities that students have explored for designing their concept forms. Fifty-eight coded concepts under *Concept* main category are grouped under eleven sub-categories: *User, Smell, Function, Elements, Feelings, Semantics, Form & Shape, Texture, Colour, Features,* and *Approaches* (see Figure 3.22 b). *Inspiration* is the second main category under *Possibilities*, which covers coded concepts showing various possibilities explored by students in terms of inspiration. Twenty-three coded concepts are identified from the analysed text, which are further categorized into four sub-categories: *Form & Shape, Patterns, Texture* and *Type* (see Figure 3.22 b).

6. Semantic Association

The key factor *Semantic Association* represents primarily the actions of design students where they try to associate their concept form semantically with some other object, person or phenomena to convey a particular meaning. Ninety-eight coded concepts were extracted from the analysed text and categorized under seven main categories: *Natural Objects, Man-made Objects, Form, User, Smell, Texture* and *Other thoughts* (see Figure 3.23 a). Hierarchical diagram of the key factor *Semantic Association* and its main categories are summarised in Figure 3.23 b.

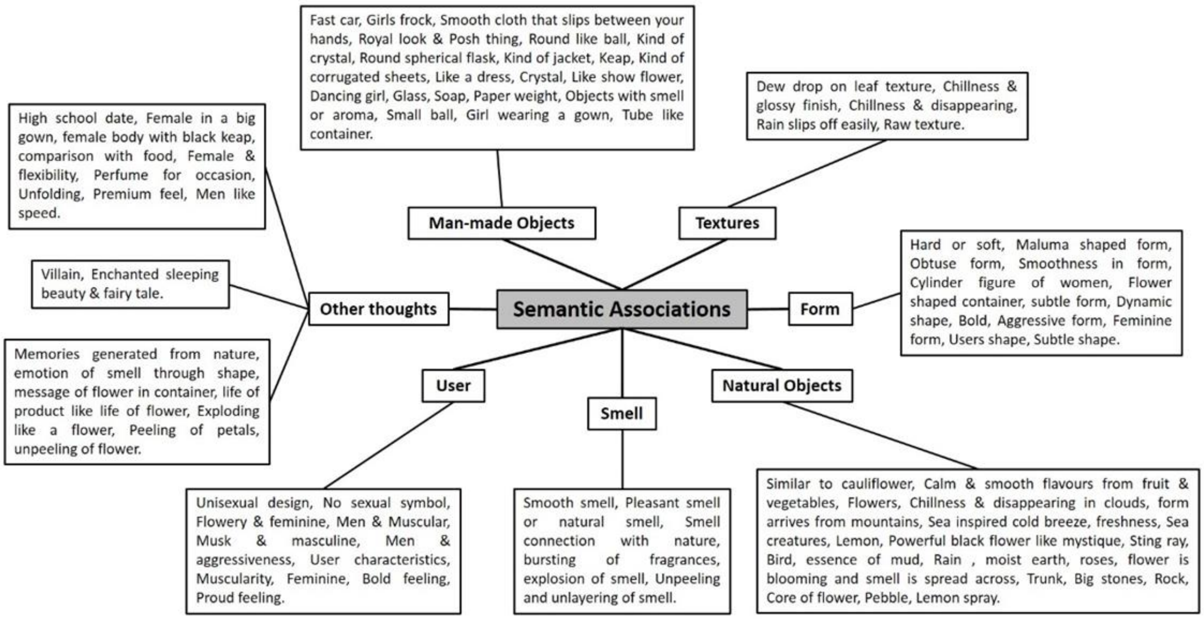


(a)

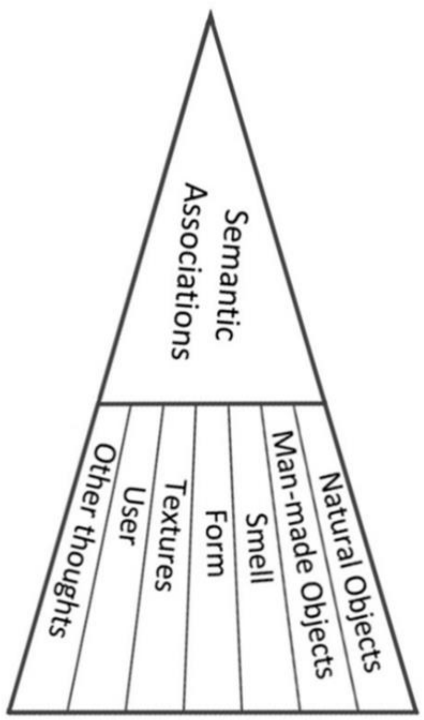


(b)

Figure 3.22 (a) Network diagram for Possibilities key factor, (b) Hierarchical diagram for Possibilities key factor.



(a)



(b)

Figure 3.23 (a) Network diagram for Semantic Association key factor, (b) Hierarchical diagram for Semantic Association key factor.

7. Experience

Experience is a key factor representing all the experiences that design students considered while designing a product form. The text analysis extracted thirty-nine coded concepts, which are further grouped under four main categories of *Product Experience, Users Experience, Past Product Experience* and *Past Experience with Natural Form* (see Figure 3.24 a). The main category *Product Experience* signifies the experience that a user will have while using the product. *Past Product Experience* consists of all the coded concepts that indicate the past experience of the design students with similar kind of products (perfume bottles). Coded concepts related to the past experience of design students with the natural form are grouped under the category *Past Experience with Natural Form*. The category *User's Experience* pertains to coded concepts relating to any kind of experience that users have while interacting with their environment (see Figure 3.24 a). The key factor *Experience* and its four main categories are represented in a hierarchical diagram as shown in Figure 3.24 b.

8. Elements Extraction

The key factor *Elements Extraction* encompasses all the coded concepts related to the activity of extracting visual elements from the inspirational form. Text analysis resulted in the identification of forty-one coded concepts, which are categorized into three main categories: *Complete Form, Selective Elements* and *Patterns & Textures* (see Figure 3.25 a). Extraction of *Complete Form* includes the use of the complete inspirational form for the product concept. In the extraction of *Selective Elements*, students took selective features like some part, a curve or a particular feature from the inspirational form. Extraction of *Patterns & Textures* represents the action of students where they extract patterns and texture from the inspirational form. Figure 3.25 b illustrates the branching out of key factor *Elements Extraction* into three main categories.

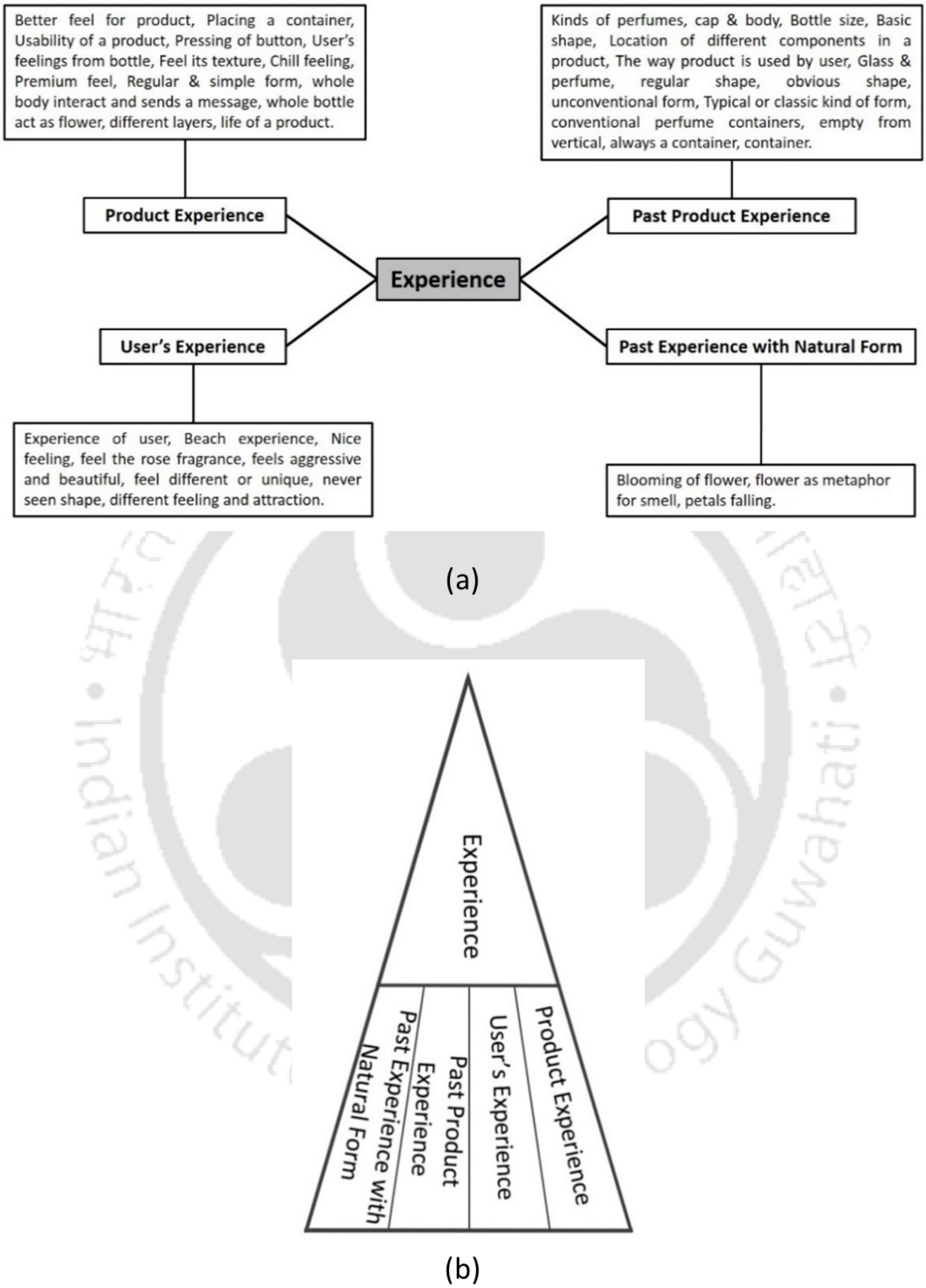
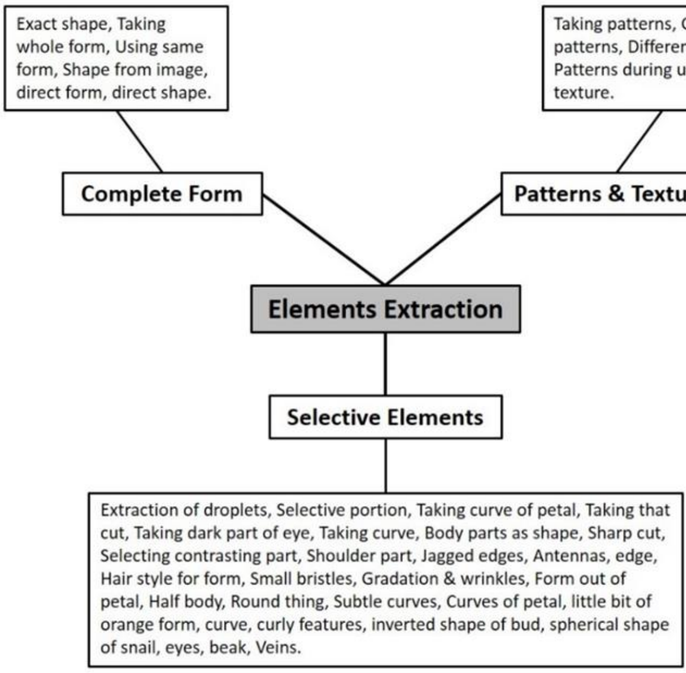
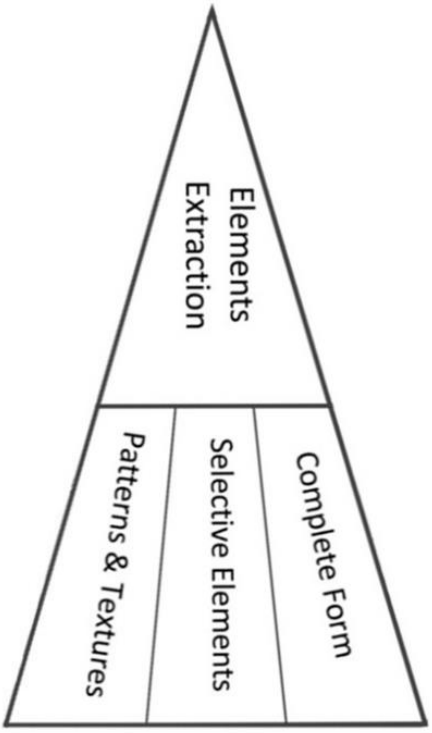


Figure 3.24 (a) Network diagram for Experience key factor, (b) Hierarchical diagram for Experience key factor.



(a)



(b)

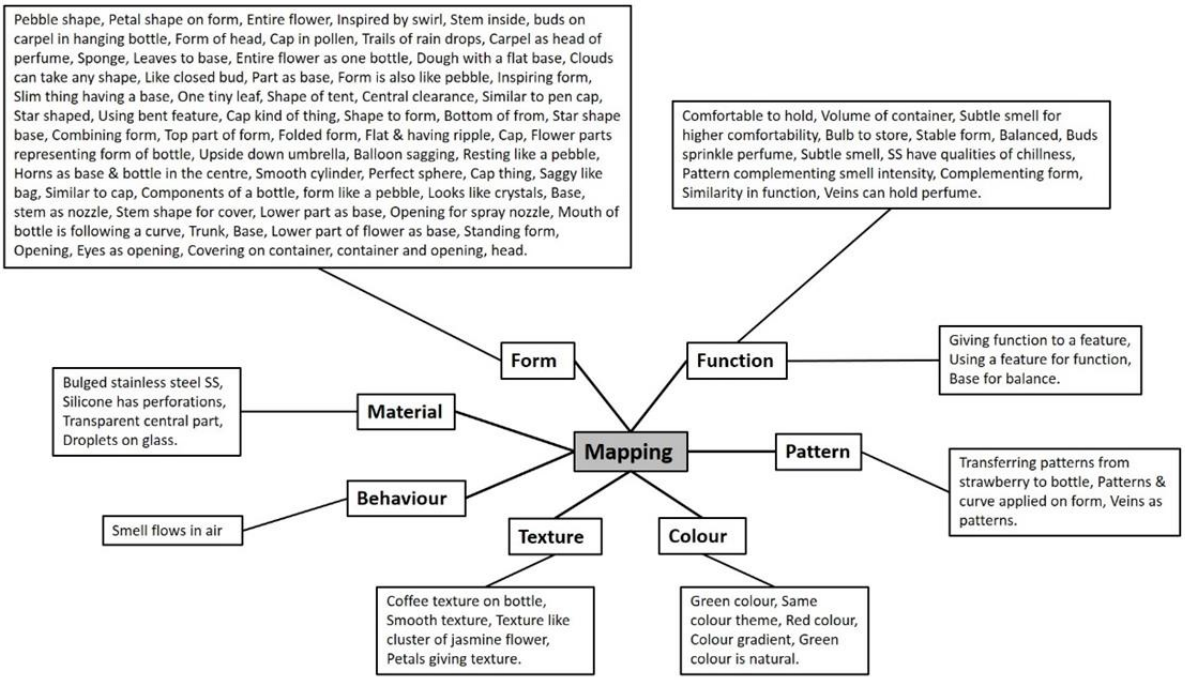
Figure 3.25 (a) Network diagram for Elements Extraction key factor, (b) Hierarchical diagram for Elements Extraction key factor.

9. Mapping

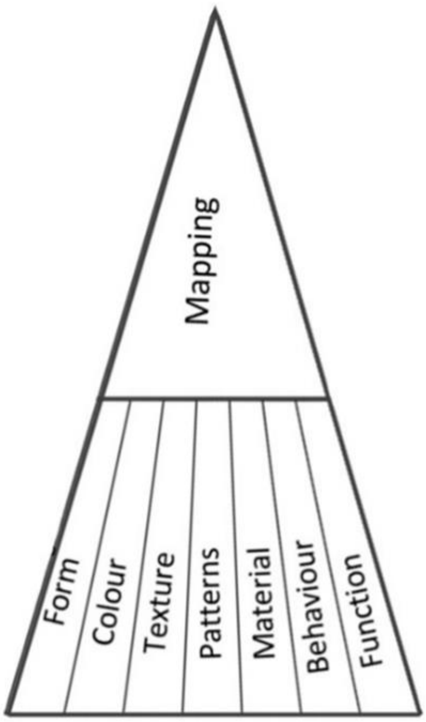
Mapping is the key factor that refers to the actions of design students when they try to map various visual and functional features between natural inspirational form and concept form that they try to develop. These features include *Form, Colour, Texture, Patterns, Material, Function* and *Behaviour*. As a result, Ninety-three coded concepts were categorized into above-mentioned seven main categories (see Figure 3.26 a). While mapping *Form*, students mapped the entire form or some part of the inspirational form with the concept product form. During *Colour* mapping, Colours from the inspirational form is mapped on to the concept product form. *Texture* and *Pattern* are the two main categories where students tried to map texture and patterns from inspirational form to concept form (see Figure 3.26 a). The main category *Material* comprises of the coded concept's that indicates the innovative ways in which different materials can be used in a product concept to get desired natural form or natural effects. The *function* is a main category where the inspirational form or a part of it is mapped to some function in concept form. Branching of the *Mapping* key factor into its categories is graphically represented in Figure 3.26 b.

10. Judgement

Judgement signifies the decisions taken by design students during the process of generating a concept. Ninety-nine coded concepts were identified under *Judgement* key factor, which were further grouped under eight main categories: *Form, Aesthetic Experience, Inspiration, Utility, Concept, Function, Inspirational Elements,* and *Others* (see Figure 3.27 a). Judgements on *Form* are related to the choice of form and manipulations to be performed on it. The main category *Aesthetic Experience* comprises the decisions on the concept form made by design students based on their aesthetic experience. Coded concepts related to the decisions on selection of inspiration are grouped under main category *Inspiration*. The *Concept* category contains the decisions taken by students on the development of concept form. *Inspiration Elements* is a category, which has coded concepts that indicate the decision of the students on the selection of inspirational elements. The categories *Function, Utility* & *Other* consists of very few coded concepts. Figure 3.27 b represents the hierarchical diagram of the key factor Judgement.



(a)



(b)

Figure 3.26 (a) Network diagram for Mapping key factor, (b) Hierarchical diagram for Mapping key factor.

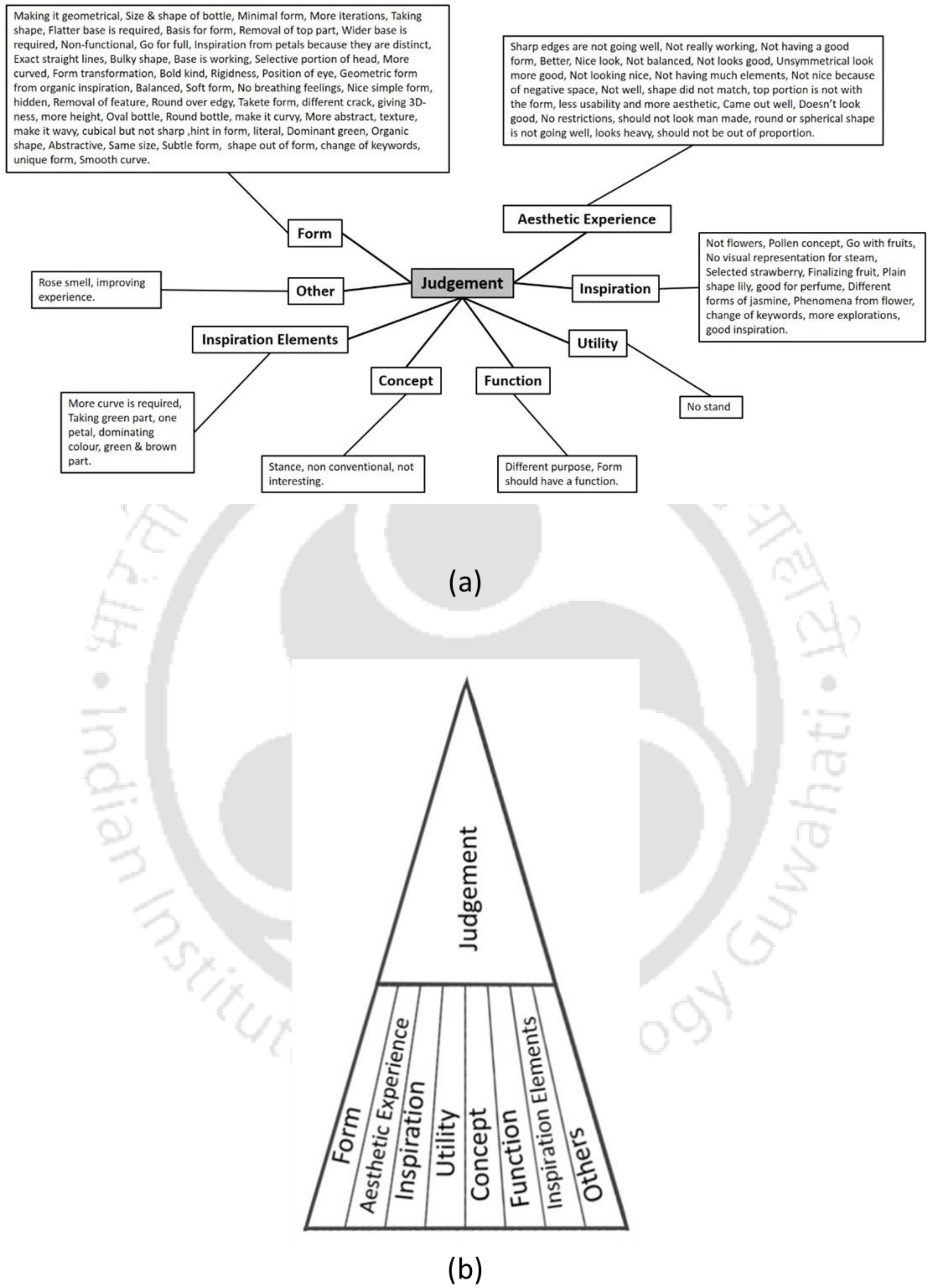


Figure 3.27 (a) Network diagram for Judgement key factor, (b) Hierarchical diagram for Judgement key factor.

11. Triggers

Triggers represent the actions performed by the design students during the design process to gain stimulation and new ideas to generate new product concept forms. A total of nineteen coded concepts identified from the analysed text are classified under *Triggers*, which are further branched into three main categories: *Previous Concepts Knowledge, Existing Product Search* and *Observing Previous Concepts* (see Figure 3.28 a). All the coded concepts indicating the use of previously developed concepts to create new concepts are categorized under the main category *Previous Concepts Knowledge*. The main category *Existing Product Search* represents the search on the internet for existing products to gain stimulation. The third main category *Observing Previous Concepts* shows the students activity of observing previously developed concepts to gain stimulation (see Figure 3.28 a). Key factor *Triggers* and its three main categories are represented in a hierarchical diagram as shown in Figure 3.28 b.

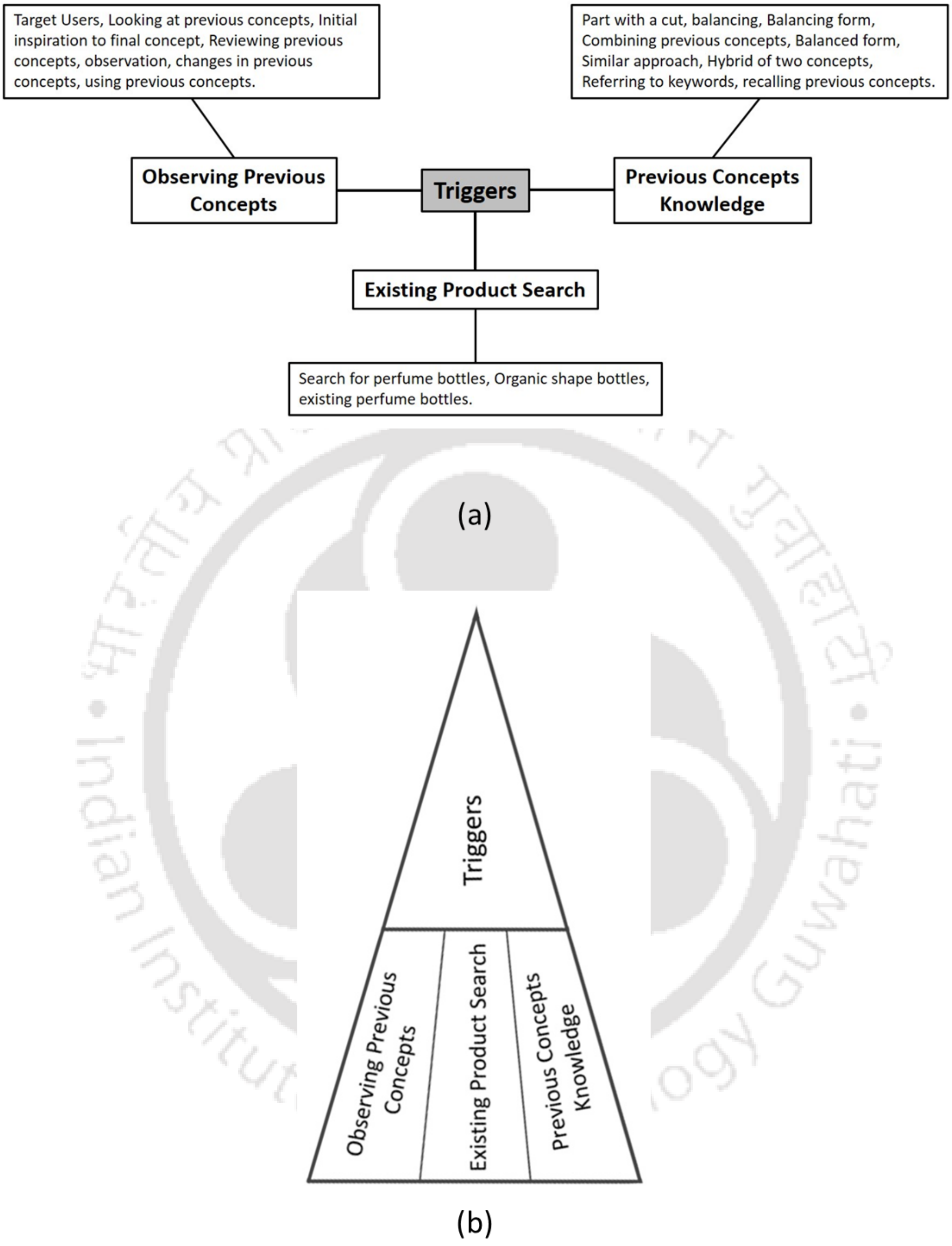


Figure 3.28 (a) Network diagram for Triggers key factor, (b) Hierarchical diagram for Triggers key factor.

Section b: Influence of eleven key factors on design process of design students

Eleven hierarchical diagrams obtained in the previous section are combined into a single diagram called a combined hierarchical diagram. This combined hierarchical diagram contains all the core categories/key factors, main categories, and their sub-categories that design students have considered while generating product forms inspired by nature (see Figure 3.29). The central ring has all eleven key factors *Semantic Association, Experience, Inspiration, Morphological Observation, Element Extraction, Strategies, Mapping, Manipulation in Form, Judgement, Possibilities,* and *Triggers*. The middle ring represents the main categories of each key factor. The main categories of key factors: *Inspiration, Morphological Observation, Strategies, Manipulation in Form* and *Possibilities* have sub-categories, represented by a third level in the diagram (see Figure 3.29).

The combined hierarchical diagram is used to compare the key factors & various categories considered by the participants during their form generation process (see Figure 3.30) along with the concept sketches in Appendix 1 to 12 which is structured as Subject-Task Number-Image Numbers e.g. F1-Task 2 - 4, 6 & 8. The key factors, main categories, and sub-categories that are under the grey area are the ones that participants have considered in their form generation process. The usage of each key factor during the form generation process will help us to understand their influence on the form generation process.

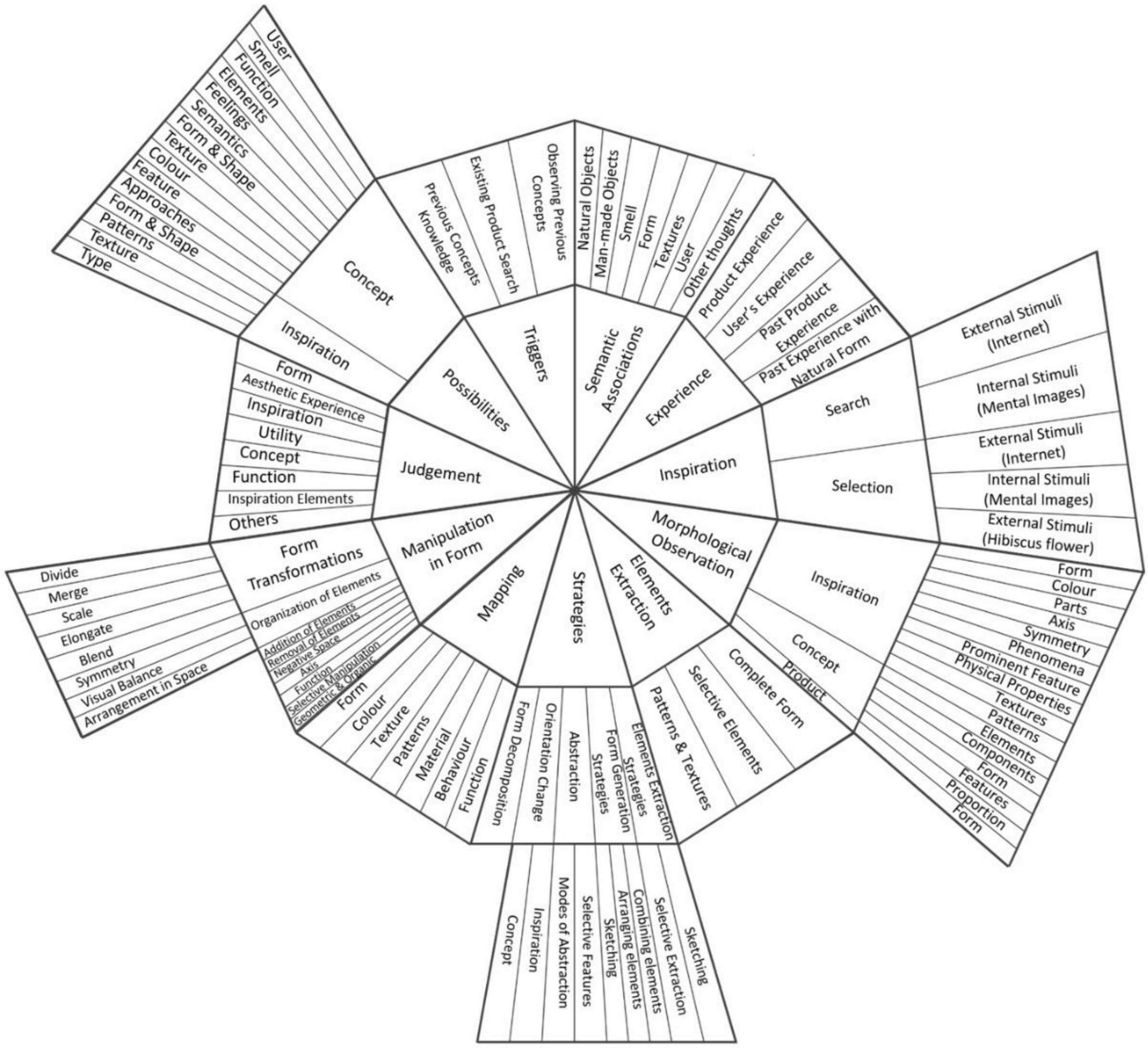


Figure 3.29 Combined hierarchical diagram

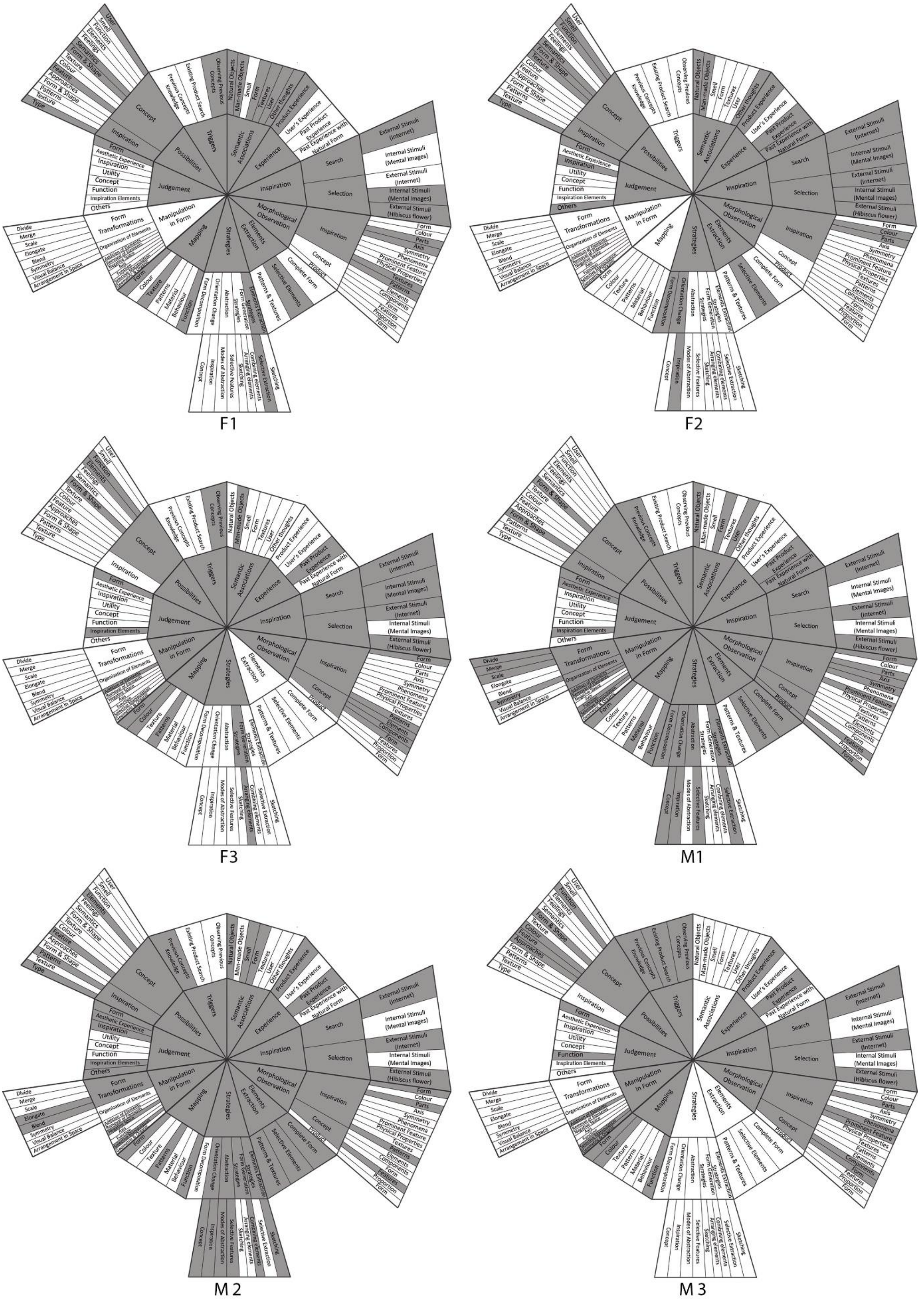


Figure 3.30 Overall comparison of each participant's approach using Combined hierarchical diagram

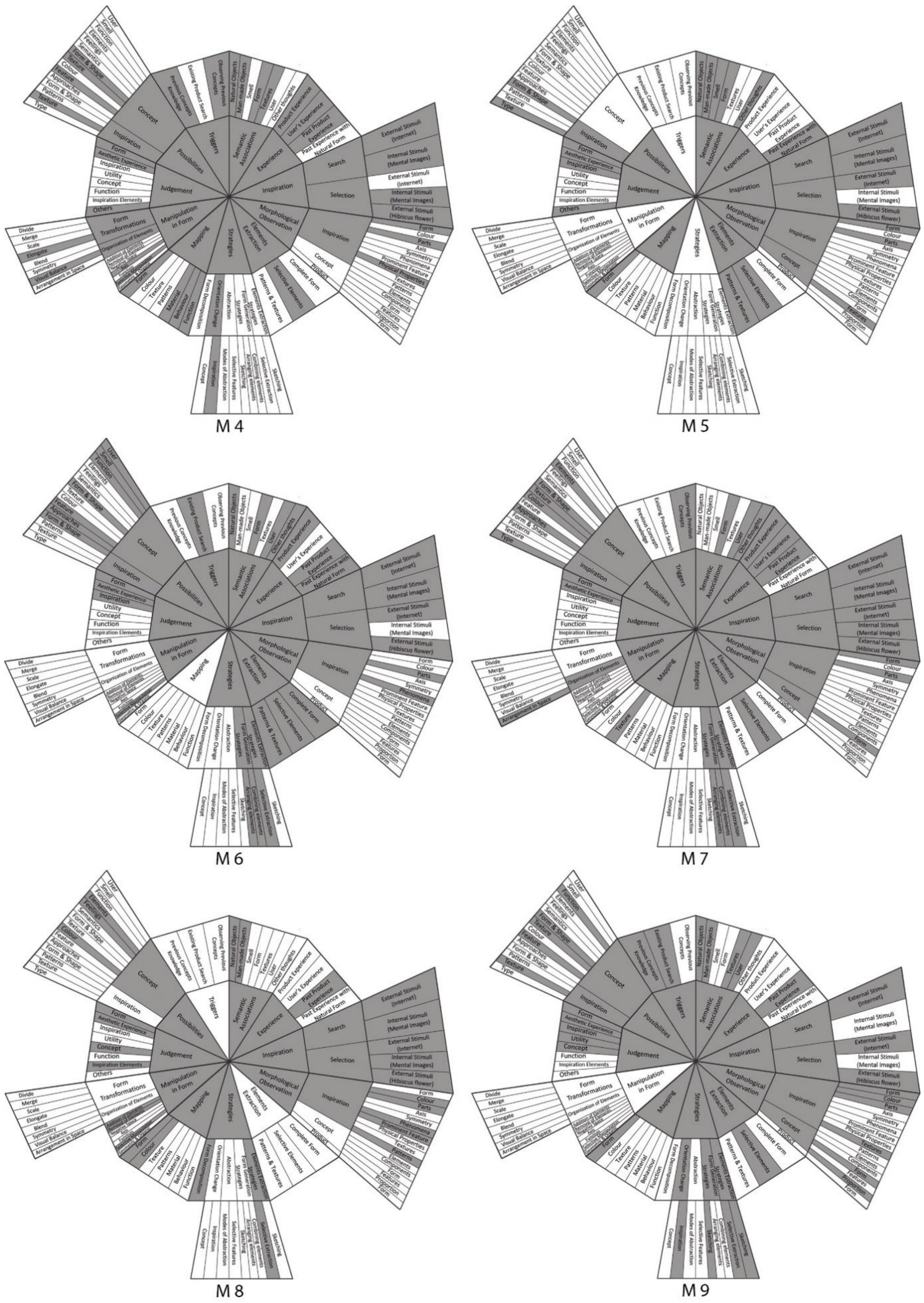


Figure 3.30 Overall comparison of each participant's approach using Combined hierarchical diagram (continued)

1. Semantic Association

Considering the brief for the design task, (F1, F2, M1, M2, M4, M5, M6, M8, and M9) have associated design concepts with *Natural Objects*. However, in the later stage of the design process (F1, F2, F3, M4, M5, M8 and M9) have also associated their design concepts with *Man-made Objects*. Such a deviation in the use of other semantics associations to achieve family belongingness in the designed products is completely a designer's free choice (Athavankar, 1989).

(F1, M1, M2, M4, M5, M6, and M7) considered *Form* as an important factor for semantic association between source and product. (F1, M1, M6, M7, and M9) have considered their *Users* and tried to associate the user's personality with product personality.

2. Experience

An individual's *Past Product Experience* plays an important factor in influencing the participants form generation process. These are varied and individualistic ranging from past experience with the source, the product, the user or use as seen in the form generation process (F2, F3, M1, M2, M3, M4, M6, M7, M8, and M9). For example (M1, M2, F3, M7, M6, and M8) have recalled their *Past Product Experience* related to the form of the product (basic shape of perfume container) and brought this experience to their concepts (Appendix 4:M1-Task 1-4,18,20,31&43) (Appendix 5:M2-Task 1-7,8,12&13) (Appendix 2:F2-Task 1-3). M7 tried a different approach of using non-obvious shapes (Appendix 10:M7-Task 1-19&20). M3 introduces a hanging element in his concept to enable storing a small quantity of perfume for spray testing based on observation of user behaviour pattern (Appendix 6:M3-Task 2-4&6). Participants also used their past experience during iterations on the different components of the product. M3 has separated the cap and nozzle consciously by changing their location (Appendix 6:M3-Task 1-8). F2 sought novelty making the container porous to overcome the stereotype of a spray (Appendix 2:F2-Task 1-6,9,10,11,13&15).

The experience that a user feels while interacting with the product is *Product experience*, the second most considered category by participants in their design process (F1, F2, M2, M3, M4, M6, and M7). M7 uses a simple square form for the container to provide a premium feel (Appendix 10:M7 Task 1-10). F1 suggested the use of jagged edges on the bottle so that the user can feel the texture of leaf (Appendix 1:F1-Task 2-6).

Past Experience with natural form (source) was relatively an important consideration in the form generation process (F2, M1, M5, and M6). F2 used the phenomena of 'falling petals from flower' to show that perfume is getting over in the different layers of the bottle (Appendix 2:F2-Task 2-11).

3. Inspiration

A comparison of the usage of the *Inspiration* factor for Task 1 (excluding the subcategory External Stimuli–Hibiscus flower) indicates that participants seek visual inspiration for form generation from images and natural elements or any medium. (F1, F2, F3, M4, M5, M6, M7, and M8) used a combination of the internet and their memory in search and selection of inspiration. (M1, M2, M3, and M9) have used only internet which indicates a preference for some visual stimuli among participants. This matches with findings of earlier studies (Henderson, 1999; Muller, 1989; Eckert & Stacey, 2000).

Referring to their respective images and sketches in Appendix, insights can be drawn on the *Inspiration Search* and *Selection* behaviour. (F1, M4, and M8) relied mostly upon mental images for inspiration (Appendix 1:F1-Task 1-7&11). M4 and M8 browsed the internet only once (Appendix 7:M4-Task 1-2) (Appendix 11:M8-Task 1-4) and F1 only twice (Appendix 1:F1-Task1-5&17) during the whole design process. (M5, M6 and M7) have searched images for each new concept (Appendix 8:M5-Task 1-1,3,6,7&10), (Appendix 9:M6-Task 1-1,4,5,8,10,14&16), (Appendix 10:M7-Task 1-2,5,12,13,15&17). F2 showed exceptional interest studying a video of a flower blooming to explore motion for her inspiration (Appendix 2:F2-Task 2-1). Drawing upon mental images (F3) fixes upon the keyword (Ice) to search for visuals on the Internet (Appendix 3:F3-Task 1-1,9&11). M1 and M9 used only internet for their search and selection but there is a diversity in their search approach which is clearly visible in images they searched (Appendix 4:M1-Task 1-2,6,9,14,16,17,19,21,23,25,30,32,33,38,40&42) (Appendix 12:M9-Task 1-1,2,5,7,9,11&15). M2 and M3 also have used only internet but they searched only one inspiration (Appendix 5:M2-Task 1-11) (Appendix 6:M3-Task 1-2).

4. Morphological Observation

For both the tasks, *Part, Form,* and *Pattern* of *Inspiration* main category are the most preferred sub-categories as seen in the choice of all participants: *Part* (F1, F2, F3, M1, M3, M5, M6, M7, M8, and M9), *Form* (F3, M1, M2, M4, M5, M7, and M9), *Pattern* (F1, F3, M2, and M8). There are also other sub-categories, preferred by few participants like *Prominent Features* (M1, M3, and M8), *Phenomena* (M3, M6, and M8), *Axis* (F1 and M1), *Texture* (F1 and M9), *Symmetry* (M1) and *Physical Properties* (M4). In *Concept* main category, the most preferred sub-categories are *Form* (F3, M3, M7, and M9) and *Features* (M1, M2, and M5).

The *Morphological Observation* patterns of the twelve participants were analysed using their concept sketches for the Hibiscus flower (Task 2). All participants have carefully observed the different forms/parts/features existing in the flower and sketched them before generating their concept forms. The details of features observed and concepts generated under the different morphological feature/s, and the ratio of morphological features used to that of morphological features observed are reflected in Table 3.9. (F1, F2, F3, M2, M4, M5, M6, M7, and M8) have used the complete form or whole form of the hibiscus flower while (F1, F3, F4, M2, M5, M7, M8, and M9) have also used the petal as the form of container in their concepts. (M1, M5, M6, and M7) took inspiration from the Calyx, (F1, M3, and M5) from the Carpel and (F2, M1, M2, and M9) from the Stigma of the flower for their concepts. Only (M6) used the Sepal and Anther in his concept.

Such Morphological Observation pattern focused on Whole flower and Petals can be explained through the Koler's theory on 'hierarchy of order in compositions' for visual forms (Koler, 1994). If we relate the hierarchy of order in inspirational form (Hibiscus flower) with the typical product form (Perfume container) we can understand this pattern of Morphological Observation (see Figure 3.31). Koler refers to this hierarchy of order in composition as Dominant, Subdominant, and Subordinate elements. The dominant is the largest form with strongest character that holds an interesting position in the composition, the subdominant has a stronger character and is smaller than the dominant while the subordinate is smallest form that is complementary to dominant and subdominant form/s. In Figure 3.31, Dominant form is bottle in the perfume container and petals in the hibiscus flower, Subdominant form is cap in the perfume container and Calyx in the hibiscus flower and Subordinate form is nozzle in the bottle and carpel in the hibiscus flower. While using the form of the whole flower as a perfume container the participants will get a form with a predefined relationship between dominant and subdominant form, which is clearly visible in their generated concepts. (F1, F2, F3, M4, M5, M6, M7 and M8) have used the dominant form of the flower (Petals) as the dominant form in their concepts (bottle) along with the Subdominant form of flower (Calyx) as the cap of the bottle.

Some participants have used the subdominant form (Calyx) and subordinate form (Carpel) of the flower as the dominant form (Bottle) in the perfume container. M1, M5, M6, and M7 used subdominant form (calyx) as the dominant form (bottle) in their concepts. F1 and M5 used subordinate form (carpel) as a subdominant form (nozzle) in their concepts.

Few participants have used other smallest form in the flower (Stigma, Sepal, and Anther) as their dominant form (bottle) in the concepts. F2 and M9 have used the form of stigma in their concept as the dominant form (bottle) and M2 used the form of stigma as a subdominant form (cap) in his concept. M6 used the form of Sepal and Anther as the dominant form (bottle) in his concept (Table 3.9).

It is observed through these examples that there is an inherent tendency to search for a hierarchy of visual order in the natural source. Participants who have used other smaller forms from the flower as the dominant form (bottle) in their concepts, they still followed the hierarchy of the order of a typical perfume container but with a shift in the hierarchy of order in the observation of the smallest form. After all these observations, we can say that one can play with the order of hierarchy to achieve abstraction. If one follows the same order of hierarchy as that of inspirational form, the designed product shows more resemblance with the inspirational form and if one follows different order of hierarchy the designed product form seems to be more abstractive (see Figure 3.32).

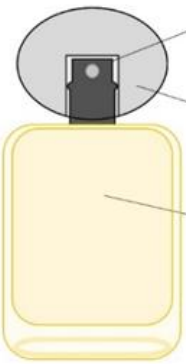


Figure 3.31 (a) Hierarchy of order in perfume container, (b) Hierarchy of order in Hibiscus flower

Table 3.9 Concepts based on observed morphological features

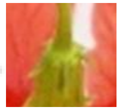
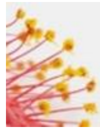
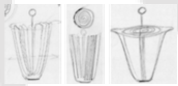
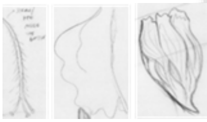
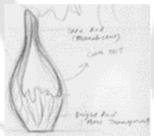
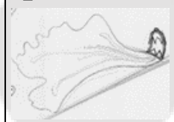
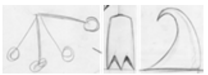
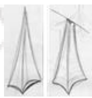
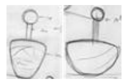
Students	Number of features observed	Number of concepts generated under each observed morphological feature							Morphological features used / Morphological features observed
		Dominant form	Subdominant form	Subordinate form					
		Whole flower 	Petal 	Calyx 	Carpel 	Stigma 	Sepal 	Anther 	
F1	3 	2 	3 		1 				3/3
F2	2 	3 				1 			2/3
F3	3 	1 	1 						2/3
M1	3 		4 	3 		2 			3/3
M2	5 	3 	1 			2 			3/5

Table 3.9 Concepts based on observed morphological features

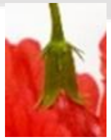
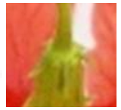
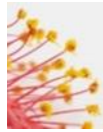
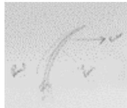
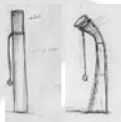
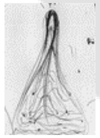
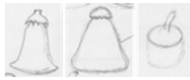
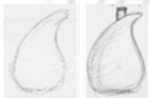
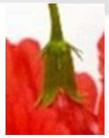
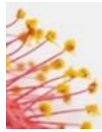
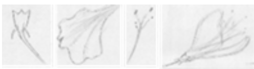
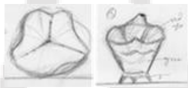
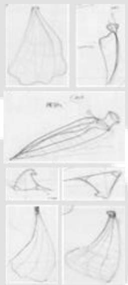
Students	Number of features observed	Number of concepts generated under each observed morphological feature							Morphological features used / Morphological features observed
		Dominant form	Subdominant form	Subordinate form					
		Whole flower 	Petal 	Calyx 	Carpel 	Stigma 	Sepal 	Anther 	
M3	1 				2 				1/1
M4	3 	1 							3/3
M5	4 	1 	1 	1 	1 				4/4
M6	4 	4 		1 			1 	1 	4/4
M7	3 	3 	2 	3 					3/4

Table 3.9 Concepts based on observed morphological features

Students	Number of features observed	Number of concepts generated under each observed morphological feature							Morphological features used / Morphological features observed
		Dominant form	Subdominant form	Subordinate form					
		Whole flower 	Petal 	Calyx 	Carpel 	Stigma 	Sepal 	Anther 	
M8	4 	2 	1 						2/4
M9	2 		7 			1 			2/2

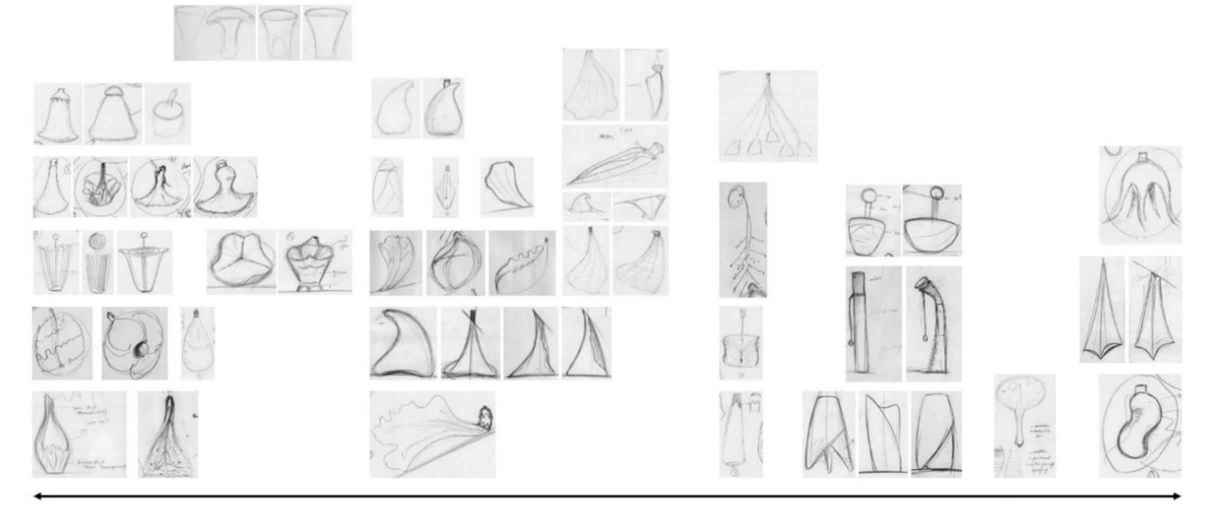


Figure 3.32 Spectrum of resemblance

5. Elements Extraction

Nine participants among twelve (F1, F2, M1, M2, M4, M5, M6, M7, and M9) considered *Selective Elements* as their most preferred subcategory in which (M1, M2 and M6) also preferred the *Complete Form* of flower (source) and (M2, M5, and M6) preferred to extract from *Pattern & Textures.*

Element Extraction was observed to be an important key factor for the generation of multiple concepts from a single inspiration. Participants freely navigate between single source and combinations of the three sub-categories for multiple conceptual solutions for form generation. M1 used *Selective Elements* for one of the concept (Appendix 4:M1-Task 1-22&24) and used both *Complete Form* (Appendix 4:M1-Task 1-35) and *Selective Elements* (Appendix 4:M1-Task 1-36&37) for another concept. M5 has also used *Selective Elements* (Appendix 8:M5-Task 2-5) and *Patterns & Textures* (Appendix 8:M5-Task 2-6) for one of his concepts. Similarly, M6 has also used *Complete Form* (Appendix 9:M6-Task 2-2) and *Selective Elements* (Appendix 9:M6-Task 2-6) in his process.

6. Strategies

The use of the Strategies supports creative thinking, as they act as design heuristics. These Strategies help participants to quickly gather visual information from an inspirational form and explore the maximum number of possible solutions.

Indicated by the concept sketches of M1, M2, and M9, a visual connection can be seen between inspirational form and developed concepts (Appendix 4:M1-Task 1-14&15,38-43,10-13) (Appendix 12:M9-Task 1- 5&6,11-14) and between a concept which is developed from previous concepts through the use of these Strategies (Appendix 4:M1-Task 2-10&11,12-14) (Appendix 5:M2-Task 1-6,7&8) (Appendix 5:M2-Task 2-9&10,13&14) (Appendix 12:M9-Task 2-7&8).

Participants with no or less use of Strategies are found with less explored concepts (Appendix 7:M4-Task 2-7) or generation of different concepts (Appendix 8:M5-Task 2-3-6) (Appendix 1:F1-Task 2-3-8) (Appendix 3:F3-Task 2-4-8).

We have also observed that Strategies work well with the use of 2D or 3D external stimuli and don't work with internal stimuli (mental images). The analysis of the transcribed text for Task 1 of F1, F2, M3, M4, and M8 shows no or very less use of strategies, as these participants relied mostly on mental images for the search of their inspirations (Task 1 of Appendix 1,2,6,7&11).

7. Mapping

Mapping is an important key factor that includes the syntactic main categories of *Form, Colour, Texture, Patterns, Material* along with *Behaviour* and *Function*. These considerations enable creative ways to show an association of a concept form with its inspirational source.

(F1, F3, M1, M2, M3, M4, M5, M8 and M9) show this association through *Form* mapping between source and product. This is visible in the correlation between features of natural form and components of the product (Bottle/Base, Cap/Head, and the nozzle).

F1 in her concept for hanging bottle draws from Carpel and in another instance uses the whole flower as source (Appendix 1:F1-Task 2-4) and (Appendix 1:F1-Task 2-8). F3 has used petal and calyx as a source to correspond with the bottle and nozzle

(Appendix 3:F3-Task 2-4) and in another instance the flower as a bottle (Appendix 3:F3-Task 2-7&8).

A similar approach can be seen in the concepts of M9 (Appendix 12:M9-Task 2-6&10); M4 (Appendix 7:M4-Task 2-7) and M1 (Appendix 4:M1-Task 1-3,4&5) who later tries to abstract the forms (Appendix 4:M1-Task 1-15; Task 2-2&3; Task 2-6,7,8,9&15; Task 2-10,11,12&14). Abstraction is also visible in other participants' concepts (Appendix 5:M2-Task 2-14) (Appendix 12:M9-Task 2-7&8). This abstraction is not random sometimes it could be intentional also like in the case of M3, where he preferred geometric forms (Appendix 6:M3-Task 2-4,5&6). One can therefore attempt to construct a bipolar spectrum of form variations ranging between less abstractive/organic and more abstractive/geometric forms (see Figure 3.33).

Therefore, *Mapping* key factor acts as a medium between the source of inspiration for co-relating syntactic, and conceptual aspects of the form with the targeted form to be designed. Variations in form can be achieved following the organic-geometric spectrum for abstraction. A prospective form generation tool to help designers generate variations in product form concepts can be designed.

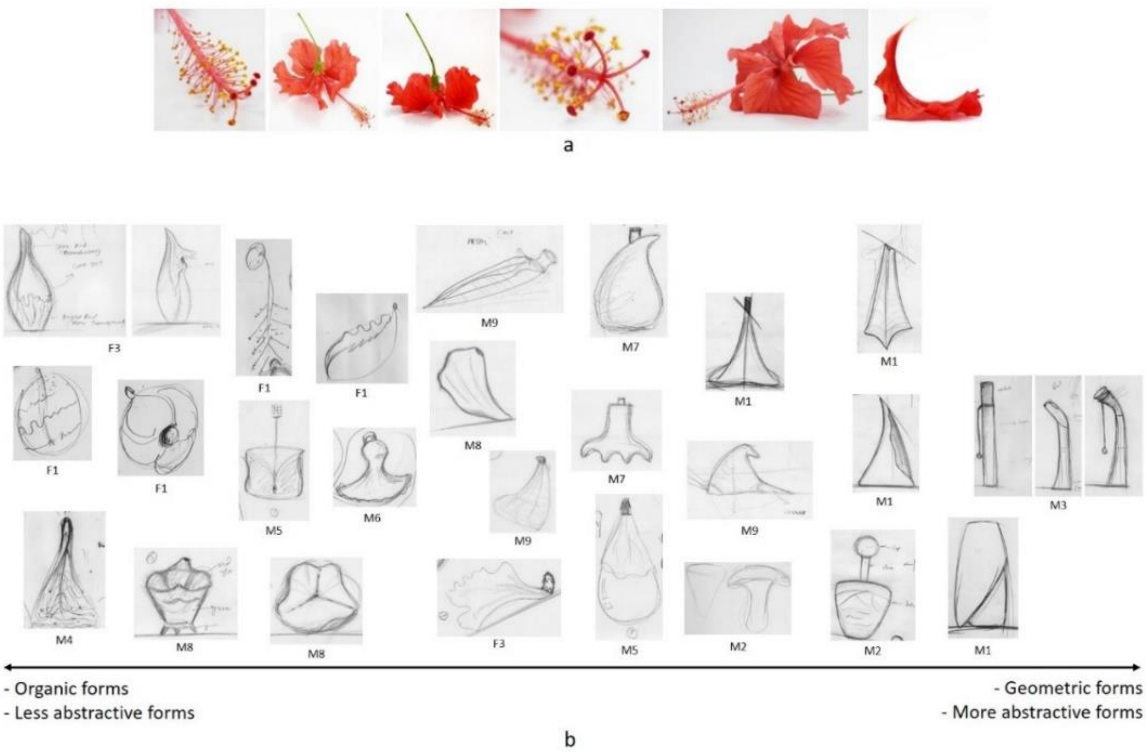


Figure 3.33 (a) Inspirational form – Hibiscus flower, (b) Organic-Geometric Spectrum

8. Manipulation in form

Manipulation in form is another key factor in the generation of a variety of creative design alternatives. Earlier studies on the systematic form-giving process have discussed the importance and application of manipulation in form for first-generation and second-generation designs (Corremans, 2008).

Participants who have used *Manipulation in form* key factor in their design process (M1, M2 & M4) are able to generate more design alternatives compared to those who did not use them (F1, F2, M5 & M9) or used very few manipulations in their concepts (F3, M3, M6, M7 & M8).

The identified categories and sub-categories of *Manipulation in Form* are seen to confirm to Koler's principles of form transitions and form organization (Koler, 1994). However, the transcribed text indicates that participants followed these principles partially and randomly. Participants also did not use bipolar spectrums while manipulating their generated forms.

9. Judgement

Judgement is a key factor resorted into evaluation of source and generated concepts. This evaluation is based on various factors that are grouped under *Judgement* as its main categories. Evaluation of *Form* followed by evaluation of *Aesthetic Experience* (M1, M2, M4, M5, M6, M7, M8, and M9) are the two dominating approaches for Judgement. Some participants have also taken Judgements on *Inspiration* (F2, M2, M5, M6, and M9) and *Inspiration Elements* (F3, M1, M2, and M8). Very few participants have considered *Utility* (M9) and *Function* (M3) during judgement.

10. Possibilities

Exploring *Possibilities* are about exploring direction for *Inspiration* and generation of *Concepts*. The majority of participants (F1, F2, M1, M2, M4, M6, M7 and M9) have explored both the main categories: *Inspiration* and *Concept*. Few have explored either only *Concept* (F3, M3, and M8) or only *Inspiration* (M5) category.

11. Triggers

It seems a natural impulse to search for *Triggers* by *Observing Previous Concepts*, or search among *Existing Products*, or draw upon *Previous Conceptual Knowledge* in seeking directions for solutions. Nine among twelve participants preferred at least one of these three main categories, which interestingly concur with a 'Designerly way of knowing' (Cross, 2006).

As the analysis of transcripts throw-up limited data, this section appears weak. However, previous studies suggest that Triggers form an interesting strategy for creativity (Goldschmidt, 1999). Developing strategies systematically for the three sub-categories can enhance the generation of more design alternatives in the design process.

Section c: Understanding the links between categories and overlapping key factors

The process of generating product forms taking inspiration from natural forms is a complex process. The eleven key factors that are organized in the hierarchical diagram are not used in the same sequence as they appear in the diagram; students have used them in a random way. The complexity of the cognitive process is also evident from the occurrence of a sub-category under two or more main categories/key factors, which leads to the overlapping of the key factors (see Figure 3.34). The sub-category 'User' of Possibilities is also the main category of Semantic Association (see Figure 3.27). 'Selective Elements' category of Element Extraction share similar qualities with 'Selective Extraction' sub-category of Strategies. The sub-category 'Arranging Elements' of Strategies have qualities identical to that of 'Arrangement in Space' sub-category of Manipulation in Form (see Figure 3.29). Therefore, the key factor Strategies is a link between the two key factors: Manipulation in Form and Elements Extraction. Similarly, Experience is a link between Morphological Observation and Inspiration. Likewise, Judgement connects three Key factors: Inspiration, Elements Extraction and Manipulation in Form.

This understanding of the links between categories and overlapping key factors leads to the development of a framework (see Figure 3.34). Through this framework, we can theorize that there are eleven essential key factors in the process of generating nature-inspired product form.

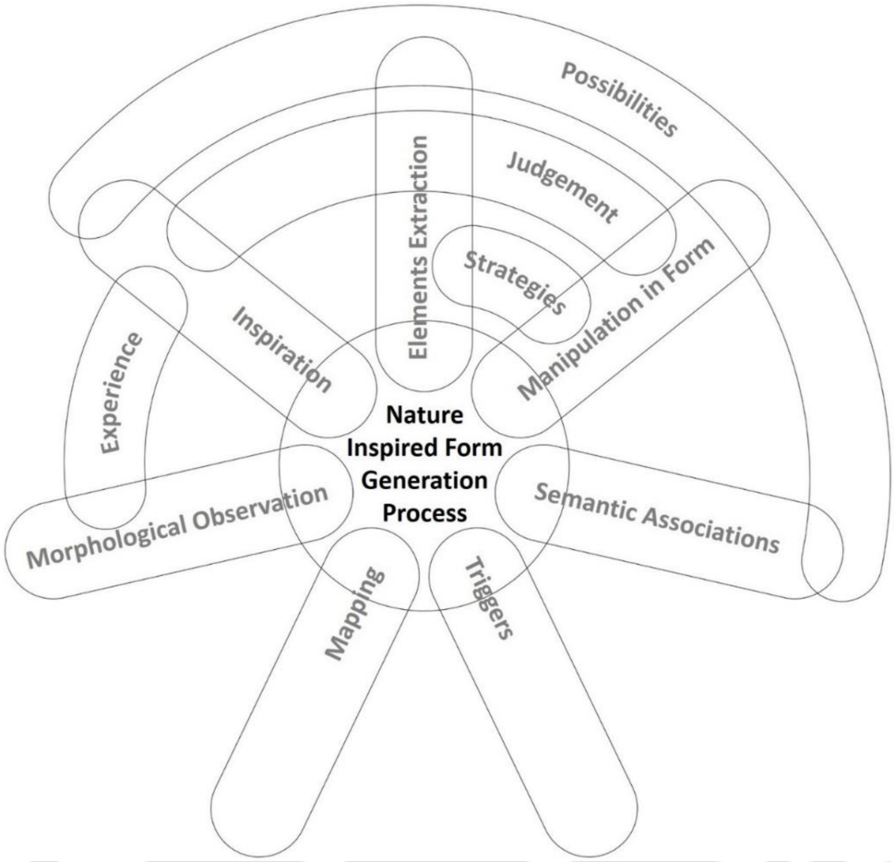


Figure 3.34 The schematic graphical representation of the resultant framework from the study (3b)

Among eleven key factors, seven key factors directly influence the form generation process and the remaining four affect the process in an indirect way. The schematic graphical representation of the resultant model/ framework of the underlying key factors is significant since it is now possible to develop more open strategies in outlining an approach to nature-inspired product form generation.

From our study we were able to identify the eleven key factors that influence the design thinking process and propose a framework for developing approaches and strategies for nature inspired form generation process. The categories in our study are grounded in the data obtained from the twelve participants. There is a possibility of some new categories to emerge if either design task or the participants are changed for e.g. novice designers are replaced by expert designers. The present framework may, therefore, be subject to certain modifications and refinement.

Chapter 4

Discussions

Based on the four studies undertaken for our research, in this chapter, we discuss the various factors and criteria that influence the process of form generation and how these can be integrated into a referral framework. Based on such a comprehensive perspective we propose and develop a Generative tool as an assisting guide in nature-inspired form generation.

4.1 Development of the framework

Following the Nigel Cross taxonomy for our research, we conducted four studies related to nature-inspired product form discussed in chapter 3. We have identified from these studies, the various factors and criteria's that are involved in the process of nature-inspired form generation. The proposed framework is an amalgamation of the findings of above mentioned four studies. Five criteria/essential requirements drawn from study 1 form the basis for identification of five dimensions of the framework: Technology, Observation, Semantics, Abstraction, and Creativity. As the evaluation of ten methods in study 1 indicates adequacy of methods in relation to the five requirements, these five criteria/essential requirements form five dimensions of the framework. Fourteen core categories emerged from study 3a on professional designers and eleven key factors emerged from study 3b with our experiment with design students (see Figure 4.1). These categories and key factors are categorized under the five dimensions graphically represented in Figure 4.2. All the findings were merged into a unified framework retaining the same order of relationship of each dimension to their categories and key factors under them.

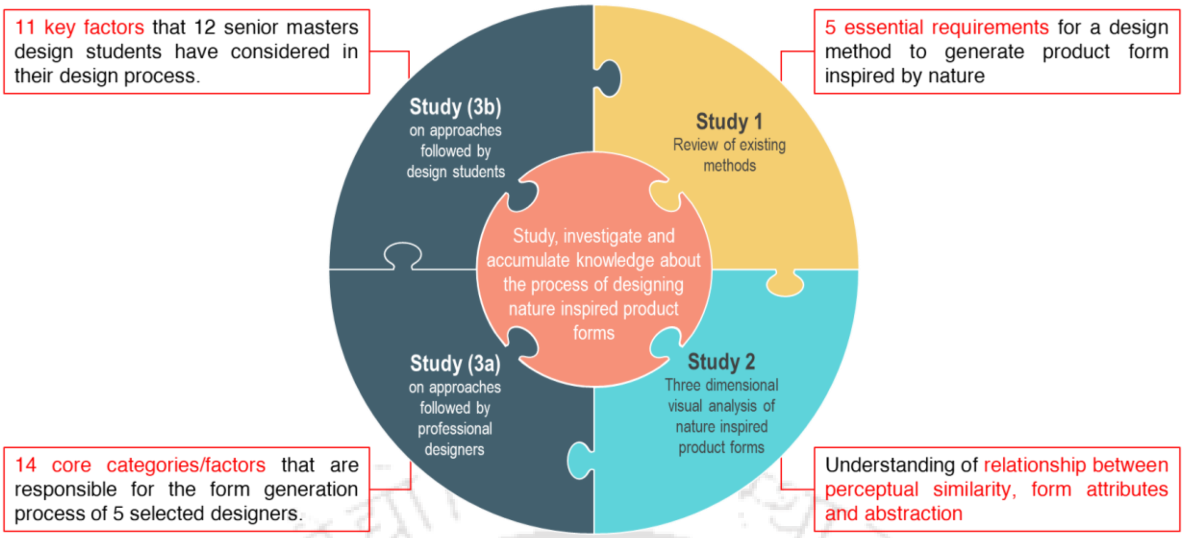


Figure 4.1 Four studies and their output

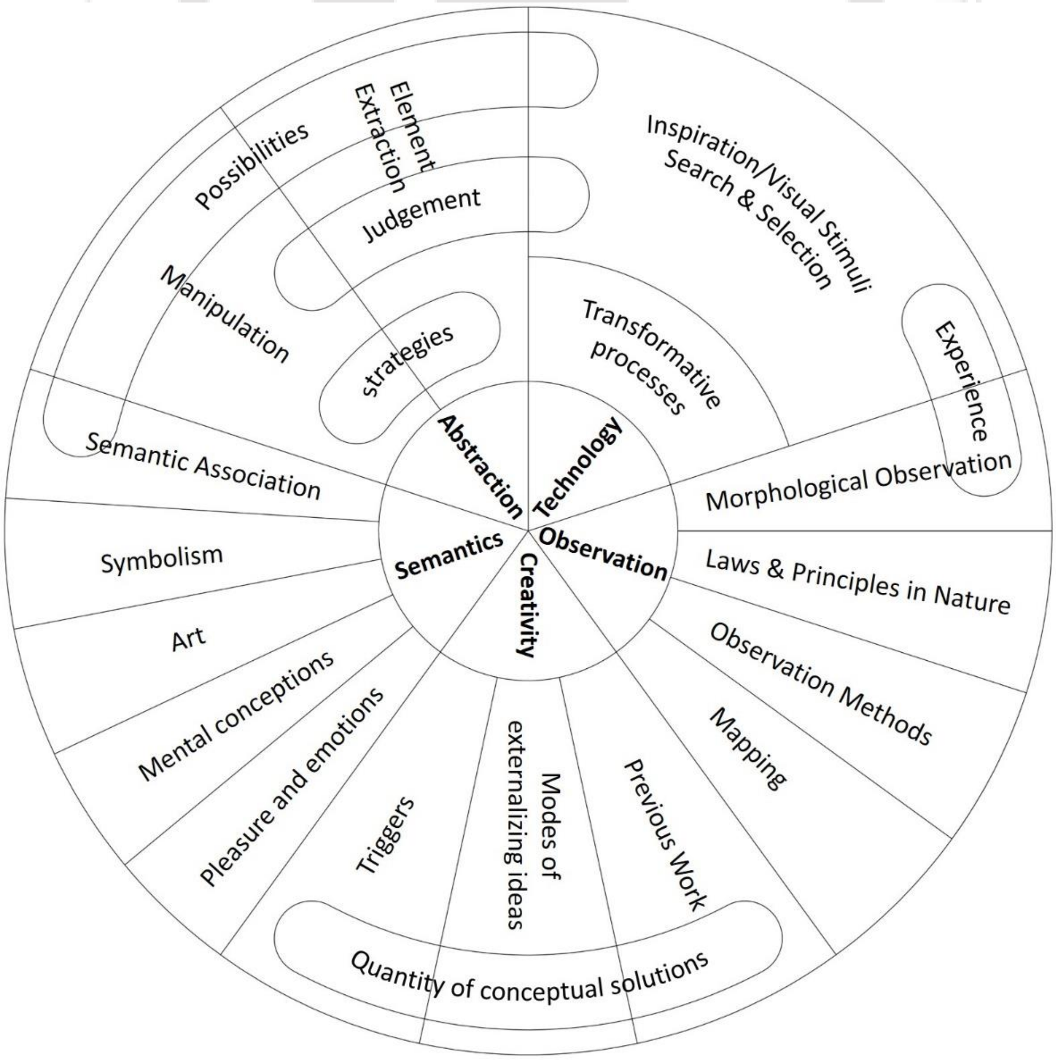


Figure 4.2 Proposed framework

We now explain the contribution of each dimension of the framework and its influence in the form generation process. The use of such a graphical representation of the proposed framework will help to give directions to design practitioners and design educators. This will enable the designer to creatively use it as a framework for the different contexts of design they are engaged in. It can suitably be adapted to develop their own tool/method to generate novel and creative concepts of nature-inspired product forms. The proposed framework is not a generalized model of a design process. Rather it is to be used as a referral guideline for the design process in design practice. Design educators could use it in the development of an advanced course on nature-inspired form studies.

We discuss below each of the five dimensions in detail.

4.1.1 Technology

The *Technology* dimension represents the integration of technology at various stages of the design process. *Transformative processes* and *Inspiration* are the two categories that come under this dimension. Designers start their design process either when they are inspired by a natural form or they search for an inspirational form in their mind or physically from a medium like the internet. The search for inspiration starts with emotion words. Finding an inspiration with related emotion word depends completely on the training of the designer. Technology can make this search more systematic and easy through software packages and databases. During initial stages of the form generation process designers need *Visual Stimuli*. In such situation technology can help them to gather more visual information of inspirational form by using instruments like 3D scanner, Digital cameras, and electron microscopes. Use of such instruments also helps to discover new forms which are not visible to the naked eye. Special cameras for slow-motion and time-lapse videos can help a designer to explore more variety in the type of visual stimuli. Through these videos, designer can closely observe the behaviour of an organism or any other natural phenomena more precisely, which is a limitation with two-dimensional images. Technology can play an important role in *Transformative processes*. Designers can perform various simulations and can test their designed product form for manufacturability. A very good example of the use of technology in the field of nature-inspired design is generative design which uses principles of nature to find optimum solutions of engineering design problems. The products designed by generative design software packages like DreamSketch are more optimized in terms of functional design but they may not be aesthetically appealing and expressive (Kazi, Grossman, Cheong, Hashemi, & Fitzmaurice, 2017). On the other hand, products that are designed by following the principles of design are not functionally optimized (Rao, Vishwakarma, & Saxena, 2019). Principles of form generation are different from the principles of engineering design. It would be a great support for industrial designers if the software can create a form that is aesthetic as well as structurally optimized. Combining the principles of design with the principles of engineering design is a challenge for researchers and software developers that can be explored in near future.

4.1.2 Observation

In our framework *Observation* is a necessary skill for learning. In *Observation* dimension, one can focus on the development of tools and methods that can assist designers in observing natural forms or improving their observation skills required to observe natural forms. *Morphological observation/attentive study of natural form*; *Laws and principles in natural form*; and *Necessary conditions for observation* and *mapping*, are the categories that come under this dimension. The *morphological observation/attentive study of natural form* can be supported by the vast body of biological knowledge of plant and animal morphology. A designer must be trained to observe various form attributes of natural form that are discussed in study two along with laws and principles in a natural form which are highlighted in the third study of the research. Once a designer is aware of these attributes, principles, and laws, he/she can easily identify them in a natural form and can translate them into design concepts. In future, one can conceive of a situation where machines can be trained to do that using Artificial Intelligence (Figure 4.3).

Figure 4.3 Illustration representing use of Artificial Intelligence to observe principles and visual cues in natural form

Prolong observation of natural form and being in its close proximity are necessary conditions for observation of minor details of natural form. To observe every detail of the natural form the designer should remain in close proximity of that form. Therefore, it is preferred to introduce real inspirational natural form in the design process rather than images. If the use of real form is not possible then designers can experience that form virtually using technologies like Virtual Reality (VR). Design practitioner/educator must explore different methods to enhance the engagement of designer/design students with the natural form for its attentive study. In our fourth study of this research it is clear from the findings that students did not observe the principles of nature completely. Use of colour and curves of natural form was common but they ignored other principles. Some tools or guidelines can assist a designer in observing various aspects of natural form and can also help to apply that observed information into form generation process. One of the interesting findings from our study 3b is Mapping. In this, students try to map their observed visual information of inspirational form with that of product form. This approach produces very quick and creative results. We expect that the outcomes of an in-depth study of this phenomena in future may lead to the development of some tools or design heuristics that may reduce the time and efforts that one spends in the form generation process.

4.1.3 Semantics

Semantic dimension explores the association of meaning of a natural form in the man-made world. It is not only about understanding a natural form but also its association with people and places. *Mental conception; Symbolism; Pleasure and emotions; Art* and *Semantic association*, are the factors that fall under this dimension. A designer must explore all the possible *semantic associations* of selected natural form. More number of associations will increase the chances of getting a strong association and a strong association will have a greater influence on the user. *Symbolism* is significance of natural form in the man-made world. It is more related to cultures and geography. The literature on people and culture may help a designer to understand this significance. *Mental conception*, which is the embodiment of idea or conception of natural form into the form of an existing object, gives a new experience to the user. Through this experience, users can relate a product form with natural form. Identification of ideas/conceptions and their application in the product form are very important aspects of mental conception. A designer can take inputs from the Observation dimension and can apply those inputs while working under the Abstraction dimension. Natural forms can influence human *pleasure and emotions*. Dresser (Dresser, 1862) suggests that a designer can design pleasurable forms by following hints of nature with an inward passion. One way to achieve this is through *Art* which can help designers to avoid direct imitation of form. An artistic perspective in the form generation process can help a designer to create a product form that displays a harmony with nature. In the *semantic* dimension, the recorded observations are synthesized. Design educators/practitioners often face challenges in enhancing metaphoric understanding of natural form, identifying the visual cues related to particular emotions, and transfer of those visual cues from natural form to product form during form generation process. However, there are few methods that involve use of cue charts (Teubner, 2008) and metaphoric means (Hekkert & Cila, 2015) but there is scope to explore more methods that can integrate metaphoric understanding with identification of visual cues. These can help transfer of visual cues during form generation process.

4.1.4 Abstraction

Abstraction is drawing out the essential qualities from an object or a situation (Hale, N. C. (1993). In the context of our framework, *Abstraction* is about extracting essential qualities of a form and reduction of visual information in the generated concept form. The *Abstraction* dimension deals mainly with *element extraction* and their *manipulation* in form generation. It involves exploring *possibilities*, *strategies*, and *judgement*. In designing product forms inspired by nature, designers must generally avoid direct imitation of natural form and should practice idealization or abstraction of the natural form. New ways of extraction of visual elements and manipulation of form may help them to achieve abstraction while staying connected to the natural inspirational form. Based on our earlier findings from study 3b, for element extraction, we suggest that a designer can extract either from the complete form or only from selective elements therein. A designer can also focus on patterns and textures present in the natural form. The results of our earlier study 2 have explained the relationship between perceptual similarity, form attributes, and abstraction. It has also been explained how abstraction can be controlled through the proposed spectrum of bi-polar limits. Designers can develop such spectrums in their design process. The findings of study 3b display a clear relationship of abstraction with order of hierarchy and mapping and the manner in which one can control abstraction across the spectrum. It may be noted that if the hierarchy of order in product form is similar to that of inspirational form, then the product form is less abstractive and if it is less similar than the product form is more abstractive. Mapping of features between inspirational natural form and generated product form while following organic geometric spectrum can help to achieve and control abstraction in a product form.

For manipulation of the form, we suggest designers to use the principles of form generation and form analysis outlined by Roweena Reed and Akner koler, whose pioneering coursework on form studies forms an important input in many design schools across the world (Hannah, 2002) (Koler, 1994). Designers may focus on combining these principles with the extracted elements to generate form. In our research one of the finding of study 3b under the core category: ‘manipulation in form’, indicates the partial and random usage of principles of form generation by students during their design process. In such situations a design tool may provide a systematic way of generating a form by utilizing maximum number of principles. Such a design tool may also hold promise in the future for developing new CAD systems.

4.1.5 Creativity

The dimension of *creativity* takes care of the creative aspect of conceptual solutions. Various definitions of creativity in design research deal with novelty and appropriateness/usefulness of designed products (Sarkar & Chakrabarti, 2011). In the context of our current research, we are focusing on artistic creativity where the criteria of beauty dominate appropriateness/usefulness (Piffer, 2012). Therefore, aspects of novelty and beauty are the core component of creativity for nature-inspired product forms. Quantity of conceptual solutions is one of the basis for measuring novelty (Shah, Vargas-hernandez, & Smith, 2003). Our study 3a and 3b revealed three conceptual categories that basically contribute towards generation of large number of conceptual solutions - *Knowledge of previous work*, *Modes of externalizing ideas* and Existing product search under *Triggers*. Design educators/practitioners must find new ways of generating large number of conceptual solution that can be integrated with the form generation process. Morphological analysis (Hsiao & Chou, 2007), creative wheel (Shende, & Das, 2018) (Jorgensen, Kjeldsen & Lenau, 2013), and design heuristics (Arbor, 2016) are among few of them. Inventing new tools/methods that can use knowledge from previous work or concepts may lead to an increase in the number of conceptual solutions. Different modes of externalizing ideas like sketching and model making must be explored by design educators/practitioners because the brain processes and assimilates lots of information during these tasks that lead to idea generation (Tovey, Porter, Newman, & Street, 2003). One of the direction could be the integration of CAD software with conventional form generation processes. CAD software are usually used during detailing process in the final stages of product development. The benefits of high computing power and ability to generate complex form can be utilized at early stages of form generation process.

4.2 Development of a generative tool

As an empowering medium for form generation, the framework outlined earlier is used for the development of a generative tool. It is a design tool that offers a systematic and logical approach in the generation of a product form inspired by nature. This 'pen and paper' based form generation tool may be useful for practising designers and for design educators offering a course on nature-inspired form generation.

The tool is based on five dimensions of the framework. It comprises of three response sheets that will guide a designer through different stages of the form generation process. These sheets are used in a sequential manner. Data from sheet 1 and 2 are used as inputs for sheet 3 (Figure 4.4).

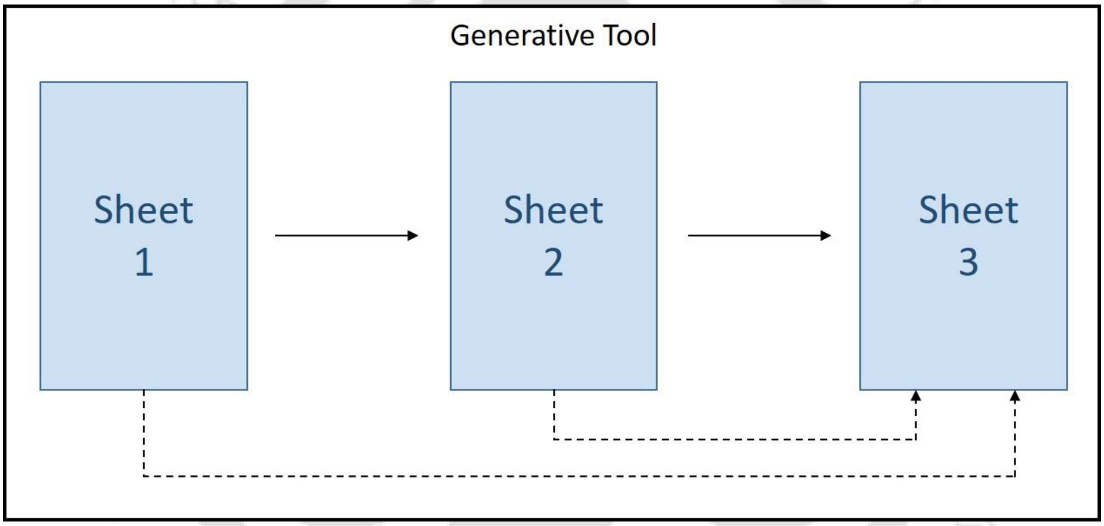


Figure 4.4 Block diagram of the generative tool

Response sheet 1 for stage 1 covers the three dimensions of the framework: Technology, Observation, and Semantics. The subcategories of these three dimensions are covered under each item of sheet 1 as shown in Figure 4.5. Sheet 1 guides a designer to collect information about inspiration using different sources and instruments such as books, internet, microscopes, and digital camera. The recorded information is in the form of texts and sketches which is used in the third stage of the process.

Response sheet 2 for Stage 2 is adopted from graphical data collection tool of study 2 which was used for visual analysis of the products. This sheet also covers the observation dimension of the proposed framework as shown in Figure 4.6. The observed visual cues and form attributes of the natural form are recorded in sheet 2.

The observation can be marked on the left-hand side of the sheet under each form attribute and designers can use the blank side of the sheet for sketching. Later designers can use this sheet as a reference for sheet 3.

Response sheet 3 for Stage 3 is an extension of the concept of form attribute controller proposed in study 2 which can help a designer to perform and control abstraction. This sheet basically covers two dimensions of the proposed framework: Abstraction dimension and Creativity dimension, graphically represented in Figure 4.7. Information from sheet 1 and 2 are also used in this sheet during the form generation process. As a result, it also covers Observation dimension. In this stage externalization of ideas take place which can provide better opportunities to integrate artistic perspective in the design process and therefore it also covers Semantic dimension with art category.

As an application of the generative toolkit, we demonstrate the three stages of the form generation process taking two examples - The ladybird beetle and the mango leaf as the source of inspiration from nature in generating product concepts for a lighting device. These are included as Appendix 13a, Appendix 13b and Appendix 13c for example 1 (Ladybird as the source of inspiration) and Appendix 14a, Appendix 14b and Appendix 14c for example 2 (Mango leaf as the source of inspiration).

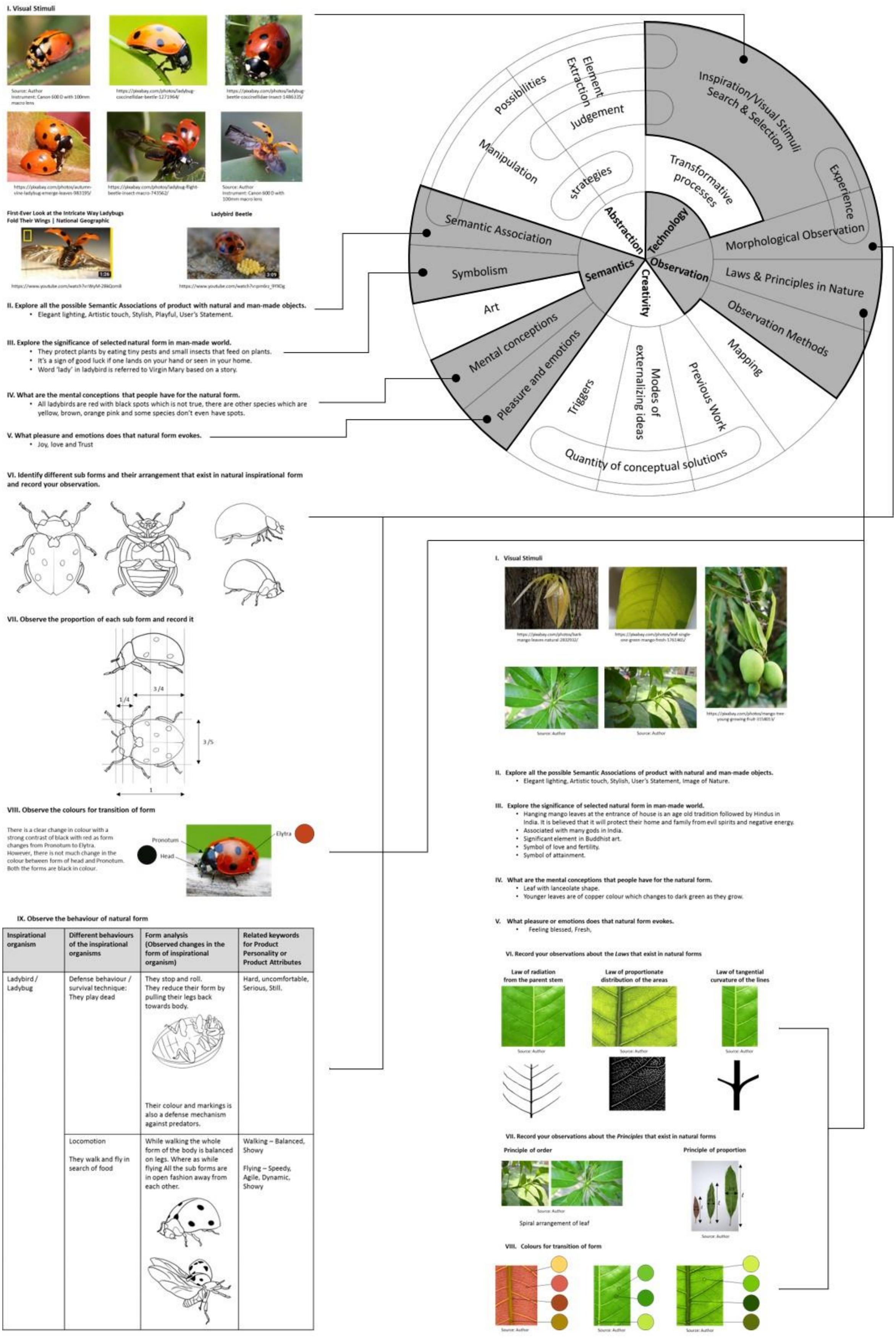


Figure 4.5 Development of sheet 1 based on the framework

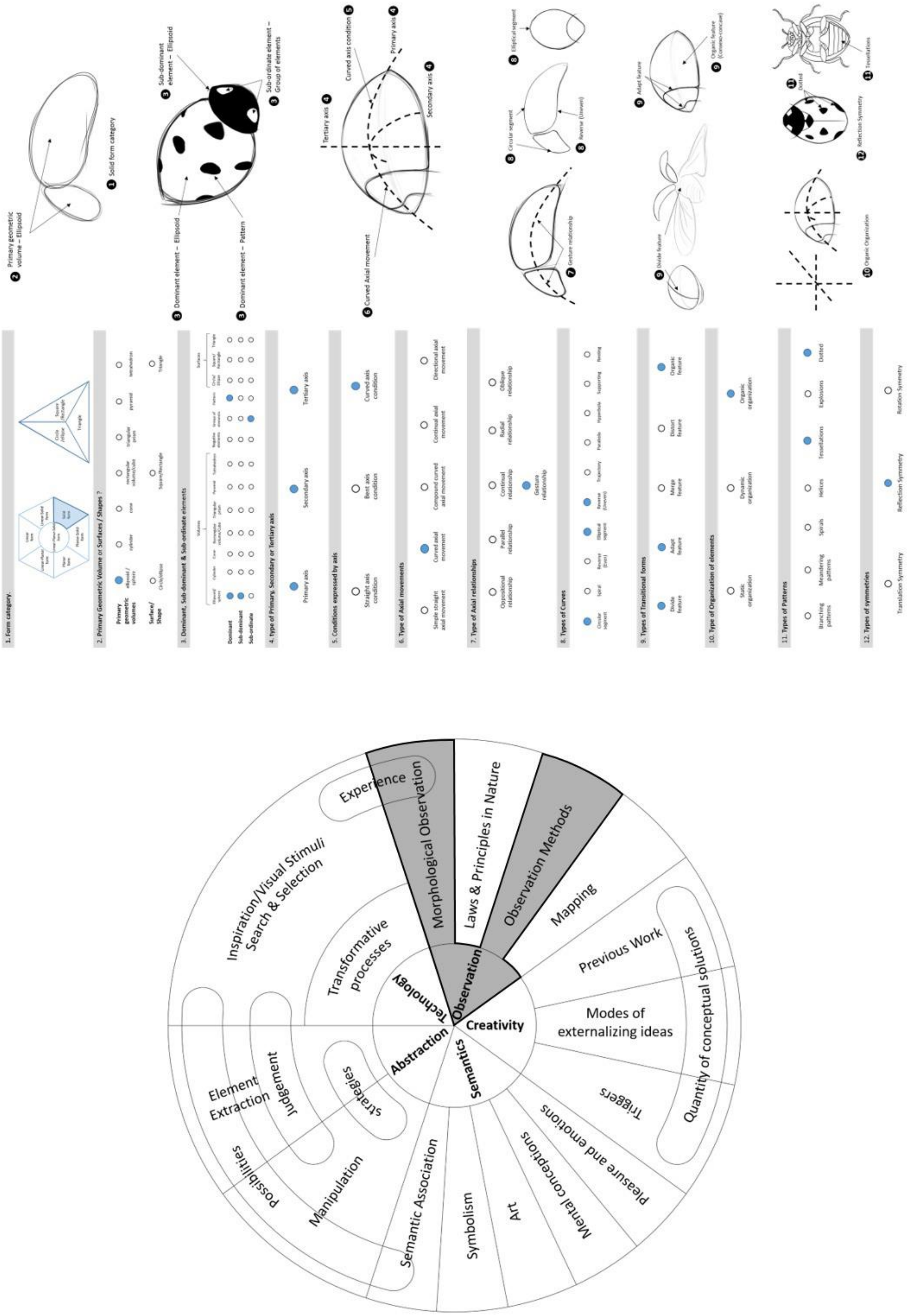
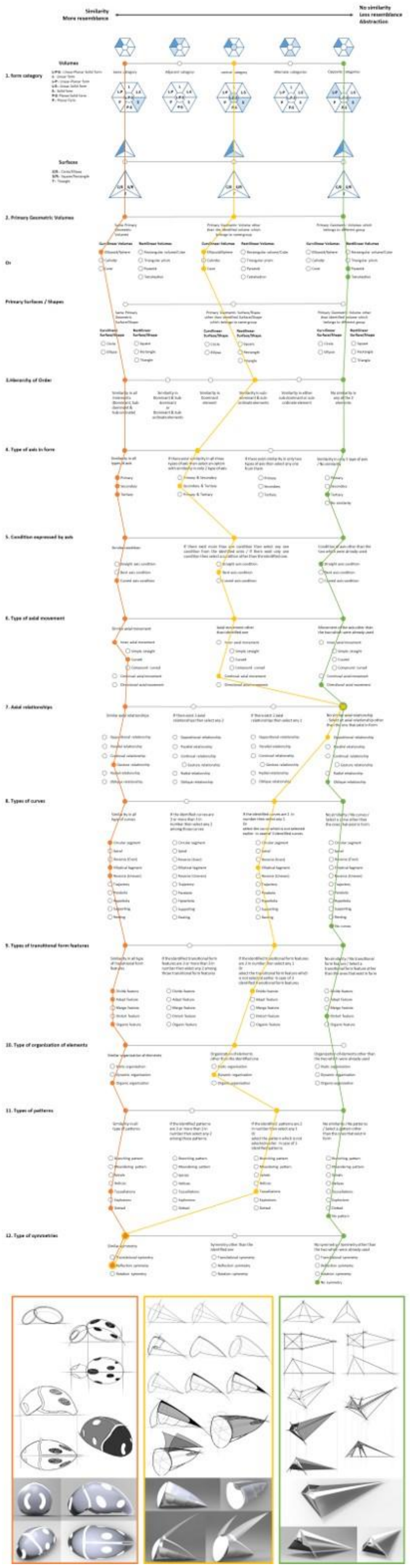


Figure 4.6 Development of sheet 2 based on the framework



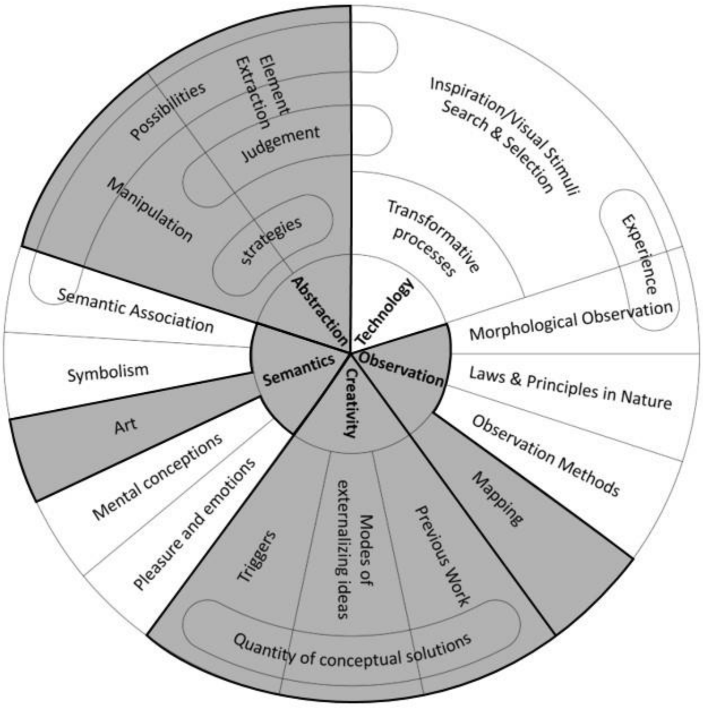


Figure 4.7 Development of sheet 3 based on the framework

4.2.1 Limitations of generative tool

In our experience of application of the Generative tool we also experienced that the respondent may find it difficult to select a form attribute while responding to the different attributes in the third response sheet. We see that sometimes the selection of an attribute can cause contradictions with previously selected attributes. For example, it may be noted that in concept two of the first design, it is not possible to select transitional or rotational symmetry because of the attributes that were selected earlier. Similarly, in concept three of the first design under attribute number 10: type of organization of elements, the only option left is static organization but due to earlier selection of attributes, it is not possible to arrange elements in a static organization. Therefore, attribute 10 is left blank in concept 3. In concept two of the second design, selection of dynamic organization and type of symmetry is not possible due to the attributes which were selected earlier in sheet 3.

We, therefore, suggest that in the use of the Generative tool one may use it as a referral guide and not necessarily cover all the attributes sequentially. If the selection of an attribute creates certain contradictions it can be left out using one's logical reasoning and judgement.

The proposed tool is our first attempt of a generative approach to control abstraction and it may have its limitations. Based on further application one may make refinement and appropriate changes to the tool in the future.

Chapter 5

Reflections on the Research Outcome

In this chapter, we revisit the basic assumptions and objectives that we set out to inquire. The outcome of the four experimental studies on the study of processes, products and people helped to outline a referral framework of understanding the various dimensions of the form generation process. This led us to propose a generative tool as an assistive guide in controlling, manipulating and transforming the product form. As is evident the processes developed clearly lean towards a mode of inquiry that is systematic, and one that enables a designer to know where in the design process one is able to generate variations to the product form. These studies point towards a systematic approach that has a design science temper underlying the process. It answers one of the objectives of our research that set the goal of seeking a systematic approach to the form generation process. This objective seems to have been adequately met.

We reflect taking an overall view of our research and discuss our understanding of the hidden science/s behind the nature-inspired form generation process to make some critical observations on our research.

5.1 Introduction

The motivation that triggered this research was the criticisms that designers face in their approach to design product forms inspired by nature. It was strongly implied that the approach adopted by designers was not 'scientific' in their approach to the design of nature-inspired product forms. Researchers argue that being inspired or just imitating a natural form, texture or colour is not nature-inspired design. A true nature-inspired design should have nature's science in it.

This set the roadmap for identifying if this argument was indeed true or a myth. It formed the basis in formulating our two research questions viz.

- Can there be a systematic approach to inquire into the process of generating nature-inspired product forms?
- Can the process of generating a nature-inspired product form be systematized?

In our journey to explore the possibilities of systematic design research and systematic design practice for the process of generating nature-inspired product forms, we found the hidden science behind the nature-inspired form generation process. While examining the methods and tools used by biologists and designers to observe natural forms, we could identify and concur that 'Goethean Science' showed considerable similarities with the designers' process. We saw it worthwhile to make a critical comparison between these two processes. In the section to follow, we first outline the Goethean Science process and then drawn critical comparisons with our findings from the four studies conducted in this research. Following this, we discuss three aspects – design science, science of design and scientific design by positing their significance and relevance to the studies we have conducted. This would help to establish that there is indeed a rigour of a design science underlying the process of nature-inspired design processes followed by designers.

5.2 Goethean Science

In 1790, Johann Wolfgang von Goethe, first studied morphology, the study of form and structure of an organism (Kaplan, 2001). He followed a unique phenomenological method he called "delicate empiricism" which means *"The effort to understand a thing's meaning through prolonged empathetic looking and seeing grounded in direct experience"* (Seamon & Zajonc, 1998). Goethe's method is unique because it is a link between the artistic and scientific domain. His observation method involved the use of all five senses. The four stages of the Goethean phenomenological method for the morphology of an organism are:

(i) Stage one: The physical/sensory information/Earth

Stage one, referred to as Earth stage, is the preconceptual phase of research. It involves an exact description of the phenomenon of form and structure, through observation based on the gathering of information from all the five senses. These descriptions characterize the plant in ways that capture the many qualities apprehended by the senses in terms of its external facts. In earth mode, the researcher should experience oneself as an external observer separate from the organism. It is a difficult phase because one must see things clearly and in an unprejudiced way, which requires mental discipline.

(ii) Stage two: Time/exact sensorial imagination/water

This stage of research is about understanding and experiencing the organism's time dimension and its growth process. It is about perceiving the dynamically relational character of the organism and understanding how one quality derives from the other, one part from another e.g. relationship between seed and stem. It involves understanding the continuity of these organs not only in space but also in time. It is about not only perceiving moments externally but also taking them within, it implies perceiving them with our inner or artistic sense. Goethe called this process of cognitive participation in organism's generative movements as "exact sensorial imagination." The qualities of fluidity, sensitivity, and capacity to experience the changes of living form are used as expressive of the movement of a form through time and of imaginative cognition.

(iii) Stage three: Gesture/inspiration/air

In this stage, metamorphic movements are perceived as formative gestures which are also called as organisms "formative life-principles." The ideas behind the formative movements of the organism are apprehended through "airy cognition." This phase requires a deeper participation in phenomena through an inner or artistic faculty and these inner perceptions are brought to outer expression, as "Gesture sketches" through a suitable medium like visual, verbal, or even musical. The approach requires less realistic and more expressive art forms. The mode of cognition associated with the air phase is called "Inspirational." These gestures of organic forms are not perceived as empirical facts or movements in time, but one has to inspire them with artistic cognition to allow their meanings to surface.

(iv) Stage four: Creative potency/intuition/fire.

The gestures obtained in the third stage are further distilled by intuitive mode, which is another mode of observation. This stage is the most inner way of experiencing the organism, and intuitive perceptions can be expressed through any medium capable of transmitting potent meanings like art. Intuitive perception is thinking from the whole to the part. This is the fire stage. The fire has the character of intensity and self-generated activity. These qualities are experienced externally as warmth and internally as the immediate warmth of identification that one feels when one has made contact with a living being's inner impulse. Poetry and paintings can be used as a way of actualizing this fire stage.

5.3 Designers approach and Goethean Science process – a comparison

When we compared our findings of study 3a on designers with four stages of Goethean phenomenological method, we found that there are much similarities in the designers' approach and Goethean phenomenological method. Table 5.1 shows the core categories from study 3a that share similar characteristics with the four stages of the Goethean phenomenological method for the morphology of an organism.

Table 5.1 Core categories from study (3a) having similar characteristics with the stages of Goethean Science

Four stages of the Goethean phenomenological method for the morphology of an organism	**Core categories/design factors from study 3a**
Stage one: The physical/sensory information/Earth	(1) Inspiration, (2) Observation, (3) Necessary conditions,
Stage two: Time/exact sensorial imagination/water	(4) Laws in natural forms, (5) Principles in natural forms,
Stage three: Gesture/inspiration/air	(9)Art, (11) Modes of externalizing ideas,
Stage four: Creative potency/intuition/fire	(6)Manipulation in natural forms, (7) Mental conceptions, (8) Symbolism, (10) Pleasure and emotions,

This similarity of designers' approach with the Goethean Science is explained based on the similar characteristics of core categories of study 3a with the four stages of Goethean phenomenological method/Goethean Science.

Stage one:

- This stage of Goethean Science involves an exact description of the phenomenon of form and structure, through observation based on the gathering of information from all the five senses. Designers observe and study natural form to identify new forms, natural growth patterns and shapes in nature. During this process, they use their senses to collect information about the natural form and record their observation through sketches which is very similar to the approach adopted by biologists. For biologists, sketching the observed organism is an important mode of recording observations and it has been practiced in both the early phases of morphology (Goethean science) and in modern methods, which includes the combination of illustrative methods like line drawings, stick diagram, and ground plan. For designers, sketching is an integral part of the design process and a mode of ideation.
- The mind plays an important role in the observation process adopted by both designers and biologists who follow Goethean Science. Goethe, suggest that one must see things clearly and in an unprejudiced way, which requires 'mental discipline'. Whereas Dresser states that to appreciate the delicacies of form and line, 'Refinement of mind' is required.

Stage two:

- In this stage of Goethean Science, biologists try to understand and experience the organism's growth process. It is about not only perceiving moments externally but also perceiving them with our inner or artistic sense. Designers also follow a similar approach by understanding various laws and principles in nature on which organisms grow. Plants follow these laws and principles in their development phase. Through these laws and principles, a designer tries to understand the order and harmony involved in the growth of an organism.

Stage three:

- In this stage of Goethean Science, metamorphic movements are perceived as formative gestures which are also called as organisms "formative life-principles". Designer Mackmurdo also suggested a similar approach in which the independent role of "formative imagination" can help to avoid transcription of nature.
- This stage of Goethean Science requires a deeper participation in phenomena through an inner or artistic faculty and these inner perceptions are brought to outer expression, as "Gesture sketches" through a suitable medium like visual, verbal, or even musical. The approach requires less realistic and more expressive art forms. Due to their professional training designers understand the link between art and nature. They support the use of art forms like impressionism for expressing ideas.

Stage four:

- During this stage of Goethean Science, the gestures obtained in the third stage are further distilled by intuitive mode, which is another mode of observation. Intuitive perception is thinking from the whole to the part. Designers display a similar behaviour during 'Manipulation in natural forms' where they modify the observed natural form by idealizing it, adding forms of exceeding beauty or performing abstraction.
- This stage is the most inner way of experiencing the organism, and intuitive perceptions can be expressed through any medium capable of transmitting potent meanings like art and poetry. Designers believe that nature has a direct link with human sensuality, pleasure and emotions. They follow a similar approach like Goethean Science to experience the organism by understanding mental conceptions related to natural forms. Their intuitive perceptions are expressed through product forms by following practices like symbolism.

Johann Wolfgang von Goethe is generally known for his poetry and literature and very less for his scientific work. This could be one of the reasons for his unique approach that display a link between the artistic and scientific domain. As a result, Goethean Science always remained controversial. His approach challenges the common paradigms of positivist, scientific methodology and still a topic of debate often contested among several scholars. However, there are several scholars and practitioners of Goethean science that support Goethe's scientific studies and his way of science (Bortoft, 1996; Goodwin, 2000; Seamon & Zajonc, 1998) (https://medium.com/age-of-awareness/zarte-empirie-goethean-science-as-a-way-of-knowing-e1ab7ad63f46).

Based on these studies we considered Goethean Science as a way of science that can connect artistic (Design) and scientific domain in a very unique way especially in the context of our research work. The similarities in designers' approach and Goethean phenomenological method /Goethean Science support the fact that there is a science behind the approach of designers for generating product forms inspired by nature and it is not completely non-scientific.

5.4 Relationship between design science, science of design and scientific design in reference to the current research

Structuring our research while following a design science approach founded on Nigel Cross taxonomy has helped us to co-relate various design and science relationships that exist in our research. In the section to follow below, we discuss these relationships referring to the definitions of scientific design, design science and science of design discussed by Nigel Cross in his book 'Designerly ways of knowing' (Cross, 2006).

5.4.1 Scientific Design

"Scientific Design refers to modern, industrialised design – as distinct from pre-industrial, craft-oriented design – based on scientific knowledge but utilising a mix of both intuitive and non-intuitive design methods" (Cross, 2006).

As discussed in the previous chapter the four stages of the Goethean phenomenological method for the morphology of an organism display a close resemblance with the steps followed by designers during their design process. The way in which Goethean phenomenology is followed to observe a natural form, to describe a natural form, understanding its growth process, and producing results through expressive art forms is very similar to the approach that designers usually follow while designing nature-inspired product forms. Designer's approach not only utilizes scientific knowledge of Goethean science but also involves the use of both intuitive and non-intuitive design methods. Therefore, referring to the definition of Nigel Cross, we think designer's approach can be considered as scientific design.

5.4.2 Design Science

"design science refers to an explicitly organised, rational and wholly systematic approach to design; not just the utilisation of scientific knowledge of artefacts, but design in some sense a scientific activity itself" (Cross, 2006).

The research framework based on the Nigel Cross taxonomy was found to be very useful for conducting an organized and systematic inquiry for our design research. This taxonomy provided a strong foundation for a 'design science approach' to understand the design process of generating product forms inspired by nature.

5.4.3 Science of Design

"science of design refers to that body of work which attempts to improve our understanding of design through 'scientific' (i.e., systematic, reliable) methods of investigation" (Cross, 2006).

Each of the four studies of the research framework that were carefully planned and conducted seems to follow the concept of Science of Design which improves our understanding of the design process through scientific methods of investigation (Figure 6.1). The comparative study of methods, three-dimensional analysis of products, and qualitative study on designers and design students were conducted using well established scientific methodologies and experimental protocols.

5.4.4 Unification of Design Science and Science of Design for Design Research

Study 1 on methods and study 2 on products contributed towards a systematic approach to design. Five essential criteria of study 1 became five dimensions of our framework and the relationship between perceptual similarity, form attributes and abstraction from study 2 helped us to control abstraction in a systematic and more logical way (Figure 6.1).

Study 3a on professional designers and study 3b on an experiment conducted with design students helped us to accumulate knowledge about the design process. Study 3a gave us fourteen core categories/factors that are responsible for the form generation process of five selected designers. Study 3b gave us eleven key factors that twelve design students have considered in their design process (Figure 6.1).

Thus, the research framework based on the Nigel Cross taxonomy has supported our design science approach which ultimately helped us to achieve our aim of the research.

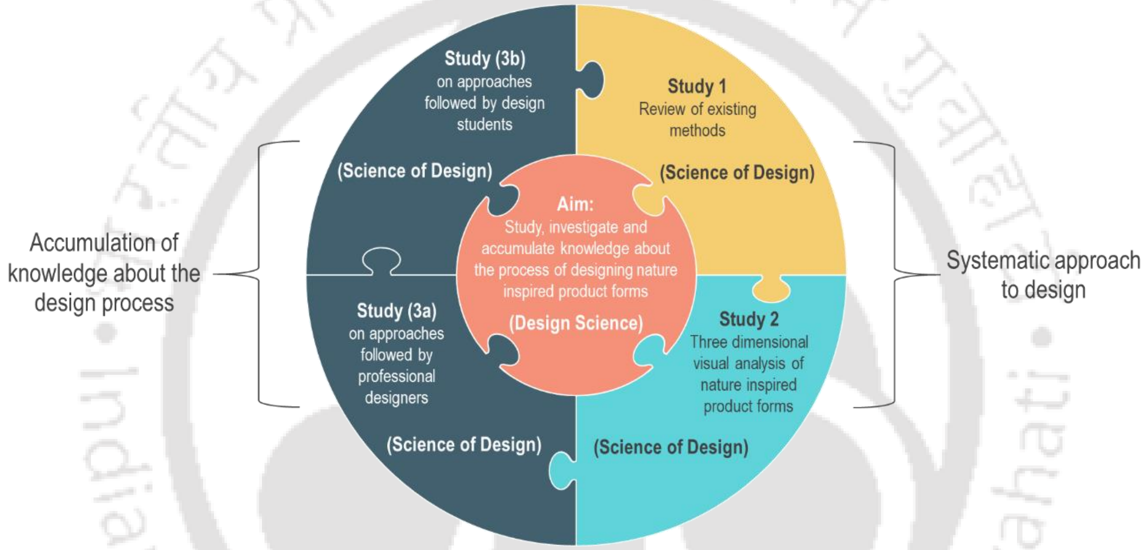


Figure 6.1 Contribution of four studies towards the aim of the research

5.4.5 Relationship between Design Science, Science of Design and Scientific Design that emerged from our Design Research

Through these arguments, we say that Design Science, Science of Design and Scientific Design can practically co-exist in Design Research (Figure 6.2). In our research, we have formulated the aim of research and objectives of individual studies based on the design science approach. We have detailed out the methodology for each study following the concept of science of design and finally, we have designed a generative tool that utilizes both intuitive and non-intuitive design methods along with scientific knowledge that contributes towards scientific design.

Graphically represented in Figure 6.2 below, such a design research approach can be adopted in a more general manner for various kinds of design research in which design science can help to formulate the aim and objectives of the research, the concept of science of design can help to plan and conduct each study. Design science and science of design both are part of experimentation. The outcome of the research can take the form of scientific design which will form a part of the research output.

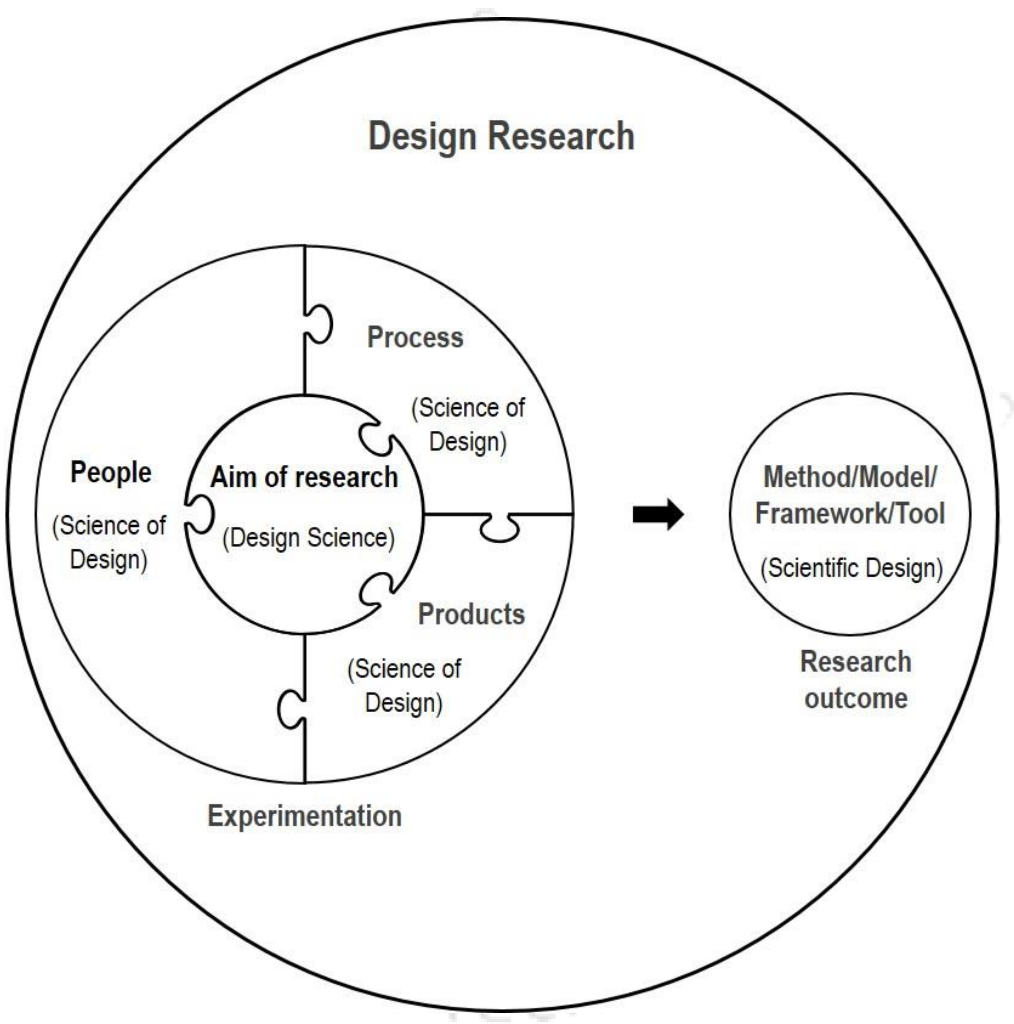


Figure 6.2 Relationships between scientific design, design science and science of design in a design research

Chapter 6

Conclusions

In the concluding chapter, we sum up our research, drawing conclusions of the achievements that our research has achieved, some of the limitations of our research, and possible scope of directions for the future in which design research on nature-inspired product form could be further directed.

6.1 Concluding remarks

Form-making/form giving/styling is a special class of design problem that involves a mix of rigorous analysis and creative problem solving (Athavankar, 2009) (Person et al., 2016). It is often the case that researchers mix issues on function and aesthetics, particularly for organic design or nature-inspired design which is also reflected in the criticisms included in the first chapter. Motivated by such criticisms, we started our journey on nature and form. We found that form giving activity for nature-inspired products is not explored much in the available literature and we decided to take that direction.

On one side we had systematic methods by the scientific community and on the other we had methods and approaches followed by designers that are more intuitive. In the middle of 'science' and 'design', we decided to follow a designerly way of knowing. The creative act of nature-inspired form generation is very complex and therefore, we explored it holistically from three perspectives: process, product, and people.

The current research work does not try to make the process of generating nature-inspired product form a scientific process. It is an attempt to explore this phenomenon through a scientific lens. The findings of this research will help to make this creative activity more systematic and not scientific.

Our research framework based on Nigel Cross taxonomy guided us in a systematic inquire into the process of generating nature-inspired product forms. In this inquiry, we used scientific methods for exploration under each individual study. This addressed our first research question. The generative tool based on the proposed framework in chapter 4 is an attempt for a systematic process of generating a nature-inspired product form that addressed our second research question. The four studies of the research framework helped us to gather knowledge about the phenomena from three perspectives which was the aim of our research.

At this point, one may argue that our findings on science/s in nature-inspired design, covered in chapter 5, tries to seek if there is indeed a scientific temper underlying creative activity. It is pertinent to clarify that our research did not set out to prove that the act of creating nature-inspired product forms generation is scientific. The findings of chapter 5 have emerged as a result of critical observation after conducting our studies. It was like solving a puzzle. When the findings from different studies were placed together we could see a pattern. Although we never aimed for it, the findings seem to point towards an underlying science to the process. As researchers, we want to report it as an important observation from this research.

6.2 Contributions of research

The novelty of this research lies in its planning and execution. This adds up new knowledge to the design research domain that offers new opportunities to explore. It opens up new discussions and deliberations for the community of design researchers and design educators. In our view, there are six key contributions from our research. These are summed up below.

6.2.1 A framework for the process of nature-inspired form generation.

As an outcome of the research aimed at seeking a systematic process of inquiry into the processes of nature-inspired product form generation for industrial designers/ educators, a structured 'proposed framework' emerged as one of the key contributions of our research. It was formulated as an outcome of four studies following a 'T' structure of inquiry on approaches and methods. This gave strength to our inquiry, combining lateral width with vertical depth, to understand various factors involved in the process of product form generation inspired by nature. Identification of these key factors and their sub-categories of the framework formed the foundation on which we could outline and propose a Generative tool for nature-inspired product form generation that could guide and assist designers and design educators to a structured and systematic manner in exploring product from generation.

6.2.2 Generative tool to systematise the process of generating product forms inspired by nature

The design & development of the generative tool is the second contribution of the research. In our view, such a generative tool has not been formally developed earlier in such a systematic and orderly manner. When compared to the conventional intuitive methods where the designer takes a decision on the form attributes based on his/her intuition the generative tool assists a designer to decide on form attributes in a systematic way. It gives the whole process a definite direction, transparency and logical reason in knowing how and why the 'visual form' is what it is. The process combines a fine balance between the lateral creative thinking process with deep logical reasoning. The outcome in proposing a generative tool perhaps adds a novel way of looking at the form generation process. While such attempts are no complete answers to our understanding of the mysteries of the thinking mind, it at best contributes as a guide towards a 'designerly way of thinking'. It enhances our understanding of underlying structures of the mysteries of the complex and creative processes in form creation, so essential and desirable for the profession of design. This generative tool can systematize the process of generating a nature-inspired product form that answers our second research question.

6.2.3 The framework of research based on Nigel Cross taxonomy

The third contribution is structuring our research following a design science approach founded on Nigel Cross taxonomy. In our view, this is a novel attempt in the field of design research. The strength of the research framework based on Nigel Cross taxonomy lies in its holistic approach that can help a researcher to investigate an unexplored research area from three different perspectives: Processes, Products, and People. To the best of our knowledge, such an approach to apply Nigel Cross taxonomy as a research framework has not been attempted earlier. It highlighted the scope for introducing a systematic approach to study the process of generating nature-inspired product forms and hence answer our first research question.

6.2.4 Methodology and experimental protocol for three-dimensional visual analysis

The fourth contribution of this research is the methodology and outline of the protocol for nature-inspired product analysis. As a part of this methodology, we developed a graphical data collection log sheet/graphical data collection tool.

Graphical data collection tool for three-dimensional visual analysis – The graphical data collection tool has been specifically developed to collect visual information on perceptual similarities during this research and can be used in two different forms for future works.

- It can be used directly in research studies involving the study and assessment of three-dimensional visual analysis of the perceptual similarity between the source in nature and the target product form.
- In research studies related to the study of nature and form, the data collection tool can be modified suitably into an observation sheet to systematically collect visual information or visual cues of natural form under study.

6.2.5 Bringing out the hidden science behind the nature-inspired form generation process.

This contribution of the research has subsequently emerged from our observations and readings. Our studies bring out the hidden similarities between designers' approach to design nature-inspired product forms and Goethean phenomenological method/Goethean Science. In our opinion, this strongly defends the designers approach against certain criticisms of following a non-scientific approach. This implies that there is indeed a science behind the nature-inspired form generation process.

6.2.6 Research explains the relationship between design science, science of design and scientific design in design research.

The sixth and last contribution is the explanation on various relationships between science and design that exist in our research. Following the research framework structured on Nigel Cross taxonomy, we demonstrated how different aspects of our research took the form of design science, science of design and scientific design separately. We have also discussed how these three are linked to the design research and the way they can co-exist in the design research. This approach of design research can also be applied for future researches.

6.3 Limitations

This research is a bigger project that includes four different studies, and it was impossible to cover every aspect. Due to the limited time and resources, this research has its own limitations which are discussed below.

There is no single standard way to design product forms inspired by nature. Many well-known designers have developed their own unique methods for this creative activity based on the experience gained with time and years of design practice. Sometimes due to the confidential reasons of the industry, these methods are not published anywhere on digital or print media. The act of nature-inspired form generation is practised by many professional designers and educators across the world but there is not much reporting on this process. Due to this, there has been a limitation in finding published literature on the design process for generating nature-inspired product forms on the internet and print media.

The products included in study 2 for visual analysis have specified three-dimensional natural inspirational sources. Many times, designers are inspired by some concepts in nature and not any specific three-dimensional natural form e.g., fractals, patterns in nature, etc. Designers use these concepts very creatively and they also combine two or more concepts and forms together to generate an abstract form. The visual analysis of such forms is a challenge and may need further work. This 'open' scope for such variations will need to be explored for the different context. Perhaps the present framework and generative tool may prove limiting.

Due to the limited time and the qualitative nature of research, we have collected data on five well-known designers. In future, data from more designers can be collected which may lead to the emergence of new core categories/key factors.

Study 3b was limited to novice designers as subjects and was focused on one type of design task (design of perfume bottle). If the design task is changed or if the participants are different e.g. novice designers are replaced by expert designers, then there is a possibility that some new categories may emerge and which might lead to certain modifications and refinement in the proposed framework.

6.4 Future scope

This research opens up new opportunities to extend the current work further in a number of ways. In the near future design, researchers can conduct a systematic study to test the proposed generative tool with professional and novice designers. The findings of this study will help to make this generative tool more adaptable and usable. The tool in its current version has three sheets each dealing with a different type of information. The tool can be improved to speed up the design process without putting much cognitive load on the designer.

Design educators can use the proposed framework to prepare an advanced course on 'nature-inspired form studies' as a part of their design curriculum. They can introduce principles and laws of visual form in nature such as the law of radiation from the parent stem, law of tangential curvature of the lines and principle of order; repetition; and alternation, etc. as discussed in our study 3a. This could constitute the theoretical inputs for the course. Based on these they can develop a series of creative classroom assignments to encourage the use of these laws and principles in the form generation process. This will sensitize students in three-dimensional visual analysis of natural form.

Future research endeavours can combine Artificial Intelligence and Machine Learning with the design process. Where computers can help designers in the form generation process by providing immense information about the natural form which is difficult for a human mind to remember and process. The advance version of such machines can also learn the design styles of the famous designers like Luigi Colani and Ross Lovegrove and can generate new product forms based on the consumer requirements.

One can also explore the dimension of customization where a consumer can decide the form attributes that one wants in a three-dimensional product form.

This research also opens up new doors of opportunities in merging nature with design. The current research is focused only on the three-dimensional form but in future, one can integrate biological studies with the design processes. Findings from the studies on animal behaviour and natural phenomena can be integrated with design processes for creative solutions. The scope indeed is very broad. It will have to be contextualized and pursed with clearly set objectives.

References

A

Arbor, A. (2016). Evidence-based design heuristics for idea generation. Design Studies, 46, 95–124. https://doi.org/10.1016/j.destud.2016.05.001

Athavankar, U. A., (1989). Categorization... Natural Language and Design. *Design Issues* 5(2), 100–111. MIT Press.

Athavankar, U., (2009). From product semantics to generative methods. *International Association of Societies Design Research. Iasdr 2009.*

B

Badarnah, L., & Kadri, U. (2015). A methodology for the generation of biomimetic design concepts. *Architectural Science Review*, *58*(2), 120-133.

Baumeister, D. (2011). Biomimicry Resource Handbook: A Seed Bank of Knowledge and Best Practices. Biomimicry 3.8, Missoula, Montana.

Baumeister, D., Tocke, R., Dwyer, J., Ritter, S., & Benyus, J. (2013). The Biomimicry Resource Handbook: A Seed Bank of Best Practices. Biomimicry 3.8: Missoula. 280 p.

Benyus, J. M. (1997). Biomimicry: innovation inspired by nature. William Morrow and Co. *Inc., NY.*

Blaich, R. I. (1989). Philips Corporate Industrial Design: A Personal Account. *Design Issues*, 5(2), 1–8.

Borek, A., Helfert, M., Woodall, P., & Parlikad, A. K. (2012). Design and Evaluation of Management Processes in IS: Application of a Process-Based Research Approach. In M. Helfert & B. Donnellan (Eds.), Practical Aspects of Design Science (pp. 27–37). Berlin, Heidelberg: Springer Berlin Heidelberg.

Bortoft, H. (1996). The wholeness of nature — Goethe's way of science. Floris Books Brook, I. (1998). Goethean science as a way to read landscape. Landscape Research, 23(1).

Bosnjak, A. (2007). Teaching Form Generation Principles. *Design Education Tradition and Modernity, International Conference, DETM 05*, National Institute of Design: NID Printing Studio, Ahmedabad.

Burgess, S. C., & King, A. M. (2004). The Application of Animal Forms in Automotive Styling, *The Design Journal*, 7(3), 41-52.

C

Casakin, H., & Goldschmidt, G. (1999). Expertise and the use of visual analogy: implications for design education. *Design studies*, 20(2), 153-175.

Chakrabarti, A., & Gupta, A. (2007). Design for emotions. In *DS 42: Proceedings of ICED 2007, the 16th International Conference on Engineering Design, Paris, France, 28.-31.07. 2007* (pp. 823-824).

Chakrabarti, A., Sarkar, P., Leelavathamma, B., & Nataraju, B. S. (2005). A functional representation for aiding biomimetic and artificial inspiration of new ideas. *Ai Edam*, *19*(2), 113-132.

Chan, C. S. (2001). An examination of the forces that generate a style. *Design Studies*, 22(4), 319–346. https://doi.org/10.1016/S0142-694X(00)00045-4

Chang, W. C., & Wu, T. Y. (2007). Exploring types and characteristics of product forms. *International journal of design*, *1*(1).

Charmaz, K. (2006). Constructing Grounded Theory: A practical guide through qualitative analysis. Thousand Oaks: SAGE Publications, Inc.

Chen, C. H., & Sung, P. Y. (2013). The investigation of organic design style – Take design elements of ross lovegrove as an example. *International Association of Societies of Design Research (IASDR 2013)*, Tokyo, Japan.

Cila, N., Hekkert, P., Valentijn, V. (2012). The role of designer expertise in source selection during product metaphor generation. *DeSForM 2012*, 79-87.

Corremans, L. J., (2008). Basic Skills in the Study of Form - Generating Different Styling Proposals based on Variations in Surface Orientation. *International Conference on Engineering and Product Design Education*, 138-143.

Creswell, J. W. (2007). Qualitative inquiry and research design: Choosing among five approaches. Sage publications.

Creswell, J. W. (2013). Research design: Qualitative, quantitative, and mixed methods approaches (4th edn.). Thousand Oaks: SAGE Publications, Inc.

Cross, N. (2001). Design cognition: results of protocol and other empirical studies of design activity. In C. M. Eastman, W. M. McCracken, & W. C. Newstetter (Eds.), *Design knowing and learning: Cognition in design education* (pp. 79-103). Amsterdam: Elsevier.

Cross, N. (2006). Designerly Ways of Knowing. Verlag London Limited: Springer.

D

De Bono, E (1992) Serious creativity: Using the power of lateral thinking to create new ideas New York: HarperCollins.

De Pauw, I. C., Karana, E., Kandachar, P., & Poppelaars, F. (2014). Comparing Biomimicry and Cradle to Cradle with Ecodesign: a case study of student design projects. *Journal of Cleaner Production*, *78*, 174-183.

De Pauw, I., Kandachar, P., Karana, E., Peck, D., & Wever, R. (2010). Nature inspired design: Strategies towards sustainability. In: ERSCP-EMSU Conference on Knowledge Collaboration & Learning for Sustainable Innovation, pp. 1–21

Denzin, N. K., & Lincoln, Y. (2000). Handbook of Qualitative research. Thousand Oaks. https://doi.org/ISBN 0-7619-1512-5

Dresser, C. (1862). The art of decorative design. London, Day and Son, Lithographers to the queen.

Dresser, C. (1876). Studies in design. London, Cassell, Petter and Calpin.

E

Eckert, C., & Stacey, M. (2000). Sources of inspiration: a language of design. *Design Studies*, 21(5), 523-538.

El-Zeiny, R. M. A. (2012). Biomimicry as a problem solving methodology in interior architecture. *Procedia-Social and Behavioral Sciences*, 50, 502-512.

Ericsson, K. A., & Simon, H. A. (1993). Protocol analysis: Verbal reports as data. Cambridge, MA: MIT Press.

Ericsson, K. A., & Smith, J. (1991). Prospects and limits of the empirical study of expertise: An introduction. In K. A. Ericsson & J. Smith (Eds.), *Toward a general theory of expertise: Prospects and limits* (p. 1–38). Cambridge University Press.

F

Fu, K., Moreno, D., Yang, M., & Wood, K. L. (2014). Bio-inspired design: an overview investigating open questions from the broader field of design-by-analogy. *Journal of Mechanical Design*, *136*(11), 111102.

G

Gebeshuber, I. C., & Drack, M. (2008). An attempt to reveal synergies between biology and mechanical engineering. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, *222*(7), 1281-1287.

Gillis, K., & Gatersleben, B. (2015). A review of psychological literature on the health and wellbeing benefits of biophilic design. *Buildings*, *5*(3), 948-963.

Gleich, A., Pade, C., Petschow, U., & Pissarskoi, E. (2010). *Potentials and trends in biomimetics*. Springer Science & Business Media.

Glier, M. W., McAdams, D. A., & Linsey, J. S. (2011). Concepts in biomimetic design: methods and tools to incorporate into a biomimetic design course. *ASME Paper No. DETC2011-48571*.

Goel, A.K., McAdams, D.A., Stone, R.B. (2013). Biologically Inspired Design. *Journal of Mechanical Design*, *135*(7). https://doi.org/10.1115/1.4024746

Goldschmidt, G. (1999). Design, in Mark A. Runco, Steven R. Pritzker Eds., Encyclopedia of Creativity (Vol. 1), Academic Press, (pp. 525-540).

Gonçalves, M., Cardoso, C., & Badke-Schaub, P. (2014). What inspires designers? Preferences on inspirational approaches during idea generation. *Design studies*, 35(1), 29-53.

Goodwin, B. (2000). From control to participation via a science of qualities. Revision, 21(4).

Gregory, S.A. (1966). Design Science. In: Gregory S.A. (Eds.), The Design Method. Springer, Boston, MA.

Grinter, B. (2010). Inter-Rater Reliability. Beki's Blog. Retrieved April 20, 2020 from https://beki70.wordpress.com/2010/09/09/inter-rater-reliability-apply-with-care/

H

Hale, N. C. (1993) Abstraction in art and nature. Dover Publications, Inc., New York.

Hannah, G. G. (2002). Elements of Design. New York: Princeton Architectural Press

Hayes, A. F., & Krippendorff, K. (2007). Answering the call for a standard reliability measure for coding data. *Communication Methods and Measures*, 1, 77-89.

Hekkert, P., & Cila, N. (2015). Handle with care! Why and how designers make use of product metaphors. *Design Studies*, *40*, 196-217.

Helms, M. K., Farzaneh, H. H., & Lindemann, U. (2016). Creating bio-inspired solution ideas using biological research articles. In *Multidisciplinary Contributions to the Science of Creative Thinking* (pp. 215-232). Springer, Singapore.

Helms, M., Vattam, S. S., & Goel, A. K. (2009). Biologically inspired design: process and products. *Design studies*, *30*(5), 606-622.

Henderson, K. (1999). On line and on paper: Visual representations, visual culture, and computer graphics in design engineering. Cambridge, MA: Cambridge MIT Press 1-14.

Hsiao, H., & Chou, W. (2007). Using biomimetic design in a product design course. *World transactions on engineering and technology education*, Vol. 6, No.1, 31-35

Hsiao, S. W., & Wang, H. P. (1998). Applying the semantic transformation method to product form design. *Design studies*, *19*(3), 309-330.

Huang, Y., & Li, J. (2014) Generative Product Design Inspired by Natural Information. In: S. Yamamoto (Ed.): *HIMI 2014, Part I, LNCS 8521*, pp. 583-593, Switzerland: Springer.

Hubka, V., & Eder, W.E. (1996). Design Science: Introduction to the Needs, Scope and Organization of Engineering Design Knowledge. Verlag London Limited: Springer.

I

Irwin, T., & Baxter, S. (2008). The dynamical view of natural form, *Design and Nature IV: Comparing Design in Nature with Science and Engineering*, Vol. 114, 129 – 138. https://doi.org/10.2495/DN080141

J

Jia, L., Becattini, N., Cascini, G., & Tan, R. (2020). Testing ideation performance on a large set of designers: effects of analogical distance. *International Journal of Design Creativity and Innovation*, 8(1), 31-45.

Johannesson, P., & Perjons, E. (2014). An Introduction to Design Science. Springer International Publishing Switzerland.

Jones, O. (1856). The grammar of ornament. London, Day and Son Limited.

Jorgensen, T. K., Kjeldsen, L. L. K., & Lenau, T. A. (2013). Applied aesthetics in biomimetic design – a guide. Technical University of Denmark.

Junior, W. K., & Guanabara, A. S. (2005). Methodology for product design based on the study of bionics. *Materials & design*, *26*(2), 149-155.

K

Kaiser, M. K., Hashemi Farzaneh, H., & Lindemann, U. (2012). An approach to support searching for biomimetic solutions based on system characteristics and its environmental interactions. In *DS 70: Proceedings of DESIGN 2012, the 12th International Design Conference, Dubrovnik, Croatia* (pp. 969-978).

Kaiser, M. K., Hashemi Farzaneh, H., & Lindemann, U. (2013). BIOscrabble-extraction of biological analogies out of large text sources. In *IC3K 2013-5th International Joint Conference on Knowlwdge Discovery, Knowledge Engineering and Knowledge Management* (pp. 10-20).

Kamehkhosh, P., Ajdari, A., & Khodadadeh, Y. (2010). Design naturally, dealing with complexity of forms in nature & applying it in product design. *Des. Complex., DRS, 2010*, 748-763.

Kaplan, D. R. (2001). The science of plant morphology: definition, history, and role in modern biology. *American Journal of Botany*, 88(10), 1711-1741.

Kaplan, R., & Kaplan, S. (1989). The experience of nature: A psychological perspective. Cambridge University Press, Cambridge.

Kazi, R. H., Grossman, T., Cheong, H., Hashemi, A., & Fitzmaurice, G. (2017). DreamSketch : Early Stage 3D Design Explorations with Sketching and Generative Design. In UIST (pp. 401-414).

Kellert, S. R., Heerwagen, J., & Mador, M. (2008). *Biophilic design: the theory, science and practice of bringing buildings to life*. John Wiley & Sons.

Kellett, R. (1990). Le Corbusier's design for the Carpenter Center: a documentary analysis of design media in architecture. *Design Studies*, 11(3), 164–179. https://doi.org/10.1016/0142-694X(90)90004-V

Kennedy, B. (2014). The application of bio-inspiration to human-centered product design. International Journal of Design & Nature and Ecodynamics. Vol. 9, No. 3, pp. 230–236.

Kim, J., Bouchard, C., Bianchi-Berthouze, N., & Aoussat, A. (2011). Measuring semantic and emotional responses to bio-inspired design. In *Design Creativity 2010* (pp. 131-138). Springer, London.

Koler, C. A. (1994). Three-Dimensional Visual Analysis. Stockholm, Sweden: Reproprint.

Krippendorff, K. (2004). Content analysis: An introduction to its methodology. Thousand Oaks, CA: Sage.

L

Lemons, G., Carberry, A., Swan, C., Rogers, C., & Jarvin, L. (2010). The benefits of model building in teaching engineering design. *Design Studies*, 31(3), 288–309. https://doi.org/10.1016/j.destud.2010.02.001

Lenau, T. A. (2009). Biomimetics as a design methodology-possibilities and challenges. In *DS 58-5: Proceedings of ICED 09, the 17th International Conference on Engineering Design, Vol. 5, Design Methods and Tools (pt. 1), Palo Alto, CA, USA, 24.-27.08. 2009* (pp. 121-132).

Lepora, N. F., Verschure, P., & Prescott, T. J. (2013). The state of the art in biomimetics. *Bioinspiration & biomimetics*, *8*(1), pp. 1-11, 013001. IOP publishing.

Liu, Y. T. (1995). Some phenomena of seeing shapes in design. *Design studies*, 16(3), 367-385.

Lloyd, P., & Snelders, D. (2003). What was Philippe Starck thinking of? *Design Studies*, 24(3), 237–253. https://doi.org/10.1016/S0142-694X(02)00054-6

Luigi Colani., (2007). Colani Trading AG. Accessed 18.02.2018. http://www.colani.ch

Lutchmansingh, L. D. (1990). Evolutionary Affinity in Arthur Mackmurdo's Botanical Design. *Design Issues*, 6(2), 51–57.

Lynch-Caris, T. M., Weaver, J., & Kleinke, D. K. (2012). Biomimicry innovation as a tool for design. In *American Society for Engineering Education*. American Society for Engineering Education.

M

Macnab, M. (2012). Design By Nature: Using universal forms and principles in design. Berkeley: Peachpit

Mathias, J. R. (1993). A study of the problem-solving strategies used by expert and novice designers. PhD Thesis, University of Aston, Birmingham, UK.

McDonald, N., Schoenebeck, S., & Forte, A. (2019). Reliability and Inter-rater Reliability in Qualitative Research: Norms and Guidelines for CSCW and HCI Practice. *Proceedings of the ACM on Human-Computer Interaction*, 3(CSCW), 1-23.

Morris, R. (2009). The Fundamentals of Product Design. Switzerland, AVA Publishing.

Muller, W. (1989). Design discipline and the significance of visuo-spatial thinking. *Design Studies*, 10(1), 12–23. https://doi.org/10.1016/0142-694X(89)90021-5

P

Parsons, R. (1991). The potential influences of environmental perception on human health. *Journal of environmental psychology*, *11*(1), 1-23.

Person, O., Snelders, D., & Schoormans, J. (2016). Assessing the performance of styling activities: An interview study with industry professionals in style-sensitive companies. *Design Studies*, 42, 33-55.

Piffer, D. (2012). Can creativity be measured? An attempt to clarify the notion of creativity and general directions for future research. *Thinking Skills and Creativity*, 7(3), 258–264. https://doi.org/10.1016/j.tsc.2012.04.009

Podborschi, V., & Vaculenco, M. (2004). Natural Shapes—A Source of Inspiration for Eco-Design. In *Product Engineering* (pp. 111-120). Springer, Dordrecht.

R

Rao G.K., Vishwakarma S., Saxena S. (2019) Applying Voronoi Structures to Artefacts for Style and Strength. In: Chakrabarti A. (eds) *Research into Design for a Connected World. Smart Innovation, Systems and Technologies*, vol 134. Springer, Singapore

Romesburg, H. C. (1984). Cluster analysis for researchers. Belmont, California, Lifetime Learning Publications.

Ross Lovegrove., (2005). Ross Lovegrove, Organic design inspired by nature, TED 2005, Accessed 15.02.2018. https://www.ted.com/talks/ross_lovegrove_shares_organic_designs

Ross Lovegrove., (2010). Ross Lovegrove on his approach to design, Accessed 18.02.2018. https://www.youtube.com/watch?v=VebEnzMrAug

Ross Lovegrove., (2017). Designer Ross Lovegrove at his studio in London, Accessed 15.02.2018. https://www.youtube.com/watch?v=6epm8fkUwzw

S

Sala, N. (2007). Complex and fractal components in industrial design, *International Journal of Design & Nature and Ecodynamics*. 1(2), 161–173. https://doi.org/10.2495/D&N-V1-N2-161-173

Sarkar, P., & Chakrabarti, A. (2011). Assessing design creativity. *Design Studies*, 32(4), 348–383. https://doi.org/10.1016/j.destud.2011.01.002

Seamon, D., & Zajonc, A. (Eds.). (1998). Goethe's way of science: A phenomenology of nature. State University of New York Press.

Shah, J. J., Vargas-hernandez, N., & Smith, S. M. (2003). Metrics for measuring ideation effectiveness. *Design Studies*, 24, 111–134. https://doi.org/10.1016/S0142-694X(02)00034-0

Sharma, Y. S., & Chakravarthy, B. K. (2009). Abstraction: Investigating the Phenomena to Facilitate Form Generation in Design. *IASDR 2009*, 747-756

Shende, A., & Das, A. K. (2018). Enhancing creativity amongst M.Des students with heterogeneous background use of combinatorial tool through generative methods, PhD. Thesis, Indian Institute of Technology Guwahati.

Sinha, S., & Chakravarthy, B. K. (2013). A Design Inquiry into the Role of Analogy in Form Exploration: An Exploratory Study. In: A.Chakrabarti and R. V. Prakash (eds.), *ICoRD'13, Lecture Notes in Mechanical Engineering*, pp. 175-186, India: Springer.

Speck, T., Speck, O. (2008). Process sequences in biomimetic research. *Design and nature IV*, *114*, 3-11.

Strauss, A. (1987). Qualitative analysis for social scientists. Cambridge: Cambridge University Press.

Strauss, A. (1991). Qualitative analysis for social scientists. Cambridge: Cambridge University Press.

Strauss, A., & Corbin, J. (1998). Basics of qualitative research: Grounded theory procedures and techniques (2nd ed.). Thousand Oaks, CA: Sage.

Suwa, M., & Tversky, B. (1997). What do architects and students perceive in their design sketches? A protocol analysis. *Design Studies*, 18(4), 385–403. https://doi.org/10.1016/S0142-694X(97)00008-2

T

Teubner, D. (2008). Form generation through styling cue synthesis. *DeSForM 2008*, pp. 70-76

The Design Museum. (2015). Luigi Colani, Accessed 18.02.2018. https://designmuseum.org/designers/luigi-colani

Tovey, M. (1994). Form creation techniques for automotive CAD. *Design Studies*, *15*(1), 85-114.

Tovey, M. (1997). Styling and design: intuition and analysis in industrial design. *Design studies*, *18*(1), 5-31.

Tovey, M., Porter, S., Newman, R., & Street, P. (2003). Sketching, concept development and automotive design, 24, 135–153. https://doi.org/10.1016/S0142-694X(02)00035-2

U

Ulrich, R. S., Simons, R. F., Losito, B. D., Fiorito, E., Miles, M. A., & Zelson, M. (1991). Stress recovery during exposure to natural and urban environments. *Journal of environmental psychology*, *11*(3), 201-230.

V

Vandevenne, D., Caicedo, J., Verhaegen, P. A., Dewulf, S., & Duflou, J. R. (2013). Webcrawling for a biological strategy corpus to support biologically-inspired design. In *CIRP Design 2012* (pp. 83-92). Springer, London.

Vattam, S. S., & Goel, A. K. (2011, August). Foraging for inspiration: understanding and supporting the online information seeking practices of biologically inspired designers. In *Proceedings of the ASME 2011 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. Volume 9: 23rd International Conference on Design Theory and Methodology; 16th Design for Manufacturing and the Life Cycle Conference*. pp. 177-186. Washington, DC, USA. ASME. https://doi.org/10.1115/DETC2011-48238

Vattam, S., Wiltgen, B., Helms, M., Goel, A. K., & Yen, J. (2010). DANE: fostering creativity in and through biologically inspired design. In *Design Creativity 2010* (pp. 115-122). Springer, London.

Versos, C. A., & Coelho, D. A. (2011). Biologically inspired design: Methods and validation. *Industrial Design-New Frontiers*, 101-120.

Vincent, J. F., Bogatyreva, O. A., Bogatyrev, N. R., Bowyer, A., & Pahl, A. K. (2006). Biomimetics: its practice and theory. *Journal of the Royal Society Interface*, *3*(9), 471-482.

Volstad, N. L., & Boks, C. (2012). On the use of Biomimicry as a Useful Tool for the Industrial Designer. *Sustainable Development*, *20*(3), 189-199.

W

Wen, H. I., Zhang, S. J., Hapeshi, K., & Wang, X. F. (2008). An innovative methodology of product design from nature. *Journal of Bionic Engineering*, *5*(1), 75-84.

Wilson, E. O. (1984). Biophilia: The Human Bond with Other Species. Harvard University Press, Cambridge.

Wilson, J. O., Rosen, D., Nelson, B. A., & Yen, J. (2010). The effects of biological examples in idea generation. *Design Studies*, *31*(2), 169-186.

Wong, J. F. (2010). The text of free-form architecture: qualitative study of the discourse of four architects. *Design Studies*, 31(3), 237–267. https://doi.org/10.1016/j.destud.2009.11.002

Wood, G. (2007). The shapes of life: Biomorphism and American design. In: Surreal Things: Surrealism and Design. London.

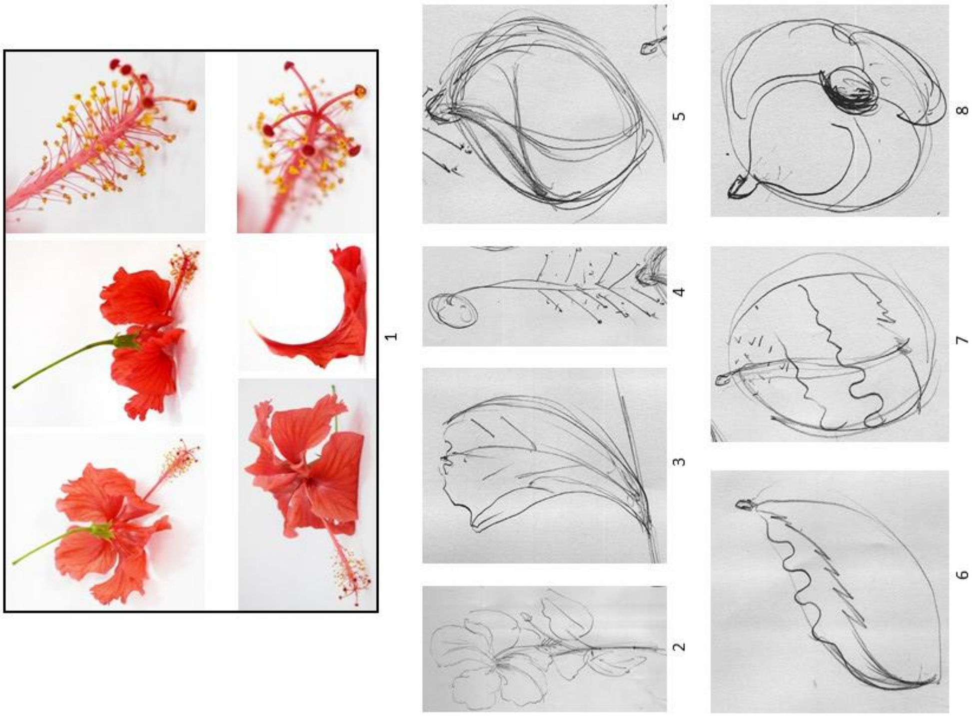
Wu, T. Y., & Chang, W. C. (2007). The study of products with bios forms in conveying pleasure. *Int. Assoc. Soc. Des. Res. The Hong Kong Polytech. Univ*, 1-14.

Y

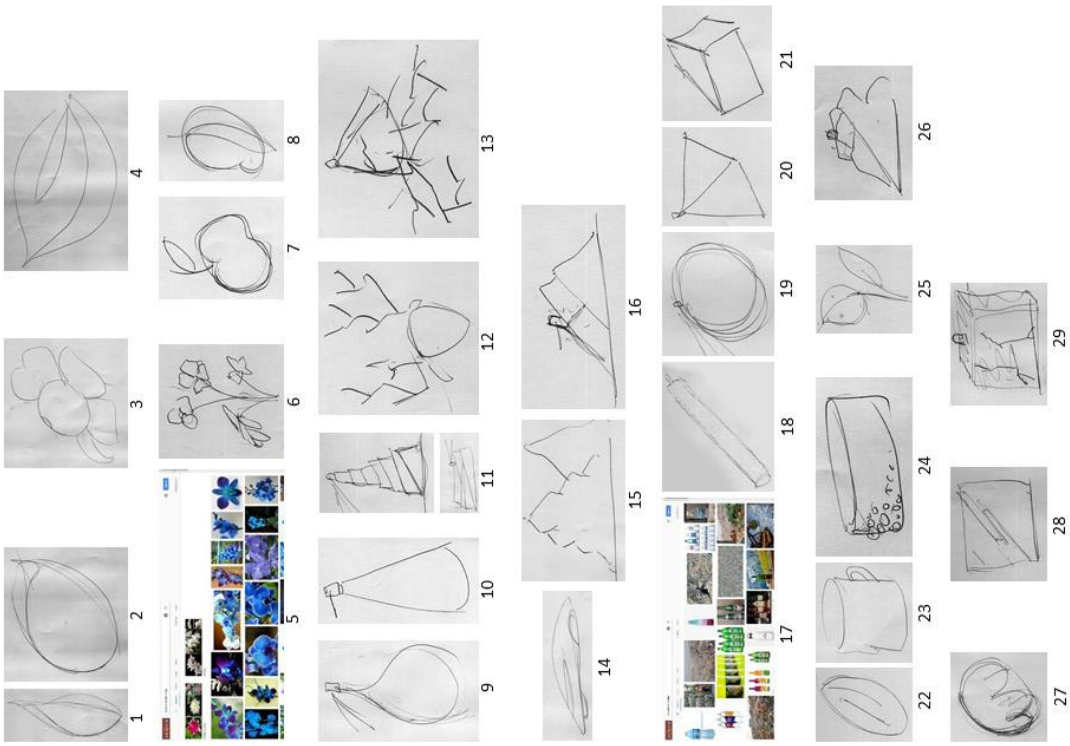
Young, F. M. (1985). Visual Studies: A foundation for artists and designers. New Jersey: Prentice-Hall, Inc.

Appendix 1 Inspiration images and concept sketches of F1 for task 1 and task 2

F1-Task 2

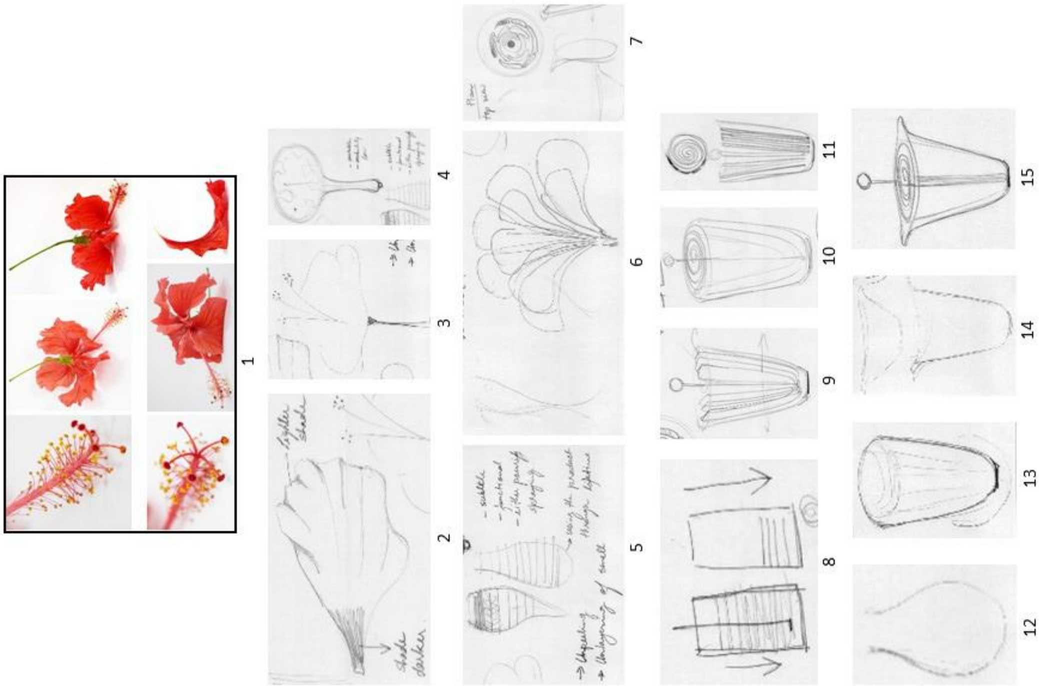


F1-Task 1

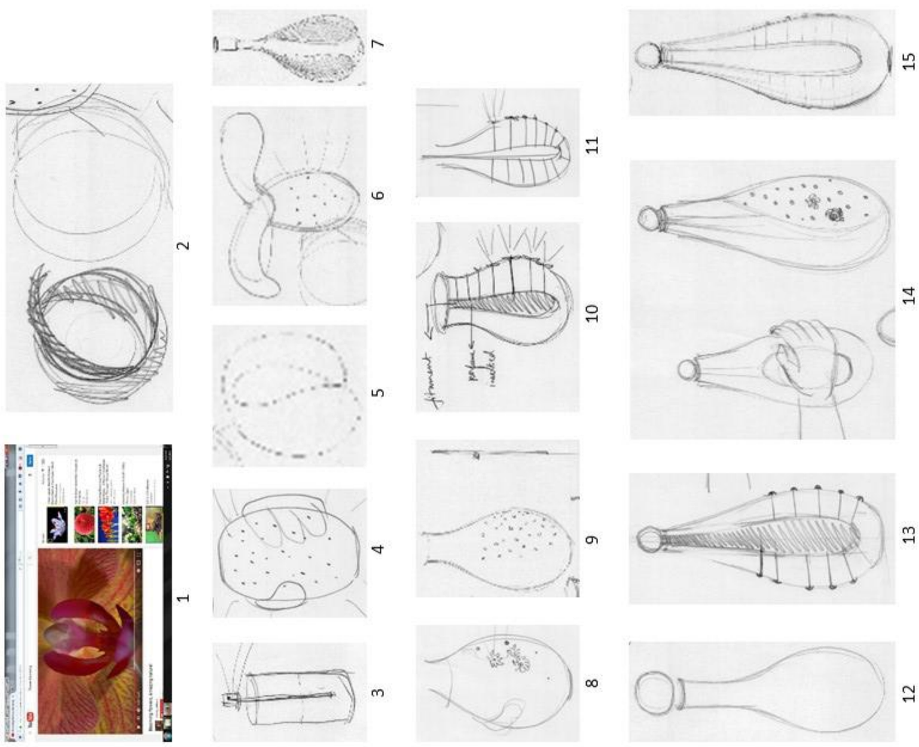


Appendix 2 Inspiration images and concept sketches of F2 for task 1 and task 2

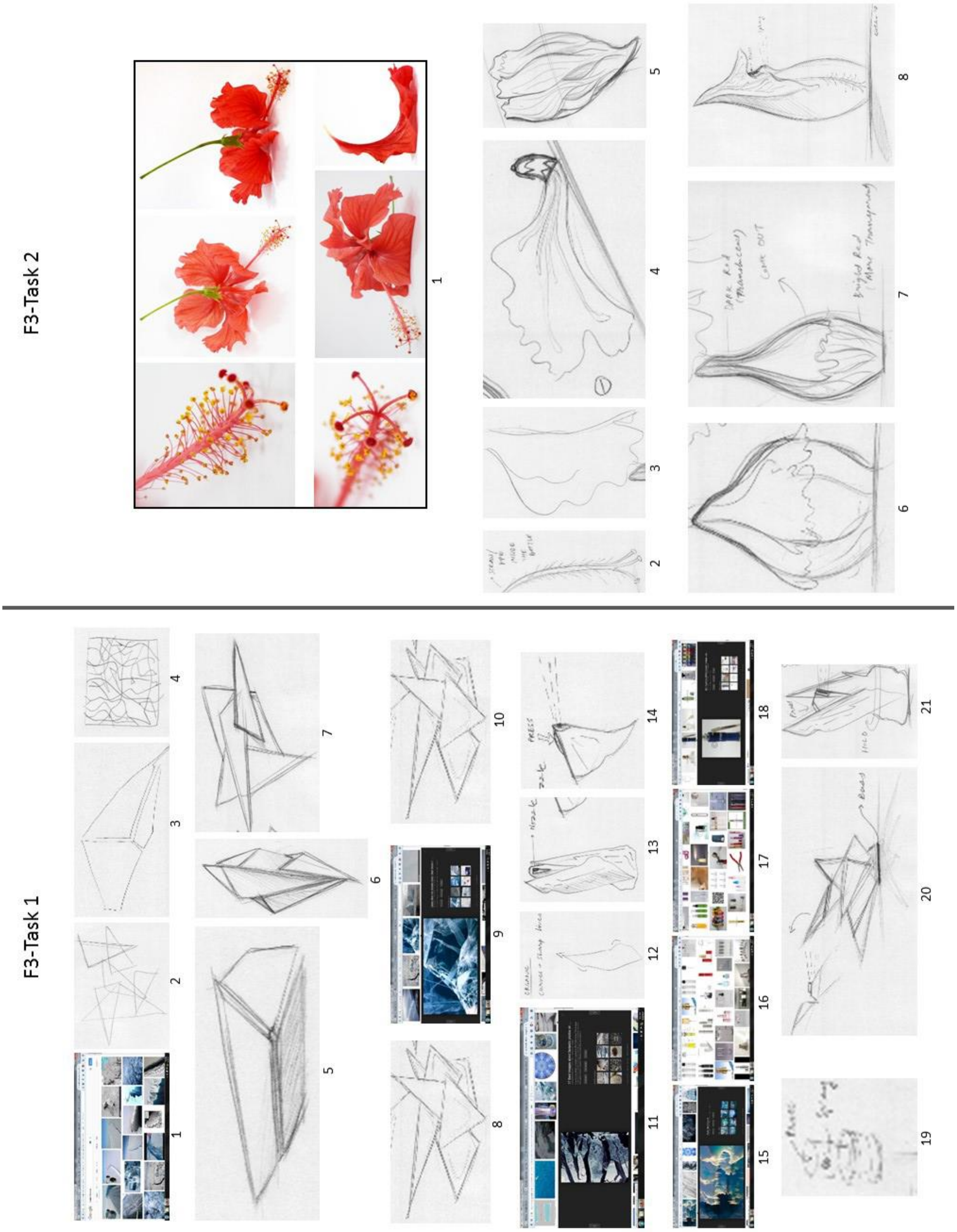
F2-Task 2



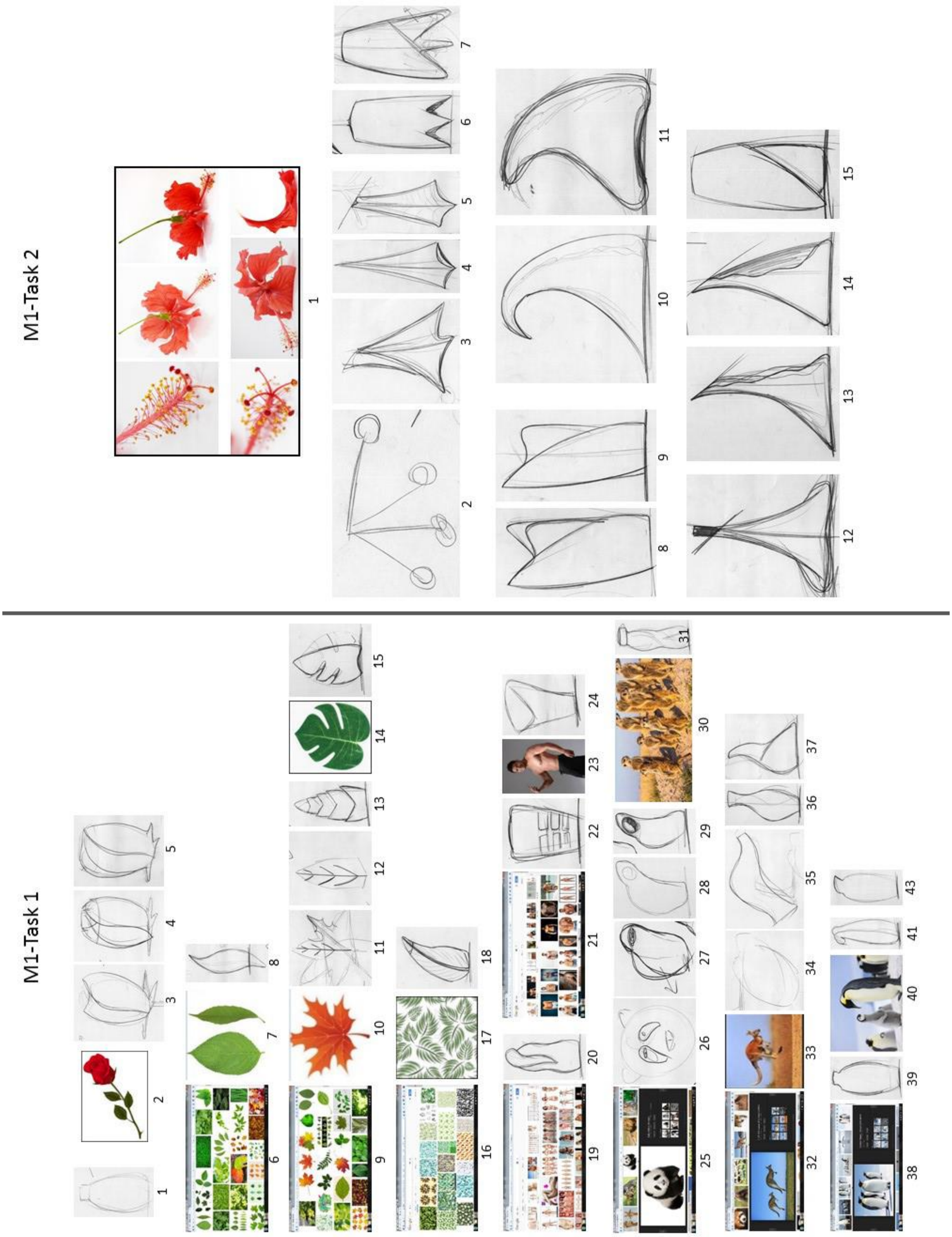
F2-Task 1



Appendix 3 Inspiration images and concept sketches of F3 for task 1 and task 2

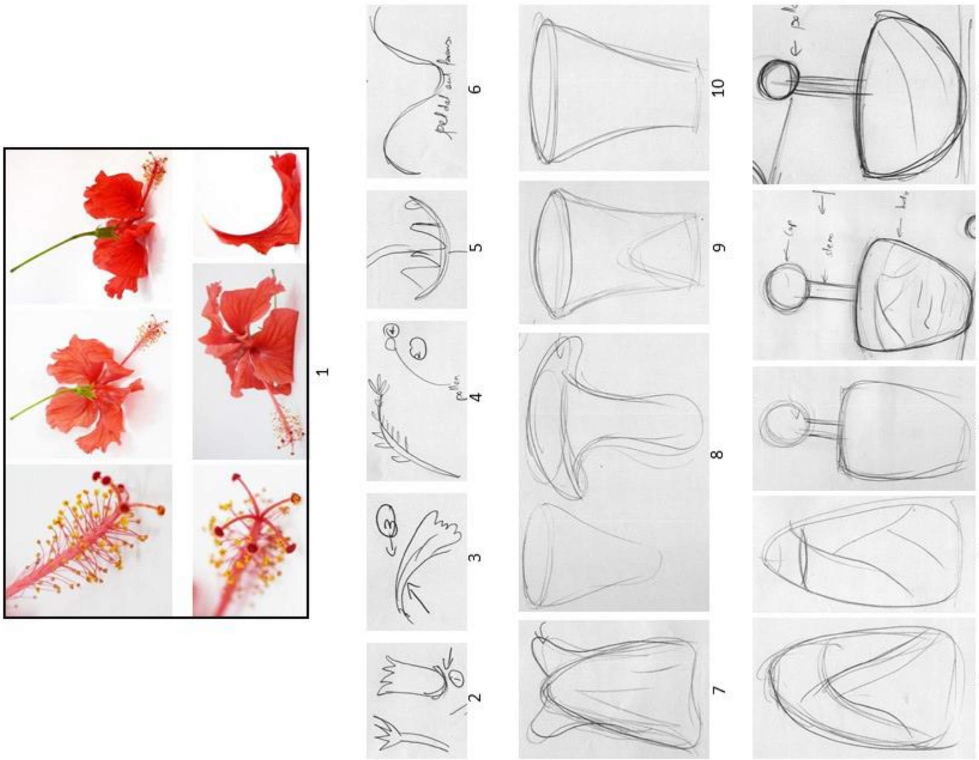


Appendix 4 Inspiration images and concept sketches of M1 for task 1 and task 2

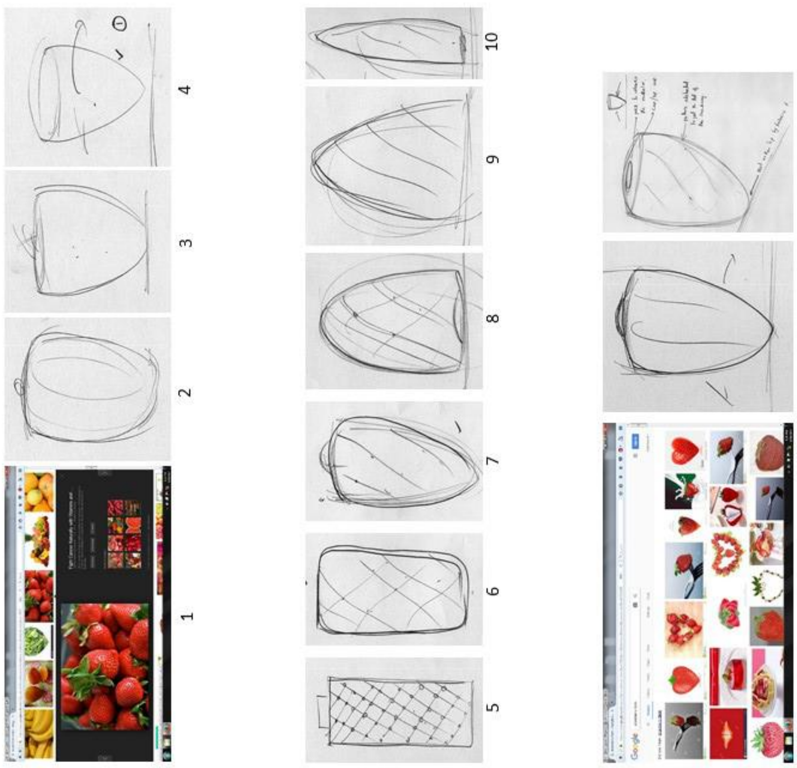


Appendix 5 Inspiration images and concept sketches of M2 for task 1 and task 2

M2-Task 2

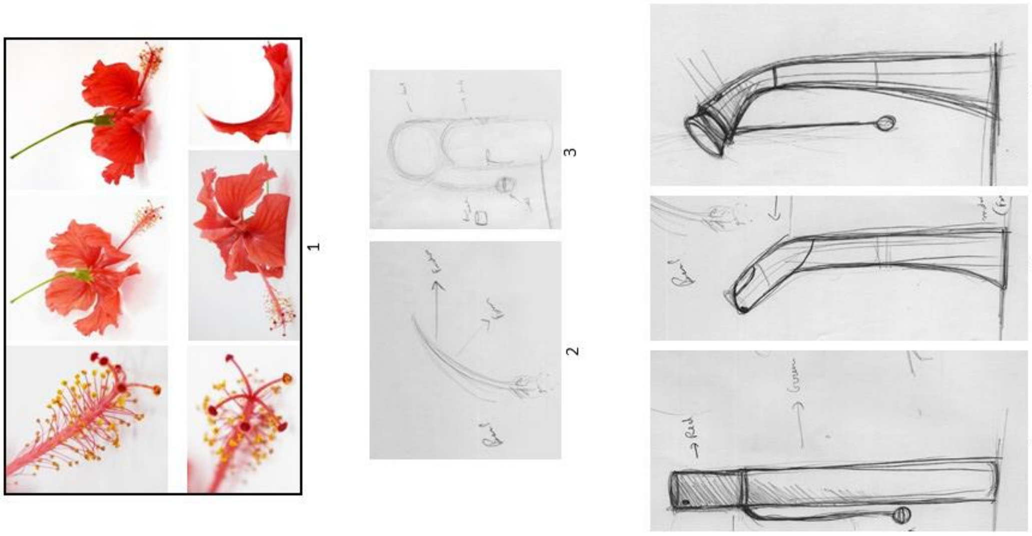


M2-Task 1

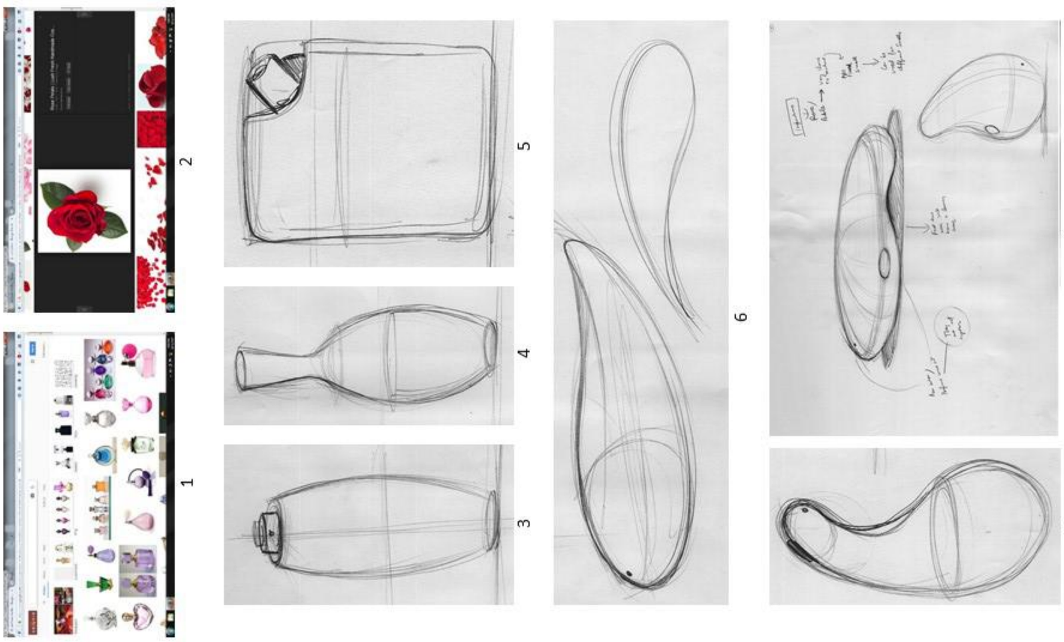


Appendix 6 Inspiration images and concept sketches of M3 for task 1 and task 2

M3-Task 2

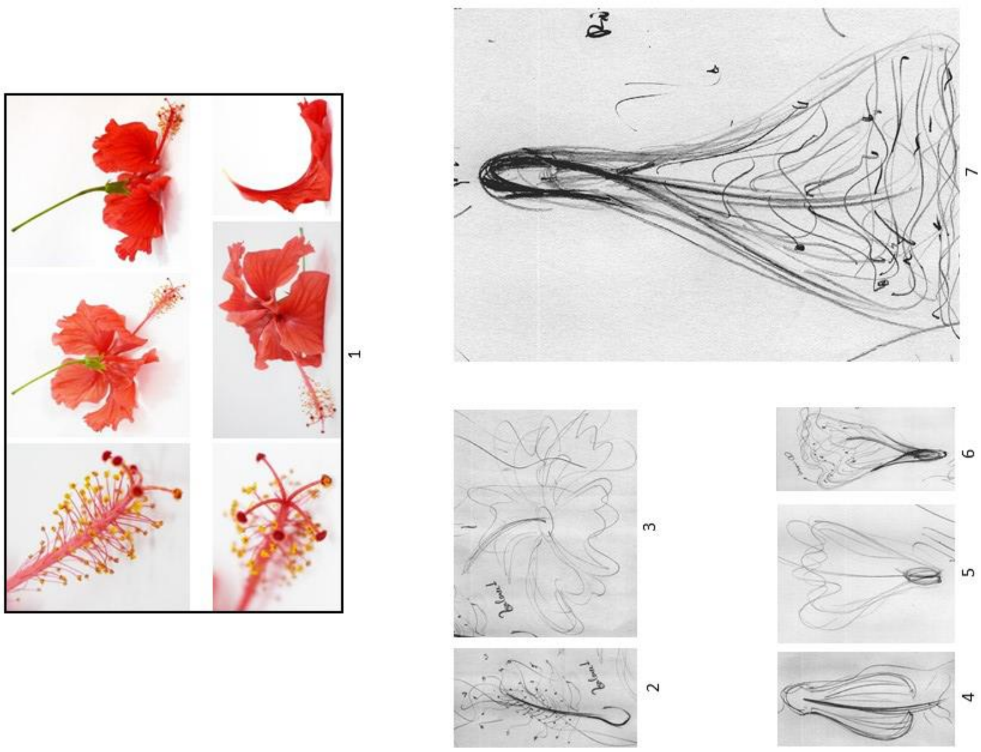


M3-Task 1

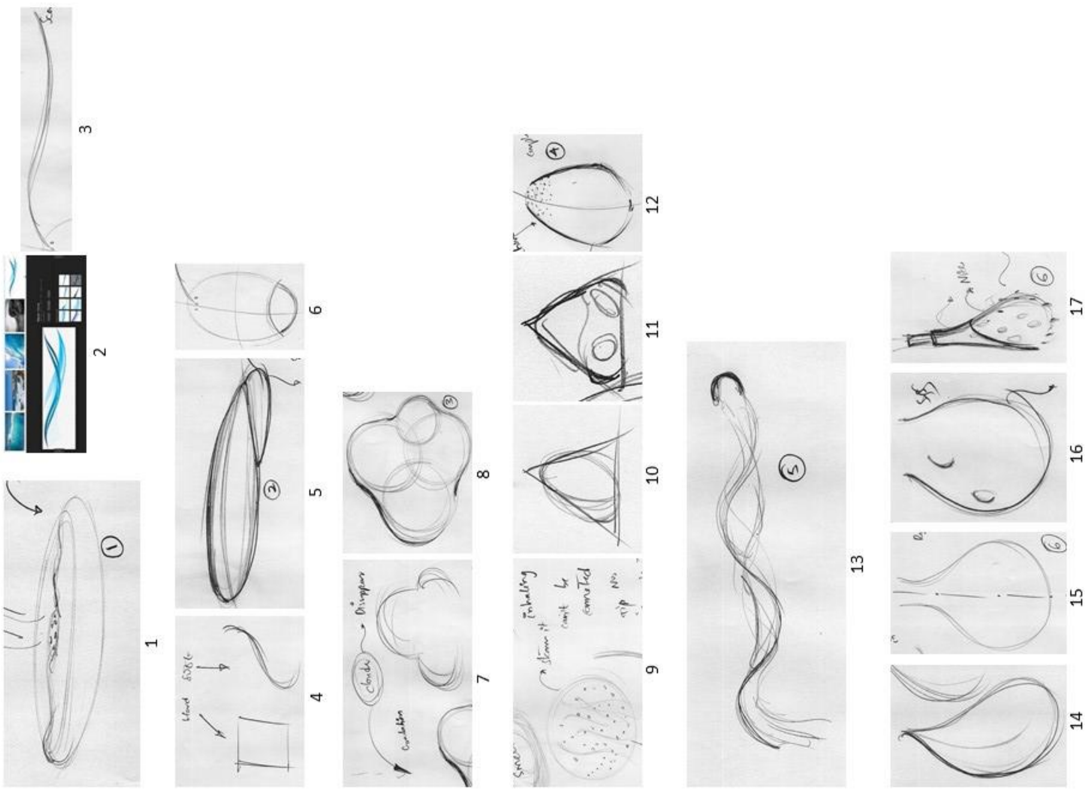


Appendix 7 Inspiration images and concept sketches of M4 for task 1 and task 2

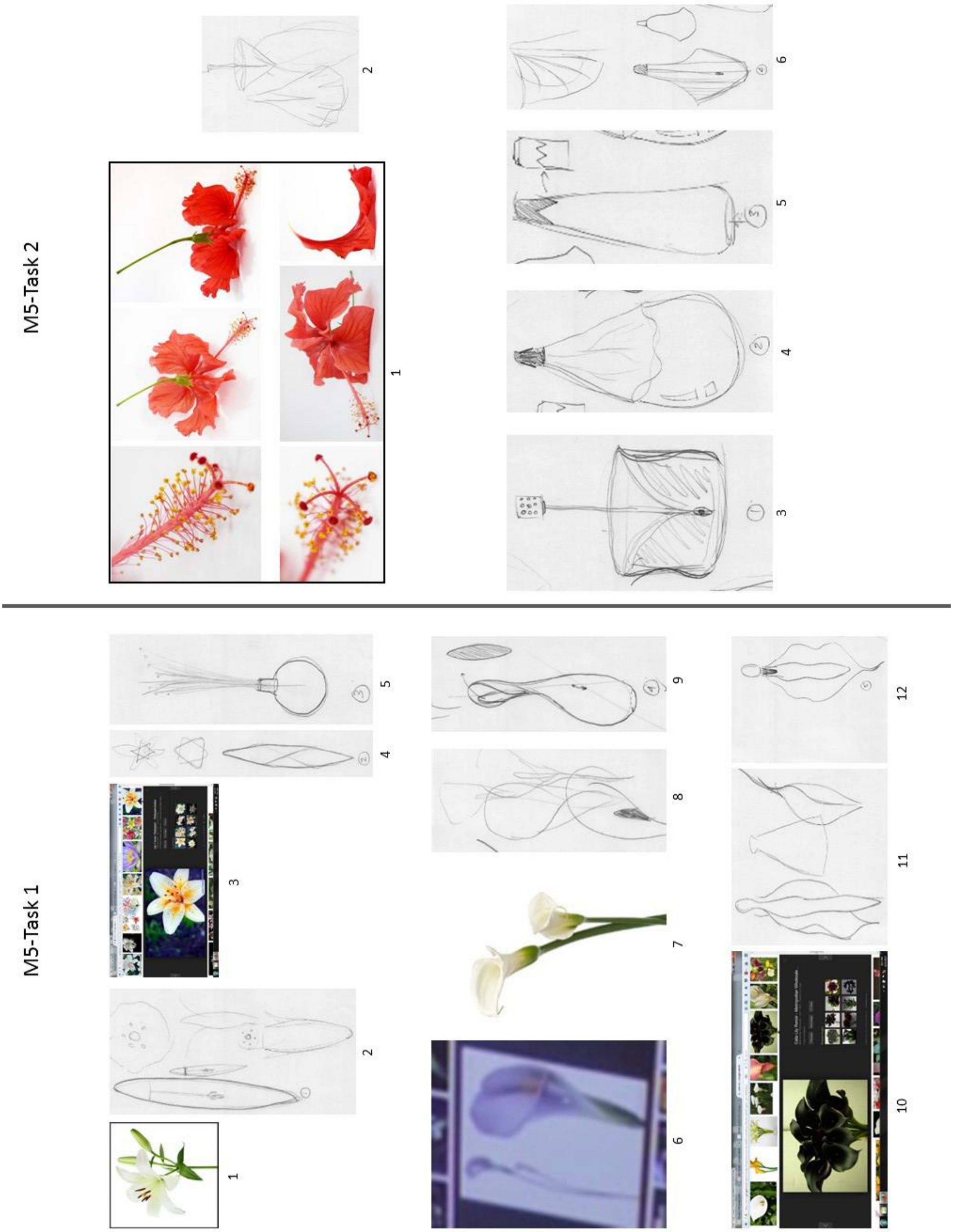
M4-Task 2



M4-Task 1

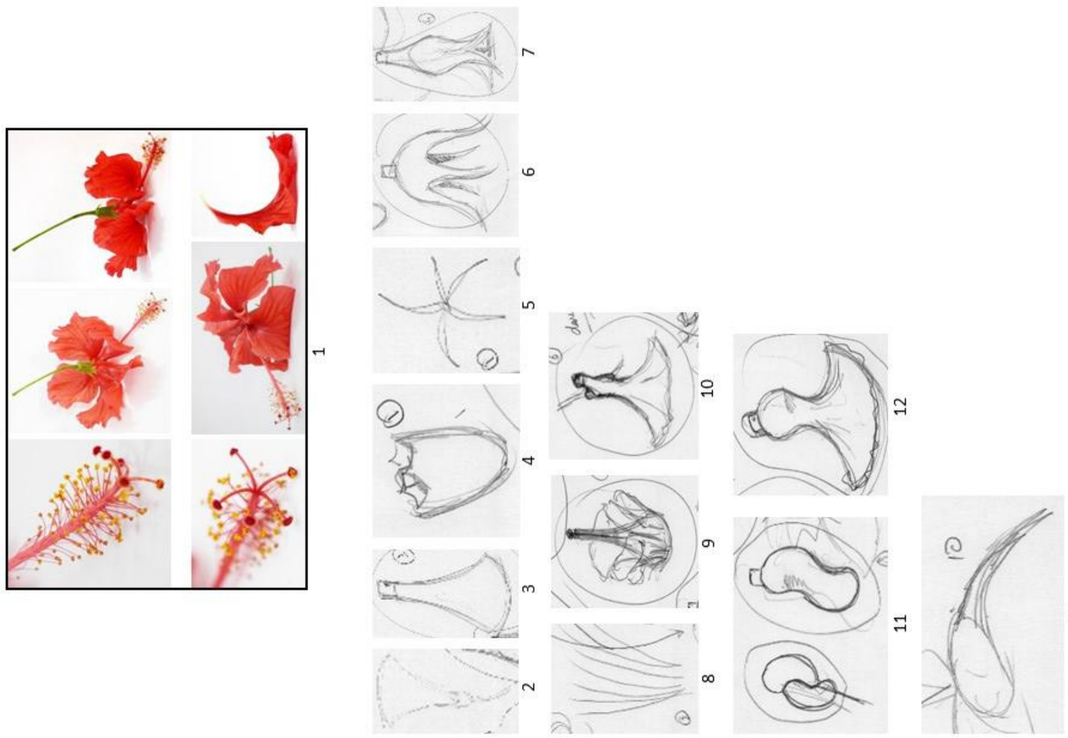


Appendix 8 Inspiration images and concept sketches of M5 for task 1 and task 2

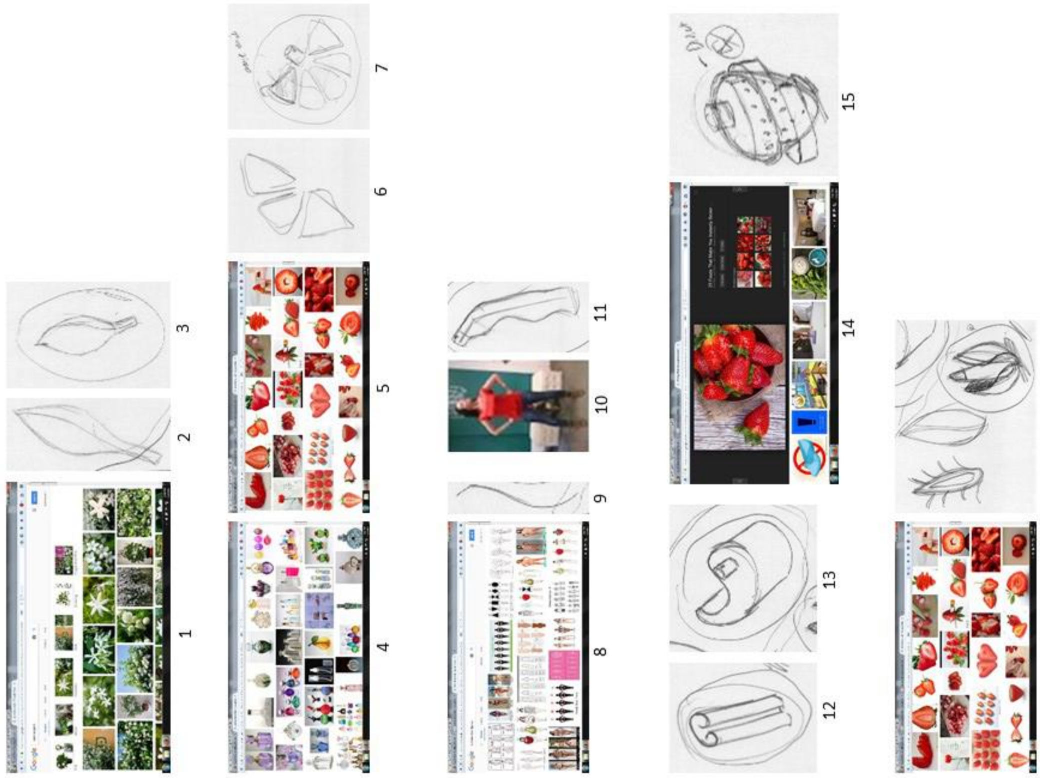


Appendix 9 Inspiration images and concept sketches of M6 for task 1 and task 2

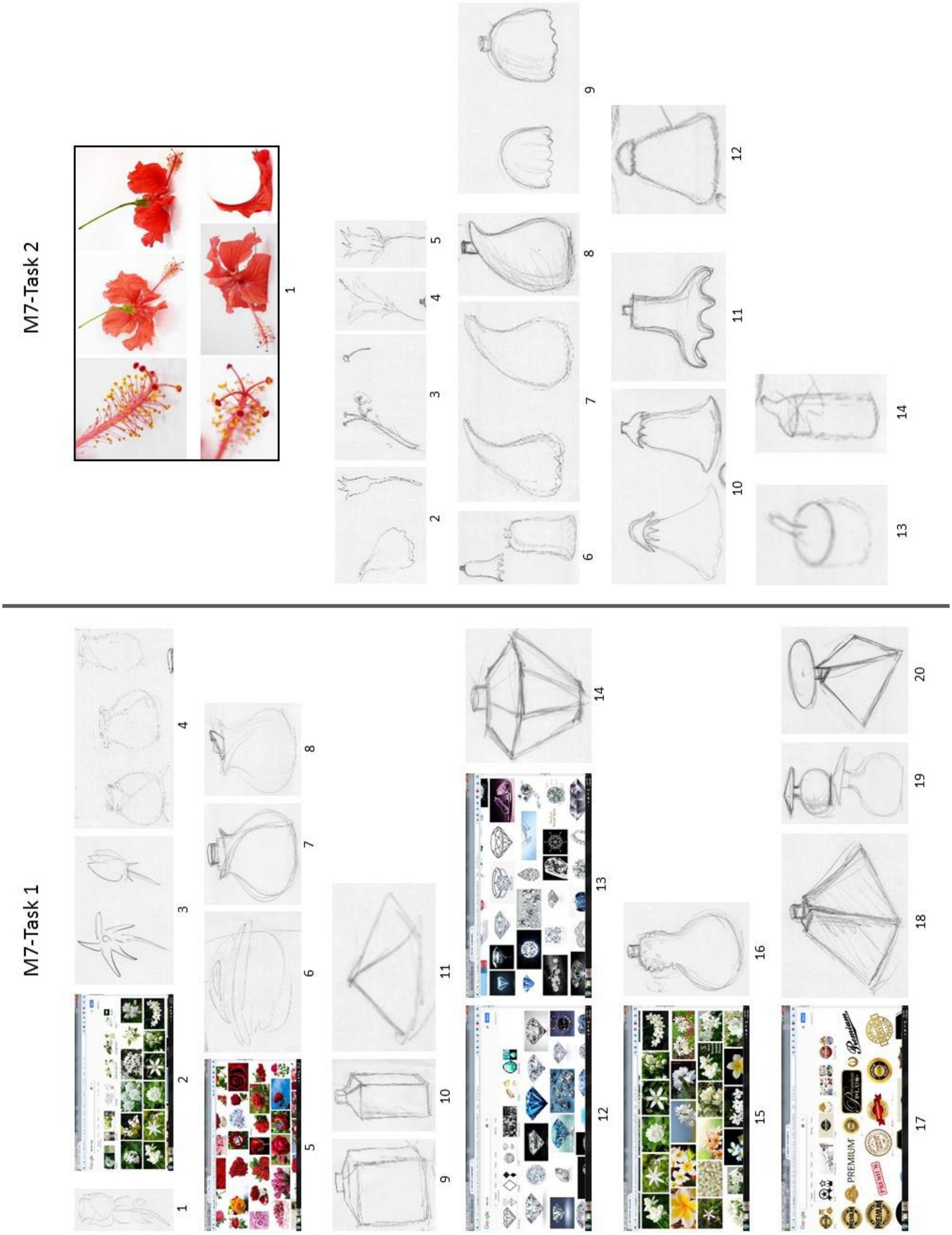
M6-Task 2



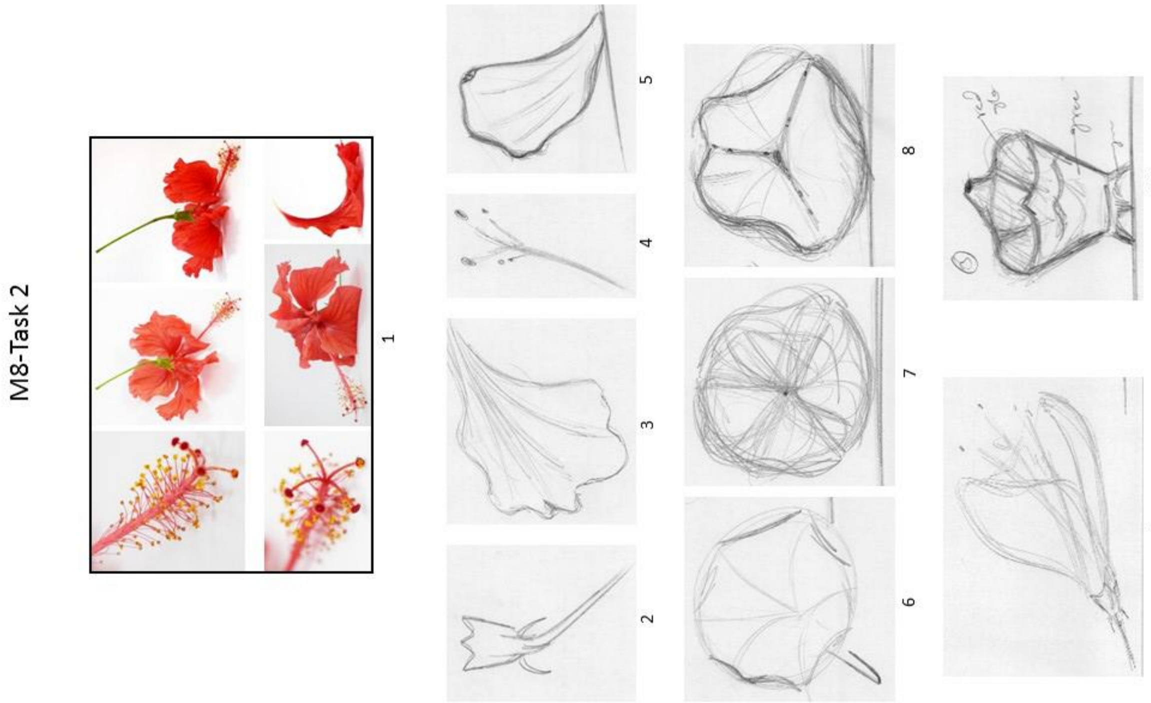
M6-Task 1

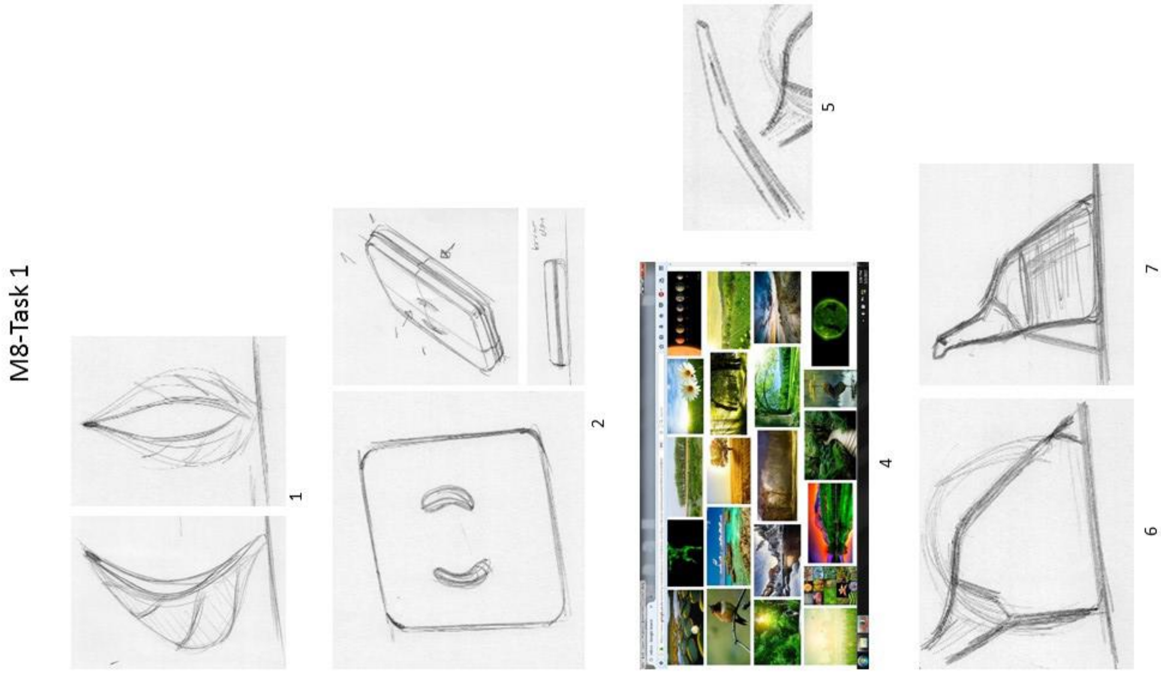


Appendix 10 Inspiration images and concept sketches of M7 for task 1 and task 2

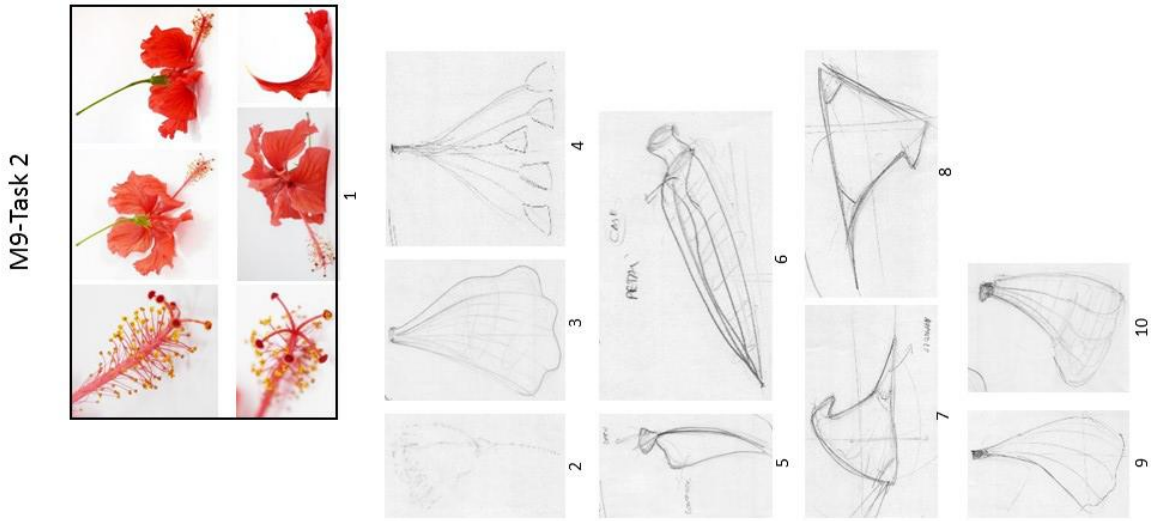


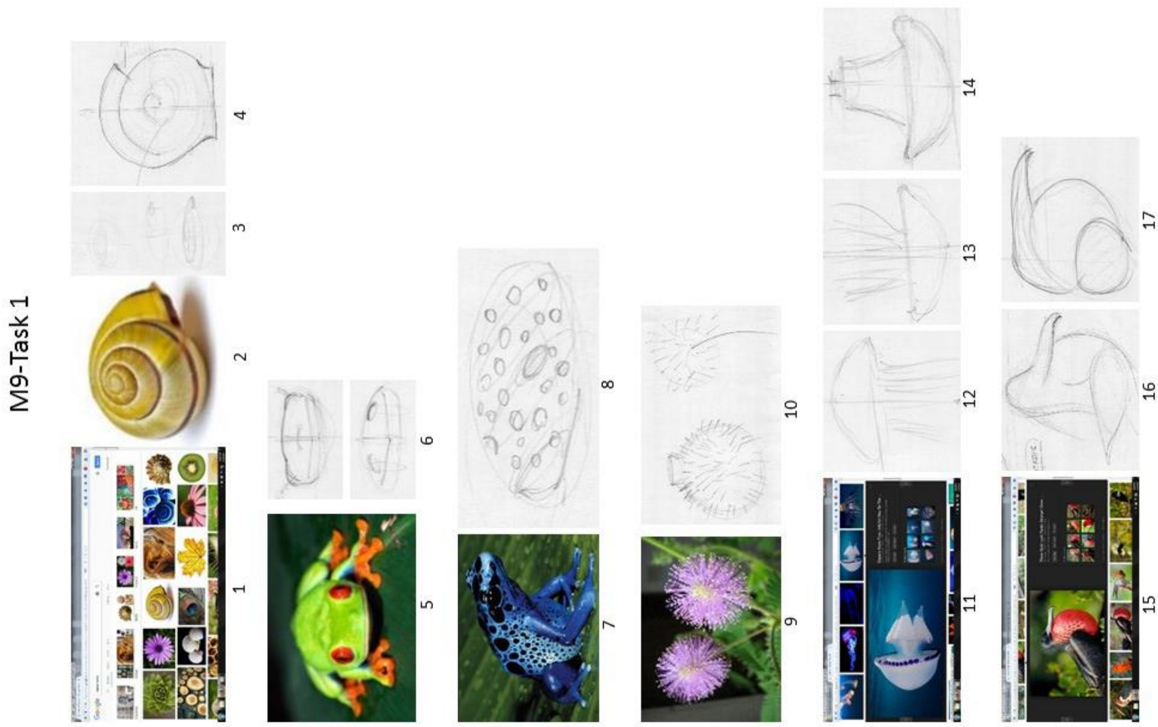
Appendix 11 Inspiration images and concept sketches of M8 for task 1 and task 2





Appendix 12 Inspiration images and concept sketches of M9 for task 1 and task 2





Appendix 13 a: Sheet 1 of example 1

Sheet 1 for Animals/Birds/Insects/Micro-organisms

I. Visual Stimuli


Source: Author
Instrument: Canon 600 D with 100mm macro lens


https://pixabay.com/photos/ladybug-coccinellidae-beetle-1271964/


https://pixabay.com/photos/ladybug-beetle-coccinellidae-insect-1486335/


https://pixabay.com/photos/autumn-vine-ladybug-emerge-leaves-983195/


https://pixabay.com/photos/ladybug-flight-beetle-insect-macro-743562/


Source: Author
Instrument: Canon 600 D with 100mm macro lens

First-Ever Look at the Intricate Way Ladybugs Fold Their Wings | National Geographic

https://www.youtube.com/watch?v=WyM-2BkQom8

Ladybird Beetle

https://www.youtube.com/watch?v=pm6rz_9YXOg

II. Explore all the possible Semantic Associations of product with natural and man-made objects.

- Elegant lighting, Artistic touch, Stylish, Playful, User's Statement.

III. Explore the significance of selected natural form in man-made world.

- They protect plants by eating tiny pests and small insects that feed on plants.
- It's a sign of good luck if one lands on your hand or seen in your home.
- Word 'lady' in ladybird is referred to Virgin Mary based on a story.

IV. What are the mental conceptions that people have for the natural form.

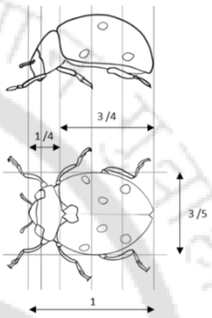
- All ladybirds are red with black spots which is not true, there are other species which are yellow, brown, orange pink and some species don't even have spots.

V. What pleasure and emotions does that natural form evokes.

- Joy, love and Trust

VI. Identify different sub forms and their arrangement that exist in natural inspirational form and record your observation.

VII. Observe the proportion of each sub form and record it



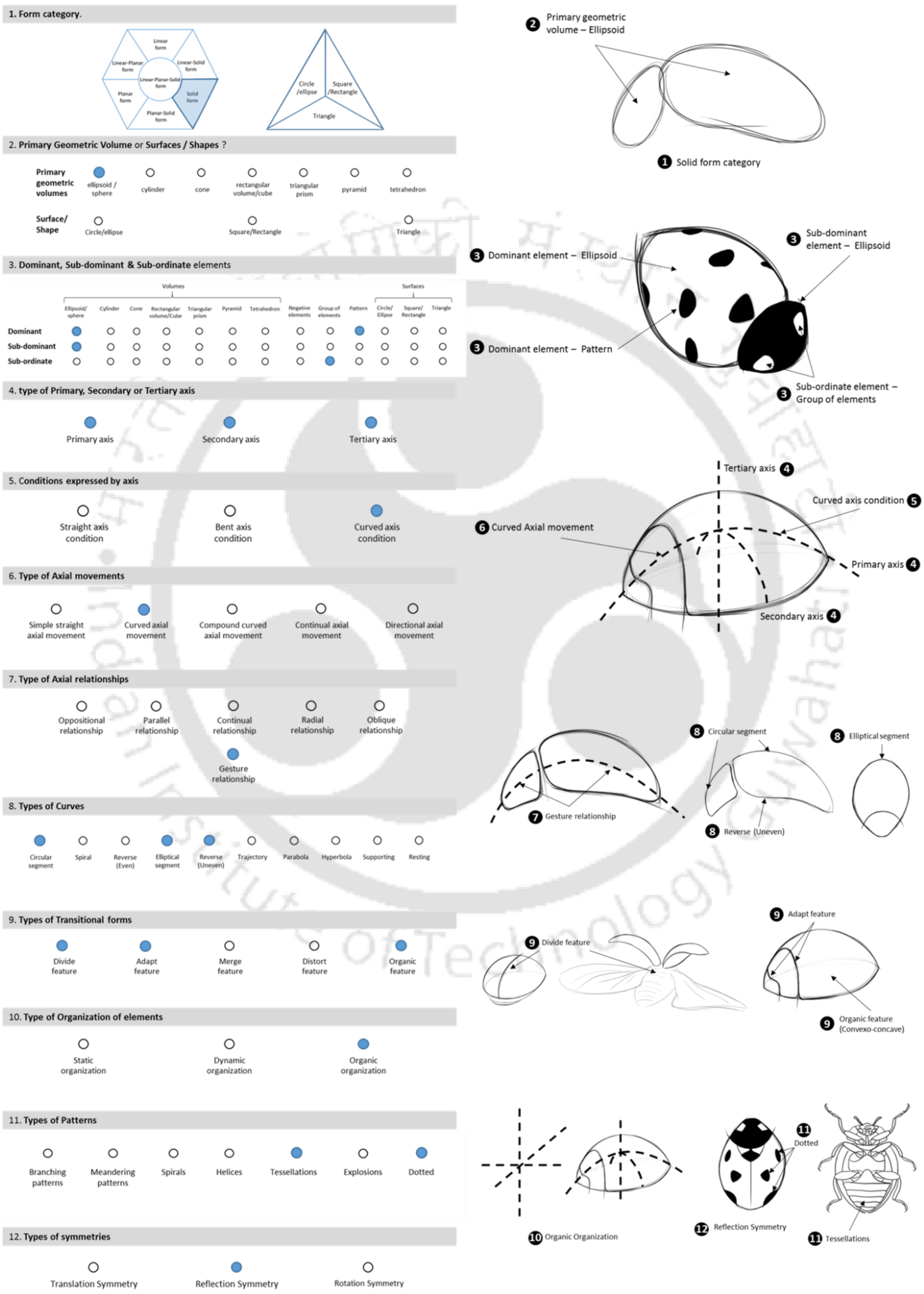
VIII. Observe the colours for transition of form

There is a clear change in colour with a strong contrast of black with red as form changes from Pronotum to Elytra. However, there is not much change in the colour between form of head and Pronotum. Both the forms are black in colour.

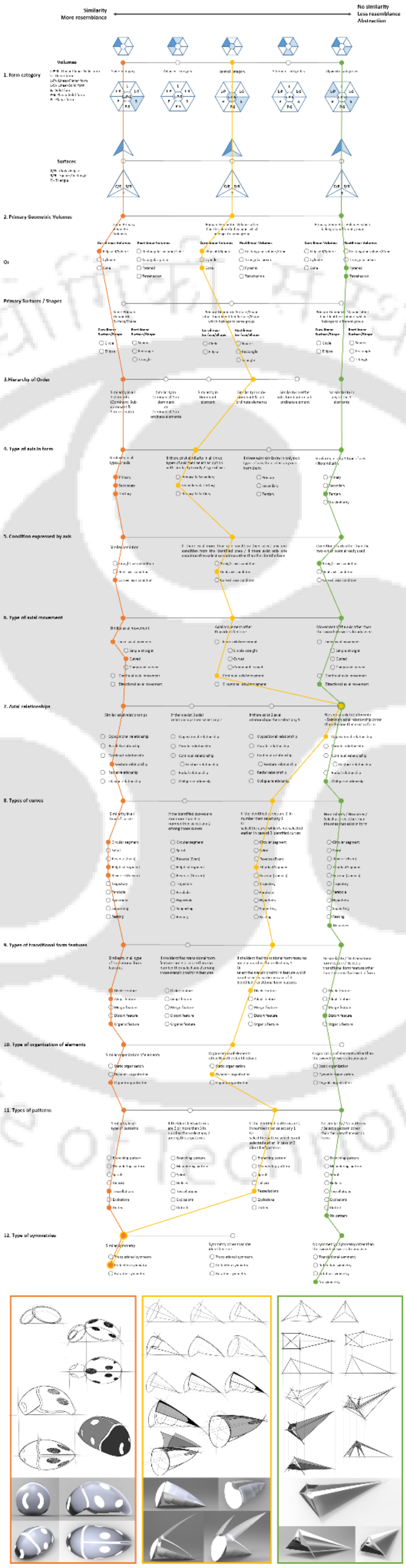
IX. Observe the behaviour of natural form

Inspirational organism	Different behaviours of the inspirational organisms	Form analysis (Observed changes in the form of inspirational organism)	Related keywords for Product Personality or Product Attributes
Ladybird / Ladybug	Defense behaviour / survival technique: They play dead	They stop and roll. They reduce their form by pulling their legs back towards body.  Their colour and markings is also a defense mechanism against predators.	Hard, uncomfortable, Serious, Still.
	Locomotion They walk and fly in search of food	While walking the whole form of the body is balanced on legs. Where as while flying All the sub forms are in open fashion away from each other. 	Walking – Balanced, Showy Flying – Speedy, Agile, Dynamic, Showy

Appendix 13 b: Sheet 2 of example 1



Appendix 13 c: Sheet 3 of example 1



Appendix 14 a: Sheet 1 of example 2

Sheet 1 for Plants

I. Visual Stimuli

https://pixabay.com/photos/bark-mango-leaves-natural-2832932/

https://pixabay.com/photos/leaf-single-one-green-mango-fresh-1761465/

https://pixabay.com/photos/mango-tree-young-growing-fruit-3158013/

Source: Author

Source: Author

II. Explore all the possible Semantic Associations of product with natural and man-made objects.

- Elegant lighting, Artistic touch, Stylish, User's Statement, Image of Nature.

III. Explore the significance of selected natural form in man-made world.

- Hanging mango leaves at the entrance of house is an age old tradition followed by Hindus in India. It is believed that it will protect their home and family from evil spirits and negative energy.
- Associated with many gods in India.
- Significant element in Buddhist art.
- Symbol of love and fertility.
- Symbol of attainment.

IV. What are the mental conceptions that people have for the natural form.

- Leaf with lanceolate shape.
- Younger leaves are of copper colour which changes to dark green as they grow.

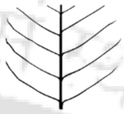
V. What pleasure or emotions does that natural form evokes.

- Feeling blessed, Fresh,

VI. Record your observations about the *Laws* that exist in natural forms

Law of radiation from the parent stem

Source: Author



Law of proportionate distribution of the areas

Source: Author

Law of tangential curvature of the lines

Source: Author

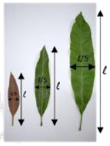
VII. Record your observations about the *Principles* that exist in natural forms

Principle of order

Source: Author

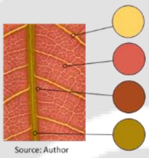
Spiral arrangement of leaf

Principle of proportion

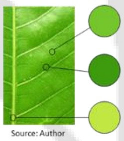


Source: Author

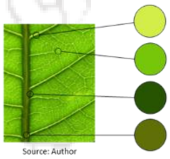
VIII. Colours for transition of form



Source: Author

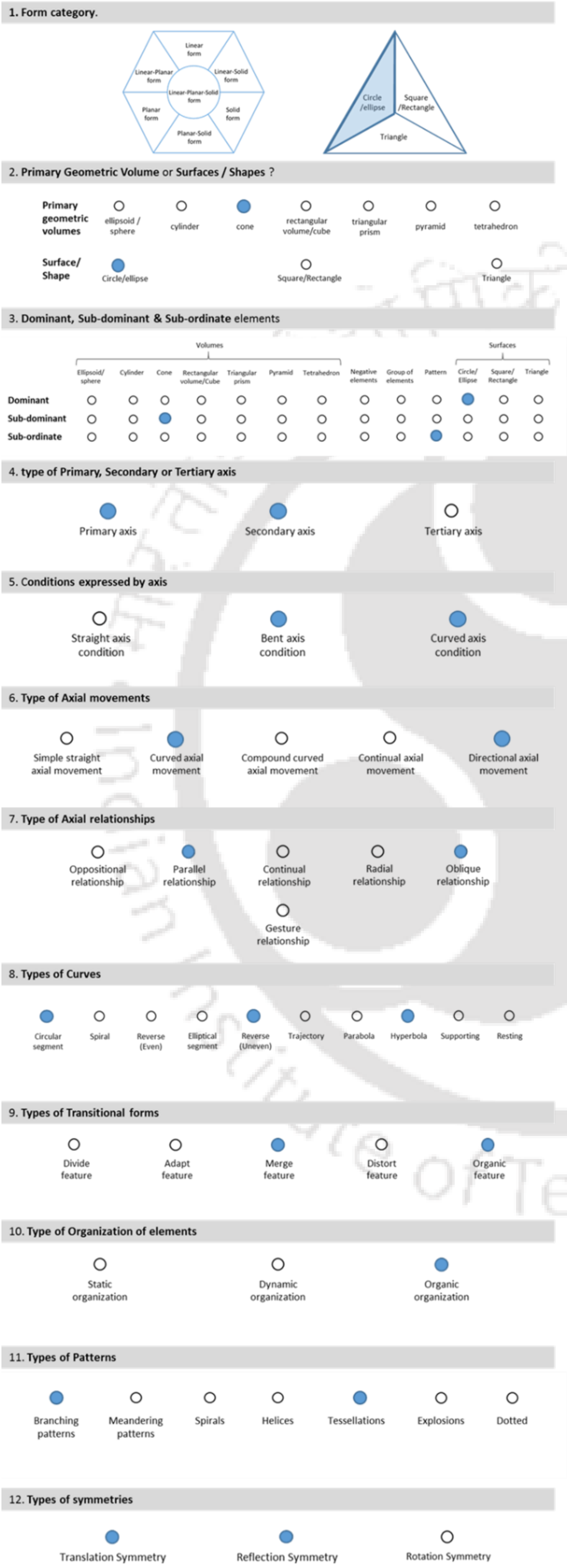


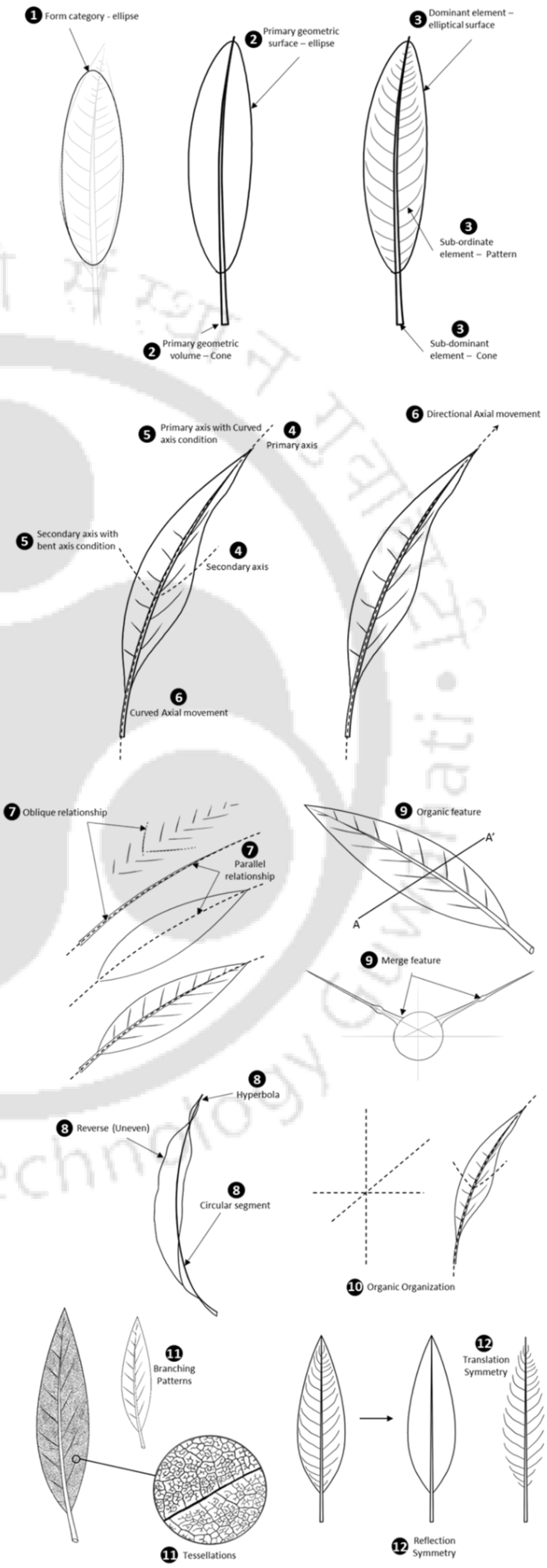
Source: Author



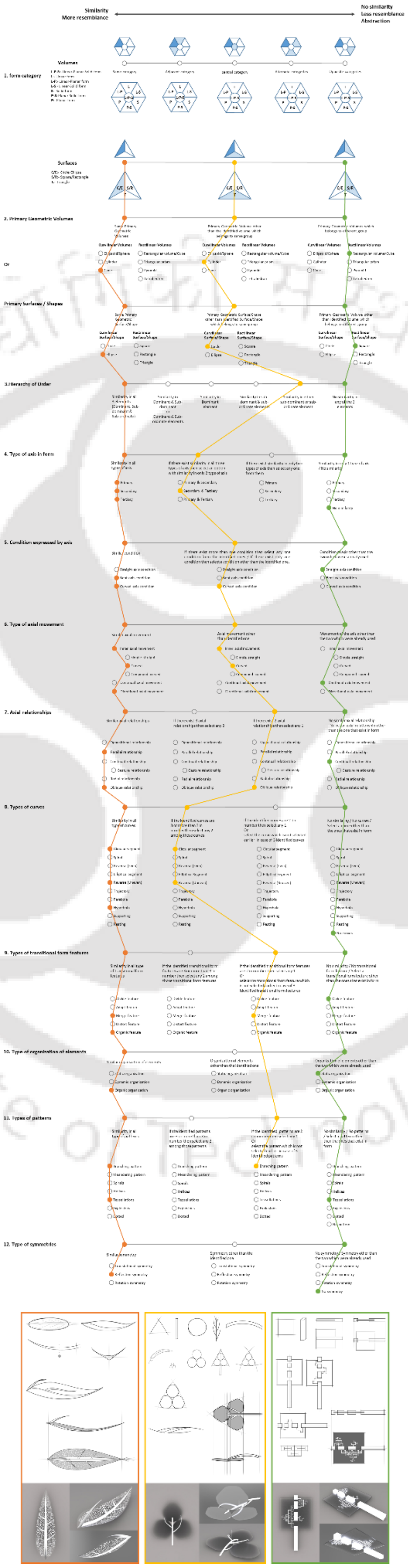
Source: Author

Appendix 14 b: Sheet 2 of example 2





Appendix 14 c: Sheet 3 of example 2



List of Publications

Published Papers

1. Verma S.K., Punekar R.M. (2017) Nature Inspired Design—A Review from an Industrial Design Perspective. In: Chakrabarti A., Chakrabarti D. (eds) Research into Design for Communities, Volume 2. ICoRD 2017. Smart Innovation, Systems and Technologies, vol 66. Springer, Singapore.

2. Verma S.K., Punekar R.M. (2019) Observing Nature—What Designers Can Learn from Biologists. In: Chakrabarti A. (eds) Research into Design for a Connected World. Smart Innovation, Systems and Technologies, vol 135. Springer, Singapore.

3. Verma S.K., Punekar R.M. (2020). Design Science Approach to Nature Inspired Product Forms: Studies on Processes and Products. Synergy: Design Research Society (DRS) 2020.

4. Verma S.K., Punekar R.M. (2021) Decoding Nature-Inspired Form Generation Processes. In: Chakrabarti A., Poovaiah R., Bokil P., Kant V. (eds) Design for Tomorrow—Volume 3. Smart Innovation, Systems and Technologies, vol 223. Springer, Singapore. https://doi.org/10.1007/978-981-16-0084-5_3

Papers under review

5. Gaining Insights into the Creative Process of Designing Nature Inspired Product Forms. (Submitted to a Journal)

Paper to be published after publishing study 1, 2, 3a and 3b.

6. Design Science Approach to Nature Inspired Product Forms: Development of the Framework and a Generative Tool.