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Design Science Approach to Nature Inspired Product Forms: Studies on Processes and Products

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Abstract: This paper follows a design science approach to inquire into the act of creation of nature-inspired product forms. Structured on Nigel Cross taxonomy, it considers three aspects for design research: Processes, Products, and People. In this paper, we discuss two aspects of the framework examining Processes & Methods by undertaking a comparative study of methods in the published literature on the generation of product forms inspired by nature. The second aspect, the study of Products is a qualitative study of visual elements of product form inspired by nature. The paper explores the possibilities of developing i) systematic design research and ii) systematic design practice in exploring nature-inspired product forms.

Keywords: nature-inspired design; design science; design research; design knowledge

1. Introduction

Nature has been a source of inspiration for man since time immemorial. Verma and Puneekar (2017) in their review of published literature on Nature-Inspired Design (NID) focused on two professional groups' viz. Researchers/Scientists/Engineers and Designers/Architects/Painters/Artists to examine terminologies, processes, and methods. The review also suggests that researchers have developed a few systematic frameworks/methods for the nature-inspired design that outline the different stages that are to be followed during the design process. Design as a discipline is often believed to be more application based and formal design guidelines for training the industrial designer to take inspiration from nature, seem poorly documented in published literature. Majority of the designers work is based on the creation and generation of product form based on intuition. Researchers, Scientists and Engineers often criticize Designers for being 'non-scientific' in their approach (Badarnah, and Kadri 2015) (El-Zeiny 2012) (Lepora et al. 2013). Motivated by such criticisms, 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, we seek to answer the following research questions:

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- 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 systematised?

Our search for systematic design led us to the literature on Design Science.

Design science is defined to be a study of the design process that is - investigative (Gregory, 1966); scientific, logical, rational, systematic and organized (Johannesson and Perjons, 2014; Hubka and Eder, 1996; Cross, 2006). 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 and Perjons, 2014) (Borek et al., 2012). From the reviewed literature, design science could be summarised as 'investigation and accumulation of knowledge about the design processes' and it is also a 'systematic approach to design'. With these directions, this **paper aims to study, investigate and accumulate knowledge about the process of designing nature-inspired product forms.**

2. Framework for research

Nigel Cross in his book 'Designerly Ways of Knowing' 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).

This taxonomy proposed by Nigel Cross forms the framework of inquiry for this research. It comprises of

- *Study 1 – A study of Processes and Methods:* It examines the methods proposed by designers and design educators to design nature-inspired product forms.
- *Study 2 – A 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 3 – A study on People:* It examines the approaches followed by professional designers as they develop nature-inspired product forms.

The research follows a mixed-method approach involving qualitative and quantitative methods. The framework for the study undertaken is schematically represented (Figure 1). In this paper, we are presenting Study 1 on Processes and Study 2 on Products.

Figure 1 Research Framework adopted from Nigel Cross Taxonomy

3. Study 1 – A study of Processes and Methods

Drawing from sources of previous researches and tools developed by a few of the design schools in their pedagogic approaches, We draw a comparative summary of ten identified methods for product form generation that are inspired by nature.

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 integrate 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, Kjeldsen and Lenau, 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) in their research work, explain the process of applying metaphors to product forms to enhance the product experience. Table 1 summarizes these different methods.

Adopted from Pugh Matrix, a comparative study of the ten methods helped to identify the strengths and weaknesses of the different methods as illustrated in Table 2. The outcome of this study on Methods and Processes highlights the following five criteria's/requirements reflected in the process of designing. These are:

1. **Integration of technology with the design process:** Only two methods (method 1 & 2) integrate technology with the design process. New technologies used in these methods include CAD-based applications like 3D scanning, generative modelling, and rapid prototyping. Although employing CAD-based applications are very helpful in quick prototyping, they involve the use of expensive 3D digitizing tools and specialized knowledge to process their output data.
2. **Observation of principles in nature and their application in the form generation process:** In table 2, methods 2, 5 and 8 involve the observation of principles in nature. Natural form is analysed in second step of method 2. The method includes the application of observed principles in design process but is limited to the principles of aesthetic patterns only. In method 5, the observed principles related to structure, geometry, proportion, etc. are recorded in the form of graphic images like photographs and diagrams. The integration of information obtained by analysing natural form and development of three-dimensional form is not clear in this method. Method 8 involves the observation of four principles on unity of rhythm, variety, balance and form found in nature and their application in design.
3. **Use of product semantics:** Product semantics seeks to convey the meaning of product form. Designers often use natural forms as a metaphor to make their products more communicative. Method 3, 4, 7, 9 & 10 are the methods in the list that involved the use of product semantics. In method-3, product semantics is the main approach in conceptual transformation. Step 1 of method 4 helps to transfer the qualities of natural elements into design expressions by analysing natural element as a product. In method-7, direct analogy in nature act as a point of association with the desired emotion of food and helps in the initial stage of idea generation. Method 9 involves the use of a cue chart that has a list of terms that represent elements of visual semantics. Method-10 discusses eight metaphoric means or modes that a designer can use to transfer source cues to the target to enhance product experience. The method is more focused on selection of source and transfer of source cues to the target but does not discuss the transfer of selected features into form during form generation process.

Table 1 Methods for designing nature-inspired product form

S.No	Methods	Stages in Form Generation								Type		
1	Product Design from Nature (PDN)	Capturing surface geometrical information	Building a 3D model	Manufacturing a prototype						CAD application based methods		
2	Generative Product design	Identifying objective patterns in nature	Natural form analysis & development	Generative modeling								
3	Diagram for Biomimetic Product Design (DBPD) (Text)	0. Describe organism name & photo (Graphics)	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	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	Analysing inspiration	Recording Observations	Compilation of result	Evolving three-dimensional form							
6	Abstraction in form generation	Perception	Conception	Visualization								
7	Designing with analogy	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	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	Source selection	Metaphoric means									

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). Instead of imitating exact natural form, designers prefer abstraction by removing extra visual cues from their designs. Method-5 makes use of photographic, allegorical, iconographic and diagrammatic representations to explore various possibilities for abstracting meaning and form. Method 6 & 8 consider abstraction as an important aspect of their form generation process. Method-6 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. The authors explain the form generation process aided by abstraction through an example, which involves four stages. In Stage 1 of the process, the number of ways to capture stimulus in its abstraction is not well defined. Abstraction in Method-8 is more oriented towards exploration through a material. Authors describe it as a technique of capturing the essence in the limitation of medium. Method 9 uses an abstraction scale to control abstraction from literal depiction to abstract interpretation.
5. **Approaches to help to 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, Vargas-hernandez, and Smith, 2003) (De Bono, 1992). Method 3 & 4 are the only methods that make use of ideation tools during form generation. Method-3 uses morphological analysis and Method-4 involves the use of inspiration wheel. Method-7 and Method-9 also support generation of alternative conceptual solutions, but they do not involve the use of any ideation tool. Method-7 uses an analogy from nature as a catalyst to trigger multiple thoughts. Method-9 merges the styling cues of two different objects to make a new one.

Considering the outcome of study 1 we can summarize that the above five considerations are essential requirements in the design process/method to generate product form inspired by nature. 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 tools and methods, which can cover all the five current requirements and the future requirements too. An in-depth study on people and products may help us to identify the factors that play an important role in the process of generating product forms inspired by nature. Combining those findings with the five essential requirements will help us in our attempt to theorize the phenomena, which can further support the development of tools and methods to help a designer in generating product forms inspired by nature.

Table 2 Comparison of ten methods based on five essential requirements.

S.No	Methods	Integration of technology with the design process	Observation of principles in nature and their application in the form generation process	Use of product semantics	Focus on abstraction	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			✓		

4. Study 2 – A study of Products

Following the taxonomy proposed by Nigel Cross, we now study products as a basis for understanding the process of designing. The objective of the study is to conduct three-dimensional visual analysis of products that are inspired by natural forms. It, therefore, becomes pertinent to examine and develop a process to collect data on the perceptual similarity between product form and their respective natural inspirational form.

We will first consider the three levels of biomimicry that include: mimicking of natural form; mimicking of natural process; and mimicking of natural ecosystems (Baumeister et al., 2013). For this study on artefacts (nature-inspired products) we draw upon the research work by Cila et al., who have discussed various past researches on analogy and metaphor and the role of two types of similarity between source and target (Cila, Hekkert and Valentijn, 2012) – i) perceptual similarity, which is the physical resemblance between two objects, and include appearance, movement, sound and interaction pattern; and ii) conceptual similarity, which represents the relation between two concepts and include function, working principle, emotions they evoke and environment/context.

In this study, we mainly examine the overall ‘exterior visual form’ of the selected products and focus on perceptual similarity between designed products and their inspiration source in nature – mainly appearance (Form, Size and Proportions).

4.1 Methodology

To undertake the study, a graphical data collection tool was developed drawing upon Rowena Reed’s methodology of ‘structure of visual relationships’ (Hannah, 2002); Cheryl Akner-Koler’s principles of three-dimensional visual analysis (Koler, 1994); Frank M. Young’s methods of three-dimensional form analysis/manipulation (Young, 1985) and Maggie Macnab’s methods on using universal form and principles in design (Macnab, 2012).

The graphical data collection tool contains 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 (figure 2). This tool guides the respondent to compare and enter the visual information or visual cues of natural and man-made three-dimensional form.

Stratified sampling of 30 nature-inspired products was undertaken for the current study based on the following two criteria’s:

1. Selected products are designed by leading designers/companies who are well known for designing nature-inspired products.
2. The inspirations for the selected products were very clear and mentioned by the designers/companies on their websites, interviews or magazines.

Following these two criteria, 15 products designed by professional Indian designers and 15 products designed by well-known professional international designers were selected for this study. Table 3 shows a detailed list of all the products with their respective designers/ company.

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

Natural form

Product 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: ☐ Continuous 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: ☐ Contradictory 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 (S-curve): ☐ Elliptical segment: ☐ Reversal (S-curve): ☐ Trajectory: ☐ Parabola: ☐ Hyperbola: ☐ Supporting: ☐ Rending: ☐

☐ 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 2 Graphical data collection tool.

Table 3 List of thirty nature-inspired products with their respective designers/company.

Products designed by International Designers	
Product	Designer/Company
Diatom Chair, Biophilia, Agaricon, Florensis, Cosmic Leaf.	Ross Lovegrove
Anyfix, Mega passenger, Tea Service "Drop", Squirrel Colani Cup, Canon Frog.	Luigi Colani
Kastor, Parrot, Piccantino, Juicy Salif	Alessi
Daisy (Coat Stand)	James Irvine/Danese Milano
Products Designed by Indian Designers	
Product	Designer/Company
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	Neil Foley
Ground or Suspended lamp	Satish Gokhale
Tiltr – Fitness Device	Axiom Consulting
Water Purifier inspired by apple	i2r Design
Perfume Packaging inspired by lotus	Onio Design

Qualitative data gathered in the form of texts were subsequently coded into numbers for further analysis. The cluster analysis method was adopted to identify the patterns of similarity that exist in the product form and inspirational form.

The visual analysis of any object can involve a high level of subjectivity and very much depends on an individual's perception. To ensure the objectivity of the study, the experiment was conducted with three respondents and in two sessions. A detailed discussion on principles of visual analysis was held before the experiment to bring the three respondents on a common ground for analysis. Respondents performed the visual analysis in two sessions (Figure 3).

Figure 3 Experimental procedure for three-dimensional visual analysis

In session-1, respondents performed the visual analysis individually and separately. The inter-coder reliability for 12 items of the tool was checked using Krippendorff alpha (Hayes and Krippendorff, 2007) (Krippendorff, 2004). The values of Krippendorff alpha for twelve form attributes for the current experiment after session 1 are represented in Table 4. In session 2, respondents A, B, and C discussed all the differences in their data for arbitration to reach 100% agreement.

The data obtained after session-2 was then used as an input for hierarchical cluster analysis and analysed using the SPSS statistical software package. Cluster analysis was performed only for those 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.

Table 4 Value of Krippendorff's alpha for Respondent A, B & C after session 1

S.No	Form attributes	Krippendorff's alpha For Respondents 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

Example – The cluster analysis result of similarity in the ‘hierarchy of order’ for thirty products reveals that there are four clusters when a cutting point is located at 7 scales as shown in figure 4.

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 4 Dendrogram of similarity in the hierarchy of order for thirty products.

4.2 Results & Discussion

The visual analysis of thirty products for twelve form attributes indicates that similarity in certain visual cues and no similarity have emerged as the major clusters/groups in outcome analysed (Table 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 similarity and no similarity in visual elements could be an important parameter for resemblance and abstraction that designers seem to consider in their product forms inspired by nature. Consider similarity/more resemblance and No similarity/less resemblance/abstraction as two extremes of a spectrum. This spectrum when merged with attributes of similarity, can help a designer to control abstraction in new designs through a form attribute controller (Figure 5). It can also help to generate more number of design concepts following a generative approach of design. This study is focused on exterior forms of artefacts (Nature-inspired products) which helped to understand the relationship between perceptual similarity, form attributes, and abstraction in such products.

Table 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 5 Proposed form attribute controller that can be used in a design tool

5. Discussion

Through a rigorous study of – processes, products, and people, Nigel Cross outlines a unique process in design research for knowledge generation. The focus of our research is to understand the process of nature-inspired approach in the generation of product form, we adopted the above taxonomy as the framework for driving our study. In this paper, we have attempted a systematic inquiry into two aspects of the research framework focused on two different modes of knowledge: Processes and Products. In this section, we discuss our observations and insights from these two considerations following a systematic mode of inquiry that is summarized below.

Under the study of Processes and Methods (Study 1), we identified five key requirements for a design process in the generation of product forms inspired by nature. These key requirements can be used as a guideline to develop a design process.

- **Technology:** Can be integrated at various stages within the design process for the generation of conceptual and novel product forms.
- **Observation:** Different methods can be incorporated into the design process to observe natural form and their fine details.
- **Semantics:** Include semantic studies that seek to answer what natural forms mean to people and how that meaning can be conveyed through the product form.
- **Abstraction:** Identify new ways in the extraction of essential visual cues for manipulating them to achieve controlled abstraction in the product form.
- **Creativity:** Develop creative approaches to facilitate the generation of more conceptual design solutions for the product form drawing from the source in nature.

In the study of Products (Study 2), we were able to identify how the presence and absence of perceptual similarity is important in form generation; its relationship with form attributes; and how it can be controlled for abstraction.

The findings assimilated from these two different modes helped us to gain knowledge about the nature-inspired form generation process that we aimed for. It highlighted the scope for introducing a systematic approach to the study of nature-inspired design.

In the view of the authors, the significant contributions that the study was able to achieve are the following:

A research framework based on Nigel Cross taxonomy – In our study, we have followed a research framework based on Nigel Cross taxonomy. The strength of this framework lies in its holistic approach that can help a researcher to investigate an unexplored research area from three different perspectives: Processes, Products, and People.

Earlier attempts to understand the design approach of the nature-inspired design were more 'People' oriented. Lutchmansingh investigated Mackmurdo's approach of botanical designs (Lutchmansingh 1990). Chen and Sung examined the organic design style of Ross Lovegrove (Chen and Sung 2013). Wong studied the work of four architects: Frank Gehry, Zaha Hadid,

Daniel Libeskind and Thom Mayne (Wong 2010). We have demonstrated a successful application of this framework for our research work focused on 'Processes' and 'Products'.

To the best of our knowledge, such an approach to apply Nigel Cross taxonomy in conducting a study on nature-inspired product form has not been attempted earlier. This research framework provided a systematic mode of inquiry to understand the process of nature-inspired form generation, which answers our first research question.

The systematic inquiry leads to a systematic approach of design – Our systematic inquiry focused on processes, products, and people has helped us to gain knowledge from three different sources. Five essential criteria identified in the study of Processes and Methods (Study 1) form a core, around which a method can be developed for undertaking a nature-inspired form generation process in design.

Although abstraction is an important aspect among four methods (Method 5,6,8 & 9) covered under the study of Processes and Method (Study 1), there is no systematic way to control abstraction in these methods. Form generation through styling cue synthesis (Method 9) involves the use of an abstraction scale but the selection and manipulation of form elements with two variables on the scale (literal depiction and abstract interpretation) is not clear. The proposed form attribute controller in the study of products (Study 2) can be developed into a creative design tool that will systematise the form generation process and will help a designer to navigate through the form generation process in a systematic way. This offers interesting possibilities for design practice and design education in the future.

Methodology and experimental protocol for three-dimensional visual analysis – The third contribution of this research is the methodology and outline of the protocol for nature-inspired product analysis.

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.

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