Design Heuristics for Furniture Design

and

Tool for Model Making

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

Doctor of Philosophy
in

Design

by

Supradip Das

Department of Design
Indian Institute of Technology Guwahati
Guwahati - 781039, INDIA

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Supradip Das
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Under the Supervision of
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October 2022

Dedication

I would like to dedicate this thesis to my parent, parent-in-law and former colleague Late Sudipto Dasgupta.

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DECLARATION

I do hereby confirm that the research work presented in the thesis titled ‘**Design Heuristics for Furniture Design (DHfFD) and Tool for Model Making (TfMM)**’ is my own research work completed under the supervision of Prof. Amarendra Kumar Das at the Department of Design, Indian Institute of Technology Guwahati (IITG), Assam. I proclaim that to the best of my knowledge; this thesis does not contain previously published materials or contents written by another person or a substantial proportion of material accepted for the award of any other degree or diploma at IITG or any other educational institute. Any contribution made to the research made by others with whom I have worked at IITG or elsewhere is explicitly acknowledged in the thesis. I also avow that the intellectual content of this thesis is the product of my own work, and following standard scientific reporting practises, due acknowledgements have been made wherever the research findings of other researchers have been cited in this thesis.

Place: Guwahati
Date:

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CERTIFICATE OF AUTHENTICITY

This is to certify that Mr Supradip Das has submitted original and bonafide research work entitled ‘**Design Heuristics for Furniture Design (DHfFD) and Tool for Model Making (TfMM)**’ to the Indian Institute of Technology Guwahati for the award of Doctor of Philosophy in Design. This work has not been submitted elsewhere for the recognition of any other degree or diploma to this institute or any other institute or university.

He has fulfilled all the requirements mentioned in the PhD ordinance for submitting the thesis for the Doctor of Philosophy (PhD) degree award at the Indian Institute of Technology Guwahati.

Place: Guwahati
Date:

Prof. Amarendra Kumar Das
(Supervisor)

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प्रथमवयसि दत्तं तोयमल्पं स्मरन्तः	prathamavayasi dattaṁ toyamalpaṁ smarantaḥ
शिरसि निहितभारा नारिकेला नराणाम् ।	śirasi nihitabhārā nārikelā narāṇām |
सलिलममृतकल्पं दद्युराजीवनान्तं	salilamamṛtakalpaṁ dadyurājīvanāntaṁ
न हि कृतमुपकारं साधवो विस्मरन्ति ॥	na hi kṛtamupakāraṁ sādhavo vismaranti ||

Verse No. 6 by Maa Gurupriya (25 Jun 2009)

Translation: Coconut trees bear nectar-like water on their heads throughout their lives, remembering the small amount of water they were given at an early age. True and noble people should not forget a favour done to them in the same way.

Doctoral research is a journey in the dark. It is a journey to explore the potential within the self and contribute knowledge to the global knowledge sphere. This research journey provided a better understanding of the research practices in product design and development by interpreting existing research, publishing my own research, and expounding and deliberating with subject matter experts from various parts of the world. Without the blessings of God and support from people who have directly or indirectly contributed to the research, the journey would not have been possible. Though expressing gratitude in words is not sufficient for all those who extended their help, I still would like to express my deepest gratitude to all of them for their constant support and guidance.

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Abstract

The furniture industry's innovation culture is shifting towards democratic design by internalizing the production process. Designers, product developers and engineers work together in a prototyping space to transform a concept into a real product, considering the prototype as the boundary object amongst different domains and stakeholders to foster innovation processes. Given design students' future endeavours in the aforementioned work environment, prototyping activity is an integral part of design education to improve the immature mental model of novice designers. In contrast, teaching prototype-driven design innovation is not that simple, as it is tacit knowledge. Furthermore, prototype-driven design innovation is difficult for novice designers, as prototyping is the main activity. Simultaneous thinking and making tend to be complex activities for novice designers. This research seeks to develop tools to support novice designers in thinking and model-making, emphasizing furniture design. An extensive literature review on prototyping culture, novice designers' mental models and requirements for prototyping were used to arrive at the specifications for developing tools. 'Design heuristics for furniture design' (DHfFD) as a catalyst for thinking and 'Tool for Model Making' (TfMM) as a catalyst for making are two different tools developed in this research. The toolsets have been developed from an analysis of the characteristics of 650 award-winning furniture (chair) designs and published compendium of well-known successful designs and introduced in the form of cards. A total of 86 DHfFD cards and 65 TfMM cards had been developed. This research extends its investigation to analyze the acceptance and effectiveness of the tools with novice design students. Students have enthusiastically accepted it to generate more diverse concepts and models with appropriate materials and processes. This study correlates DHfFD with more alternative concepts and TfMM with the quality of the appearance model in furniture design. This research integrates evidence, methods, and perspectives from cognition and design, correspondingly providing a pedagogical recommendation to use DHfFD and TfMM to overcome prototype-driven design innovation issues in furniture design among novice designers.

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List of Abbreviations

ARC	Areas of Relevant Contribution
ASME	American Society of Mechanical Engineers
CDH	Comprehensive Design Heuristics
CES	Cambridge Engineering Selector
DH	Design Heuristics
DHfFD	Design Heuristics for Furniture Design
DHS	Design Heuristics Sets
DHsfX	Design heuristics for X
DRM	Design Research Methodology
E	Excerpts
EPS	Expanded Polystyrene
F-B-S	Function-Behaviour-Structure
InDeaTe	Innovation Design Database and Template
INSPEC	Information, Service for Physics Engineering And Computing
IQQR	Iterative Qualitative-Quantitative Research Process
K-J	Kawakita Jiro
m/c	Machine
MDF	Medium-density fibreboard
MiPS	Materials in Products Selection
MIT	Massachusetts Institute of Technology
NPD	New Product Development
O	Obvious
PLEX	Playful Experiences
PM	Paradigm Modifying
P-M-I	Plus, Minus, Interesting
PP	Paradigm Preserving
PVA	Polyvinyl Acetate
S	Specifications
SCAMPER	Substitute, Combine, Adapt, Modify, Put to other use, Eliminate, Reverse

SUTD	Singapore University of Technology & Design
TfMM	Tool for Model Making
TRIZ	Teoriya Resheniya Izobretatelskikh Zadatch (Theory of Inventive Problem Solving)

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Chapter 1

Research Clarification

1.1 Introduction

"Innovation is an iterative process. You learn, you continue to improve, you stay ahead."

*Mehmood Khan**,** PepsiCo Chief Scientific Officer*

In a competitive world where change is the only constant, innovation is a creative trend for survival and industrial growth. Innovation focuses on cultivating the strategic position of the organization through creative exercises. Product innovation aims to add value, gain a competitive edge, and achieve long-term success through developing and commercializing new products and services. Product innovation encompasses numerous indispensable aspects:

i. Identification of the need for new products, processes, and services
ii. Conceptualization of new products and improvement of existing products
iii. Validation of the prototype of the product for user acceptance
iv. Commercialization of new products (Rainey, 2005)

Product innovation examines the need for innovative products and processes. A funnel model is commonly used to depict the innovation process (Müller-Prothmann, T., & Dörr, 2009). It establishes the role of new product development (NPD) in facilitating transformation (Rainey, 2005). Because of the similarity and natural occurrence of the steps involved in New Product Development (Phal & Beitz, 1984) and innovation (Müller-Prothmann, T., & Dörr, 2009), design (Newman, 2019) is implicitly part of the innovation process. Figure 1.1 illustrates the juxtaposition of design, innovation and the NPD process.

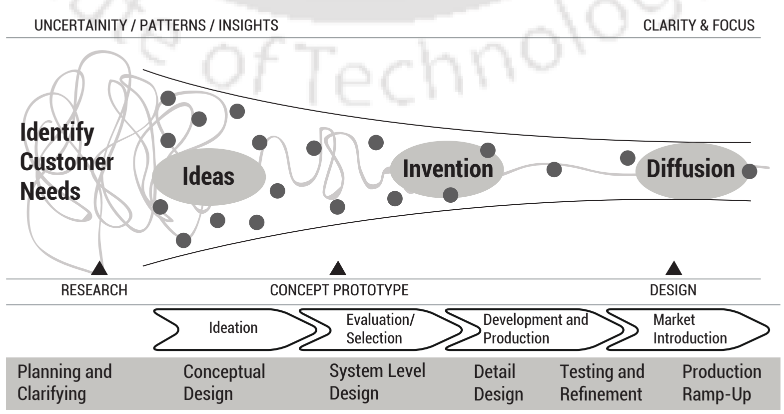

Figure 1.1 Juxtaposition of design, innovation and NPD process (Author)

1.2 Research Rationale

Numerous success stories give testimony to the effect of efficacious innovation, and thus, innovation is considered a silver bullet (Ord, 2020). Despite the success stories, successful innovation ventures exemplify the small apex of an iceberg, predominately comprising disastrous innovation ventures (Figure 1.2) (Huber, Kaufmann, & Steinmann, 2014).

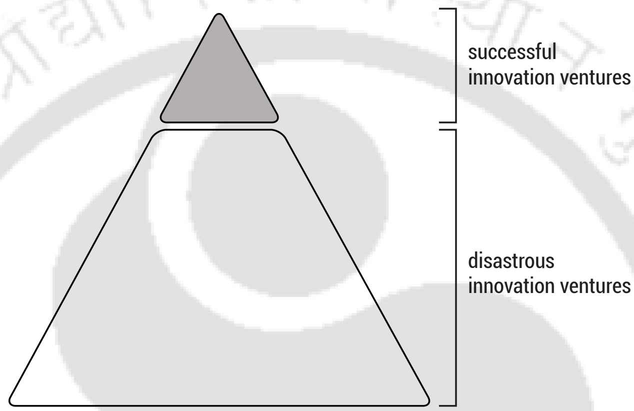

Figure 1.2 Innovation iceberg (Huber et al., 2014)

Henry Chesbrough says, “Most innovations fail. And companies that don’t innovate die” (Chesbrough, 2003). On the one hand, innovation gives the impression to be indispensable for being competitive and progressive. On the other hand, innovation practices are fraught with risk and threat. These aforementioned paradoxical situations are indeed innovator’s dilemma and express the conflicts encountered by organizations.

Some of the literature made an effort to explain the following whys and wherefores for innovation project failures:

i. Analysis of the innovation phases reveals that undesirable project terminations are frequently occurring at two points (Figure 1.3) in the innovation process:

   a) after concept selection and just before product development,

   b) after introducing the product to the market (Huber et al., 2014)

   Therefore, the innovation process should be re-configured to select the best idea for the development phase.

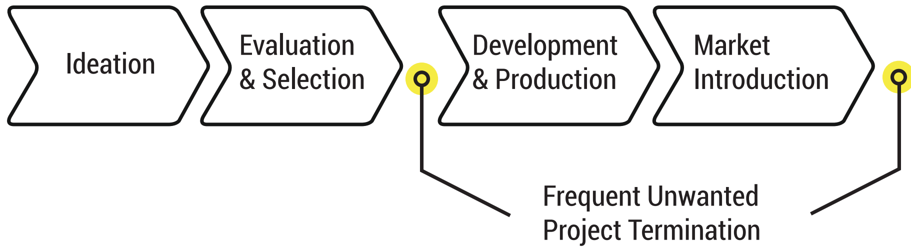

Figure 1.3 Frequent unwanted project termination points

ii. Products fail as they do not address the user's experience and emotional response. Products do not connect to their emotional journey (Brown, 2009).

These issues are critical and also a matter of research. However, the existing literature suggested a few possible solutions to these issues:

I. Making a prototype early in the process is an excellent measure to foster an innovation culture, inspiring new ideas (Brown, 2009). Failing at the beginning of the process ensures success at the end. Identifying design flaws early on with prototypes reduces the risk associated with sunk cost (V. K. Viswanathan, Atilola, Esposito, & Linsey, 2014).

II. Experience prototyping (Buchenau & Suri, 2000) or collaborative prototyping (Bogers & Horst, 2014) would lead to balanced functional and usable deliverables by engaging design team members, users and clients with prototypes.

Initial literature review reveals that design prototypes are the boundary objects in the innovation process (Rhinow, 2012), and prototyping drives the overall innovation process (Schrage, 1999). Above all, the literature vouch for **prototype-driven innovation** (Schrage, 1993), where prototypes elicit user feedback and help to modify the product before final production, thereby reducing the risk of failure in the innovation process.

For that matter, there is a change in the furniture industry. In the progression of mass manufacturing and democratization (Kristoffessson, 2014), furniture industries are shifting from solely external design and development services (Era, Marchesi, & Verganti, 2010) to in-house design services (Howarth, 2015).

Designers, product engineers, and technicians work together to transform a concept into a prototype in a prototyping space. The intention is to develop a design repository. During prototyping in IKEA, designers experience the form, function, ergonomics and detail of a product (IKEA, 2016). Early live prototyping helps the design team understand the potential of an idea and the limitations of the form and material before developing the final prototype (IKEA, 2019).

Independent designers Konstantin Grcic, Oskar Zieta, Ronan and Erwan Bouroullec practice the culture of prototyping in their studios (Terstiege, 2012). History reveals that furniture designers like Marcel Breuer (Wilk, 1981), Charles Eames (Drexler, 1973), Verner Panton and many more worked closely with the production processes, explored materiality and developed creative furniture forms. Understanding production techniques and tools help the designer to exploit to the fullest.

A professor of Swinburne University of Technology, Australia, Ian de Vere (De Vere, 2011) emphasized furniture prototyping in academics as a process of continuous exploration and evolution of concepts rather than manifesting the design concept.

It is evident that prototype is the keyword in recent innovation culture, and there is an interplay between concept and prototype. As prototypes, specifically physical prototypes, play a vital role in innovation, countries like Singapore, Korea, China, and India invest in education, precisely ‘design programs’, to accentuate innovation (Beckman & Barry, 2007), including prototyping courses. Still, novice designers have issues with concept generation and prototyping (Petrakis, Wodehouse, & Hird, 2021).

The research rationale derives from the fact that prototyping culture in the furniture industry will drive the innovation process. Novice designers should be trained in that direction, and appropriate support (tools and methods) would enhance their understanding and efficacy.

1.3 Research Motivation

With a decade-long experience as a design educator and instructor of courses on 'model-making and prototyping' and 'creative furniture design', the researcher constantly deals with creative thinking and model-making and prototyping issues. Even though undergraduate students are taught about material and manufacturing before introducing model-making and prototyping, they still face difficulties in model-making and prototyping. They fail to execute their conceptual design. A similar situation is observed among postgraduate students while modelling and prototyping, even though many are engineering graduates. Novice design students also need support (tools, methods, clues or inspiration) to generate creative concepts for furniture design. Existing supports and research are product design-centric, and very few of them are partially relevant to furniture designs. A preliminary study supports these obvious observations and reports the following two issues:

A. Issues related to concept generation: The success of the design innovation depends on the concept generation phase (Liu, Bligh, & Chakrabarti, 2003). And statistically, the success of concept generation relies on the quantity of the concepts generated in the early design phase (Yang, 2003). However, research on concept generation has revealed two serious cognitive issues (Leahy, Seifert, Daly, & McKilligan, 2018):

i. attachment to the early concepts and
ii. unable to explore a variety of designs

These are because feasible and efficient diverse concept generation by exploring 'the problem space' (Simon & Newell, 1971) is difficult for novice designers (Cross, 2004), and novice designers fixate on the features of their initial concepts or available concepts (Linsey et al., 2010), (Crilly, 2015).

B. Issues related to prototyping: Research on prototyping for novice designers pointed out several problems. When novice designers lack skills, they take more time and resources to build. This adds to the sunk cost and that causes fixation (V. Viswanathan, Atilola, Goodman, &

Linsey, 2014). Deininger et al. addressed the issues related to intentionality, quality and frequency. Overall, novice designers have problems with awareness of the scope and purposes of prototypes (Deininger, Daly, Sienko, & Lee, 2017).

The above studies express the need for furniture design-specific studies on novice designers and scopes available to develop furniture design-specific supports. This scenario motivated the current research on developing concept generation and prototyping supports for novice designers.

1.4 Initial Reference Model and Initial Impact Model

The reference model and impact model graphically represent research facts. Figure 1.4 shows the graphical representation of a statement and associated modelling in the reference model.

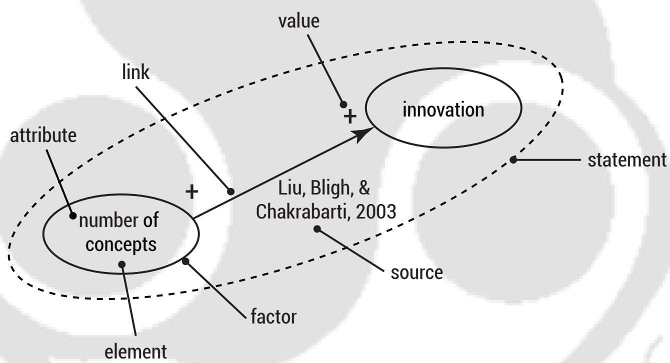

Figure 1.4 Graphical representation of a statement (Blessing & Chakrabarti, 2009)

Graphical representation of a statement/argument/scenario shows the impact of a factor over another factor. Each factor has an element and associated attribute with value. In a graphical representation, key factors are influencing factors that seem to be the most valuable factors to address and improve the prevailing condition. In the reference model, influencing factors influence the other aspects of the model. The links between elements represent the influence of factors and desired effects. The combination of '+' and '-' signs at the ends of a link represents the positive and negative impact of factors. The following abbreviations are used in the reference and impact model to show the sources:

[X]: citation number;

[A]: assumption-based statement;

[E]: experience-based statement;

The reference model signifies the existing condition in design (Blessing & Chakrabarti, 2009) and leads toward the impact model. This reference model uses direct citations instead of the citation number. The influencing factors are considered measurable success criteria for this thesis. Figure 1.5 represents the initial reference model based on the references and experiences.

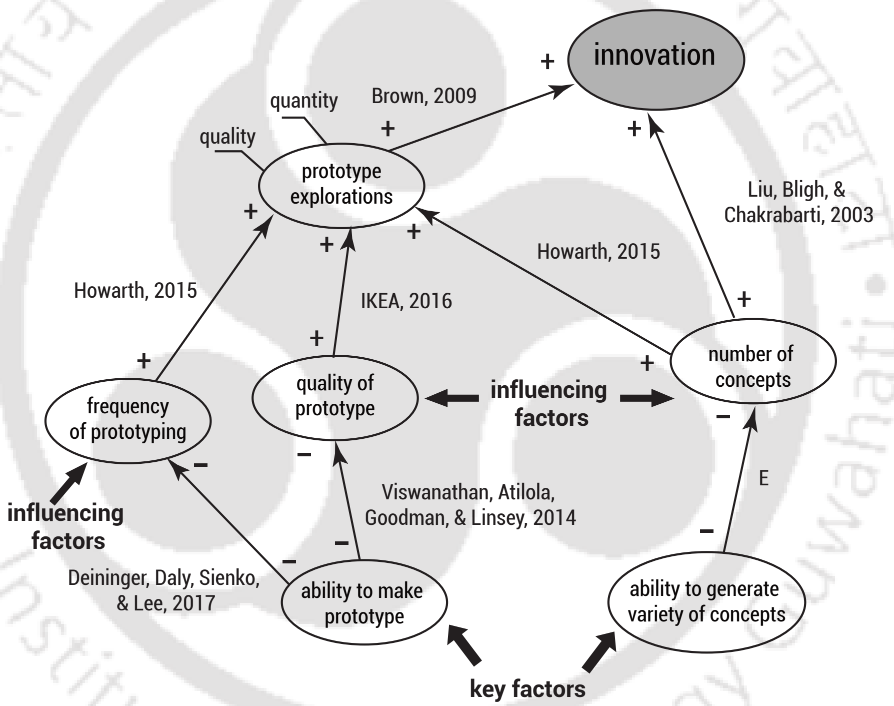

Figure 1.5 Initial reference model

The impact model represents the desired supports and expected effects. The supports are added to the key factors and shown as hexagonal elements. The impact model illustrated in Figure 1.6 is based on assumptions and references. The impact model portrays that support for concept generation and model-making (physical) or prototyping would enhance the capability to prototype and generate various concepts successively for novice designers. The capability enhancement of novice designers would create an impact on the culture of furniture design innovation.

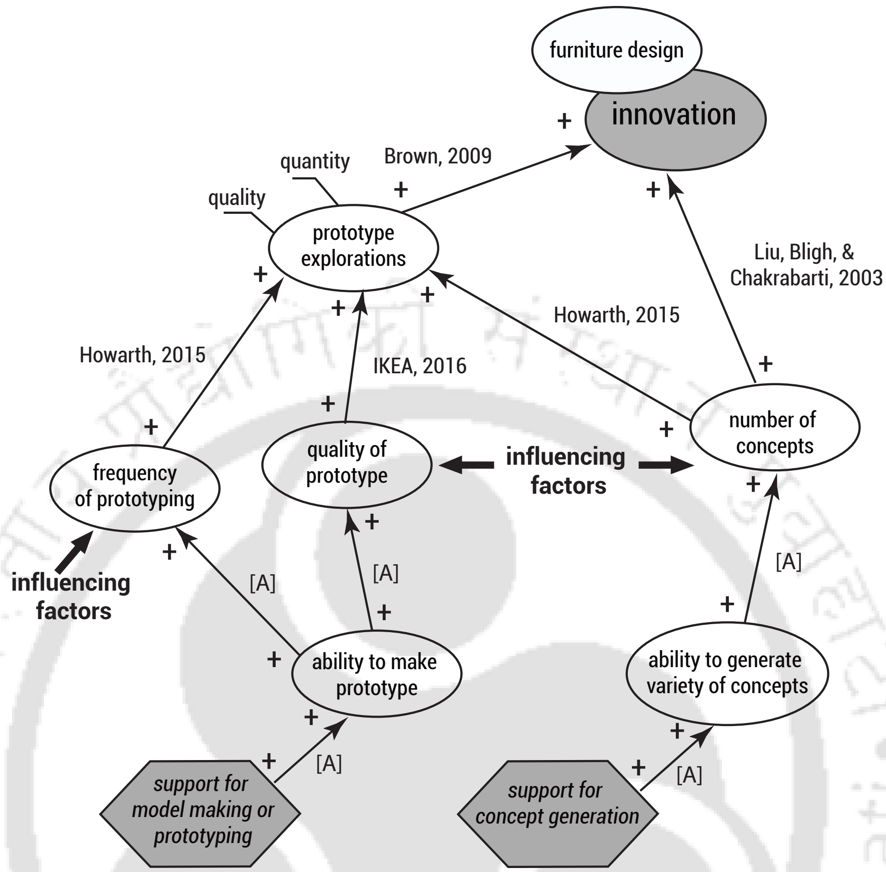

Figure 1.6 Initial impact model

1.5 Aim and Objectives

Aim

The research aims to develop concept generation, and model-making/prototyping supports to facilitate novice designers in the early stages of furniture design.

Objectives

1. To further understand the approaches with the prototype as a boundary object in furniture design and the interplay between concept and prototype in furniture design.
2. To develop furniture design-specific supports for concept generation for novice designers.
3. To assess novice designers' outcomes of creative concept generation before and after using the support.

4. To develop furniture design-specific support for model-making or prototyping for novice designers.
5. To assess the outcomes of model-making or prototyping by novice designers before and after using the support.

1.6 Scope of Research Enquiry

This dissertation explores and contributes to the overlapping research domain of design approach with the prototype as a boundary object, furniture design, and support for novice design students. The relevant sub-areas associated with the above-mentioned primary areas will be considered for descriptive study in Chapter 2. The scope of the research is illustrated in Figure 1.7.

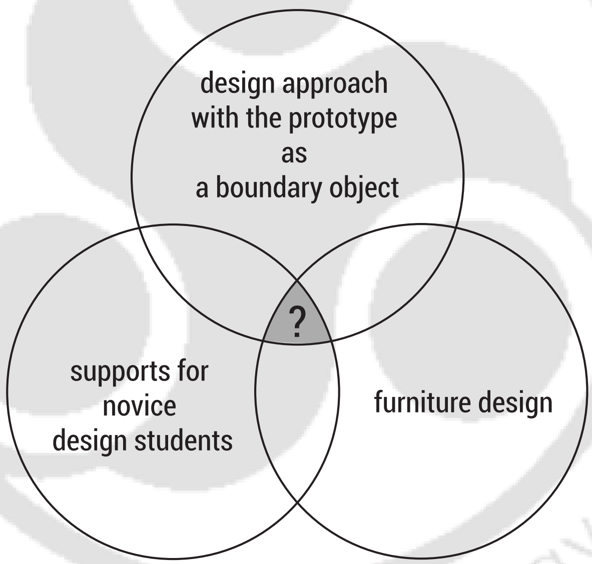

Figure 1.7 Scope of the research

The scope of the research enquiry provides the foundation for formulating the research questions. The first two pertinent questions are related to the state-of-the-art knowledge in approaches with the prototype as a boundary object in furniture design.

Q1. What is the nature of approaches with the prototype as a boundary object in design innovation?

Q2. What is the interplay of concept and prototype?

The systematic investigation of the first set of questions leads to the second set of questions related to the supports for novice designers in design research and supports specific to furniture design:

Q3. What supports are available in design research, and what are the attributes of design supports?

Q4. What are the specifications to be considered while developing supports for concept generation?

Q5. What specifications should be considered while developing supports for model-making/prototyping?

The next set of research questions is related to the supports intended to be developed:

Q6. What is the impact of the structured concept generation tool on novice designers?

Q7. What is the impact of the structured model-making/prototyping tool on novice designers?

1.7 Research Methodology

The Design Research Methodology (DRM) proposed by Blessing and Chakrabarti (Blessing & Chakrabarti, 2009) is followed in this research. Precisely the type 4 DRM framework is adopted for this research work. Figure 1.8 illustrates the design research methodology followed to develop support for novice designers.

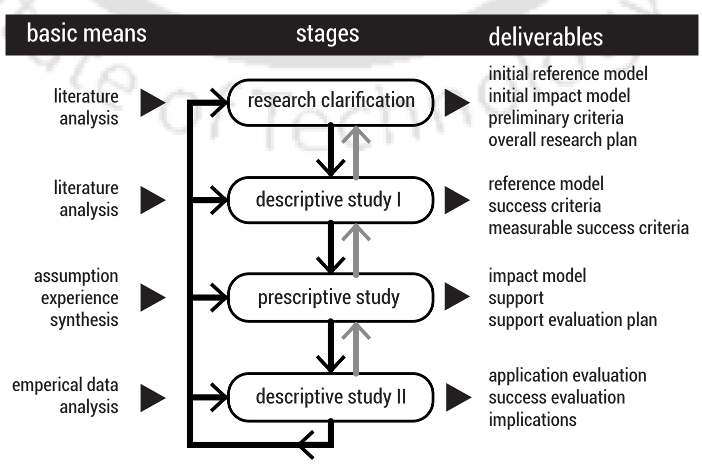

Figure 1.8 Design research methodology (Blessing & Chakrabarti, 2009)

The research was carried out in four stages to achieve the research objectives and answer the research questions. The four stages are research clarification, descriptive study I, prescriptive study and descriptive study II. The visual representation of the research flow, research stages and corresponding chapters is shown in Figure 1.9.

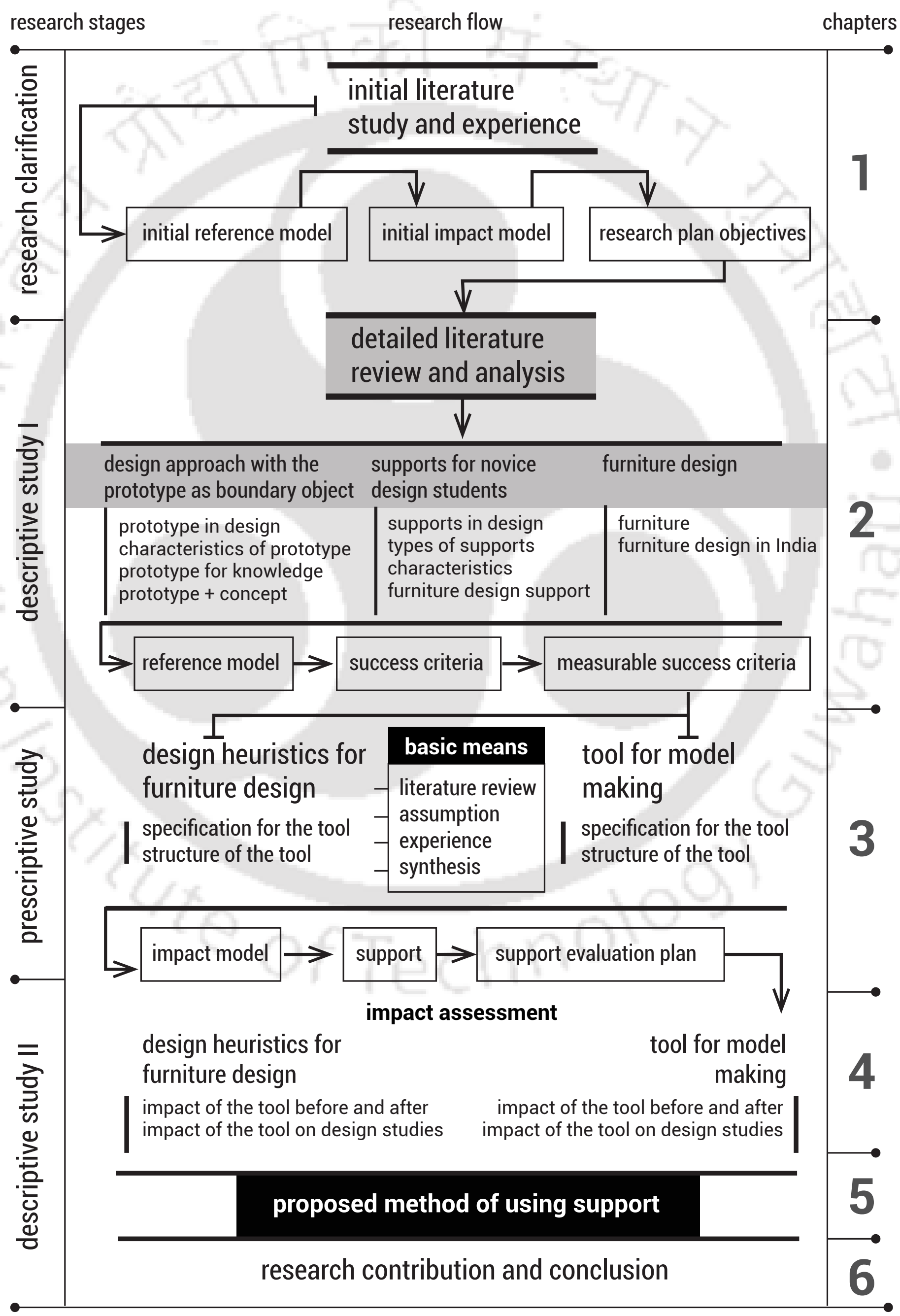

Figure 1.9 Flow of the research

The research clarification phase focused on mining literature and observed situations related to prototyping culture in the furniture industry. The prototyping behaviour of novice designers is observed as a related topic. The objective of the phase is to identify the research goal, initial reference model and initial impact model. The initial reference and impact models helped define the research scope and construct research questions. A research flow is also streamlined based on the initial understanding, observations and expectations.

A thorough investigation of the literature was conducted in the descriptive study-I phase, based on the research scope and relevant areas of contribution. The primary objective was to better understand the prevailing situation by identifying and analyzing the factors influencing the preliminary criteria.

The prescriptive study, through literature review, assumptions, experience and synthesis, provides the specification and structure of the supports required to improve the situation. At this stage, an evaluation plan is also finalized.

Descriptive study-II assesses the support's impact and verifies the impact model.

1.8 Structure of the Thesis

Chapter 1, titled **Research Clarification,** presents the research rationale, research motivation, initial reference model, initial impact model, research aim and objectives, research questions, and research methodology.

Chapter 2, titled **Literature Review,** provides detailed information on the prototype in design, characteristics of prototypes, prototype as a boundary object in design, a prototype for knowledge, the interplay between prototype and concept, available supports in design, types of supports, features of design supports, a brief overview on furniture construction and classification and furniture design in India.

Chapter 3, titled **Development of Supports,** highlights specifications for concept generation support and prototyping support to discuss the systematic development of supports for novice furniture designers and define the tool's structure.

Chapter 4, titled **Assessing the Impact of DHfFD and TfMM,** discusses the methodology and methods used to assess the impact of the developed tools. This chapter also reports the impact assessment results, describes their implications for novice designers and evaluates their success.

Chapter 5, titled **Designing with DHfFD and TfMM Cards,** showcases all the cards and the process of using them.

Chapter 6, titled **Research Contributions and Future Work,** summarises the research contributions. It also discusses the limitations of the research and concludes with the future direction of the research.

1.9 Summary

This chapter highlights the research context and rationale for this thesis. Subsequently, an introduction to novice designers' issues in prototyping culture is discussed. The research objectives are outlined, and the research questions are framed. This chapter concluded with a schematic presentation of the research flow and delineated the dissertation structure.

Design Heuristics for Furniture Design

and

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Chapter 2

Literature Review

2.1 Introduction

A diagram for Areas of Relevant Contribution (ARC) was made by expanding the research scope to represent and clarify the foundation of the research (Blessing & Chakrabarti, 2009). Works of literature were reviewed from the database of publishers such as Elsevier, Scopus, Inderscience, INSPEC, Thompson Reuters, Proquest, Common Ground Research Network, SAGE, and the societies' databases related to design, such as Design Society, Design Research Society, American Society for Engineering Education and American Society of Mechanical Engineers (ASME). Design-related or design-focused journals were also reviewed, identified by Gemser et al. (Gemser & de Bont, 2016). Furthermore, theses related to the focused areas were also considered for understanding and analysis. Figure 2.1 shows the Areas of Relevant Contribution.

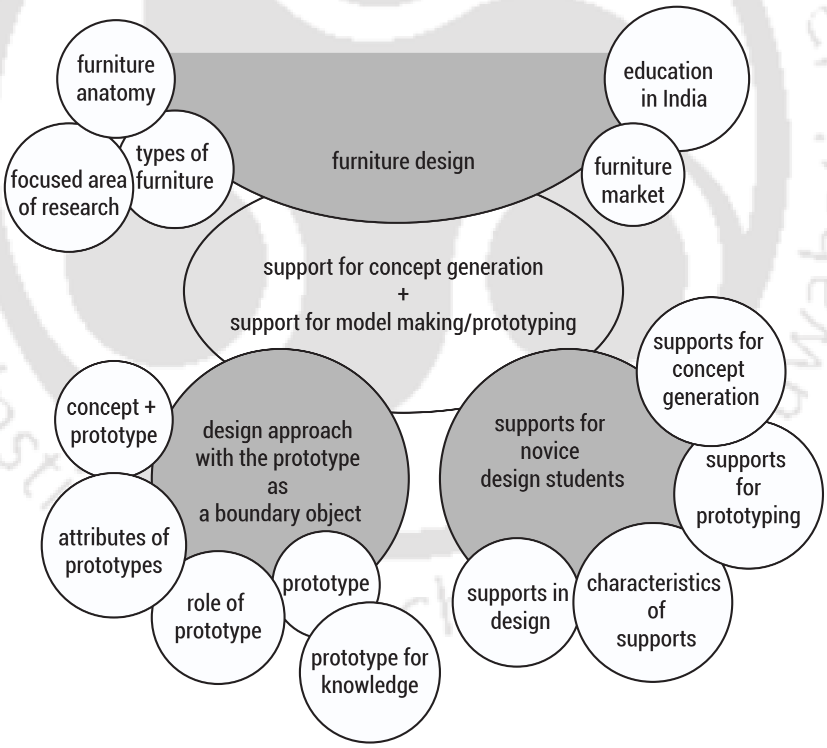


Figure 2.1 Areas of Relevant Contribution

The systematic review presented in this section of the thesis seeks to answer the following questions:

- What is the nature of approaches with the prototype as a boundary object in design innovation?

- What is the interplay of concept and prototype?
- What supports are available in design research, and what are the attributes of design supports?

SECTION-A PROTOTYPE and CONCEPT

2.2 Physical Model and Prototype

The word 'model' and 'prototype' were interpreted and explained by authors in many ways. A physical model is an object or set of objects fabricated from various materials to approximate an aspect(s) of how a product concept will perform (Otto & Wood, 2003). Also, a model is a miniature version of something to be made or an example for imitation or emulation (Dym, C. L., Little, P., & Orwin, 2014). And the process of continuous development of the model is a method of developing a Prototype (Hallgrimsson, 2012).

The models are generally smaller in size and can be made of any materials and used to illustrate certain behaviours or phenomena of a product concept. The tangible models are better suited for early design stages, and the 3D properties of a model allow designers to describe the aesthetic and functional aspects of a design (Pei, Campbell, & Evans, 2011).

On the other hand, a physical prototype interprets a product concept (Otto & Wood, 2003). It is also defined as the first full-scale and usually functional form of a product concept. They are working models tested in the same operating conditions in which they are expected to function as final products (Dym, C. L., Little, P., & Orwin, 2014). Prototypes are prepared towards the later stages of the design process (Pei et al., 2011).

Physical models of products are often called prototypes (Ullman, 2003). Physical models can be termed as physical prototypes synonymously (Otto & Wood, 2003). The terms physical prototype and model are used interchangeably by designers to describe a preliminary 3D representation of a product, service or system (Hallgrimsson, 2012). The definitions of prototypes and models sound alike enough, but prototypes and models are not the same things. The distinctions

between prototypes and models can be drawn based on the intents behind their making and the testing environments (Dym, C. L., Little, P., & Orwin, 2014).
Even though prototyping and model-making are theoretically different activities, they are inherently related terms. A comprehensive and well-accepted definition of a prototype is "an approximation of the product along one or more dimensions of interest". As stated by this definition, any entity exhibiting at least one attribute of the product of interest to the design team can be viewed as a prototype (Ulrich & Eppinger, 2012).

2.3 Classification of Physical Models and Prototypes in Design

Authors classified prototypes according to the materials, usage, context, fidelity etc. Prototype classifications available in the design research literature are presented in Table 2.1.

Table 2.1 Classification of physical prototypes in design research

Author(s)	**Classification of models/prototypes**	**Aspects considered**
(Budde, Kuhlenkamp, Mathiassen, & Züllighoven, 1984)	Exploratory prototype Experimental prototype Evolutionary prototype	Form, function and feature Product details System adaptability
(Shimizu, Kojima, Tano, & Matsuda, 1991)	Image models Rough mock-up models Presentation models Prototype models	Visual aspects Feasibility aspect Form & aesthetics Functionality
(Wagner & Steger, 1995)	Design prototype Geometrical prototype Functional prototype Technical Prototype	Aesthetics & ergonomics Accuracy, form & fit Function & features (sub-system prototype) All functional aspect (different material & process)

(Johansson, Råberg, & Apelskog Killander, 1996)	Visualization model Control model Process model	Appearance Production tooling Production process
(Houde & Hill, 1997)	Role prototype Look and feel prototype Implementation prototype	Role of the product Visual aspect Performance
(Mascitelli, 2000)	Rough model Refined model Formative prototype Refined Prototype	Visual aspect Technical feasibility Usability Performance
(Otto & Wood, 2003)	Proof of concept model Industrial design prototype DoE experimental prototype Alpha prototype Beta prototype Preproduction prototype	Feasibility aspect Look & feel Sub-system performance Material, geometry Functionality Production capability
(Ullman, 2003)	Proof of concept or proof of function prototype Proof of product Proof of process Proof of production	Feasibility aspect Product geometry Manufacturing process Production process
(Beaudouin-Lafon & Mackay, 2007)	Horizontal prototype Vertical prototype Task-oriented prototype Scenario-based prototype	All product features Implementation aspect Sub-system task Product application scenario
(Ankarbranth & Mårtenson, 2013)	Visual mock-up Functional mock-up Prototype Pre-serial	Visual aspects of components Function of sub-systems Combination of visual and functional aspects All functional features

(Ulrich & Eppinger, 2012)	Soft model	Feasibility aspect
	Hard model	Appearance
(Isa & Liem, 2014)	Presentation model	Embodies usability, aesthetic and marketing aspects
	Prototype	Almost all product features
(Setlhatlhanyo, Motshubi, & Dichabeng, 2017)	Sketch models	Visual aspects
	Block models	Aesthetics & ergonomics
	Working models	Function & fit
	Prototype models	All functional aspects

Literature shows inconsistency while defining and classifying models and prototypes. A comprehensive and detailed classification is available in a study proposed by Pei et al. (Pei et al., 2011). The taxonomy for models offered by Pei et al. is shown in Table 2.2:

Table 2.2 Taxonomy of models proposed by Pei et al.

Three-dimensional visual design representations	Models	Industrial models	Sketch model	Low-definition 3D model to capture form feature
			Design development model	Mock-up to understand the component-level relationship
			Operational model	Communicates the usability and ergonomic features
			Appearance model	Represents aesthetic appearance in 3D
		Engineering models	Functional model	Captures functional features and operating principles
			Assembly model	Assess the methods and tools required to assemble
			Production model	Assess the methods and tools required to sub-assemblies
			Service model	Demonstrates the service and maintenance model

The study follows the overarching idea of prototyping proposed by Ulrich and Eppinger (Ulrich & Eppinger, 2012). Industrial designers make prototypes to validate concepts, and engineers prototype functional designs. The taxonomy also says that industrial models are to explore form, ergonomics and appearance aspects. At the same time, engineering models are to explore functional, production and maintenance aspects. Pei et al. also offered a taxonomy for prototypes. Table 2.3 shows the taxonomy of prototypes.

Table 2.3 Taxonomy of prototype proposed by Pei et al.

Three-dimensional visual design representations	Prototypes	Industrial prototypes	Appearance prototype	Represents detailed product appearance in combination with functionality, which simulates production materials
		Engineering prototypes	Experimental prototype	Contains accurate component models for performance measure
			Alpha prototype	Combination of appearance and function to simulate production material
			Beta prototype	Improvement of the alpha prototype to finalize specifications for components
			System prototype	Evaluates electronic and mechanical performance integrating components specified for production without considering the appearance
			Final hardware prototype	Improved system prototype that represents functional elements of the product
			Off-tool component	Represents tooling for production, considering actual material and appearance
			Pre-production prototype	Produced by low-volume production components to test before production

Excerpt 1: Early prototypes made by industrial designers focus on appearance.

2.4 Role of Prototypes

Ulrich and Eppinger (Ulrich & Eppinger, 2012) defined and classified prototypes along these dimensions to describe the role of prototypes:

A. **Physical as opposed to analytical:** Physical prototypes are three-dimensional tangible artefacts representing the look and feel of the product, whereas analytical prototypes may be two-dimensional or three-dimensional, represented through sketches, mathematical models or computer-aided graphical models.

B. **Focussed as opposed to comprehensive:** Focussed prototypes include one or a few attributes of the prototypes. In contrast, comprehensive prototypes have most of the characteristics of the product.

Figure 2.2 shows the positioning of the types of prototypes along these dimensions.

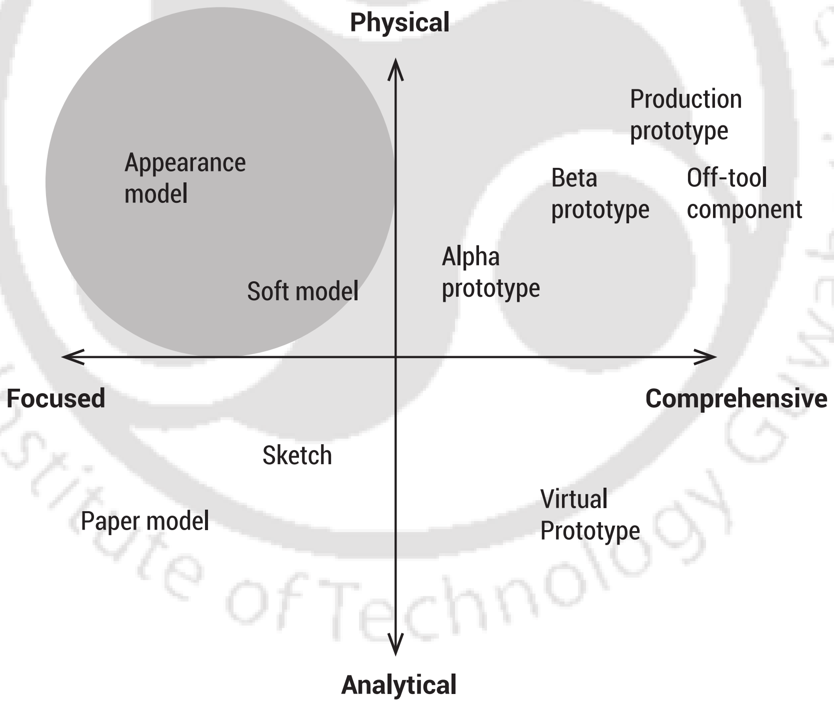


Figure 2.2 Positioning of the prototypes along the dimension of physical-analytical and focused-comprehensive

Focused-analytical and focused-physical are used in the early phases of design to refine ideas. Focused-physical models are to explore three-dimensional forms.

Ulrich and Eppinger further defined the role of prototypes and suggested prototypes appropriate for those purposes. The role of the prototypes are:

1. **Learning:** In the early design phases, prototypes help to learn. It is a learning device for the designers, as it clarifies the ambiguity related to form, function and feasibility.

2. **Communication:** A physical prototype represents visual, tactile and three-dimensional aspects of a product and communicates to the investors, top management, users, vendors, designers and other partners. The look and feel of the prototype convey the aesthetic aspect of the product communicating to all the stakeholders.

3. **Integration:** Prototypes can be used to understand component-level functional integration. A comprehensive physical prototype is an effective tool to realize subassembly and physical interconnections in a product.

4. **Milestones:** In the later stages of the design, comprehensive-physical prototypes are used to showcase all the detailed functionality to communicate the achievement of the prototypes. Comprehensive-physical prototypes demonstrate certain functionality and are intended to pass the qualification tests.

The appropriateness of various types of prototypes and corresponding purposes proposed by Ulrich and Eppinger are shown in Table 2.4.

Table 2.4 Different types of prototypes and purposes (●= more appropriate, ○= less appropriate)

	Learning	Communication	Integration	Milestone
Focused analytical	●	○	○	○
Focused physical	●	●	○	○
Comprehensive physical	●	●	●	●

Excerpt 2: The early three-dimensional prototypes are focused-physical intended for learning and communication.

2.5 Attributes of Prototypes

Attributes of a physical model/ prototype are essential because these may help to set the success criteria for prototyping. These are the elements which can be modified for a better prototype experience. Hence these can be considered as the drivers for prototyping.

According to Ulrich and Eppinger, “prototype is an approximation of the product along one or more dimensions”. As stated by this definition, any object unveiling at least one attribute of the product that is of concern to the development team can be considered a prototype. It means a model/ prototype (Pt) has a set of attributes (Pa…Pn) of the products (P), but all.

High fidelity prototype Product (P) = $Pa_1 + Pa_2 + Pa_3 + Pa_4 \ldots\ldots\ldots Pa_{n-1} + Pa_n$ (1)

↑ Prototype (P_t) = $Pa_1 + Pa_2 + Pa_3 + Pa_4 \ldots\ldots\ldots Pa_{n-1}$ (2)

or

Low fidelity prototype Prototype (P_t) = $Pa_1 + Pa_2 + Pa_3 + Pa_4$ (3)

The greater the number of product attributes in a prototype, the higher the quality of the prototype. So, the difference between product and prototype attributes (P-Pt) defines the quality of the prototype. But, how many attributes of the product to be incorporated into a prototype?

Houde and Hill (Houde & Hill, 1997) presented a prototype model that illustrates a three-dimensional space that corresponds to the prototype’s three attributes of prototype such as 1.role, 2.look and feel, and 3.implementation. “Role” states the function with which it is helpful to the user. “Look and feel” denotes the sensory experience of using an artefact. “Implementation” means the techniques and components through which an artefact performs its function. Being at one corner of the triangle is the designer’s judgement based on specific design issues. Once the designer clarifies the specific design issues, all the attributes are integrated to make the final design. The purposes of the prototypes are shown in Figure 2.3.

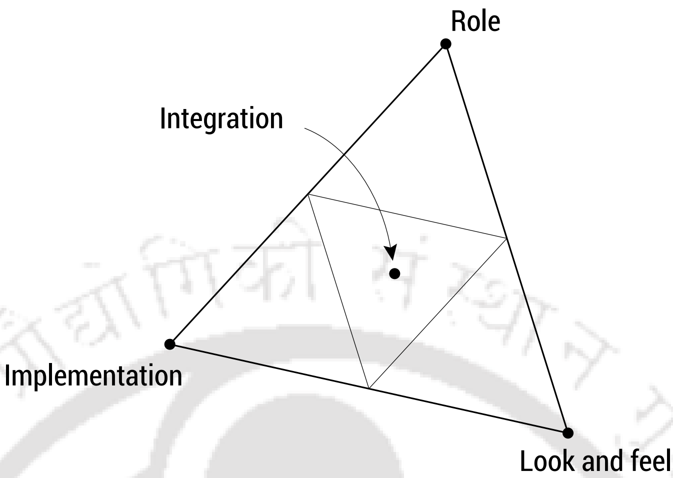


Figure 2.3 Purposes of prototypes (Houde & Hill, 1997)

Later, Broek et al. (Broek, Sleijffers, Horváth, & Lennings, 2000) provided an exhaustive list of characteristics. These are appearance, shape and design, strength and stiffness, shape accuracy, tolerance, geometric accuracy, texture, surface quality, application of features, material properties, material hardness, prototype weight, colour, conductivity, and transparency. The surface quality, shape and design, and application and availability of features are critical for the conceptualization stage.

Moreover, Lim et al. (Lim, Stolterman, & Tenenberg, 2008) describe prototypes' attributes under two major classes, filtering dimensions, which exhibit the design's physical properties and manifestation dimensions, which must be considered while crafting a prototype. Table 2.5 shows the filtering dimensions.

Table 2.5 Filtering dimensions (Lim et al., 2008)

Filtering dimension	Example variables
Appearance	size; color; shape; margin; form; weight; texture; proportion; hardness; transparency; gradation; haptic; sound
Data	size; type; use; privacy type; hierarchy; organization
Functionality	users' functionality needs and system functionality
Interactivity	behaviour related to input, output, feedback etc.
Spatial structure	relationships and proportions among spaces

Designers can ensure careful integration of each filtering dimension in design by exploring each dimension separately. Although filtering dimensions are prescribed for interactive products, appearance and spatial structure dimensions can be used in furniture prototyping. In relation to the filtering dimensions, manifestation dimensions provide the initial direction to prototype construction for physical prototypes. Three manifestation dimensions are **material** (medium of construction), **resolution** (level of detail) and **scope** (range of what is covered to be manifested). Table 2.6 represents furniture prototypes and corresponding manifestation dimensions based on the examples explained by Lim et al.

Table 2.6 Furniture prototypes and corresponding manifestation dimensions

Manifestation dimension	Definition	Example Variables
Material	The medium used to form a prototype	Physical media, e.g., paper, MDF, wood, and plastic; tools for forming physical materials, e.g., cutter, scissors, and sandpaper
Resolution	Level of detail or sophistication of what is manifested (corresponding to fidelity)	Accuracy of function, e.g., a swivel chair rotating 360^{o}; appearance details, e.g., shape details, proportion
Scope	Range of what is covered to be manifested	Number of product attributes corresponding to the design phase, related to the type of prototype, and stakeholders associated with the discussion, e.g., form feature and proportion in appearance model

Lim et al. made clear that "to create a prototype is to find the manifestation that, in its most economical form, will filter the qualities in which the designer is interested, without distorting the understanding of the whole". It means the filtering dimensions dictate manifestation dimensions.

Excerpt 3: The designer's task is to select an appropriate prototyping process for manifestation to meet filtering dimensions.

2.6 Prototype as Boundary Object

Literature culled from the repositories discussed prototypes as boundary objects directly or indirectly. However, there is a disparity in the terms they used.
Schrage (Schrage, 1993) proposed a prototype-driven culture for organizations seeking innovation instead of specification-driven innovation. He also suggested a prototype culture diagnostic matrix to be followed by organizations (Figure 2.4).

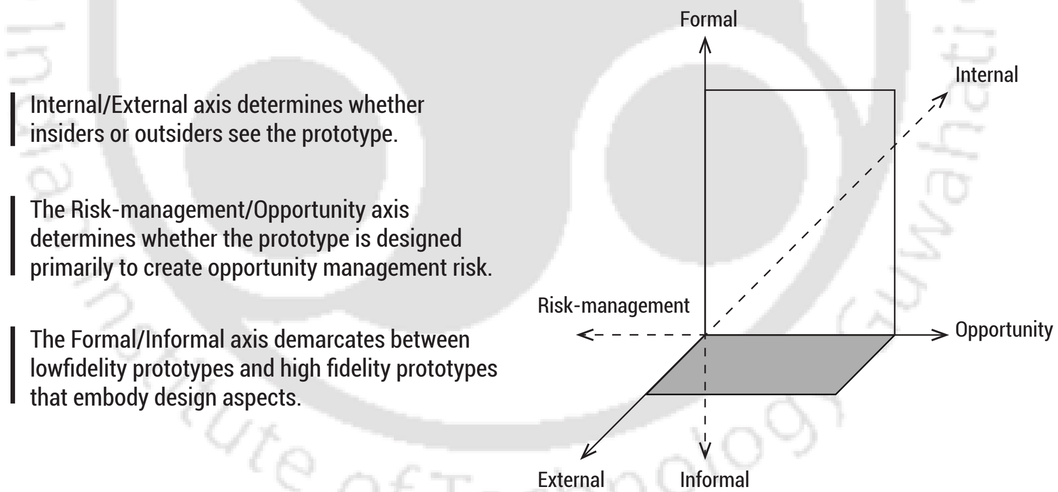


Figure 2.4 Prototype culture diagnostic matrix

Organizations that are strongly typified risk-management/internal/formal tend to follow a specification-driven culture. Whereas organizations typified opportunity/internal/formal tend to follow the prototype-driven culture. In a recent study, Jensen et al. reintroduced the above concept as prototrial-driven culture. Organizational culture consciously intending to elicit unknown unknowns is prototrial-driven culture (Jensen, Elverum, & Steinert, 2017).

Ignoring the terminological differences, innovation culture with prototypes as boundary objects follows these common strategies:

1. **Exploratory prototyping:** Prototype-driven culture generates ideas and explores enormously. In this strategy, design teams build multiple concepts during a particular period to select the best. In this case, the number of prototyping cycles per unit of time is essential (Schrage, 1993). This strategy is also called parallel prototyping (Dahan & Mendelson, 1998). The more prototyping cycles per unit time, the more polished the final product (Schrage, 1996).
2. **Evolutionary prototyping:** In this scenario achieving the best possible design is iterative. One prototype is developed during a particular period. Design teams continue a dialogue between the stakeholders to modify prototypes until the best possible design arrives (Schrage, 1993). This strategy is also called sequential prototyping(Dahan & Mendelson, 1998). The process starts with 'soft and hard forms' and increasingly arrives with sophisticated prototypes embodied in most product details (Mascitelli, 2000). Iterative prototyping is illustrated in Figure 2.5.

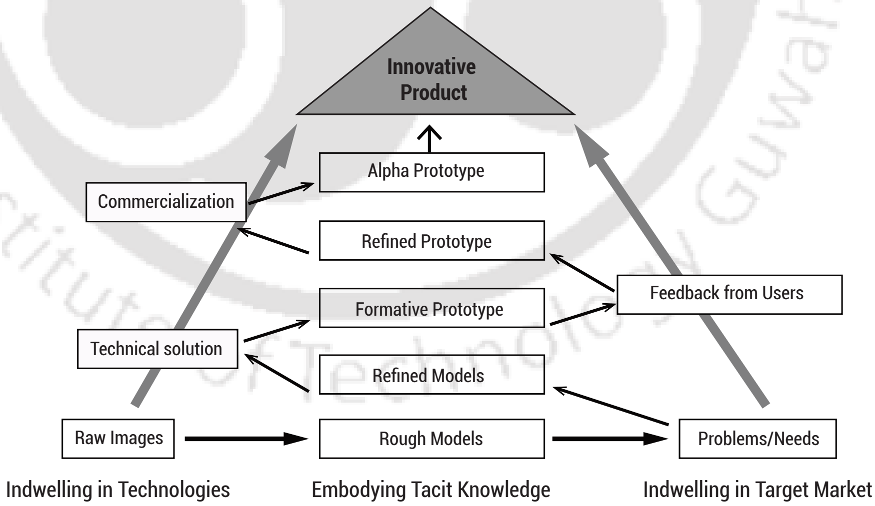


Figure 2.5 Iterative prototyping process (Mascitelli, 2000)

Beckley et al. (Beckley, Paredes, & Lopetcharat, 2012) proposed the iterative qualitative-quantitative research process (IQQR) resembling the formerly presented process by Mascitelli. This process fosters quick prototyping and screening from the early phases and encourages a dialogue with consumers to derive quantitative markers from the qualitative exploration process. A series of iterative qualitative-quantitative explorations delivers protocept and prototypes at the end of the innovation cycle. Figure 2.6 represents the iterative qualitative-quantitative process.

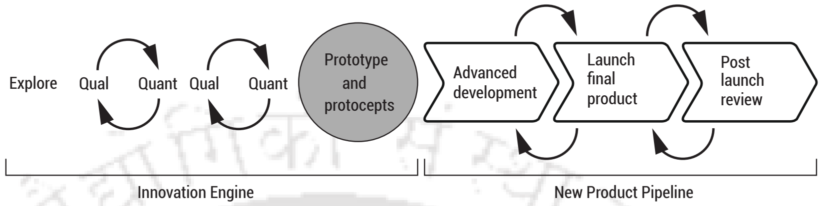


Figure 2.6 Iterative qualitative-quantitative research process

3. **Periodic prototyping:** Periodic prototyping is a strategy where design teams produce prototypes on a tightly fixed schedule (Bowen, Clark, Holloway, & Wheelwright, 1994).
4. **Collaborative prototyping:** Collaborative prototyping is a participatory design process where end-users design and prototype a custom product or service with the design team (Terwiesch & Loch, 2004).

Excerpt 4: Time for prototyping is the critical marker for distinguishing between specification-driven and prototype-driven cultures.

2.7 Protocept

It is entirely self-evident that in innovation processes, where prototypes are the stimulant, protocepts are the indispensable entities. Though multiple researchers used the term protocept in their research, a clear definition is missing in design research. However, based on the attributes explained in pieces of literature, protocepts can be defined as the artefacts developed and delivered at the end of the exploratory endeavour of the early phases of the innovation (Beckley et al., 2012). Mr David Lundahl, President of Insights Now, Inc.,explained 'protocept = concept + rough prototype' (Lundahl, 2005).

Excerpt 5: Protocept = concept + rough prototype.

2.8 Prototyping for Knowledge

2.8.1 Design Cognition Perspective

Understanding design cognition, i.e. human information processing in the design process, is essential for understanding the impact of prototyping in the knowledge domain.

To solve a particular design problem, designers travel through the external world to take information from objects (designs), observation (context of other designs), and external and internal archives of previous experience and learning. Referring to all the sources, designers mentally encode a rich fractal and experiential knowledge structure (Eastman, 2001).

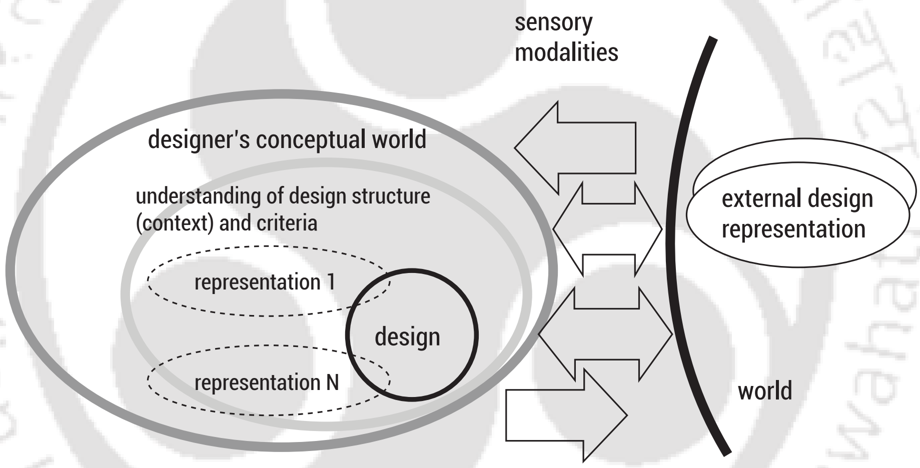


Figure 2.7 Representation of the designer's knowledge of the internal and external World (Eastman, 2001)

It is important to externalize an internal mental model through multiple representations. This process helps designers to select the best solution. Prior research expounds that prototypes help to enhance designers' incorrect mental models and lead them to better ideas satisfying all the design requirements (V. K. Viswanathan & Linsey, 2010). It was also observed that physical prototyping could mitigate design fixation (Kershaw, Hölttä-otto, & Lee, 2011).

2.8.2 Creativity Perspective

Kolb's (Kolb, 1984) experiential learning theory focuses on how knowledge is created by transforming experiences; when a person performs a specific action in a particular setting, reflects on the effects of that action and attempts to understand those effects, modifies actions to accommodate new ideas. Owen (Owen, 1998) later elaborated on this with a knowledge-building model and application in design using the theory of realm and theory of practice. According to Owen, knowledge is generated and gathered through action. The general model is doing something and judging the results (Figure 2.8).

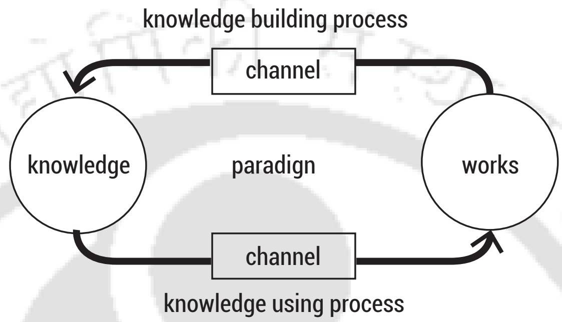


Figure 2.8 General model of generating and gathering knowledge

Owen extended the model and presented it in the context of product design (Figure 2.9). The design process starts with the analytic phase and ends with the synthetic phase. The objective of the analysis is to find a discovery, and synthesis is to make an invention.

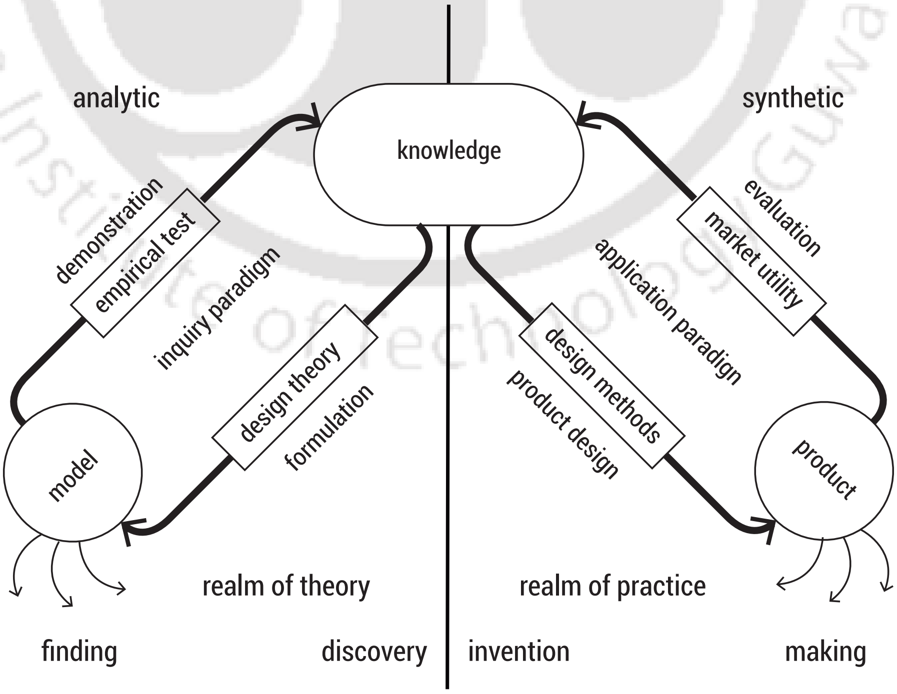


Figure 2.9 Using and accumulating knowledge in the product design domain

In design, finders explore the form through a model to understand specific values, such as cultural fit, appropriateness and effectiveness in the analytic phase. The exploration and inquiry generate new knowledge as measures and principles. Makers use the measures and principles in the synthetic phase. The experience through exploration in the analytic phase enhances creative thinking in the synthetic phase (Owen, 2007).

2.8.3 Naïve physics

Naïve theory, also known as naive physics, refers to research that relies on the mental model construct. Naïve physics explains that people understand causal phenomena associated with physical or mechanical systems through analogical thinking. Thus people tend to have an inaccurate mental model (Jones, Ross, Lynam, Perez, & Leitch, 2011). Because of less exposure to the outer world and less experience, novice designers are also most likely to have inaccurate mental models. An inaccurate mental model of the designer affects creative thinking. That is why extensive use of physical models is suggested throughout the design process to support and enhance an engineer's inaccurate mental models (Viswanathan & Linsey, 2010).

2.8.4 Tacit knowledge

Tacit knowledge is defined as data or content that exists only in the mind of the knower. It consists of both cognitive and technical components. The knower uses cognitive components and mental models that data or any representations cannot directly express. Technical components are concepts that can be described using actions or knowledge representations. In totality, the transfer of tacit knowledge is costly, complex and less mobile (Mascitelli, 2000). Teaching physical prototyping in design is not that simple because it is tacit knowledge. It is easy to demonstrate tacit knowledge than articulate (Dym, C. L., Little, P., & Orwin, 2014). Learning by doing gives experience, allows experimentation, and helps accumulate tacit knowledge below the surface of conscious thought (Mascitelli, 2000).

Excerpt 6: Prototyping skill is tacit knowledge, and it can be accumulated through learning by doing.

2.9 Interplay of Concept Generation & Prototyping

Research on prototyping advocates early prototyping to avoid fixation. Two significant studies with empirical data are available to understand the position of prototyping in the design process.

Walker et al. (Walker et al., 2010) positioned prototyping before concept generation and conducted a pilot design study at the US Air Force Academy and the University of Texas at Austin. The experiment was conducted between the control and experimental groups. The experimental group was introduced with an early prototyping experience. Following the completion of the EPE by the experimental group, both groups went through a similar concept generation process, and experts judged the results. The number of unique ideas was tabulated for each group, and the concepts were rated for innovativeness, diversity, and feasibility. These data served as the basis for a quantitative assessment of the level of design fixation. The results are summarised as follows:

- However, the experimental group developed fewer unique solutions than the control group but did not exhibit fixation, reducing its innovativeness.
- The experimental group developed concepts with greater feasibility than those created by the control group.
- The study reported significant qualitative advantages by finding latent customer needs.

The study is limited to the data and verification through reverse research, i.e. analyzing the creative output with concept generation first and prototyping later.

Later, Bao et al. (Bao, Faas, & Yang, 2018) conducted a detailed study between three groups, viz. sketching only, prototyping only and sketching (concept generation) +prototyping (P&S). In this study, a two-phase experiment was carried out to understand the role of two tools, sketching and prototyping, in the early stages of product design.

Sketching-only was associated with generating more and more diverse ideas in the early stages of the product design activity, indicating the exploration of a broader design space and likely contributing to the higher novelty of their final designs. Prototyping-only designers tested their ideas early through fabrication, which encouraged more feasible and aesthetic ideas. Free sketching and prototyping allowed designers to reiterate design ideas with both tools, generate more ideas, and explore the concepts more in-depth. Expert and user assessments indicated that the P&S (prototyping & sketching) group produced the most creative ideas. These findings highlight how the interplay of sketching and prototyping can increase idea generation efficacy, particularly design creativity.

Excerpt 7: Concept generation and prototyping together allow designers to explore broader design space and generate more feasible-creative concepts.

2.10 Novice Designers' issues in Prototyping

Existing literature highlighted prototyping issues with novice designers. Table 2.7 showcases all the issues.

Table 2.7 Aspects and issues related to novice designers

Aspects	Issues	Reference
Prototype making	Issues related to compromised material selection	(Deininger, Daly, Sienko, Lee, & Kaufmann, 2020)
Prototype making	Issues related to material, process and tool selection	(Das & Das, 2019)
Prototype making	Difficulty with choosing from the materials	(Schaeffer & Palmgren, 2017)
Prototyping skill	Lacks prototype building skill	(V. Viswanathan, Atilola, Goodman, & Linsey, 2014)

Excerpt 8: Novice designers have problems with material and process selection in prototyping.

2.11 Concept Generation in Design

The generation of promising concepts is a primary goal of conceptual design. It is critical to generate diverse concepts to avoid overlooking valuable concepts to accomplish this goal. If designers can develop promising ideas, the chances of creating better products should increase. Following the generation of several concepts, these should be evaluated and chosen as soon as possible. According to design research and creativity, the whole conceptual design process has been suggested by many researchers as divergent-convergent, fully convergent containing deliberate divergence or progressive divergent-convergent. In all cases, the primary intent is to generate more concepts. Increasing the number of concepts increases the chances of finding better concepts (Yang, 2003). This belief is also supported by evidence (Brophy, 2010). Therefore the solution exploration process should follow multiple divergences and convergences to gradually increase the number of solutions for the concept generation, followed by a divergent-convergent affinity to detail these concepts with an overall reduction in the solution number (Liu, Bligh, & Chakrabarti, 2003). This approach is shown in Figure 2.10.

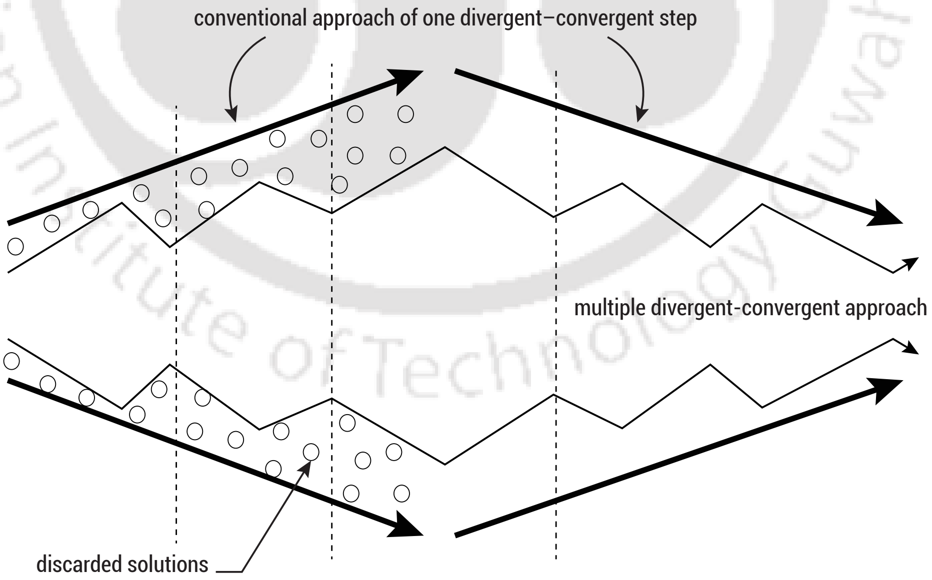


Figure 2.10 Multiple divergent-convergent approach

Excerpt 9: Concept generation aims to generate several concepts and screen concepts toward an ideal solution.

2.12 Novice Designers' issues in Concept Generation

Design research on concept generation by novice designers reported issues related to design fixation. Design fixation was initially defined as blind adherence to a set of ideas that limit conceptual design output (Jansson & Smith, 1991). Design fixation is also considered a mental block for novel idea generation during problem-solving when designers cannot think beyond what they are exposed to (Howard, Maier, Onarheim, & Friis-Olivarius, 2013). Youmans and Arciszewski (Youmans & Arciszewski, 2012) proposed three types of design fixation:

1. **Unconscious adherence**: With minor tweaks, novice designers replicate existing products or ideas, but the product remains the same (Jansson & Smith, 1991) (Purcell & Gero, 1996). It is because unconscious internal drives and motivations influence humans.
2. **Conscious adherence:** Novice designer sometimes adheres to a limited set of ideas, and the designer becomes aware of their fixation.
3. **Intentional Resistance:** Novice designers fixate on their early design solutions and are reluctant to let go of previous design solutions.

There are multiple reasons which contribute to design fixation: 1) experience (Linsey et al., 2010), 2) domain knowledge (Purcell & Gero, 1996), 3) personality traits, 4) awareness of recent advancement, 5) unawareness of the superior supporting methods or tools, 6) self-imposed constraints. Design research explored and proposed many solutions such as: 1) short breaks (Kaufman & Sternberg, 2019), 2) extended incubation such as short naps or night sleep (Marguilho et al., 2015), 3) physical prototyping (V. Viswanathan, Atilola, Esposito, & Linsey, 2017), 4) use of analogy-based design heuristics (S. Daly, Yilmaz, Seifert, & Gonzalez, 2010), 5) use of computer-based design tool (Dong & Sarkar, 2011). Research shows that analogy-based problem-solving (Linsey, Murphy, Markman, Wood, & Kurtoglu, 2006), assisted by the solutions from past problems, is an effective tool for scaffolding in design education (Daugherty & Mentzer, 2008).

Excerpt 10: Design by analogy approach is more effective in mitigating fixation.

SECTION-B SUPPORTS FOR NOVICE DESIGNERS

2.13 Supports in Design

Design supports are all possible means, aids and measures that can be used to improve the design (Blessing & Chakrabarti, 2009). Design support includes strategies, principles, methodologies, procedures, tools, techniques, guidelines, etc.

Strategy can be defined as the set of choices that dictate the actions to accomplish a task (Bradley Adam Camburn et al., 2013).

A principle in design is defined as "A fundamental rule or law, derived inductively from extensive experience and/or empirical evidence, which provides design process guidance to increase the chance of reaching a successful solution" (Fu, Yang, & Wood, 2016).

Design methodology includes plans of action that link working stages and design phases (Phal & Beitz, 1984). Methods support the action plans.

Design methods signify specific procedures to complete a design task in the design process (Sakae, Kato, Sato, & Matsuoka, 2016).

A formal definition of guideline proposed by Fu et al. (Fu et al., 2016) is "A context-dependent directive, based on extensive experience and/or empirical evidence, which provides design process direction to increase the chance of reaching a successful solution".

Tools in the design context are implements or aid that make it easier to use a method. It can be manual or computer-based methods or frameworks with the potential to improve efficiency in one or more stages of the product development process (Lutters, Van Houten, Bernard, Mermoz, & Schutte, 2014).

Dalsgaard (Dalsgaard, 2017) describes the following five qualities of design tools:

- Perception- enable and support perception, reveals facets of a design
- Conception- enable and support conception, helps to understand and articulate
- Externalization- enable and support externalization, helps to envision design solution

- Knowing-through-action- enable and support knowing-through-action, generates new knowledge
- Mediation- enable and support mediation between actors and artefacts

2.13.1 Classification of Design Tool

Tools can be classified as one or more two of the following:

1. **Computer-aided tools:** These tools are web-based or software-based tools with a systematic design template and database to support the design process or particular design stage. These types of tools can be online or offline tools. Idea Inspire 3.0 and InDeaTe (Chakrabarti & Chakrabarti, 2017) are from this category.
2. **Analogue tools:** These kinds of tools are paper or card-based tools. This category includes PLEX cards and IDEO method cards (Wölfel & Merritt, 2013).

Card-based design tools have grown in popularity to disseminate design research insights and make them usable in the design process. Card-based design tools have many strengths as a design tool (Roy & Warren, 2019):

- Facilitates creative combinations of concepts
- Provides a common foundation for team understanding and communication
- Provides tangible illustrations and demonstration of design information
- Providing convenient instruction for steps to be followed

Card decks may also have some weaknesses, including:

- Overburdening users with too much information
- Over-simplified information owing to space limitations
- Complicated for users to comprehend and apply
- Difficult to update

The general benefits of card-based tools are tangibility and visualized content; designers can quickly browse and organize the cards, gaining knowledge from the cards (Yoon, Desmet, & Pohlmeyer, 2016).

Roy and Warren (Roy & Warren, 2019) provided a classification of card-based tools by analyzing 155 card-based tools (details available in **Appendix A**):

1. **Systematic design methods and procedures:** Systematic methods and processes for identifying, analyzing, and resolving design/innovation issues. This category contains representations for various stages of the design process to assist designers in working systematically from problem or design brief to detailed solution (e.g. SUTD-MIT design method cards).
2. **Human-centred design:** This kind of method card assists designers in focusing on the user needs, desires, and requirements of a product, service, or system (SILK method deck).
3. **Domain-specific design:** This category provides methods, information or checklists for domains not covered elsewhere (e.g. Design Play Cards).
4. **Creative thinking and problem-solving:** These are tools for creative thinking design tasks (e.g. Design Heuristics).
5. **Team building and collaborative working:** This kind of card aim to help create an effective design or co-design teams (e.g. Totem cards).
6. **Future thinking:** This category is concerned with transformation awareness and planning or problem-solving based on trends or fact-based analyses of future scenarios (e.g. The Thing from the Future).

2.13.2 Design Attributes for Card-Based Tool

Wolfel and Merritt (Wölfel & Merritt, 2013) proposed five key design attributes for card-based tools:

1. **Intended purpose & Scope:** Card-based tools should specify their specificity; general or context-specific use.
2. **Duration of use and placement in the design process:** Card-based design tools should specify the time of engagement and position in the design process.
3. **System or methodology of use:** Methodology is a critical component of card-based tools. With no systematic methodology, the designer may or may not achieve the desired results. Card-based tools should include usage and methodology instructions.

4. **Customization:** Card-based tools should allow the designer to customize cards according to their purposes. There must be some possibilities for optimal customization of the tool kit for the designer as and when required.
5. **Formal Qualities:** The simplest cards contain only text or images, whereas most cards contain text, images, or illustrations. The image should be abstract enough to allow for a wide range of interpretations but detailed enough for the user to relate to and interpret.

Excerpt 11: Tangibility and visualized contents make card-based tools more acceptable.

2.14 Supports for Concept Generation

Researchers suggested many formal methods (more than 172) for idea generation in the conceptual design phase (Leahy, Seifert, Daly, & McKilligan, 2018) (Smith, 1998) and have been categorized in Table 2.8.

Table 2.8 Categorization of methods for idea generation

Formal Idea Generation Methods	Intuitive	Germinal	Morphological Analysis
			Brainstorming
			K-J Method
		Transformational	P-M-I method
			SCAMPER
			Lateral thinking
		Progressive	6-3-5 method
			C sketch
		Organizational	Affinity method
			Storyboarding
			Fishbone
		Hybrid	Synectics
	Logical	History-Based	TRIZ
		Analytical	Division
			Inversion

Existing supports for concept generation have the following issues: 1) unstructured or intuitive (Gero, Jiang, & Williams, 2013), 2) difficulty in acquisition (Ilevbare, Probert, & Phaal, 2013), 3) difficulty in assessing the concepts (Al-samarraie & Hurmuzan, 2018), 4) lack of validation (Kotys-schwartz, Daly, Yilmaz, Knight, & Polmear, 2014).

Numerous studies proposed analogical reasoning as an effective technique in the conceptual phase. Analogy-based design approach transfer knowledge from one design situation to another. Experiments revealed that the representation of a simple verbal analogy influenced its use in design innovation (Linsey et al., 2006). Design heuristics also apply an existing mechanism (approach to finding a solution) in a new way (S. R. Daly, Yilmaz, Christian, Seifert, & Gonzalez, 2012). Design heuristics transfer visual and verbal analogies through a generic abstraction process (Goel, 1997). Generic abstractions are not simply abstractions over features of objects but the relational structure among objects and processes. In the design context, generic abstractions may specify the structure of topological, geometric, causal, temporal, and functional associations between design elements. Generic design abstractions might also determine the structure of goals and methods in a design strategy. It means generic design abstraction is a significant process in analogical design.

The design heuristic approach uses domain-specific generic abstraction, promotes more successful concept generation and is based on empirical research with novice designers and practitioners (S. Yilmaz, Seifert, & Gonzalez, 2010).

Excerpt 12: Design heuristics is the most effective concept generation tool that uses the domain-specific generic abstraction of design elements.

2.15 Heuristics in Design

Design heuristics can be defined as scientifically validated (Hinton, 2014), empirically tested (Seda Yilmaz, Seifert, Daly, & Gonzalez, 2016), context-specific tacit knowledge derived from experiences (Seda Yilmaz & Seifert, 2011), which are used as principles or methods (Fu et al., 2016) for improving the effectiveness of the problem-solving (De Carvalho, Wei, & Savransky, 2003). However, design heuristics do not provide direct and definitive answers nor guarantee a solution for a problem (Seda Yilmaz & Seifert, 2011)(Tessari & De Carvalho, 2015). Heuristics are also considered as a rule of thumb (Li, Tan, & Chan, 1996), cognitive short-cut (S. R. Daly, Christian, Yilmaz, Seifert, & Gonzalez, 2011), engineering strategy (Koen, 1985) and cognitive problem-solving tool (Christian, Daly, Yilmaz, Seifert, & Gonzalez, 2012). Notwithstanding the limitation, design heuristics are widely used because they aid in divergent thinking and support two modes of idea generation: initiating novel ideas and transforming existing ideas (Christian et al., 2012)(S. Yilmaz et al., 2010). It is because design heuristics help stretch the thinking paradigm (McFadzean, 1998). It is an easy aid for finding complex problems by reducing the number of solutions searched for inspiration (Chu, Li, Su, & Pizlo, 2010).

Previous research has evidence of many design heuristics (DH) or Design Heuristics Sets (DHS) for idea generation, which include: SCAMPER (Eberle, 1996), TRIZ 40 inventive Principles (Altshuller, 1996), 121 Heuristics (De Carvalho et al., 2003), Design Synectics (Roukes, 1988), 77 Design Heuristics (Seda Yilmaz, Daly, Seifert, & Gonzalez, 2016), Transformation design theory (Weaver, Wood, Crawford, & Jensen, 2010)(Singh et al., 2009), Portability Design Heuristics (Hwang & Park, 2015), Design Heuristics Set for X (Hwang & Park, 2018).

The design heuristics above are categorized into two (Hwang & Park, 2018):

1) Design heuristics without pre-specified purposes are considered ‘Comprehensive Design Heuristics’(CDH), which are helpful across all domains.

2) Design Heuristics with pre-specified purposes are considered ‘Design heuristics for X’ (DHsfX), which help address domain-specific problems.

Excerpt 13: Design Heuristics with pre-specified purposes addresses domain-specific issues.

2.16 Processes and Supports for Prototyping

Exner et al. (Exner et al., 2016) proposed a process model by investigating three dimensions of the prototyping process: objectives, dimensions and fidelity. The process model has three phases: clarification of the task, conception of the idea, and design (Figure 2.11). The process starts with the externalization of concepts through sketches and ends with a three-dimensional prototype. The intermediate phase intends to realize the concept using simple materials and techniques.

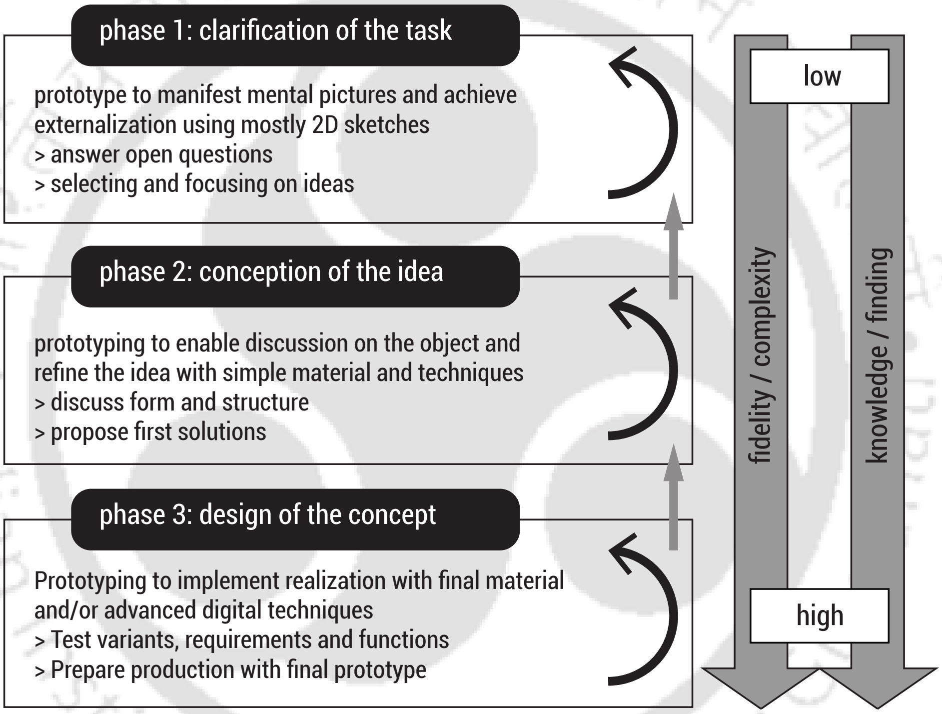


Figure 2.11 Prototyping process by Exner et al. (Exner et al., 2016)

Yu et al. studied the nature of prototyping practices between designers and engineers to suggest a prototyping process over Exner et al., which is more elaborative (Yu, Pasinelli, & Brem, 2018). Research done by Yu et al. says that Engineers focus on the features and functional aspects of the prototype. In contrast, designers explore prototypes to understand the design space for new possibilities and explore materials and tools, particularly for low-fidelity prototypes. Engineers follow a linear process with a specific goal, and designers follow small loops to validate ideas quickly.

Figure 2.12 shows the process proposed by Yu et al. based on the observation from the behavioural study of engineers and designers while prototyping.

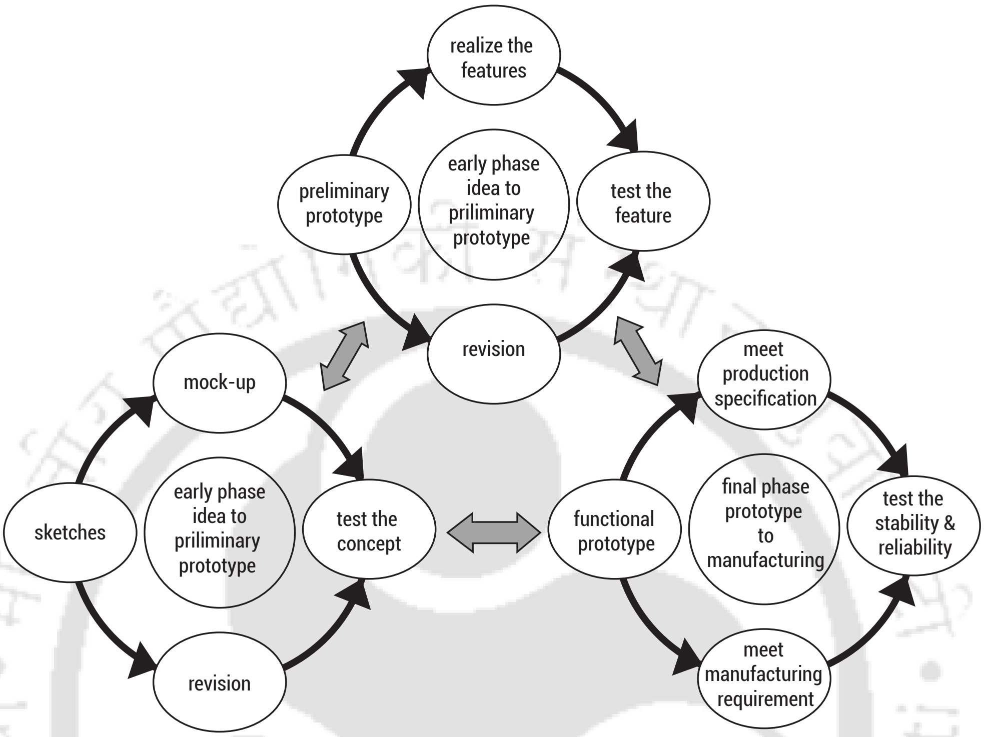


Figure 2.12 Prototyping process by Yu et al. (Yu et al., 2018)

The model describes early-phase prototyping as developing an idea and then building preliminary prototypes to verify the concept or technology. This phase encompasses Exner's model's first and second phases, namely task clarification and idea conception. The third phase (concept design) is subdivided and classified as the middle and final phases of prototyping. The intermediate stage is used to realize the features for proof of concept, and the final phase is used to ensure that prototypes meet the product specifications required for manufacturing.

Later, Hallgrimsson (Hallgrimsson, 2012) proposed a prototyping process (Figure 2.13) to support ethnographic research. The proposed model intends to build a prototype, test it with a real user and observe the user interaction. The objective is to simulate the product-user interaction that may lead to unexpected and exciting opportunities. Hallgrimsson suggested beginning with low-fidelity material and increasing the fidelity of the prototype toward the final prototype.

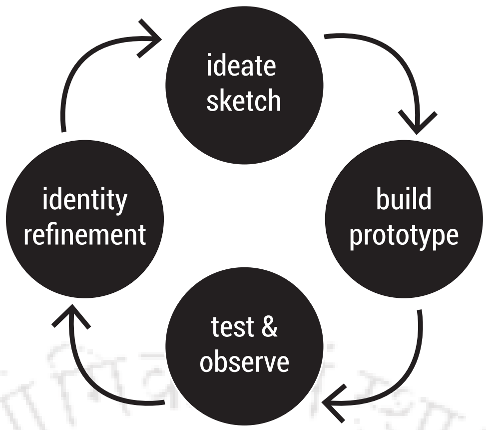


Figure 2.13 Prototyping process by Hallgrimsson (Hallgrimsson, 2012)

In addition to the process, Hallgrimsson proposed a workflow to execute the making of a prototype (Figure 2.14).

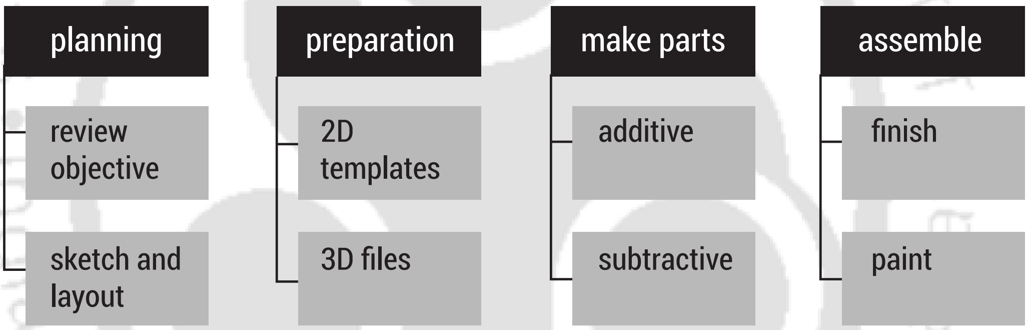


Figure 2.14 Prototyping workflow by Hallgrimsson (Hallgrimsson, 2012)

1. **Planning**

   The starting point for the workflow is sketching. Sketching of the concept and representation on paper is essential. The review and choices of appropriate material and processes are made based on the prototyping objectives, sketch and layout. Planning for sub-component prototyping and related two-dimensional and three-dimensional model-making starts at this stage.

2. **Preparation**

   Conversion of three-dimensional models into two-dimensional drawings takes place in this stage. The two-dimensional drawings are printed and glued on the surface of the material as a pattern for forming. Three-dimensional files in stereolithography (STL) format can be used for rapid prototyping.

3. **Making parts**

   Subtractive modelling for solid material and additive modelling for planner material is the objective of this stage. Models are sometimes made into parts to ease the production process.

4. **Assembly**

   Assembly of all the components takes place at this stage. Once the assembly is done, the final model or prototype goes for finishing and coating with paints based on the fidelity.

Detand et al. (Detand, Bastiaens, Grimonprez, & Rysman, 2010) proposed a vision-oriented prototyping checklist, 'Why Prototype?' (Figure 2.15).

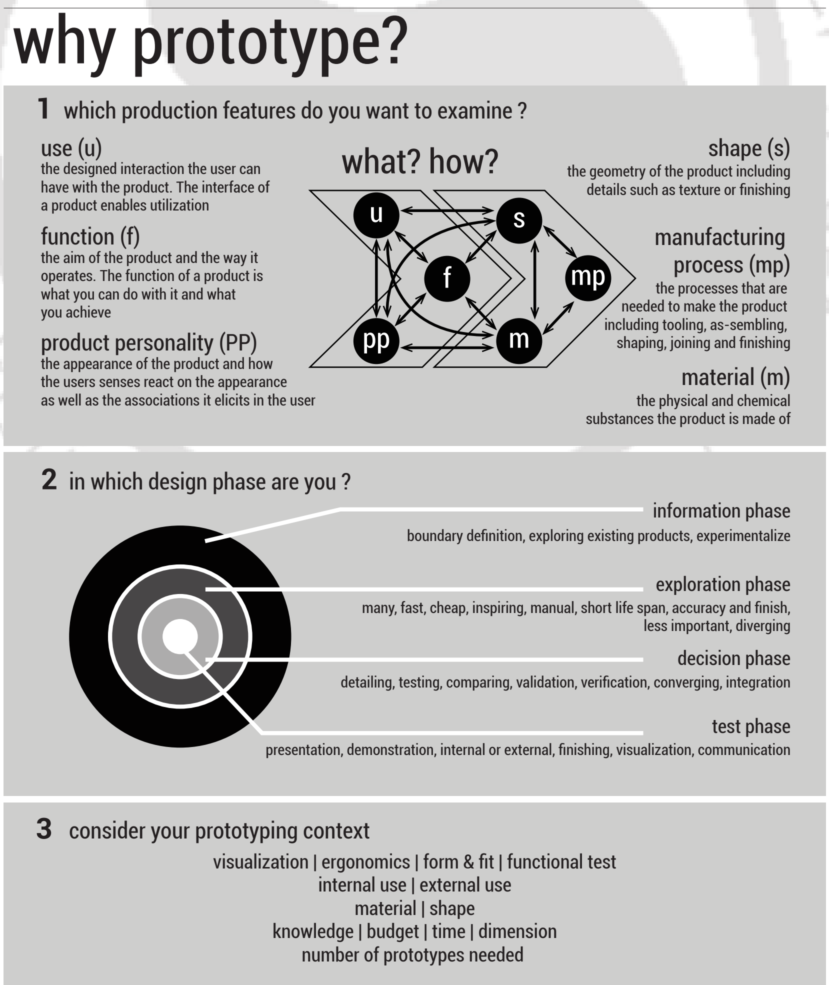


Figure 2.15 Prototyping checklist 'Why prototype?' (Detand et al., 2010)

The above checklist is based on the six product characteristics, design stages and prototyping context. The initial three product characteristics, viz. product personality (pp), function (f), and use (u), are related to user experience; the latter three product characteristics, viz. shape, material, and manufacturing process, are technical aspects. Technical aspects decide how to manifest a prototype.

In the category of prototyping tools, Velásquez-Posada (Velásquez-Posada, 2005) proposed a tool for physical model-making using two distinct processes of adding material and subtracting material. Figure 2.16 shows the technical classification of methods on the tool in tabular form.

Process	Characteristic	Material	Technique	Product
Adding material	Empty volumes defined by their planar faces	Paper tape	Glue layer by layer of the paper tape	Household plastic products
		Thin card board	Revolved surfaces	Bottles
		Thick card board	Descriptive geometry, templates and agglomerating material	Kitchenware
	Solid volumes made from agglomerating material	MDF	Serial planes, agglomerated or separated by regular gaps	Workshop tools
Subtracting material	Volumes cut-off from a solid block	Polyurethane foam	Carving	Toys
		Balsa or soft wood	Carving	Vehicle parts

Figure 2.16 Prototyping tool by Posada (Velásquez-Posada, 2005)

The proposed tool has the following issues:

- maybe appropriate for low-fidelity prototypes but may not be suitable for medium-fidelity or high-fidelity prototypes
- the tool did not consider complex forms
- limited material list and processes proposed

Jessica Menold and her team (Menold, Simpson, & Jablokow, 2016) proposed a theoretical framework for prototyping called Prototype for X or PFX (Figure 2.17) to support product design flow (Menold et al., 2016). However, the framework is based on three critical aspects of prototyping, i.e. Prototyping for Desirability, Prototyping for Feasibility and Prototyping for Viability. The framework produces end designs that fulfil user satisfaction, desirability, and manufacturability.

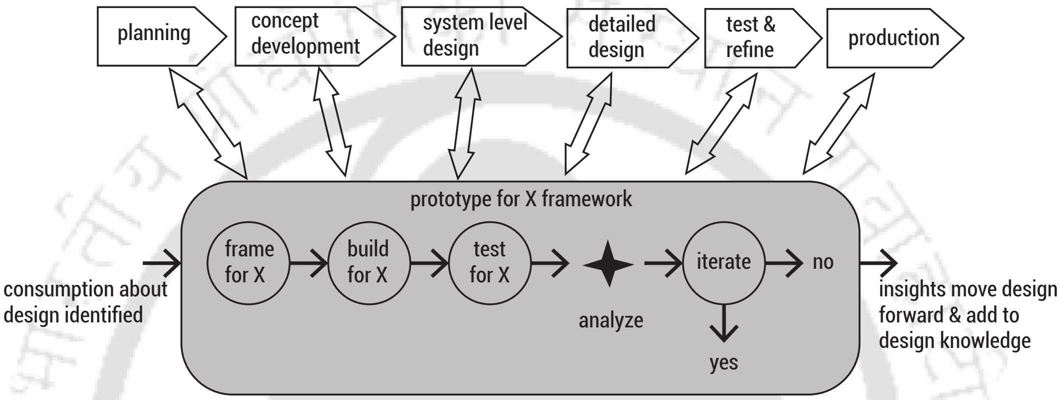


Figure 2.17 Prototype for X (Menold, Jablokow, & Simpson, 2017)

Aspects of desirability, feasibility, and viability must be considered while framing. The desirability aspects are aesthetics, ergonomics and general appeal to the consumer. The feasibility aspects are performance, function and features. The viability aspects are related to manufacturing.

Decision-making during prototyping is a critical step. Prototyping can take place in either a physical or virtual environment. A physical prototype can be either full-scale or scaled-down. A physical prototype can consist of subsystems or an entire system. The number of prototypes is another critical factor. Christie et al. (Christie et al., 2012) developed a set of decision variables (factors) that influence prototyping strategy. However, all the factors may not be applicable in all prototyping endeavours. The list of the factors is available in **Appendix B**. This list of factors focuses on the elements that comprise critical engineering decisions about transitioning from prototype concept to reality. Secondary factors, such as resource utilization, fall on the project management side. A list of questions was proposed based on the identified factors to determine the prototyping strategy. The matrix for prototyping strategy helps the designer to develop a concrete strategy for moving forward with prototype development. The strategy matrix is attached in **Appendix C**.

Camburn et al. (Camburn et al., 2013) carried forward the work of Christie et al. and proposed five prototyping strategy variables that are dependent on six design context variables. Five prototyping strategy variables are:

1. Number of design concepts
2. Number of iterations of each concept
3. Scaling
4. Subsystem isolation or design of an integrated system
5. Relaxation or rigid application of design requirements

Six design context variables are:

1. Budget
2. Time
3. Difficulty of meeting the design requirements
4. Interactivity
5. Designer's experience
6. Rigidity of design requirements

The strategy consists of four primary phases: (1) to decide the number of iterations needed to achieve the desired operational performance for each concept under consideration, (2) to assess the need for scaling, functional isolation, and subsystem isolation for each iteration of each concept, (3) to decide on which concepts to pursue in parallel, (4) write-up of prototyping strategy and execution. Figure 2.18 shows the flow of the prototyping strategy proposed by Camburn et al.

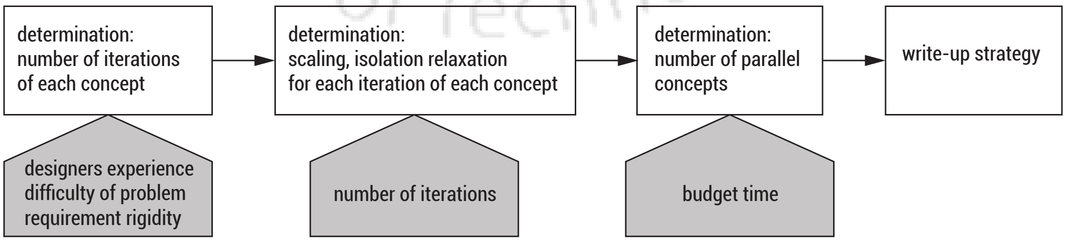


Figure 2.18 Prototyping strategy (Camburn et al., 2013)

Dunlap et al. (Dunlap et al., 2014) proposed a heuristic-based prototyping strategy tool. The tool considered the tangibility aspect as a new variable to the five prototyping strategies proposed by Camburn et al. (Camburn et al., 2013). The new set of variables are:

1. Number of design concepts simultaneously prototyped
2. Number of iterations for each concept
3. Scaling
4. Subsystem isolation
5. Relaxation of design requirements
6. Physical vs virtual models

The strategy tool reflects the designer's experiential knowledge in a Likert scale prompts to get analytical findings for prototyping. The strategy matrix is provided in **Appendix D**.

Lauff et al. proposed a 'prototyping canvas' tool to aid designers in purposeful prototyping (C. Lauff, Menold, & Wood, 2019). The tool identifies critical assumptions and instigates questions to guide prototype development. A version of the prototyping canvas is provided in **Appendix E**.

In the recent past, Hansen et al. (Hansen, Jensen, Özkil, & Pacheco, 2020) proposed a tool, 'prototyping planner'. The tool aimed to facilitate novice designers to adopt a formal approach to prototyping. The tool has four steps, viz. 1. Frame (Think), 2. Build, 3. Test (Expose), and 4. Act. Each step includes domain-specific questions designed to elicit reflections and guide the design team in adapting best-practice behaviour. The latest version of the prototyping planner is provided in **Appendix F**. Purpose, and questions in each prototyping step are provided in **Appendix G**.

The study on processes and supports for prototyping reflects the following issues:

1. Strategies, heuristics, or other supports available in design research are not intended to facilitate novice designers (except prototyping planner).
2. The available supports for prototyping facilitate sequential progress with triggers to define the purpose of prototyping, not to facilitate the production process (except support provided by Velásquez-Posada).

Excerpt 14: Available prototyping supports are not facilitating the technical aspects of prototyping to manifest a prototype.

SECTION-C FURNITURE DESIGN

2.17 Furniture

Jim Postell defines furniture design as a discipline where a combined synthesis of furniture and design articulates an emerging field (Postell, 2012). According to Postell, furniture + design + (x) = furniture design. Furniture refers to objects for mobile or permanent furnishing of residential interiors or outdoor environments intended to serve for work, eating, sitting, storage, holding objects, lying down, sleeping and relaxing, usable individually, in suites or sets (Smardzewski, 2015). According to the SIT furniture design award, furniture can be categorized as (SIT, n.d.):

- Furniture-Seating
- Furniture-Bedding
- Furniture-Lighting
- Furniture-Tables and Desks
- Baby and Child Furniture
- Furniture by Room
- Outdoor furniture
- Homeware and Decocartion

Although many pieces of furniture are available, industrial designers (Lawson, 2013) and architects (Toromanoff, 2016) are intrigued with designing a chair. When style, elegance, and wit persuade architects to design chairs (Emery, 1988), industrial designers cross-pollinate material and manufacturing knowledge with chair design (Lawson, 2013). According to the former director of Design museum Deyan Sudjik, “Because chairs have become such important markers of stylistic and technological shifts, architects and designers who want to be considered important have to have designed at least one successful example to demonstrate their credentials” (Design Museum Enterprise Limited, 2009). Creating a chair has become an explanation and reflection of self-fulfilling prophecy over the years. New material and process inventions have transformed the form and functions of chairs throughout the centuries. For instance, Michael Thonet exquisitely designed a lightweight flat-pack chair, No. 14 (Figure 2.19). He used the steam bending process to make a wooden chair with six pieces.

Figure 2.19 The chair no. 14 by Michael Thonet (source: www.dearchiworld.wordpress.com)

Later, Marcel Breuer designed steel tube furniture chair B3, also known as Wassily (Figure 2.20), and became part of the modern classics.

Figure 2.20 Wassily chair by Marcel Breuer (Massey, 2010)

After world war II, Charles and Ray Eames explored plywood as material and designed the first-ever moulded plywood chair LCW for Knoll and Lounge Chair and Ottoman for Herman Miller (Figure 2.21).

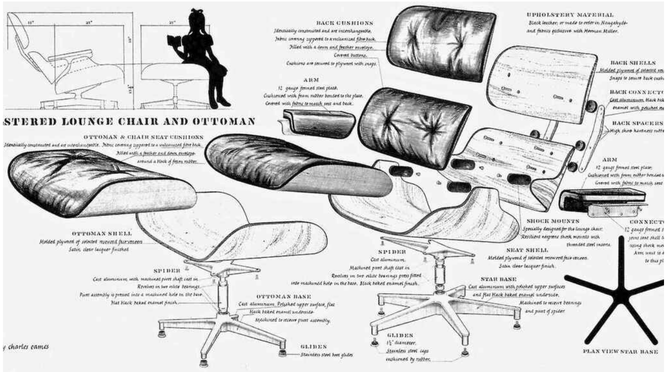


Figure 2.21 Exploded view of Lounge Chair and Ottoman (Massey, 2010)

In the 21st century, German designer Konstantin Grcic designed Chair One (Figure 2.22) for Italian manufacturer Magis with die-cast aluminium treated with fluoridated titanium and polyester lacquer.

Figure 2.22 'Chair One' off the tool (source: www.konstantin-grcic.com)

Ross Lovegrove designed a Biophilia chair collection for VONDOM (Figure 2.23). The nature-inspired fluidic form seems to have sprouted from nature. Beyond form, the collection showcase the progressive domain of polymerization.

Figure 2.23 Biophilia lounge chair by Ross Lovegrove (source: www.vondom.com)

Recently Autodesk revealed the world's first chair made using Artificial Intelligence, designed by Philippe Starck for Kartell (Figure 2.24). The optimized chair was designed using an algorithm (generative neural network) to study several iconic designs.

Figure 2.24 AI Chair (source: www.dezeen.com)

Regardless of material, process, form or technology dominance, the chair is always a point of attraction for research and design. American industrial designer George Nelson said, " every truly original idea – every innovation in design, every new application of materials, every technical invention for furniture – seems to find its most important expression in a chair". Beyond all, no other object symbolizes social and cultural meaning, displays the designer's presenc e or craftsman skill, and characterizes the transformation of modernity like the chair among all ubiquitous objects (Massey, 2010).

Excerpt 15: No other object characterizes the transformation of modernity like the chair.

2.18 Furniture Design in India

2.18.1 Furniture Design Market in India

Demand for furniture in India increased at a 12 % annual rate from 2007 to 2012 and grew at a 15 % annual rate in 2013 (KPMG Advisory Services Pvt Ltd, 2014). Figure 2.25 shows the demand for furniture in India.

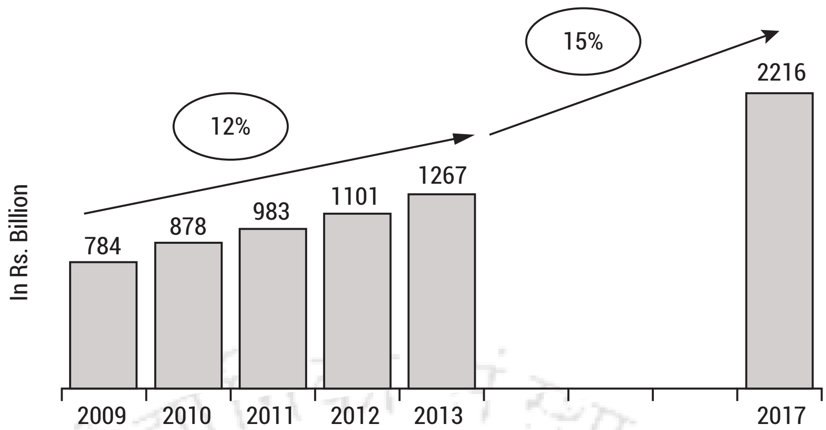


Figure 2.25 Demand for furniture in India (KPMG Advisory Services Pvt Ltd, 2014)

IKEA, Nilkamal, Damro, Godrej and Boyce, HNI Corporation, Durian, Featherlite, Praxis, Wipro Furniture, Home Retail, Forte Furniture Product, Furniturewala, Millenium Lifestyle, Pepperfry, Urban Ladder, Geeken and Evok are the key player in the furniture market in India. A report prepared by KPMG Advisory Services Pvt. Ltd. informs about an investment of Rs. 10,500 in FDI retail by IKEA. With increasing market and competition, clients prefer gradually high-end, low-maintenance, easily installable customizable products with more options to meet their specific requirements (KPMG Advisory Services Pvt Ltd, 2014). Moreover, the competitive furniture market demands innovative contemporary design and necessitates design education training.

2.18.2 Furniture Design Education in India

India's Design education celebrated its golden jubilee in 2011. Until around 2004, design education was provided by a handful of government institutions. In 2004, a few private institutions ventured into the field of design education. Since then, design education in India has grown at an exponential rate. More than 70 institutes teach design at various levels (Deshpande, 2016). Although many institutes do not specialize in furniture design, they teach furniture design as an elective course and encourage students to pursue thesis projects in furniture design. Government institutions that offer furniture design in India are IDC School of Design-IIT

Bombay, Department of Design-IIT Guwahati, Department of Design-IIT Hyderabad, National Institute of Design, National Institute of Fashion Technology, School of Planning and Architecture, Jawaharlal Nehru Architecture and Fine Arts University, and Indian Institute of Craft and Design (IICD). Apart from that, several private institutions have specializations in furniture design or interior design.

Excerpt 16: The competitive furniture market demands innovative design and skill-based education.

2.19 Insight on Supports

A study on prototyping supports reveals that:

1. The existing supports for prototyping follow a one-way process (Figure 2.26), where prototypes are made to manifest the abstract concepts generated in the concept generation phase.

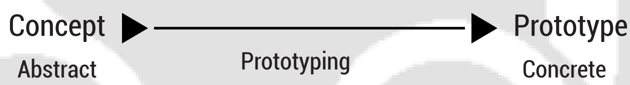


Figure 2.26 Existing process of prototyping

2. A prototype is considered merely a tool to ensure clear communication among the design team members and aids in learning to support decision-making (Figure 2.27) (Lauff, Kotys-Schwartz, & Rentschler, 2018).

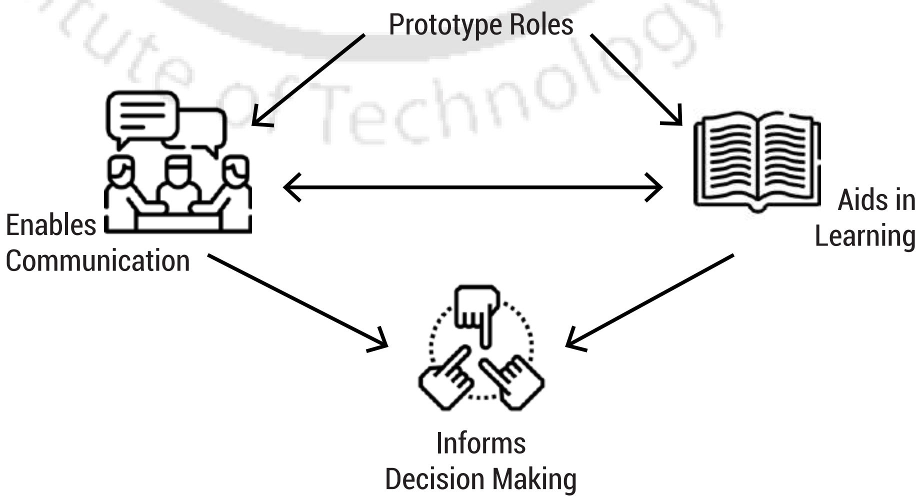


Figure 2.27 Existing role of prototyping (Lauff et al., 2018)

Proposal

Towards prototype-driven innovation, where prototypes are the boundary object, and the prototyping process is the central activity, this research defines "prototyping as a process to explore and think for new concept generation". In the case of prototype-driven design innovation, prototyping must be a two-way process to generate ideas. Thinking and making both should happen together. Novice designers should be allowed to explore, envision, and refine mental models through prototyping. Appropriate support should be provided to scaffold novice designers during this endeavour. The proposed model of prototyping is illustrated in Figure 2.28.

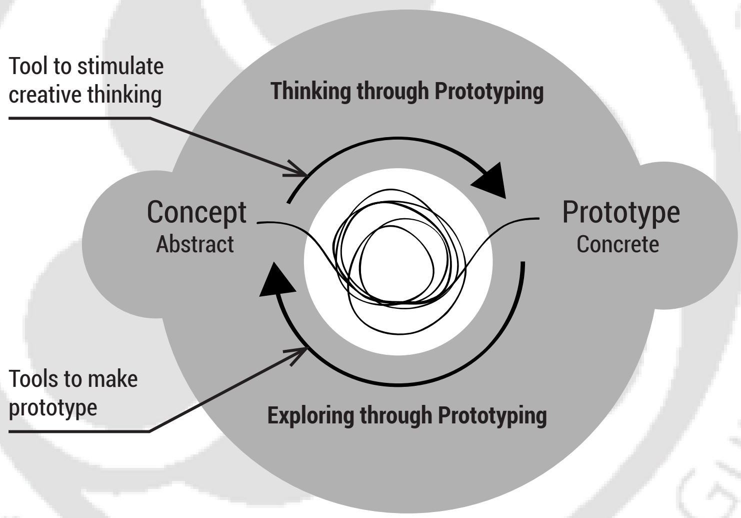


Figure 2.28 Proposed model of prototyping

2.20 Final Reference Model

An initial reference model presented in Chapter 1, section 1.4, represented the initial understanding and connection between the knowledge in the research context. The said reference model has been modified based on the literature review in this chapter. The final reference model is now concrete, with more established connections that describe the most appropriate factors to improve the situation. Besides, the final reference model showcases the measurable success factors to be considered in the research for measuring, i.e. deliverable of the prototyping phase and the deliverable of the concept generation phase. Figure 2.29 shows the final reference model. Measurable success factors decide the success of the research and are qualitatively or quantitatively measurable.

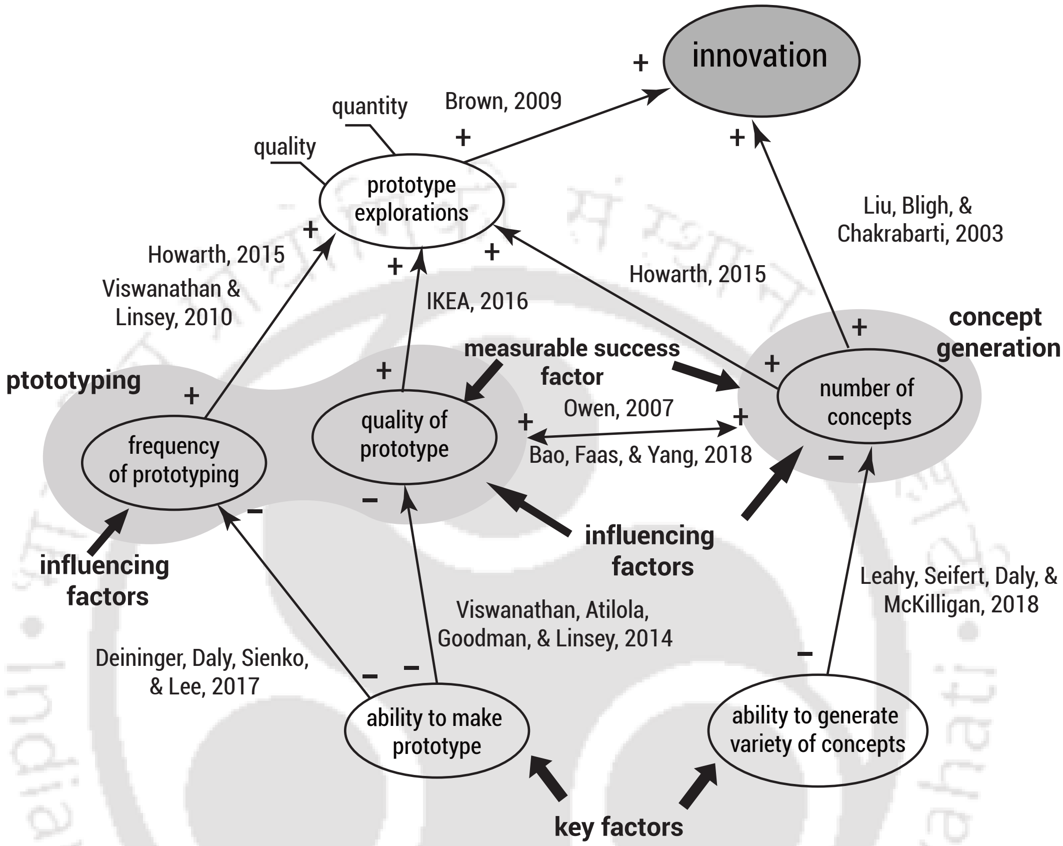


Figure 2.29 Final reference model

2.21 Summary

The chapter discusses the existing literature and research premise in three sections. Section A-prototype and concept discusses the prototype's role, attributes, prototype as a boundary object and the interplay between concept and prototype. Section B-supports for novice designers focused on the classifications and characteristics of the supports available in design research. This section also discusses the available supports for concept generation and prototyping. Section C-furniture design renders the importance of research with chair design and gives an overview of the furniture design scenario in India. Besides all, the excerpts from the sections are significant findings. The excerpts would be converted as specifications for developing supports in the upcoming chapters.

Design Heuristics for Furniture Design

and

Tool for Model Making

Chapter 3

Development of Supports

3.1 Introduction

The objectives of this chapter are:

- To develop an impact model grounded on the reference model describing the preferred situation addressing the selected key factors using the supports;
- To develop supports systematically for concept generation and prototyping;

While doing so, this section of the thesis carries forward the excerpts from the literature review to answer the following research questions:

- What are the specifications to be considered while developing supports for concept generation?
- What specifications should be considered while developing supports for model-making?

The desired impact model is developed based on the descriptive study in Chapter 2. At this stage, the desired impact model is presented with two proposed supports (Figure 3.1): concept generation and model-making support.

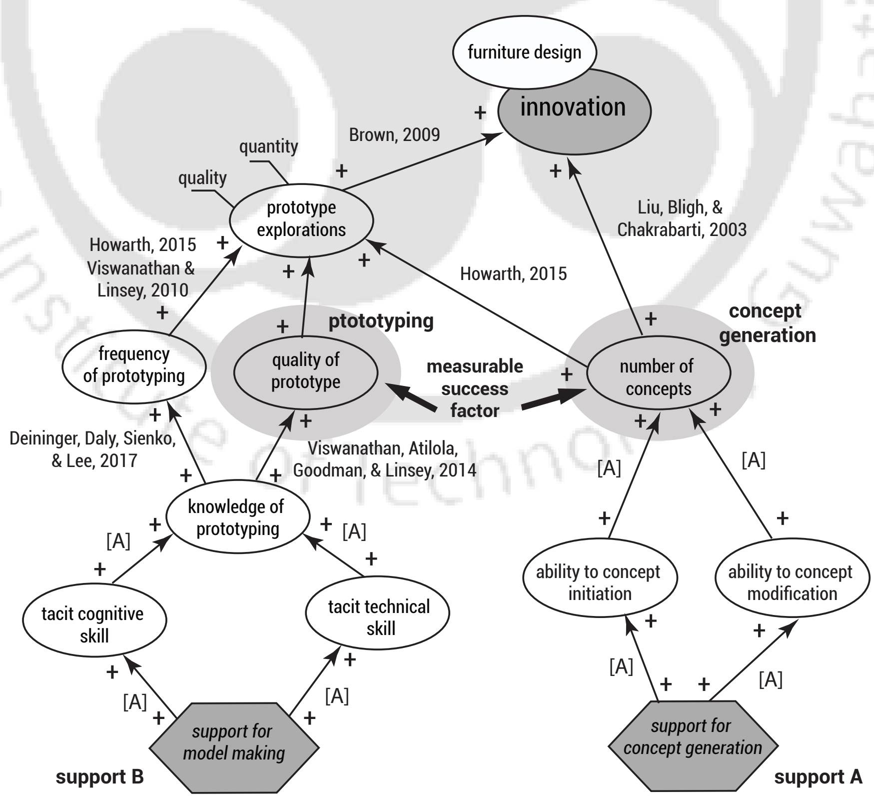


Figure 3.1 Desired impact model

Support A is support for concept generation that intends to scaffold novice designers for concept initiation and concept modification, which upshot innovation in furniture design by intensifying the number of concepts.

Support B is support for model-making to enhance novice designers' tacit-technical and tacit-cognitive skills, improving prototyping knowledge. The positive impact of prototyping knowledge affects the frequency and quality of prototyping, which out-turn innovation in furniture design by intensifying prototyping explorations.

Measurable success factors in the impact model indicate the key factors responsible for the desired situation's success. They will be measured qualitatively or quantitatively to assess the impact of the proposed supports.

The support development process followed a five-step process proposed by Bracewell et al. (Bracewell, Shea, Langdon, Blessing, & Clarkson, 2001):

i. task definition
ii. choice of representations
iii. choice of methods
iv. defining visualization and interaction strategies
v. theoretical and experimental validation

3.2 Specifications for Supports

Based on the excerpts (E) from the descriptive study from Chapter 2 and the desired impact model, a list of specifications (S) is prepared for developing holistic and structured toolsets for concept generation and model-making. The specification list is formulated as identified by Jessica Menold (Menold, 2017) in her PhD thesis and inspired by the requirement list for support development proposed by Blessing and Chakrabarti (Blessing & Chakrabarti, 2009). This context uses the definition of specification by Ulrich and Eppinger as "the requirements a product must fulfil that enable the designer to define and understand the problem he/she is trying to solve". This section developed specifications for concept generation support and specifications for model-making support.

3.2.1 Specifications for Concept Generation Support

The list of specifications for concept generation support is given in Table 3.1.

Table 3.1 Specifications for concept generation support

Problem Statement:	
Develop support to help novice furniture designers to generate concepts in the early design stage.	
E	Design concept generation aims to generate several concepts and screen concepts toward an ideal solution.
S	Concept generation support should enable novice designers to generate several concepts promptly.
E	The design-by-analogy approach is more effective in mitigating fixation.
S	Concept generation support should use a design-by-analogy approach.
E	Tangibility and visualized contents make card-based tools more acceptable.
S	For more acceptability, concept generation support must be a card-based tool with visualized content.
E	Design heuristics is the most effective concept generation tool that uses the domain-specific generic abstraction of design elements.
E	Design Heuristics with pre-specified purposes addresses domain-specific issues.
S	A concept generation support must be heuristics-based, using the domain-specific generic abstraction of design elements.

Final brief: To develop a card-based design heuristics for furniture (Chair) design to enable novice designers to generate several concepts promptly.

3.2.2 Specifications for Prototyping Support

The list of specifications for concept generation support is given in Table 3.2.

Table 3.2 Specifications for model-making support

Problem Statement:	
Develop support to help novice furniture designers make models early in the design stage.	
E	Early prototypes made by industrial designers focus on appearance.
S	Prototyping support for novice designers should facilitate making appearance models in the early design phase.
E	Prototyping skill is tacit knowledge, and they can be accumulated through learning by doing.
S	Prototyping support for novice designers should transfer the tacit knowledge associated with prototype building.
E	Time for prototyping is the critical marker for distinguishing between specification-driven and prototype-driven cultures.
E	The designer's task is to select an appropriate prototyping process for manifestation to meet filtering dimensions.
E	Novice designers face difficulties related to material and process selection in prototyping.
S	Prototyping support for novice designers should promptly facilitate appropriate materials and process selection.
E	Tangibility and visual contents make card-based tools more acceptable.
S	Prototyping support for novice designers should be a card-based tool with visual content for more acceptability.

Final brief: To develop a card-based appearance model-making tool that allows novice furniture designers to select appropriate materials and processes promptly.

SECTION-A DEVELOPMENT OF DESIGN HEURISTICS FOR FURNITURE DESIGN

3.3 Form and Furniture

This section provides an overview of the elements of form and structure to understand furniture as a form.

Form, Structure and Conceptual Elements

Form is concerned with both the realization of concrete objects and the organization of ideas. form can be used as a noun and a verb (Akner-koler, 2007).

- Form as a noun refers to the physical dimensions that it occupies and activates within a space.
- Form as a verb refers to the skill and craftsmanship required to make.

Definitions of the Elements

The primary elements of form are point, line, bar, surface, body and space (Knauer, 2008).

Form as point: A form is recognized as a point when length, width and height tend to zero. Point is a zero-dimensional phenomenon.

Form as line: A form is recognized as a line when the length is a prominent variable and width and height tend to be zero. The line is also a one-dimensional phenomenon.

Form as bar: A form is recognized as a bar when the length is a dominant variable, whereas width and height are negligible. The bar is a three-dimensional phenomenon.

Form as surface: A form is recognized as a surface when length and width are variable, whereas the height is negligible. The surface is a three-dimensional phenomenon.

Form as body: A form is recognized as a body when length, width and height are variable. The body is a three-dimensional phenomenon.

Form as space: Space is a three-dimensional phenomenon that can be determined as form by its boundaries.

The elements of form are visually represented in Figure 3.2.

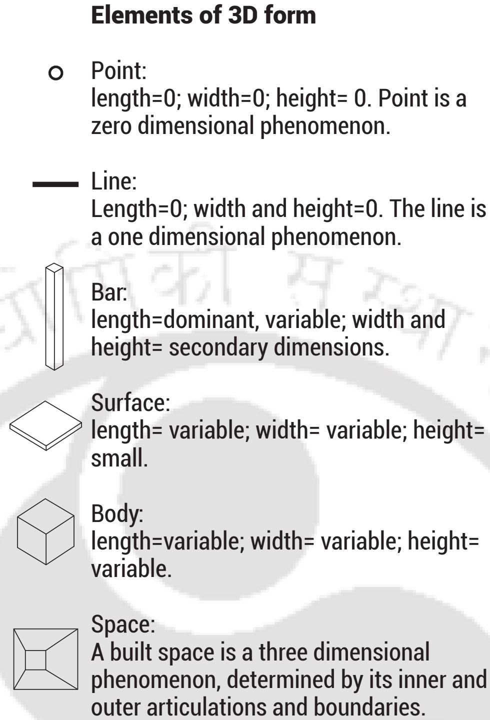


Figure 3.2 Elements of form (Knauer, 2008)

The transformation of the bar to surface and body can be achieved with variations in length, width and height. Figure 3.3 illustrates the transformation of the bar, body and surface with variations in length, width and height.

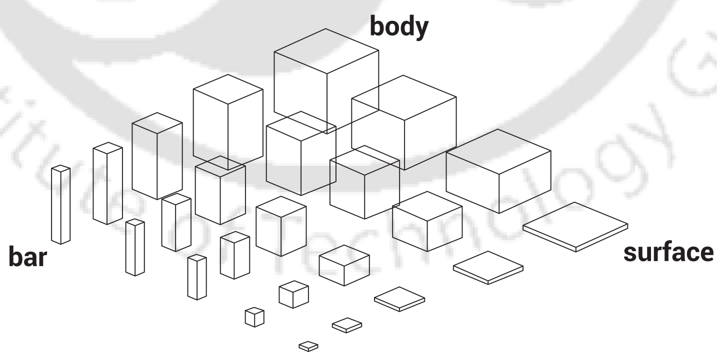


Figure 3.3 Transformation of bar, body and surface (Knauer, 2008)

Structure governs the way form is constructed (Wong, 1993). The arrangement of the elements or the number of forms together constitutes the basic syntax/structure (Puhalla, 2011). The structure is the spatial organization, the frame beneath the outer surface.

When a design is composed of several identical forms, those identical forms are unit forms or modules. The larger unit made of more than one module is called super unit form.

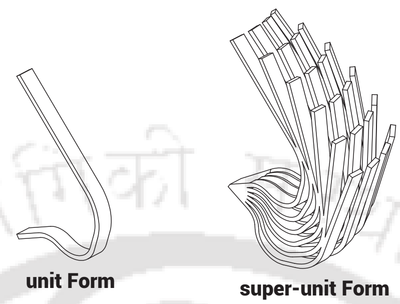


Figure 3.4 Unit form and super-unit form

While making a structure, a composition of forms is created using a subtle relationship between them using the features that determine the composition hierarchy. The hierarchy of order in a composition can be realized through the illustration in Figure 3.5.

The features that determine the hierarchy of order in compositions are:

Dominant -
- character - strongest
- size - largest
- interesting position
- spacial articulation
- structural importance
- influence over other parts

Subdominant -
- character - strong
- size - smaller than Dominant
- interesting position
- spacial articulation
- structural importance
- influenced by Dominant

Subordinate -
- character - complementary to dominant and subdominant
- size - smallest
- spacial articulation
- dependent on the dominant and subdominant

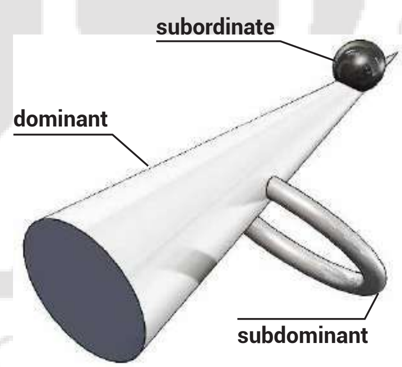


Figure 3.5 Hierarchy of order in a composition (Akner-koler, 2007)

This research took the opportunity to explore the elements of form in the context of furniture design. Three-dimensional form elements bar, surface and body as the construct of furniture (Chair) are shown in Figure 3.6.

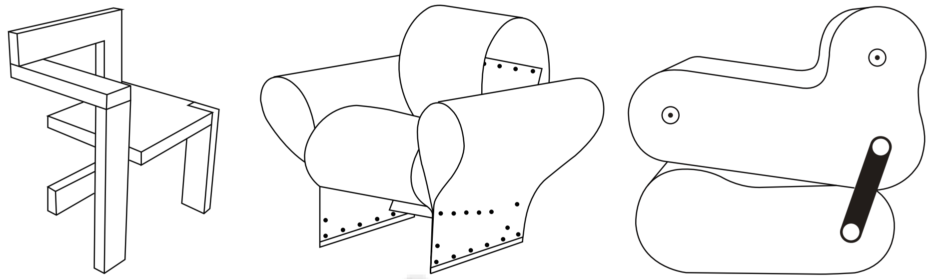


Figure 3.6 Examples of bar, surface and body as the construct in furniture

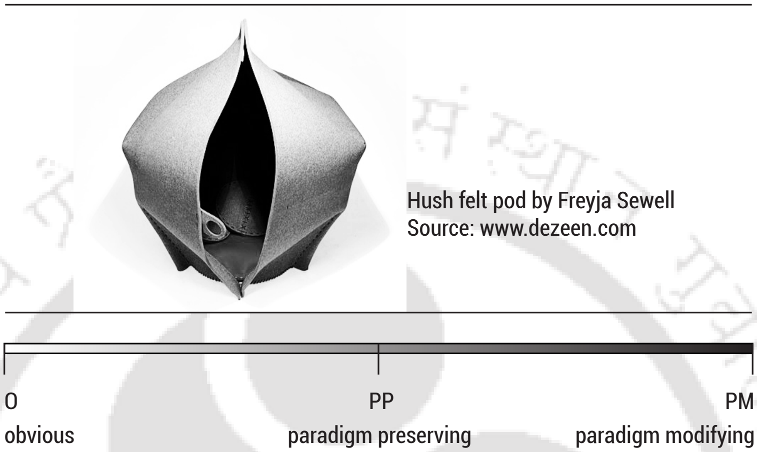
3.4 Function-Behaviour-Structure Ontology

The Function-Behaviour-Structure ontology (Gero, 2014) defines three properties of an object:

- Function (F): It defines the teleology of an object, i.e. "what the object is for".
- Behaviour (B): It defines the attributes of an object that are derived or expected to be derived from its form & structure (S), i.e. "what the object does". The behaviour aspect differs from the function in terms of how it completes a task or set of tasks.
- Structure (S): It defines the relationships between the components of an object, i.e. "what the object consists of". The geometry, topology and material describe most objects' structure (S).

The FBS ontology provides eight fundamental transformations. However, the most basic perspective of design consists of transformation from F ►B and from B ► S. Thus, analysis of the structure of an existing design will derive the behaviour from the design solution, and behaviour will derive the performance expected to achieve the desired function.

While analyzing the FBS ontology regarding furniture design, the dominance is also analyzed in terms of its obviousness and paradigm-relatedness (Nagasundaram & Bostrom, 1995). The paradigm-relatedness framework considers paradigm preserving (PP) and paradigm modifying (PM) to assess any idea. Primarily adaptations are considered paradigm preserving (PP). Paradigm modifying (PM) considers new ideas through redesign, transformation or introduction of new elements. The plotting of Function (F), Behaviour (B) and Structure (S) in a scale of obvious (O), Paradigm Preserving (PP) and Paradigm Modifying (PM) is illustrated in Figure 3.7.



Function (F)	Behaviour (B)	Structure (S)
Description: To work or rest in private	Description: To encapsulate and enjoy private space using the foldable, flexible structure	Description: The outer shell made from industrial wool felt gives a form of pod.

Figure 3.7 Plotting of Function (F), Behaviour (B) and Structure (S) in a scale of obvious (O), Paradigm Preserving (PP) and Paradigm Modifying (PM)

In the context of the Hush felt pod chair, the function to work or rest in private is an obvious phenomenon, as it exists in different contexts. The behaviour to encapsulate and enjoy personal space using the foldable, flexible structure is paradigm preserving, as the use of flexible, foldable materials making a chair is a case of adaptation. However, the transformation of material and structural geometric change is exciting and surprising, making it innovative.

3.5 Existing Methods for Extracting Design Heuristics

This research draws upon the concept of Design Heuristics for Furniture Design (DHfFD), emphasizing the chair, which would help in furniture concept design for novice designers. Towards the development of a tool, a systematic study was carried out to understand the development of the existing heuristics. Systematic investigation of the existing design heuristics and their development elucidates that design heuristics are mainly based on the heuristics evident in successful innovative products.

The theory of inventive problem solving, also known as TRIZ, was developed to identify heuristics in technological innovations in patents in engineering (Altshuller, 1996).

A list of 77 design heuristics was derived from a detailed study and analysis of more than 400 award-winning products (Yilmaz, Daly, Seifert, & Gonzalez, 2016).

Design heuristics for transformation design theory, which describes the principles for transformation and facilitator for transformational design construct, was proposed based on the analysis of patents, analogies from nature and existing products (Weaver, Wood, Crawford, & Jensen, 2010)(Singh et al., 2009).

Portability design heuristics were proposed by Hwang and Park (Hwang & Park, 2015) by clustering existing products and patents into groups.

Saunders et al. (Saunders, Seepersad, & Hölttä-Otto, 2011) investigated specific characteristics in innovative mechanical products from 197 major innovation award-winning products and identified 13 'innovation characteristics'.

Blösch-Paidosh and Shea (Blösch-Paidosh & Shea, 2017) derived 29 process-independent heuristics for additive manufacturing by studying and analyzing 275 existing artefacts made by additive manufacturing.

Hwang and Park (Hwang & Park, 2018) developed a design heuristics set (DHSfX) to facilitate designers or a design team to create products for one-handed people. The DHSfX was developed by studying 100 numbers of existing products and 39 patents.

In almost all cases, heuristics have been identified by collecting and analyzing the example solutions.

3.6 Heuristics Extraction and Analysis Process

This research followed a three-step process based on the inductive approach (Singh et al., 2009) to study and analyze an extensive repertoire of furniture (chair) design analogies. The heuristics development schema is illustrated in below Figure 3.8.

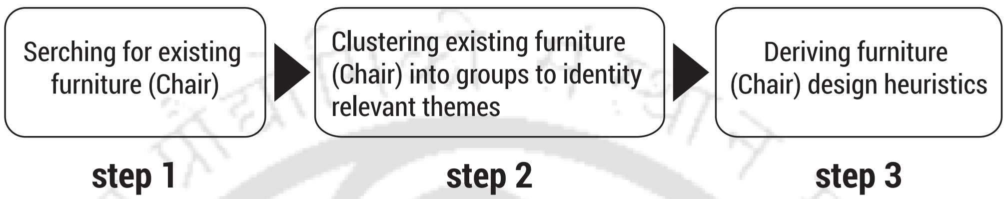


Figure 3.8 Heuristics development schema

Step 1-Collecting and pre-processing furniture (chair) data

The process was initiated by searching the repertoire of existing furniture (indoor chair) designs from independent award competitions (Table 3.3), published compendiums of furniture designs (Table 3.4), catalogues of leading furniture manufacturers (Table 3.5) and online design magazines (Table 3.6). A total of 650 pieces of furniture were selected for analysis.

Table 3.3 Design award repertoire of furniture design (chair)

Award Name	Organizing Body
Red-Dot Design Award	Organized by Red-Dot (www.red-dot.org) It is the largest and most renowned design competition in the world
A' Design Award	A' Design Award is organized with the collaboration of many institutions, including MOOD-Museum of Design (www.competition.adesignaward.com) A'Design Award recognizes and endorses good design and emerging talents in design
iF Design Award	Organized by iF Design Foundation (www.ifworlddesignguide.com)

The Good Design Award	The Chicago Athenaeum Museum of Architecture and Design and Metropolitan Arts Press Ltd. (www.good-designawards.com)
Elle Deco International Design Award	Organized by Elle Decoration International Network (www.edida-awards.com)
International Design Excellence Award	Organized by Designers Society of America (www.idsa.org/IDEA)
National Design Awards	Organized by Cooper-Hewitt, Smithsonian Design Museum (www.cooperhewitt.org)
SIT Furniture Awards	Organized by Farmani Group (www.sitaward.com)

Table 3.4 Published compendium of furniture design (chair)

Title and Author	**Publication Details**
Design Secrets: Furniture: 50 Real-Life Projects Uncovered, by Laurel Saville & Brooke Stoddard	Publisher: Rockport Publishers Inc.
Prototyping and Modelmaking for Product Design (Portfolio Skills), by Bjarki Hallgrimsson	Publisher: Laurence King Publishing
The Making of Design, by Gerrit Terstiege	Publisher: Birkhäuser Architecture
Process: 50 Product Designs from Concept to Manufacture, by Jennifer Hudson	Publisher: Laurence King Publishing
Furniture Design: An Introduction to Development, Materials and Manufacturing, by Stuart Lawson	Publisher: Laurence King Publishing

Scandinavian Furniture: A Source Book of Classic Designs for the 21st Century, by Judith Gura	Publisher: Thames & Hudson

Table 3.5 Websites of furniture manufacturers

Organization Name	**Product Range**
Steelcase (www.steelcase.com)	Leading manufacturer of office furniture
Herman Miller (www.hermanmiller.com)	Researching, designing and manufacturing innovative interior furniture
Knoll (www.knoll.com)	Manufacturer of office systems, seatings and storage furniture
Vitra (www.vitra.com)	Manufacturer of the renowned designers
Cassina (https://www.cassina.com/en)	Manufacturer of high-end chairs, sofa and armchairs
Artek (www.artek.fi/en)	Manufacture of furniture and accessories designed by Finnish masters and leading designers
Kartel (www.kartel.com)	Manufacturer of contemporary plastic furniture
Dovetail (www.dovetail.in)	Manufacturer of school furniture in India
Godrej Interio (www.godrejinterio.com)	Leading furniture manufacturer in India

Table 3.6 List of the online design magazines

Source Name	Details
Dezeen	architecture, interiors and design magazine Alexa Rank 3.7K
Design Milk	architecture to modern furniture and home décor Alexa Rank 40.9K
Yanko Design	design magazine covering international product design Alexa Rank 35.2K
Designboom	critique of art, technology, architecture and design Alexa Rank 6.7K
Core77	articles and discussion forums for product and furniture designs Alexa Rank 54.2K
Fast Co.Design	innovation and business stories through the lens of design Alexa Rank 11.5K

The details of the existing furniture were analyzed based on the Function-Behaviour-Structure ontology (Gero, 2014). The Function (F), Behaviour (B) and Structure (S) features were plotted on a scale of obvious (O), Paradigm Preserving (PP) and Paradigm Modifying (PM), as discussed in section 3.4. The form & structure was further deconstructed into bar, body and surface (Knauer, 2008), and the orientation and dominance of the elements were also analyzed (Akner-koler, 2007).

Step 2-Clustering existing furniture (chair) using the K-J method

After the analysis, existing pieces of furniture were grouped (Figure 3.9) according to the similarity in the paradigm modifying aspect, as suggested in the Kawakita-Jiro method (Figure 3.10) (Kunifuji, 2013)(Iba, Yoshikawa, & Munakata, 2017). For each design, a card is prepared that illustrates the design and describes the F-B-S ontology and plots against O-PP-PM. The cards were randomly distributed on a work surface to make them visible to all the coders. The coders grouped the cards and extracted design heuristics.

Figure 3.9 Grouping and labelling of the existing furniture

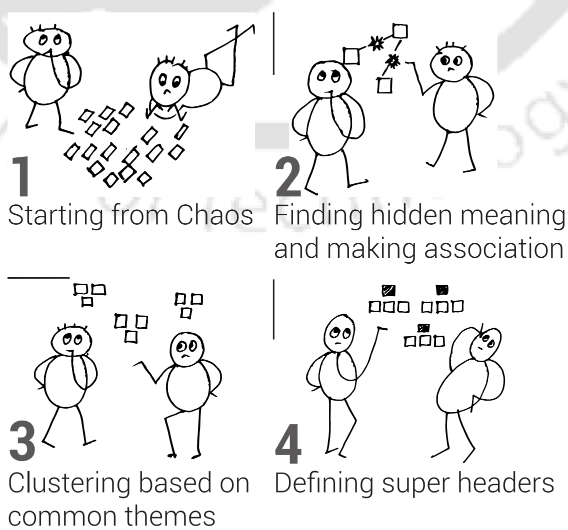


Figure 3.10 Steps of the K-J method

Step 3-Deriving furniture design heuristics

Following the methodology recommended by Yilmaz et al., analysis and heuristics extraction (Figure 3.11) of the existing furniture have been done (Yilmaz, Seifert, Daly, & Gonzalez, 2016).

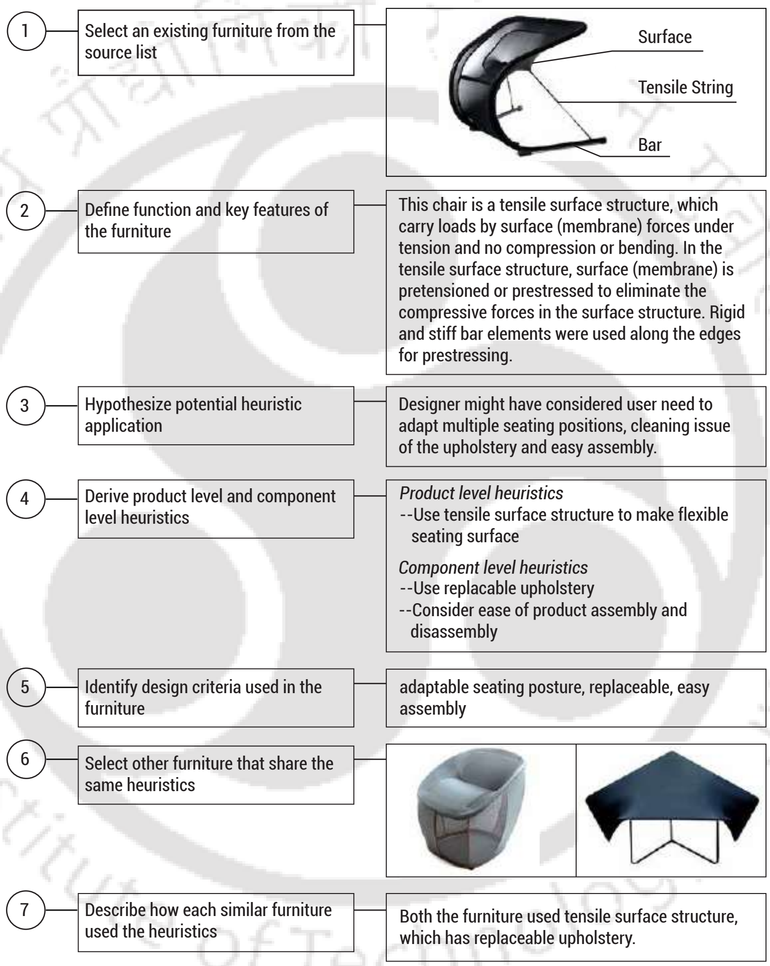


Figure 3.11 Heuristics extraction and analysis process

Step-1 in the heuristics extraction process and analysis was done by the researcher and three coders were used for step-2 and step-3. At step-2 and step-3 of the heuristics extraction process and analysis, three coders worked independently. Disagreements between the coders were resolved through discussions, and 100% reliability was achieved.

3.7 Design Heuristics for Furniture Design (DHfFD) Identified

Analysis of 650 chairs and systematic design heuristics extraction resulted in 86 design heuristics for furniture (chair) design. The list of the design heuristics card is presented in Table 3.7, and a sample card is shown in Figure 3.8.

Table 3.7 Furniture design specific design heuristics card list

Adjustable	Alter dimension	Alter Elements
Alter Material	Anthropomorphic	Art & Craft
Bar and Panels	Bent Surface	Bent tube/bar
Biophilic	Brush Stroke	Bulge Surface
Bulge/ Swelling	Cantilever	Centipede
Cobweb	Cocoon/Pod	Coil
Collapsible	Comet Structure	Continuous Block
Contradiction	Cord	Experimental Joinery
Experimental Material & Process	Extension	Flat-Pack
Genealogical Tower	Grow	Hammock
Hand Fan	Hirsute/Furry	Hollow
Illusion	Inflatable	Locked Cushion (Knot/ Knit/ Weave)
Locked String or Rope (Knot/ Knit/ Weave)	Log Joint	Mobius Loop
Modular	Motion	Multifunctional (Chair + X)
Nervous System	Nest	Origami
Peeled Surface	Playful	Polyhedron
Posture	Reduce-Reuse-Recycle	Reinforced
Revolving Bundle	Rocking	Roll
Sculpture	Sensory	Shaft to Blade
Space Truss	Spilled structure	Spiral
Spring	Stack Bar	Stack Body
Stack Surface	Storage	Street Pattern Tower
Stud Surface	Suspended/ Hang	Swollen Bar
Technology	Tensegrity Bar	Tensile Surface Structure
Transformed Body	Transformed Non-Uniform Grid	Transformed Uniform Grid
Twist	Wave Surface	Wearable
Wiggle	Wrap	3D Print

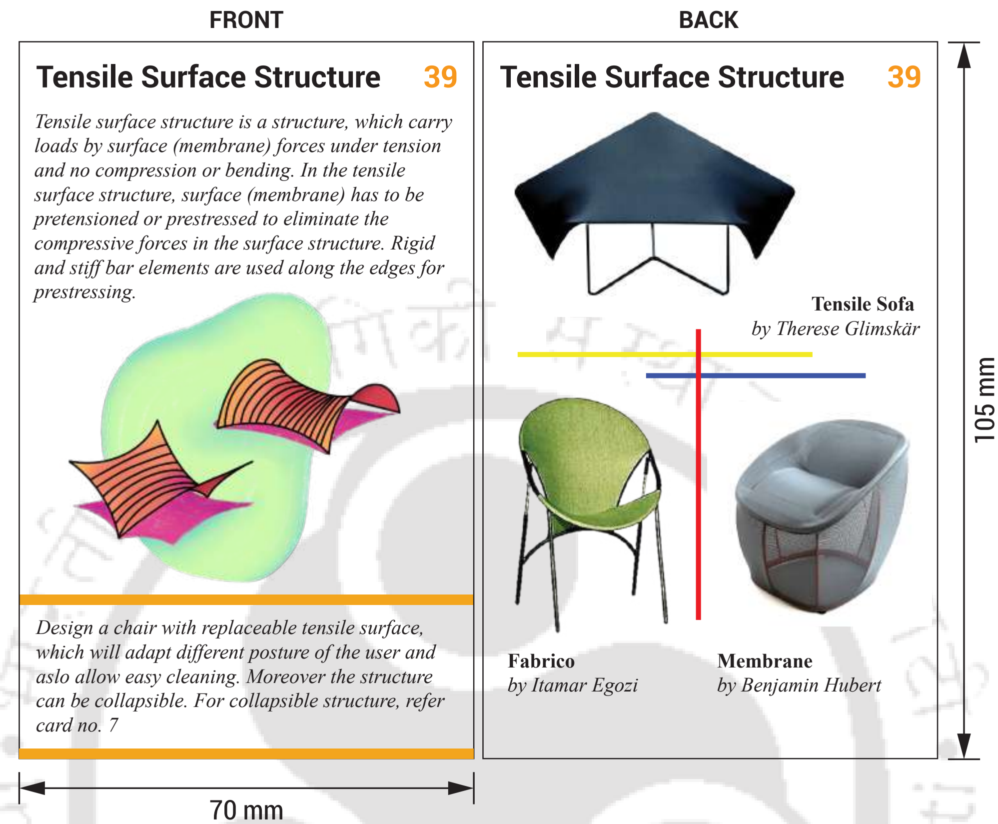


Figure 3.12 Example of DHfFD card: Tensile Surface Structure

SECTION-B DEVELOPMENT OF TOOL FOR MODEL-MAKING

3.8 Form, Material and Processes in Furniture Design

While discussing product experiences in design and factors associated with it, Kesteren et al. (Kesteren, Stappers, & Kandachar, 2005) illustrated a model showing the relationship between product meaning factors and product form factors and product-making factors (Figure 3.13). The integrated model describes product personality, function, and use are the product meaning attributes. Product shape and material are the product form attributes. The manufacturing process is the product-making attribute. When the regular design process starts with a need or want, the design process can be initiated by exploring materials or exploring forms. It is needless to say, Kesteren et al. developed the integrated model based on the models proposed by Michael F. Ashby (Ashby, 1999), N. F. M. Roozenburg & J. Eekels (Roozenburg & Eekels, 1991) and W. Muller (Muller, 2001).

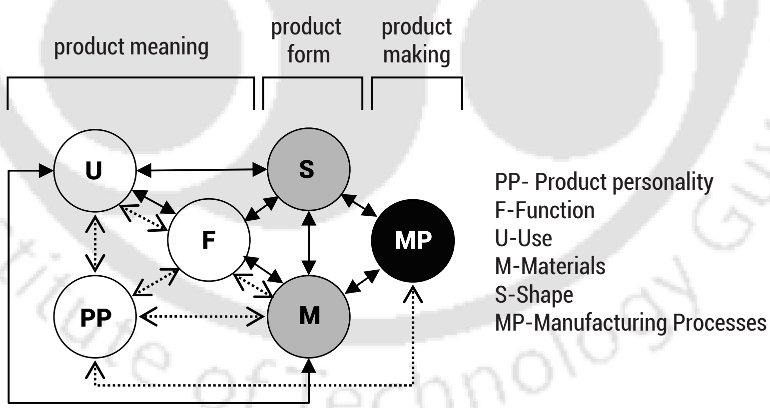


Figure 3.13 Integrated model for product experience and role of material, shape and manufacturing processes (I. van Kesteren, Stappers, & Kandachar, 2005)

Alaa El Anssary (Anssary, 2006) simplified the model and proposed a triangulated model where form, material properties, and processes impact visual, tactile and structural features (Figure 3.14) for furniture design.

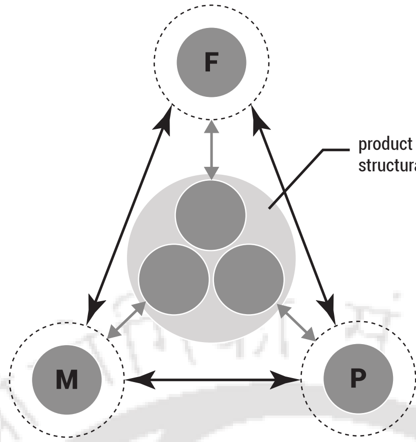


Figure 3.14 The combination of form, material properties and process impact sensory elements of the product (Anssary, 2006)

Alaa El Anssary expanded the model and offered three different contexts which affect visual, tactile and structural features (Figure 3.15).

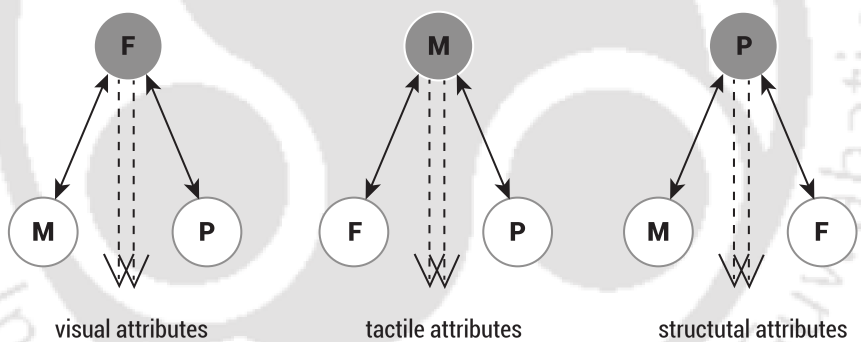


Figure 3.15 Possibilities offered by form, material and processes (Anssary, 2006)

As the intended tools focus on appearance and discussion on visual attributes, connected models are significant in this context. The first model represents F=form refers to the arrangement of all the elements within the form. Material properties such as hardness, thickness, transparency, density, colour etc., develop visual tension between the elements and create harmony within the three-dimensional form. In conjunction with this, precise processing techniques allow the form to transfer specific information and meaning through the surface and shape appearance. Thus, sophistication in design expression is a deliverable of appreciation of form, exploration of potential material and understanding methods and tools (Bramston, 2009). As the development of design heuristics for the furniture (Chair) provided an exhaustive list with function, behaviour and structure as the dominant feature, the research carried forward the structure-dominant groups to develop a model-making tool.

3.9 Existing Supports for Material Selection in Design

Several tools are available for material selection processes by designers. However, they are primarily engineering-based tools dominated by technical information with material data most beneficial for the embodiment design phase of new product development (Karana, Hekkert, & Kandachar, 2010). Though engineers and designers are both concerned with material selection and manufacturing processes, the designer's way of exploring material is different. Designers explore materials for ideation to prototype, whereas engineers are interested in selecting new materials and manufacturing processes (Sörensen, Jagtap, & Warell, 2016).

Ashby and Johnson defined four complementary methods for selecting materials: Selection by analysis, selection by synthesis, selection by similarity and selection by inspiration (Ashby & Johnson, 2009). The method of material selection by Mike Ashby is illustrated in Figure 3.16.

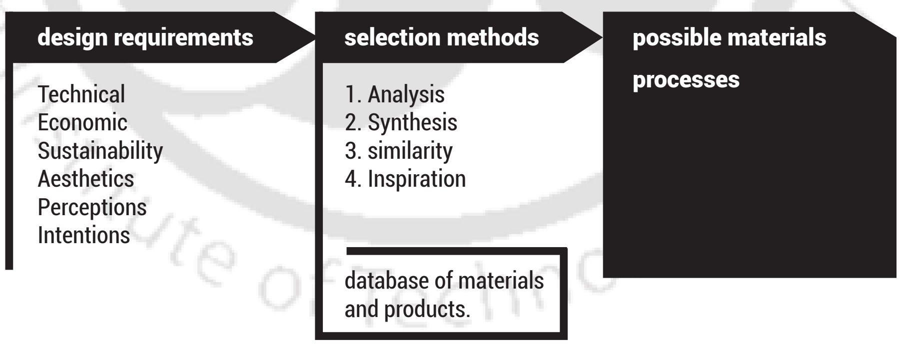


Figure 3.16 Methods of material selection (Ashby & Johnson, 2009)

As product designers deal with intangible characteristics of materials (Karana, Hekkert, & Kandachar, 2008), Karana et al. (Karana et al., 2010) conceptualized a meaning-driven material selection tool. The meaning-driven material selection tool incorporated 76 meanings, which designers may convey through the materials. Considering the sensory dimensions of materials, Valentina Rognoli (Rognoli,

2010) developed an Expressive-Sensorial Atlas to teach the sensory aspects of materials (Figure 3.17).

Figure 3.17 Expressive-Sensorial Atlas by Rognoli (Rognoli, 2010)

To enhance user interaction through adequate feedback and pleasant emotional experience incorporating sensory aspects of materials, Kesteren et al. (Kesteren, Stappers, & Bruijn, 2007) developed Materials in Products Selection (MiPS) tools. MiPS consists of three tools viz. picture tool: images of product examples and materials (Figure 3.18), sample tool: actual materials samples (Figure 3.19) and question tool: which initiates discussion on sensory aspects of materials related to several phases of the user-product interaction (Figure 3.20).

Figure 3.18 Picture tool by Kesteren et al. (Kesteren et al., 2007)

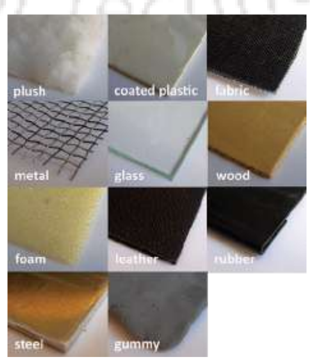


Figure 3.19 Sample tool by Kesteren et al. (Kesteren et al., 2007)

PHASE	*QUESTIONS*	
First contact Distinctiveness	How will the product attract attention? How will the product differentiate itself? Compared to similar existing products, dissimilar products, and the environment? → Which sensory aspects play a role in this?	
Try out Distinctiveness	How will the product convince the user as they try it out? Compared to similar existing products, dissimilar products, and the environment? → Which sensory aspects play a role in this?	
Transport Product experiences	What kind of feedback will the product provide during transport? → Which sensory aspects play a role in this?	
Unwrapping Product experiences	What lasting experiences will the product evoke? → Which sensory aspects play a role in this?	
Usage Functional use	What kind of interaction takes place while using the product? How does the product elicit feedback? What can disturb the interaction? What can intensify the interaction? What can disturb the feedback? What kind of feedback can be intensified? → Which sensory aspects play a role in this?	
Rest Product experiences	How will the product convince to be used again? How will the product fit in its environment and with related products? How will the product say good bye? → Which sensory aspects play a role in this?	

Figure 3.20 Question tool by Kesteren et al. (Kesteren et al., 2007)

Apart from the published paper-based tools, some databases are available, such as Cambridge Engineering Selector (CES), Materials ConneXion, Designing Site, ASM Material Handbook, and MatWeb Material Property Data. Furthermore, there are other methods available for material selection proposed by Ramalhete et al. (Ramalhete, Senos, & Aguiar, 2010), Albiñana & Vila (Albiñana & Vila, 2012), Piselli et al. (Piselli, Baxter, Simonato, Curto, & Aurisicchio, 2018), to name a few. Available supports for material selection have the following issues:

- Supports are for new product development
- Proposed material selection methods are not prototyping specific
- An extensive database considered, which may not be applicable for prototyping

3.10 Tool for Model-Making (TfMM)

The development of Tool for Model-Making (TfMM) followed a ten-step process:

i. Making a set of forms
ii. Making a set of standard model-making materials
iii. Making a set of standard model-making processes
iv. Making a set of standard model-making tools
v. Making a set of finishing materials
vi. Making a set of finishing processes
vii. Exploring multiple materials for a specific form
viii. Making material/process matrix
ix. Framing a structure for the TfMM card
x. Defining TfMM card

The tool development process is illustrated in Figure 3.21.

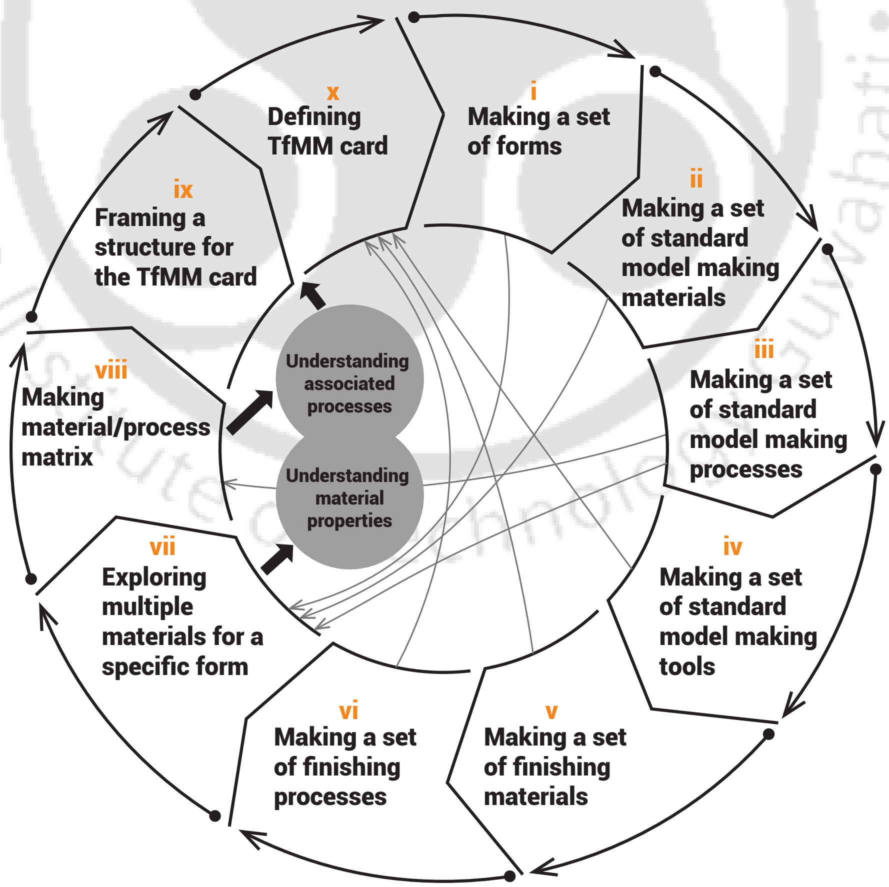


Figure 3.21 TfMM tool development process

3.10.1 Making a set of forms

For the development of TfMM, 48 different forms were selected. Three-dimensional principles and forms showcased by Ronald Knauer (Knauer, 2008) and Cheryl Akner-koler (Akner-koler, 2007), inspired the collections of forms that are part of the study. The selected forms conform to the following principles of the three-dimensional form:

1 Body (Regular)
2 Transformed body
3 Body with movement and growth
4 Body with sectional modification
5 Convex body
6 Concave body
7 Transformed bar
8 Polyhedron
9 Bar connection in movement
10 Bar intersection
11 Body and bar intersection
12 Bar Connection
13 Modulated connection
14 Bar (hollow) joint
15 Bar (hollow)connection
16 Bar assimilated body
17 Self-contained connection
18 Nodal (Body and bar) connection (with a sphere as a body)
19 Nodal (Body and bar) connection (with a cylinder as a body)
20 Surface (rigid) with cavity
21 Isotopic lattice
22 Kinematic connection
23 Surface movement with change in axis
24 Bent surface
25 Cubic lattice structure

26 Bar and surface connection
27 Bar movement with change in axis
28 Wrapped lattice
29 Lattice with infill (rigid)
30 Folding lattice
31 Kinematic lattice
32 Curved lattice
33 Lattice with infill (flexible)
34 Heterogeneous lattice
35 Spiral growth of surface
36 Surface network
37 Torus
38 Curved surface
39 Bulge surface
40 Surface intersection
41 Interlocked flexible bar lattice
42 Membrane surface
43 Surface transformation in an axial direction
44 Transformation of spheres
45 Bar to surface transformation in a linear direction
46 Geometric sequences of surfaces
47 Stretching lattice
48 Modified geometric surface

The collections of forms are showcased in **Appendix H**.

3.10.2 Making a set of standard model-making materials

As part of the TfMM development process, the following materials were considered:

- Materials for construction
- Materials for cushioning
- Materials for upholstery

The following criteria were applied while considering materials (Otto & Wood, 2003):

- Cost: Low-cost materials were considered without sacrificing the prototyping objectives and use.
- Availability: To avoid delay in prototype construction, readily available off-the-shelf materials were considered. Locally available craft materials were also considered for this research.

Appendix I presents the list of materials for construction that were considered for form and structure giving during prototyping.

Appendix J showcases the list of materials for puffy cushions.

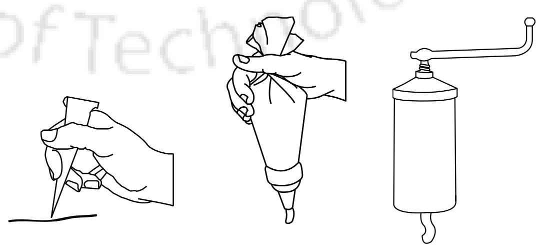
Appendix K displays only the types of upholstery materials to give an understanding of the material texture, visual effect, stretchability and thickness.

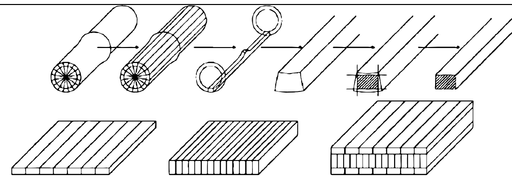
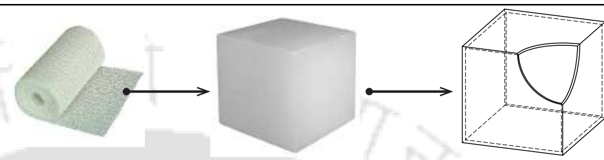
3.10.3 Making a set of standard model-making processes

Forming Process

Many processes exist for model-making. However, processes were considered from standard manufacturing processes (Thompson, 2007) (Lefteri, 2007), adapted from craft processes and scientific experiments for this research. For example, the extrusion of semi-solid paste is adapted from the icing and Mehendi art techniques. Table 3.8 showcases the adapted processes.

Table 3.8 Adapted processes for model-making

Process	**Adapted from**
Extrusion of semi-solid paste	 Adapted from the Mehendi art technique and food extruding technique

Moulded lamination	 Adapted from the laminated bamboo lumber-making process
Core removing	 Covering the solid EPS form with surfaces (Paper & adhesive / POP bandage) and then removal of the solid EPS form by applying petrol or gasoline Adapted from the scientific phenomenon of EPS getting dissolved in petrol/gasoline

The following forming processes were considered:

i. Cutting with an industrial cutter
ii. Cutting with hot wire
iii. Sawing operation with a hand saw, hacksaw, hole saw, handheld circular saw, jigsaw etc.
iv. Sanding or grinding operation
v. Planning procedure by hand planer or electric planer
vi. Bending
vii. Machining related to turning, boring, milling, drilling, knurling etc.
viii. Jiggering and Jollying
ix. Laser cutting
x. Heat forming
xi. Extrusion of semi-solid paste
xii. Moulded lamination
xiii. Sculpting with armature
xiv. Silicon moulding
xv. Core removing
xvi. Press forming
xvii. Knitting or knotting
xviii. Steam bending

Joining Process

Basic joining processes were considered in the research:

i. Thermal Joining
ii. Stitching
iii. Thermal impulse sealing
iv. Joining with screws, bolts and rivets
v. Joining with adhesives

Appendix L presents the list of adhesives considered.

As adhesives, filler materials play a significant role in model-making. Fillers help: fill the gaps between the joints and create a seamless part, make features like inside fillets and repair mistakes and dents, or fill existing holes in the base material.

The list of the filler materials considered in the research is presented in **Appendix M**.

3.10.4 Making a set of standard model-making tools and equipment

Model-making tools were considered associated with forming processes and joining processes. The tools required for processing a specific material were also considered. For example, an electric foam cutter to cut EPS, an electric kitchen knife for sponge cutting, and Perspex Cutter for plastic sheet cutting.

Appendix N presents the list of hand tools, portable machine tools, machine tools and other equipment.

3.10.5 Making a set of finishing processes

Though many finishing processes are available, a few basic finishing processes were considered in this research. During the finishing process, the following steps were considered:

- Preparation of the surface
- Painting the surface
- Protection of the surface

Processes considered related to each step are listed in Table 3.9.

Table 3.9 Finishing processes for model-making

Preparation of the surface
• Grinding, sanding and polishing • Dent filling with filler material • Priming • Wet sanding for non-water-soluble filler coating • Fine sanding with water-soluble sandpaper (grit >P400)
Painting the surface
• Spray painting with spray cans • Spray painting with spray guns • Spray painting with the airbrush
Protection of the surface
• Electroplating • Melamine coating • Varnishing

3.10.6 Making a set of finishing materials

Materials associated with the finishing process are the finishing materials. The list of materials related to finishing is presented in **Appendix O**.

3.10.7 Exploring multiple materials for a specific form

In this research phase, the 48 different forms selected in section 3.10.1 were constructed with three different materials.

Participants

Two workshop technicians with more than 15 years of experience and three undergraduate students pursuing B.Des participated in this activity. They are the coders in the TfMM development process. As the tool is intended for novice designers, undergraduate students were also considered coders alongside workshop technicians in the tool development process. However, they must be trained to understand the correlation between form, material, and processes.

Objective

This activity aimed to train undergraduate students about the correlation between form, material, and processes in design and train them to select appropriate materials and processes.

Exploration Procedure

The activity was conducted in three phases, as illustrated in Figure 3.22. Initially, forms were selected from the listicle mentioned in section 3.10.1. Then after technicians proposed appropriate materials and processes to the participating students. Based on the suggestions participating students made physical models of the forms. At the end of this activity, three undergraduate participants produced 144 (48 forms x 3 different materials).

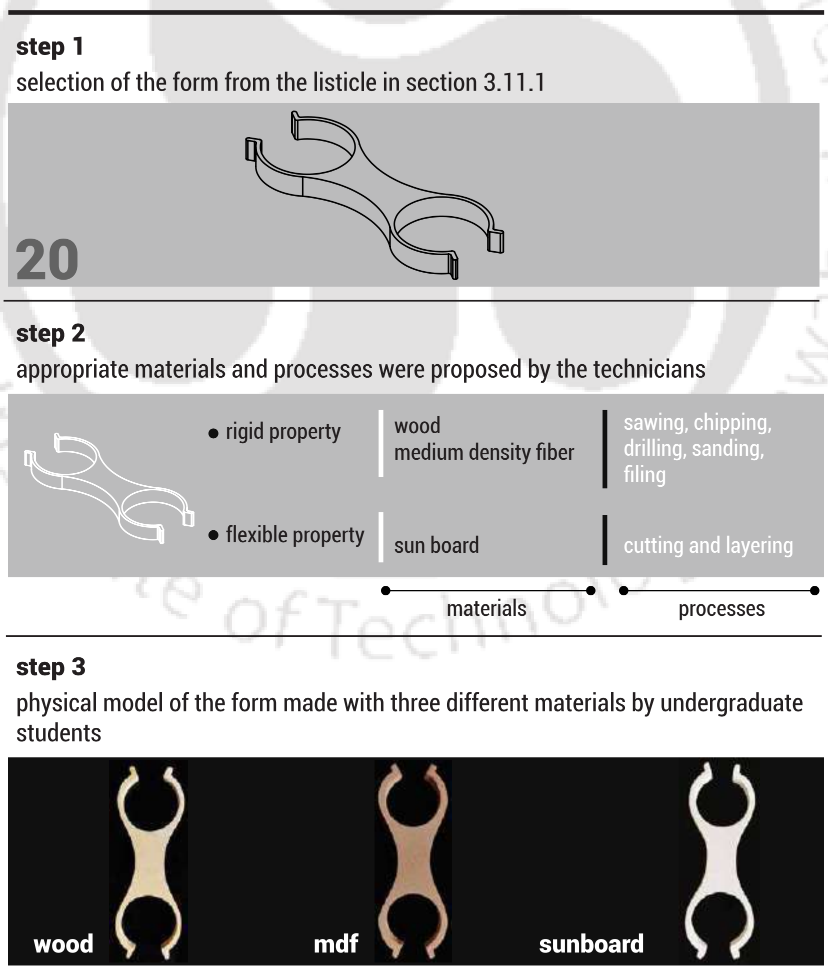
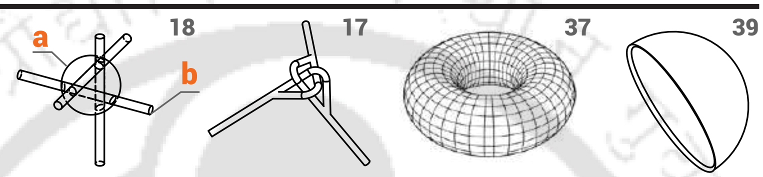


Figure 3.22 Exploring multiple materials for a specific form

3.10.8 Making form-material-process matrix

Based on the activity done in section 3.10.7, two technicians and three undergraduate students made a form-material-process matrix inspired by Ashby and Johnson (Ashby & Johnson, 2009). Figure 3.23 illustrates how a specific form can be achieved with a combination of materials and processes. The numbered cells represent the corresponding forms that can be made conveniently.



matrix — processes

materials	Machining	Cutting with industrial cutter	Sawing	Sanding	Moulded lamination	Bending	Heat forming	Thermal joining	Joining with adhesives
Wood	18a, 18b, 37, 39M		18b, 37, 39M	18a					
Polyurethane foam	18a, 39M			37, 39M					
High density Expanded Polystyrene	39M			37, 39M					
Paper-mâché					39				
Mild Steel rod						17		17	
Nylon/ Nylatron rod							17		17
Aluminium						17		17	
Jute plant straw		18b							
Elephant grass reed		18b							
High Impact Polystyrene							39		
Acrylic sheet							39		

Figure 3.23 Form-material-process matrix

The following abbreviations were used while preparing the matrix:

[N]=Number corresponding to the form

[N]M= Mold for the corresponding form

[N]a/b=Part of the form

The complete matrix is presented in **Appendix P**.

3.10.9 Framing a structure for the TfMM card

Upon completing the activities mentioned in sections 3.10.7 and 3.10.8, two technicians and three undergraduate students framed the tool's structure. While framing the structure for the TfMM card, participants considered different orientations and sizes, such as square ■, portrait ▮, and landscape ▬. After discussions and deliberations, the landscape layout was finalized. During the discussion, answers to the following questions were explored:

- What must the card communicate to fulfil the purpose?
- What common features should be there as an associated tool to design heuristics for furniture design?
- What would be the method of use?

Participants considered form & structure-dominant groups and assigned materials, processes and tools required to make a physical model corresponding to the dominant features (bar/body/surface) for the existing furniture (chair). A sample Tool for Model-Making cards for furniture design is presented in Figure 3.24.

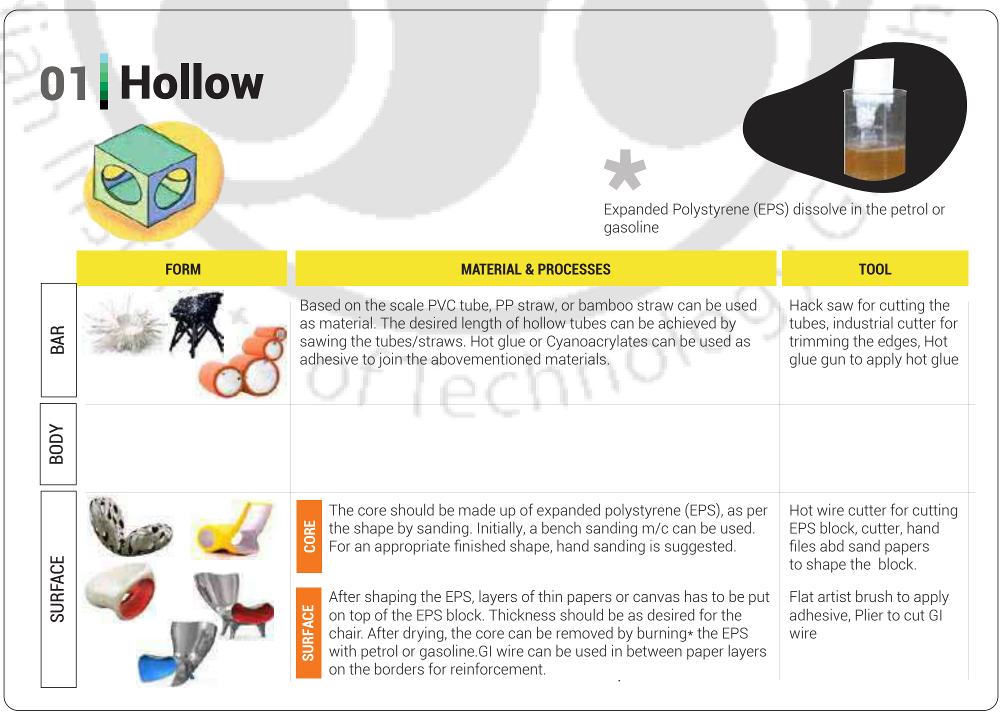


Figure 3.24 TfMM sample card

3.11 Summary

This chapter of the thesis presents the final impact model with proposed supports. The excerpts from the literature review determined the specifications for developing supports to improve the existing situation. Furthermore, this chapter showcases the systematic development of Design Heuristics for Furniture Design and Tool for Model-Making to facilitate novice designers. Section-A discussed the development of Design Heuristics for Furniture Design cards from a study and analysis of 650 pieces of furniture. Section-B methodically presented the development of Tool for Model-Making cards.

Design Heuristics for Furniture Design

and

Tool for Model Making

Chapter 4

Assessing the Impact of DHfFD and TfMM

4.1 Introduction

The objective of this chapter is:

- To confirm efficacy, validate Design Heuristics for Furniture Design (DHfFD) and Tool for Model Making (TfMM).

This section of the research strives to answer the following research questions:

- What is the impact of the structured concept generation tool on novice designers?
- What is the impact of the structured model-making/prototyping tool on novice designers?

While assessing the impact of DHfFD and TfMM, the following sub-research questions were crafted and sought to answer:

I. How do novice designers perceive DHfFD in use?
II. Does using DHfFD result in more innovative furniture design concepts?
III. How do novice designers perceive TfMM in use?
IV. Does using TfMM result in models with improved quality?

SECTION-A ASSESSING THE IMPACT OF DHfFD

Previous research has underscored the effects of design heuristics on creative concept generation (Kotys-schwartz, Daly, Yilmaz, Knight, & Polmear, 2014) (Kramer, Daly, Yilmaz, Seifert, & Gonzalez, 2015)(Leahy, Daly, Murray, McKilligan, & Seifert, 2019). However, this research made an effort to investigate the impact of DHfFD, as the tool is new to the category and domain-specific.

4.2 Related Work

A review of existing related research publications and doctoral dissertations related to card-based tools for creative concept generation and their evaluation gave an understanding of the following aspects for the assessment of the design tools:

I. Experiment procedure

It has been observed that most of the card-based tools are developed by educators or design management consultants. The success of the tools is reported in publications, often testing with the students or registering the use of the tools in commissioned work (Roy & Warren, 2019).

77 Design heuristic cards were developed by Yilmaz (Yilmaz, 2010) and evaluated in a controlled experiment with 357 participants through twelve instructional conditions.

Plex cards (Lucero & Arrasvuori, 2013) were evaluated in workshop mode in two stages with designers and researchers. They assessed the perceived helpfulness and illustrated combined participant mean ratings and standard deviations on the helpfulness of each of the PLEX Cards.

In recent years Blösch et al. (Blösch, Ahmed-Kristensen, & Shea, 2019) developed 29 design heuristic cards for additive manufacturing and evaluated the efficacy via a controlled experiment with 27 master students. Furthermore, Blösch (Alexandra, 2020) also reported the validation through projects in the doctoral thesis.

K. Blake Perez evaluated Design principle cards developed for Design Innovation with Additive Manufacturing (DIwAM) (Perez, 2018) via a within-subject experiment with a total of 85 participants.

II. Evaluation metrics

A brief review of design research publications specific to card-based tool evaluation has revealed the evidence of using majorly two evaluation metrics, Shah, Vargaz-Hernandez, and Smith's metrics (SVS) (Shah, Vargas-hernandez, & Smith, 2003) and Amabile's Consensual Assessment Technique (CAT).

Yilmaz assessed the creativity score of the concept sketched while evaluating 77 Design heuristic cards using CAT (Yilmaz, 2010). However, Amabile's CAT has not been used much in design research (Jeffries, 2012). Amabile herself mentioned the limitation of the CAT in the encyclopedia of creativity (Runco & Pritzker, 2011). The process is impractical when time concerns are paramount. Additionally, choosing the appropriate task and managing the body of judges are highly time-consuming.

Sio et al. (Sio, Kotovsky, & Cagan, 2015) presented a comprehensive meta-analytic study on the role of examples and measures the impact on novelty, quantity, quality, and variety as proposed by SVS metrics.

Perez (Perez, 2018) evaluated the effectiveness of the Additive Manufacturing Design Principles Cards while analyzing quantity, quality, novelty and card utility.

Blösch (Alexandra, 2020) validated Design Heuristics for Additive Manufacturing quantity, variety and novelty.

Jessica Menold reported a review of the creative concept evaluation while assessing the holistic framework of Prototype for X (PFX) (J. D. Menold, 2017). The assessment for Prototype for X followed the metrics of originality, effectiveness, implementability, and applicability modifying the metrics suggested by (Dean, Hender, Rodgers, & Santanen, 2006), where novelty, workability, relevance, and specificity are the construct for the metrics.

4.3 Research Methodology

In this study, a within-subjects experiment was conducted. The same group of novice designers generated ideas before and after introducing the tool Design heuristics for furniture design. The main reason behind adopting a within-subjects experiment approach was to confirm the treatment effect on participants and register changes in individual participants.

The experiment was conducted in four phases, as illustrated in Figure 4.1. The four phases are the control treatment phase, the experimental treatment phase, the survey phase, and the evaluation phase.

Phase I provided a baseline measurement of concepts in an unaided setting. The DHfFD cards were used as a stimulus in Phase II to influence conceptualization. In both phases, participants were asked to develop creative furniture design concepts. During the survey phase, participants were given a set of questions to understand how designers perceived the cards in use. During the evaluation phase, coders were appointed to evaluate the concepts generated in Phases I and II. Based on the participants and the nature of the design brief, quantity, originality, and implementability were assessed for the concepts.

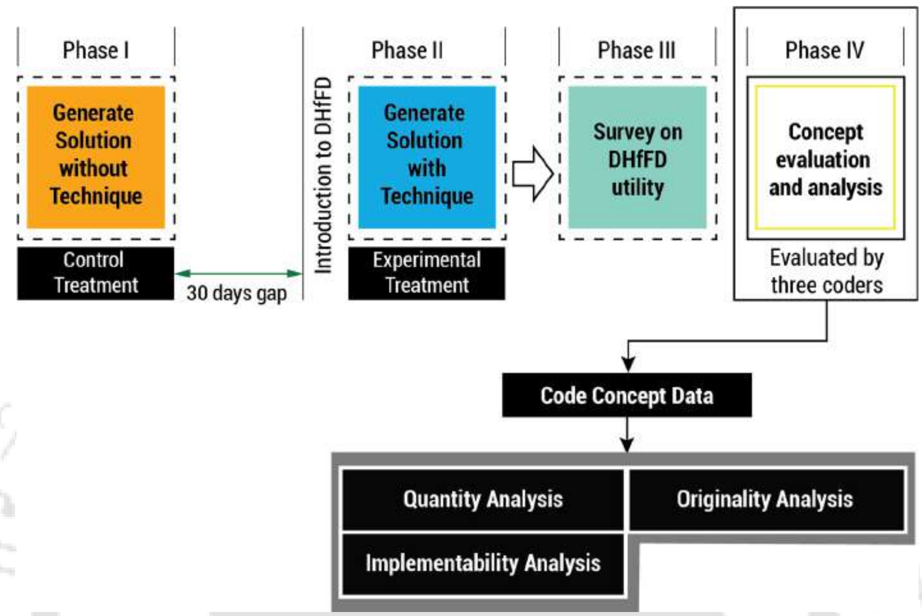


Figure 4.1 Experimental execution diagram for the validation of DHfFD

4.3.1 Participants

A total of 28 novice designers participated in the study from undergraduate and postgraduate design courses with no prior experience in furniture design and no idea about DHfFD. Out of 28 participants, 23 were male, and 5 were female (Figure 4.2).

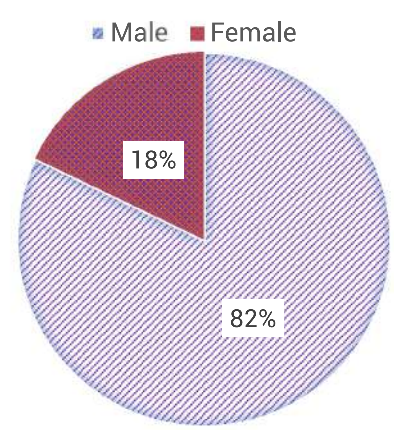


Figure 4.2 Percentages of participants in terms of gender

4.3.2 Design Brief

In both phases, I and II, i.e. during control and experimental treatment, the students were given an open-ended challenge and asked to produce as many ideas as possible in 30 minutes.

Brief: Design as many indoor chairs as possible for urban housing. There is no constraint on cost, material, and process.

4.3.3 Stimulus

In this study, during the experimental treatment phase, a total of 12 DHfFD cards were introduced. The cards were selected randomly from a set of 81 heuristic cards set. On a two-sided 80 x 100 mm card, each heuristic was presented. Cards were not provided one at a time, in a standard order, as it may restrict the flexible use of the tool in more than one manner, and it may also create a problem for future acquisition of the tool. They were given the liberty to use the cards the way they wanted. A subset of the whole DHfFD card set was given to avoid overwhelming feelings with 81 cards. The provided card list is shown in Table 4.1.

Table 4.1 Set of 12 Heuristics Provided in Study

Cantilever	Wave surface	Spring
Wiggle	Tensegrity	Coil
Extension	Playful	Tensile surface structure
Collapsible	Comet structure	Science & Technology

4.3.4 Experimental Procedure

The control treatment phase began by asking participants to generate solutions without any tool being given. Participants got 30 minutes to complete the task. A gap of 30 days was there between phase I and phase II to avoid the pre-treatment assessment's effect on post-treatment. At the beginning of the experimental treatment phase, the DHfFD tool was introduced through a lecture. Participants were asked to generate concepts within 30 minutes using DHfFD cards during the experimental treatment phase. Table 4.2 illustrates the experiment design.

Table 4.2 Experiment design for validating DHfFD

	Group	
Order of activities	Control N=28	Experimental N=28
1. Lecture on DHfFD (15 min.)		X
2. Receives Design Brief	X	X
3. Receives Design Heuristics for Furniture Design Cards		X
4. Completes Design Task (30 min.)	X	X

4.3.5 Concept Documentation

The concepts generated during the control and experimental treatment phase were documented by having the students personally write or draw them out on the A3 size template provided. The following instruction was given to the participants to follow while registering concepts:

i. Use pencils, a black ball pen or a liner pen to showcase your concepts.
ii. Do not overlap concept sketches.
iii. Showcase your concept sketches with more clarity and less dialogue.
iv. Explain your concepts with legible texts.
v. Showcase how the furniture works and how to use the furniture.
vi. Take extra pages to showcase more concepts.

Participants were also asked to mention the heuristics card number(s) during the experimental treatment phase.

4.3.6 Survey Questions

The students were asked the following questions in Table 4.3 during the survey phase.

Table 4.3 Questions submitted to the students

Q#	Text of Questions	Scale
Q1	How effective was the tool in helping you to generate more concepts of a chair?	(1 = Not effective, 5 = Very effective)
Q2	How would you rate the appropriateness of the textual content of the tool?	(1 = Very poor, 5 = Very good)
Q3	How would you rate the appropriateness of the visual content of the tool?	(1 = Very poor, 5 = Very good)
Q4	How do you find the DHfFD for creative concept generation for chair design?	(1 = Not effective, 5 = Very effective)
Q5	Was there a need to explain any basic concepts during the application of the new tool?	(1 = Quite always, 5 = Not at all)
Q6	Was the tool useful for understanding the types of forms and structures of chairs?	(1 = Not effective, 5 = Very effective)

4.3.7 Coding

In phase IV, three coders were trained to evaluate the concepts generated at the control and experimental stages. Coders were from the background of accessory design, applied arts, and architecture. The coders also investigated the evidence of the use of DHfFD for the corresponding concepts generated by the participants during the experimental stage and assessed the card's utility. Furthermore, they analyzed and evaluated all concepts from the control and experimental phases based on their quantity, originality, and implementability. Krippendorff's alpha (α) (Krippendorff, 2011) was measured for each instance to check inter-rater reliability.

4.3.8 Quantity Analysis

According to Shah, Vargaz-Hernandez, and Smith's effectiveness metrics (Shah et al., 2003), quantity refers to "the total number of distinct concepts generated by an individual throughout the designated time for the given design task". The rationale for using quantity as a measure is that many researchers believe that developing multiple concepts increases the probability of innovative concepts. Quantity was assessed by following the procedure outlined in Figure 4.3. The concepts developed in the control and experimental treatment were compared using statistical methods to complete the quantity analysis.

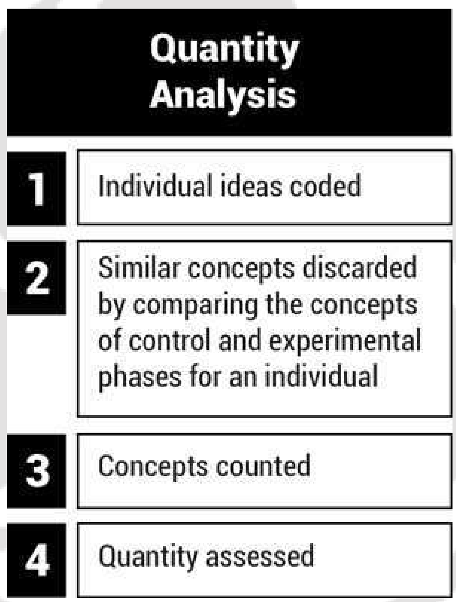


Figure 4.3 Quantity analysis procedure for validating DHfFD

4.3.9 Originality Analysis

According to Dean et al.'s effectiveness metrics (Dean et al., 2006), originality refers to "the degree to which a concept is not only rare but is also ingenious, imaginative, or surprising". The originality score is different from the novelty score, as the originality score is not relative to other concepts in the group. A four-point Likert-type scale (1-4) was used to assess originality, as suggested by Dean et al. (Figure 4.4). Originality assessment followed the procedure outlined in Figure

4.5. Originality score was compared for the concept sets before and after providing the card using statistical methods.

Originality Scale			
1	2	3	4
Common, mundane, boring	Interesting	Unusual, interesting; shows some imagination	Not expressed before (rare, unusual) And Ingenious, imaginative or surprising;may be humorous

Figure 4.4 Originality scale (Dean et al., 2006)

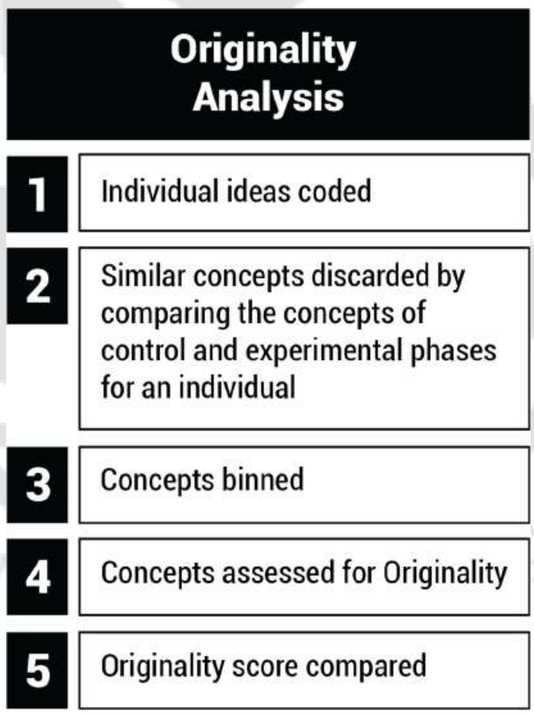


Figure 4.5 Originality analysis procedure

4.3.10 Implementability Analysis

According to Dean et al.'s effectiveness metrics (Dean et al., 2006), implementability refers to "the degree to which a concept can be easily implemented and does not violate known constraints". As suggested by Dean et al., a four-point Likert-type scale (1-4) was used to assess implementability (Figure 4.6). The implementability assessment followed the procedure outlined in Figure 4.7. The implementability score was compared to the control and experimental phases concepts using statistical methods.

Implementability Scale	
1	Totally infeasible to implement or extremely financially nonviable
2	Significant change or expensive or difficult but not totally impossible to implement
3	Some changes or reasonably feasible promotions or events
4	Easy to implement at low cost or non-radical changes

Figure 4.6 Implementability scale (Dean et al., 2006)

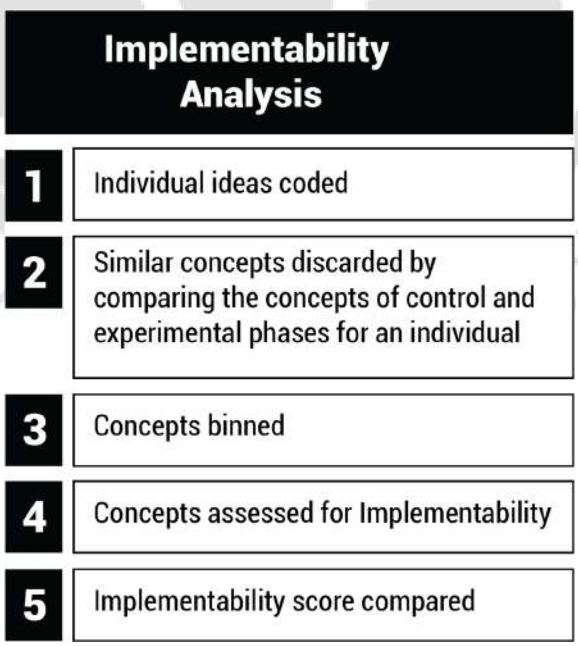


Figure 4.7 Implementability analysis procedure

4.4 Qualitative Impact Assessment of DHfFD Cards: Results and Discussions

4.4.1 Major Findings from Phase I

In phase I, during control treatment, 28 participants generated 140 concepts within a range of 3 to 12. The concepts developed at this phase without any support of technique/tool have the following issues:

i. indistinguishable concepts presented
ii. existing ideas presented with minor modifications, and
iii. impractical concepts presented

Some of the examples with low originality and implementability score are shown in Figure 4.8. Students in their sophomore years lack an understanding of furniture (chair) form and structure, which might be the primary reason behind the indistinguishable concepts. Impractical concepts resulted from a lack of experience and exposure of the participants. The scenario necessitates domain-specific support to scaffold novice designers for creative concept generation. Nevertheless, this phenomenon is not valid for all participants.

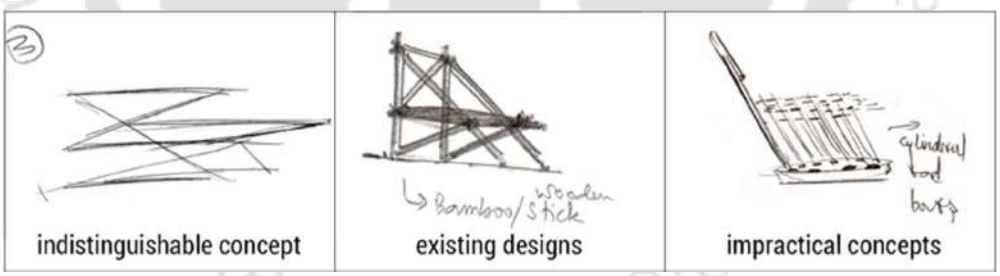


Figure 4.8 Concepts sketches from phase I using DHfFD

4.4.2 Major Findings from Phase II

In phase II, during experimental treatment, 28 participants generated 294 concepts within a range of 4 to 20. The concepts in phase II were substantially improved compared to the concepts in phase I. Concepts with high novelty scores were observed when a few participants combined more than one DHfFD card. Some examples of concepts with evident DHfFD heuristics are shown in Figure 4.9.

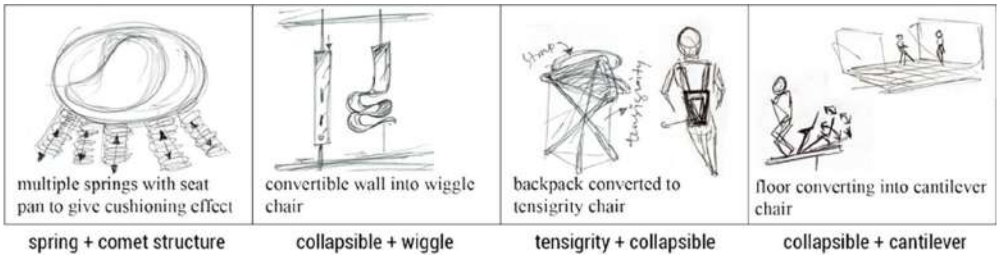
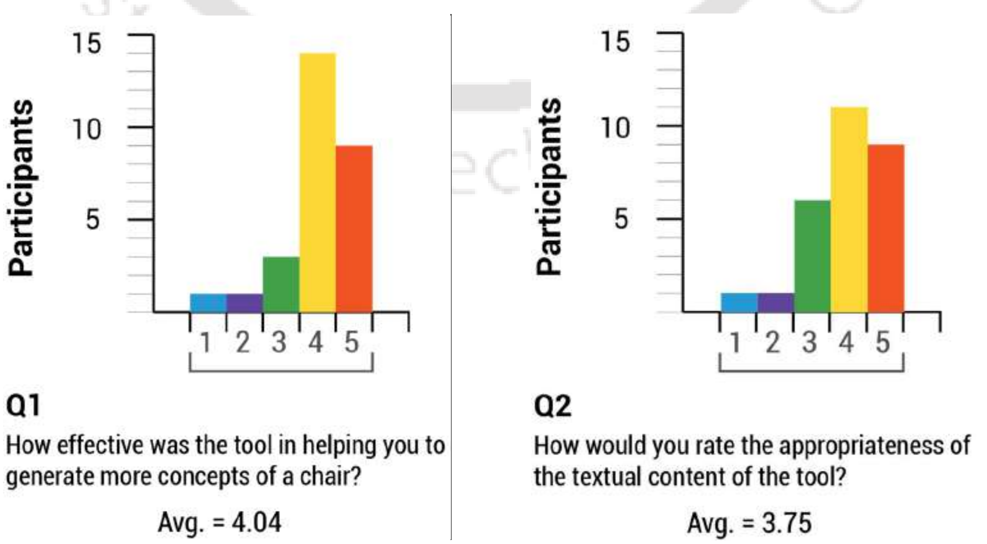


Figure 4.9 Example concepts with evident combined DHfFD heuristics

The presence of heuristics is observed in maximum concepts. It is important to say; maximum concepts are novel and practically possible with minor modification.

4.4.3 Major Findings from Phase III

During control treatment, participants developed concepts without any support; during experimental treatment, participants developed concepts with the help of DHfFD cards. In Phase III, during the survey phase, participants were asked various questions to understand how the participants perceived the DHfFD tool. Participants were asked questions as listed in section 4.3.6. Along with the questions, participants were requested to register their responses on a Likert scale from 1-5. It is evident from the results and responses that the tool is helpful in creative concept generation, and overall the perspective of the participants towards the DHfFD tool is positive, which reflects on the histograms of responses to the questions asked in phase III. The responses are visually summarized in Figure 4.10.



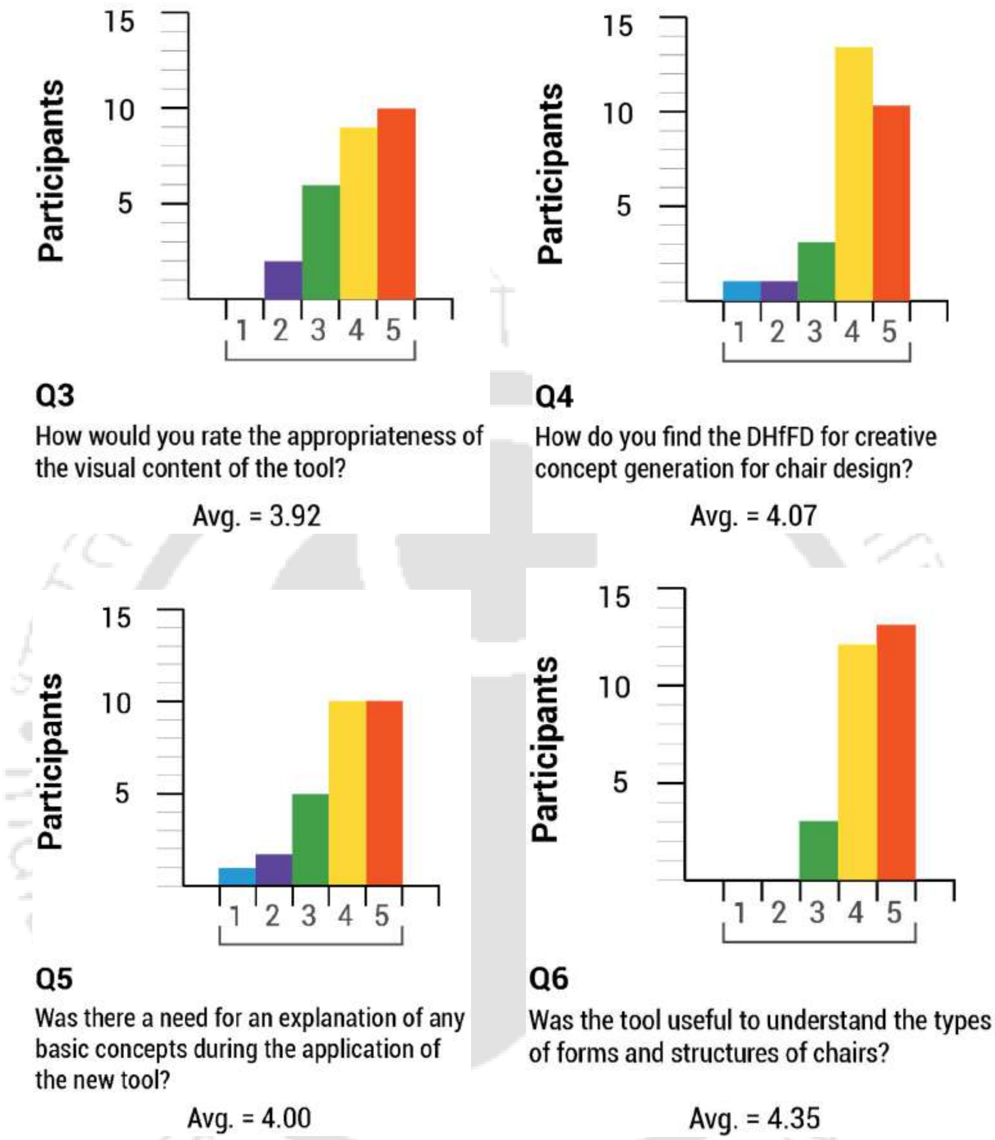


Figure 4.10 Responses of the participants in phase III of the DHfFD assessment

Along with the positive responses to the tool, a few invaluable pieces of feedback were registered during the discussion with the participants regarding the tool. The following are the significant points that emerged from the conversation:

1. ***Transformational principles:*** Novice designers lack knowledge of transformational principles of the basic form and suggested the inclusion of cards with content related to transformational principles.

2. ***Tool for a tool:*** It is more important to refine concepts than the generation of concepts. It would be helpful for beginning designers if support is provided to make a prototype for the feasibility study.

3. ***Separation of citation of furniture:*** Existing designs are influential and divert novice designers' minds while using the card and suggestions received to separate the instruction card and citation cards.

4.5 Quantitative Impact Assessment of DHfFD Cards: Results and Discussions

4.5.1 Quantity Analysis Results

All the participants showed improvement in generating more concepts with DHfFD except for a few, even after discarding similar concepts. Twenty-eight participants developed 140 concepts during the control and 294 concepts during the experimental treatment phases. Thirty-five concepts were discarded from the total of 294 concepts by the coders, as they closely resembled the concepts developed during the control treatment phase. Figure 4.11 illustrates participant-wise concepts developed in each stage and concepts discarded.

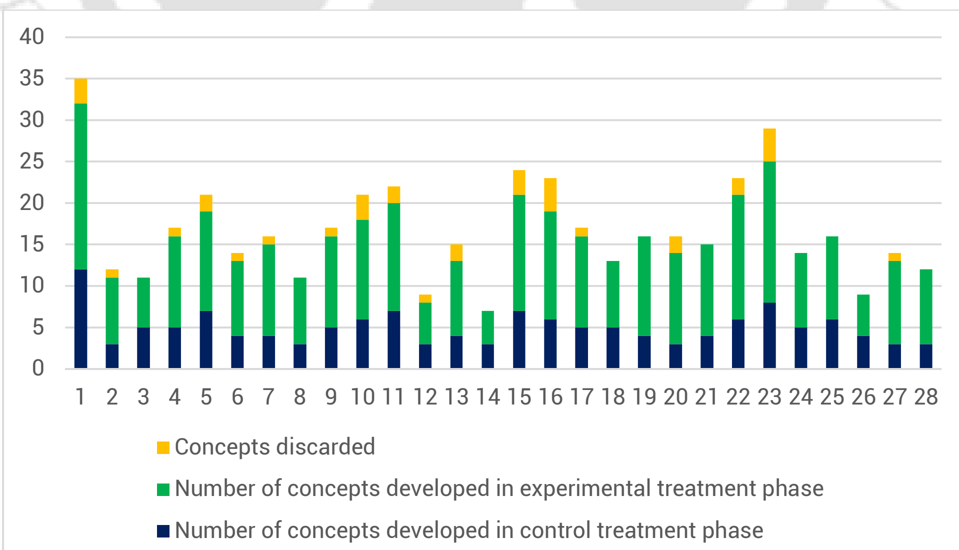


Figure 4.11 Visual representation of the number of concepts developed by individual participants

Statistical tests were also conducted to measure the significance of the difference between the control and experimental treatment data. As the sample size is less than 50, the Shapiro-Wilk normality test was run to understand the nature of data distribution. The p-value for the Shapiro-Wilk test observed is less than 0.05 for both the data sets; also, the boxplot (Figure 4.12) showcases outliers in the data, which determined that the data sets (number of concepts generated in control and experimental phases) were not normally distributed.

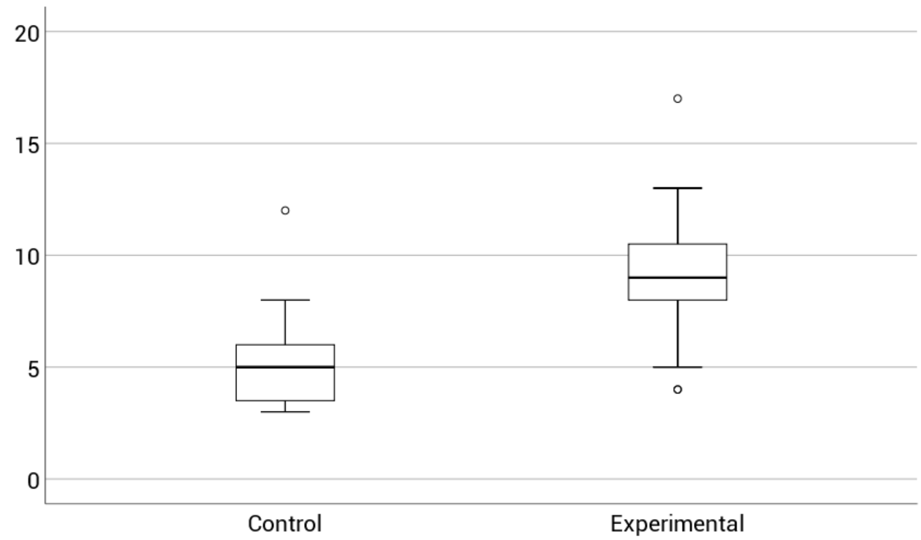


Figure 4.12 Distribution of the number of concepts in the control and experimental treatment phases

Overall, the number of concepts registered after introducing the DHfFD card in the experimental treatment phase was higher than the number of concepts developed in the control treatment phase. However, as the data sets were not normally distributed, a Wilcoxon signed-rank test was conducted as a nonparametric alternative statistical analysis to the dependent samples t-test to check the statistical significance. The Wilcoxon signed-rank test reflects a statistically significant difference between the control and experimental treatment in terms of the number of concepts produced by the participants ($Z = -4.639$, $p < 0.001$). The correlation coefficient calculated to interpret effect size for nonparametric data (Fritz, Morris, & Richler, 2012), $r=0.88$, exceeded the convention for large effect size as indexed by Cohen (Cohen, 1988).

4.5.2 Originality Analysis Results

The coders assessed all the concepts developed during the control and experimental treatment phase according to the four-point originality scale discussed in section 4.3.9. The inter-rater reliability was measured using Krippendorff's alpha (α) (Krippendorff, 2011) to define the satisfactory agreement between the raters. Krippendorff's α was calculated as 0.92, considered a significantly high agreement level (Saura, Reyes-Menendez, & Palos-Sanchez, 2019). Each participant's average originality scores were measured for the control and experimental phase. Figure 4.13 illustrates the average originality score for individual participants during the control and experimental phases. The visual illustration shows an improvement in the average originality score for individual participants.

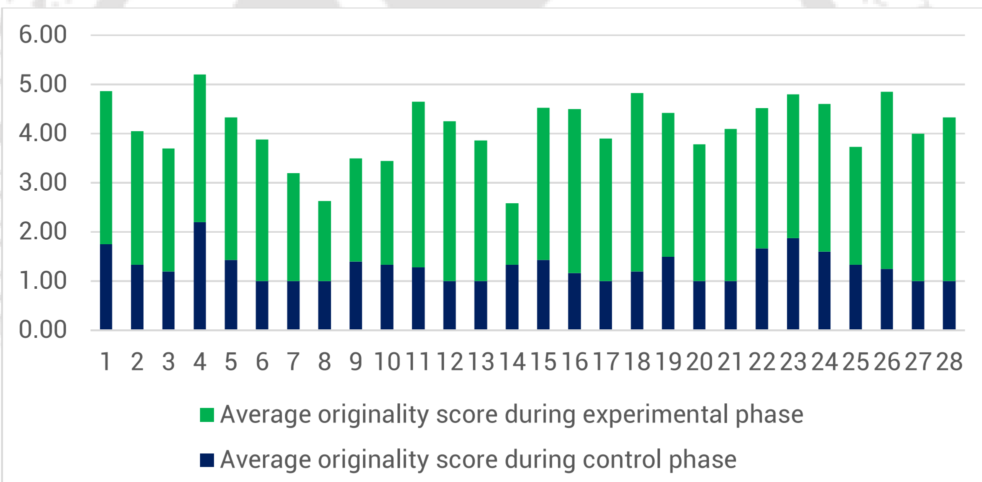


Figure 4.13 Average originality score for individual participants

Statistical tests were also conducted to measure the significance of the difference between the average originality score in the control and experimental phase. The Shapiro-Wilk test of normality was run to examine if the variables are normally distributed as sample size N<50. The p-value for the Shapiro-Wilk test observed is less than 0.05 for both the data sets; also, the boxplot (Figure 4.15) showcases outliers in the data, which determined that the data sets (average originality score in control and experimental phases) were not normally distributed.

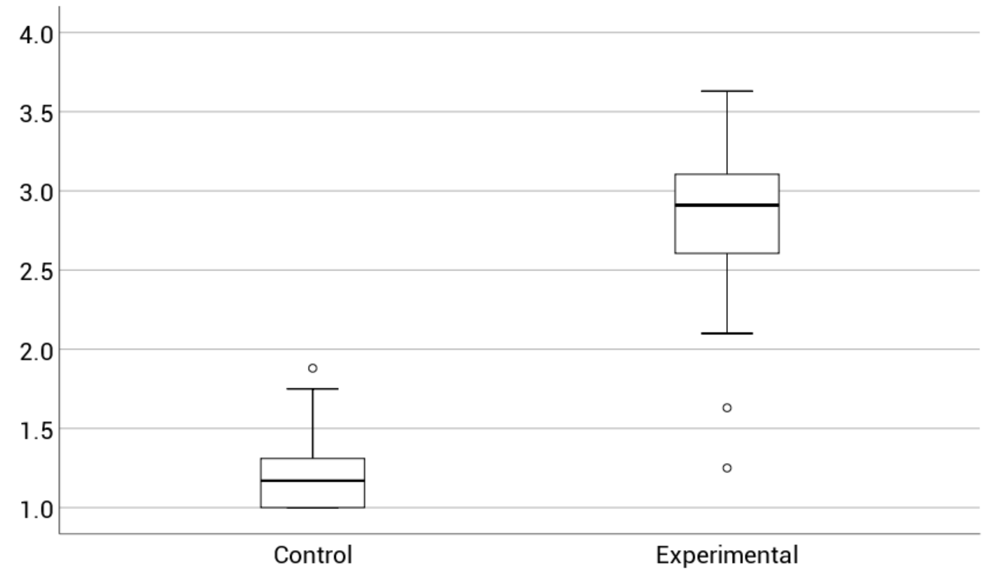


Figure 4.14 Distribution of the average originality score in the control and experimental treatment phases

A Wilcoxon signed-rank test was conducted because the data sets were not normally distributed. The Wilcoxon signed-rank test reflects a statistically significant difference between the control and experimental treatment in terms of the average originality score of the participants (Z = -4.60, p <0.001). The correlation coefficient, r=0.87, exceeded the convention for large effect size as indexed by Cohen (Cohen, 1988).

4.5.3 Implementability Analysis Results

The feasibility aspect of the concepts generated in the control and experimental phases were assessed using the four-point implementability scale discussed in section 4.3.10. The inter-rater reliability, Krippendorff's α, was calculated as 0.86, considered a significantly high agreement level (Saura et al., 2019). The average implementability score was measured for each participant for the control and experimental phase. Figure 4.16 illustrates the average implementability score for individual participants during the control and experimental phase. The visual illustration shows an improvement in the average implementability score for individual participants.

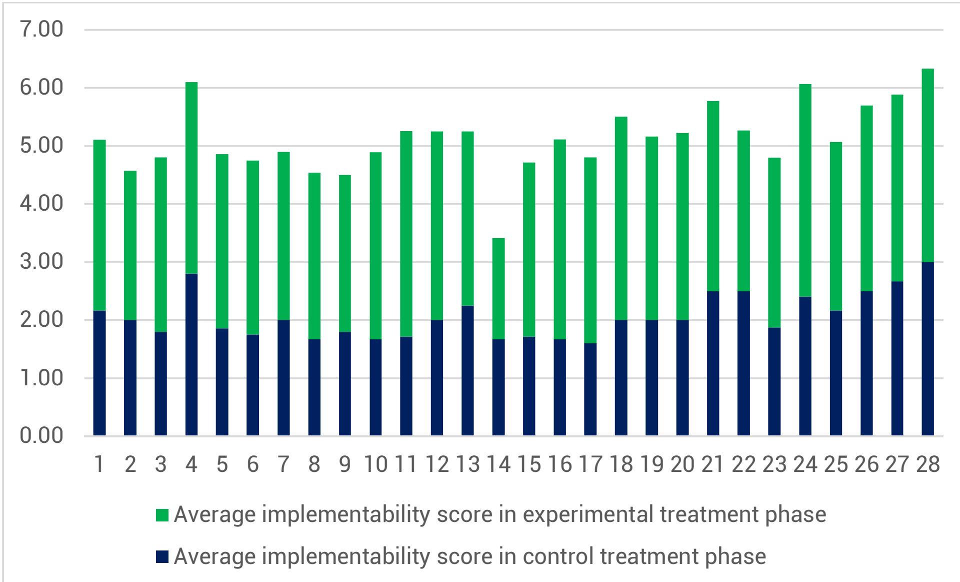


Figure 4.15 Average implementability score for individual participants

Statistical tests were also conducted to measure the significance of the difference between the average implementability score in the control and experimental phase. The Shapiro-Wilk normality test shows a p-value less than 0.05 for both data sets, and the boxplot (Figure 4.17) showcases outliers in the data, meaning average implementability scores were not normally distributed.

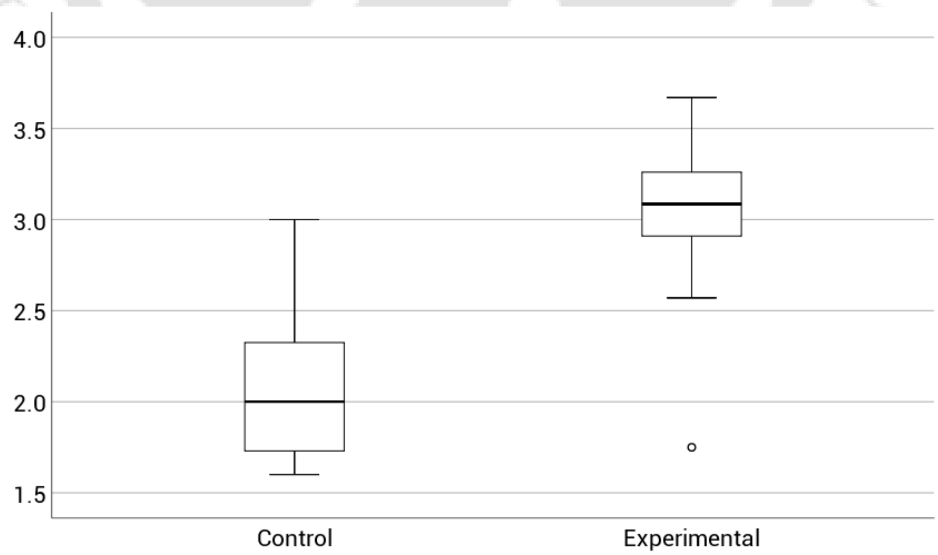


Figure 4.16 Distribution of the average implementability score in the control and experimental treatment phases

A Wilcoxon signed-rank test was run to check the statistical significance of the difference between the average implementability score in the control and experimental treatment phases. The Wilcoxon signed-rank test reflects a statistically significant difference between the control and experimental treatment for the average implementability score of the participants (Z = -4.62, p <0.001). The correlation coefficient, r=0.87, exceeded the convention for large effect size as indexed by Cohen (Cohen, 1988).

4.5.4 Discussion on DHfFD Effectiveness

The controlled experiment reveals a statistically significant improvement in the output of the participants while using DHfFD cards. Table 4.4 shows the consolidated results from all the tests with the difference in mean score.

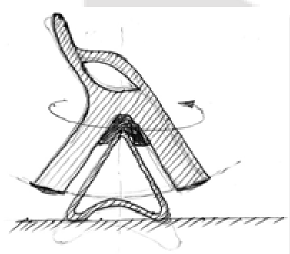
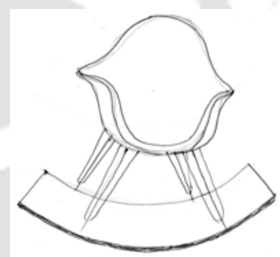
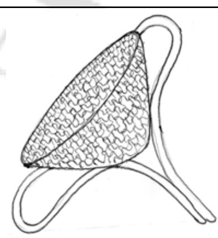
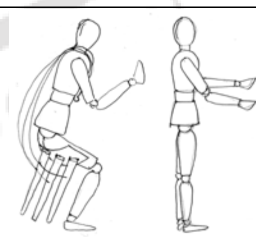
Table 4.4 The mean score and standard deviation from all the treatment phases with and without the DHfFD tool

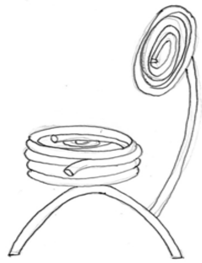
Quantity analysis								
Treatments	N	Mean	SD	SE	95% Confidence Interval for Mean		Min	Max
					Lower bound	Upper bound		
Control	28	5.00	2.00	0.38	4.22	5.78	3	12
Experimental	28	9.25	2.77	0.52	8.18	10.32	4	17
Originality analysis								
Treatments	N	Mean	SD	SE	95% Confidence Interval for Mean		Min	Max
					Lower bound	Upper bound		
Control	28	1.30	0.31	0.06	1.18	1.42	1	2.20
Experimental	28	2.81	0.55	0.10	2.59	3.02	1.25	3.63
Implementability analysis								
Treatments	N	Mean	SD	SE	95% Confidence Interval for Mean		Min	Max
					Lower bound	Upper bound		
Control	28	2.06	0.38	0.07	1.92	2.21	1.60	3.00
Experimental	28	3.06	0.36	0.07	2.93	3.21	1.75	3.67

This study clarifies that participants developed more concepts in the experimental phase with a higher average originality score and average implementability score than in the control phase. Pearson’s bivariate analysis does not reveal any inverse relationship between originality and implementability score from the experimental phase, r=(.75), N=(28), p<.001, which is contradictory to the previous research findings on creativity for the correlation between novelty and quality (Perez, 2018)(Sarkar & Chakrabarti, 2011). It may be because of the heuristic-based support. A detailed study is required in future to analyze this aspect.

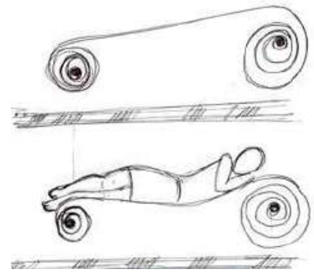
Some example cases are showcased in Table 4.5 with originality and implementability scores from the experimental phase, which also shows the heuristics used by the participants.

Table 4.5 Example cases of DHfFD use from the experimental phase

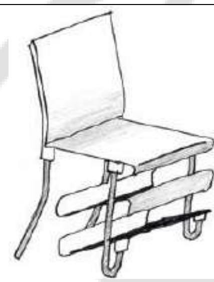
 Description: Spinning chair Heuristics: Playful Originality score: 4 Implementability Score: 2	 Description: Rocking chair Heuristics: Playful Originality score: 3 Implementability Score: 4
 Description: Coiled seat pan with the cane Heuristics: Coil Originality score: 3 Implementability Score: 4	 Description: Body extension will be used as sitting support under tension for people standing for a long duration Heuristics: Extension+Tensegrity Originality score: 3 Implementability Score: 2



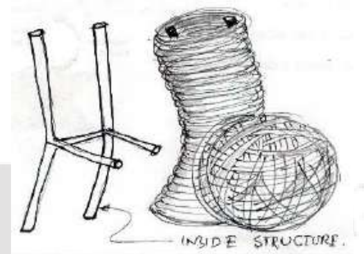
Description:
Heuristics: Coil
Originality score: 3
Implementability Score: 4



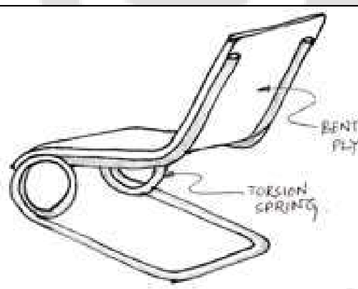
Description:
Heuristics: Extension + Coil
Originality score: 4
Implementability Score: 3



Description: Wiggle chair with storage facility
Heuristics: Wiggle
Originality score: 4
Implementability Score: 4



Description: Coiled rope around a structure
Heuristics: Coil
Originality score: 4
Implementability Score: 4



Description: Spring chair with a bent ply seat pan
Heuristics: Spring
Originality score: 4
Implementability Score: 4

Description: Rocking chair for kids with tensile fabric
Heuristics: Tensile Surface Structure
Originality score: 4
Implementability Score: 4

SECTION-B ASSESSING THE IMPACT OF TfMM

Previous research on prototyping supports has emphasized prototype making tool (Velásquez-Posada, 2005), prototyping checklist (Detand, Bastiaens, Grimonprez, & Rysman, 2010), prototyping workflow ((Hallgrimsson, 2012), prototyping strategy (Christie et al., 2012) (Camburn et al., 2013) (Dunlap et al., 2014), prototyping process (Hallgrimsson, 2012) (Exner et al., 2016), prototyping framework (Menold, Simpson, & Jablokow, 2016), prototyping canvas (Lauff, Menold, & Wood, 2019), and prototyping planner (Hansen, Jensen, Özkil, & Pacheco, 2020). Except for the prototyping tool by Velásquez-Posada, other supports are not to facilitate novice designers to make prototypes. However, Velásquez-Posada did not empirically validate the tool. As the developed tool TfMM is new, this research makes an effort to investigate the impact of the tool.

4.6 Related Work

Studies on the existing related research publications and doctoral dissertations related to prototyping supports and their evaluation were reviewed to understand the following aspects related to the assessment of the design tools:

I. **Experiment procedure:** While the success of prototyping supports is reported in publications, testing with students or registering the use of the supports in commissioned work, many of them only explain how supports are to be used. Detand et al. (Detand et al., 2010) reported the success of the prototyping checklist showcasing the commissioned work. Hallgrimsson (Hallgrimsson, 2012) explained the prototyping workflow and prototyping process with steps in detail. Table 4.6 summarizes experiment procedures adopted for the validation of various prototyping supports.

Table 4.6 Experiment procedures adopted for the validation of various prototyping supports

References	Experiment procedure	Participants	Experiment environment
(Christie et al., 2012)	qualitative assessment	mechanical engineering students	classroom setting
(Camburn et al., 2013)	between-group controlled study	senior engineering design students	university design course
(Dunlap et al., 2014)	between-group controlled study	mechanical engineering design	classroom setting
(Exner et al., 2016)	qualitative assessment	multidisciplinary team	workshop
(J. Menold et al., 2016)	between-group controlled study	junior-level mechanical engineering students	university design course
(Lauff et al., 2019)	between-group controlled study	professional designers	design innovation sprint workshops
(Hansen et al., 2020)	qualitative assessment	novice designers enrolled for the design engineering program	design challenge

II. **Evaluation metrics:** When there are many metrics available to evaluate concepts, “there is no standard method or set of metrics to evaluate prototypes” (J. D. Menold, 2017). Hence, Menold attempted to apply ideation metrics to evaluate the artefact from the prototyping phase, which comes after the concept generation phase. As there are no defined metrics to assess prototypes, most of the research on prototyping used an ordinal rating scale to evaluate the design tasks and aspects related to prototyping.

4.7 Research Methodology

A between-subjects experiment was conducted to validate the TfMM tool. Two groups of novice designers built prototypes without and with the tool. The main reason behind adopting a between-subjects experiment approach was to avoid the learning effect on participants and register differences in the output.

The experiment was conducted in four phases, as illustrated in Figure 4.17. The four phases are the control treatment phase, the experimental treatment phase, the survey phase, and the evaluation phase.

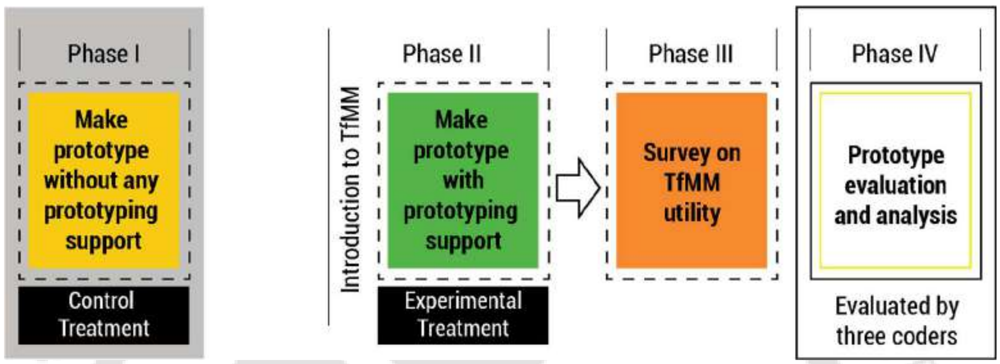


Figure 4.17 Experimental execution diagram for the validation of TfMM

Phase I provided a reference measurement of prototypes in a control condition without any support. The TfMM cards were introduced in Phase II as a stimulus for prototype making. In both phases, participants were asked to develop an appearance model of furniture.

During the survey of TfMM utility in phase III, participants were asked a set of questions to understand the perceived effects of the TfMM tool. Coders were appointed to examine and score the prototypes developed in all the phases.

4.7.1 Participants

Two different groups participated in this study. A total of 36 novice designers participated in the control treatment phase from the undergraduate design course with no prior experience in prototyping and no idea about TfMM. Out of 36 participants, 33 were male, and 3 were female. A total of 50 novice designers participated in the experimental treatment phase from the undergraduate design course with no prior experience in prototyping and no idea about TfMM. Out of 50 participants, 45 were male, and 5 were female. Figure 4.18 illustrates the sample size of each group while validating TfMM.

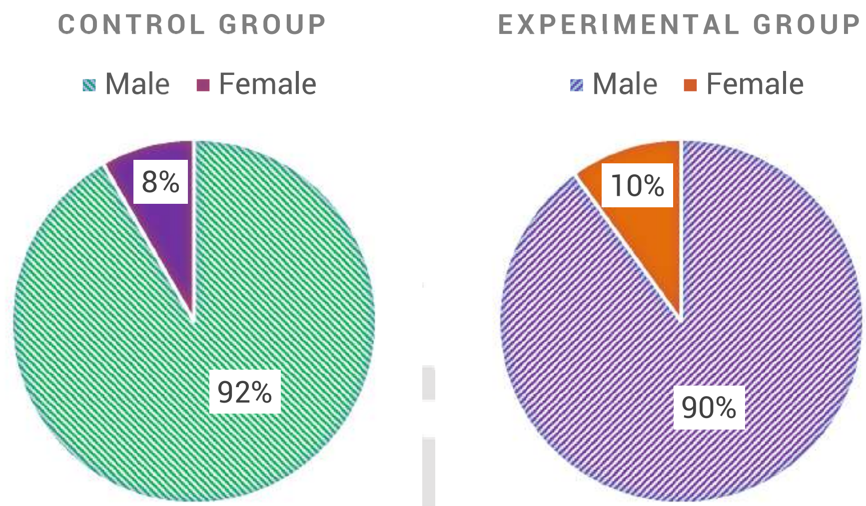


Figure 4.18 Percentages of participants in terms of gender in control and experimental groups

4.7.2 Prototyping Task

In both phases, I and II, i.e. during control and experimental treatment, the students were given an open-ended prototyping challenge and asked to produce an appearance model in 3 days.

Task Brief: Build an appearance model (scaled down) of an iconic/award-winning chair design.

4.7.3 Stimulus

This study introduced a set of TfMM cards during the experimental treatment phase. The TfMM toolset was given to all individuals for appropriate material, process, and handtool selection. All the participants received TfMM cards with dimensions 120 x 80 mm.

4.7.4 Experimental Procedure

The control treatment phase began by asking participants to make an appearance model without any tool being given. Participants got three days (21 hours) to complete the task. At the beginning of the experimental treatment phase, the TfMM tool was introduced through a lecture. During the experimental treatment phase, participants were asked to make an appearance model with the support of TfMM in three days (21 hours). Table 4.7 illustrates the experiment design for validating TfMM.

Table 4.7 Experiment design for validating TfMM

	Group	
Order of activities	Control N=36	Experimental N=50
1. Lecture on TfMM (20 min.)		X
2. Receives Prototyping Task	X	X
3. Receives Tool for Model Making Cards		X
4. Completes Design Task (21 Hrs.)	X	X

4.7.5 Survey Questions

The students were asked the following questions in Table 4.8 during the survey phase.

Table 4.8 Questions submitted to the students

Q#	Text of Questions	Scale
Q1	How effective was the tool in helping you to select materials for model-making?	(1 = Not effective, 5 = Very effective)
Q2	How effective was the tool in helping you to select model-making processes?	(1 = Very poor, 5 = Very good)
Q3	How effective was the tool in helping you to select hand tools for model-making?	(1 = Very poor, 5 = Very good)
Q4	How effective was the tool in helping you to select finishing techniques for model-making?	(1 = Not effective, 5 = Very effective)

Q5	How would you rate the appropriateness of the visual content of the tool?	(1 = Very poor, 5 = Very good)
Q6	Was there a need to explain any basic concepts during the application of the new tool?	(1 = Quite always, 5 = Not at all)
Q7	How do you find the TfMM for making an appearance model for chair design?	(1 = Not effective, 5 = Very effective)

4.7.6 Coding

Three coders analyzed and evaluated appearance models developed at the control and experimental stages in phase IV. Coders were from the background of product design with experience in design education. As three coders were not available all at a time to evaluate the whole data set, inter-coder reliability was measured using Krippendorff's alpha (α) with a random sample (20 per cent) of the data to justify inter-coder exchangeability (Hayes, 2005). The coders investigated the evidence of the use of TFMM for the corresponding appearance models developed by the participants during the experimental stage. Based on their physical properties, they evaluated all appearance models from the control and experimental phases.

4.7.7 Appearance Model Quality Score

An ordinal rating scale was used to evaluate the quality of appearance models. Based on their physical qualities, the models were rated on a scale of 1 to 10. The following aspects were considered under physical qualities during the appearance model evaluation as proposed in the literature (Houde & Hill, 1997), (Broek, Sleijffers, Horváth, & Lennings, 2000), (Pei, Campbell, & Evans, 2011) and (Hallgrimsson, 2012):

i. **Scale and proportion (spr):** The size of an appearance model can be bigger or smaller than the actual design; however, a minimum scale of 1:5 is appropriate for furniture design. Furthermore, proportional reduction of the relational components and representation of the overall form and size is essential.

ii. **Shape and surface quality (ssq):** The realistic form and texture of the model gives an understanding of the proposed design and initiate a discussion with the stakeholders.

iii. **Strength and stiffness (sst):** Structural stability and stiffness are essential, allowing the user to handle it and transport it. A flimsy model can not retain its shape for long, and achieving good resolution on a flimsy model is a challenge.

iv. **Resolution and fidelity (rf)**: Resolution means the "amount of appearance details" or sophistication corresponding to the fidelity, whereas fidelity refers to "closeness to the eventual design".

v. **Material and processes (mp)**: According to the economic principle of prototyping, the simplest and most efficient material and processes deliver prototypes that showcase visible and measurable possibilities and limitations.

A highly defined three-point rating scale was used for assessing each aspect inspired by the quality scale proposed by Julie Stahmer Linsey (Linsey, 2007) so that the cumulative score becomes 10. Figure 4.19 illustrates the highly defined rating scale for assessing each aspect.

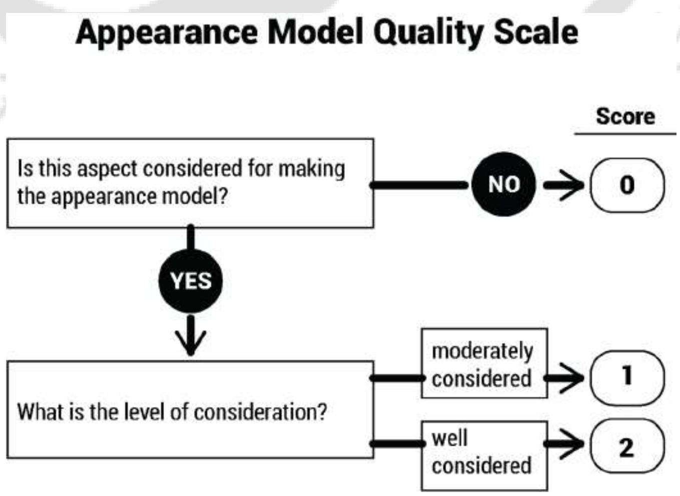


Figure 4.19 Quality scale for assessing each aspect of the appearance model Quality scale

The Cumulative Appearance Model Quality Score (CAMQS) was assigned following the procedure outlined in Figure 4.20.

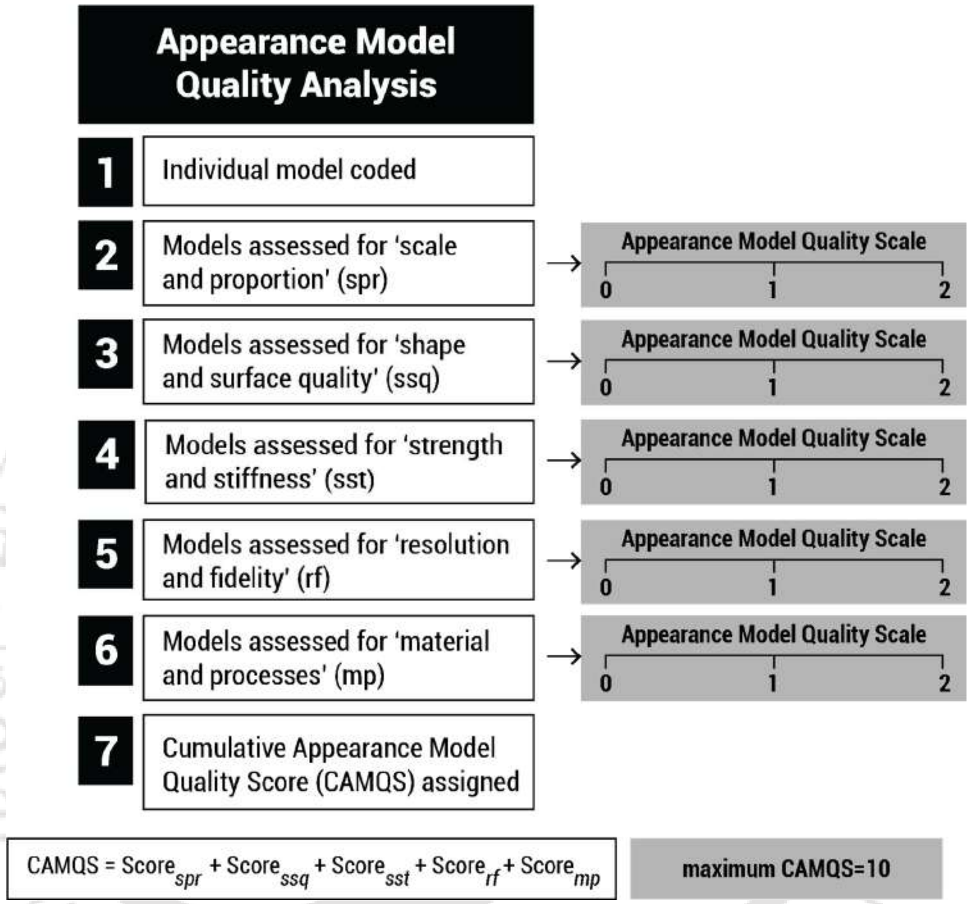


Figure 4.20 Appearance model analysis procedure

4.8 Qualitative Impact Assessment of TfMM Cards: Results and Discussions

4.8.1 Major Findings from Phase I

In phase I, during control treatment, 36 participants completed the task of developing an appearance model of an iconic chair design. The deliverables at this phase without any support of technique/tool showcased the following:

i. out of scale and disproportionate models
ii. inappropriate surface treatment leads to a shoddy model

iii. flimsy model

iv. models with inaccurate details

v. incomplete submission

vi. material-process mismatch with the form

Some of the examples of the issues mentioned above are shown in Figure 4.21. Lack of understanding of material properties and process understanding is the possible reason behind these issues, which satisfies the previous research.

Figure 4.21 Appearance models from phase I

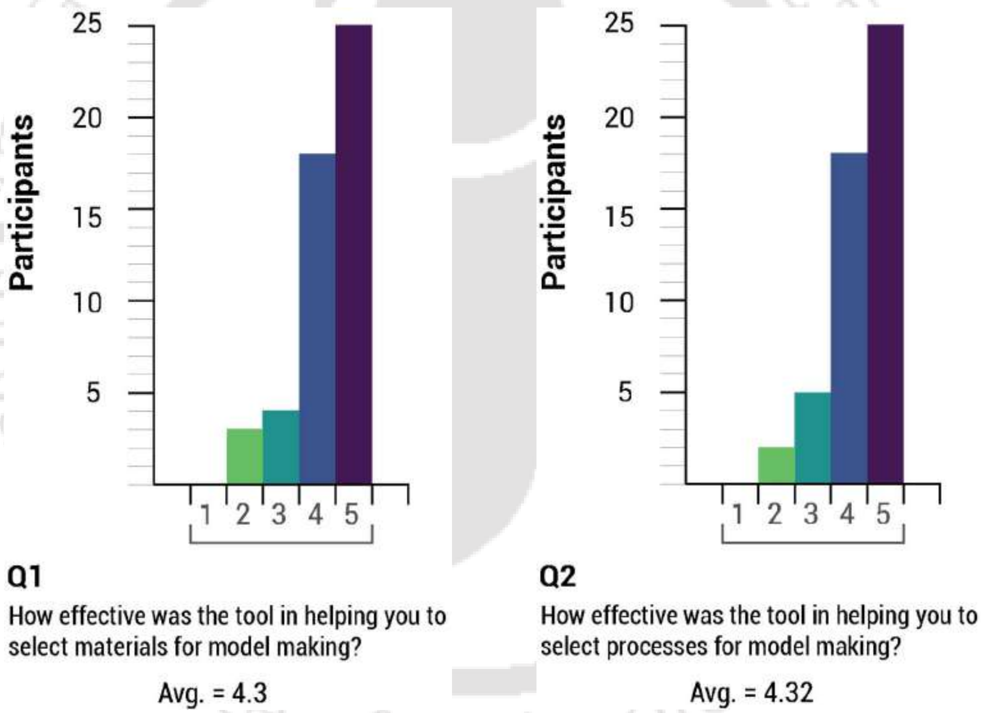
4.8.2 Major Findings from Phase II

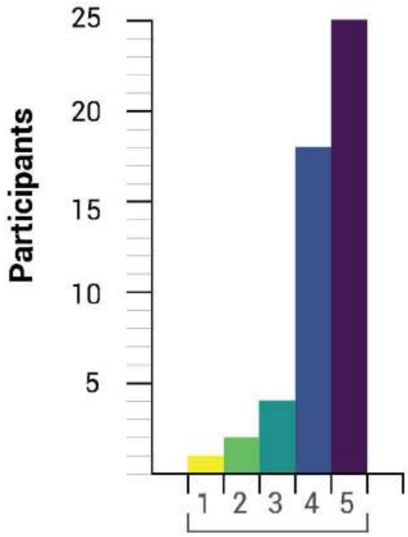
In phase II, during experimental treatment, 50 participants completed the task of developing an appearance model of an iconic chair design. The appearance models at this phase were substantially improved with TfMM support in terms of the following aspects, as mentioned in Figure 4.22.

Figure 4.22 Appearance models from phase II

4.8.3 Major Findings from Phase III

In Phase III, during the survey phase, participants from the experimental group were asked various questions to understand how the participants perceived the TfMM tool. Participants were asked questions as listed in section 4.7.5. Along with the questions, participants were requested to register their responses on a Likert scale from 1-5. It is evident from the results and responses that the tool helps in appearance model-making, and overall the perspective of the students towards the TfMM tool is positive, which reflects on the histograms of responses to the questions asked in phase III. The responses are visually summarized in Figure 4.23.

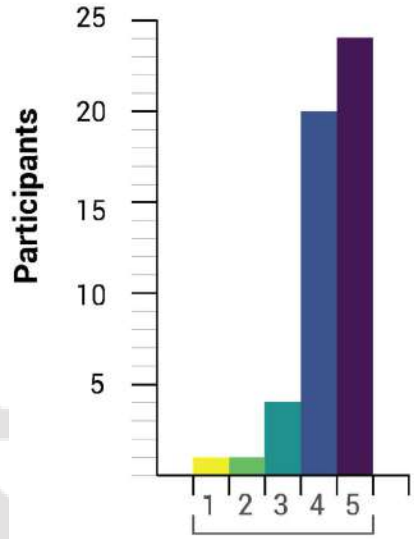




Q3

How effective was the tool in helping you to select hand tools for model making?

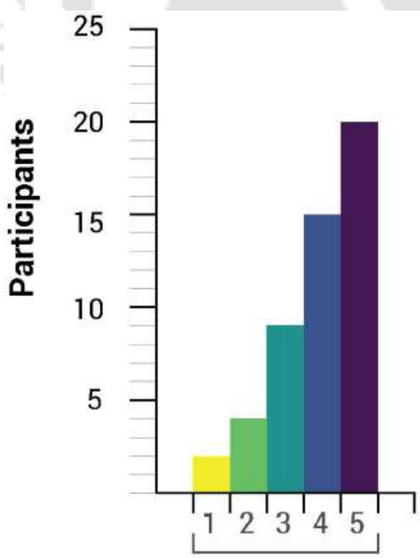
Avg. = 4.28



Q4

How effective was the tool in helping you to select finishing techniques for appearance model making?

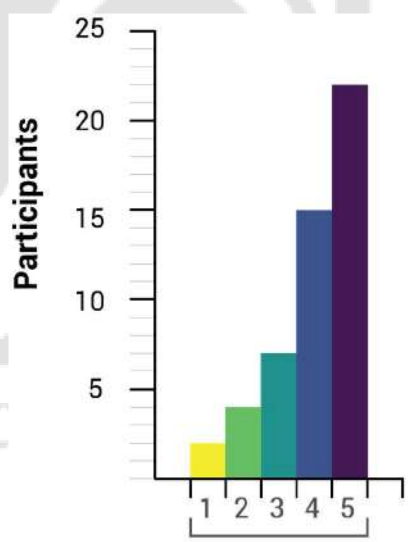
Avg. = 4.3



Q5

How would you rate the appropriateness of the visual content of the tool?

Avg. = 3.94



Q6

Was there a need to explain any basic concepts during the application of the tool?

Avg. = 4.02

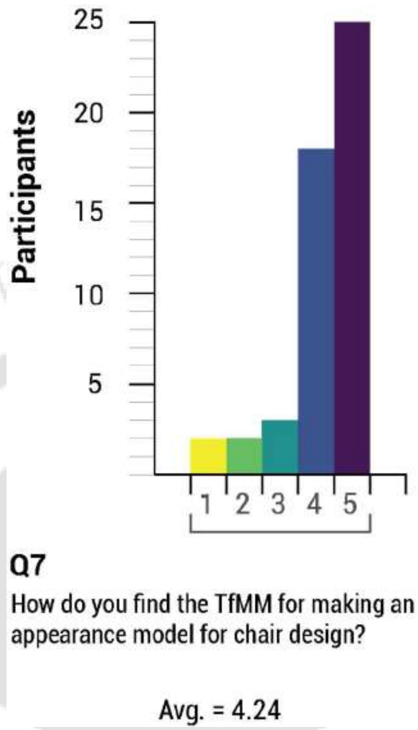


Figure 4.23 Responses of the participants in phase III of the TfMM assessment

During the discussion with the participants, positive responses related to the tool were recorded. Furthermore, issues and feedback related to the following aspects were registered:

- ***Visual content**:* A few participants found the visual content presented in the tool card cumbersome and overwhelming. It is because more content is presented in a small space (120x80 mm).
- ***Understanding**:* A few participants could not co-relate the elements of the selected chair with the materials, processes, and tools. Post-experiment discussion revealed that the participants looked for cards with the same furniture as a reference to co-relate materials, processes, and tools. Unable to match the exact card disappointed a few participants and led to disappointment.

4.9 Quantitative Impact Assessment of TfMM Cards: Results and Discussions

4.9.1 Appearance Model Quality Analysis Results

The appearance model quality score was calculated following the procedure discussed in section 4.7.7. The Shapiro-Wilk normality test showed $p<0.05$ for both the control and experimental groups, which eliminated the independent samples t-test as an option to check the difference between the experimental and control classes. The Mann-Whitney U test was chosen as it is a rank-based nonparametric test alternative to the independent t-test. The Mann-Whitney U test using an exact sampling distribution of U showed a statistical difference in 'appearance model quality scores' between the experimental and control group ($U=497.5$, $z= -4.814$, $p<0.05$). The correlation coefficient, $r= 0.52$, was calculated to interpret the effect size for nonparametric data (Fritz et al., 2012) estimates the large effect size as indexed by Cohen (Cohen, 1988). The boxplot shows the distribution of the appearance model quality score for the control and experimental groups in Figure 4.24. The result highlights an advantage of using TfMM for appearance model-making for novice designers.

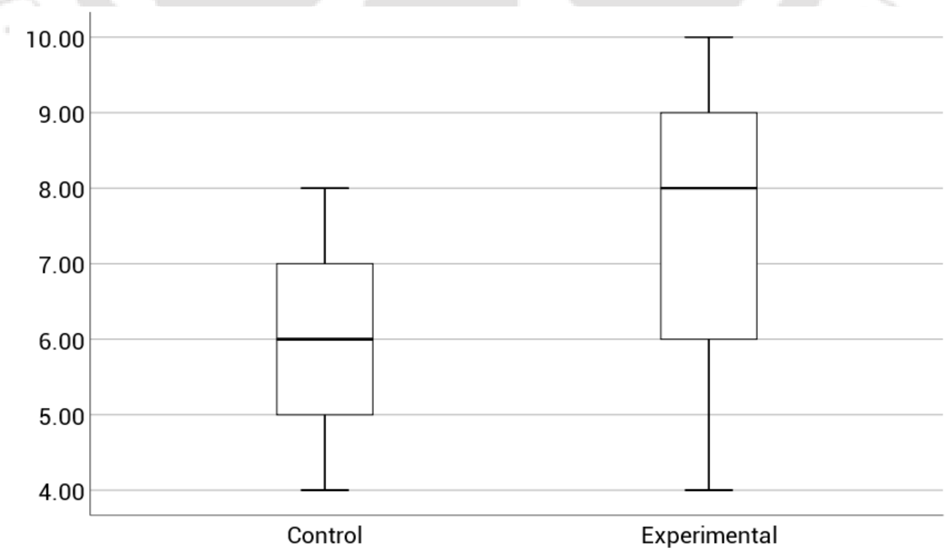


Figure 4.24 Distribution of the appearance model quality score for the control and experimental groups

4.9.2 Discussion on TfMM Effectiveness

The control experiment for TfMM effectiveness shows that participants from the experimental group delivered appearance models with better quality than the control group. It also reveals a statistically significant improvement in the appearance model quality score for the experimental group using TfMM cards. Table 4.9 shows the consolidated results from all the tests with the difference in mean score.

Table 4.9 The mean score and standard deviation from all the treatment phases with and without the TfMM tool

Appearance Model Quality analysis								
Treatments	N	Mean	SD	SE	95% Confidence Interval for Mean		Min	Max
					Lower bound	Upper bound		
Control	36	6.00	1.07	0.18	5.64	6.36	4	8
Experimental	50	7.72	1.67	0.24	6.98	8.19	4	10

This study satisfies the effectiveness of the TfMM tool for appearance model-making. It also confirms the previous research on the impact of structured prototyping methods in increasing novice designers' self-efficacy in the prototyping process (J. D. Menold, 2017). Some example cases are showcased in Table 4.10 with high Cumulative Appearance Model Quality Scores from the experimental phase.

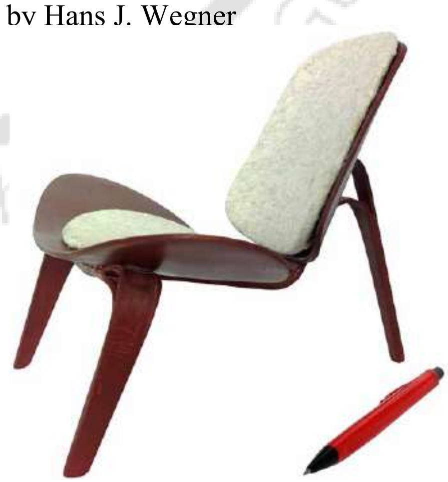
Table 4.10 Example cases of DHfFD use from the experimental phase

Original design: Knotted Chair by Marcel Wanders
CAMQS: 10

Original design: Sagano Chair by Alice Minkina
CAMQS: 8

Original design: Saddle Seat Chair by Masahiko Ito
CAMQS: 9

Original design: Shell Chair, Model CH07 by Hans J. Wegner
CAMQS: 10



Original design: Wassily Chair by Marcel Breuer
CAMQS: 8

Original design: Festival Hall 658 Chair by Robin Day
CAMQS: 7

Original design: Plastic Side Chair DSW by Charles and Ray Eames
CAMQS: 8

Original design: Red and Blue Chair by Gerrit Thomas Rietveld
CAMQS: 10

Original design: Multichair by Joe Colombo
CAMQS: 10

Original design: Woopy Chair by Karim Rashid
CAMQS: 9

SECTION-C CASE STUDY OF THE APPLICATION OF DHfFD AND TfMM IN COMBINATION

This section discusses the application of the tools in design thesis projects. The following are the objectives: i) to check the effectiveness of these tools beyond the controlled experiment, ii) to validate these tools in real design projects completed by novice designers and iii) to make a comprehensive recommendation to use these tools. DHfFD and TfMM were introduced in long-term thesis projects to check the outcome of the projects after applying the tools in combination. These projects were carried out by students from a postgraduate programme in design at the Department of Design, Indian Institute of Technology Guwahati, India. Having a background of Bachelor of Engineering, students completed a year in the Master of Design programme before starting their thesis projects. Two classic case studies are presented here which got international recognition.

4.10 Case Study 1: DOT Furniture Design

4.10.1 Conceptualization

This concept was developed using the DHfFD card ‘modular’. The side view of the final design resembled the dot-connecting game, which inspired to name of the chair ‘DOT’. The design philosophy was to deconstruct a chair into usable and useful units to allow the user to construct furniture of their own choice. DOT enable people to construct ‘n’ a number of furniture of their own choice for specific purposes. Design for human variability is the unique feature of the design, which gives maximum comfort to people. Figure 4.25 illustrates the modular arrangements of the DOT chair for different contexts.

Figure 4.25 Modules and modular arrangements of the DOT chair for different contexts

4.10.2 Prototyping

The appearance model was built using the TfMM card 'Bar and Panels'. Figure 4.26 shows a brief look at the glimpsed appearance model-making, and Figure 4.27 of full-scale prototyping of the DOT chair.

Figure 4.26 A few glimpses of appearance model-making of DOT chair

Figure 4.27 A few glimpses of full-scale prototyping of the DOT chair

The prototyping process in sequence and manifestation dimensions for the DOT chair are explained in Table 4.11.

Table 4.11 Prototyping process in sequence and manifestation dimensions for DOT chair

Mock-up	Appearance model	Final prototype
		
Material: Corrugated Cardboard, bamboo skewers	Material: Acrylic sheet 5mm, nylon rod 5mm diameter	Material: Medium Density Fiberboard 25mm, mild steel rod 25 mm diameter
Resolution: Rough and simplified model to communicate to the internal design team	Resolution: Detailed and sophisticated model to communicate to all the stakeholders	Resolution: Detailed, sophisticated full-scale prototype, same as the final product
Scope: Limited to understand the form feature and proportion	Scope: Limited to understand the form feature and proportion	Scope: Same as the final product to experience form and function features.

4.10.3 International Recognition

The DOT chair was shortlisted to showcase at Global Grad Show Dubai in 2017. Global Grad Show is an initiative by the Art Dubai Group to showcase graduate thesis projects from universities worldwide whose research and ideas offer innovative solutions to solve major social and environmental issues. Global Grad Show reveals its innovators through a yearly showcase complementing knowledge exchange, entrepreneurship opportunities and international exposure. Figure 4.28 illustrates the chair assembly and glimpses of the Global Grad Show Dubai 2017.

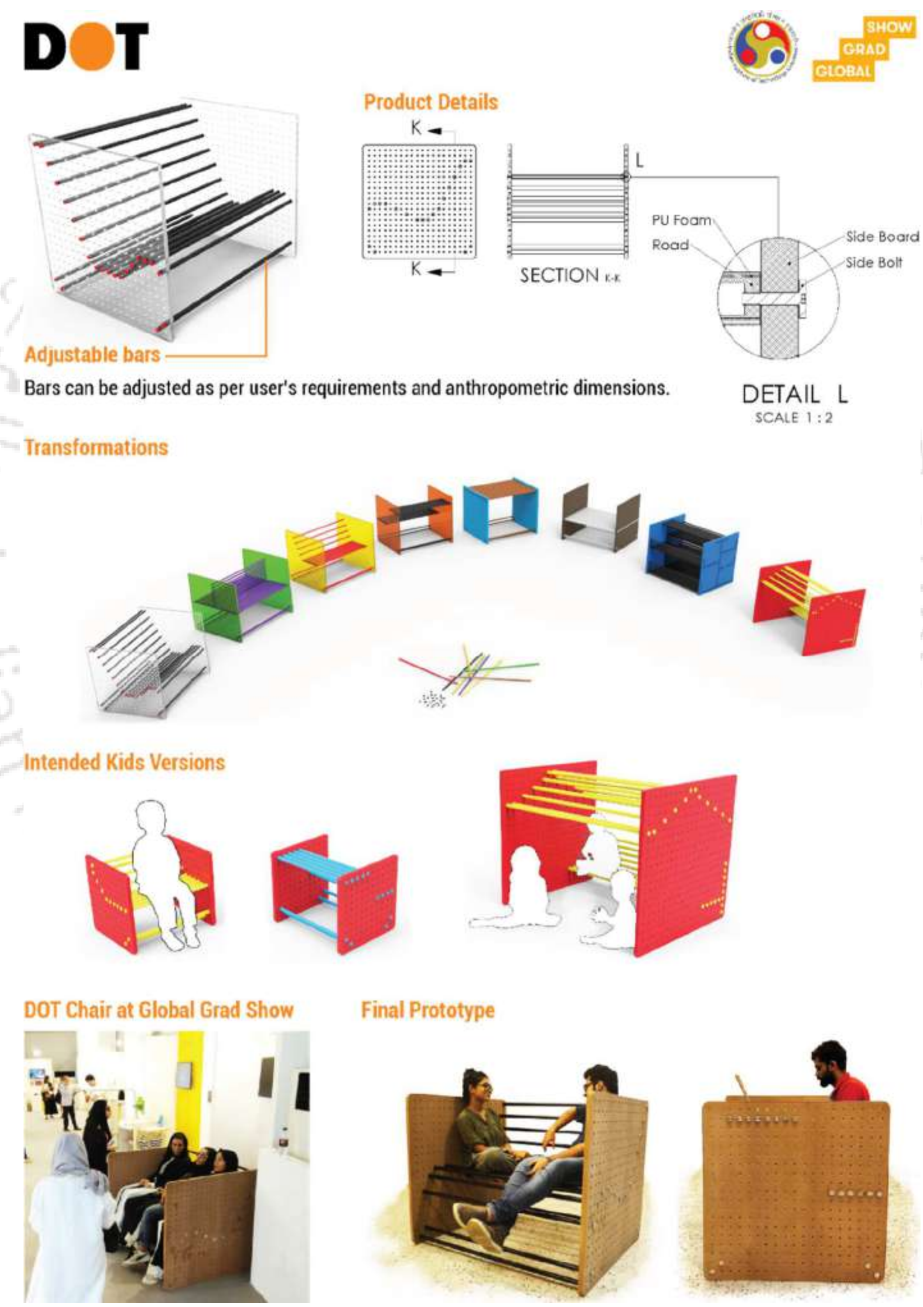


Figure 4.28 DOT chair assembly details and final prototype at Global Grad Show

4.11 Case Study 2: DHOLM Furniture Design

4.11.1 Conceptualization

This concept was developed using the DHfFD card 'Experimental Material & Process' and used to create a chair piece. Several experiments were carried out to create a new natural composite. In this case, natural aromatic resin '**Dho**op' and fibres from 'Pa**lm**' leaf sheath was used to make a composite; thus, the concept design was named 'Dholm'. The design philosophy was to transform nostalgic memories into objects that withhold nostalgic memories to disappear from our conscious thoughts. Dholm would help recollect the early childhood memories of unsophisticated, unwheeled, pulled transportation dramatic play with the palm leaf/areca nut leaf in Northeast India. After successfully creating a composite, the form of the chair was finalized that reflects DHfFD card 'Rocking'. The explorations with the materials and exploration of the form of the chair are showcased in Figure 4.29.

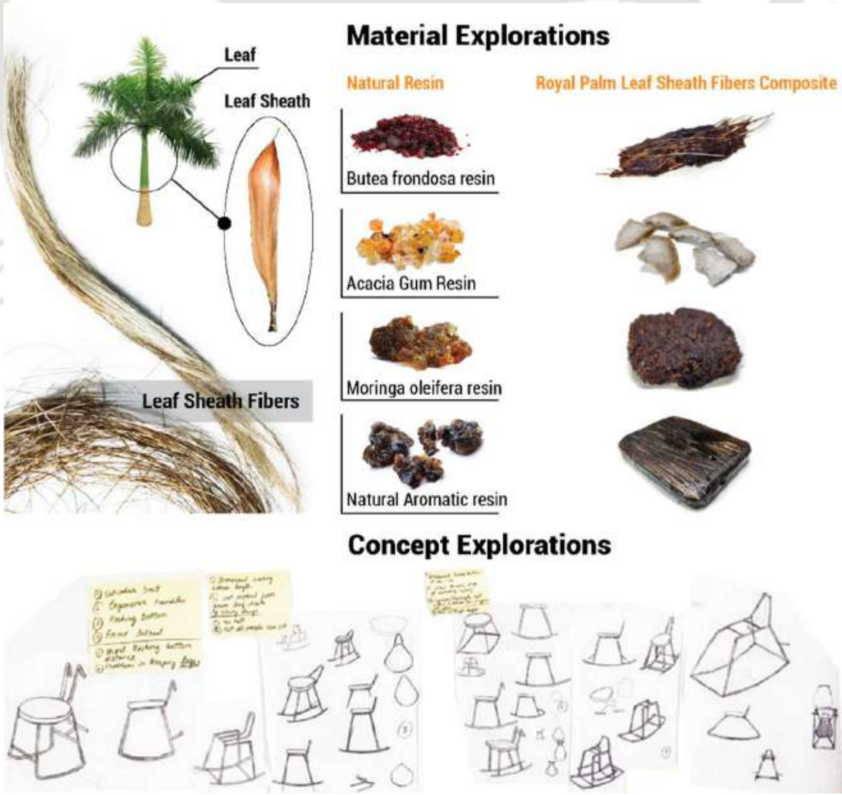


Figure 4.29 Material and concept exploration of the Dholm chair

4.11.2 Prototyping

The appearance model was built using the TfMM card 'Bar and Panels'. Figure 4.30 shows a brief look at the glimpsed appearance model-making, and Figure 4.31 of full-scale prototyping of the DHOLM chair.

Figure 4.30 A few glimpses of the appearance model-making of the DHOLM chair

Figure 4.31 A few glimpses of full-scale prototyping of the DHOLM chair

The prototyping process in sequence and manifestation dimensions for the DHOLM chair are explained in Table 4.12.

Table 4.12 Prototyping process in sequence and manifestation dimensions for the DHOLM chair

Mock-up ⇨	Appearance model ⇨	Final prototype
		
Material: Rattan reed, expanded polystyrene (EPS) foam,	Material: Mild steel 5mm diameter, MDF 10mm	Material: Brass rod 10mm, Royal palm sheath fiber composite 20mm thickness
Resolution: Rough and simplified model to communicate to the internal design team	Resolution: Modified, detailed and more sophisticated model compared to mock-up to communicate to all the stakeholders	Resolution: Detailed, sophisticated full-scale prototype, same as the final product
Scope: Limited to understand the form feature and proportion	Scope: Limited to understand the form feature and proportion	Scope: Same as the final product to experience form and function features.

4.11.3 International Recognition

The DHOLM chair was shortlisted for pre-selection for the Green Concept Award 2022. The Green Concept Award recognizes products and services concepts from established businesses, start-ups, and students for excellence in sustainability, design, and innovation. Since 2013, the Award has made 'best practice' examples available to a broad public on an international scale from a pool of 1500 submission entries. Figure 4.32 illustrates the DHOLM chair assembly showcased on the Green Concept Award website.

Figure 4.32 DHOLM chair showcased on the Green Concept Award website

4.12 Discussion on the Case Studies

The long-duration project case studies and their success show acceptance and effectiveness. Project deliverables reflect the application of DHfFD and TfMM cards. As the cards were derived from successful innovative products, the project deliverables were also recognized on international platforms. Because of the availability of the resources, both projects explored multiple possibilities within the scope and guidelines suggested by DHfFD and TfMM cards. Though TfMM cards do not suggest how to make full-scale prototyping, it was observed that appearance model-making gave an understanding of the materials and processes that helped to create full-scale prototypes. However, the impact of model-making knowledge in full-scale prototyping is a matter of future research investigation.

4.13 Summary

This chapter assessed the impact of the structured concept generation tool, Design Heuristics for Furniture Design (DHfFD) and Tool for Model Making (TfMM) to understand the effect of DHfFD on creative concept generation and TfMM on model-making by novice designers. The effectiveness of DHfFD and TfMM was analyzed through qualitative impact assessment, quantitative impact assessment and introducing DHfFD and TfMM in combination in long-duration thesis projects. Section-A discusses the impact assessment of DHfFD. The qualitative impact assessment shows the positive impact of the tool on idea generation and reveals that novice designers perceived the toolset well. The quantitative impact assessment on quantity, originality and implementability shows statistically significant improvement in the experimental group compared to the control group. Section-B discusses the impact assessment of TfMM. The qualitative impact assessment shows the positive impact of the tool on appearance model-making, and the tool is well-received by novice designers. The quantitative impact assessment on the appearance model quality shows statistically significant improvement of the experimental group compared to the control group in terms of scale and proportion, shape and surface quality, strength and stiffness, resolution and fidelity, and material and processes. Finally, Section-C discusses the impact of the DHfFD and TfMM in combination with thesis projects. The designs from the thesis projects received international recognition, which satisfies the effectiveness of the tools in combination.

Design Heuristics for Furniture Design

and

Tool for Model Making

Chapter 5

Designing with DHfFD and TfMM cards

5.1 Introduction

This chapter presents 86 DHfFD, and 65 TfMM cards developed and validated in the previous chapters. This chapter also discusses the proposed method of using DHfFD and TfMM Cards.

SECTION-A DHfFD and TfMM Cards

5.2 DHfFD Cards

This section presents an improved version of the card set with similar content based on the feedback and graphic design principles. Figure 5.1 illustrates the anatomy of a TfMM card:

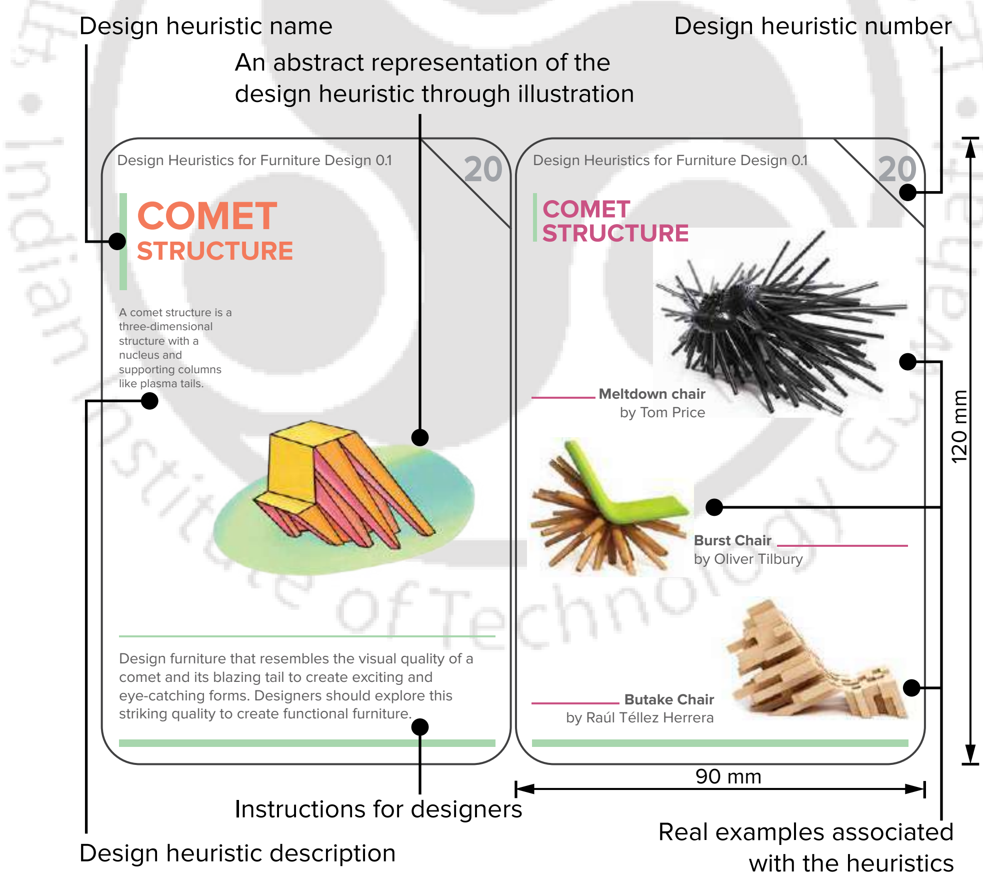


Figure 5.1 Improved version of DHfFD card with different elements

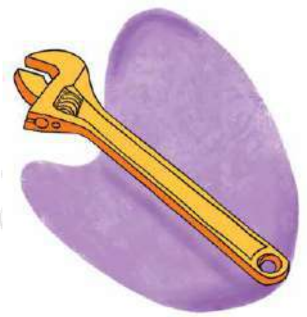
Following are the 86 DHfFD cards developed as a part of this research.

Design Heuristics for Furniture Design 0.1

01

ADJUSTABLE

Things that have the flexibility of being changed according to the requirement to make it suitable to the case are adjustable.



Design the function of furniture with adjustable parameters, such as height, width, rotation, etc., to address human and context variability. Designers must explore possibilities to include features such as rearranging, reorienting, reconfiguring, flexibility etc., to be done manually or automatically.

Design Heuristics for Furniture Design 0.1

01

ADJUSTABLE

Flip chair
by Marco Hemmerling

Fauld Chair
by Andy Gilles

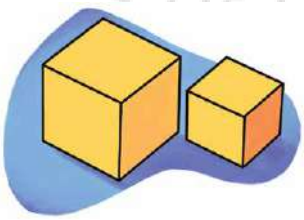
Ladder Chair
by KIDS DESIGN LABO

Design Heuristics for Furniture Design 0.1

02

ALTERED GEOMETRY

Altered geometry describes anything that has been modified in terms of geometry.



Design or redesign chairs, altering the geometry in accordance with different contexts or different visual perceptions. Designers must modify designs in terms of length, breadth, height, depth, shape and relative arrangement of the parts.

Design Heuristics for Furniture Design 0.1

02

ALTERED GEOMETRY

Kinderstoel
by Gerrit Thomas Rietveld

Hogestoel
by Gerrit Thomas Rietveld

Orgone Chair
by Marc Newson

Alufelt chair
by Marc Newson

Fauteuil Uncut
by Ron Arad

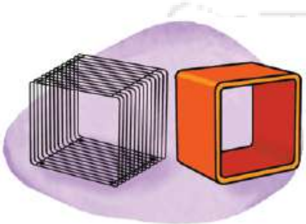
Tom VAC
by Ron Arad

Design Heuristics for Furniture Design 0.1

03

ALTERED
FORM ELEMENT

Altered form element describes a change in the existing elements (bar/body/surface) with other elements; ex- change surface to bar.



Design or redesign chairs, altering the form elements in accordance with different user requirements and different contexts. Designers must explore possibilities by changing existing form elements with other form elements. For example, change the surface to a bar.

Design Heuristics for Furniture Design 0.1

03

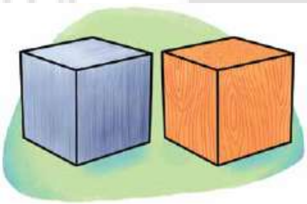
ALTERED
FORM ELEMENT

Design Heuristics for Furniture Design 0.1

04

ALTERED
MATERIAL

Altered material describes a change (add/delete/merge) in material(s) in any part or whole.



Design or redesign chairs, altering the existing material in accordance with different user requirements and different contexts. Designers must explore possibilities to alter material or composites of any part or the whole.

Design Heuristics for Furniture Design 0.1

04

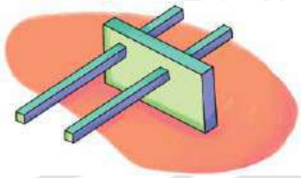
ALTERED
MATERIAL

Design Heuristics for Furniture Design 0.1

05

BAR
AND PANELS/SURFACE

The combination of bars and panels signifies a super-unit form composed of bars and panels in different orientations.



Design furniture by creating compositions, establishing the difference in proportion between a ‘body’ and a ‘surface’, in which these elements play functional roles. Designers must explore the dimensions of each of these elements to explore their functional possibilities.

Design Heuristics for Furniture Design 0.1

05

BAR
AND PANELS

Red and Blue Chair
by Gerrit Thomas Rietveld

Handcrafted Chair
BY Klein Agency

K1 Chair
by Marta Adamczyk

Design Heuristics for Furniture Design 0.1

06

BENT
SURFACE

Bent surface is the result of plastic deformation into a curve of any material surface by forming processes under heat and pressure. There are two ways to achieve bent surfaces, laminating and moulding.

Design furniture by exploring the different formations created by bending surfaces and the functions they may cater to. Designers must explore different dimensions, material choices and functionality of different formations created by bending surfaces in space.

Design Heuristics for Furniture Design 0.1

06

BENT
SURFACE

'LCW' lounge Chair
by Charles & Ray Eames

Well Tempered Chair
by Ron Arad

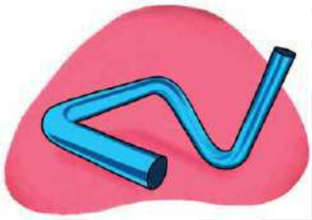
Oto chair
by Peter Karpf

Design Heuristics for Furniture Design 0.1

07

BENT
TUBE/BAR

A hollow tube or solid bar that is not flat is called a bent or curved tube/bar. It may be single curved or multiple curved.



Design furniture by exploring the different formations created by bending bars and the functions they may cater to. Designers must explore different dimensions, material choices and functionality of different formations created by bending bars in space.

Design Heuristics for Furniture Design 0.1

07

BENT
TUBE/BAR

Steel tube bending chair
by Thomas Feichtner

Bold Tubular Chair
by Big-Game

Line chair
by Toni Grilo

Design Heuristics for Furniture Design 0.1

08

BIOS
FORM

Form mimicking animal, human figure, or natural element to seek attention and mesmerize called bios form.

Design furniture with forms that are inspired by natural forms or features. Designers should explore the relationship between the furniture's aesthetics and function with the natural features.

Design Heuristics for Furniture Design 0.1

08

BIOS
FORM

Prickly Pair Chairs
by Valentina Gonzalez Wohlers

Puppy
by EeroAarnio

Dodo rocking bird
by Oiva Toikka

Design Heuristics for Furniture Design 0.1

09

BIOPHILIC (FDLOs)

Biophilia and biophilic design propose a reconnection with nature. Furniture design embedding living organisms is a section in the biophilic design called Furniture Design with Living Organisms (FDLOs).

Design furniture by incorporating nature or living organisms. Designers must explore how nature or living organisms can be a part of the furniture based on the context and aesthetic requirements.

Design Heuristics for Furniture Design 0.1

09

BIOPHILIC (FDLOs)

Mycelium Chair
by Eric Klarenbeek

Mirror Chair with magnifying glass and planter
by Guangcai Yin and Sha Yang

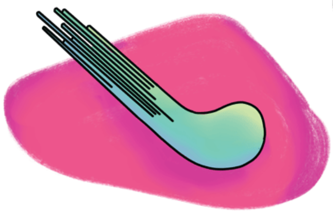
The Inner Life Nature Chair
By Martin Azua

Design Heuristics for Furniture Design 0.1

10

BRUSHSTROKE

Brushstroke in this context is a three-dimensional form that resembles the mark made by a paintbrush.



Design furniture that resembles the visual quality of a brushstroke. Designers must experiment with the different materials to represent a brushstroke as per the functional requirements.

Design Heuristics for Furniture Design 0.1

10

BRUSHSTROKE

SIE17 by
Pawel Grunert

Yoda Easy Chair
by Kenneth Cobonpue

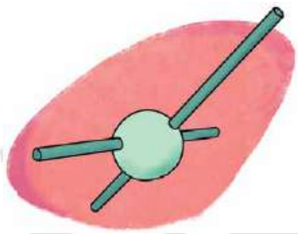
Tea Ceremony Chair
Hiroki Takada

Design Heuristics for Furniture Design 0.1

11

BODY
AND BAR

The combination of body and bar signifies a super-unit form composed of body and bars in different orientations.



Design furniture by creating compositions, establishing the difference in proportion between a 'body' and a 'bar', in which these elements play functional roles. Designers must explore the dimensions of each of these elements to explore their functional possibilities.

Design Heuristics for Furniture Design 0.1

11

BODY AND BAR

Wingback Lounge chair
by Tom Dixon

Embryo chair
by Marc Newson

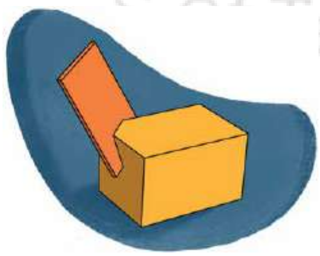
Pipe Sofa
by Sebastian Herkner

Design Heuristics for Furniture Design 0.1

12

BODY
AND SURFACE

The body and surface/panel combination signify a super-unit form composed of different body and surfaces/panel orientations.



Design furniture by creating compositions, establishing the difference in proportion between a 'body' and a 'bar', in which these elements play functional roles. Designers must explore the dimensions of each of these elements to explore their functional possibilities.

Design Heuristics for Furniture Design 0.1

12

BODY AND SURFACE

Cradle
by Benjamin Hubert

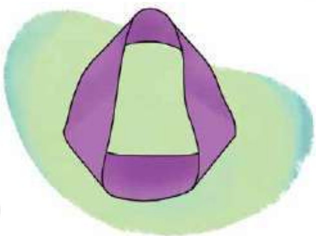
Keno' chair
by Noora Liesimaa

Cut chair
by Toni Grilo

Design Heuristics for Furniture Design 0.1 13

BUCKLED RIBBON

Buckled ribbon hoop is a deformed circular band of ribbon with applied force at one or multiple points.



Design furniture forms inspired by deformed ribbon hoops, exploring functional possibilities by playing with its spread and orientation. Designers must explore the relationship between the surface orientations and the functions they can support.

Design Heuristics for Furniture Design 0.1 13

BUCKLED RIBBON

Perillo
by Martin Ballendat

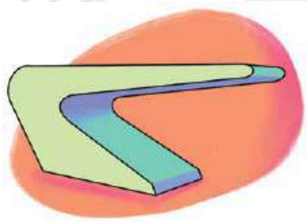
Nike2007 chair/stool
by Hiroki Takada

Lyubkka Chair
by Studio Nuvist

Design Heuristics for Furniture Design 0.1 14

CANTILEVER

A cantilever is a rigid structural element projecting one end beyond the support point.



Design furniture inspired by a cantilever support structure with rigid support at one end, which bears the load of the other non-supported ends. Designers should use cantilever structure mechanics to create striking and explorative forms to create aesthetic and functional pieces.

Design Heuristics for Furniture Design 0.1 14

CANTILEVER

Vitra Panton Chair
by Verner Panton

Cantilever Lounge Chair
by Alvar Aalto

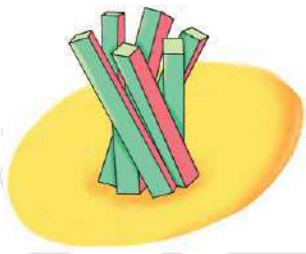
Vondom Vertex Chair
by Karim Rashid

Design Heuristics for Furniture Design 0.1

15

CENTRALLY ORGANIZED LATTICE

A centrally organized lattice means a bundle of bars or bar forms of any cross-section and height arranged in radiation and forming a circular shape around the vertical axis.



Design furniture by organizing members around a central axis. Designers should experiment with the shapes and orientation of these members to incorporate functionality.

Design Heuristics for Furniture Design 0.1

15

CENTRALLY ORGANIZED LATTICE

Maria Chair
by Raul Herrera Téllez

Nest
by Markus Johansson

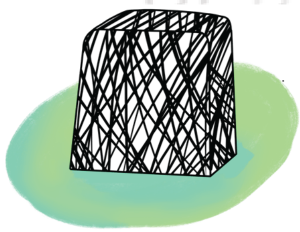
Stick Chair
by Carlo Volf

Design Heuristics for Furniture Design 0.1

16

COBWEB

Cobweb refers to a three-dimensional structure that seems constructed by tangled fibres. Cobweb is woven with an irregular pattern of fibres, often asymmetrical, but not necessarily.



Design furniture inspired by the structure of cobwebs to showcase order in chaos. Designers should explore the different ways of creating such forms, materials, and processes.

Design Heuristics for Furniture Design 0.1

16

COBWEB

Moooi Carbon Chair
by Bertjan Pot and Marcel Wanders

Carbon fiber C-stone
by Peter Donders

Random Chair
by Bertjan Pot

Design Heuristics for Furniture Design 0.1 17

COCOON/POD

A cocoon or pod is a self-contained, isolated unit that encapsulates the inside entity from the outer world with the help of the outer envelope in a protective or comforting way.

Design furniture by incorporating the features of a cocoon to create an enclosed, pod-like form to isolate the user, letting them have their personal space. Designers should explore the different functions or emotions such forms bring about in people.

Design Heuristics for Furniture Design 0.1 17

COCOON/POD

Squishy monster fishy!
by Jason Goh

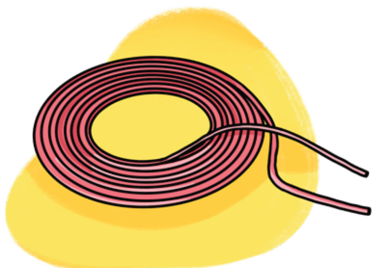
Capsule Chair
by Kateryna Sokolova

Tink Things
by Benussi&theFish

Design Heuristics for Furniture Design 0.1 18

COIL

A coil is something rounded into a spiral or a series of such spirals by gathering or winding one above the other.



Design furniture forms using the coiling technique. Designers should explore several coiling techniques from other disciplines and modify them to create functional furniture.

Design Heuristics for Furniture Design 0.1 18

COIL

Tamashii chair
by Anna Stepankova

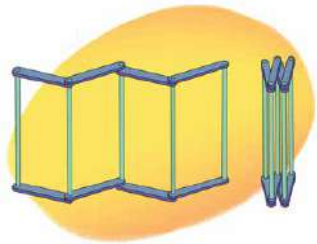
Sagano Chair
by Alice Minkina

Coiling chair
by Yael Mar and Shay Alkalay

Design Heuristics for Furniture Design 0.1 19

COLLAPSIBLE

Collapsible mechanisms are defined as those that allow post-compression collapsing of a structure.



Design furniture that can be folded out for use and folded back to save space. Designers should explore different principles of collapsibility and look at related examples of mechanisms to realize this feature.

Design Heuristics for Furniture Design 0.1 19

COLLAPSIBLE

Lu Chair
by Edoardo Accordi

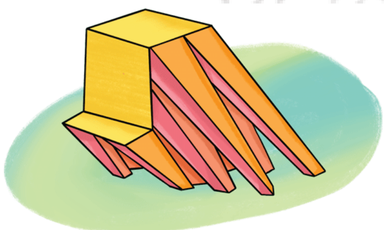
Two faced chair
by Chrsitian Desile

Rising Chair
by Robert van Embricqs

Design Heuristics for Furniture Design 0.1 20

COMET STRUCTURE

A comet structure is a three-dimensional structure with a nucleus and supporting columns like plasma tails.



Design furniture that resembles the visual quality of a comet and its blazing tail to create exciting and eye-catching forms. Designers should explore this striking quality to create functional furniture.

Design Heuristics for Furniture Design 0.1 20

COMET STRUCTURE

Meltdown chair
by Tom Price

Burst Chair
by Oliver Tilbury

Butake Chair
by Raúl Téllez Herrera

Design Heuristics for Furniture Design 0.1

21

CONCAVITY & CONVEXITY

Forms featuring positive and negative volumes in juxtaposition to create functional and aesthetic furniture.

Design furniture that creates an interplay between positive and negative volumes that can be very organic, inherently creating softer, fluid forms to support or comfort the user. Designers should explore this quality to create functional furniture.

Design Heuristics for Furniture Design 0.1

21

CONCAVITY & CONVEXITY

Egg Chair
by Arne Jacobsen

UP5 Donna Chair
by Gaetano Pesce

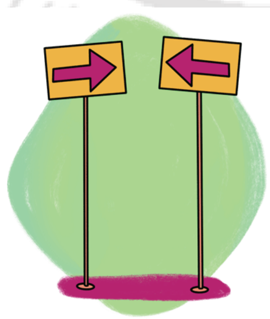
Rocking chair Voido
by Ron Arad

Design Heuristics for Furniture Design 0.1

22

CONTRADICTION

Contradiction is a situation of a combination of features opposite to each other.



Design furniture that contradicts the perception it creates. Such furniture has an element of surprise that can make people think or want to inspect it further. Designers should explore bipolar characteristics to embed in their designs to make people stop and ponder.

Design Heuristics for Furniture Design 0.1

22

CONTRADICTION

Superleggera Chair
by Gio Pont

Anodized Aluminum Chair
by Yeon Jinyeong

The Spurt Lounge Chair
by Paulsberg

Design Heuristics for Furniture Design 0.1 **23**

CORD/STRAP
AND BAR STRUCTURE

A cord is a flexible string made by extruding a material or several strands braided, twisted, or woven together. A strap is a strip of flexible material to fasten or hold. Cord/strap and bar structure is an arrangement where bar structure gives support, and individual cords/straps drawn at different angles through holes, eyelets, or hooks make surfaces.

Design furniture where several strands of string are tied parallelly to form a surface that supports the user's load. Such furniture has the quality of fitting itself according to the form of the load. Designers should explore the different ways of incorporating this quality with cords of different materials.

Design Heuristics for Furniture Design 0.1 **23**

CORD STRUCTURE

Harp Chairs
by J. Høvelskov

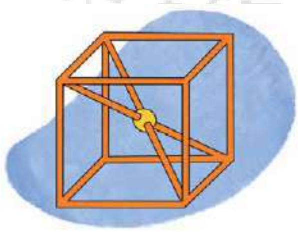
Maya Chair
by Arya Alfieri

The Loom Chair
by Laura Carwardine

Design Heuristics for Furniture Design 0.1 **24**

CUBIC LATTICE

Cubic lattice structure refers to a lattice structure in the form of a cube filled with various fillings on the cube's six faces and in the different diagonal positions, face and body-centred. It may or may not be isotopic where bars are identical and intersect in the same way.



Design furniture inspired by the principles of cubic lattice in which cubic structure is filled with various fillings on the cube's six faces and in the different diagonal positions, face and body-centred with bars. Designers must explore various fillings for the faces and centre of the volume to generate different furniture geometry.

Design Heuristics for Furniture Design 0.1 **24**

CUBIC LATTICE

Zeed Chair
by Sara Leonor

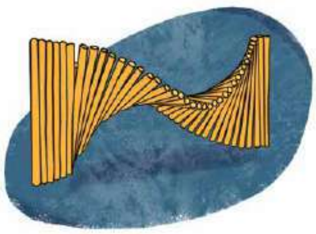
M3 Chair
by Thomas Feichtner

Purkersdorf Sanatorium Armchair
by Koloman Moser

Design Heuristics for Furniture Design 0.1 **25**

CURVED LATTICE

Curved lattice structure refers to a lattice structure composed of straight or curved struts having the characteristics of a curved surface.



The members: bars or planes are arranged consecutively in such furniture, following a curve and a rule of gradual increment or decrement of dimension, orientation or rotation. These pieces of furniture can create a strong sense of movement, creating dynamic, eye-catching forms.

Design Heuristics for Furniture Design 0.1 **25**

CURVED LATTICE

Curvy chair
by Eduardo Benamor Duarte

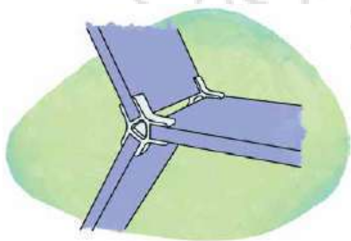
Revolving Chair
by Jeon Kyung

Octave Looping Plywood Chair
by Estampille 52

Design Heuristics for Furniture Design 0.1 **26**

EXPERIMENTAL JOINERY

Experimental joinery involves a radically new and innovative style of joining two or more numbers of bars in different orientations.



Design furniture in which the joinery is the notable feature. These pieces of furniture are innovative in the way the parts: bars or surfaces, are connected. Explorations can be directed towards designing creative locking mechanisms or even designing a component which joins the necessary parts in the required fashion.

Design Heuristics for Furniture Design 0.1 **26**

EXPERIMENTAL JOINERY

Electron Chair
by Konstantin Achkov

Shrink chair
by Nicola Zocca

Synapse Chair
by Andrew Perkins

Design Heuristics for Furniture Design 0.1

27

EXPERIMENTAL
MATERIAL AND PROCESS

Experimental material & process involves the application of radically new materials and innovative process modification to develop products.

Designers must explore a material-driven design approach to design with novel materials and unique processes to create furniture. These unusual materials and processes help in creating radical designs.

Design Heuristics for Furniture Design 0.1

27

EXPERIMENTAL MATERIAL AND PROCESS

Knotted Chair
by Marcel Wanders

Oh Void II
by Ron Arad

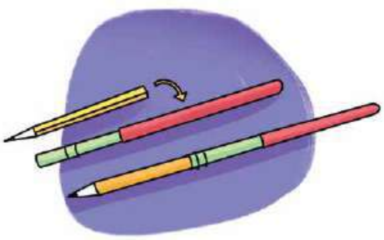
Inflatable metal chair
by Oskar Zieta

Design Heuristics for Furniture Design 0.1

28

EXTENSION

An extension is an extra part added to something to e or prolong it.



Design furniture that appears to be an extension of an already existing larger object or by extending a part of the furniture onto it. When it's designed as an extension of a larger object, the attachment must be securely attached to ensure safe usage. On the other hand, furniture with a permanent extension of a part may have aesthetic or functional value. Designers should study the nature of the extension and the form of the attachment.

Design Heuristics for Furniture Design 0.1

28

EXTENSION

T'ROI Chair
by Sarah Hossli

Pole Chair
by Nicola Trudgen

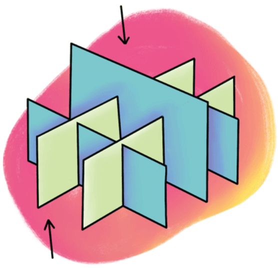
JumpSeat Wall
by Ziba Design

Design Heuristics for Furniture Design 0.1

29

FLAT-PACK

Flatpack furniture is furniture packed in pieces in flat boxes for easy transportation and can be assembled later as per convenience.



Design furniture that can be dismantled, assembled or deployed as per requirement, making it portable and easily packable. Designers must explore different mechanisms and joinery to make this possible while also experimenting with the scale, proportion, orientation and dimensions of the piece.

Design Heuristics for Furniture Design 0.1

29

FLAT-PACK

T02 soft chair
by Takt

C07 Flat Pack Chair
by Chris Streng

Flat Chair
by Sarah Fisher Paculdo

Design Heuristics for Furniture Design 0.1

30

FOLK
ART & CRAFT

Folk art encompasses all types of visual art rooted in traditional folk culture, such as floor and wall motifs or paintings. On the other hand, folk craft covers objects showcasing dexterity in traditional community practices.

Design furniture that is inspired by and/or is made using folk arts and crafts techniques. These pieces of furniture can significantly showcase the vernacular styles, culture and traditional art and craft. Designers have to explore ways to showcase the art or craft forms without altering originality while experimenting with novel design ideas.

Design Heuristics for Furniture Design 0.1

30

FOLK
ART & CRAFT

Binta Armchair
by Moroso

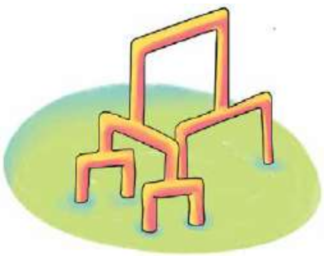
Channapatana wooden chair
by Sandeep Sangaru

The Kimono Chaise
by William Gordon

Design Heuristics for Furniture Design 0.1 **31**

GENEALOGICAL TOWER

A genealogical tower is a tall structure of bars resembling the genealogical tree in three-dimensional space.



Design furniture composed of bent and joined bars that resemble a genealogical tree, creating visual hierarchy and steps. Designers should experiment with the directions of bending, dimensions, proportions and the orientation of these bars to create functional furniture.

Design Heuristics for Furniture Design 0.1 **31**

GENEALOGICAL TOWER

Love me tender
by Didier Faustino

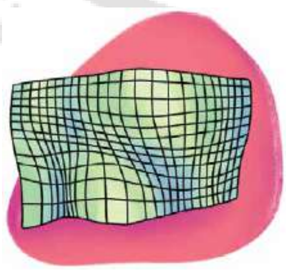
Ekstrem chair
by Terje Ekstrøm

Globe Garden chair
by Peter Opsvik

Design Heuristics for Furniture Design 0.1 **32**

GRID

A grid is a structure of a series of intersecting straight (vertical, horizontal, and angular) or curved bars in a plane. A grid can be uniform or non-uniform. A uniform grid has vertical, horizontal and angular bars at equal distances. A non-uniform grid has unequal distances between vertical, horizontal and angular bars of the grid.



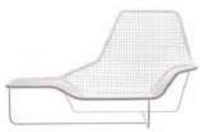
Design furniture where grids are a predominant visual element. With any material, an organized network of bars generates different furniture forms. Designers should experiment by using such grids in different parts and sizes to generate the desired look and feel as per the context.

Design Heuristics for Furniture Design 0.1 **32**

GRID

Eiffel Tower Wire Chair
by Modernica

Grid Chair
by Nordic Studio

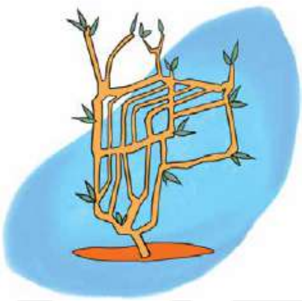


Lama Lounge Chair
by Ludovica & Roberto Palomba

Design Heuristics for Furniture Design 0.1 — 33

GROW

Grow means producing naturally and increasing in size by gradually assimilating new matter into the living organism.



Let nature grow furniture as per the desired form. The unique feature of such furniture lies in how the furniture is 'grown'. Designers should explore how natural elements can be grown with fixtures, moulds, or other means to create desirable forms for usage.

Design Heuristics for Furniture Design 0.1 — 33

GROW

Full Grown
by Gavin Munro

Terra
by Studio Nucleo

Design Heuristics for Furniture Design 0.1 — 34

HAND FAN

A hand fan may be any flat surface waved back and forth or mounted on a rigid structure to create airflow. Generally, hand fans are made of thin material, such as paper, feathers, fabric, cardboard, leaf etc., mounted on slats that may be fixed/rigid (uchiwa) or foldable (sensu).

Design furniture that resembles the visual quality of a hand fan. The main striking feature is the straight lines that seemingly radiate from a point, as it does in a hand fan. Designers must experiment with modifying the form and features of a hand fan to explore how the desired function can be achieved.

Design Heuristics for Furniture Design 0.1 — 34

HAND FAN

Fan chair
by Hiroki Takada

Peacock Chair
by Dror Benshetrit

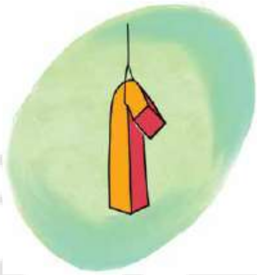
Joseph felt chair
by LotharWindels Industrial Design

Design Heuristics for Furniture Design 0.1

35

HANGED

Hanged means suspending something from support above (permanent or temporary; one or multiple) with the lower part dangling free. It can be ceiling hanging, hanging with a stand or hammock.



Design furniture which is suspended from one or multiple ends from the ceiling or on a structure. The unique quality of this furniture is its tendency to 'swing', introducing fun and relaxing element. Designers must explore different ways of creating such furniture according to usage.

Design Heuristics for Furniture Design 0.1

35

HANGED

Recliner (single) Hanging chair
by Joanina Pastoll

Seóra Hammock
by Anthony Logothetis

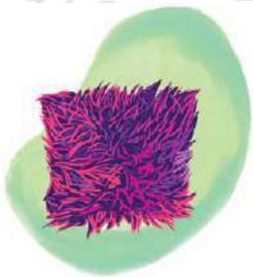
DROPi
by Erla Dogg Ingjaldsdottir and Tryggvi Thorsteinsson

Design Heuristics for Furniture Design 0.1

36

HIRSUTE / FURRY

Anything that is covered with hair is hirsute, and anything that is covered with fur is furry.



Design furniture with a hairy surface texture or use hair-like material as the main component. Such furniture can create soft textured plush forms that can comfort the user. Designers should get inspired by the flow of different hair types and other furry objects.

Design Heuristics for Furniture Design 0.1

36

HIRSUTE / FURRY

The Rabbit Chair
by Seungji Mun

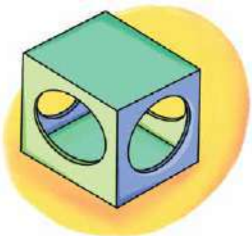
PRETTYPRETTY Hair Chair
by Dejana Kabiljo

Bolotas Armchair
by Fratelli Campana

Design Heuristics for Furniture Design 0.1 **37**

HOLLOW

Hollow has space inside by removing the excess material from a body to make a lightweight object.



Design furniture in which the form is hollowed out from the inside to create considerably lightweight forms. Sometimes, the form of the hollowed portion supports the intended use, while sometimes, it's an interesting visual feature. Designers must explore different ways to use these surface formations to support the function and enhance the aesthetic features.

Design Heuristics for Furniture Design 0.1 **37**

HOLLOW

Ball chair
by Eero Aarnio

Fish chair
by Satyendra Pakhalé

MT3 Rocking Chair
by Ron Arad

Design Heuristics for Furniture Design 0.1 **38**

HYBRID
SHELL STRUCTURE

Hybrid shell structure combines portions of two or more basic shell structures to form a super unit form.

Design furniture combining two or more shell structures or sections of shell structures which support the intended use. Designers must explore the dimensions and orientation of the hybrid structures to design such furniture.

Design Heuristics for Furniture Design 0.1 **38**

HYBRID SHELL STRUCTURE

Lobster & Shelley chair
by Lund & Paarmann

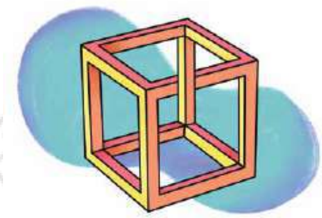
Coconut chair
by George Nelson

The Barca bench
by Jacob Joergensen

Design Heuristics for Furniture Design 0.1 — 39

ILLUSION

Illusion is an instance of misinterpreted perceptual experience, where information from external stimuli leads to an incorrect perception.



Design furniture that isn't quite what it seems. Such furniture plays tricks with people's minds, creating visuals that make people do a double-take and observe it keenly to understand it. Designers must explore and design the experience of the furniture, keeping in mind the way it will be viewed, used and observed to create the drama it inspires.

Design Heuristics for Furniture Design 0.1 — 39

ILLUSION

The Cut Chair
by Peter Bristol

Fadeout Chair
by Oki Sato

Shadow Chair
by Duffy London

Design Heuristics for Furniture Design 0.1 — 40

INFLATABLE

An inflatable is an object that can be filled with air or gas before use.

Design furniture that should be inflated to use it. Such furniture is usually easily packable and lightweight. It usually requires a pump facility to fill it up, which may or may not be available at every place. Designers should explore different materials to inflate and understand the behaviour of the surfaces when it is inflated.

Design Heuristics for Furniture Design 0.1 — 40

INFLATABLE

Inflatable Steel Chair
by Oskar Zieta

Blow Inflatable Armchair
by Paolo Lomazzi, Donato D'Urbino, Jonathan De Pas

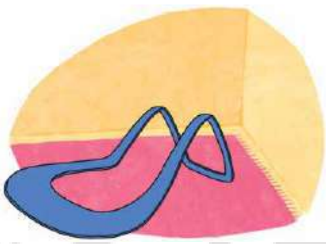
Blow Sofa
by Malafor

Design Heuristics for Furniture Design 0.1

41

LEGLESS

Legless means without legs, something is resting on the floor.



Design furniture which doesn't use legs as a support. These kinds of designs can be greatly context-specific. Designers can experiment significantly with various forms for various activities, such as bar, body or surface that are geometric or organic.

Design Heuristics for Furniture Design 0.1

41

LEGLESS

Hosu
by Patricia Urquiola

STORVIK, lounger
by Carl Öjerstam

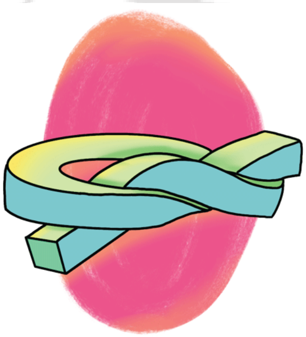
Bold legless chair
by Wonjun Jo

Design Heuristics for Furniture Design 0.1

42

LOCKED CUSHION (KNOT/KNIT/WEAVE)

A locked cushion is a structure made from a long cylindrical cushion through knots, knitting or weavings.



Design furniture with a long cushion that is knotted, knitted or woven, with or without a frame. The unique feature is how the cushion is locked around that serves the function. Designers should explore different types of knots, knitting and weaving techniques.

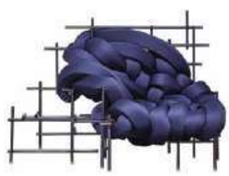
Design Heuristics for Furniture Design 0.1

42

LOCKED CUSHION (KNOT/KNIT/WEAVE)

Chunky Knit
by Veega Tankunby

Knot Seat
by Atelier Blink



The Lawless Chair
by Evan Fay

Design Heuristics for Furniture Design 0.1

43

LOCKED STRING/ STRAP (KNOT/KNIT/WEAVE)

A locked string or rope is a structure made from twisted string or rope through knots, knitting or weavings.

Design furniture with knotted, knitted or woven string or rope of different sizes, with or without a frame. The unique feature is how the string or rope is locked around that serves the function. Designers should explore different types of knots, knitting and weaving techniques.

Design Heuristics for Furniture Design 0.1

43

LOCKED STRING (KNOT/KNIT/WEAVE)

Telar chair
by Paola Lenti

Knotted Chair
by Marcel Wanders

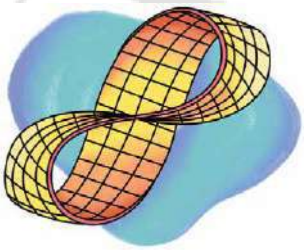
Hammock Lounge chair
by Paola Lenti

Design Heuristics for Furniture Design 0.1

44

MOBIUS LOOP

Möbius loop is a non-orientable surface with only one side and only one boundary component. A model of a Möbius loop can be made by connecting the ends of a paper strip with a single half-twist.



Design furniture inspired by the form of a Mobius loop. Such forms usually tend to divide themselves into two dominant parts, each modified to suit the usage. The unique feature of this style lies in how the single half-twist inherent to the loop aids in establishing the functional requirement of the piece. Designers should take advantage of this feature and play with its dimension, proportion and orientation to support different activities.

Design Heuristics for Furniture Design 0.1

44

MOBIUS LOOP

Moebius Chair
by Onyx Furniture

The Mobius Chair
by Takeshi Miyakawa

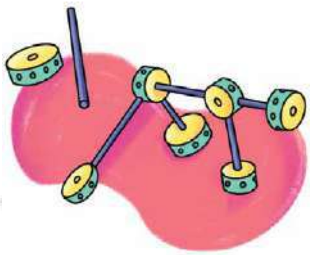
Infinite Love Seat
by Pedro Reyes

Design Heuristics for Furniture Design 0.1

45

MODULAR

The meaning of modular is relating to a self-contained unit or item that can be combined or interchanged with others to create different designs.



Design furniture with components that can be rearranged and combined. The unique feature of such furniture is the freedom it gives users to adjust and create their desired form, giving them a sense of satisfaction and involvement in making them. Hence, designers should experiment with different forms of modules and modes of connections to create something user-friendly.

Design Heuristics for Furniture Design 0.1

45

MODULAR

Array
by Tijs Gilde

Lincoln chair
by Davide Tonizzo

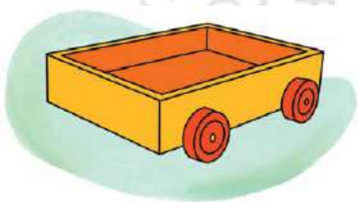
Magic Sticks!
by SPYNDI

Design Heuristics for Furniture Design 0.1

46

MOTION

Motion is the action or process of moving or being moved.



Design furniture which has the feature of movement. This can be achieved either by providing wheels or designing the form to support different types of movement. The designer should explore the different possible variations per the intended purpose and usage.

Design Heuristics for Furniture Design 0.1

46

MOTION

Assaya armchair
by Satyendra Pakhalé

ILY-I mobile chair
by Setsu & Shinobu Ito

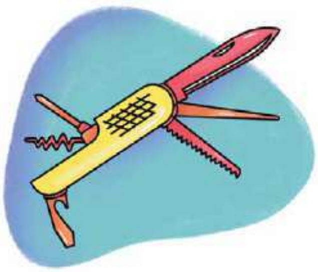
Brackett chairproduced
by Nienkämper

Design Heuristics for Furniture Design 0.1

47

MULTIFUNCTIONAL (CHAIR + X)

Multifunctional is something having more than one function and fulfilling several purposes.



Design furniture that can facilitate various activities. Along with the primary function of sitting, multiple features can be added. Designers have to explore the different ways of incorporating multifunctionality according to the context of its usage.

Design Heuristics for Furniture Design 0.1

47

MULTIFUNCTIONAL (CHAIR + X)

Flip-Flap Children's Chair
by Theo Luvisotto

Paq Chair Bed
by Maform

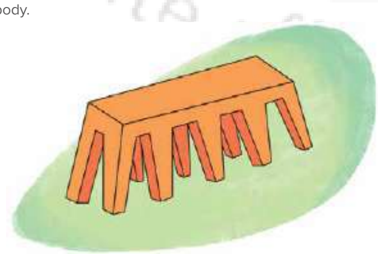
Senses of the Future chair
by Tokujin Yoshioka

Design Heuristics for Furniture Design 0.1

48

MYRIAPOD

Myriapods have elongated bodies with numerous pairs of legs on the two sides of the body.



Design furniture with several legs. The position and orientation of these legs can create dynamic and interesting forms supporting different purposes. Designers must explore the different ways to tweak such forms to create functional furniture.

Design Heuristics for Furniture Design 0.1

48

MYRIAPOD

Cervo chair
by Antonio Pio Saracino

The Milli Chair
by Duffy London

Rocking chair KUDIRKA
by Paulius Vitkauskas

Design Heuristics for Furniture Design 0.1

49

NERVOUS SYSTEM

A heterogeneous lattice structure with irregular cell geometry and variable strut sections resembling synaptic connectivity of the neurons in the nervous system.

Design furniture that resembles the visual quality of how neurons are connected in our body's nervous system. This style is characterized by its organic formations and structure. Designers must explore the nature of these formations and experiment with ways of structuring to arrive at creative support solutions.

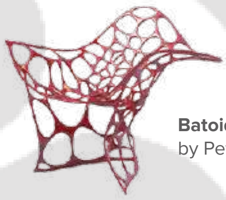
Design Heuristics for Furniture Design 0.1

49

NERVOUS SYSTEM

Bone Chaise
by Joris Laarman

Go chair
by Ross Lovegrove



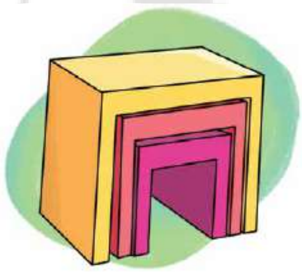
Batoidea Chair
by Peter Donders

Design Heuristics for Furniture Design 0.1

50

NEST

Nesting refers to a stacking or arrangement process where similar objects of graduated sizes are placed one inside the other.



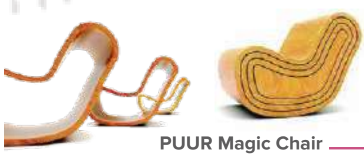
Design furniture with a unique 'stacking-within-itself' feature, in which the parts of the furniture can be nested one inside the other as a space-saving measure. Each component can cater to the same function or be arranged together to facilitate another. Designers should experiment with how forms interact with one another to explore ways in which one can nest inside or under another.

Design Heuristics for Furniture Design 0.1

50

NEST

GVAL Chair
by Vanesa Moreno Serna



PUUR Magic Chair
by Dripta Roy

Nesting Chairs
by Frank O. Gehry

Design Heuristics for Furniture Design 0.1 — 51

ORIGAMI

Origami is a technique of modelling and manipulating flexible objects by folding with functional and geometric-mathematical principles (Dureisseix 2012)(Kasahara 2001).

Design furniture that is inspired by origami. These forms have strong geometric features, vertices, edges and surfaces, characteristic of origami. Designers must explore using such strong features to create functional furniture by simplifying the actual origami structure.

Design Heuristics for Furniture Design 0.1 — 51

ORIGAMI

Flux Chair by Douwe Jacobs & Tom Schouten

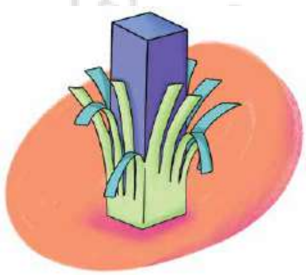
The Flat Stanley Origami Chair by Brett Mellor

Origami Chair by James Dieter

Design Heuristics for Furniture Design 0.1 — 52

PEELED SURFACE

A peeled surface is an object's outer surface or covering in one single layer or multiple small strips after peeling.



Design furniture with forms that resemble a body with a peeled surface. This feature can be a functional or aesthetic element, which should be determined as per the intended purpose. Designers should explore various materials and textures to create this effect.

Design Heuristics for Furniture Design 0.1 — 52

PEELED SURFACE

Sushi chair by Studio campana

Edra 'Sushi" Chair by Studio campana

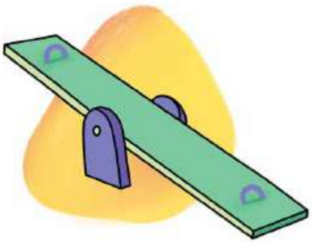
Cabbage Chair by Nendo

Design Heuristics for Furniture Design 0.1

53

PLAYFUL

Playful is the state or experience of finding something frolicsome, sportive or jocular.



Design furniture that incorporates an element of play in it as its primary purpose. Such furniture can change the way people move around it and interact, thereby also having an impact on the space where it is present. Hence, designers should explore the different ways of establishing such playful elements according to the intended context.

Design Heuristics for Furniture Design 0.1

53

PLAYFUL

Spun Chair
by Thomas Heatherwick

Lazy Basketball Chair
by Emanuele Magini

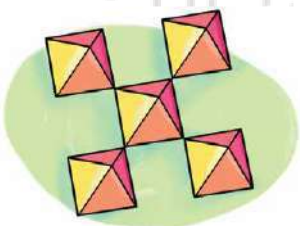
Schaukelwagen Rocking chair
by Hans Brockhage & Erwin Andrä

Design Heuristics for Furniture Design 0.1

54

POLYHEDRON

A polyhedron is a three-dimensional entity, maybe a solid or a surface consisting of a system of polygons. A system of polygons means a network of flat polygonal faces with straight edges and sharp corners or vertices.



Design furniture that emphasizes geometric surfaces, sharp vertices or straight edges. These are inspired by the various polyhedra and incorporate functionality by taking advantage of their form. Designers must explore the scale and proportion of these elements to create functional furniture.

Design Heuristics for Furniture Design 0.1

54

POLYHEDRON

Vondom Vertex Chair
by Karim Rashid

Chair_ONE
by Konstantin Grcic

Dodecahedronic chair
by Hiroaki Suzuki

Design Heuristics for Furniture Design 0.1 — 55

POSTURE

Posture means the position in which someone holds their body when sitting. It may be formal or informal sitting posture.

Design furniture which supports unique and different postures as per requirement. They will have a special focus on being able to support the various postures that support one specific activity and not for the usual usage. Designers need to study the activity thoroughly and experiment with forms and materials to support it.

Design Heuristics for Furniture Design 0.1 — 55

POSTURE

Zen Circus yoga chair
by Caroline Kermarrec

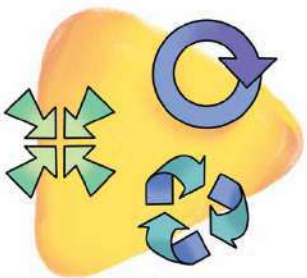
Meditation Seat Ware
by Gao Fenglin

Flexible chair
by Madhu Priyanka Kannabiran

Design Heuristics for Furniture Design 0.1 — 56

RECYCLE

To recycle is to use again, especially in a different way or afte reclaiming or reprocessing.



Design furniture with material that has been reclaimed or reprocessed. The main focus in these pieces of furniture is the usage of recycled material most efficiently, with less wastage. Designers must explore the different ways to transform materials that can be used to create furniture.

Design Heuristics for Furniture Design 0.1 — 56

RECYCLE

Seaweed chair
by Gaetano Pesce

Re-PLY Chair
by Dan Goldstein

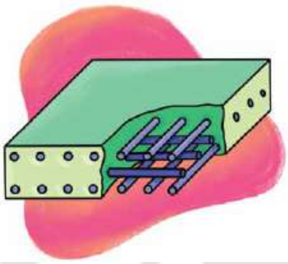
Tubular Armchair
by Lucas Munoz

Design Heuristics for Furniture Design 0.1

57

REINFORCED

Reinforcement is a process of reinforcing to engineer a composite material with two or more significantly different physical or chemical properties to achieve more strength and stiffness, often low density.



Design furniture using reinforced material to utilize the composites' physical properties or showcase the composites' texture with appropriate semantics of form. Designers must explore reinforcement materials and binder materials to combine using unique processes to form furniture.

Design Heuristics for Furniture Design 0.1

57

REINFORCED

Straw

Garden Chair
by Jurgen Bey

Fiberglass

Fold Chair
by Olivier Gregoire

Concrete

Armchair
by Jonas Bohlin

Design Heuristics for Furniture Design 0.1

58

ROCKING

Rocking means moving backwards and forwards or from side to side after a regular interval.

Design furniture that sways forward and backward, or side to side, in a rhythmic, repetitive pattern for relaxing or solitary usage. Designers must explore unique ways of incorporating this motion in furniture by studying forms that can support it.

Design Heuristics for Furniture Design 0.1

58

ROCKING

ODÚ Rocker Cavern
by Flo Florian and Sascha Akkermann

Rocker No. 1
by Brendan Gallagher

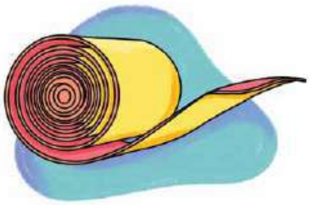
Easy Edges Rocking Chair
by Frank O. Gehry

Design Heuristics for Furniture Design 0.1

59

ROLL

Roll is a cylinder formed by winding flexible material around a tube or by spinning it over and over on itself without folding.



Design furniture which is inspired by the physical form of a rolled sheet. Such furniture may be suggestive of another object or could even have mechanisms that facilitate the 'pulling' of the sheet to aid different functionalities. Designers must explore the uses of such pieces of furniture and experiment with different materials to facilitate it.

Design Heuristics for Furniture Design 0.1

59

ROLL

Karpett
by 5.5 Designers

The MIESROLO
by Uros Vitas

Childrens Paper Chair
by Charlotte Friis

Design Heuristics for Furniture Design 0.1

60

SCULPTURE

A sculpture is a three-dimensional abstract form curved out of material. In this context, the overlapping area between sculpture and furniture is relevant. The furniture sculpture of Ai Weiwei and furniture inspired sculpture of Mike Nivelson is worth exploring in this regard.

Design sculptural furniture. Like pieces of art, these pieces of furniture may or may not hold and convey a metaphoric meaning, making people stop and speculate, impacting the space where they are situated. Hence, designers have to be sensitive to the context where the furniture is placed and explore with forms to create a statement or convey a story.

Design Heuristics for Furniture Design 0.1

60

SCULPTURE

Abstraction Chair
by WoongKi Ryu

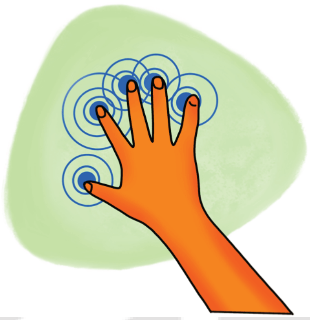
Nirvana Chair
by Wendell Castle

Bamboo Chair Flow
by Cheng-Tsung Feng

Design Heuristics for Furniture Design 0.1 — 61

SENSORY

The meaning of sensory relates to sensation or the senses. Sensory furniture involves making sense of sensations to support sensory needs.



Design furniture with features that relax or stimulate our senses. During usage, users would be mindful of their senses. Designers should be sensitive to the senses they want to stimulate and explore related forms and technology.

Design Heuristics for Furniture Design 0.1 — 61

SENSORY

Mind Chair
by Peter Marigold & Beta Tank

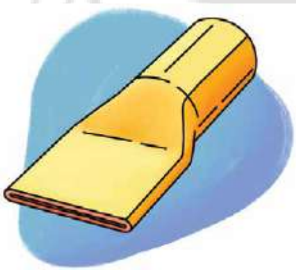
Hugging Chair
by Alexia Audrain

Massage Chair for Physical & Sound Therapy
by Kim Taek

Design Heuristics for Furniture Design 0.1 — 62

SHAFT TO BLADE

Shaft to blade loop transforms the shaft into a flat blade-like boat paddle.



Design furniture that emphasizes the feature of transformation, from the shaft to the blade, to suit the purpose. The modifications cater to the functions it supports and is usually made of the same material. Designers must explore the positioning and dimensions of these transformations, creating attractive, functional

Design Heuristics for Furniture Design 0.1 — 62

SHAFT TO BLADE

Spoon Chair
by Philipp Aduatz

E-Turn
by Brodie Neill

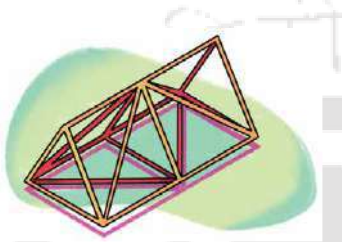
@chair
by Brodie Neill

Design Heuristics for Furniture Design 0.1

63

SPACE TRUSS

A space truss consists of members joined together at their ends to form a stable three-dimensional structure. The simplest form of a space truss is a tetrahedron formed by connecting six members.

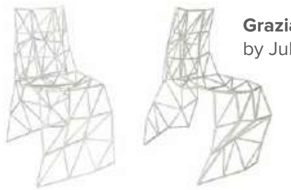


Design furniture using a space truss as the structural component. The members of these forms have strong geometric qualities. Designers should explore the scale of these trusses and experiment with the different functionalities that can be integrated.

Design Heuristics for Furniture Design 0.1

63

SPACE TRUSS



Graziano Chair
by Julian Mayor

Bat Chair
by Baltasar Portillo

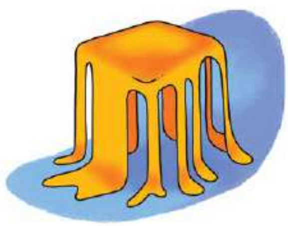
'Six' chair
by Ian Giles Mason

Design Heuristics for Furniture Design 0.1

64

SPILLED/MELTED STRUCTURE

A spilled surface is an imaginary liquefied surface that seems to flow over the edge and form a structure, whereas a melted structure gives an impression of flow of melted material.



Design furniture by creating forms that resemble the visual quality of the flow of a spilling liquid or melting. These forms depict an unusual movement and direction, which designers should explore using different materials and processes to realize them.

Design Heuristics for Furniture Design 0.1

64

SPILLED/MELTED STRUCTURE

Melting Chair
by Philipp Aduatz

Living Systems
by Jerszy Seymour

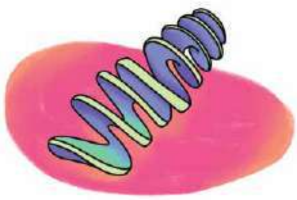
Melting Foam Chair
by Therese Granlund

Design Heuristics for Furniture Design 0.1

65

SPIRAL

A spiral in three-dimensional space is a curve that turns around an axis at a constant or continuously varying distance while moving parallel to the axis. It is also known as a helix. A ruled surface having a spiral path is a helicoid. Different types of helicoids are circular helicoid, conical helicoid, paraboloidal helicoid, hyperbolic helicoid, lituus helicoid, and logarithmic helicoid.



Design furniture by arranging surfaces or bars in the form of a spiral to attain the unique quality of continuum, elegance and pragmatism. Designers must explore different helicoids with different form elements to get different results.

Design Heuristics for Furniture Design 0.1

65

SPIRAL

Loope Lupita Chair
by Victor Aleman

Spiral Chair
by Louis Durot

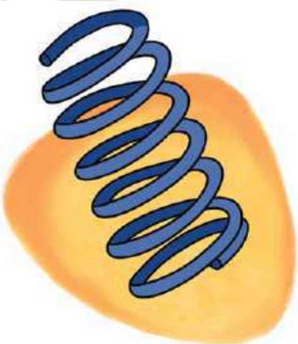
Spiral chair
by Fredrik Mattson

Design Heuristics for Furniture Design 0.1

66

SPRING

Spring is a resilient member that deflects under the load condition and regains its original shape under no-load conditions. It is also used for storing energy.



Design furniture with springs to achieve a cushioning or a swinging effect. The cushioning effect may provide comfort, while the swinging effect may make it playful. Designers must experiment with the dimensions and different types of springs to get the desired result.

Design Heuristics for Furniture Design 0.1

66

SPRING

Spring Rider Lounge Chair
by Igor Chak

Spring Chair
by Xin Zhang

Bow Spring Chair
by Conor Coghlan

Design Heuristics for Furniture Design 0.1

67

STACKABLE

Stackable means capable of being arranged in a stack vertically or horizontally.

Design furniture that can be stacked onto itself, helping store and assemble many units that can be arranged, rearranged, or removed as per requirement. Designers should explore the different ways in which notches and dimensions of the furniture can be determined to facilitate stacking in the preferred direction in different ways.

Design Heuristics for Furniture Design 0.1

67

STACKABLE

Kulms Stackable Chair
by Daisuke Nagatomo and Minnie Jan

Hillestak Chair
by Robin Day

Y Chair
by Tom Dixon

Design Heuristics for Furniture Design 0.1

68

STACKED BAR

A stacked bar is a super-unit of bars stacked on or around or arranged in a pile.

Design furniture in which several units of rods or bars are stacked to create a form. Designers should experiment with different shapes, sizes, proportions and orientations of these bars to suit the required function.

Design Heuristics for Furniture Design 0.1

68

STACKED BAR

Interlux Chair
by Manfred Kielnhofer

Wooden Chair
by Marc Newson

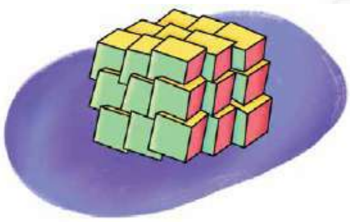
Teak Wood Chaise
by Linda Horn

Design Heuristics for Furniture Design 0.1

69

STACKED BODY

A stacked body is a super-unit of bodies stacked on or around or arranged in a pile.



Design furniture where several smaller blocks or bodies are put together to create a form. Designers should experiment with different shapes, sizes, proportions and orientations of blocks to suit the required function.

Design Heuristics for Furniture Design 0.1

69

STACKED BODY

Westside Lounge Chair
by Ettore Sottsass

Do Lo Res Armchair
by Ron Arad

Quartz Armchair
by Davide Barzaghi and CTRLZAK

Design Heuristics for Furniture Design 0.1

70

STACK SURFACE

A stacked surface is a super-unit of surfaces stacked on or around or arranged in a pile

Design furniture in which several surfaces are stacked to create a form. The advantage of such furniture lies in the fact that by modifying its dimensions and orientation, it can support several functionalities while maintaining the language of the form. Designers should explore the ways in which these surfaces can be modified to create contours that can suit the required functionalities.

Design Heuristics for Furniture Design 0.1

70

STACK SURFACE

Mamulengo Rocking Chair
by Eduardo Baroni

Layer Chair
by Jorrit Taekema

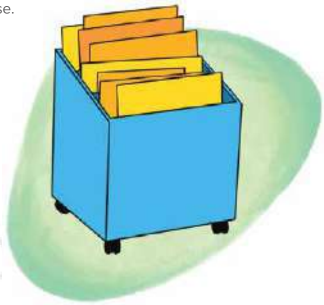
Coffee Bench
by BEYOND Standards

Design Heuristics for Furniture Design 0.1

71

STORAGE

Storage is a structural creation that provides a place for putting things for future use.



Design furniture having features which support storage. Such furniture can have storage as a primary purpose or even an additional feature. Designers should explore the different ways in which forms can be modified to support storage.

Design Heuristics for Furniture Design 0.1

71

STORAGE

Storage Chair
by Fishbol Furniture

Bibliochaise Chair
by Nobody & Co

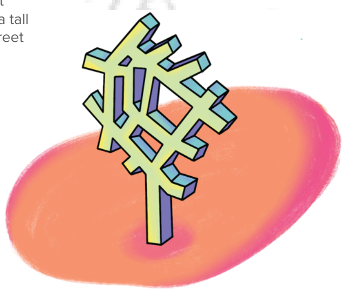
Sunflower Chair
by He Mu and Zhang Qian

Design Heuristics for Furniture Design 0.1

72

STREET
PATTERN TOWER

Street patterns are geometric and net-like patterns of the cities (Alexander 1966). And Street pattern tower is a tall structure with Street patterns.



Design furniture in which the street patterns inspire the form. Designers can explore how such patterns can be used to form a structural or aesthetic feature in a piece of furniture.

Design Heuristics for Furniture Design 0.1

72

STREET PATTERN TOWER

The Twiggy Chair
by Vido Nori

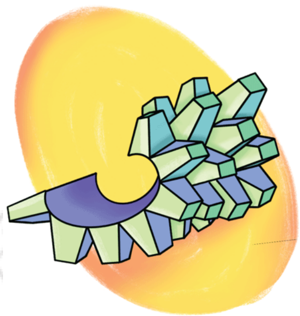
Ribbon Chair
by John Liston

Vegetal Chair
by Ronan & Erwan Bouroullec

Design Heuristics for Furniture Design 0.1 73

STUD SURFACE

Any number of a slender knob, nailhead, metal piece or any protuberance projecting from a surface is called stud surface.



Design furniture in which several 'studs' of fixed or varied heights are accumulated on a stiff or flexible surface. Modifying the orientation, positioning, and arrangement of these studs can contribute to the dynamic feel of the furniture in various ways. Designers must explore incorporating such modifications to integrate several functionalities while maintaining the language of the form.

Design Heuristics for Furniture Design 0.1 73

STUD SURFACE

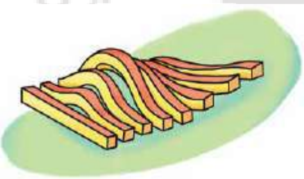
Tessera Lounge Chair
by Marc Baroud

Calibration Lounge
by Animal Studio

Design Heuristics for Furniture Design 0.1 74

SWOLLEN BAR/SURFACE

The swollen bar describes a state of a bar expanded by or as if by the pressure from inside.



Design furniture in which the surface formed by the bars appears 'swollen' due to pressure from inside. In these cases, primarily, the swell of the bar contributes to the functionality of the piece. The advantage of such furniture lies in the fact that by incorporating such modifications, several functionalities can be achieved while maintaining the language of the form. Designers must explore the positioning, dimensions, proportion, orientation, etc., of the swell to create attractive, functional pieces.

Design Heuristics for Furniture Design 0.1 74

SWOLLEN BAR/ SURFACE

Sculptural Sinewy Seating
by Bae Sehwa

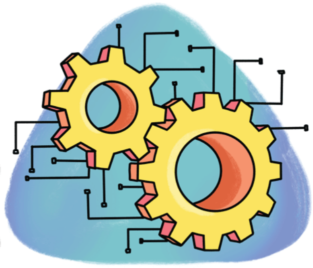
Organic funiture
by Matthias Pliessnig

Distortion Bench 6
by Najla el Zein

Design Heuristics for Furniture Design 0.1 — 75

TECHNOLOGY

Technology is the systematic application of scientific knowledge together with skills and processes for practical application in a specific domain.



Design furniture by putting a scientific phenomenon under the spotlight. It usually garners interest and attention by creating forms and effects that are out of the ordinary. Designers should blend science and technology to conceptualize.

Design Heuristics for Furniture Design 0.1 — 75

TECHNOLOGY

Levitating Lounger
by Splinter Works - Bodice Rocker

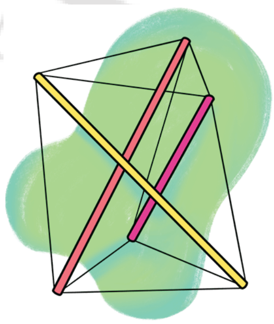
Cloud Sofa
by D.K. Wei

Brain Wave Sofa
by Lucas Maassen & Dries Verbruggen

Design Heuristics for Furniture Design 0.1 — 76

TENSEGRITY BAR

Tensegrity means tensile integrity structures (Fuller 1962). Tensegrity is a structural principle with components under compression inside a tensile structure. The compressed members (bars) are untouched, and the prestressed tensioned members (cables) demarcate the system boundary.



Design attention-grabbing furniture using the principle of tensegrity to make people wonder and experience cushioning effect while using. Designers should explore the positioning of compression members in a particular fashion to make it dramatic and fascinating.

Design Heuristics for Furniture Design 0.1 — 76

TENSEGRITY BAR

Suspension Lounge Chair
by Robby Cuthber

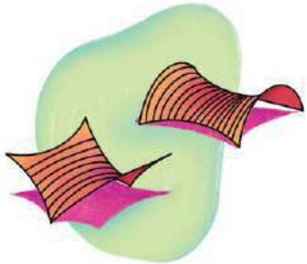
Tension Lounge Chair
by Verner Panton

Z-TENSE
by Konstantin Archov

Design Heuristics for Furniture Design 0.1 77

TENSILE
SURFACE STRUCTURE

Tensile surface structure is a construction carrying tension by the surface with no compression or bending. The surface has to be pre-tensioned or prestressed with the help of rigid and stiff bar elements along the edges to eliminate the compressive forces in the surface structure.



Design furniture by using a tensile membrane which would either support the applied load or be the element which attracts visual interest. This feature is usually supported by a frame that holds the tensed membrane. Designers should explore different ways of composing these members to create exciting compositions while fulfilling the functionality.

Design Heuristics for Furniture Design 0.1 77

TENSILE SURFACE STRUCTURE

Tensile Sofa
by Therese Glimskär

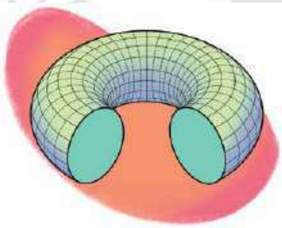
Membrane
by Benjamin Hubert

Twoface Chair
by Christoph Massak

Design Heuristics for Furniture Design 0.1 78

TORUS

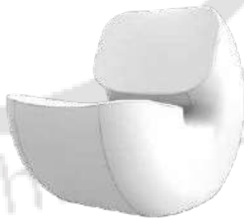
These are bodies created by rotation, wherein the directrix is a circle, that is followed by the generatrix, which is also a circle, to form a three dimensional form. Variations in the geometry of directrix and generatrix creates toroidal polyhedra, for example: using a pentagon as the directrix and a triangle as the generatrix.



Design furniture inspired by the form of a torus. Designers must experiment by altering the generatrices, directrices or even playing with different sections of a torus to design furniture.

Design Heuristics for Furniture Design 0.1 78

TORUS



Torus chair
by Giovanni Tomasini

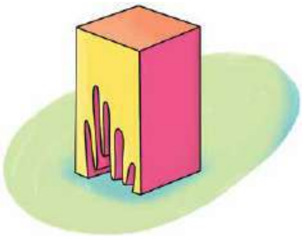
Torus Chair
by Reid Eric Anderson

The Torus Chair
by Studio Niels & Sven

Design Heuristics for Furniture Design 0.1 — 79

TRANSFORMED BODY

A transformed body can be referred to as a body transformed by altering one or more of its dimensions using the principle of addition, subtraction, manipulation or substitution.



Design furniture by altering a form's dimensions by addition, subtraction, manipulation or substitution. In such furniture, it's the modification made that would contribute to making the furniture functional, hence attracting attention. Designers should experiment with different forms and how they can be modified as per the function they should support.

Design Heuristics for Furniture Design 0.1 — 79

TRANSFORMED BODY

Karelia Lounge Chair
by Liisi Beckmann

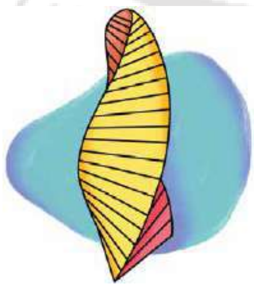
Kashiwado Chair
by Isamu Kenmochi

Zocker
by Luigi Colani

Design Heuristics for Furniture Design 0.1 — 80

TWIST

The twist is a phenomenon that is observed due to an applied torque on an object.



Design furniture in which the form has a 'twist'. These pieces of furniture have a strong sense of movement and direction and are eye-catching owing to their unique stance. Designers should explore different ways of incorporating the twist in their creations, experiment-ing with dimensions and orientation for various functions.

Design Heuristics for Furniture Design 0.1 — 80

TWIST

Twist Chair
by Stefan Heiliger

Twist Chair
by Jonas Lyndby Jensen

Twisted Sofa
by Nina Edwards

Design Heuristics for Furniture Design 0.1

81

WABI-SABI

Wabi-sabi is the philosophy that celebrates imperfect, temporary, and unfinished beauty. It is the antithesis of the philosophy of beauty as perfect, permanent, and finished.

Design furniture, the aesthetic of which follows the philosophy of celebrating imperfections, showcasing the beauty of natural and raw forms. Such pieces blend well with the context or stand out starkly, attracting attention. Designers should experiment with various materials while maintaining their natural textures and finish.

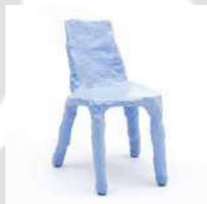
Design Heuristics for Furniture Design 0.1

81

WABI-SABI

African Wooden Chair
by Andrianna Shamaris

Cloud Chair
by Philipp Aduatz



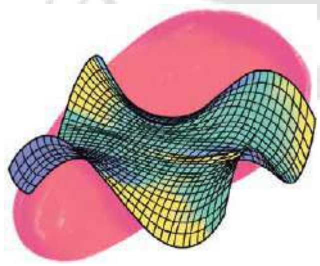
Thanatos Chair
by Philipp Aduatz

Design Heuristics for Furniture Design 0.1

82

WAVE SURFACE

Wave surface is a phenomenon that occurs due to wave propagation on a surface.



Design furniture that is inspired by the surface of propagating waves. Such furniture often indicates movement and direction as it has a flow. The organic depressions and peaks formed can be designed to support their intended purpose. Designers have to explore the dimensions, proportions, orientation, etc., of these features to support the intended function.

Design Heuristics for Furniture Design 0.1

82

WAVE SURFACE

Lungomare Bench
by Enric Miralles y Benedetta Tagliabue

Waves Bench
by EJ 142 by Ernst & Jensen

Lounge Landscape
by Nicola Burggrafv

Design Heuristics for Furniture Design 0.1

83

WEARABLE

The meaning of wearable is capable of being worn.

Design furniture that can be worn on your body. Such furniture is designed by closely studying the human biomechanics to understand how it can be strapped seamlessly and deploy or support the user's activities. Designers must closely examine the body's movements and corresponding mechanisms and forms that can be seamlessly applied to context-specific requirements.

Design Heuristics for Furniture Design 0.1

83

WEARABLE

Archelis
by Hiroaki Nishimura

Lex chair
by Astride Bionix

Wear Your Seat
by Olivier Peyricot

Design Heuristics for Furniture Design 0.1

84

WIGGLE

Wiggle describes the motion, where the object moves up and down or from side to side with small rapid movements.

Design furniture which has a 'wiggle' in its form. Such furniture often indicates movement and direction as it has short, rapidly curved lines. Designers must explore different ways to accentuate such strong suggestive lines to create the drama it inspires.

Design Heuristics for Furniture Design 0.1

84

WIGGLE

Vitra Wiggle Side Chair
by Frank Gehry

Berserker Chair
by Barberini & Gunnell

SCULPTURE Carbon Fiber Chair
by Ventury Lab

Design Heuristics for Furniture Design 0.1

85

WRAPPED

Wrapped means covered or surrounded with paper, cloth, or other material.

Design furniture which can be closed off or opened, with a feature that blankets the form. Such furniture can be used for temperature control and make the user feel comfortable and safe. Designers must explore the proportions, materials, form and the mechanism of its working so as to design as per requirement.

Design Heuristics for Furniture Design 0.1

85

WRAPPED

Cole chair
by Kseniya Alferova

HUSH
by Freyja Sewell

Feltri Chair
by Gaetano Pesce

Design Heuristics for Furniture Design 0.1

86

3D PRINT

3D print is the output of the additive manufacturing process of additively building parts. 3D printing can create highly complex and intricate forms with fine details and interlocking.

These include furniture that are created with the help of 3D printing technology. The use of this technology gives the designer freedom to experiment with those kinds of forms, the creation of which, through traditional methods, could be challenging or not possible.

Design Heuristics for Furniture Design 0.1

86

3D PRINT

Solid C2 Chair
by Patrick Jouin

Ogonori chaise-longue
by Manuel J. García

Durotaxis Chair
by Alvin Huang

5.3 TfMM Cards

This section presents the TfMM card set. Every card has three columns, i.e. form, material & processes and tools. While the ‘form’ column shows the existing furniture design, the ‘material & processes’ column suggests materials and processes make models of the furniture that resembles the existing furniture form. The ‘form’ column is further divided into three rows based on the dominant feature, i.e. bar, body and surface. Figure 5.2 illustrates the anatomy of a TfMM card:

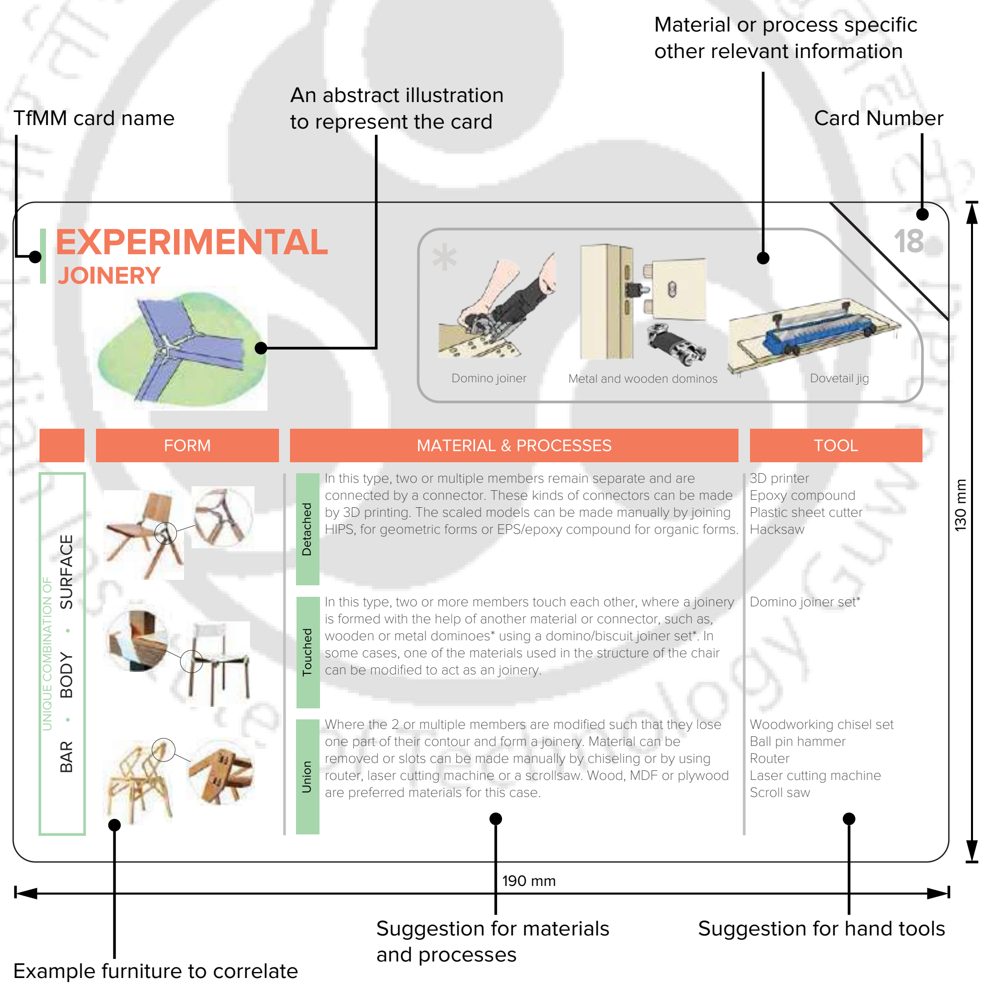
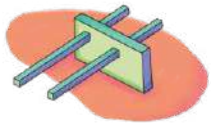


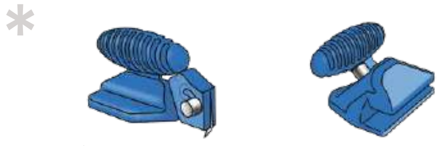
Figure 5.2 TfMM card anatomy

Following are the 65 TfMM cards developed as a part of this research.

BAR
AND PANELS/SURFACE

01

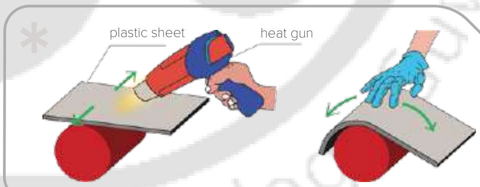




	FORM	MATERIAL & PROCESSES	TOOL
BAR		Square or rectangle section bars can be made using foamboard or softwood. Different shapes can be given by sanding with different grades of sandpaper. For cylindrical bars, metal wire or rods should be used, depending on the design. If the wire gauge is less than 8 (3.26mm), then gas welding is recommended. If the wire gauge is is more than 8, arc and gas welding both can be done. Furthermore, cylindrical bars can be also made by turning wood or nylod rod to create cross-sections with uniform or varying diameter.	Sanding machine Hand file Cutting mat Cutter Steel ruler
BODY			
SURFACE		Panels can be made out of foamboard (sunboard) or thick paper. Layers of panels can be used to increase the thickness. Different types of foamboard cutter such as straight and bevel cutter or rabbet cutter* can be used to cut foamboard. A panel of unique form and material can be made with the composite of resin and fiber by compression moulding process. If the new material is in surface form, follow card 36.	Hand file Cutting mat Foamboard Cutters Steel ruler

BENT
SURFACE

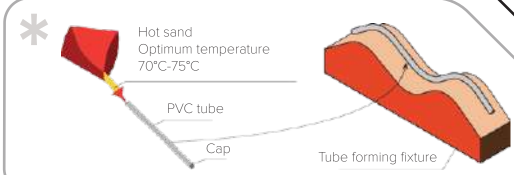
02



	FORM	MATERIAL & PROCESSES	TOOL
BAR			
BODY			
SURFACE		Foamboard is preferred to achieve desired curved surfaces. Hot air gun* can be used to soften the surface, which can then be bent, by applying force gently. Bending moulds or existing products with similar curvature should be used to achieve uniformity. For thinner surfaces, 1 mm High Impact Polystyrene sheets or papers more than 400 gsm can be used. Note: To add thickness, acrylic putty can be applied wherever required. On top of the base surface, cushion and proper upholstery can be used if required.	Hot air gun Scissor Cutting mat Foamboard cutter Steel ruler Plastic sheet cutter

BENT
TUBE/BAR

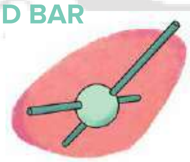
03



	FORM	MATERIAL & PROCESSES	TOOL
BAR		For metal bars, Galvanized Iron wire (GI wire) or mild steel rod should be used according to the proportion. Wire bending jigs or moulds can be used for bending metal wires or rods. For surface treatment of metal bars/tubes, chrome plating can be done. For Poly Vinyl Chloride pipes (PVC), hot sand (70°C-75°C) should be used to soften the tube first, which can then be placed on the tube forming fixture. While filling the pipe with hot sand, the other end of the pipe should be closed with a cap. For cushioning, Polyethylene foam tube can be used as a covering over the metal/plastic wire/tubes.	Hacksaw Pliers Wire bending jigs Metal tube bending mould Plastic tube bending fixtures
BODY			
SURFACE			

BODY
AND BAR

04



	FORM	MATERIAL & PROCESSES	TOOL
BAR		Medium Density Fibre (MDF) board, foamboard[1], metal bars/wires[3] or plastic pipes[3] can be used to make bar structure. MDF can be cut using a hand saw or a band saw. Proper shape can be given manually with sand papers of different grades or using sanding machine.	Hand saw Band saw Sand paper Sanding machine
BODY		High density Expanded Polystyrene (EPS) can be used. Texture appropriate upholstery can be used.	Hot wire EPS cutter Sand paper Cutter Electric EPS cutting pen
SURFACE			

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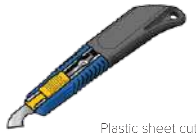
BODY AND SURFACE

05



Plastic sheet cutter

	FORM	MATERIAL & PROCESSES	TOOL
BAR			
BODY		High density EPS, MDF or softwood can be used to make the body. If there is any material-specific texture has to be achieved, then the actual material should be used. EPS can be shaped by sanding. MDF and wood can be shaped by sanding or other machining processes such as turning shaping, milling, etc.	Hand saw Cutter Sand paper Sanding machine Lathe Milling machine Shaper machine
SURFACE		For panels[1] or surfaces, foamboard, HIPS, fabric, spandex or lycra can be used based on the design. Stiff curved surfaces can be achieved through heat bending[2] process or vacuum forming. For flexible surfaces such as fabric, spandex or lycra, a basic bar structure should be used to hold these materials in place. NOTE: HIPS is the preferred material for vacuum forming.	Scissor Plastic sheet cutter*

BRUSHSTROKE

06

Bamboo stick making with table top modular bamboo cutting tool

	FORM	MATERIAL & PROCESSES	TOOL
BAR		Bamboo is the preferred material in this case. It gives flexibility and strength together. Bamboo can be shaped as per requirement as it retains the given shape. Applicability of other flexible materials like cane or coconut leaf stick can also be alternatively used. Note: A round bamboo stick can be made in the stick making tool. If it is not available, one can make a low cost modular bamboo cutting tool*. Bamboo/Wood plank or metal parts can be added as per requirement.	Bamboo stick making tool Sanding machine Handsaw Scissor Cutter Steel ruler Wood planer Hand/bench drill
BODY			
SURFACE			

BUCKLED RIBBON

07

*

Rapid heating with heat gun

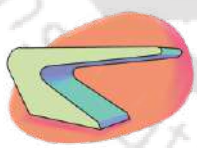
Rapid cooling with cold air blower

Joining of edges with acrylic joining solvent cement

	FORM	MATERIAL & PROCESSES	TOOL
BAR			
BODY			
SURFACE		Thin HIPS has to be bent first to create cylindrical, pericline, conically folded by securely holding it, after which heating can be done with a heat gun*. When the material begins to soften, rapid cooling should be done with a cold air blower* to ensure that it retains the form. Once the required form has been achieved, the edges can be joined using acrylic joining solvent cement*. Note: To add thickness, acrylic putty can be applied wherever required. On top of the base surface, cushion and proper upholstery can be used if required.	Hot air gun Scissor Cutting mat Steel ruler Plastic sheet cutter Cold air blower

CANTILEVER

08



*

Wooden mould for forming

	FORM	MATERIAL & PROCESSES	TOOL
BAR		**Structure**: METAL: Bend GI wire, MS rod or aluminium rod as per the profile. WOOD: Engineered wood can be used after laser cutting. BAMBOO: Steam/hot bending[47] using proper template, fixed with c-clamps and metal plates. **Seat pan/back**: FOAM BOARD (Sunboard): For straight and curved surface. PAPER: For complex forms, use papier-mâché with mould. OTHERS: If the product is made with a material whose colour and texture cannot be replicated with other materials, use the actual material.	Bending machine Jigsaw/ Laser cutting m/c Steam bending unit/heat gun C - clamp Cutter Steel ruler Paint brush
BODY			
SURFACE	Organic  Geometric 	A mould* can made, on top of which, papier-mâché mixture or small pieces of paper can be applied. Multiple layers of material can be added to increase the thickness with the help of Polyvinyl Acetate adhesive. GI wire can be used in between layers/on the borders for reinforcement. HIPS/Styrene sheet can be vacuum formed to make curved surfaces if draw ratio is 1:1 (Draw Ratio = the Surface Area of the part / Footprint of the part). Foamboard or thick paper can be used for geometric forms. Thickness of the paper can be decided according to the scale.	Cutter Steel ruler Plastic sheet cutter[6] Vacuum forming machine NOTE: For mould making processes and tools, follow Card 51.

CENTRALLY
ORGANISED LATTICE

09

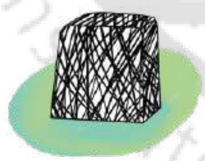
*

Scroll saw

	FORM	MATERIAL & PROCESSES	TOOL
BAR		A bundle of bars (straight, curved or a combination of both) are revolved by opposite axial twist. Creativity lies in the locking arrangement of bars. Wood or metal bars can be locked by interconnecting, using strings or continuous looping. For straight wooden bars, bandsaw should be used and for curved wooden bars, scroll saw* should be used. GI wire or mild steel rods/flat bars can be bent with the help of a ball pin hammer on an anvil. It can be joined by welding. Wooden bars can be joined by interconnecting multiple rods through holes.	Lathe Sanding machine Hand saw Scroll saw* Scissor Cutter Steel ruler Welding machine Wood planer
BODY			
SURFACE			

COBWEB

10



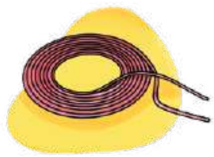
*

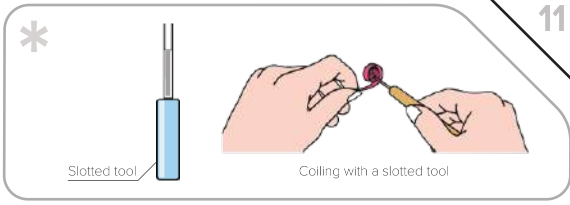
Papier-mâché + Polyvinyl Acetate

	FORM	MATERIAL & PROCESSES	TOOL
BAR		Core: Core should be made up of expanded polystyrene (EPS), as per the shape. Surface: Cobweb can be made by 3D pen or piping bag* or twine thread over shaped EPS. After drying, the core can be removed by burning[24] the EPS with petrol or gasoline. NOTE: Some of the furniture can also be made without core, using strong, straight bars of bamboo, wood or metal based on the design.	EPS cutter Cutter Sandpaper Sanding machine Handfiles 3D pen Piping bag
BODY		Core: Since this kind of furniture seat pan resembles body structure, the core should be retained even after the completion of the model. Core should be made up of expanded polystyrene (EPS), as per the shape. Surface: Cobweb can be made by 3D pen or piping bag* over shaped EPS.	EPS cutter Cutter Sandpaper Sanding machine Handfiles 3D pen Piping bag
SURFACE			

COIL

11

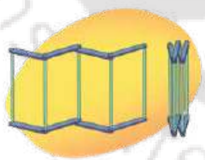




	FORM	MATERIAL & PROCESSES	TOOL
BAR		Rattan, twine thread or rope of different sizes can be used to coil manually in different ways to create various forms. While coiling, the layers can be sewed or glued to hold the form intact.	
BODY			
SURFACE		Paper of different gsm can be coiled with a slotted tool*. The resultant coils can be transformed by applying force at the centre or in the periphery according to the design.	Slotted tool Cutter Cutting mat

COLLAPSIBLE

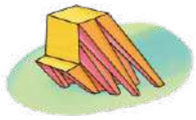
12



	FORM	MATERIAL & PROCESSES	TOOL
BAR		Hard materials such as MDF or HIPS are suggested for collapsible mechanisms. Laser cutting or manually cutting individual bar components (linkages) can be made with the plastic sheet cutter or hack saw. Slots or grooves must be made by milling or laser cutting. For hinges, rivets or bolts can be used based on the design. Metal bars should be used for any bar having bends or varying cross-sections. On top of metal bars, epoxy putty can be used to achieve varied cross-sections. Stainless steel taper tubes or polypropylene tubes can be used for telescopic mechanisms	Hammer Hacksaw Plier Industrial Cutter Steel ruler Laser cutting machine Drill Needle file Sandpaper
BODY		Body structure can be made as described in card 51. Linkages can be made of High Impact Polystyrene or MDF using laser cutting machine or manually.	Laser cutting machine Industrial cutter Hacksaw Sandpaper
SURFACE		MDF or wood should be used for flat surfaces as it may have to hold hinges or sliding mechanisms with nails, bolts or screws. Plyboards are not suggested as it has gaps and will not correctly hold nails, bolts or screws. For curved surfaces, follow the instructions in card 2.	Laser cutting machine Hand drill

COMET
STRUCTURE

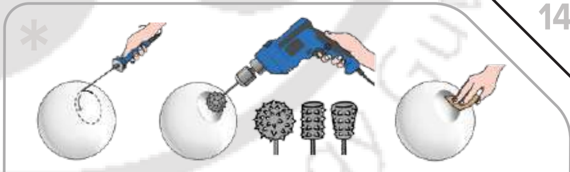
13



	FORM	MATERIAL & PROCESSES	TOOL
BAR		**No separate seat pan/back rest:** Plastic bars must be joined by melting around a mould, and the mould must be removed later to get the cavity, or wooden/metal bars should be joined with adhesive/welding and by removing materials to a form of seat pan and backrest can be given.	Planer Sanding Machine Hand saw Rotary wood carving file with hand drill[14].
		Separate seat pan/back rest: A scaled model of the seat pan and backrest can be made using card 2. Legs of uniform diameter can be made using metal rods or PVC pipes. Tapered legs can be made with wood/mild steel rod by machining on lathe machine. For legs having varied cross section along the length, epoxy compound on top of GI wire can be used.	Lathe machine Hacksaw Pliers Crosscut saw
BODY			
SURFACE			

CONCAVITY & CONVEXITY

14



	FORM	MATERIAL & PROCESSES	TOOL
BAR			
BODY		High-density EPS or polyurethane foam is preferred for this form and can only be achieved through material subtraction. EPS can be cut with the hot wire cutter, and a basic form can be given using a sanding machine. For convex form, manual sanding with sandpaper is suggested*. Concavity can be achieved by removing material with the EPS cutting pen* or rotary wood carving files* as an attachment to a hand drill.	Hot wire cutter Industrial cutter Sanding machine Sandpaper EPS cutting pen Rotary wood carving files as an attachment to a hand drill
SURFACE			

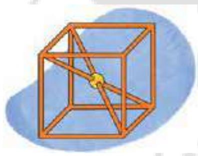
CORD
AND BAR STRUCTURE

15

	FORM	MATERIAL & PROCESSES	TOOL
BAR		Mild steel rod/tube or PVC pipe can be used for curved frame[3]. Aluminium rod/tube can be used, provided there is facility for welding. For the frames with straight bars, wood, MDF or styrene can be used. Wood or MDF bars/panel can be joined using polyvinyl acetate glue or wooden dowel pins. Styrene can be joined with chloroform or acrylic joining solvent cement. A portable drilling machine is required to make holes on the frame for the cord to pass through. Utility cord, nylon string/cord/twisted rope or polypropylene plastic lacing cord can be wound around the frame to give the desired appearance. A needle can be used, if there is any difficulty in passing the cord through the holes.	Hacksaw Pliers Anvil Metal tube bending mould Plastic tube bending fixtures Hand drill Needle Scissor
BODY			
SURFACE			

CUBIC LATTICE

16



	FORM	MATERIAL & PROCESSES	TOOL
BAR		The cross section of the bars used are mostly circular, rectangular or square. If a circular cross section bar is desired, wood can be turned using the lathe, or processed wooden sticks, with circular cross-section, can be bought from hardware stores. For rectangular cross section, the wooden battens can be bought from the hardware store, or can be customised using the bandsaw. Metal bars and styrene sheets can also be used to make the frame. Mitre saw* can be used to cut the bars at specific angles. They can be joined using polyvinyl acetate glue or wooden dowel pins. Traditional joineries can also be used if the scale permits.	Handsaw Mitre saw Bandsaw
BODY			
SURFACE			

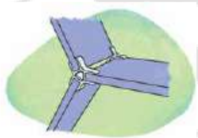
CURVED LATTICE

17

	FORM	MATERIAL & PROCESSES	TOOL
BAR		Wood or MDF bars can be used to make the individual units of the piece[16]. For making curved or other unique shapes, a jigsaw can be used. They can be connected either by a single rod passing through them or by connecting the adjacent units by using adhesive or connectors. Once the individual units are made, a strong, rigid rod is required for arranging and joining the bars along a curve with plastic or metal spacer in between. Mild steel rods are preferred for centrally connecting the units.	Handsaw Jigsaw Drilling machine
BODY			
SURFACE			

EXPERIMENTAL
JOINERY

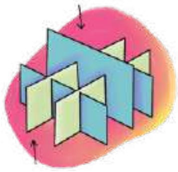
18



UNIQUE COMBINATION OF BAR • BODY • SURFACE	FORM	MATERIAL & PROCESSES		TOOL
		Detached	In this type, two or multiple members remain separate and are connected by a connector. These kinds of connectors can be made by 3D printing. The scaled models can be made manually by joining HIPS, for geometric forms or EPS/epoxy compound for organic forms.	3D printer Epoxy compound Plastic sheet cutter Hacksaw
		Touched	In this type, two or more members touch each other, where a joinery is formed with the help of another material or connector, such as, wooden or metal dominoes* using a domino/biscuit joiner set*. In some cases, one of the materials used in the structure of the chair can be modified to act as an joinery.	Domino joiner set*
		Union	Where the 2 or multiple members are modified such that they lose one part of their contour and form a joinery. Material can be removed or slots can be made manually by chiseling or by using router, laser cutting machine or a scrollsaw. Wood, MDF or plywood are preferred materials for this case.	Woodworking chisel set Ball pin hammer Router Laser cutting machine Scroll saw

FLAT-PACK

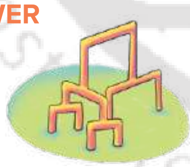
19



	FORM	MATERIAL & PROCESSES	TOOL
BAR			
BODY			
SURFACE		Panels can be made out of foamboard (sunboard) or thick paper. Layers of panels can be used to increase the thickness or acrylic putty can be added after completion of manufacutring processes. For complex shapes, wood/ Engineered wood can be used after laser cutting.	Laser cutting machine Sanding machine Hand File Cutting Mat Industrial cutter Steel rule

GENEALOGICAL
TOWER

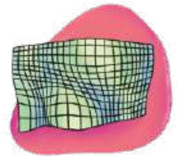
20



	FORM	MATERIAL & PROCESSES	TOOL
BAR		It can be achieved by bending metal rods. Metal pipe bending machine with moulds can be used to bend metal pipes. For smaller diameter, plastic PVC pipe is preferred. For plastic PVC pipe bending, please refer card 3. Bar structures can be covered with polyethylene foam tube to provide cushioning.	Pipe bending machine Metal welding setup Hack saw Plier Scissor Cutter
BODY			
SURFACE			

GRID

21



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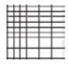
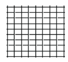


Non-Uniform Grid



Uniform Grid

Mould

Wire-bending jig

	FORM	MATERIAL & PROCESSES	TOOL
BAR		Non-uniform grid: To get non-uniform grid lines, wire bending jigs* are required to maintain the design pattern. Mild steel/GI wire is preferred to make individual units, bending them with a wire bending jig. Bent wire can be joined by arc or gas welding to make the super unit. Uniform grid: To get transformed uniform grid a mould* is required to maintain the designed form. Using the mould wire mesh bending has to be done to achieve the desired form. On the periphery, comparatively thick wire should be used. NOTE: If wire gauge is less than 8 (3.26mm), gas welding is recommended. Otherwise, both arc and gas welding can be done. This is applicable for both uniform and non-uniform grid surfaces.	Manual wire Bending machine Welding facility Plire for wire cutting Hammer for wire bending Chipping Hammer
BODY			
SURFACE			

HAND FAN

22

*

Hot glue gun

	FORM	MATERIAL & PROCESSES	TOOL
BAR			
BODY			
SURFACE		It can be achieved by folding felt material, PE coated paper, non-woven fabric or canvas. Plastic/metal rivets, hot glue gun* or epoxy resin can be used for joining purposes.	Scissor Industrial cutter Cutting mat Hammer Hot glue gun* Plier Steel rule

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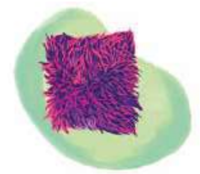
HIRSUTE / FURRY

23



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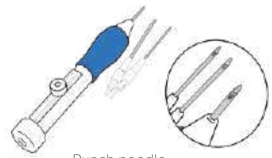
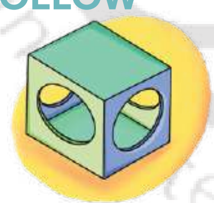


	FORM	MATERIAL & PROCESSES	TOOL
BAR			
BODY			
SURFACE		Faux fur fabric - It can be joined by stiching, adhesive, staple gun or nailing Wool roving - Different forms can be made with the help of a felt needle without adhesive or stiching. Natural fibres - Long strands of banana, jute ot other natural fibres can be used to give the furry look. They can be stitched or joined with the help of glue gun or resin. Silk/wool thread - Punch needle* can be used to embroider the design on a piece of fabric. The stitches can then be cut along the centre to create the furry effect.	Scissor Cutter Stitching needle Punch needle* Felt needle Staple gun

HOLLOW

24



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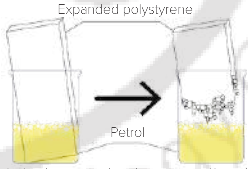


	FORM	MATERIAL & PROCESSES	TOOL
BAR		Based on the scale PVC tube, PP straw, cardboard tube or bamboo straw can be used as material. The desired length of hollow tubes can be achieved by sawing the tubes/straws. Hot glue or Cyanoacrylates can be used as adhesive to join the abovementioned materials.	Hack saw Industrial cutter Hot glue gun
BODY			
SURFACE		Core: The core should be made up of expanded polystyrene (EPS), and the shape can be achieved by sanding machine. For an appropriate finished shape, hand sanding is suggested. Surface: After shaping the EPS, layers of thin paper or canvas has to be put on top. Thickness should decided as per the scale of the model. After drying, the core can be removed by burning* the EPS with petrol or gasoline. GI wire can be used in between the layers or on the borders for reinforcement.	Hot wire cutter Industrial cutter Hand files Sand paper Flat artist brush Plier

25

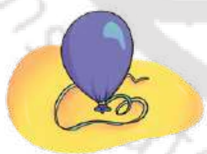
HYBRID
SHELL STRUCTURE

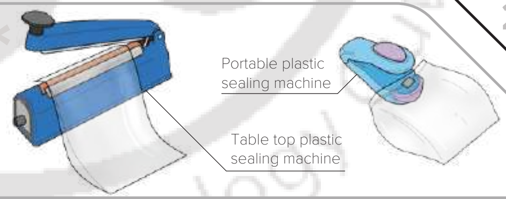
Mould is made from wood   Vacuum formed HIPS

	FORM	MATERIAL & PROCESSES	TOOL
BAR		To make shell structure by joining multple strips/panels, foam sheets (sunboard) or paper board/cardboard can be cut into pieces and joined. Glue gun or polyfix-cyanoacrylate adhesive can be used for joining foamboard and PVA can be used for joining paper board.	
BODY			
SURFACE		Hybrid shell structure can be made using vacuum forming, joining multiple strips/panels or papier-mâché casting. Vacuum forming process should be chosen only if the draw ratio is 1:1. HIPS/styrene sheet can be vacuum formed[8] with the help of a mould*. An inward draft angle of minimum 4° must be given on the mould. Mould should be made of wood, MDF or PU foam. To make shell structure with papier-mâché, follow card 8.	Vacuum forming machine Industrial cutter Steel ruler Plastic sheet cutter[6] Glue gun NOTE: For mould making processes and tools, follow Card 51.

26

INFLATABLE



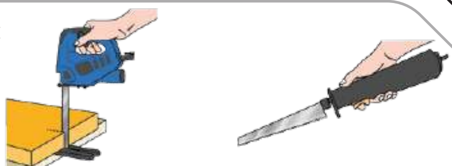


	FORM	MATERIAL & PROCESSES	TOOL
BAR			
BODY			
SURFACE		To achieve the desired three-dimensional form, one should explore the two-dimensional shapes that have to be outlined on the desired fabric, cut and then sealed. The tailored Polyethylene sheet edges should be sealed by a portable or table-top plastic sealer* as per requirement. An inflatable plastic valve should be fixed at one point to inflate and achieve the three-dimensional form with an air pump.	Portable plastic sealer Table top plastic sealer French curves Scissor Industrial cutter Flexible curve ruler Air pump

27

LOCKED CUSHION
(KNOT/KNIT/WEAVE)

*



	FORM	MATERIAL & PROCESSES	TOOL
BAR		A locked cushion can be achieved by applying different knotting techniques with the cushion tube or knotting with a big diameter rope. A cushion made with cotton, polyester fibre, coir fibre or sponge covered with elongated tubular fabric or a big diameter rope can be used to make different knots. Sponge cutter or electric kitchen knife can be used to cut and shape the cushion.	Sewing machine Industrial Cutter Needle
BODY			
SURFACE			

28

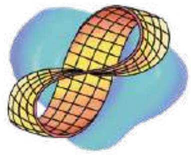
LOCKED STRING/
STRAP (KNOT/KNIT/WEAVE)

*

	FORM	MATERIAL & PROCESSES	TOOL
BAR		It can be achieved by applying different knitting, knotting and weaving techniques over a bar structure. It can also be achieved by reinforcing the knitted, knotted or weaved structure by applying epoxy resin over it.The base structure can be made with mild steel rods, wood, or MDF. Utility cord, nylon string/cord/twisted rope or polypropylene plastic lacing cord can be used to make separate or integrated seat pan and back rest.	
BODY			
SURFACE		It can be achieved by weaving plastic or cotton straps over a bar structure and joined with the help of plastic/metal snap rivets*. The base structure can be made by mild steel rods, wood, or MDF. Polypropylene plastic strap or cotton webbing can be wound or wrapped around the frame to make the seat pan and backrest. NOTE: If the colour and texture of actual knotting or weaving material can not be achieved by other material, then use actual material.	Sewing machine Industrial Cutter Needle Scissor

MOBIUS LOOP

29



* A sequence of steps to make a mobius loop

	FORM	MATERIAL & PROCESSES	TOOL
BAR		For woven furniture, a frame can be made by heat/steam bending a piece of cane/bamboo. The structure can be covered with the help of woven surface made of rattan or bamboo slivers.	Industrial cutter Steam bending set-up Kerosene blow lamp
BODY			
SURFACE		Cut a strip of paper or 1 mm HIP sheet as per the design requirement*. Make a loop and then flip one end over. For paper, join the ends with tape to seamlessly connect them. For HIP sheet, refer card 7. NOTE: To add thickness, acrylic putty can be applied wherever required. On top of the base surface, cushion and proper upholstery can be used if required.	Industrial cutter Scissor Steel ruler

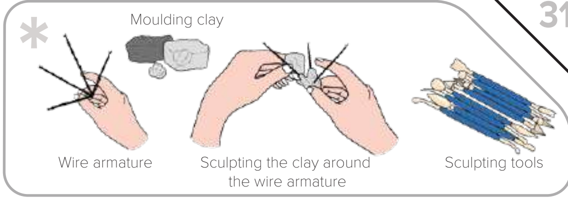
MYRIAPOD

30

	FORM	MATERIAL & PROCESSES	TOOL
BAR		Bars can be cylindrical, rectangular or organic. These can be made with the different methods as mentioned in card 1. These bars can be attached to surfaces or bodies which form the seat pan and the back rest by using nail, resin based adhesive or pressed fit.	Hammer Mallet
BODY			
SURFACE		Plastic sheet, foam board or thick paper can be used to create surfaces. The procedure to create bent surfaces has been illustrated in card 2. These surfaces have to cut at intervals to form the myriapod structure as per the design.	Industrial cutter Cutting mat Steel ruler

NERVOUS SYSTEM

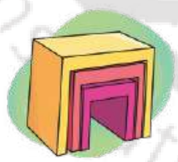
31

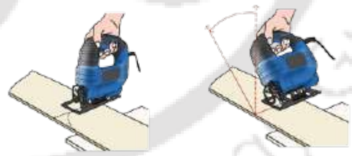


	FORM	MATERIAL & PROCESSES	TOOL
BAR		Wire armature* is required as per the design. Epoxy resin based moulding clay* has to be applied on top of the armature to get the desired form. Further, proper shape can be given using the sculpting tools*. NOTE: 1. Mix less hardener to increase the setting time. 2. Apply any kind of oil or lotion in hand to avoid sticking.	Hack saw Plier Needle files Sculpting tools Sand paper
BODY			
SURFACE			

NEST

32

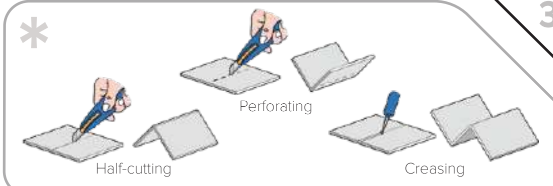




	FORM	MATERIAL & PROCESSES	TOOL
BAR			
BODY			
SURFACE		Geometric: MDF board, HIPS or foamboard of appropriate dimensions can be cut, with the edges cut at an angle using the jigsaw*, according to the design. The edges can be then be joined by using adhesive, nails or appropriate joinery[18].	Jigsaw* Industrial cutter Hammer
		Organic: The side profile of the nested structure, with appropriate thickness, can be drawn onto a MDF board and it can be cut using a jigsaw or a laser cutting machine. Several profiles can be cut, as per the thickness fo the sheet and joined to create an accurate model. Sheets can also be bent as illustrated in card 2.	Jigsaw* Industrial cutter

ORIGAMI

33



	FORM	MATERIAL & PROCESSES	TOOL
BAR			
BODY			
SURFACE		Furniture of this kind can be made by paper folding techniques used for making origami. Paper is the highly preferred for making these models. However, if there are minimal folds, thicker paper or plastic sheet can also be used, by half-cutting, perforating or creasing*.	Industrial cutter Cutting mat Steel ruler Creasing tool Plastic sheet cutter

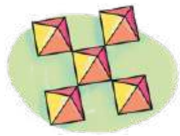
PEELED SURFACE

34

	FORM	MATERIAL & PROCESSES	TOOL
BAR			
BODY			
SURFACE		It can be achieved by peeling a roll of canvas, fabric, felt fabric or non-woven fabric. Peeling can be done with multiple radial cuts or one single cut at one side. If it is a super unit form of smaller unit forms, then it should be connected by a metal wire arrangement.	Scissor Industrial cutter Steel rule Plier

POLYHEDRON

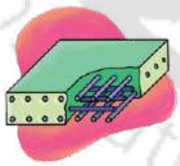
35



	FORM	MATERIAL & PROCESSES	TOOL
BAR			
BODY		If the form is made up of several units, then each unit polyhedra should be made of EPS or PU foam by sanding using the sanding machine or sand paper. The union of two units should be explored. However, paper can also be used as a material for making these modules.	Sanding Machine Power saw Cutting mat Scissor Steel rule Industrial cutter
SURFACE		Each face should be cut and joined to get the desired form. For this, paper with gsm more than 200, foamboard, MDF or HIPS can be used.	Hacksaw Cutting mat Scissor Steel rule Industrial Cutter

REINFORCED

36

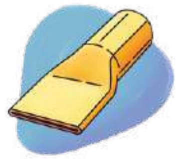


Sequence of operation for making re-inforced surfaces.

	FORM	MATERIAL & PROCESSES	TOOL
BAR			
BODY			
SURFACE		Mix resin and hardener according to the instructions given on the package*. Apply PVA mould release agent on the surface of the mould. Lay a fibre mat or fabric onto the mould. Apply the resin mixture over the mat evenly with a brush or a roller. Area outside the mould can be cleaned using an acetone based solvent. Let it dry for sometime and release it when it has completely dried. Dry fibre dust mixed with the resin and hardener mixture, can be shaped using a mould/plug technique, following the above mentioned steps. Trimming and cutting should be done with the help of electric shear cutter or circular saw with diamond-coated blade. NOTE: Apart from resin and hardener mixture, other kinds of binding agents can also be used to make reinforced structures. Eg. cement, agar-agar, natural rubber, etc.	Brush Roller

SHAFT TO BLADE

37



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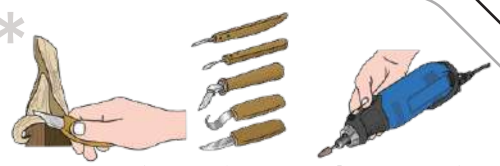
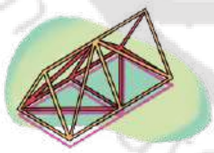


	FORM	MATERIAL & PROCESSES	TOOL
BAR		These kind of models can be made by joining smaller pieces of wood or MDF. In case of wood or MDF, it can be carved using wood carving tool* or rotary carving tool*. Final finished product can be achieved by using the sanding machine or sand paper. As per the design, epoxy resin based moulding clay can also be used using a wire armature as described in card 31.	Wood carving tools* Rotary carving tool* Hammer Sanding machine Sand paper
BODY			
SURFACE			

SPACE TRUSS

38



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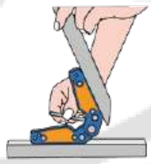
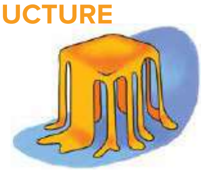


	FORM	MATERIAL & PROCESSES	TOOL
BAR		The individual members can be made by using square or rectangle section mild steel bars. Sections such as L-section, C-section, etc., are also available and can be used according to the design. For cylindrical bars, mild steel rods or GI wire should be used. They can be cut in the required dimension with a hacksaw or a metal cutting saw and welded. For welding the members at an angle, an adjustable magnetic welding holder* can be used. If the wire gauge is less than 8 (3.26mm), then gas welding is recommended. If the wire gauge is more than 8, arc and gas welding both can be done.	Hacksaw Metal cutting saw Adjustable magnetic welding holder*
BODY			
SURFACE			

SPILLED/MELTED
STRUCTURE

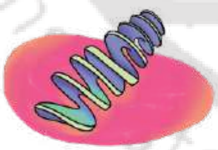
39

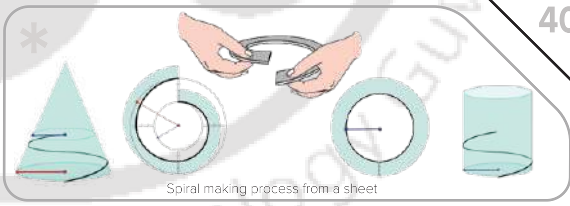


	FORM	MATERIAL & PROCESSES	TOOL
BAR			
BODY			
SURFACE		Air drying clay, epoxy based moulding clay, silicone rubber used for casting, plaster of paris, or any other viscous fluid which has quick setting properties can be used to make spilled/melted surfaces by pouring the material over a pre-formed structure. For definite shapes, sculpting tools can be used.	Sculpting tools

SPIRAL

40



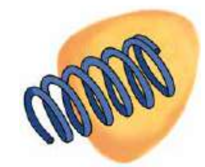


Spiral making process from a sheet

	FORM	MATERIAL & PROCESSES	TOOL
BAR		Rattan, cane or bamboo sticks can be used to make spiral structures. They can be bent by heat or steam bending[47] around a mould as per the design to create the desired effect. NOTE: Bamboo sticks, made form the outer layer of bamboo, have to be soaked in 15% NaOH solution for 2-5 hours at room temperature to improve the strength and flexibilty.	Industrial cutter Handsaw
BODY			
SURFACE		Spiral structures can be made by using foamboard or thick paper. These materials can be given a spiral form by either winding them around a mould or using appropriate supports. The dimensions have to be calculated* and cut from a piece of board. While using paper, a mixture of water and PVA glue can be applied over the surface. Some arrangement has to be made to hold the form until it dries, after which, the paper will retain the shape. For bending foamboard, refer cards 2 and 7.	Industrial cutter Cutting mat Steel ruler Drawing instruments Brush

SPRING

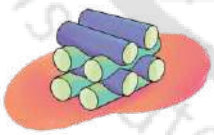
41



	FORM	MATERIAL & PROCESSES	TOOL
BAR		Coil spring or torsion spring can be made using MS rod, GI wire or nylon spring by bending them on the spring making jig* as per the dimension. Further twisting, bending or spacing can be done using different types of pliers.	Spring making jig* Pliers Crimpers
BODY			
SURFACE		HIPS can be used to make different layers of a leaf spring or bow spring by bending[2] with the help of heat gun. Rivets and cyanoacrylate glue can be used to join the corners and layers respectively.	

STACKED BAR

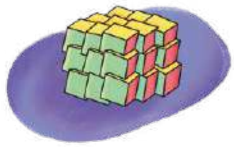
42

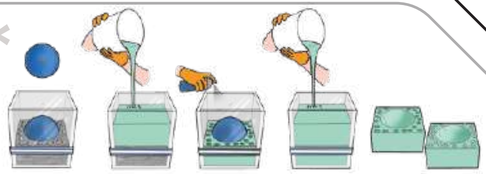


	FORM	MATERIAL & PROCESSES	TOOL
BAR		Profiles of individual bars have to be prepared by cutting and bending[3] as per the design. If the bars are to be arranged with spacing, an extra bar with the required markings should be used as a guide to fix individual units. Epoxy adhesive can be used to join two different materials. Synthetic resin adhesive can be used for wood, MDF and bamboo. Circular cross-sections can be made by turning in lathe or using a disc sander*. Square/triangular/rectangular/any specific cross-section, a jigsaw[32] can be used for cutting. Profile cutting tools should be used for profile making. Preferred materials are foamboard, MDF, wood, cane, rattan, bamboo, PVC pipes, cardboard tubes or nylon rods.	Jigsaw Hacksaw Power saw Profile cutter Industrial Cutter Sanding Machine Hand File Cutting Mat Steel rule
BODY			
SURFACE			

STACKED BODY

43





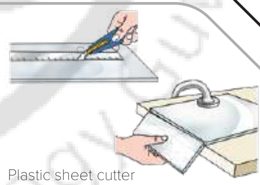
Silicone mould making process

	FORM	MATERIAL & PROCESSES	TOOL
BAR			
BODY		Regular: Systematically stacked bodies are considerably harder than irregularly stacked bodies. For the representation model, EPS or PU foam can be used. A hot-wire cutter should be used for EPS cutting and an electric knife should be used for PU foam cutting. Textured fabric can be used on top of the form as desired. For making multiple units of the same form, silicone rubber mould* should be used to cast PU foam, mixing isocyanate and polyol in 1:1 ratio. Irregular: Irregularly stacked bodies are considerably softer than the systematically stacked bodies. Cotton, polyester fibre, coir fibre, sponge or polyester fibre can be wrapped with fabric to make cushions.	Hot-wire cutter Electric knife Scissor Handheld Sewing Machine
SURFACE			

STACK SURFACE

44

Corrugated sheet cutter

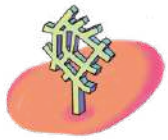


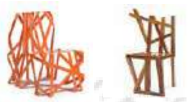
Plastic sheet cutter

	FORM	MATERIAL & PROCESSES	TOOL
BAR			
BODY			
SURFACE		Stiff: Profiles of individual layers has to be cut by jig saw. If the surfaces are to be arranged with spacing, an extra bar/surface with the required markings should be used as a guide to fix individual units. Preferred materials are foamboard, HIPS, corrugated polypropylene sheet, MDF or wood. For corrugated PP sheets*, corrugated sheet cutter can be used and for other plane plastic sheets, plastic sheet cutter* can be used. Flexible: Felt fabric, canvas or any mat made of natural materials can be used to make stacked surfaces. They can be joined by sewing, adhesives or customized step studs (non-threaded). Felt fabric can also be joined by needle felting[56].	Jigsaw Hacksaw Corrugated sheet cutter* Scissor Industrial cutter Plastic sheet cutter* Cutting mat Steel ruler Needle punch

STREET
PATTERN TOWER

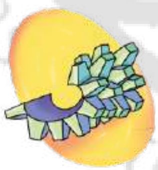
45



	FORM	MATERIAL & PROCESSES	TOOL
BAR		Bars of the desired cross-section can be cut into pieces and joined to make the designed pattern. Long continuous strips of paper with >300 gsm or HIPS of 1 mm thickness can be wrapped around a core made of EPS or PU foam to make street pattern. The core can be pulled out or removed by burning[24]. If the object is made up of material with a specific texture, then same material or print of the texture can be applied on the surface. Wood or layered foamboard is preferred in this case.	Sanding Machine Power saw Hand saw Industrial cutter Plastic sheet cutter Cutting mat Steel ruler
BODY			
SURFACE		Street patterns can also be made by removing specific portions from a paper or HIPS formed surface. For paper forming, refer card 8 and material can be removed with the help of an industrial cutter. HIPS forming should be done by vacuum forming process[8,25]. Plastic sheet cutter can be used to remove material.	Plastic cutter Industrial cutter

STUD SURFACE

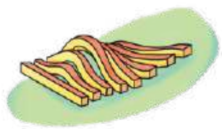
46

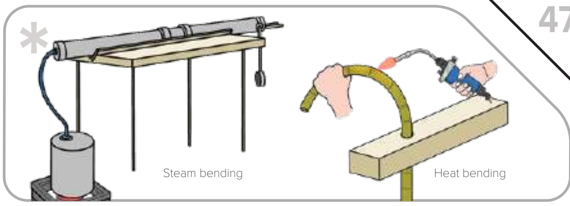


	FORM	MATERIAL & PROCESSES	TOOL
BAR			
BODY			
SURFACE		In this case, studs are fixed on a flexible surface. Flexible surface can be made using canvas, felt fabric, Polyvinyl Chloride (PVC) mat or Thermoplastic Elastomer (TPE) mat. Studs can be made up of Wood or MDF.	Sanding Machine Hand saw Scissor Industrial cutter Plastic cutter Steel rule

SWOLLEN
BAR/SURFACE

47

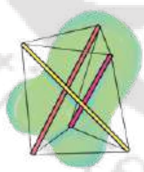




	FORM	MATERIAL & PROCESSES	TOOL
BAR		As per the designed form, a mould has to made with wood or PU foam. Foamboard (sunboard) strips have to be bent[3] over the mould and joined to get the desired form. Foamboard strips can be joined by Cyanoacrylate glue. NOTE: If the design is such that it allows the easy removal of the mould after completion, wood is the preferred material. Otherwise, PU foam should be used to made the mould so that it can be broken and removed.	Sanding Machine Hand File Cutting Mat Industrial cutter Steel rule Heat gun
BODY			
SURFACE		A bulged surface can be made with HIPS by vacuum forming[8,25]. If the draw ratio is more that 1:1, then resin based moulding clay should be used to make bulged surfaces.	

TENSEGRITY BAR

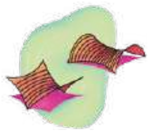
48

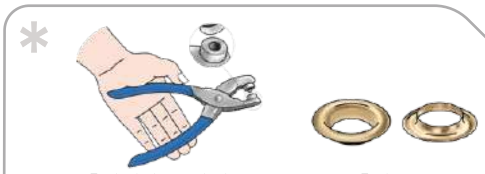


	FORM	MATERIAL & PROCESSES	TOOL
BAR		Bar and strings are in tension in this case. Metal or wooden bars of varied cross-section can be used. Mild steel or wooden bars can be made by cutting with a power saw, hand saw or a jigsaw. For using bent metal bars, refer card 3. Flexible steel wire rope cable or nylon cord of 1.5 mm diameter can be used along with struts to create tensegrity structures. NOTE: Strings should be in tension and not slack. Slackness in any string may cause the collapse of the structure.	Power Saw Hand Saw Hack saw Plier Hand Drill
BODY			
SURFACE		For flat panels, MDF or wood can be used. HIPS can be used to make curved members. Wood/MDF can be made by cutting with a power saw, hand saw, jigsaw or a laser cutting machine. HIPS can be bent by the methods mentioned in card 2. In this case also, flexible steel wire rope cable or nylon cord of 1.5 mm diameter can be used along with struts to create tensegrity structures.	Power saw Hand saw Jig saw Industrial cutter Hand drill

TENSILE
SURFACE STRUCTURE

49

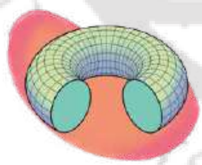




	FORM	MATERIAL & PROCESSES	TOOL
BAR			
BODY			
SURFACE		A basic bar structure can be made up of MS rod, wood or MDF to hold the fabric in tension. Hosiery fabric, canvas or leather can be used as a surface, as it can be stretched across the bars and provide good strength. Following are the ways to connect the fabric with the frame: - Making slots onto the fabric/leather, by stitching, to pass the frame through it. - Attaching eyelet rivets*, with the help of eyelet hole punch plier* on the fabric/leather an later tying a nylon/twine thread. - Using snap rivets to fasten the fabric/leather around the frame.	Manual wire Bending machine Welding facility Plire for wire cutting Hammer for wire bending Scissor for fabric cutting

TORUS

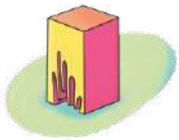
50



	FORM	MATERIAL & PROCESSES	TOOL
BAR		When a torus form is created as an arrangement of several bars, the profiles of each of the individual units can be cut from MDF/foam-board/HIPS/paper-based boards. They can be arranged with the required spacing by using another bar as a reference.	Jigsaw Laser cutting machine Industrial cutter Cutting mat Steel ruler
BODY		Torus forms can be carved out of high density EPS or PU foam. A hot wire cutter can be used to create the overall form. The finish can be brought by using a sanding machine or manually, by using sandpapers of grade 80, 120, 320, 500 one after the other. An electric EPS cutting pen can also be used to shape the form or to remove material from the centre.	Industrial cutter Sanding machine Sand paper
SURFACE		Strips of crêpe paper or continuous strips of fabric can be wound around a core to create torus forms.	Scissors Industrial cutter

TRANSFORMED
BODY

51



	FORM	MATERIAL & PROCESSES	TOOL
BAR			
BODY		It can be achieved by transforming EPS or PU foam. A hot wire cutter can be used for cutting EPS and an electric kitchen knife for cutting PU foam. Fast wire contour cutting machine can also be used for cutting PU foam. Finishing can be done with a sanding machine or manually, by using sandpapers of grade 80, 120, 320, 500 one after the other. NOTE: Use the actual material, if its colour and texture cannot be achieved with alternative materials.	Hot wire cutter Fast wire contour cutter Electric EPS cutting pen Industrial cutter Sanding machine Sand papers Hand Files
SURFACE			

TWIST

52


Twisting process in sequence

	FORM	MATERIAL & PROCESSES	TOOL
BAR			
BODY		High density EPS or PU foam can be given a twisted form. Initial material removal can be done by using an industrial cutter. Finishing can be done with a sanding machine or manually, by using sandpapers of grade 80, 120, 320, 500 one after the other.	Industrial cutter Sanding machine Sand papers
SURFACE		HIPS sheet or foam board can be used to make twisted surfaces. With the use of a heat gun, the boards, can be gently twisted* as per the design and held in place with the help of a support. A cold air blower may be used to expedite the process of cooling. Cushioning materials and desired upholstery can be attached to the twisted surface as per the design. Metal bars can be placed beneath the twisted surface to give support as per the design.	Heat gun Cold air blower Industrial cutter Plastic sheet cutter

WAVE SURFACE

53

	FORM	MATERIAL & PROCESSES	TOOL
BAR			
BODY			
SURFACE		Mould is required for forming. Mould can be prepared with wood, MDF, POP or PU foam. Foamboard (sunboard) or HIPS can be easily formed over the mould applying heat with the heat gun. Papier-mâché can also be applied over the mould to form wave surfaces.	Heat Gun Plastic sheet cutter Industrial cutter

WEARABLE

54

	FORM	MATERIAL & PROCESSES	TOOL
BAR		HIPS or MDF board can be used to make bars of varied cross sections with the help of laser cutting machine. Straps made of leather, velcro or fabric can be attached to the surface with the help of resin-based adhesives.	Laser cutting machine Plastic sheet cutter Scissors Steel ruler Cutting mat
BODY			
SURFACE		HIPS and foamboard can be bent to make curved surfaces that are in contact with the body. To make bent surfaces, refer card 2. Trimming and finishing can be done with the help of rotary carving tool. To cushion the inner part of the bent surfaces polypropylene/polyethylene foam sheet can be used. They can be joined with the bent surfaces using resin based adhesives.	Rotary carving tool Scissor Steel ruler Cutting mat

WIGGLE

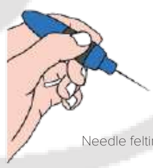
55

	FORM	MATERIAL & PROCESSES	TOOL
BAR			
BODY			
SURFACE		It can be achieved by removing materials with a scroll saw or a portable jigsaw from a block of MDF or wood. PU foam can also be used for making wiggle forms and it can be cut using fast wire contour cutting machine. NOTE: In case of non-availability of the above mentioned materials, high density EPS can be used. However, maintaining uniform thickness while cutting and filing EPS is very difficult. Also, EPS doesn't give good strength to the surface structure, hence EPS is not preferred.	Portable jigsaw Scroll saw Hand Files

WRAPPED

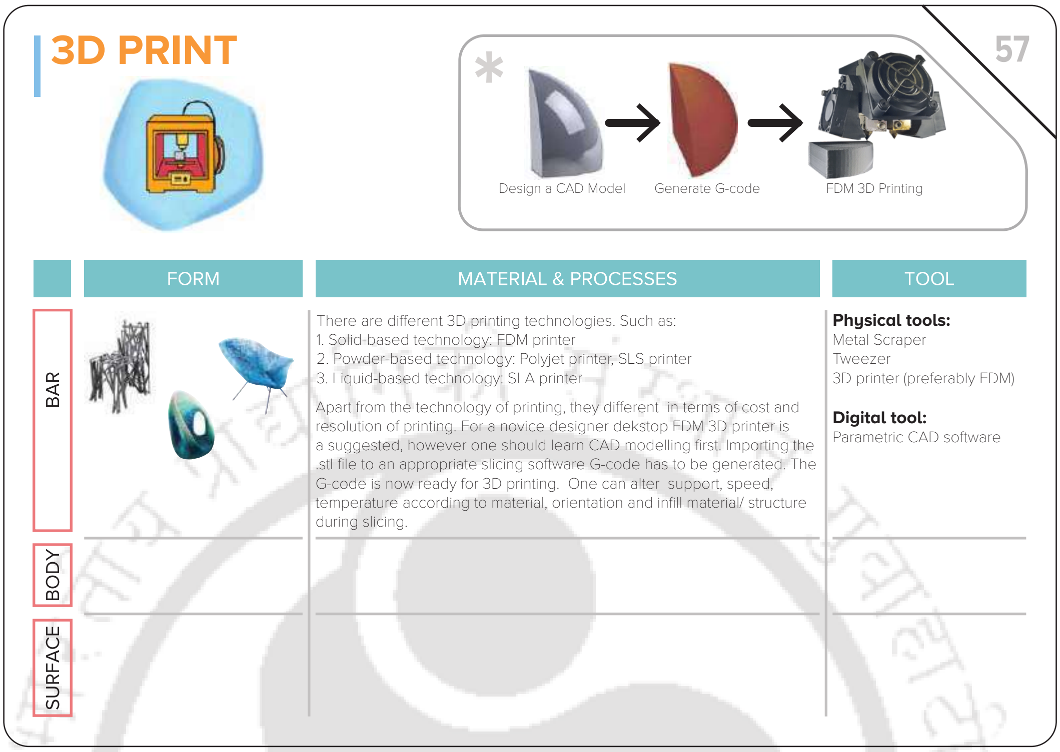
56

*

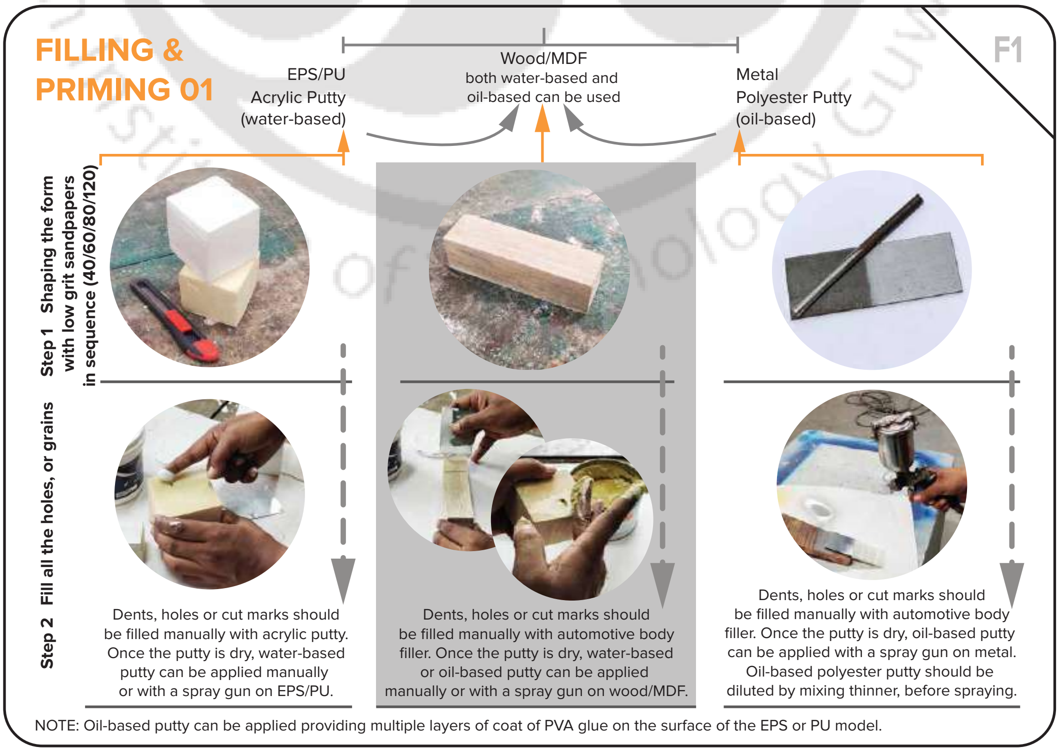


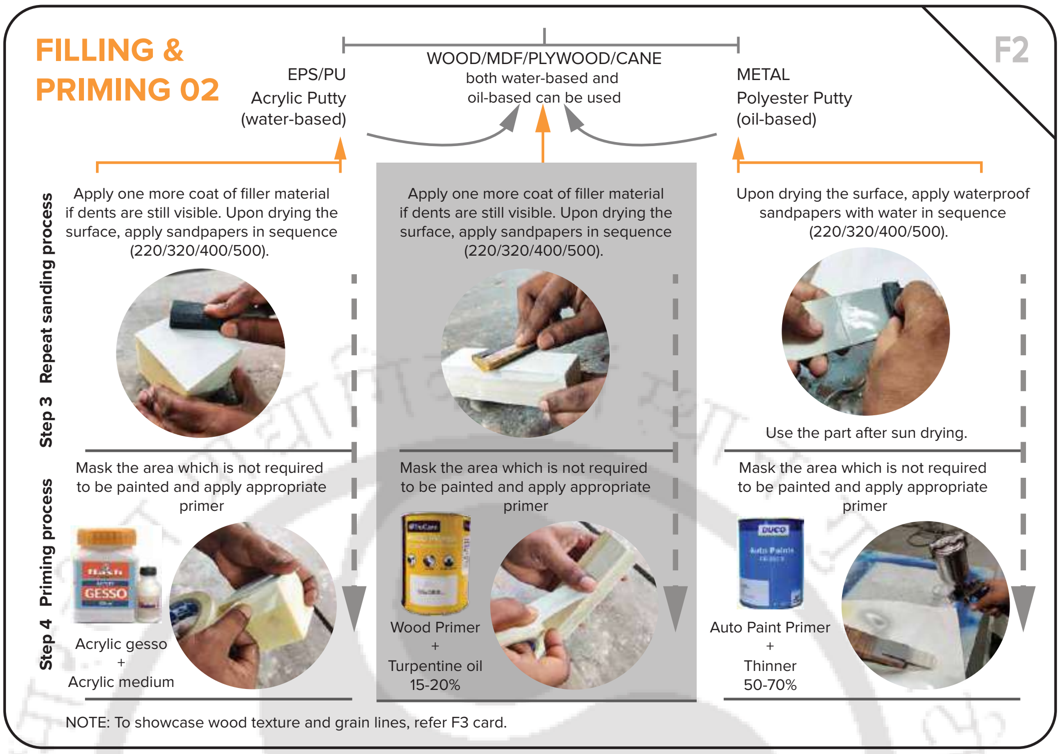
Needle felting tool

	FORM	MATERIAL & PROCESSES	TOOL
BAR			
BODY			
SURFACE		Cotton quilt stuffed with cotton, polyester fibre or sponge can be used to make the envelop of the wrapped furniture. Quilt can be made by hand sewing or a sewing machine. Felt fabric also can be used to make the envelop. Felt fabric can be joined by sewing, adhesives or needle felting*.	Needle felting tool* Scissor Needle Sewing machine



Finishing Cards (F-series Cards)




FILLING &
PRIMING 02
F2
EPS/PU
Acrylic Putty
(water-based)
WOOD/MDF/PLYWOOD/CANE
both water-based and
oil-based can be used
METAL
Polyester Putty
(oil-based)
Step 3 Repeat sanding process
Apply one more coat of filler material if dents are still visible. Upon drying the surface, apply sandpapers in sequence (220/320/400/500).
Apply one more coat of filler material if dents are still visible. Upon drying the surface, apply sandpapers in sequence (220/320/400/500).
Upon drying the surface, apply waterproof sandpapers with water in sequence (220/320/400/500).
Use the part after sun drying.
Step 4 Priming process
Mask the area which is not required to be painted and apply appropriate primer
Acrylic gesso
+
Acrylic medium
Mask the area which is not required to be painted and apply appropriate primer
Wood Primer
+
Turpentine oil
15-20%
Mask the area which is not required to be painted and apply appropriate primer
Auto Paint Primer
+
Thinner
50-70%
NOTE: To showcase wood texture and grain lines, refer F3 card.


FILLING &
PRIMING 03
FOR WOOD/MDF/PLYWOOD/CANE
F3
DENT FILLER (Hand made)
Step 1
Mix
Wood polish powder
+
French chalk powder
+ Paraffin wax
Step 2
Heat and mix
Step 3
Fill the dent
DENT FILLER
(Available in market)
Asian Paints Aquadur Dent Filler
or
Asian Paints Woodtech Filler
GRAIN FILLER (Hand Made)
Step 1
Mix and apply
Shellac flakes
+
Denatured alcohol
or Methylated spirit
100 gm in 500 ml
Step 2
Upon drying the surface, apply sandpapers in sequence (300/400/500)
Step 3
Apply wood polish powder (according to the wood color), french chalk powder and water/ PVA glue mixed wood filler
Step 4
Repeat step 1 ans step 2 to make the surface clean and smooth
GRAIN FILLER
(Available in market)
at step 1
at step 2
Shellac clear coat mixing with denatured alcohol at 1:1 ratio or AquaCoat grain filler

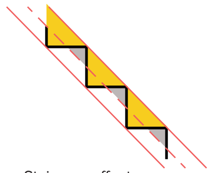
FILLING & PRIMING 04

F4

3D PRINTED PARTS

Post-processing of 3D printed parts can be categorized into two groups as mechanical and chemical processes. Mechanical process involves removing the peaks and checmical processing involves filling the valleys and reducing surface roughness with vapor bath specifically during model making.

SURFACE RELATED ISSUES IN 3D PRINTED PARTS



Staircase effect on an inclined surface

ridge pattern on a flat surface

MECHANICAL PROCESSING

Step 1

Apply waterproof sandpapers with water in sequence (220/320/400/500)

Step 2

Dry it under sun

Step 3

Polish with the help of Dremel polishing tool kit after the sanding process

Step 4

Fill dents or marks visible manually with acrylic gesso

Or,
Apply acrylic gesso with the help of airbrush spray gun.

Step 5

Dry it under sun

Step 6

Sand the part again with sand paper again in sequence (400/500)

NOTE: Mix medium with acrylic gesso to to make acrylic paints pour and flow smoothly and freely.
Instead of gesso, glazing & spot putty also can be applied.

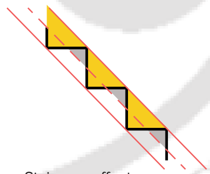
FILLING & PRIMING 05

F5

3D PRINTED PARTS

Post-processing of 3D printed parts can be categorized into two groups as mechanical and chemical processes. Mechanical process involves removing the peaks and checmical processing involves filling the valleys and reducing surface roughness with vapor bath specifically during model making.

SURFACE RELATED ISSUES IN 3D PRINTED PARTS



Staircase effect on an inclined surface

ridge pattern on a flat surface

CHEMICAL PROCESSING

Method 1 | Epoxy Coating

Step 1

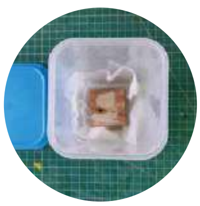
Mix resin and hardener according to the propertion suggested by the brand

Step 2

Apply the resin-hardener mix with a paint brush or sponge brush

Method 2 | Vapor Bath Smoothing

Step 1



Pour acetone into a plastic container, which must have a platform to keep the 3D printed part/product

Step 2

Wait for 20-30 min after closing the lid of the container. Acetone vapor will melt the surface of the 3D printed part/product

NOTE: For epoxy coating XTC-3D and Z-POXY is available in market.

PAINTING

F6

EPS/PU
Acrylic/ Enamel Paint
(water-based)

Wood/MDF
both water-based and
oil-based can be used

Metal
Polyurethane/ Enamel Paint
(oil-based)

PAINT MIXING

Step 1 Prepare the surface
according to the filling & priming card

Step 2 Paint mixing
Consistency:

Step 3

• Water/medium is used to thin the acrylic paints (20-30 percent)
• Paint thinner is used to thin oil-based paints

Thin (50-60 percent)

paint drips off the stirrer

Thick (20-30 percent)

paint falls off the stirrer in globs

Finish: **Glossy** **Matte**

Compressor pressure: Spray gun 25-29 PSI; Airbrush 15-45 PSI (Suggested to experiment with pressure depending on the viscosity of the fluid.)

PAINT APPLICATION METHODS

SPRAY CAN

Aerosol spray paint cans are sealed pressurized container that dispenses mist of paints. Spray cans of oil-based, water-based and glossy clear coats are available.

AIRBRUSH

Airbrush is a painting tool, which uses compressed air to atomize paint and helps to apply into a controlled pattern.
Mostly acrylic paints are applied using airbrush.

SPRAY GUN

Spray gun is a painting tool, which uses compressed air to atomize paint and helps to apply into a controlled pattern.
Oil-based paints and water-based paints both can be applied using spray gun.

NOTE: Water-based enamel or acrylic paints can also be applied on metals.
Oil-based paints can be applied provided the surface of the EPS or PU model was coated before applying filler material.

ADHESIVES

F7

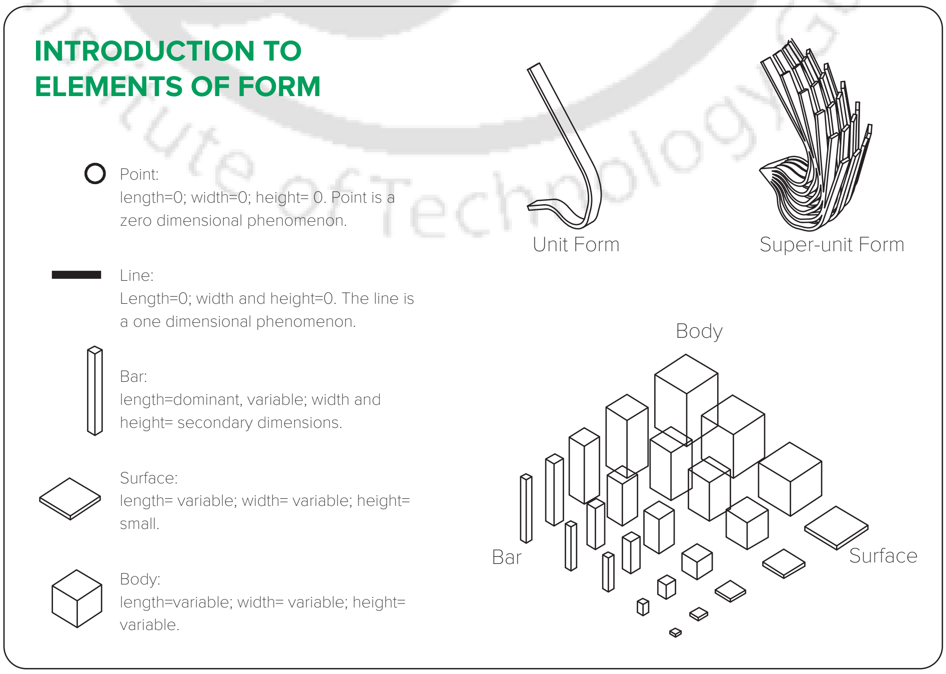
Adhesives are an interesting alternative for model makers to join two similar or dissimilar materials. Bonding with adhesives is the most accessible and manageable technique for novice designers. Product designers should be aware of the types of adhesives to join metals and non-metals or mixed materials.

	Types of Adhesive	Brands Available in Market	Approximmate Cure Time	Material Compatibility
Non-reactive adhesives bond through a physical change useful for non-structural joints	Glue stick	Fevistick, 3M Scotch, Pritt Stick, Asian Paints TRUGRIP, Kores Glue Stick, Faber-Castell Glue Stick	2-5 min	Paper, Corrugated Cardboard
	Polyvinyl Acetate (PVA)	Elmer's Glue-All, Faber-Castell White Glue, Fevicol MR Elmer's Wood Glue Max	30 min - 1 Hr 50 min - 1 Hr (White PVA for joining Wood or MDF may take upto 24 Hr)	Paper, Styrofoam, Polyurethane foam, Cardboard, Foamboard, Jute Wood, MDF
	Synthetic Rubber Adhesive	Dendrite, Fevibond, SR 998, Asian Paints Trugrip Xtreme	10 min - 3 Hours	Paper, Leather, Metal, Rubber, Rexine, Canvas, Cork, Fabric, Wood, Plywood
	Hot melt adhesive	Glue gun and glue stick from various brands are available	30 sec	Cork, Leather, Metal, Rubber, Rexine, Canvas, Fabric, Felt, Styrofoam, Wood, Plywood, Jute
Reactive adhesives bond through a chemical reaction useful for structural joints	Acrylic Cement	WELD ON SCIGRIP 16	10 min Working time 24 Hr Full curing time	Cellulose Acetate Butyrate, Polycarbonate, Acrylic, Styrene
	Cyanoacrylate	Fevikwik, Super Glue, T7000, B7000, POLYFix	1 - 3 sec	Leather, Metal, Rubber, Rexine, Canvas, Cork, Fabric, Wood, Plywood, Ceramic, Glass, Plastic
	Bi-Component Adhesive (Resin + Hardener)	J-B Weld, LOCTITE Epoxy, Lapox, Fevilite, Araldite, PRATLEY	5 min - 12 Hr	Metal, Cork, Wood, Plywood, Plastic, Ceramic, Glass, Felt, Leather, Canvas
	Aerosol-adhesives	3M Super 77, OH 99, FEVICOL Ezee Spray, WEICON Adhesive spray	15 seconds to 30 minutes	Styrofoam, Polyurethene foam, Wood, Glass, Paper, Leather, Plastic, Metal

Safety Card

Additional Card

Based on the feedback from students, an additional card has been included along with the DHfFD and TfMM to introduce the elements of form.



SECTION-B METHOD OF USING THE TOOLSET

5.4 Proposed method for using DHfFD

Study and analysis of the designs produced by celebrated designers helped us understand the application of design heuristics within the designs of a designer. Table 5.1 describes the evidence of heuristics while redesigning a chair.

Table 5.1 Evidence of heuristics while redesigning

Initial design	Experimental Material & Process	Alter Material	Transformed Body
			
Oh-Void 1 | 2002	Oh-Void 2 | 2004	Oh-Void 2 | 2006	Blo-Void 4 | 2006
Oh-Void 1 is the first in the void series by designer Ron Arad. It was made up of a Composite of aramid fibres and Nomex.	Oh-Void 2 by Ron Arad results from an experiment with unusual materials and techniques. The synthetic material Corian sheets were bonded together and milled to make the masterpiece.	Ron Arad altered the material with clear and coloured Acrylic and exhibited Oh-Void 2 again.	Ron Arad produced the design with polished aluminium and anodized aluminium mesh. Beyond material, the Blo-Void 4 was presented with a transformed body.

The examples showcased in Table 5.1 are from the iconic designs by Ron Arad. Arad's design from the void series explicates a few heuristics that are presented here.

For Oh-Void 2, function and behaviour are the same as Oh-Void 1; hence the dominance factor 'structural composition' is considered heuristics. For Oh-Void 2 (2004), a new composite material, Corian (a composite of acrylic polymer and alumina trihydrate), was used. Oh-Void 2 (2006), made in Acrylic, had similarities in function and behaviour except for the change in material, which was not exceptional. Furthermore, Blo-Void 4 appeared in an extraordinary form with innovative material, which is equally dominant. As Ron Arad always explore materials and processes, the dominant form of Blo-Void is considered heuristics.

The purpose of Design Heuristics for Furniture Design, derived from the iconic designer's work, is to facilitate novice designers to develop innovative concepts. Table 5.2 showcases an example that shows the initiation of ideas using DHfFD.

Table 5.2 Initiation of ideas with DHfFD cards

Brief	Concept	Design heuristics and Description
Design furniture for kids, irrespective of context		Applied design heuristics: Modular / Bar and panels / Adjustable
		Description: The concept suggests arrangement and adjustments of modules by the user according to the use and user height.
		Applied design heuristics: Experimental Material & Process
		Description: The concept proposed a seat pan with a composite of natural aromatic resin and natural fibre from the areca nut leaf.
		Applied design heuristics: Bar and Panels
		Description: The illustration showcased a concept with a composition of bent tubes and panels.

The examples in Table 5.2 describe a case of initiating concepts for designing furniture for kids irrespective of context. Beyond initiating ideas, the Design Heuristics for Furniture Design help to refine ideas. Table 5.3 showcases an example of the evolution of a concept from Table 5.2 taken forward for continuous refinement using DHfFD.

Table 5.3 Application of multiple heuristics for varied concepts

	Design Heuristics for Furniture Design		
Initial concept	Adjustable	Chair + X	Storage
			
The initial idea presents a chair with bent tubes, a flat seat pan, and a flat backrest.	The adjustable feature allows the user to adjust the height.	Combining the chair with the table allows the user to use it as a furniture unit.	The additional storage facility provides the advantage of storing necessary items with the furniture unit.

The process begins with the selection of an initial concept generated with the application of multiple DHfFD cards, as described in Table 5.3. As evident in Table 5.3, multiple heuristics were applied by the designer to explore the solution space with a new perspective. The application of design heuristics facilitated the designer to think beyond the design brief and brought new dimensions to the solution with usable functions. Thus DHfFD helps generate alternative novel design concepts by initiating and modifying ideas. However, using one or multiple heuristics is entirely the designer’s choice, and the degree of innovation is not a function of the number of heuristics applied to generate concepts.

5.5 Proposed method for using TfMM

Tool for Model Making aims to assist novice designers in selecting materials and processes to make an appearance model. The proposed method workflow is illustrated in Figure 5.3, and the following sub-sections describe each step in detail with examples.

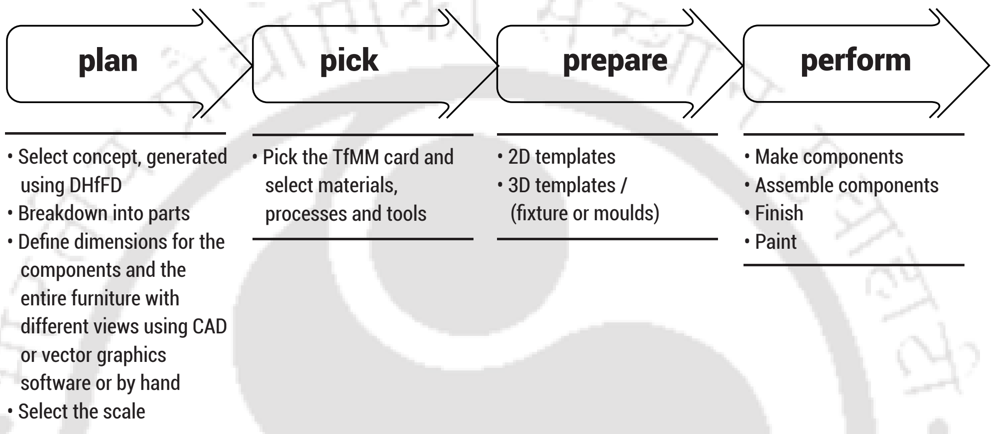


Figure 5.3 Method workflow for appearance model-making using TfMM

5.5.1 Plan

- The model-making process begins with the selection of concepts generated using DHfFD. Figure 5.4 showcases an example of selecting a concept developed with DHfFD.

Figure 5.4 Selection of a concept

- The selected concept has to be broken down into parts in the next step. The selected concept converted into parts is illustrated in Figure 5.5.

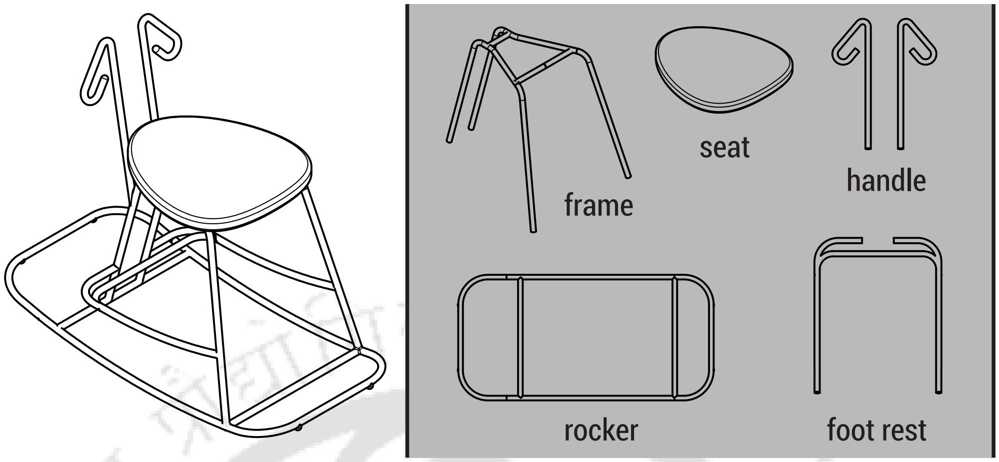


Figure 5.5 Break down of furniture into parts

- At this stage, dimensions for all the pieces have to be defined. The dimensional drawing can be drawn using any CAD software or vector graphics software like Adobe Illustrator or Corel Draw. Figure 5.6 illustrates different views with dimensions.

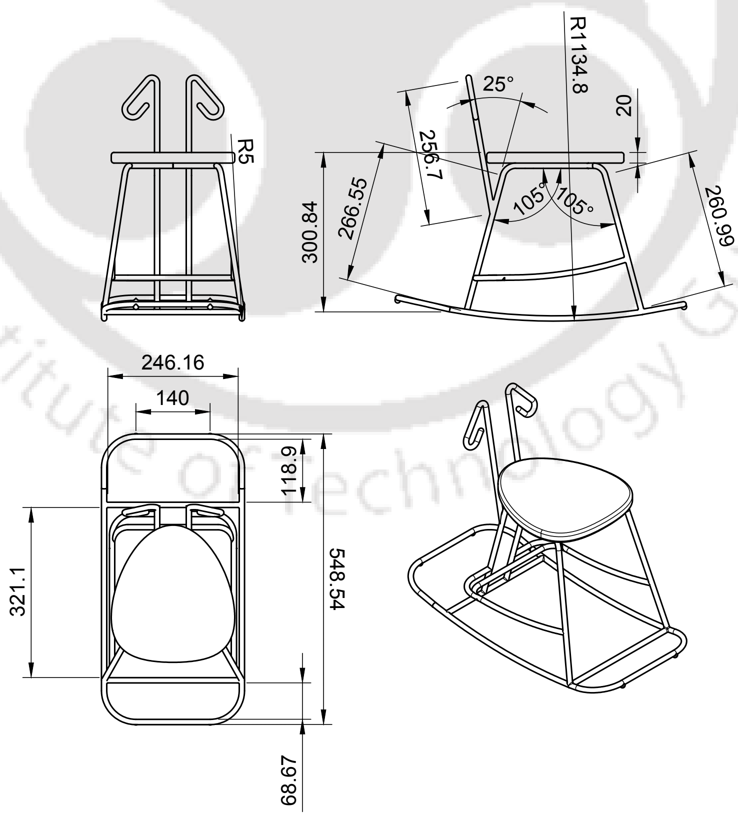


Figure 5.6 Dimensional drawing (all dimensions are in mm)

- The final task in the planning stage is to define the scale. For the scaled-down model, mostly scale of 1:4, 1:5, or 1:6 is considered.

5.5.2 Pick

This phase allows picking the TfMM card based on the structural composition of the furniture design. Most likely, one may find an exact match with the card. However, if an exact match is not available, one should look for the component level match with the elements given in TfMM cards.
The appropriate card for the selected chair, in this case, is ‘Bar and Panels’.

The TfMM card suggests the following:

- Materials: M.S. rods, nylon rods or aluminium rods.
- Processes: Bending, heat bending, thermal joining for metals, and joining with adhesives for non-metals.

Furthermore, TfMM suggests MDF, wood, HIP or foam board for panels. Beyond all that, flat panels with new composite material can be moulded and used.

5.5.3 Prepare

Two-dimensional prints for all the parts should be handy at the preparation stage, and all the 3D fixtures or moulds have to be made first.
As suggested by the TfMM card, the process demand composite material to be moulded, and Figure 5.7 shows the process of making it using a mould.

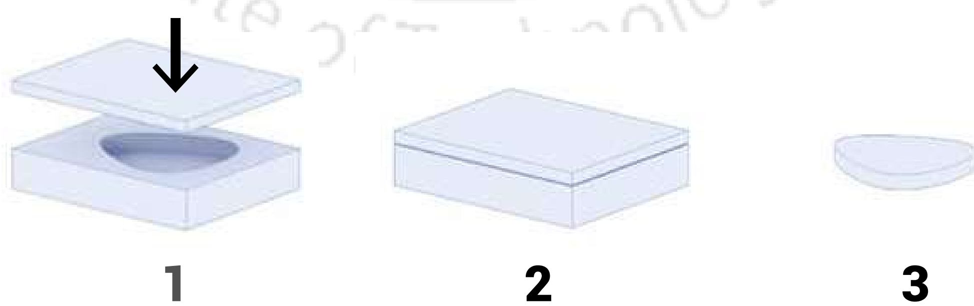


Figure 5.7 Moulding process

5.5.4 Perform

At this stage, the following things are to be done:

- Making all the parts
- Assemble all the parts
- Finish and paint

Figure 5.8 showcases the seat made with compression moulds, and Figure 5.9 showcases the final scaled model.

Figure 5.8 Scaled furniture seat made using actual composite

Figure 5.9 Scaled model

One should follow the F-series cards in the TfMM deck for finishing and painting.

5.6 Summary

This chapter demonstrates the anatomy of the DHfFD and TfMM cards which has a uniformity of text-based stimuli and visual-based stimuli. All 86 Design Heuristics for Furniture Design and 65 Tool for Model Making cards are showcased in this chapter. The method of using the DHfFD and TfMM is also explained with examples for future use.

Design Heuristics for Furniture Design

and

Tool for Model Making

Chapter 6

Contributions and Future Work

6.1 Summary and Conclusion

As discussed earlier, concept generation and prototyping are two crucial phases of successful innovation. The success relies on the quantity of the concepts generated (Yang, 2003), and prototyping drives and delivers improvised products (Schrage, 1993). This research attempted to develop concept generation, and prototyping (model-making) supports to facilitate novice designers in the early stages of furniture design. This dissertation showcased the systematic development of Design Heuristics for Furniture Design (DHfFD) and Tool for Model Making (TfMM) for novice designers. Both tools were developed based on the specifications derived from the literature and validated to confirm their efficacy.

This research endeavour fulfilled five objectives presented at the beginning of this dissertation. Table 6.1 clarifies each research objective and related research questions with references.

Table 6.1 Research objectives and references clarification

Research Objectives	References
Research Objective 1	
To further understand the approaches with the prototype as a boundary object in furniture design and the interplay between concept and prototype in furniture design.	Chapter 2: Literature Review Section 2.6: Prototype as Boundary Object Section 2.9: Interplay of Concept Generation & Prototyping
Research Questions	
Q1.What is the nature of approaches with the prototype as a boundary object in design innovation? Q2.What is the interplay of concept and prototype?	

Research Objective 2	Chapter 2: Literature Review
To develop furniture design-specific supports for concept generation for novice designers.	Section 2.13: Supports in Design Section 2.14: Supports for Concepts Generation --
Research Questions	Chapter 3: Development of Supports
Q3. What supports are available in design research, and what are the attributes of design supports? Q4. What are the specifications to be considered while developing supports for concept generation?	Section 3.2.1: Specifications for Concept Generation Support
Research Objective 3	Chapter 4: Assessing the Impact of DHfFD and TfMM
To assess novice designers' outcomes of creative concept generation before and after using the support.	Section 4.3: Research Methodology Section 4.4: Qualitative Impact Assessment of DHfFD Cards-Results and Discussions
Research Questions	
Q6. What is the impact of the structured concept generation tool on novice designers?	Section 4.5: Quantitative Impact Assessment of DHfFD Cards-Results and Discussions
Research Objective 4	Chapter 2: Literature Review
To develop furniture design-specific support for model-making or prototyping for novice designers.	Section 2.13: Supports in Design Section 2.16: Processes and Supports for Prototyping

Research Questions	Chapter 3: Development of Supports Section 3.2.2: Specifications for Prototyping Support
Q3. What supports are available in design research, and what are the attributes of design supports? Q5. What specifications should be considered while developing supports for model-making/prototyping?	
Research Objective 5	Chapter 4: Assessing the Impact of DHfFD and TfMM
To assess the outcomes of model-making or prototyping by novice designers before and after using the support.	Section 4.7: Research Methodology
Research Questions	Section 4.8: Qualitative Impact Assessment of TfMM Cards- Results and Discussions
Q7. What is the impact of the structured model-making/prototyping tool on novice designers?	Section 4.9: Quantitative Impact Assessment of TfMM Cards- Results and Discussions

Chapter 1 presented the research objectives and questions based on the initial understanding of the existing and desired situations, i.e. 'initial reference model' and 'initial impact model'. Furthermore, a detailed investigation of the literature in Chapter 2 provided a better understanding of the research context. The detailed review of prototypes and concepts in Section 2.6 revealed the innovation approaches with prototypes as boundary objects, specifically, i) Exploratory prototyping, ii) Evolutionary prototyping, iii) Periodic prototyping, and iv) Collaborative prototyping. In all cases, prototyping is the critical marker; however, the central idea of driving the innovation process with prototypes is the same in all cases. Innovation processes, where prototypes are the stimulant, and protocepts are the indispensable entities, where 'protocept = concept + rough prototype' (Lundahl, 2005). That is why Section 2.9 discusses the interplay of concept generation and prototyping. An empirical study by Bao et al. (Bao, Faas, & Yang, 2018) shows that both concept generation and prototyping allow designers to explore broader design space and generate more feasible-creative concepts. On the contrary, there are issues with concept generation and prototyping for novice designers, which necessitates the development of support for concept generation and prototyping. Toward developing support, Section 2.13 discusses the attributes of supports in design and successively, Section 2.14 and Section 2.16 focus on supports for concept generation and prototyping. Detail review of the literature in Chapter 2 delineated useful excerpts at the end of all the sections.

The excerpts from Chapter 2 helped to construct specifications for concept generation support in Section 3.2.1 and specifications for prototyping support in Section 3.2.2. Chapter 3 also illustrates the systematic development of the Design Heuristics for Furniture Design (DHfFD) and Tool for Model Making (TfMM); thus, research objectives 2 and 4 are fulfilled.

Chapter 4 assesses the impact of DHfFD through a within-subjects controlled experiment based on quality, originality and implementability. The controlled investigation reveals a statistically significant improvement in the output of the participants while using DHfFD cards. A between-subjects controlled experiment to validate the TfMM tool shows a statistically significant improvement in the appearance model quality score for the experimental group. Having validated the DHfFD and TfMM research objectives 3 and 5 are fulfilled.

Beyond statistical validation, this research took the effort to introduce the DHfFD and TfMM in combination in design thesis projects carried out by students from a postgraduate program in design. Two case studies, which got international recognition, show these tools' effectiveness beyond the controlled experiment. One chair was shortlisted to showcase in Global Grad Show Dubai in 2017, and the other got nominated for the pre-selection category for the Green Concept Award 2022.

This research recommends using DHfFD and TfMM in design education.

6.2 Research Contributions

Design research should have the following objectives (Blessing & Chakrabarti, 2009) (Figure 6.1):

- Formulation and validation of theories and models about the design phenomenon with all its facets (knowledge/methods/tools, product, process, people, organization, micro-economy, and macro-economy); and
- Development and validation of support based on these models and theories to improve design practice and its outcomes in industry or academia or both

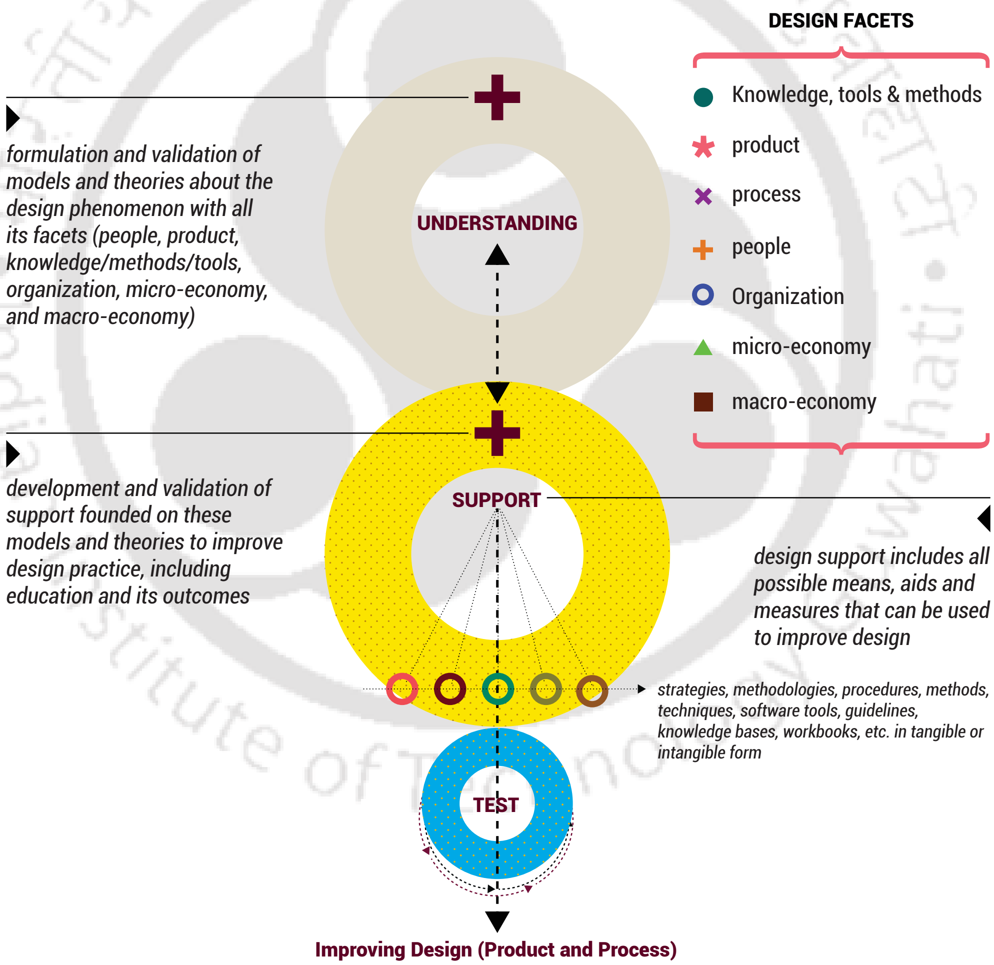


Figure 6.1 Design research objectives

The contributions from this research also focused on the *understanding and support* in furniture design, specifically for prototype-driven innovation. The following are the specific theoretical contributions and contributions to the practice from this dissertation:

- Proposed model for prototyping towards prototype-driven innovation
    - This dissertation proposed a prototyping model for prototype-driven innovation, where prototypes are the boundary object, and the prototyping process is the central activity. This research defines "prototyping as a process to explore and think for new concept generation," meaning prototyping must be a two-way process to generate ideas in the case of prototype-driven design innovation. Thinking and making both should happen together through iterative prototyping. Novice designers should be encouraged to explore, envision, and refine concepts through prototyping. This dissertation suggests introducing appropriate support to scaffold novice designers during this endeavour.

- Establishment of specifications for structured tools for concept generation and prototyping
    - Excerpts from the detailed literature review propounded four specifications for concept generation support and four specifications for model-making or prototyping. These specifications are the construct for developing concept generation support and support for model-making or prototyping. Future researchers can further use these specifications to explore structured concept generation support and support for model-making or prototyping.

- Development of the Design Heuristics for Furniture Design (DHfFD)
    - This research developed Design Heuristics for Furniture Design (DHfFD), emphasizing the chair, which would help in furniture concept generation for novice designers. This research followed a three-step process to study and analyze an extensive repertoire of furniture (chair) design analogies: 1) Collecting and pre-processing furniture (chair) data, 2) Clustering existing furniture (chair) using the K-J method, 3) Deriving furniture design heuristics. Analysis of 650 chairs and systematic design heuristics extraction resulted in 81 Design Heuristics for Furniture Design.

- Development of the Tool for Model Making (TfMM)
  - As the development of design heuristics for the furniture (Chair) provided an exhaustive list with function, behaviour and structure as the dominant feature, the research carried forward the structure-dominant groups to develop a model-making tool. This research illustrated a ten-step process to create the Tool for Model Making, which would be helpful for future researchers while exploring tools for prototyping. Analysis of the relation between form, material and processes and systematic tool development resulted in Tool for Model Making with 57 cards. TfMM also includes *finishing cards* to assist novice designers with knowledge of material and processes for finishing during prototyping.

- Method for using DHfFD
  - The purpose of Design Heuristics for Furniture Design, derived from the iconic designer's work, is to facilitate novice designers to develop innovative concepts. This dissertation proposed a method for using DHfFD for the initiation of ideas and to generate varied concepts by applying multiple heuristics.

- Method for using TfMM
  - Tool for Model Making aims to assist novice designers in selecting materials and processes to make an appearance model. This dissertation proposed using TfMM with the workflow plan, pick, prepare and perform.

- Creation of the evaluation metrics for appearance model quality
  - There is no standard method or set of metrics to evaluate prototypes. Previous research evaluated prototypes with binary metrics to indicate a successful or unsuccessful design prototype or using an ordinal rating scale or metrics adapted from management science, engineering design, and marketing studies. This research measured the appearance model quality using attributes of prototypes: 1) Scale and proportion, 2) Shape and surface quality, 3) Strength and stiffness, 4) Resolution and fidelity, and 5) Material and processes.

- Validation of the effect of the tool DHfFD for novice furniture designers
    - Research in the furniture design domain lacks structured tools and methods for creative concept generation. This research assesses the impact of the tool DHfFD on novice designers. The qualitative impact assessment reflects participants' positive perceptions of the tool, and the controlled experiment reveals a statistically significant improvement in the output of the participants in terms of quantity, originality and implementability while using DHfFD cards. Assessing the impact of the tool DHfFD on novice furniture designers, this research integrates concept generation, design tools and design cognition.
- Validation of the effect of the tool TfMM for novice furniture designers
    - Most of the existing prototyping tools are strategic or planning tools that do not facilitate prototype making but a few. An available prototyping tool that assists in prototype-making is not empirically validated. This research presents a qualitative and quantitative assessment of TfMM on novice designers. While the qualitative impact assessment reflects participants' positive perceptions of the tool, the controlled experiment divulges a statistically significant improvement in the output of the participants in terms of appearance model quality while using TfMM cards. Assessing the impact of the tool TfMM on novice furniture designers, this research integrates prototype development, design tools, and tacit knowledge.
- Exploration of the impact of the toolset in combination with long-duration thesis projects
    - While previous research validated the impact of the design tools only through controlled validation, workshop validation, or comparison to other similar tools/methods, this research explored the impact of the toolset in combination with long-duration thesis projects by novice designers. This research confirmed the effectiveness of these tools beyond the controlled experiment, validating the innovation aspect of the end designs on international platforms.

6.3 Limitations

This research work is limited to the following aspects:

- Sample size
  - As furniture design is a specialized domain, the number of participants in all the experiments are less. However, the large effect size reflects the experiments' statistical significance. Thus despite the limited sample size, the findings may apply to similar circumstances.
- Experiment procedure
  - While assessing the impact of the DHfFD cards, a subset of the DHfFD card set was given during the experimental treatment phase to avoid overwhelming feelings with the entire collection. Though all the experiment shows a positive result with the subset of DHfFD cards, impact assessment is pending for other cards.
  - This research did not explore the influence of time while using DHfFD for concept generation and TfMM for prototyping. A detailed study is needed to understand the correlation between time and the transformation of concepts and prototypes while using DHfFD and TfMM.
- Nature of design briefs
  - This research is limited to the design briefs presented to the students. While assessing the full potential of the structured tool DHfFD and TfMM, future research is needed to determine the impact of these tools on different design briefs and design contexts.
- Different validation scenarios
  - This research assessed the tool's impact only in one design institute in India. Further studies are required to evaluate the utility of the tools in different scenarios.
  - Since DHfFD and TfMM were developed to facilitate novice designers, this research only assessed the tool's impact on novice designers. However, there is a scope to explore with the industry participants working on design scenarios developing chairs.

6.4 Future Research Directions

The following potential future research directions in furniture design research are envisaged:

- DHfFD beyond chair
  - This research focused on developing the Design Heuristics for Furniture Design, emphasizing the chair, which would help in furniture concept design for novice designers. Future research would emphasize developing Design Heuristics for Furniture Design for other furniture categories; for example, Design Heuristics for Storage Furniture Design. Additionally, while this research concentrated on living room chair design, future research may explore possibilities for heuristics extraction for other contexts.
- TfMM beyond furniture
  - Support Tool for Model Making (TfMM) developed in this research facilitates appearance model-making for novice designers, specifically furniture design. Over time, it was realized that the core principle of TfMM may apply to other domains with minor modifications. TfMM can be extended to other design domains in future.
- Heuristics within heuristics
  - Local heuristics define the characteristics and relationships of design elements within a single concept, such as Multifunctional (Chair + X): Create a multifunctional chair by combining multiple functions in a chair. There are heuristic principles within local heuristics. Future research may propose heuristics within heuristics. In that direction, research has been pursued to identify heuristics for *playful* furniture design.
- Heuristics for artificial intelligence
  - Artificial Intelligence (AI) has been realized as a new design opportunity, especially in furniture design, over the last few years. Hence, future research in the overlapping space of AI-DHfFD-furniture design practice and AI-DHfFD-principles of furniture design is also envisaged.

6.5 Educational Implications and Recommendations

Instruction scaffolding leads to development and facilitates the maturing of knowledge structures, and the transfer of tacit knowledge is required to help the novice comprehend new knowledge. Such interventions are most effective in the conceptual space *zone of proximal development*. Lev Vygotsky defined *the zone of proximal development* as "*the distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem-solving under adult guidance, or in collaboration with more capable peers*" (Vygotsky, 1978). While Design Heuristics for Furniture Design (DHfFD) assists novice designers in generating diverse and novel concepts and Tool for Model Making (TfMM) facilitates novice designers in developing improved-quality appearance models, they act as scaffoldings for cognitive development. Thus the development of a heuristic-based curriculum or course would inform design pedagogy.

Concurrently, while creating meaningful artefacts, designers follow a research-driven design strategy to follow the person-first design approach. The person-first design approach employs research to understand the target user's need, behaviour, and culture and deliver context for user-artefact engagement. Proposed designs are then tested and refined with the actual users (Visocky O'Grady & Visocky O'Grady, 2017). The same process applies to furniture design also (Eamesoffice, 2015). However, there are issues with instructional scaffolding in this process related to concept generation and prototype building from the design education perspective. Furniture design-specific tools are not available for concept generation and prototyping. Teaching concept generation and prototyping without tools is often a challenge for design educators. There comes DHfFD and TfMM to provide instructional scaffolding.

The research work undertaken in this dissertation has produced DHfFD for concept generation and TfMM for appearance model-making for novice designers that fill the gap in furniture design and contribute to design cognition.

Finally, based on the findings, this research recommends pedagogical practices in design schools using DHfFD and TfMM in furniture design.

Figure 6.2 illustrates the educational implications of the research outcomes.

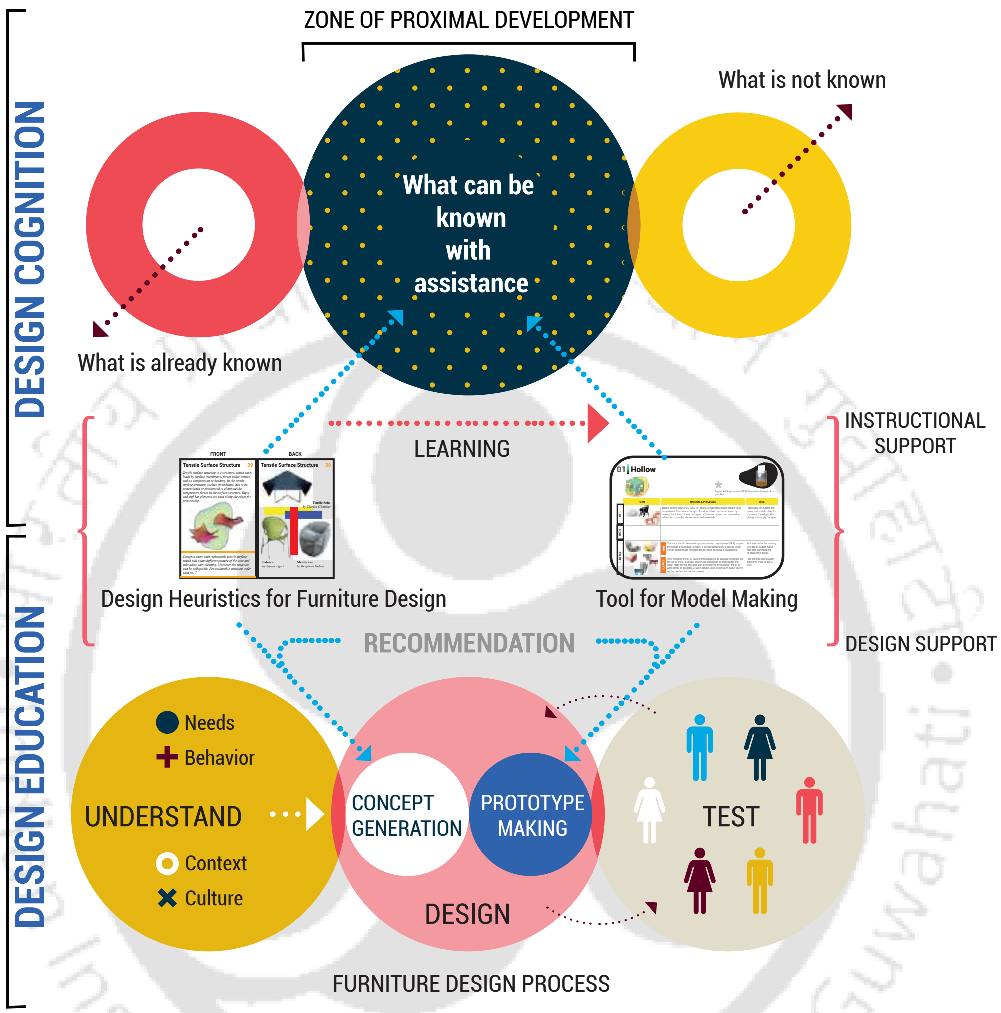


Figure 6.2 Implications of this research and recommendation

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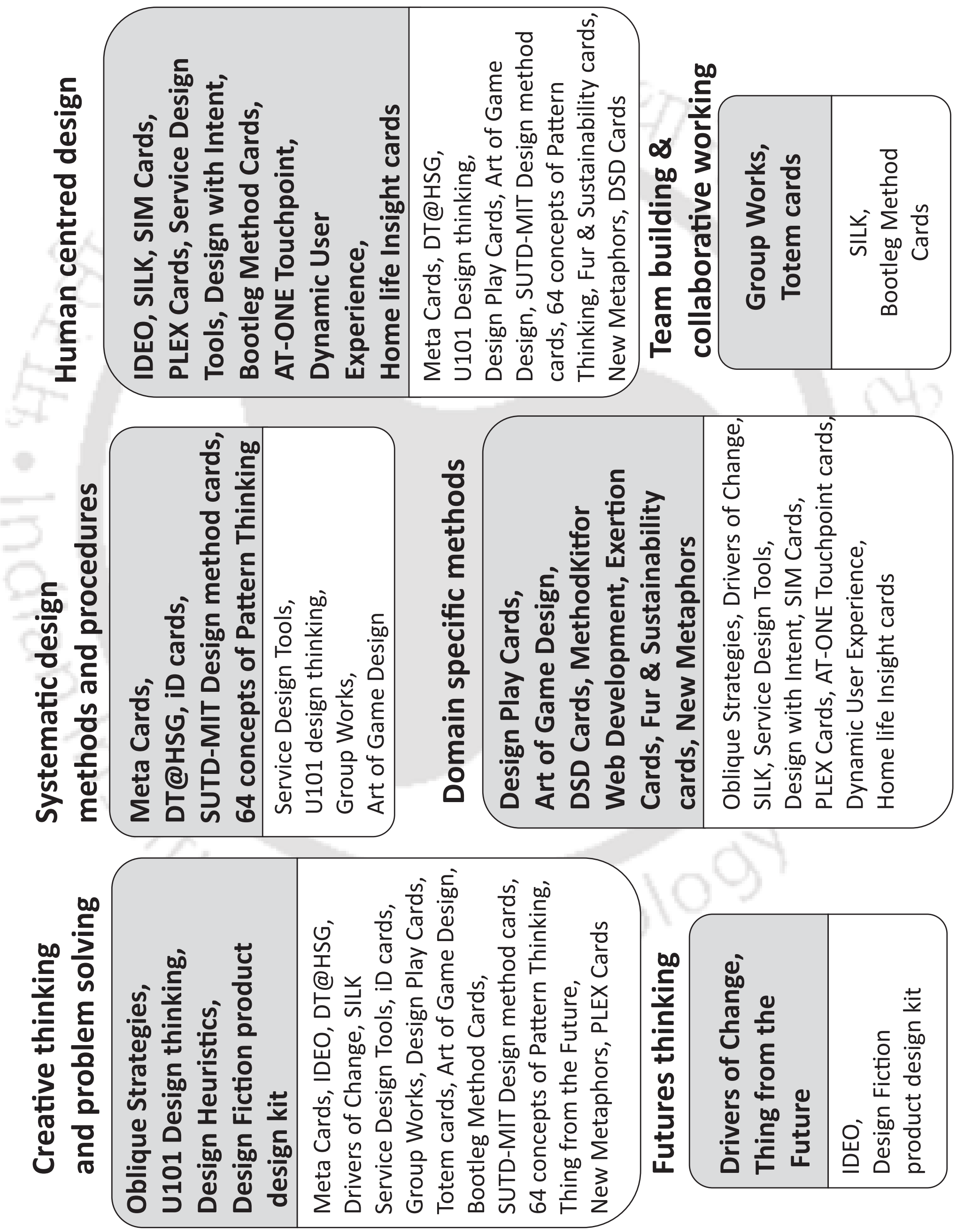
Appendix A

Classification of card-based tools in design based on the purpose (Roy & Warren, 2019)



Appendix B

Factors in prototyping strategy (Christie et al., 2012)

1. Prototypes can be of a single subsystem, of a set of subsystems, or of the entire system

When approaching the creation of a large system, it may be beneficial to break the effort down into smaller subsystems that can each be approached with optimal strategy.

2. Prototyping multiple concepts in parallel vs. prototyping only a single concept

While only one or two concepts will likely eventually be chosen to fully developed, the development of multiple prototypes at an early stage can help provide critical feedback.

3. Iterative prototypes vs. only 1 prototype per concept

This factor considers whether or not it makes sense to tackle a prototype all at once, or to focus on ensuring that certain design requirements are met before adding others. This is useful when paring down the number of concepts to a final few, or interfacing working designs from multiple efforts.

4. Prototypes can be virtual (analytical, CAD, FEA, CFD etc.) or physical

Complex analyses are generally more easily performed by computer than by hand, and development of a CAD model can translate into production benefits for both prototype development and final product manufacturing. However, some of the best feedback a team can get for product development is to have a physical product available for user interaction.

5. Prototype manufacturing can be outsourced, rapid prototyped or completed inhouse

Outsourcing can be resource heavy in terms of cost and time without the item, but frees up the team to work on other aspects of the project and provides access to resources that may not be available internally. Rapid prototyping technologies allow for fast production of parts for evaluation, but available materials are limited, which may not allow parts to be fully evaluated against design requirements. Finally, prototypes may be completed in house, assuming the resources and skill are available. This option tends to be cheaper in cost, but more time intensive for the team.

6. Prototypes can be physically scaled

With certain large products, such as ships and airplanes, creating a full size prototype may not be feasible until the final stage of prototyping, where any full-scale prototype is basically a final product. Additionally, for certain testing methods, such as wind tunnel testing, teams may not have equipment large enough to test a full size device.

7. Prototypes can be functionally scaled

It may be beneficial for teams to design prototypes that contain only a few design requirements at a time, to be able to properly ensure and evaluate the successful implementation of requested features. This can allow for easier testing of prototypes and a more robust final product, but may lead to issues when interfacing multiple prototypes into one final design.

8. Prototypes can use similar or different materials than the final design

Because prototypes have the advantage of not having to meet final design requirements at all stages, some leeway may be given to material selection for prototype development.

9. Prototypes can use similar or different manufacturing and assembly techniques than the final design

With the rise of rapid printing and rapid tooling, teams are able to decide if they want prototypes to be manufactured and assembled in a similar fashion to the final products.

Appendix C

Strategy matrix (Christie et al., 2012)

Prototype (identify if this is a full system or subsystem)	Type	% of $	% of person-hrs	Use Rapid Prototyping technologies?	Possibly Outsource?	Dimensionally scaled?
Concept 1 – iteration A	Analysis	0	10	No	No	N/A
Concept 1 – iteration B	Physical	30-50	20-40	No	Yes	No
Concept 2 – iteration A	CAD + Simulation	0	20	No	No	N/A
Concept 2a – iteration A	Physical	20	10	Yes	No	Yes
Concept 2b – Iteration A	Physical	20	10-20	No	Yes	No

Prototype (identify if this is a full system or subsystem)	Functionally scaled?	Which requirements are/aren't tested?	Which failure modes are/aren't tested?	Using same materials as final design?	Using same manf. & assembly as final design?
Concept 1 – iteration A	Yes	3 <2-9>	a-c <d-m>	Yes	N/A
Concept 1 – iteration B	No	1,2,6-8 <3-5,9>	e-i <a-d,j-m>	Yes	Yes
Concept 2 – iteration A	Yes	3,4 <1-2,4-9>	d-f <a-c,g-m>	Yes	N/A
Concept 2a – iteration A	Yes	6-9 <1-5>	j-m <a-k>	No	No
Concept 2b – Iteration A	Yes	1,2 <3-9>	a-f <g-m>	Yes	Yes

List design requirements in order of decreasing priority (include threshold and objective values)
1. Velocity (threshold = 30 MPH, objective = 50 MPH)
2. Power (threshold = 40 HP, objective = 70 HP)
3. …
9.

List failure modes in order of decreasing importance (from FMEA)
a. Frame yields
b. Gears strip
c. …
m.

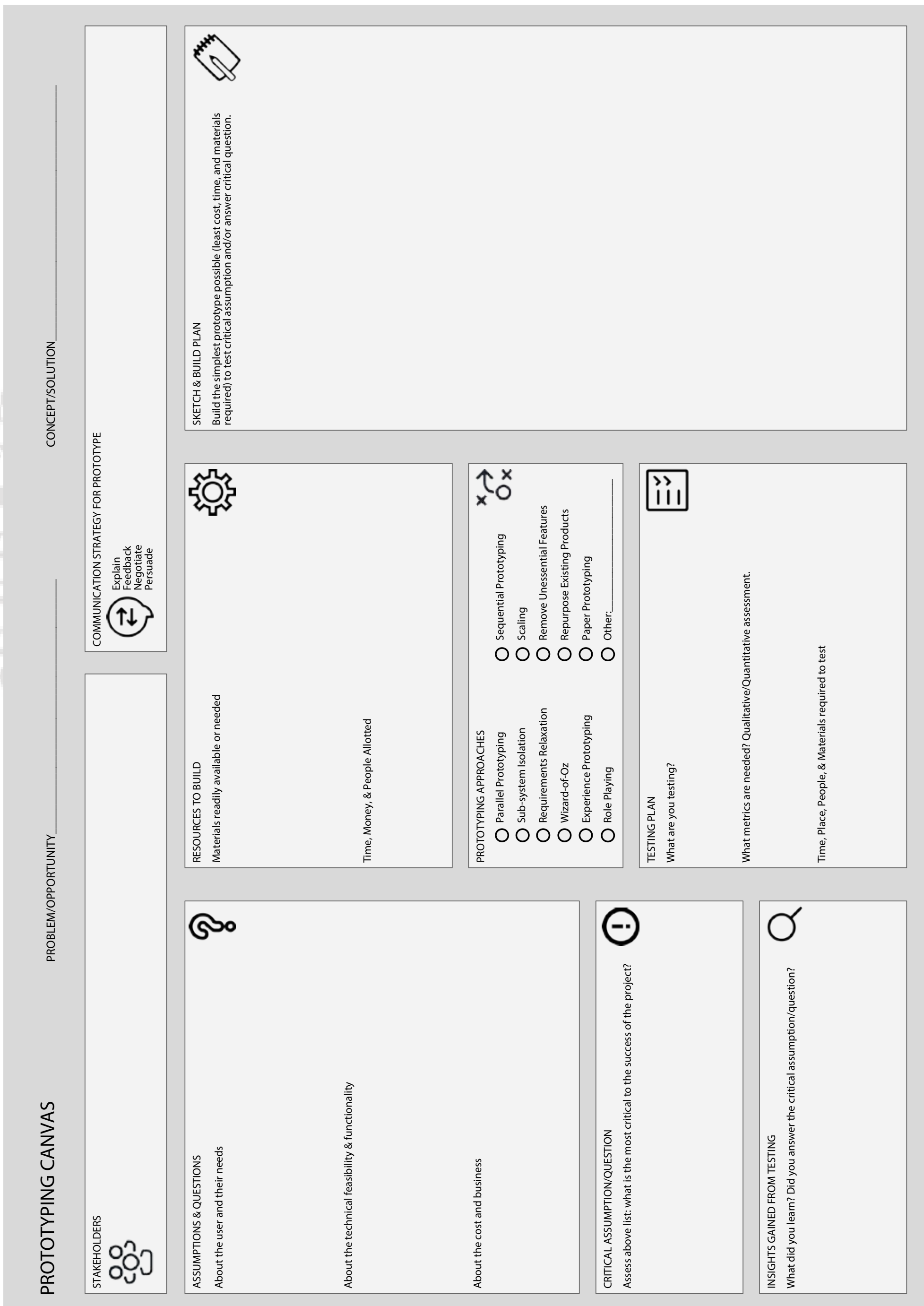
Appendix D

Heuristic-based prototyping strategy tool with Likert scale (Dunlap et al., 2014)

	Compute the average response to the prompts under each category to determine strategy.	Strongly Disagree. -2	Disagree. -1	Neutral. 0	Agree. 1	Strongly Agree. 2
1	For high avg, develop multiple concepts; else, build one only.	One concept				Multiple concepts
a	There are sufficient materials to prototype multiple concepts.					
b	There is sufficient time to prototype multiple concepts.					
c	Rankings of several concepts are very close (e.g. from Pugh chart).					
2	For a high avg, iterate; else, build once.	No not iterate				Iterate
a	The difficulty of meeting the requirements will necessitate iteration.					
b	The difficulty of manufacturing will necessitate iterative prototyping.					
c	My team has minimal prototyping experience.					
3	For a high avg, use a virtual prototype; else, use physical models.	Physical				Virtual
a	Virtual prototype(s) will require less time than a physical one(s).					
b	Virtual modeling will validate: physics, interfaces and/or requirements.					
c	A CAD model is needed for analysis (FEA, CFD, etc.) or manufacture.					
d	Time & budget allow pursuit of both virtual and physical prototypes.					
4	For a high avg, isolate subsystems.; else, integrate the system.	Integrate Subsystems				Isolate Subsystems
a	Interfaces between subsystems are predictable and/or are NOT critical.					
b	1 or 2 subsystems embody critical design requirements & need iteration.					
c	A subsystem build would significantly reduce time, cost or complexity.					
d	An isolated subsystem can be properly tested.					
5	For a high avg, use a scaled model; else, use a full size model.	Do not scale				Scale
a	Scaling law(s) will permit accurate system modeling via a scaled build.					
b	Scaling will significantly simplify the prototype.					
6	For a high avg, relax requirements.; else, pursue full requirements.	Do not relax				Relax design requirements
a	Requirement flexibility allows significant results from a relaxed model.					
b	Requirement relaxation will significantly simplify the prototype.					

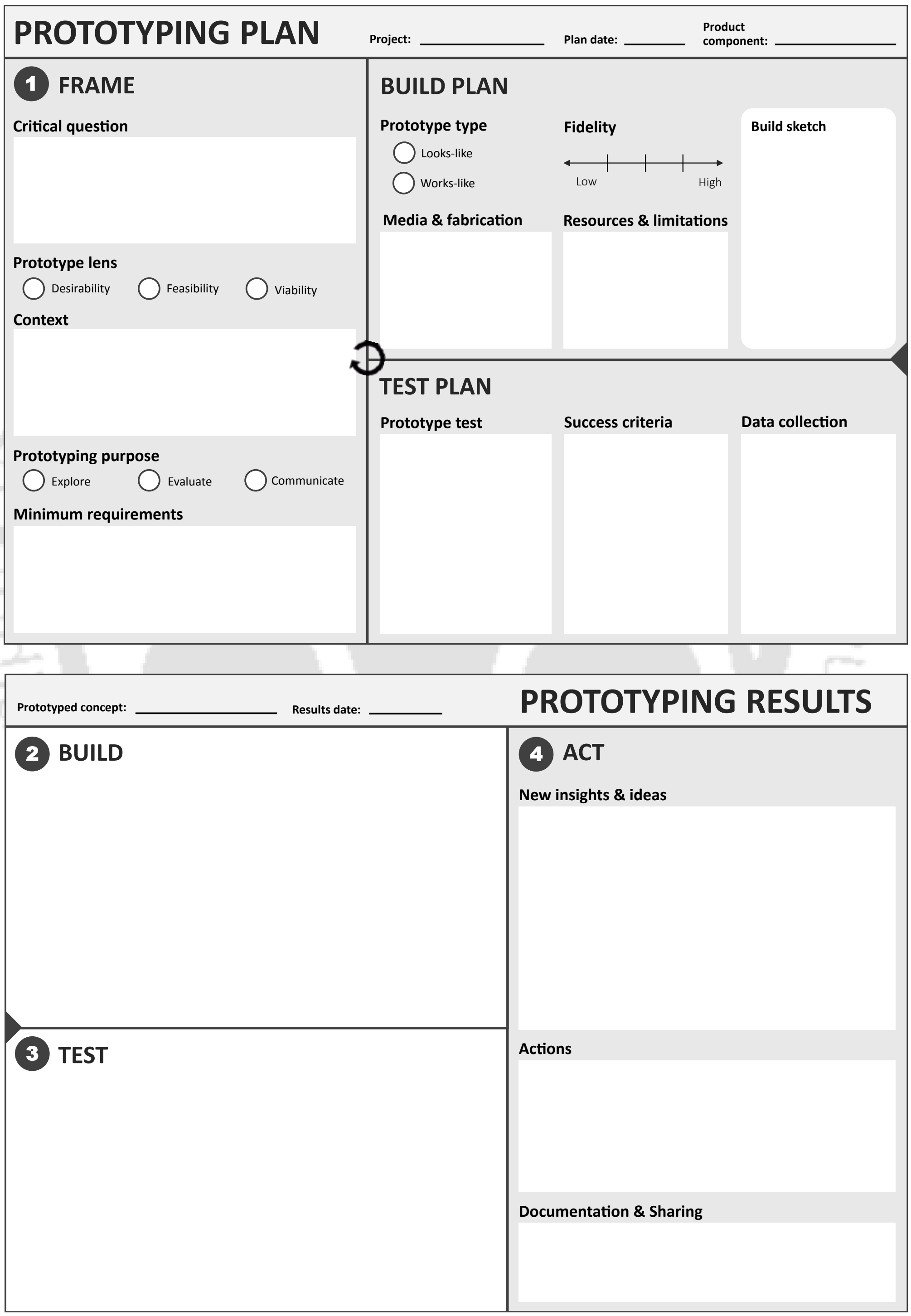
Appendix E

Prototyping canvas (Lauff, Menold, & Wood, 2019)



Appendix F

Prototyping planner (Hansen, Jensen, Özkil, & Pacheco, 2020)



PROTOTYPING PLAN Project: ______ Plan date: ______ Product component: ______

1 FRAME

Critical question

Prototype lens
◯ Desirability ◯ Feasibility ◯ Viability

Context

Prototyping purpose
◯ Explore ◯ Evaluate ◯ Communicate

Minimum requirements

BUILD PLAN

Prototype type
◯ Looks-like
◯ Works-like

Fidelity
Low — High

Build sketch

Media & fabrication

Resources & limitations

TEST PLAN

Prototype test

Success criteria

Data collection

Prototyped concept: ______ Results date: ______

PROTOTYPING RESULTS

2 BUILD

3 TEST

4 ACT

New insights & ideas

Actions

Documentation & Sharing

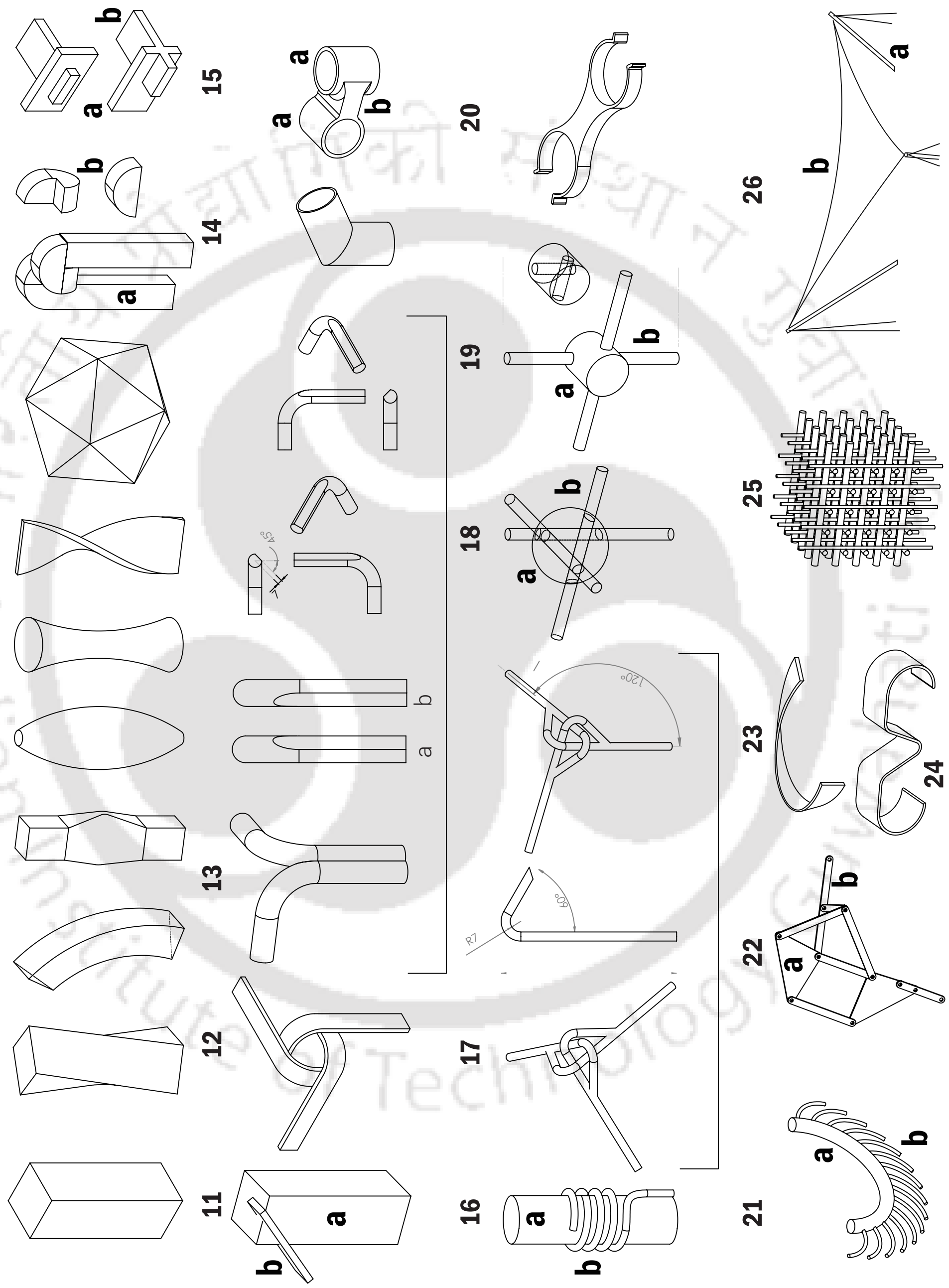
Appendix G

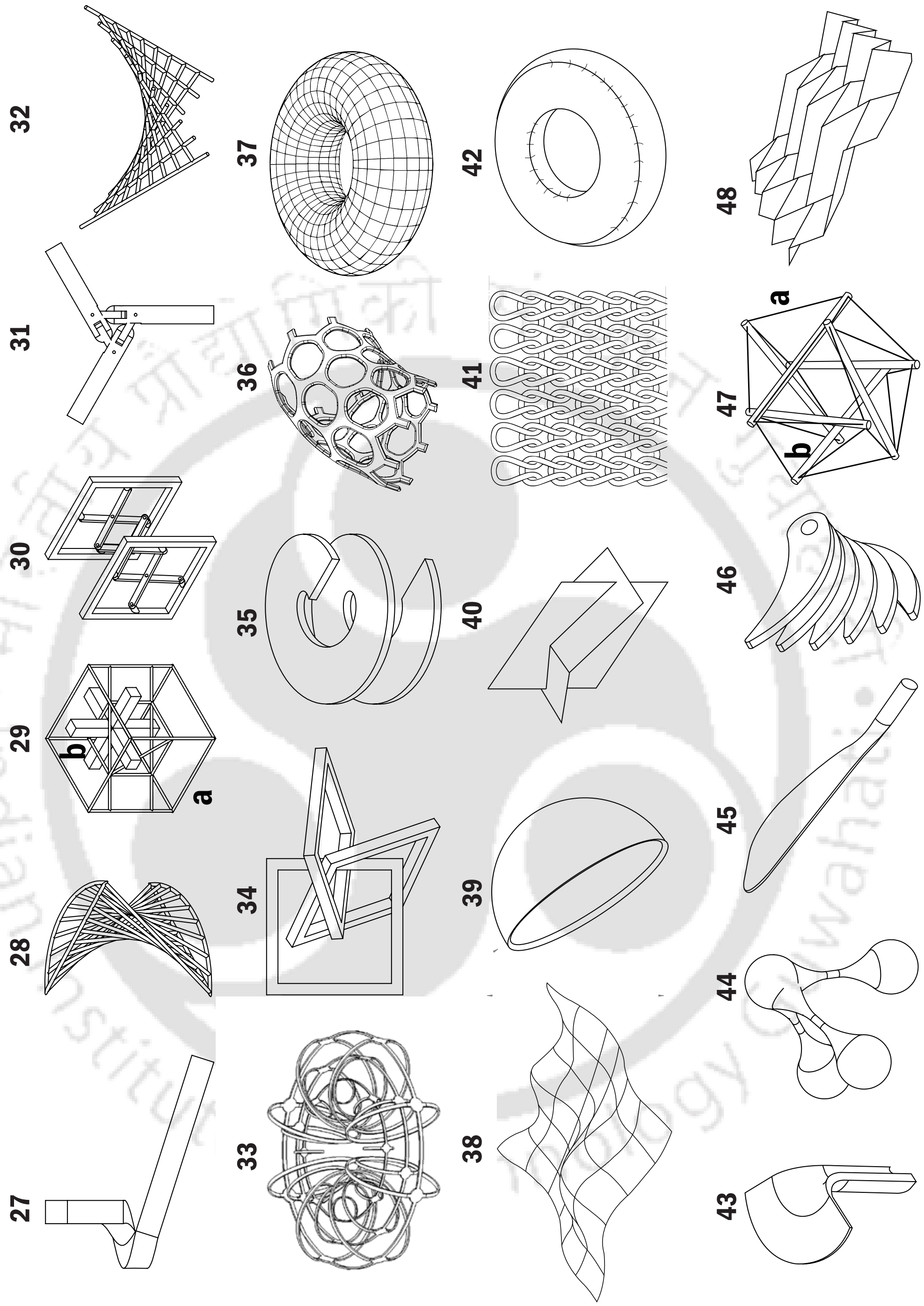
Purpose and questions in each prototyping step (Hansen et al., 2020)

Step	Questions
THINK. Reflect on the development of the project and clarify current objectives. Answers to the Think step should inform the following Build and Expose steps	What is the timing in the development project? What is the overall objective and critical question that the prototype should answer? Does the prototype need to test desirability, feasibility, or viability aspects of the product? Does your objective require a divergent or convergent development approach? Who can answer the critical question and how will the prototype communicate with these stakeholders? What are the minimum requirements for the prototype to answer the critical question?
BUILD. Prepare the prototype fabrication by considering the most optimal prototype scope	What type of prototype will you build? Which prototyping strategies to use during fabrication? How will you build the prototype? Which media and fabrication techniques to use? What resources are needed and what are the limitations? The generated information feeds into establishing the Build plan
EXPOSE. Define the activity, where the prototype is put into use to answer the critical question	How will you test the prototype? How will the test be conducted? What is the expected outcome and success criteria for the test? What data will you collect from the test? How will you collect data from the test? The generated information feeds into establishing the Test plan
When the design team has considered the Think, Build, and Expose steps, they carry out the prototyping following the prepared Build and Test plans. In the centre of the Prototyping Planner V2, pictures of the pro - totype are placed to document the prototype activity itself and follow prototype evolution	
ACT. Evaluate the obtained insights and define actions	What l earnings and insights did you obtain from the prototyping? What actions and design decisions will you make? Is there a need for further prototyping? How will you document and share the results with stakeholders?

Appendix H

Collection of 48 forms considered while developing TfMM

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Appendix I

	Materials for construction
1	Wood [Pinewood *(Pinus),* Gamari wood *(Gmelina arborea)*] a) Block b) Bar
2	Expanded Polyethylene (EPE foam)
3	Rattan Cane *(Calamus thwaitesii)*
4	Air-Dry Modelling Clay
5	Paper (with varied GSM)
6	Cardboard (300 GSM)
7	Corrugated Cardboard Sheets
8	Polyurethane foam
9	High-density Expanded Polystyrene (density >400 kg/m^3)
10	High-density EPS beans
11	Sun board or foam board (3mm and 5mm)
12	High Impact Polystyrene (HIPS Plastic - 3mm and 5mm)
13	Felt cloth
14	Galvanized Iron Wire (1.5mm and 3mm)
15	Aluminium wire (1mm & 3mm)
16	Aluminium rod (with varied diameter)
17	Aluminium tube (with varied diameter and thickness)
18	Aluminium sheet (with varied thickness)
19	Mild Steel rod (with varied diameter)
20	Mild Steel tube (with varied diameter and thickness)
21	Mild Steel Sheet (with varied thickness)
22	Plaster of Paris
23	Polyvinyl Chloride sheet
24	Epoxy compound (Resin + Hardener)
25	Nylon/ Nylatron rod (with varied diameter)

26	Nylon string
27	Nylon twisted rope
28	Nylon cord
29	Galvanized Iron wire mesh
30	Veneered particle board
31	Medium Density Fibreboard
32	Plywood
33	Paper-mâché
34	Acrylic sheet a) Transparent b) Coloured
35	Polypropylene (PP) straw
36	PVC Tube
37	Polypropylene twisted rope
38	Cotton twisted rope
39	Hosiery fabric
40	Ethylene-Vinyl Acetate foam sheet
41	PVC rod
42	Glass fibre
43	Jute straw
44	Natural Clay
45	Bamboo Bamboo stick *(Bambusa balcooa)* Bamboo straw *(Melocanna baccifera)* Solid Bamboo (*Thyrsostachys oliveri*)
46	Elephant Grass reed *(Pennisetum purpureum)*
47	Jute fibre/Jute rope
48	Coconut leaf stick

Appendix J

Materials for cushioning	
1	Cotton
2	Polyester fibre
3	Sponge
4	Coir fibre

Appendix K

	Materials for upholstery
1	Cotton
2	Linen
3	Silk
4	Wool/felt
5	Leather
6	Polyester
7	Rexine
8	Nylon
9	Acrylic
10	Rayon
11	Valvet
12	Olefin

Appendix L

List of Adhesives	
Types of Adhesives	**Material Compatibility**
Glue stick	Paper, Corrugated Cardboard
Polyvinyl Acetate (PVA)	Paper, Styrofoam, Polyurethane foam, Cardboard, Foamboard, Jute, Wood, MDF
Synthetic Rubber Adhesive	Paper, Leather, Metal, Rubber, Rexine, Canvas, Cork, Fabric, Wood, Plywood
Hot melt adhesive	Cork, Leather, Metal, Rubber, Rexine, Canvas, Fabric, Felt, Styrofoam, Wood, Plywood, Jute
Acrylic Cement	Cellulose Acetate Butyrate, Polycarbonate, Acrylic, Styrene
Cyanoacrylate	Leather, Metal, Rubber, Rexine, Canvas, Cork, Fabric, Wood, Plywood, Ceramic, Glass, Plastic
Bi-Component Adhesive (Resin + Hardener)	Metal, Cork, Wood, Plywood, Plastic, Ceramic, Glass, Felt, Leather, Canvas
Aerosol-adhesives	Styrofoam, Polyurethane foam, Wood, Glass, Paper, Leather, Plastic, Metal

Appendix M

List of Filler Material

Types of Filler Material	**Material Compatibility**
Acrylic putty	Polyurethane foam, styrofoam, wood, plywood
Automotive body filler	Wood, plywood, MDF, Metal
Polyester putty	Metal
Acrylic gesso	Polyurethane foam, styrofoam, wood, plywood
Wood filler	Wood, plywood, MDF
Wood polish powder + French chalk powder + Paraffin wax	Wood/ MDF/ plywood/ cane

Appendix N

List of Tools
Hand tools
Adjustable magnetic welding holder
Balpeen Hammer
Bamboo stick making tool
Chipping Hammer
Clamps (C and Quick Action)
Coping Saw
Corrugated sheet cutter
Creasing tool
Crimper
Eyelet hole punch plier
Foam board cutters (Rabbet cutter, straight and bevel cutter)
Hack Saw
Hand file set
Industrial cutter
Linesman Pliers
Mallet
Needle felting tool
Needle file set
Needle Nose Pliers
Punch Needle
Scissor
Sculpting tools
Slotted quilling tool
Snap fastener plier
Staple gun
Steel Ruler and flexible ruler
Wood curving tools

Electric Portable Hand Tools
Angle grinder
Cold air blower
Electric EPS cutting pen
Electric kitchen knife
Hand drill
Hand Router
Handheld sewing machine
Heat gun
Hot glue gun
Portable jigsaw
Portable plastic sealing machine
Rotary carving tool
Rotary wood carving tool

Machine Tools
Band saw
Bench drill
Domino joiner set
Hotwire EPS cutter
Jigsaw machine
Laser cutting machine
Lathe machine
Milling machine
Mitre saw
Power saw
Sanding machine
Scroll saw
Shaper machine
Welding machine
Wood planer

Other Tools or Equipment
3D pen
3D printer
Anvil
Bench vice
Kerosene blow lamp
Manual pipe bending machine
Metal tube bending moulds
Piping bag
Plastic pipe bending jig
Steam bending
Wire bending jig

Appendix O

List of Finishing Material

Types of Finishing Material	**Purpose**
Acetone	Melting rough surface of 3D printed parts
Acrylic gesso + Acrylic medium	3D printed parts, PU foam and Styrofoam priming
Auto paint primer	Metal priming
Epoxy coating	3D printed parts priming
Oil-based paints	Wood and metal coating
Sand paper	Sanding metal or 3D printed surfaces
Shellac flakes + Denatured alcohol or Methylated spirit	Wood priming
Water-based acrylic paints	3D printed parts, PU foam and Styrofoam coating
Wood primer + Turpentine oil	Wood priming

Appendix P

	Cutting with an industrial cutter	Cutting with hot wire	Sawing	Sanding or grinding	Planning	Bending	Machining (manual or CNC) [turning, boring, milling, drilling, knurling, forming routing etc.]	Jiggering and Jollying	Laser cutting	Heat forming	Extrusion of semi-solid paste	Moulded lamination	Sculpting with armature	Silicon moulding	Core removing	Press forming	Knitting or knotting	Steam bending	Thermal Joining	Stitching	Thermal sealing	Joining with screws, bolts and rivets	Joining with adhesives
Wood			1, 4, 9a, 10,11, 20, 29b, 30, 34	1, 4, 10, 11a,b, 29b, 30, 34, 9a	1, 4, 9, 10, 11, 29b, 30, 34, 9a		5, 6, 9b, 14,15, 16a, 18b, 19b, 20, 22b, 26a, 31, 37, 39, 44, 45, 46, 47a		1, 9, 10, 11, 12, 20, 29b, 30, 34, 46									7, 12, 13, 17, 21, 23				22, 30, 31, 46	9, 12, 13, 14, 15 17, 21, 29, 30, 34
Expanded Polyethylene (EPE foam)	33, 35, 36, 38								33, 35, 36, 38														
Rattan Cane	18b, 19b, 25, 28, 29a		13, 16a, 21a							13, 16b,17, 21													
Air-Dry Modelling Clay											13, 16, 17, 18b, 19b, 21, 37		27, 36, 37, 44, 45										
Paper (with varied GSM)	1, 2, 3, 4, 8, 9, 10, 11, 29b, 34, 35, 40, 48																						1, 2, 3, 4, 8, 9, 10, 11, 29b, 34, 35, 40, 48
Cardboard (300 GSM)	1, 4, 9, 10, 11, 20, 34, 40, 46								40														1, 4, 9, 10, 11, 20, 34, 40, 46
Corrugated Cardboard Sheets	1, 4, 9, 10, 11, 34, 40																						1, 4, 9, 10, 11, 34, 40
Polyurethane foam	1, 4, 9, 10, 11, 29b, 30, 34	1, 4, 9, 10, 11 29b, 30, 34		2, 3, 5, 6, 37, 44 39 core			1, 4, 5, 6, 9, 10, 11, 16a, 18a, 19a, 29b, 30, 34, 37, 44								39								
High-density Expanded Polystyrene (density >400 kg/m3)	1, 4, 9, 10, 11, 29b, 30, 34	1, 4, 9, 10, 11 29b, 30, 34		2, 3, 5, 6, 37, 44 39 core			1, 4, 5, 6, 9, 10, 11, 16a, 18a, 19a, 29b, 30, 34, 37, 44								39								
High-density EPS beans																							
Sun board or foam board (3mm and 5mm) [single or multiple layer]	1, 4, 9, 10, 11, 29b, 30, 34			45					1,4 , 9, 10, 11, 12, 20, 29b, 30, 34, 46	7, 12, 23, 35													
High Impact Polystyrene (3mm and 5mm)	1, 4, 9, 10, 11, 29b, 30, 34								1,4 , 9, 10, 11, 12, 20, 29b, 30, 34, 46	7, 12, 23, 35													
Felt cloth	38											38								36, 38			36, 38
Galvanized Iron Wire (1.5mm and 3mm)			16b, 17, 21	13, 17															17, 21, 25, 28, 29a, 32				
Aluminium wire (1mm & 3mm)			16b, 17, 21	13, 17															17, 21, 25, 28, 29a, 32				
Aluminium rod (with varied diameter)			16b, 17, 18b, 19b, 21, 25	13, 17		13, 16b, 17, 21, 28	5, 6, 14, 15, 44												17, 21, 25, 28, 29a, 32				
Aluminium tube (with varied diameter and thickness)			14, 15a			13													14, 15a				
Aluminium sheet (with varied thickness)						7, 12, 23, 35			7, 12, 23, 35										35				
Mild Steel rod (with varied diameter)			16b, 17, 18b, 19b, 21, 25	13, 17		13, 16b, 17, 21, 28	5, 6, 14, 15, 44												17, 21, 25, 28, 29a, 32				
Mild Steel tube (with varied diameter and thickness)			14, 15a			13													14, 15a				
Mild Steel Sheet (with varied thickness)						7, 12, 23, 35			7, 12, 23, 35										35				
Plaster of Paris or wall putty														18a, 37, 44									
Polyvinyl Chloride sheet	42								42												42		
Epoxy compound Resin + Hardener along with glass fibre												39, 43											
Nylon/ Nylatron rod (with varied diameter)			16b, 17, 18b, 19b, 21, 25																				
Nylon string	22a, 41, 47b																22a, 41, 47b						
Nylon twisted rope	41																41						
Nylon cord	41																41						
Galvanized Iron wire mesh						32										38			25				
Veneered particle board			1, 4, 9a, 10,11, 20, 29b, 30, 34				9b, 20, 22, 46, 47a		1, 9, 10, 11, 20, 29b, 30, 34, 46													22, 30, 31, 46	9, 12, 13, 14, 15 17, 21, 29, 30, 34
Medium Density Fibreboard			1, 4, 9a, 10,11, 20, 29b, 30, 34				5, 6, 9b, 14,15, 16a, 18b, 19b, 20, 22b, 26a, 31, 37, 39, 44, 45, 46, 47a		1, 9, 10, 11, 12, 20, 29b, 30, 34, 46													22, 30, 31, 46	9, 12, 13, 14, 15 17, 21, 29, 30, 34
Plywood			1, 4, 9a, 10,11, 20, 29b, 30, 34				9b, 20, 22, 46, 47a		1, 9, 10, 11, 20, 29b, 30, 34, 46													22, 30, 31, 46	9, 12, 13, 14, 15 17, 21, 29, 30, 34
Paper-mâché												39, 43											
Acrylic sheet	1, 4, 9a, 10, 11, 20, 29b, 30, 34						9b, 22, 30, 31, 46			7, 12, 23, 35, 39, 43												22, 30, 31, 46	9, 12, 29, 34
Polypropylene (PP) straw	18b, 19b									17													
PVC Tube										13													
Polypropylene twisted rope	41																41						
Cotton twisted rope	41																41						
Hosiery fabric	26b																						
Ethylene-Vinyl Acetate foam sheet	33, 36								33, 36														33, 36
PVC rod			16b, 17, 18b, 19b, 21, 25	13, 17			5, 6, 14, 15, 44			13, 16b, 17, 21, 28									17, 21, 25, 28, 29a, 32				
Glass fibre												39, 43											
Jute plant straw	18b, 19b																						
Natural Clay								39			13, 16, 17, 18b, 19b, 21, 37		27, 36, 37, 44, 45										
Bamboo					1, 4, 9, 10, 11 29b, 30, 34							12, 23											
Elephant Grass reed	18b, 19b																						
Jute fibre/Jute rope	41																41						
Coconut leaf stick	25																						

List of Publications and Presentations

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1. Das, S., Rijas M.P. "A Multipurpose Transformable Furniture Assembly". *The Patent Office Journal*, No. 20/2020, Dated 15/05/2020. [Indiian Patent file Application No. – 201931044202 A] Publication Date: 15/05/2020

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2. Das S., Das A.K. (2019) Tool for Teaching Physical Model Making in Product Design. In: IOP Conference Series: Materials Science and Engineering, Volume 686. https://doi.org/10.1088/1757-899X/686/1/012021

3. Das S., Das A.K. (2021) Prototype-Driven Innovation: Propositions Based on Challenges and Opportunities. In: Chakrabarti A., Poovaiah R., Bokil P., Kant V. (eds) Design for Tomorrow—Volume 2. Smart Innovation, Systems and Technologies, vol 222. Springer, Singapore. https://doi.org/10.1007/978-981-16-0119-4_79

4. Das S., Das A.K. (2021) Development of Design Heuristics for Furniture Design. 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_13

5. Das S., & Das A.K. (2021) Introducing design heuristics for furniture design in a furniture design course. In DS 110: Proceedings of the 23rd International Conference on Engineering and Product Design Education (E&PDE21), Design Education and Human Technology Relations, VIA Design, VIA University, Herning, Denmark, 09-10.09. 2021. https://doi.org/10.35199/EPDE.2021.22

6. Das S. & Das A.K. (2022) Assessing the Effectiveness of Design Heuristics for Furniture Design. In: 16th International Conference on Design Principles and Practices, 19^{th}-21^{st} January, at the University of Newcastle, Newcastle, Australia.[Proposal Accepted]

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1. Das S. (2017) A Tool for Teaching Physical Prototyping and Model Making. In: 11th International Conference on Design Principles and Practices, 3^{rd} March, at George Brown College, Toronto, Canada.

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1. Das S., & Das A.K. (2021) Design Heuristics for Furniture Design. In: 8^{th} International Conference on Research into Design, 10^{th} January 2021. [Virtual mode]