Investigating use of CAD during Idea generation stage of Product Design

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by

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Approval Sheet

This thesis entitled *Investigating use of CAD during idea generation stage of product design* by Purba Joshi is approved for the degree of Doctor of Philosophy.

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Abstract

CAD is an important innovation of this era that has enabled designers and engineers to visualize their ideas in 3-dimensions and communicate the same across various platforms. It is a well-accepted tool that is being used at various stages in the process of new product design and development.

Many researchers (Stappers and Hennessey 1999, Tovey and Owen 2000, Robertson et al. 2007, Ibrahim et al. 2010, Won 2001) have argued the suitability of CAD when the ideas are crystallized and not for idea generation stage. CAD is well accepted as the drafting, visualization, and detailing tool but not as an exploration tool. However, it is an important tool and one of the many skills needed for a holistic design education without overriding the design process and curbing student's design conception process. The literature illustrates gradual inclination towards the inclusion of CAD in the early stages of design with new input devices, better systems, and advanced software systems.

Many studies (Lawson 2002, Jonson 2005, Won 2001, Abdelhameed 2007, Wojtczuk et al. 2011, Ibrahim et al. 2010, Tovey and Owen 2000) related to CAD have compared it with sketching and physical modeling. These are the most established and well-accepted tools for the early phase of design.

The research focuses on investigating the impacts of using CAD on creative exploration during the idea generation stage of product design. It does not compare

CAD with other tools but tries to understand its role when used in conjunction with conventional tools. As the role of CAD is well established in the later stages of design, the study focuses on the early idea generation stage in the context of product design (Cross 2005, Paul and Alex 2011). It was identified as a gap through the literature review.

The research methodology is based on qualitative research. For the exploratory phase of the research, two pilot studies were conducted. For the first pilot, a time-bound design task was given to the students of product design. Their outputs, along with their feedbacks, were collected at the end of the exercise. The analysis of the collected renders, sketches, and verbal feedback helped focus the study in the right direction. Analysis of this data, in addition to the literature review, helped to formulate the study parameters for the study.

The next pilot study was conducted with the professionals where they were given a design task to be performed in limited time. The data used for the analysis was the visual data recorded during the design exercise and verbal data from the interviews. Semi-structured interviews were conducted with participants to collect supportive data for the analysis. The video recording of the whole activity was tabulated and occurrences of various parameters were mapped visually. This also helped establish a method to analyze a design activity with the visual mapping of study parameters. Supportive verbal data from the interview helped qualify some of the findings and cover the missing points that were difficult to identify in the time-bound exercise or through observation.

Based on the findings from both the pilot studies, an interview guide was formulated. The audio-recorded interviews were transcribed and coded using MaxQDA software. MaxQDA helped organize, cluster, and retrieve coded data,which was further used for interpretation and re-interpretation to draw the inferences and articulate findings.

The findings inform readers about how 3D solid modeling CAD tool positions itself in the idea generation phase of product design. Research sheds light on the advantages CAD offers as a tool and the limitations that it can impose. Findings make designers aware of the limitations so that they can make informed decisions while designing. It helps establish a research methodology that can be adapted to study parallel contexts like fashion, craft, interior, and accessory design. Research informs pedagogy and can be used to develop the teaching strategies to make students more aware and not let tools drive their design decisions. Further, software developers can adopt the study to develop CAD programs more aligned with the needs of the designers.

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List of abbreviations

2D	Two Dimensional
3D	Three Dimensional
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAID	Computer Aided Industrial Design
CNC	Computer Numerical Control
IvT	Innovation Technology
NPD	New Product Development
RE	Reverse Engineering
RID	Reverse Innovative Design
RPT	Rapid Prototyping
TRIZ	Teorija Rezben Ijalzobretatelskib Zadach Theory of inventive problem solving
VR	Virtual Reality

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Chapter 1
Introduction

The Chapter talks briefly about the motivation and context of this research. It provides an overview of the work done to seek an answer to the research questions. The last section summarizes the structure of the thesis.

1.1 Research background

The stage of the invention is the most important phase in the process of product development, as this is the phase where ideation, scoping, and business plans are prepared (Cooper 2008). This is the stage where a thought converts into a concept and in which designers play an important role. The role of a product designer is to make products user-friendly and easy to use, sometimes by improving certain aspects of a product's function; or make it more efficient, by exploiting latest manufacturing and technology developments; make it more economical by optimizing or utilizing new and innovative materials; or enhancing product's appeal by making it more aesthetic and suitable for particular user group (Milton and Rodgers 2013). A product must appeal to the customer and bring profit for the manufacturer (Caplan (1969) cited in Aldoy, 2011).

The design process for new product development has seen enormous changes since the introduction of CAD (Aldoy 2011). CAD is an important innovation in this era that has changed the face of the design industry and has influenced the lives of designers and engineers (Brown 2009). Brown (2009) states that the vast intervention of CAD has changed the culture of product design giving birth to a new

generation of engineers and designers who are separated by their mentors by the technological divide. This new generation of designers and engineers has new processes and technologies at their disposal and are evolving their approaches involving these.

Designers today are much more acquainted with the new age tools and have adopted them as an essential part of the design process. This has affected the ways in which designers are working today. Proper investigation is needed to find out how CAD is affecting the designer's work and approach towards new product development, the role it plays in innovation and its practical implementation.

Until a few years back, the application of CAD was mainly restricted to later stages of design, but in recent years, it has seen increased attention in the concept generation stage. Many new-age computerized tools have evolved to assist innovation, such as TRIZ, IvT (Innovation Technology), RE (Reverse Engineering), VR (Virtual Reality), 3D scanning, and 3D printing. However, desktop-based 3D modeling software is predominant in the industry as these are the most economical, readily available and well-established systems.

Studies were found in the literature that compares CAD with manual tools like sketching and physical modeling. The importance of manual design tools like sketching and modeling is well known (Wojtczuk and Bonnardel 2011), and CAD may or may not replace these tools completely. CAD is an added tool, and it would be wrong to consider it a replacement of the conventional tools. The conventional tools also have certain limitations (Wojtczuk and Bonnardel 2011), and CAD may help to plug in those limitations. At the same time, excessive use of CAD brings in concerns about its influence on certain aspects of the creative exploration such as fluency, self-expression, premature fixation and circumscribed thinking.

This study is an attempt to understand ways in which product designers adopt CAD in their design process and how it affects their approach during the idea generation stage. The focus of this study is the exploratory phase of the design stage in the process of new product development. The exploratory phase is defined as the phase where designers are exploring initial ideas for the given problem and ideas have not been fully defined or evolved into a concept.

1.1.1 Researcher's motivation

The researcher is a postgraduate in Product Design. She is also a SolidWorks certified professional and works on Rhinoceros, AutoCAD, and Fusion 360 software as well. She experienced a shift in the approaches and design process while working in the industry. The pressure to deliver in a short time, globally situated teams and clients and ubiquitous availability of computers and various software, had been changing the way designers work. It was different from how she was trained at the design school.

Further, she started teaching the digital modeling and representational tools to the product design students. She realised a difference in attitudes approaches of these young designers, who now had access to laptops and continuous internet on their phones and tablets. Being a product designer, an educator and a CAD expert, it seemed appropriate to further the understanding in this field.

1.2 Research aim

The research aims to qualitatively analyze the way CAD is used as a tool in the idea generation stage of product design. It does not intend to compare CAD with conventional tools like sketching and physical modeling. Instead, the researcher aims to understand the effects of using CAD in conjunction with other tools. CAD in this research is interpreted as 3D solid-modeling tools, and the study does not

include digital sketching and surface modeling. One of the most popular 3D modeling software used in the product design industry, *SolidWorks* was kept as a constant across studies. This helped eliminate the software features as variables. It was ensured that all the participants across all the studies were the users of *SolidWorks* software.

1.3 Thesis organization

The thesis consists of eight chapters. The relationship between the chapters is shown in figure 1.1. A small description of what following chapters address is given in the following pages.

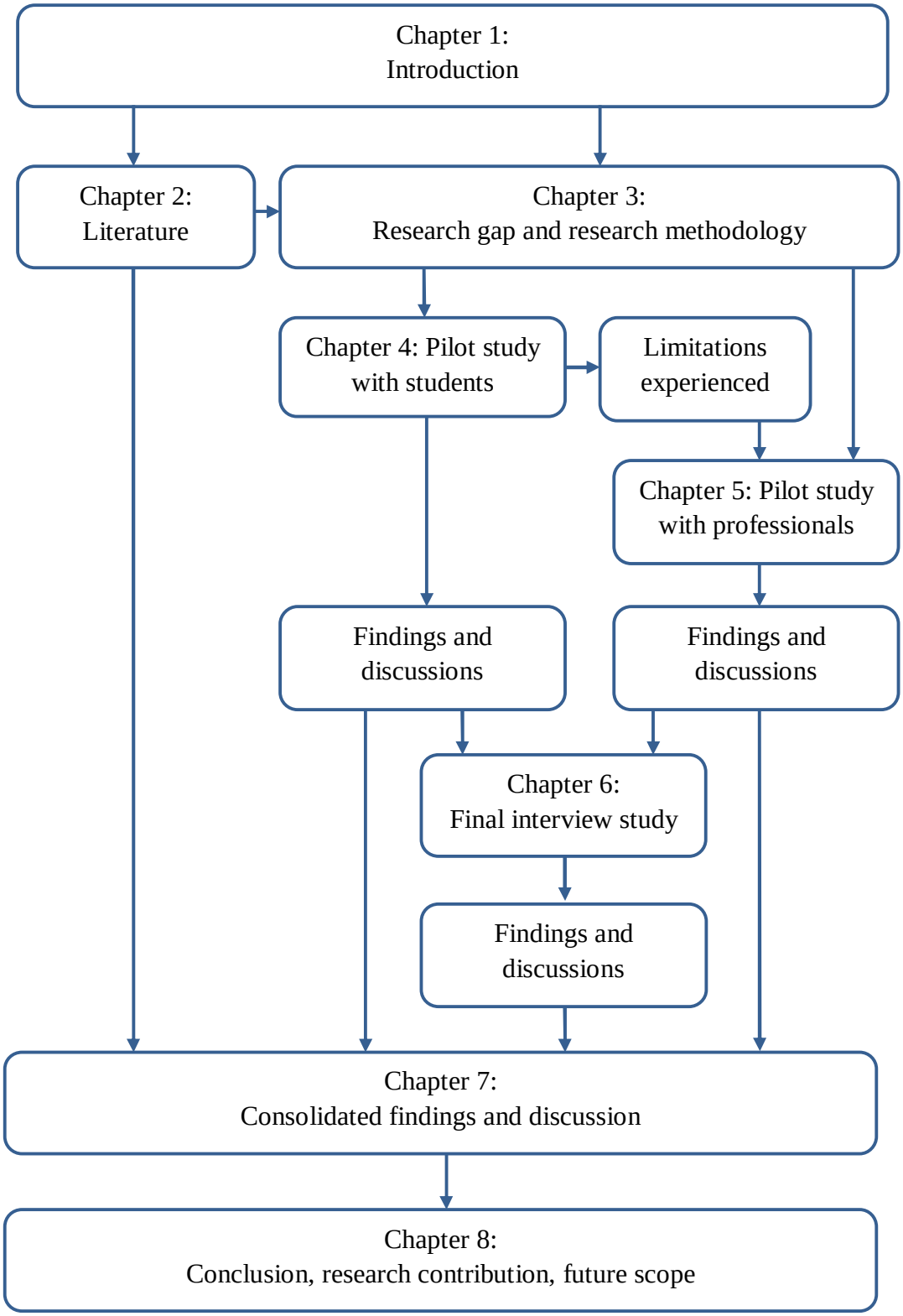

Fig 1.1: Relationship between chapters

Chapter 2: Literature review

The literature review undertaken as a part of the study enabled the researcher to identify the gap, define the research question, and formulate a plan for data collection and analysis. It started with a vast area of the investigation involving innovation and the role of CAD in innovation. Further, after identifying the gap, the literature review narrowed down to the product design process, early idea generation phase, creativity, and its relation to CAD. Literature that compares CAD with other established tool in the process of idea generation like sketching and physical modeling were also analyzed to understand the changing views on the inclusion of CAD in idea generation phase of product design over a period of time and mixed-media environment.

Parallel research was carried out to find out the appropriate research methods for the study. After narrowing down to a qualitative research approach, various methods of data collection and analysis were also reviewed.

Books, journals, conference papers and online resources were employed for the purpose. A list of references from various publications also helped in finding other potential references. Online references were searched through research gate, academia, IIT Bombay OPAC search, IIT Bombay central library journal search and google scholar.

Table 1.1 lists down some of the keywords used for searching the relevant literature.

Table 1.1: List of keywords used in literature search

Keywords		
CAD	**Design Process**	**Research Methods**
Computer aided design CAD and creativity CAD and product design CAD in design process CAD and idea generation CAD and design tools	NPD process Product design process Idea generation phase Tools for idea generation Mixed-media environment Tools and product design	Qualitative research Quantitative research Interview Observation Analysing design activity Participant selection MaxQDA

Chapter 3: Research gap and research methodology

This chapter defines the research question based on the research gap identified. It further breaks the main research question into sub-questions to focus the study and help articulate findings better.

It was realized that the design act is a manipulation of the designer's knowledge, thinking style and skills (Musta'amal 2010). This makes it complex to understand and analyze. Hence it is essential to have efficient methods for collecting data and analyzing it to draw inferences. Qualitative research methods were studied to collect rich, in-depth understanding of the phenomena.

Figure 1.2 illustrates the overview of the research plan.

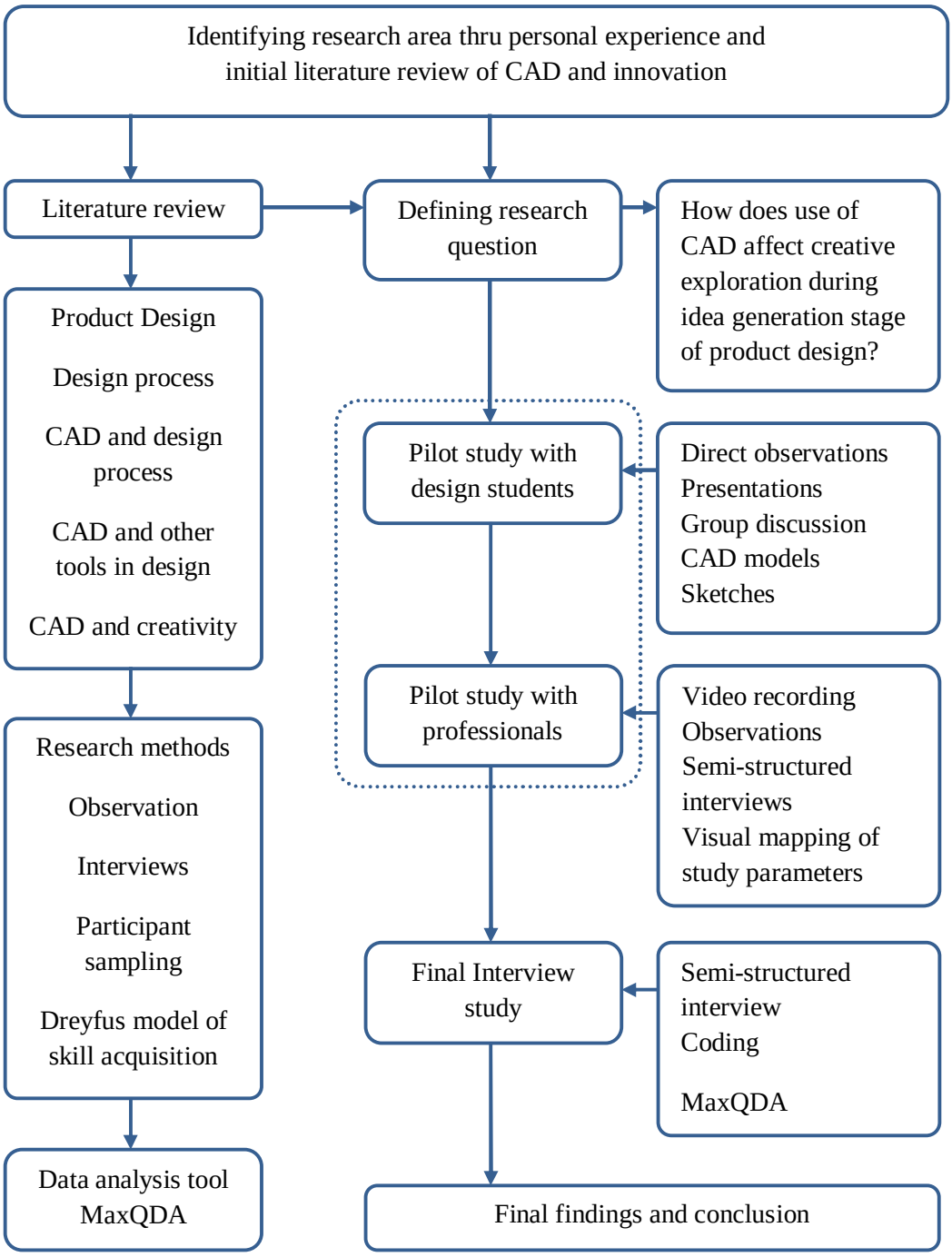

Fig 1.2: Research plan overview

Chapter 4: Pilot study with design students

The initial study was conducted with ten postgraduate product design students. A time-bound design task was conducted, and direct observations were taken in the form of notes during the task by the researcher. Students presented their ideas at the end of the session. A group discussion session was conducted afterward in which students shared their experiences and thoughts. The overview of the study is shown in figure 1.3.

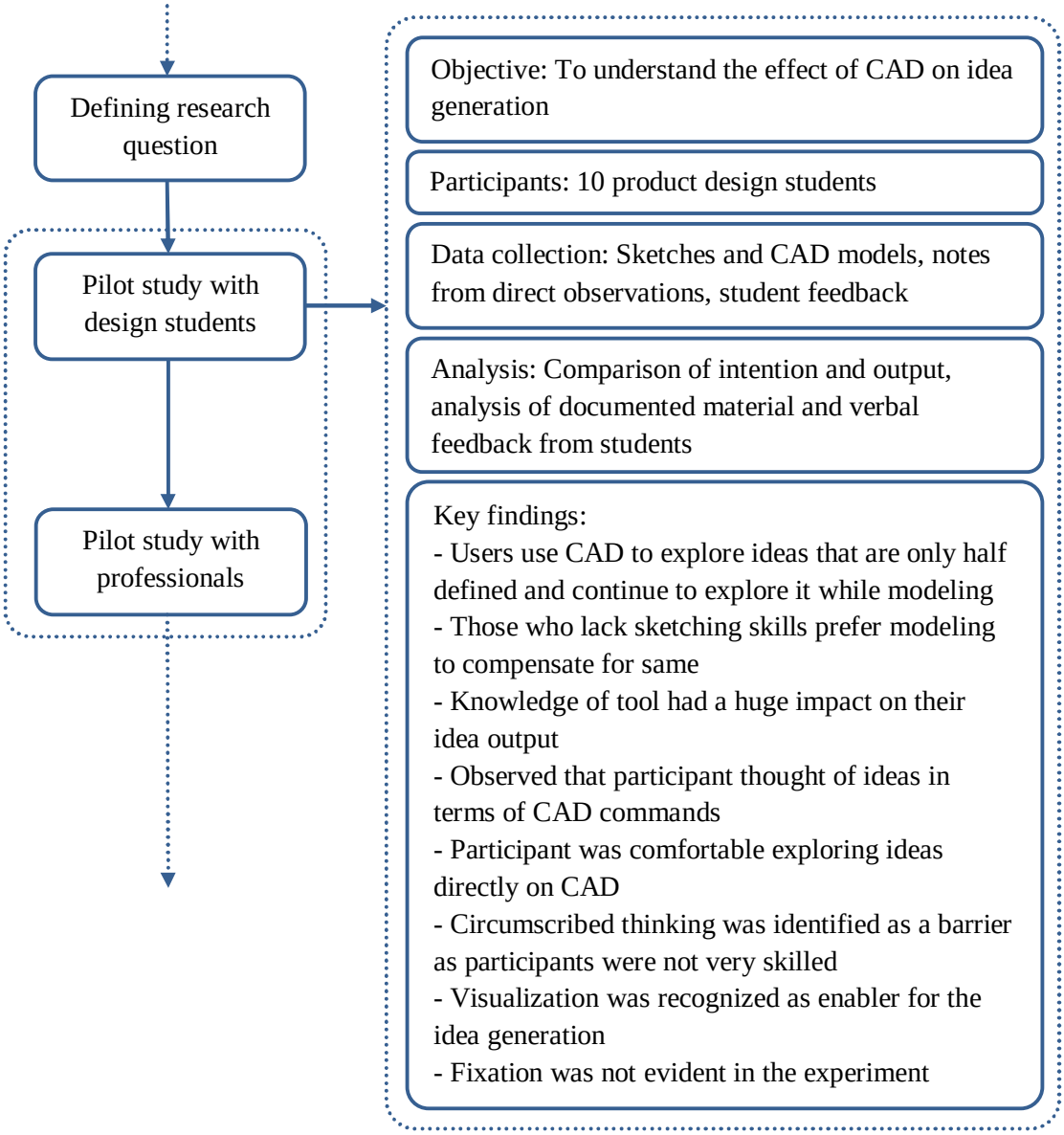

Fig 1.3: Overview of pilot study with students

Chapter 5: Pilot study with design professionals

A design task was conducted with five professional product designers. The whole task was video and desktop recorded. Participants shared their experiences in the semi-structured interviews following the design task. This study helped establish a method to analyze the design task. An overview is shown in figure 1.4.

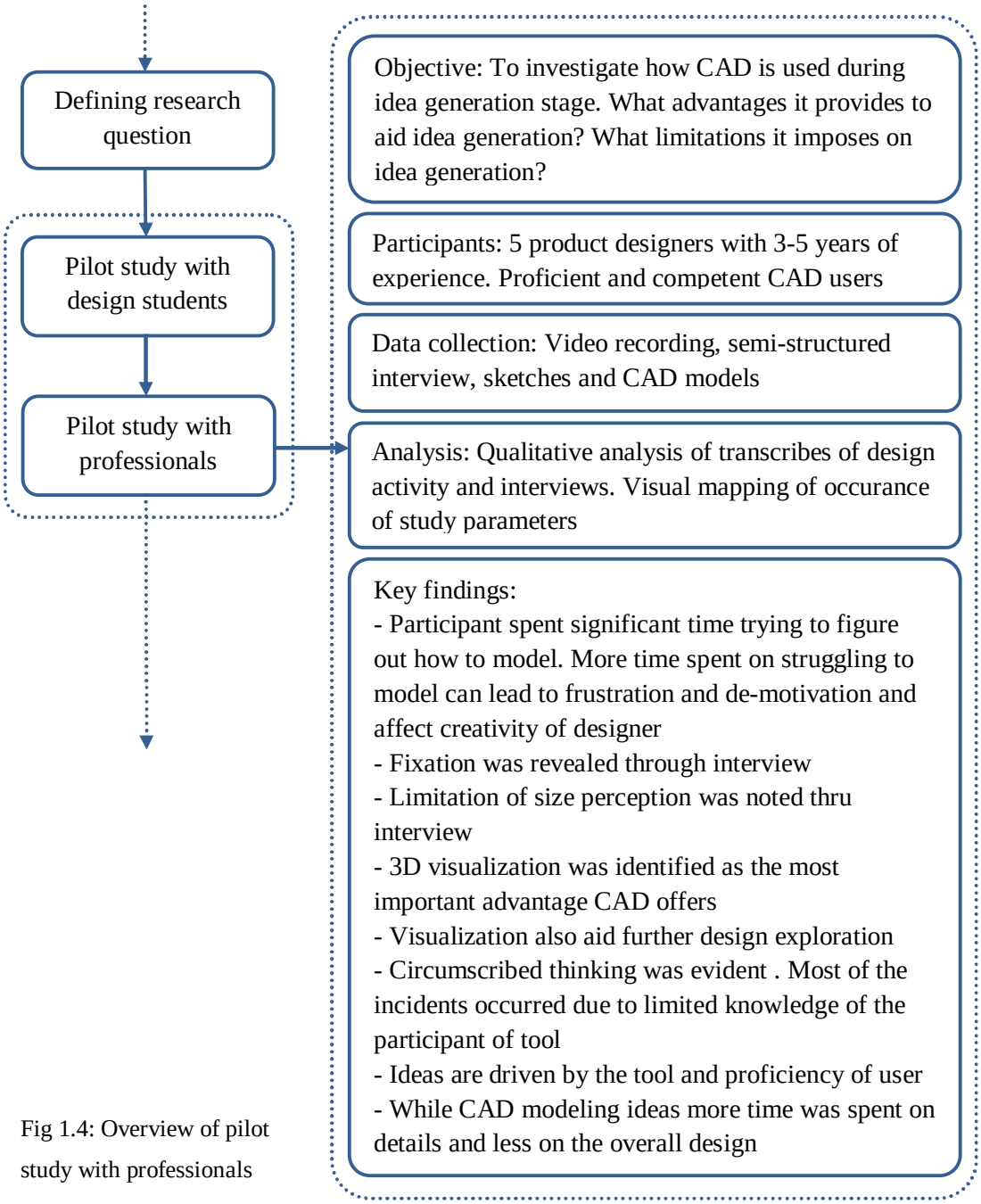

Fig 1.4: Overview of pilot study with professionals

Chapter 6: Final interview study

The final phase of the study involved in-depth interviews with 25 professional product designers. The interview guide was drawn from the findings of pilot studies. It helped to collect elaborate and rich narrative data. Transcribes were coded using MaxQDA software. The analysis helped articulate findings through iterative interpretations.

Chapter 7: Consolidated findings and discussions

The chapter revisits the research questions and tries to answer those by bringing together the findings from all three studies and learnings from the literature review. It further compares findings to identify similarities and differences based on proficiency levels and vastness of exploration space.

Chapter 8: Conclusion and research contribution

The chapter concludes the thesis by drawing conclusion and states the research contribution. It further suggests some directions for future work.

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Chapter 2
Literature review

To be able to add new knowledge in a domain, it is essential to know what exists. Literature review helps establish the importance of study and provides a benchmark for comparing the findings with other results.

This chapter illustrates the learning from the literature reviewed. The researcher studied the various stages in the design process and how CAD positions itself in these stages and issues surrounding it. The review further focuses on the initial phase of design and the tools used in this phase. The chapter concludes by summarising the learning from the literature.

2.1 Product design as a discipline

Everything manufactured around us, everything we use that is untouched by nature, has been designed by someone. One fundamental characteristic of the human being is that we design a variety of products, and as the purpose or requirements change, we re-design or create newer products (Cross 2005). What differentiates a designer from a sculptor or artist is that the act of making starts after the act of designing is finished. The process of designing needs to be accomplished to describe the artifact that needs to be made (Cross 2005).

The terms industrial design and product design are used interchangeably in the industry. There are various views on the differences and similarities between the two terms. For the ease of understanding, we shall be using ‘product design’ as the term

to define the discipline. The simplest definition of product design is the design of a product. The word product is widely used to describe anything from a website to a home loan, but in this context, it will be of relevance wherever ‘hardware’ and people interact (Milton and Rodgers 2013). Julia Lohmann mentioned during an interview, *“Product Design concerns itself with the three-dimensional world and our interaction with objects”* (Milton and Rodgers 2013). Product design encompasses the range of different types of products like consumer products, special-purpose products, industrial products, engineering products, and consumables. (Milton and Rodgers 2013).

ICSID (International Council of Society of Industrial Design) describes, *"Industrial Design is a strategic problem-solving process that drives innovation, builds business success and leads to a better quality of life through innovative products, systems, services and experiences."* They further elaborate that industrial designers collaborate with other disciplines and harness creativity to co-create solutions to make a product, system, service, experience of business better. Designers acquire a deep understanding of user needs through empathy and apply a pragmatic process to come up with user-centric solutions. Industrial designers are strategic stakeholders in the process of innovation and are uniquely positioned to bridge the gap between various professional disciplines and business interests. Van Doren ((1940) Cited by Aldoy, 2011) defines industrial design as "practice of analyzing, creating and developing products for mass manufacture".

A product designer mostly works in collaboration with engineers, ergonomists, marketing people, and various field experts like material, tools, or domain experts. The role of a product designer is to make products user-friendly and easy to use, sometimes by improving certain aspects of a product’s function; or make it more efficient, by exploiting latest manufacturing and technology developments; make it more economical by optimizing or utilizing new and innovative materials; or enhancing product’s appeal by making it more aesthetic and suitable for specific user group (Milton and Rodgers 2013). A designer needs to integrate the

performance of the product with its appearance. A product must appeal to the customer and bring profit for the manufacturer (Caplan (1969) cited by Aldoy, 2011).

2.2 Design as a process

Process of 'new product development' involves set of activities beginning from the perception of a market opportunity, passing through stages of planning, concept development, system-level design, detail design, testing and refinement, production and ending with sale and delivery of the product (Ulrich, Eppinger and Goyal 2009). The process aims to meet customer needs economically, at the earliest. Ideas evolve into concepts at the design stage. In the design stage, the designer develops solutions that will meet user needs, determine the ergonomics and appearance of the product and create a product identity (Aldoy 2011).

There is no linear step-by-step process for design. Design is an iterative process of analysis, synthesis, and evaluation (Lawson 2006). Lawson (2006) suggests that the design process may be divided into four phases: assimilation, general study, development, and communication. Ulrich, Eppinger, Goyal (2009) explained a more elaborate generic product development process that involves stages of planning, concept development, system-level design, detail design, testing and refinement, and production. After the user needs identification, designers move toward idea generation and concept development. They are engaged in the process of product development until the production stage, with a gradual reduction in their participation. Hatvany et al. (1993) classify the design activity in four phases; conceptual design, design analysis, detail design, and design documentation. The maximum participation of the designer in the process of new product development takes place in the idea and concept generation stage or conceptual design phase where the product is envisaged (Ulrich, Eppinger and Goyal 2009).

Graham (1926) explains the overall design process in four steps: Preparation, Incubation, Illumination, and Verification. Teresa (1983) further detailed this into five steps of problem formulation, preparation, idea generation, idea evaluation, and idea selection. Chakravarthy (2013) further elaborated the generic design process into seven stages, named as 7C's of design. These stages were:

- The Cause - The concern to solve a problem. Identifying a need and design opportunity is usually the first step.
- The Context- Understanding the user and the scenario and parallel products in market
- The Comprehension- Arriving at design insights by analyzing all the data available and gathered and writing down their inferences.
- The Check- The blue print for designs, a clear plan of action. This is the design brief based on the design insights. This defines criterion for ideation and concept evaluation.
- The Conception- Creating multiple ideas and combining them to general concepts that are evaluated against the design brief and a final concept is chosen for further development.
- The Crafting- The final concept is further developed and detailed. Depending on the complexity and requirement of the project small scaled mock up, full-scale model, working rig or CAD models are created for visual representation of the idea.
- The Connection- Connecting with the user with the solution provided. Getting user feedback on the proposed design is an important step to understand whether product meets the actual needs of the user and to predict its demand and success in the market.

Figure 2.1 shows the 7C's of design process defined by Chakravarthy (2013) when compared with Graham's (1926) four stages of design.

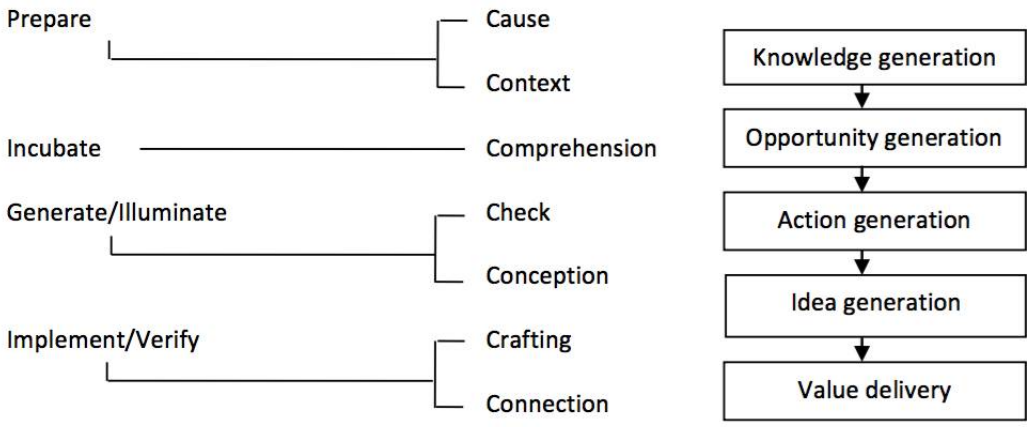

Figure 2.1: Design process

This is a generic design process where some stages may occur differently. The product designer is involved in all the stages of the process. However, the stage where the creative role of the designer is most prominent is the conceptual design stage, the 5th stage in 7C's known as conception, where idea generation and concept development takes place. This is the stage where a designer is required to generate multiple ideas, convert them into concepts, create renderings and models to visualize and present to stockholders, evaluate and finally detail out the final design.

It is crucial to understand that though the design process is represented as a linear order of individual stages, it is a highly iterative process. Design passes through various stages and with each stage having several iterative phases. Cross (2005) defines the design process in a simple four-stage model shown in figure2.2.

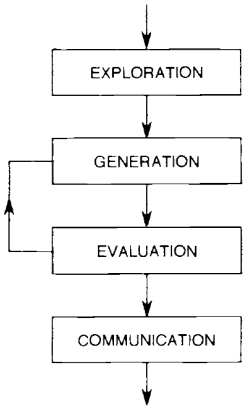

Fig 2.2: Simple four stage design process from Cross, Engineering Design Methods: Strategies for Product Design, 2005

The feedback loop in the evaluation and generation stage depicts the iterative nature of the design phase. The generative stage, defined by Milton and Rodgers (2011) as concept design stage include, generating ideas based on the design brief, clustering these ideas, and further bringing them together to develop them into concepts. This is a highly iterative phase where many ideas are created either by an individual or by a group of people. These ideas could be explored in isolation to resolve one problem at a time or an overall holistic solution. Iteration is a common feature of designing (Cross 2005). Creating ideas is a continuous process of finding possible solutions and refining those. It is not something that takes place just at the beginning of the project (Bramston 2009). Searching for ideas require many diverse activities and an open and free mind.

In the process of design, the problem and ideas to resolve the problem evolve together through an iterative cycle (Cross 2005) (Carroll, Cavagnaro and Goldman 2012). Luchs (2016) also mentioned that the early phase of design involves identifying problems and solving problems. His design-thinking framework (shown in figure 2.3) shows the iterative cycle of problem identification and problem solution.

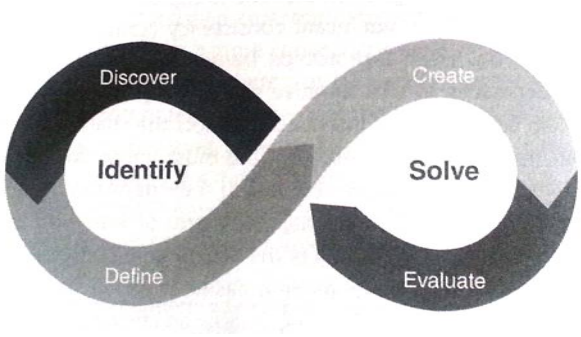

Fig 2.3: Framework for design thinking by Luchs (2016)

In the 'Discover' mode, user insights are gathered. Further, the inferences are drawn from the collected insights, and the problem is defined in the 'Define' mode. The purpose of 'Create' mode is to develop concepts that can be shared for feedback and can be improved upon through iterations. In the 'Evaluate' mode feedback on the ideas are collected for further iterations (Luchs 2016).

The first significant activity in 'Create' mode is idea generation. The two primary activities in this mode are idea generation and prototyping for the evaluation of ideas. These could be quick mockups or "low-resolution prototypes" (Luchs 2016). The objective of the idea generation stage is to generate a large number of ideas without considering if they are feasible and practical. It is important to suspend judgment at this stage (Carroll, Cavagnaro and Goldman 2012) (Liu, et al. 2011). The next step is to externalize the idea so that it can be communicated. This externalization can be in the form of a sketch, a simple construction of a quick mockup, or a digital model (Carroll, Cavagnaro and Goldman 2012). Carroll, Cavagnaro and Goldman (2012) define this step as prototype. The design process from Stanford University as quoted by them is shown in figure 2.4.

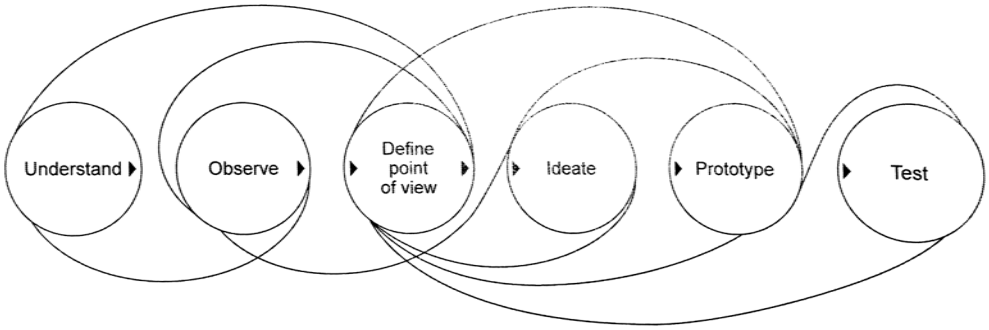

Fig 2.4: Design Process at Hasso Plattner Institute of Design, Stanford University (Carroll, Cavagnaro and Goldman 2012)

It is indisputable that the process of design is highly iterative. Several ideas need to be generated in the conceptual design phase. It means lateral, as well as vertical explorations, are required in this phase. This is a highly creative and fluid phase in the process of design. In this phase, no idea is complete or rigid.

2.3 CAD and its role in design process

The design process that is facilitated by computer is generally known as CAD (Musta'amal 2010). In the paper titled as "world survey of computer-aided design" by Hatvany, Newman, and Sabin (1993), CAD is defined as the integration of appropriate computer hardware and software modules to create design systems for particular requirements.

Coyne et al., (1987) states that *'CAD system can be described in terms of objects, operations on objects, and some controller that decides which operations to perform and when.'* The set of operators constitutes knowledge in the system. Knowledge defines the design space. In a knowledge-based CAD system, *'the knowledge that makes possible the mapping between intentions and design is supplied by the human operator who either makes selections between competing rules or evaluates the design so produced.'* (Coyne, et al. 1987).

The computer is considered an essential tool in design practice and is employed at every stage of the design process (Pipes (2007) cited by Aldoy, 2011). Tools range from computer-aided sketching and illustration tools to 3-D solid modeling systems (Mckay 2012). The CAD (Computer-Aided Design) and CAID (Computer-Aided Industrial Design) tools are becoming popular in the design community and have gained complete acceptance. State of the art 3D CAD systems usually have characteristics as feature-based, parametric, history-based, design variation, and product family. CAID, on the other hand, is used mainly to define the form and appearance of the product. CAID is mostly surface-based, whereas CAD generates solids. Characteristics of CAID involve- surface modeling, flexibility in deformation, material rendering, and flashy graphics (Xiuzi, et al. 2008).

Several modeling technologies have been developed and are being developed since the last decade such as image-based modeling, haptic modeling, subdivision-based modeling, freeform deformation techniques, reverse engineering (RE) and reverse innovative design (RID) (Xiuzi, et al. 2008). Xiuzi et al. (2008) propose a model of RID that integrates 3D digitizing, 3D CAD and CAID, RE, CAE analysis, and RP. The core of their RID methodology is 'reconstructing feature-based parametric solid models from scanned data.' These parameters can then be changed to form new designs and product families. They conclude by saying that this can help achieve seamless data integration between RE, 3D CAD, and CAID and CAE analysis for verification and optimization of design (Xiuzi, et al. 2008). CAD tools today are not only used for visualization and communication purpose, but these also support standardization, prototyping, analysis and simulation, design documentation, and reversibility (Murthy and Mani 2012).

CAD tools have become ubiquitous today. There are varieties of tools available today to suit the different requirements and even different working approaches. It has also become a necessity in today's fast-moving, technology-driven world (Shih, Sher and Taylor 2017) (Murthy and Mani 2012) (Liu, et al. 2011) (Sonmez 2013) (Atilola, Tomko and Linsey 2016) (Zboinska 2019) (Lee and Yan 2016).

Widespread adoption of CAD by designers had led to a range of views on the consequences it could bring for individual design ability, efficiency, and quality of the output. Hodgson and Fraser (2005) emphasize that 'we must better understand the contribution that CAD makes to the design process and be careful that its implementation does bring changes in the awareness and capabilities of participants that may be regarded as central to capability in design'.

Cooley (1977) mentions that 'in a man-machine environment, man is the dialectical opposite of the machine in that he is slow, inconsistent, unreliable and highly creative. The machine is fast, consistent, reliable, and totally non-creative'. The inconsistency of thoughts in humans allows them to skip and jump the logic and come up with highly creative and out-of-the-box ideas. Machines are reliable, quicker, and work on the logic (Lawson 2002). Machines do not forget. It is precise and has definite formulas. However, machines are inferior in recognition and interpretation (Lawson 2002). Therefore, it is quite unlikely for computers to come up with and suggest new ideas.

Various researchers like Van Dijk (1995), Verstijnen (1998), Stappers and Hennessey (1999), Tovey (2000), and Won (2001) have argued that CAD systems are useful only at the design stages where ideas have been sufficiently crystallized. The reasons for this, Tovey (2000) mentioned, as CAD programs focus mainly on producing an end product or form and hence are not very helpful in the conceptualization stage. Mckay (2012) mentioned that CAD is well suited for downstream activities like design evaluation, analysis, prototyping, and manufacturing, but it is challenging to apply CAD before shapes have been created. This indicates that CAD is less suitable for the early conceptual stage of the design (Mckay 2012).

In a case study investigation, Tovey and Owen (2000) found that when modeling is introduced in the very early stage of design, fewer ideas were produced as compared to the traditional method. As per De Bono (1970), lateral thinking is an essential

requirement for creative idea generation in the early phase of design. The lateral exploration in simple words can be explained as the generation of many ideas that are different from each other. The thoughts in this phase jump from one idea to another. Whereas vertical thinking or vertical exploration is done when a specific idea is explored in-depth, applied logic, analyzed and argued (Bono 1970).

Tovey and Owen (2000) proposed that CAD should be used only after the concepts for development are chosen, i.e., the stage where rough clay or foam models may have been produced. At this stage, designs are less subjected to radical changes as compared to the conceptualization phase, where rapid and radical changes are freely tolerated. They mention that introducing CAD at the early stages results in a convergent approach where a divergent one is needed. In development-stage concepts develop from ill-defined proposals to detailed designs and are then handed over to engineers. 'This stage is increasingly supported by CAD techniques' (Tovey and Owen 2000). Stappers and Hennessey (1999) also support the thought by mentioning that currently, CAD systems are useful only at the design stages where ideas have been sufficiently crystallized (Oxman 2006).

CAD is well accepted as a drafting, visualization, and detailing tool. However, there are not many takers of the idea of using CAD as a tool in the early phases, like product conceptualization (Athavankar 1990). Verstijnen (1998) and Van Dijk (1995) also mentioned that CAD tools fail to meet the requirement of being helpful in the early creative phases of design. On the other hand, Hanna and Barber (2001) argue that CAD tools are adapting to the needs of the design process, thus increasing its chances of being used as a design tool at an early stage of design. The introduction of digital media has introduced new design methods and processes and the design professionals today are moving beyond the traditional practices (Oxman 2006).

Tovey and Owen (2000) propose a modeling method using 'Texture mapping' to facilitate a faster process for 3D visualization of a large number of idea sketches. In

this method, the sketches are mapped onto a standard form model. The resultant model can be animated, rotated, and scaled. A 3D perspective image of base models can be used as an underlay for sketching the ideas, and these can then be texture mapped onto the base model. This method was found significantly useful, quick and comfortable at early phases of design in the context of automotive styling.

Findings of an experiment conducted by Gibson (2000) suggest that CAD may be beneficial at expanding ideation through systematic manipulation. She mentions in her study that prior experience and mental blocks can limit the designer's thinking. To overcome these mental blocks, designers use many methods like brainstorming, analogies, and metaphors. She used an automated topology method (i.e., morphing) in the study with which students could generate an abundance of different ideas using only two to three initial ideas in a short time. In turn, this resulted in much more time required for the assessment of ideas. Also, as the computerized process is unbiased, the computer accurately combined divergent ideas without giving preference to one over others. On the other hand, during the manual morphing phase, the assessment of ideas was an integral and repetitive process. This resulted in more time for ideation but much less time for assessment. The personal biases of designers also could not be overruled (Gibson 2000). Gibson (2000) suggests that using CAD as a tool may release the designer from habitual and routine patterns so that alternative connections or new concepts may arise to recurring problems.

Many new systems like texture mapping (Tovey and Owen 2000) and automated morphing (Gibson 2000) are being explored to make CAD systems suitable for the early phase of design. Yet, commercially available 3D CAD software has a predominant presence in the industry and designers are using the same software from idea generation stage to the detailing and prototyping.

Many researchers (Tovey 2002; Tovey and Owen 2000; Stappers and Hennessey 1999; Hanna and Barber 2001) believe that sketching is still the best means of coming up with more creative ideas and it is evident that it plays a significant role in

the design process. The earlier generation of designers finds designing with mouse and keyboard awkward to handle, unlike pencils. When a designer sketches s/he shifts and reorganizes the information in his/her mind. This simulates more ideas. Even the sketches that s/he makes get absorbed as information and evaluation of it help create the next idea (Tovey 2012).

Hanna and Barber (2001) mention that the conventional design process has a well-established formal structure of analysis – synthesis – evaluation – presentation. However, the computerized design process does not have any such established structure and is more like an added activity. They also emphasize the need to identify the changes to the nature and structure of the design process that need to be made if CAD is to be used as a design tool in the early phases of design. Tovey (1989) suggests that CAD 'cannot match design sketching' and 'inhibit fluid design thinking.' CAD programs focus mainly on producing an end product or form and hence are not very helpful in the conceptualization stage. Athavankar (1990) too mentions that for the mind to be free for creative thinking, it is essential that the process and the act of representation does not demand too much of mental attention and match the pace at which the mind can think of alternative solutions.

Cross (2005), concerning the architectural design process, stated, "CAD would be of limited positive effectiveness as a design aid, but could have profound negative effects on design activity and the job of being a designer." But he also mentioned that good or bad, using computers in design practice was inevitable (Cross 2005).

On the other hand, Schneiderman (1999) mentions that 'technology has always been part of the creative process, whether in Leonardo's paint and canvas or Pasteur's microscope and beaker. Supportive technology can become the potter's wheel and mandolin of creativity – opening new media of expression and enabling compelling performances.'

2.4 CAD and representation tools in the design process

Visualization is an integral part of the design process. Designers need to visualize their ideas, and with the help of different mediums, they convey these ideas to others. An effective visualization plays a vital role in decision-making. Stappers and Hennessey (1999) mention that 'design solutions emerge from the interaction between the designer and the visualizations.' Bilda and Gero (2005) also discuss that the externalizations of ideas are central to design. Externalizations represent the development of designs; have an interactive role to play and a crucial effect in the mechanism of the design activity.

The nature of representation can be different for the different stages of design. Designers use sketches, doodles, and quick mock-ups extensively to help them visualize their ideas and have an exploratory dialogue. Drawings and models are the physical manifestation of visual thinking (Tovey 2012). Creating and using representations are a vital component of creative problem solving (Tovey 2012). These representations can be sketches, renderings, models, diagrams, or drawings depicting component details. Tovey (2012) stated that today the distinction between digital and tangible has blurred, and designers repeatedly shift between different techniques for creating these representations. CAD and sketching today are part of the design environment that supports the exploration of ideas by translating them in visual representations (Oxman 2006).

Freehand sketching has always been considered as a core conceptual tool. It allows designers to externalize their thoughts and engage in a dialogue with the idea (McKim 1980). The abstract and ambiguous nature of sketches allows designers to make unexpected discoveries and come up with various interpretations and new ideas (Wojtczuk and Bonnardel 2011). *'Despite the importance of sketches in concept building, these are 2D representations of what is hoped to become 3D forms'* (Tovey and Owen 2000). While comparing CAD with sketching, Lawson

(2002) mentions that *'visual sensitivity needed to design and to draw are so similar that it would be unlikely for a student to be skilled in one area but not in the other.'* This is not the case with CAD and design.

Sketches also have certain limitations. It may have proportional errors, a lack of precision, and a distorted angle of vision. Sketching is a skill that needs to be acquired. The representations made using CAD are highly precise and accurate. It is considered to be ill-suited for the early stages of design where ideas are still vague and incomplete, and this may curtail the effect of discovery. Design thinking contains a high proportion of non-verbal thinking (Tovey 2012), and sketching helps externalize and record these thoughts.

Modeling is another tool vastly used by designers for conceptualization. Mock-up models and prototypes provide designer extensive tactile feedback and allow them to reflect continuously on the design. In an experiment conducted by Jonson (2005) to compare the CAD with sketching and modeling, he found that though sketching is used as a primary tool, it is always used in combination with CAD or modeling. He found the role of sketching less prominent in practice than that advocated in the literature (Jonson 2005).

Production of rough clay or foam models of the concepts is time-consuming and expensive. This limits the number of concepts that can be visualized in three-dimensions. If these sketches can be converted into fast 3D CAD models, the number of concepts may increase drastically (Tovey and Owen 2000).

In an investigation conducted by Wojtczuk and Bonnardel (2011), they compare CAD with modeling. They presented designs made by two groups of designers, one using CAD systems and other using manual modeling to a panel of judges; a significant preference for objects designed with a CAD system was noted. It indicates the effect of digital representations on decision-making. They also found

that the CAD users were less hesitant about experimenting with different effects and features as compared to modelers. CAD reduced the physical workload of the designer, giving them more room for experimentation and conceptualization (Wojtczuk and Bonnardel 2011).

The physical model making remains an essential and integral part of the design and development process, but virtual modeling, simulation, and RP have gained wide acceptance in product design (Xiuzi, et al. 2008; Ingram 2012). These technologies help designers and decision-making team overcome the limitations of size perception on the screen. A physical or virtual reality life-size model can provide a better interaction between product and humans and help in decision-making and overcome limitations of size perception (Xiuzi, et al. 2008). With immersive prototyping, it has become possible to generate real size, virtual models. Ingram (2012) discusses that the virtual model takes longer to produce but offers the advantage of being reproducible and transmissible. Some properties, such as colors, textures, transparencies, and backgrounds, can be changed and tried instantaneously. However, a physical model is needed to understand the weight, feel, size, balance, strength, flexibility and other physical properties of design that cannot be achieved from a virtual model (Ingram 2012).

Jonson (2005) also mentions that CAD is not just a technical tool but is capable of developing new ways of perceiving and conceiving design. It may allow exploration of new patterns, relations, and aesthetics, expanding the designer's creativity options (Jonson 2005).

Ibrahim and Rahimian (2010) discuss the inability of sketches to handle articulation of design ideas and complexities effectively. They also mention that design creativity diminishes with excessive use of CAD software. To overcome these limitations, they propose a balanced combination of manual and digital tools as the best representation methodology (Ibrahim and Rahimian 2010). In practice,

designers use physical and virtual models both at various stage of design along with sketching (Ingram 2012).

2.5 CAD and Creativity

Today information technology is a significant factor affecting creativity. A designer can make use of knowledge-base technology, information searching technology, artificial intelligence, and CAD tools to improve their creativity. Creative problem solving is essential at every stage of the design process, but it is of critical importance at the conceptual design stage.

The definition of creativity from Webster's dictionary is- *Creativity is marked by the ability or power to create, to bring into existence, to invest with a new form, to produce through imaginative skill, to make or bring into existence something new.* As per De Bono (1994), creativity is dealing with the transformation of existing ideas, views, and approaches to doing things to the new ones. He mentions that creative thinkers can break out of conventional ways of thinking. It need not be something new but can also be a novel combination of old ideas (Bono 1970). Ripples (1989) also mentions that creative people are open to experience and take risks more freely and have many different ideas. Creative ideas are novel and original and are perceived to be of value to people or society (Tovey 2012). Creative ideas inspire and influence others. Novelty is defined as being new and uncommon. Originality is being the first example of something (Tovey 2012).

Knowledge and thinking style are vital attributes of creative problem-solving. Knowledge and experience lay a substantial foundation for creativity, and design thinking serves as the backbone of creativity. Design thinking is the crucial ingredient in the realization of products and services and is required to harness the individual and collective creativity (Stuart 2008). Design thinking allows us to focus on new ideas. Wikipedia defines 'Design Thinking' as a style of thinking that is

generally considered the ability to combine empathy for the context of a problem, creativity in the generation of insights and solutions, and rationality to analyze and fit solutions to the context. 'It is a way of thinking that produces transformative innovation or an empathetic, customer-led approach to innovative problem solving' (Stuart 2008). Design thinking is a "*systematic and collaborative approach for identifying and creatively solving problems"* (Luchs 2016). In simple words, it is a way to approach and solve a problem as a designer would.

Indirect thinking and expression improve creativity and may inspire the designer to come up with different and novel solutions (Kulogun and Asasoglu 2010). Kulogun and Asasoglu (2010) mention, "To perceive, interpret and communicate the world and the facts differently is an important goal of design education and can only be obtained through creative thinking." "*Design activity itself is a relation between thought and expression"* (Kulogun and Asasoglu 2010). What a designer needs and tries to represent is a 'thought.' A thought can be abstract or concrete. In terms of creativity, abstraction is superior to figuration (Kulogun and Asasoglu 2010).

Coyne et al. (1987) describe the design as a process of search within spaces of possible design. They mention that creativity is concerned with explorations within a space that is only partially defined as against Innovation as a process of exploration in a defined space. The paraphernalia that defines search space in design is knowledge. Creativity involves searching for new knowledge (Coyne, et al. 1987).

Visual design thinking is the essence of the design exploration process, and creativity plays an essential role in design thinking (Abdelhameed 2007). Seeing is the experience of sensation, and knowledge is the construction of meaningful perception. The media used by designers affect the process of design exploration and design thinking. Certain ideas can only be derived from specific tools and individual use of media (Abdelhameed 2007). On the other hand, the use of specific media can dictate the design output.

In an in-depth study conducted by Robertson and Radcliff (2009) with engineers, they realized that at times developing a CAD model consumes so much of time and effort that it results in an unwillingness and resistance to make changes in design even if the changes can bring advantages. More time spent on detailing a particular idea limits the number of ideas developed. They define this phenomenon as 'premature fixation' (Robertson and Radcliffe 2009).

The forms and ideas being explored can also get restricted by the limitation of CAD tools or by the proficiency of the user. At the same time, a highly proficient user may end up introducing complicated and unnecessary details. When ideas are driven by the limitations of CAD tools or by the proficiency of the designer, it is identified as 'circumscribed thinking' (Robertson and Radcliffe 2009).

Robertson and Radcliffe (2009) mention that excessive use of CAD under stressful conditions affects the motivation of the user and hence the creative potential of the user. Creative problem solving requires efforts and without any incentive or motivation, this might not take place. This results in bounded ideation. The best environment for ideation is away from computers (Robertson and Radcliffe 2009).

Through the online survey, Robertson and Radcliffe (2009) confirmed the widespread presence of enhanced visualization and communication, premature fixation, and circumscribed thinking, but the occurrence of bounded ideation was found rare. They argue that CAD has an important role to play and is one of the many skills needed to complete design education, but it should not be allowed to dominate the design education process and the student's conception of design.

Lubart (2005) also mentions that the proficiency level of users has a significant impact on the ways computers can help them in the creative process. Designers also have different abilities, preferred working styles, and personality traits. The creative potential of designers depends on all these traits.

Taking analogies from human relations, Lubart (2005) explores the roles computers can play in the creative process. Though he does not mention the role of CAD directly, computers will need the help of CAD systems to perform the roles he describes. He mentions that ‘computers may facilitate the management of creative work, communication and collaboration on creative projects, use of creativity enhancement techniques and ideation through integrated human-computer cooperation. He defines four different roles that can facilitate these as- computer as a nanny, computer as a pen pal, computer as coach and computer as a colleague (Lubart 2005).

Stappers and Hennessey (1999) describe is that in the ideation and conceptualization stage, ‘designers use the visual, intuitive, and integrating skills that have been associated with the right cerebral hemisphere. CAD programs enforce a verbal, analytical, deductive, sequential way of working associated with the left hemisphere.’ To support designers, an interface that can match the visual cognitive style is needed. ‘It should present its image in an overview and allow a user dialogue which is visual’ (Stappers and Hennessey 1999). Won (2001) reports the difference in the cognitive behavior of the designer when using CAD as compared to sketching. He mentions that cognitive behavior is much more complicated when a designer uses CAD when compared with the traditional methods of representation (Won 2001).

CAD can facilitate impressive visualizations, but there is always a tradeoff between time and quality of presentation. This again, is a function of proficiency. Wergles and Muhar (2009) mention that computer visualizations are becoming more sophisticated, but the understanding of its impact on viewers' perceptual and evaluative response is still lagging behind.

The illusion of completeness shown in realistic renderings can lead to premature fixation of ideas. Gero (2011) mentions that fixation can be of two types; first in which the designer appears trapped by an existing precedent solution and other that

occurs due to commitment to a particular set of design decisions that the designer does not want to change. Jansson and Smith (1991) argue that a pictorial representation of a design solution before the design session can result in fixation. This prevents innovation because the designer cannot move to the conceptual space, which is where they consider that innovative changes can occur (Jansson and Smith cited by Gero, 2011).

Robertson and Radcliffe (2009) define premature fixation as the reluctance to make changes in the design due to excessive detailing and time spent on a particular design. Wergles and Muhar (2009) quote that realistic visualizations cause a "genuine excitement and anticipation" that can bias the decision-makers. They mention that the "visualizations are used by planners often to 'sell' the idea rather than to make it transparent and defensible". The "wow-effect" of the photorealistic visualization can sometimes override critical assessment of the content (Pietsch 2000) and hence lead to fixation.

Wergles and Muhar (2009) also observe that in the presentation of realistic renderings, 'the quality of the image is being evaluated and not the content of the project.' Also, the visualizations can direct the attention of the viewers authoritatively. The way perspectives are selected can dictate the viewer's focus. This might not be the case in the actual scenario (Wergles and Muhar 2009). Lawson (2002) expressed his concerns about design students combining poor designs with impressive and convincing computer presentations. He mentions that 'we live in such a televisual age that any information that looks televisual is automatically considered authoritative' (Lawson 2002). Stappers and Hennessey (2009) mention that computer graphics are over precise and realistic and leave no room for expressive techniques such as intentional and controlled ambiguity, quick annotation, and personal style. The personal style also plays an important role in communicating the designer's personality and intend.

Tovey and Owen (2000) mention that the advantage of using CAD in the early stage is that it allows designers to engage in three-dimensional characteristics of the design. They argue that ‘stylists need speedy data input, easily specified and modified geometry, precision only where required, good display quality and convenient display’. CAD cannot replace the traditional sketch-based approach. They conclude by proposing a combination of direct modeling and sketching and sketch mapping may provide an optimum process. This will help retain the ambiguity and personal style of the designer and will provide sufficient 3D visualization. This method can help avoid premature fixation due to the illusion of completeness or premature detailing.

Lawson (1999) argues that CAD could support designers in exploring ideas and give freedom to visualize their creative imagination. Although quality of outcomes can be debatable, he agrees that CAD enables designers to produce convincing original designs.

A CAD model undoubtedly gives a better 3D visualization. The client or the other team can rotate the models, visualize from various angles and perspectives, and render in realistic scenarios. The organization of various components in a product can be visualized very effectively in CAD models. This helps in visualizing the final product much better and in decision-making. On the contrary, it has been criticized for biasing the viewer’s responses (Sheppard, 2005). Wergles and Muhar (2009) mention that a ‘valid simulated environment can be defined as one that produces a cognitive, affective, and behavioral response in the observer equivalent to the response produced by the real environment.’ Despite all the efforts, visualization cannot represent all the aspects of the complex real world, nor is it worthwhile. A “good enough” or “sufficient” realism can be measured by the degree to which the simulation appears to look like the real world when judged based on the image alone (Wergles and Muhar 2009). A realistic image need not be necessarily naturalistic.

One strong point of CAD visualization is its ability to handle complexities, details, and keep track of the whole interaction history. This outweighs the complexities its interface imposes on the user (Stappers and Hennessey 1999).

With the advent of tools like generative algorithm and parametric modeling techniques, designers have got the freedom to play with the variables and generate a large number of ideas or form variations. Once the basic initial structure is made in CAD, it may lead to idea generation and results in an unlimited number of ideas. The better visualization also aids the generation of more ideas and hence creativity. This is true not only for form generation but also for the detailing phase. However, developing a CAD model consumes so much of the time and effort that it limits the number of ideas developed. This is also a function of the proficiency of the designer. One huge advantage that CAD has brought in is that it promotes and facilitates communication. This, in turn, can support the collaborative creative explorations to a great extent.

With CAD tools becoming ubiquitous, it is essential to understand its effect on the working style and design output of designers. With technological advances, new tools are being introduced to assist designers and engineers in their work and aid their creativity and visualization at a rapid rate. Few of these include TRIZ, virtual reality, reverse engineering, innovation technology, texture mapping, and haptic devices. However, the designers and engineers still predominantly use desktop-based 3D modeling software. Hence, this study focuses on the effects of commonly available 3D CAD modeling software on designer.

2.6 Summary of literature review

There are various views researchers have on the use of CAD in the fuzzy front end and the stages in which CAD may be used. Few are listed in table 2.1 chronologically to provide a glance.

Table 2.1: CAD in the early idea generation stage of design process

Author	
Van Dijk (1995) Verstijnen (1998) Stappers and Hennessey (1999)	CAD systems are useful only at the design stages where ideas have been sufficiently crystallized
Tovey (2000)	CAD programs focus mainly on producing an end product or form and hence are not very helpful in conceptualization stage.
Won (2001)	CAD was mainly restricted to later stages of design but in recent years, it has seen increased attention in the concept generation stage as well
Hanna and Barber (2001)	CAD tools are adapting to the needs of the design process, thus increasing its chances of being used as a design tool at an early stage of design
Hanna and Barber (2001)	Conventional design process has a well-established formal structure of analysis – synthesis – evaluation – presentation. However, the computerized design process does not have any such established structure and is more like an added activity.
Robertson et al(2007)	The best environment for ideation is away from computers
Brown (2009)	CAD is an important innovation in this era that has changed the face of design industry and has influenced the lives of designers and engineers
Ulrich et al (2009)	CAD had a significant impact on the work of industrial designers and designers today are using modern 3D CAD tools to generate, display and rapidly modify their designs.
Ulrich et al (2009) Clare(2009)	CAD can and/or is used from the early conceptualization stage of design, right through to manufacturing.

Author	
Musta'amal et al (2012)	CAD plays role through the various phases of design including styling, conceptual design, simulation, product design and detailed design.
Shih, Sher, Taylor (2017)	Switching between sketching and CAD is an ideal approach for conceptual design. Switching between media help designers take better and more appropriate design decisions.

When arranged chronologically, it can be seen that there has been a shift in the views. Earlier researchers argue that the CAD tools should be used only when the ideas are crystallized. However, gradually views are changing towards the inclusion of CAD in the fuzzy front end. There are views on CAD tools becoming intuitive and efficient to use and are adapting to the needs of designers. New age designers and engineers are increasingly adapting CAD tools in the early stages of design. The design research has to move away from comparing the media but explore more the mixed-media environment (Shih, Sher and Taylor 2017). It is crucial to identify the changes to the nature and structure of the design process that need to be made if CAD is to be used as a design tool in the early phases of design.

As the focus of the study is the early phase of design, it was essential to understand the relation of CAD with the other tools available. A review of the literature comparing CAD with sketching and manual prototyping was carried out. The limitations and advantages of CAD compared to manual tools are listed in table 2.2 and 2.3 respectively.

Table 2.2: Limitations of CAD compared to manual tools

Author	
Won (2001)	Cognitive behavior is much more complex when a designer uses CAD when compared with the traditional methods of representation.

Author	
Lawson (2002)	'Visual sensitivity needed to design and to draw are so similar that it would be unlikely for a student to be skilled in one area but not in the other'. This is not the case with CAD and design.
Jonson (2005)	Though the sketching is used as a primary tool, it is always used in combination of CAD or modeling.
Abdelhameed, 2007	The media used by designers affect the process of design exploration and design thinking. Certain ideas can only be derived from specific tools and from individual use of media
Wojtczuk et al (2011)	- The abstract and ambiguous nature of sketches allows designers to make unexpected discoveries and come up with various interpretations and new ideas - Designing with mouse and keyboard is awkward to handle

Table 2.3: Advantages of CAD as compared to manual tools

Author	
Jonson (2005)	CAD is not just a technical tool but is capable of developing new ways of perceiving and conceiving design. It may allow exploration of new patterns, relations and aesthetics, expanding designer's creativity options
Ibrahim et al (2010)	Inability of sketches to effectively handle articulation of design ideas and complexities can be overcome by use of CAD
Wojtczuk et al (2011)	- CAD users are less hesitant about experimenting with different effects and features as compared to modelers. - CAD reduced the physical workload of the designer, giving them more room for experimentation and conceptualization

It is imperative to understand that CAD is not a replacement for sketching and physical modeling. The CAD should be looked at as a new age tool with distinct advantages and limitations and needs to find a defined role in the process of design. CAD should help overcome the limitations of conventional methods. A mixed-media environment that includes sketching and digital modeling have proven to be more efficient and effective as compared to any single medium (Ibrahim and Rahimian 2010; Oxman 2006). To overcome the limitations of CAD, it is important to propose a balanced combination of manual and digital tools (Ibrahim and Rahimian 2010)

The literature reviewed further assessed the various views on the limitations and advantages of using CAD in the early idea generation stage. The summary is tabulated in table 2.4 and 2.5.

Table 2.4: Limitations imposed by CAD in idea generation stage

Author	
Stappers and Hennessey (1999)	Computer graphics are over precise and realistic and leave no room for expressive techniques such as intended and controlled ambiguity, quick annotation and personal style.
Tovey and Owen (2000)	Introducing CAD at early stages result in convergent approach where a divergent one is needed.
Tovey (2000)	CAD ‘cannot match design sketching’ and ‘inhibit fluid design thinking’.
Lawson (2002)	‘We live in such a televisual age that any information that looks televisual is automatically considered authoritative’
Pietsch (2000) Sheppard (2005)	The “wow-effect” of the photorealistic visualization can sometimes override critical assessment of the content and hence lead to premature fixation.
Lubart (2005)	Proficiency level of users has a great impact on the ways computers can help them in creative process.

Author	
Robertson et al 2007	Excessive use of CAD under stressful conditions affects the motivation of the user and hence creative potential of the user. Creative problem solving requires efforts and without any incentive or motivation this might not take place. This results in *bounded ideation.*
Robertson et al 2007	The forms and ideas might also get limited by the limitation of CAD tools or by the proficiency of the user. At the same time, a highly proficient user may end up introducing complicated and unnecessary details. This effect is known as *circumscribed thinking*.
Robertson et al 2007	Once a lot of detailing is done in a complex model, designers show reluctance to make changes. This results in *premature fixation.*
Wergles and Muhar (2009)	Realistic visualizations cause a “genuine excitement and anticipation” that can bias the decision makers.
Ibrahim et al (2010)	Design creativity diminishes with excessive use of CAD software.
Wojtczuk and Bonnardel (2011)	Digital representations can influence the decision-making

Table 2.5: Advantages offered by CAD in idea generation stage

Author	
Lawson (1999)	CAD could support designers in exploring ideas and give freedom to visualize their creative imagination.
Tovey and Owen (2000)	Production of rough clay or foam models of the concepts is time consuming and expensive. This limits the number of concepts that can be visualized in three-dimensions. Advantage of using CAD in the early stage is that it allows designers to engage in three-dimensional characteristics of design.
Gibson (2000)	Using CAD as a tool may release the designer from habitual and routine patterns so that alternative connections or new concepts may arise to recurring problems
Robertson et al 2007	Effective visualizations facilitated by CAD help communicating ideas more effectively.
Stappers and Hennessey (2009).	CAD visualization is able to handle complexities, details and keep track of whole interaction history.
Ulrich et al (2009)	CAD allows designers to generate greater number of detailed concepts more quickly that may lead to more innovative design solutions.
Musta'amal (2010)	Provides indications that CAD might potentially encourage creativity in design

As can be seen in tables 2.4 and 2.5, there are various views on the limitations and advantages of using CAD. Limitations include fixation, circumscribed thinking, and bounded ideation. On the contrary, CAD can reduce the time and physical efforts required to visualize ideas in 3D and make designers less hesitant to experiment and explore certain aspects of design. Since, the literature covers the various contexts like architecture, automotive design, and engineering; it needs to be studied and analyzed from the product design perspective.

CAD is an indispensable tool in the designer's environment and has become ubiquitous today. It is one of the many skills needed in a designer and thus, has found its way into their work and design process. A systematic investigation is needed to understand how CAD positions itself in the design process and its impact on the ideas generated.

Chapter 3
Research question and research methodology

This section describes the research gap and articulates the process of arriving at the research question. Further, it discusses the design of the research study and the rationale behind choosing the qualitative nature of the study to seek answers to the research question.

3.1 Defining research question

It was realized that innovation, the complete process of new product development, and CAD are all very vast in their scope, and it is crucial to narrow down and clearly define the scope for further research.

Identifying the knowledge gap is central to any research. The study can be designed to contribute to the domain knowledge only if one can identify the gap, define the research question and determine a methodology to seek the answers.

3.1.1 Gap identification

Through the literature review, it was realized that the process of design cannot be explained in a linear diagram and is an iterative process of analysis – synthesis – evaluation – presentation (Hanna and Barber 2001). The generic product design process, as explained by Ulrich and Eppinger (2009), explains various stages and phases of NPD, as shown in figure 3.1. The focus of research is on the design stage of the process (highlighted by box).

Phase 0: Planning	Phase 1: Concept Development	Phase 2: System-Level Design	Phase 3: Detail Design	Phase 4: Testing and Refinement	Phase 5: Production Ramp-Up
Marketing • Articulate market opportunity. • Define market segments.	• Collect customer needs. • Identify lead users. • Identify competitive products.	• Develop plan for product options and extended product family. • Set target sales price point(s).	• Develop marketing plan.	• Develop promotion and launch materials. • Facilitate field testing.	• Place early production with key customers.
Design • Consider product platform and architecture. • Assess new technologies.	• Investigate feasibility of product concepts. • Develop industrial design concepts. • Build and test experimental prototypes.	• Generate alternative product architectures. • Define major subsystems and interfaces. • Refine industrial design.	• Define part geometry. • Choose materials. • Assign tolerances. • Complete industrial design control documentation.	• Reliability testing. • Life testing. • Performance testing. • Obtain regulatory approvals. • Implement design changes.	• Evaluate early production output.
Manufacturing • Identify production constraints. • Set supply chain strategy.	• Estimate manufacturing cost. • Assess production feasibility.	• Identify suppliers for key components. • Perform make-buy analysis. • Define final assembly scheme. • Set target costs.	• Define piece-part production processes. • Design tooling. • Define quality assurance processes. • Begin procurement of long-lead tooling.	• Facilitate supplier ramp-up. • Refine fabrication and assembly processes. • Train work force. • Refine quality assurance processes.	• Begin operation of entire production system.
Other Functions • Research: Demonstrate available technologies. • Finance: Provide planning goals. • General Management: Allocate project resources.	• Finance: Facilitate economic analysis. • Legal: Investigate patent issues. • General Management: Supporter and Reviewer	• Finance: Facilitate make-buy analysis. • Service: Identify service issues. • General Management: Supporter and Reviewer	• General Management: Supporter and Reviewer	• Sales: Develop sales plan. • General Management: Supporter and Reviewer	• General Management: Supporter and Reviewer

Fig 3.1: The Generic Product Development Process (Ulrich, Eppinger and Goyal 2009)

CAD can be used in almost every phase of the ‘design’ stage, as explained in figure 3.2. This proves it to be a key tool for the design industry to generate, modify, present and implement their designs (Clare 2009).

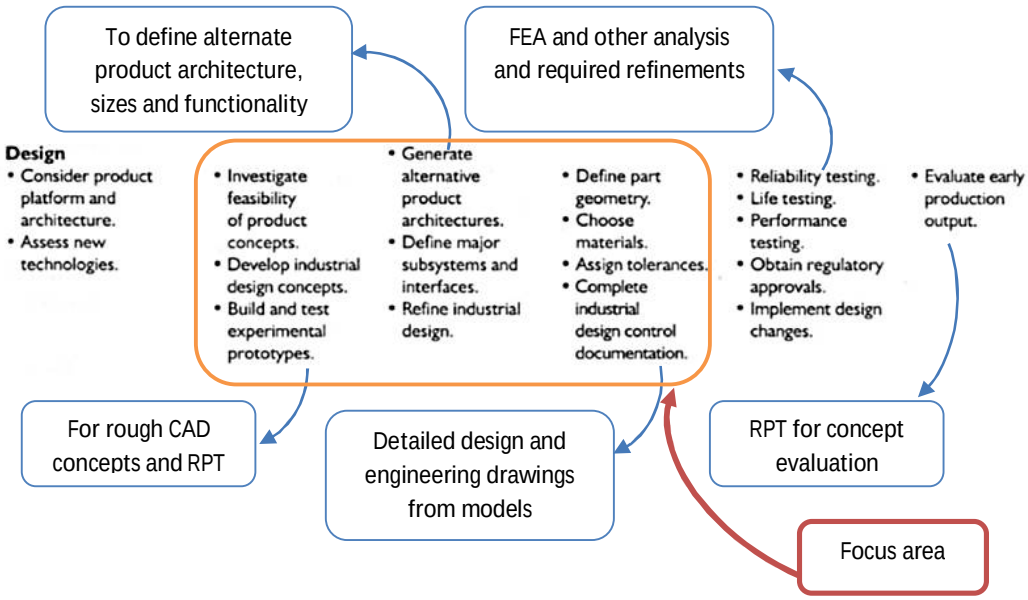

Fig 3.2: Example of how CAD can be used in 'Design' aspect of generic product development process explained by Ulrich et al (2009) (Clare 2009) and focus area of research

The focus area for the research is further narrowed down to the exploratory phase of the design stage in the process of NPD. This is the phase where the initial idea generation takes place. This is the 'ideate' phase in the design process shown in figure 2.4.

Innovation is a holistic process. It deals with translating an idea into a tangible product or service or system. Domain expertise is an essential component of innovation. Gann and Dodgson (2007) also mention that 'the full innovation process involves the design, research, engineering, development, operation management, commercialization, marketing, customer relation and management of the intellectual property.' Today collaboration is considered as an integral part of the innovation process. It is interesting to understand how the structure of the innovation process has changed with time and technology (Chakravarthy, 2003). Creativity forms the base for innovation. In other words, the successful implementation of a creative idea can lead to innovation. The creative exploration and tools to support the creativity of designers are of utmost importance in the early phase of design. Thus, the research

further narrows down to ‘the early design phase’ or idea generation stage of product design.

The early design phase here is defined as the phase where ideation and concept development takes place. Since there is enough literature proving the importance and effects of CAD in the concept development phase, the context for research is further focused down on the idea generation phase. This is the time where after receiving or defining the design brief, a designer starts to generate ideas. This stage mostly starts with little doodles and conversations, along with mind maps and brainstorming, followed by CAD modeling. The sequence is highly dependent on the designer and the project-brief requirements.

Today to aid creativity and visualization, various CAD and related tools have been developed. These include haptic devices, reverse engineering, virtual reality, 3D scanning, TRIZ, and innovation technology. For various reason the most ubiquitously available tool for product designers and design engineers is desktop-based 3D modeling software. Also, it has been observed that almost all the design students are using various CAD programs on their personal laptops that are affecting their approaches and designs at multiple levels. Hence, this study focuses on commonly available 3D CAD modeling software.

Thus, the research narrows down to ‘Investigating implications of using CAD during the idea generation stage for product design’.

3.1.2 Research aim

The research aims to investigate the implications of using CAD during the idea generation stage of product design. It attempts to understand how does CAD position itself as a tool in the mixed-media environment and is used while

generating ideas. How does it affect the process and the idea exploration? It further tries to explore if it offers any advantages to the designer or imposes any limitations.

3.1.3 Research scope and limitations

The research focuses on investigating and reporting the effects of using CAD during the idea generation stage and the ways it has been adopted in the process of design. The focus of the study is the idea generation phase and not the later stages of the design process where concepts are finalized and tested.

Research does not aim to compare CAD with other design tools like sketching and physical model making. It focuses only on the domain of product design in the mixed media environment.

CAD tools in the study are defined as 3D solid modeling tools that are commonly available and used and do not include computer-aided sketching, haptic devices, and virtual reality.

3.1.4 Research question

In a qualitative study, the researcher defines a research question and not specific objectives or hypotheses. The central or main research question is a broad question that explores the concept of study or the core study phenomenon (Creswell 2011). The research explores the complex factors surrounding this central phenomenon. The sub-questions help narrow down the focus of study and feed into the main research question (Creswell 2011).

Zina O'Leary (2011) describes a simple way to define research question in her book, 'The Essential Guide to Doing Your Research.' Taking reference from that, the key points related to topic, goal, context, nature of question and relationship, are

answered in one or two words as described below and then further formulate into the question (O' Leary 2011).

What is the topic? – CAD and Creative exploration
What is the context? – Product Design, idea generation phase of design
What is the goal? – To investigate
What is the nature of question? – How
What are the potential relationships? – Effect / impact / influence and limitations

Main question-
How does use of CAD affect creative exploration during idea generation stage of product design?

The main question is further broken into sub-questions in order to answer the larger question -

RQ1: How does CAD position itself in the idea exploration stage of design process?
RQ2: What advantages CAD offers to the designer, if used in early phase of design?
RQ3: What limitations CAD impose on the designer's way of thinking?
RQ4: Does using CAD during idea generation results in more vertical exploration and hinders lateral exploration?
RQ5: How does CAD affect the design outcome because of its intervention?

3.2 Design of research methodology

The research design addresses the plan and procedure to carry out research. It informs the reader about the methods of data collection, analysis and interpretations (Creswell 2011). The selection of the methodology depends on the nature of research problem.

The main focus of this research is to acquire data and evidence that could shed light on how CAD affects the creative exploration of the designer in the idea generation phase of product design. The research aims to identify the enablers and barriers for the process of idea generation triggered by the use of CAD tools.

The literature review helped in identifying key parameters for the research. These are visualization, circumscribed thinking, and fixation. Other parameters that affect the idea generation process employing CAD are size perception, bounded ideation, and proficiency of the designer. These parameters need to be tested qualitatively through design exercises employing CAD for idea generation.

In order to ensure that the data were collected and analyzed accurately, it was essential to explore the nature and relevance of key research methodologies and methods.

3.2.1 Qualitative and quantitative research in this context

"Not everything that can be counted counts and not everything that counts can be counted" - Albert Einstein (O' Leary 2011)

Design research does not fit “obviously” within either qualitative or quantitative (Crouch and Pearce 2012). Qualitative research focuses on the collection and analysis of qualitative data like words, images, videos, and artifacts. Quantitative

research works around the collection of numerical data analyzed through statistical or other tools of measurement (Crouch and Pearce 2012). Beyond this simple distinction, both methods differ in many ways. Quantitative research is characterized by the positivist (objective) search. It is used for testing objective theories and hypotheses (Creswell 2011). Whereas, qualitative research acknowledges the post-positivist approach (O' Leary 2011). Post-positivist researcher acknowledges world as experienced by human being in its natural setting. The research can be intuitive and holistic and aims at achieving the depth of understanding, not breadth (O' Leary 2011, Crouch and Pearce 2012). The post-positivist approach can be employed to determine the causes that influence the outcomes in a given context and scenario (Creswell 2011). This makes qualitative research a suitable approach for the research context.

Though qualitative research produces in-depth information and knowledge from a small number of cases or participants, it lacks the potential for generalization (Patton 2002). However, this qualitative research aims to gather rich qualitative data in order to answer the questions related to how CAD in incorporated in the designer's idea exploration phase and how does it affect their output.

In this research, the researcher was the key instrument i.e., all the data was collected and analyzed by her through examining models and sketches, observing activities, and interviewing participants (Creswell 2011). The multiple forms of data were collected through interviews, design tasks, and observations for the study. The tools and methods used for each study are described in the respective chapters. However, an overview of the methods (observation and interview) and participant selection and classification criteria is discussed in the following sections.

3.2.2 Observation

Observation has been described as the ‘most comprehensive of all types of research strategies’ (Patton 2002). It is defined as ‘a systematic method of data collection that relies on a researcher’s ability to gather data through his or her sense’ (O' Leary 2011). It can help the researcher put together a complete picture of a particular event. It is an act of noting a phenomenon, often with an instrument and recording it for analysis purposes (Crouch and Pearce 2012). It is more capable of capturing the complexities of events and experiences than other approaches like an interview (Crouch and Pearce 2012). Observation allows the researcher to get a sense of reality (O' Leary 2011).

In the pilot study with students, the observations were taken in the form of notes through direct observation. In the pilot study with professionals, conducted with professionals, video recorder and screen capturing software were used as recording instruments to capture the complete activity.

The experience from the pilot study with students made the researcher realize the difficulties in direct-observation, especially when dealing with on-screen CAD observation. Furthermore, this pilot study was conducted with ten students in a classroom, with all of them performing the design activity simultaneously. It was not possible to observe all of them simultaneously throughout the session. On-screen CAD activities are complicated to observe and understand and are not supported with additional information like verbalization. Therefore, for the pilot study with professional designers, video recording was considered as a recording tool, and a single participant performed the task at a time. The type of observation can be defined as non-participant candid observations. The researcher was unobtrusive throughout the design task, and the observations were drawn from the video recording of the task. Some observations were also drawn from the session after the design task, where the participant described his experience and design outcome. The

purpose of the study and nature of data collection were disclosed to participants before the design task and their consent to record the sessions was sought.

3.2.3 Interview

Interviewing is a method of collecting data through a conversation between interviewer and interviewee (O' Leary 2011). Interviews can support the collection of rich, in-depth data on a topic from a specific group of people. Interviewing is a time-consuming method, but provides great flexibility to the researcher (Guthrie 2010). The three different types of interviews involve: unstructured, semi-structured, and structured (Guthrie 2010, O' Leary 2011). The interview method used in this research is semi-structured, informal, and one-on-one. The researcher conducted all the interviews in the pilot study and final study one-on-one. One-on-one interviews allow the interviewee to express his/her thoughts freely. An informal setting like meeting over a cup of coffee at a local cafe provides a friendly environment and comfort and helps establish rapport and gain the trust of the interviewee (O' Leary 2011). Semi-structured interview guides provide the researcher more flexibility and freedom to change the order of questions to make the process more conversational, add prompts to seek in-depth information about certain topics, and have open-ended follow up questions to understand the respondent's views better (Guthrie 2010). At the same time, semi-structured interviews help collect comparable data across all the interviews while making sure that no topic is missed.

The interview guide can be divided into three broad sections. The interviews need to begin with some ice-breaker questions that would help gain the confidence of the interviewee and make the atmosphere relaxing and comfortable. These are further followed by the questions related to the main body of research. The last phase concludes the session with summary and thanking (Creswell 2011).

In this study, interviews provided the researcher with rich information and insights that were helpful to the research. The information obtained through interviews supported the findings from observational data and provided insights into the areas that were not directly observable. All the interviews were transcribed from the audio recordings and transcripts were used for analysis purpose.

The pilot study with professionals involved two phases of interviews – pre and post. The preliminary (pre) interview was a structured interview with pre-defined questions. This was emailed to the participant well before the design task. This questionnaire was used as a qualifier for the participant. Its purpose was to gather enough knowledge about the respondent to discover whether s/he is suitable to be a participant for the study. The second interview was conducted post design tasks with one-on-one interaction with the participant. It was a semi-structured interview to gain insights on the practice, experience, and perspective of the participant related to using CAD in the idea generation phase of the design.

The final study employed one-on-one semi-structured interviews with participants. It was realized that observing participants in their natural work setting was difficult due to copyright issues and company policies. Interviews helped gain insights about their experiences and practices. It allowed participants to recall experiences from the past and talk in a more relaxed environment. The tool used for data collection was a Sony digital audio recorder. The interviews were transcribed verbatim and coded using MaxQDA software.

3.2.4 Qualitative analysis and interpretation of data

In the pilot study with students, the observation notes, notes from group discussion and presentations, the CAD models, and sketches were used as data. All were compared and interpreted to draw the findings. The study further helped define study parameters.

In the pilot study with professionals, the design task was video recorded with the help of a digital camera and desktop recorded using Webinar software. It was further segmented in 5-minute intervals, and each activity was transcribed. The occurrences of study parameters identified through literature and previous study were visually mapped onto transcribe (Annexure-II). The supporting data was collected through interviews and feedback from the participant that was audio-recorded and transcribed. The findings were drawn from the interpretation of this data.

In the final study, interviews were transcribed and coded using MaxQDA. Coding helped chunk and segregate information from a large amount of data. These chunks were further interpreted and re-interpreted to articulate the findings. MaxQDA is a program that can help the researcher systematically evaluate and interpret qualitative data. It can help the researcher code, index, group, and store, explore, make the graph, retrieve the data, or anything that one can do manually in a more efficient manner (O' Leary 2011). Though the researcher still has to go through each line of transcribes and assign codes, yet using a software make the process more effective and faster than manual coding.

3.2.5 Participant selection

To seek answers to the research question, it is essential to find out who might hold the answers. Finding the right participants for the study and be able to classify them is an important aspect of research methodology. In a qualitative research one seeks rich data and narratives from 'few' participants rather than 'many' (O' Leary 2011).

For the pilot study with students, the convenience sampling method was used. Whereas, for the pilot study with professional and final study purposive or handpicked sampling method was used.

All the participants in the study needed to be the user of 3D solid modeling software SolidWorks. Their proficiency levels had a significant impact on their approaches. Therefore, it was important to cluster participants based on their proficiency levels. Dreyfus (1980) defines five levels of skill acquisition: novice, advance-beginner, competent, proficient, and expert (Honken 2013, Hunt 2008). For any new skill, an individual is required to start from the novice and then progress through each stage of expertise. Hunt (2008) mentioned that most of the population for any skill is advance-beginners, and they never get to the higher stage. They do not thrive on learning new things unless the need arises and continue performing regular tasks. They do not have a more broad-based conceptual understanding. The Dreyfus model of skill acquisition was required to be interpreted in terms of knowledge of SolidWorks software to define the proficiency levels of participants. Based on the SolidWorks certification exams and stages to tool learning the Dreyfus model was interpreted. The different stages are as follows:

Novices:

- Have little or no previous experience in the skills. Their target is to achieve the goal and they are not interested in learning the skill. They essentially need a recipe / a step-by-step process to complete certain task. (Hunt 2008, Honken 2013)
- In this case, a novice will be a person who has just started using SolidWorks and is just aware of basic functions like extrude, revolve, cut, loft and sweep. The person can probably review the model but is unable to create one all by him/her.

Advance Beginner:

- Advance beginners have basic knowledge. They can start the work on their own but have problem trouble-shooting. They do not have a holistic understanding and can use advice to correct context based on past experiences (Hunt 2008).

- In this case, advance beginner is someone capable of building simple and basic models. Is aware of basic functions but might require more time and use more steps / functions to create the same shape as compared to a proficient user. He/she is not aware of advance features and surface modeling in SolidWorks.

Competent:

- Competent users have conceptual knowledge and can troubleshoot on their own. They can work on new problems that they have not experienced in past. They are open to seeking advice from experts and use it effectively (Hunt 2008). As per graph shown by Hunt (2008), they are the second largest user population for any skill.
- In this case, competent users will have fair knowledge of the tool and its features. They are capable of creating new forms and using advance features. If stuck with certain features or formal details, instead of changing it they should be able to create the intended form using other features. This would be the ideal user group for the study.

Proficient:

- Proficient practitioners understand a larger conceptual framework around the skill. They can reflect on what was done previously and revise their approach to do it better. Before this stage, self-improvement was not available. They have good experience and from their experience they know what plans should be discarded and what needs to be done to achieve a goal (Hunt 2008).
- In this case, a proficient user would be one who can combine surface and solid modeling tools to achieve desirable forms. He/she is capable of coming up with new strategies to develop challenging design details, can use configurations and is capable of achieving the desired results faster with lesser commands. The person can switch between assembly and parts and build parts inside assembly.

Expert:

- Experts are source of information and knowledge. These are the people who write books and articles. They have extensive experience and can apply it in the correct context. They work by intuition and have inherent knowledge of skill (Hunt 2008). Hunt (2008) mentioned that it takes about 10 years to become an expert.
- In this case, these practitioners know the tool thoroughly. They do not need to plan their steps and can fluently create any form or design detail and animations. They can carry out various analyses using the tool and can shift between different software as well. They can be from the team that creates or tests software or people who teach this software. They can also be certified professionals. However, 10 years of experience or more put them beyond the scope of this research.

The participants for the research fall in advance-beginner, competent and proficient users. The summary of Dreyfus model of skill acquisition interpreted for SolidWorks proficiency is shown in Table 3.1.

Table 3.1: Dreyfus model of skill acquisition reinterpreted for SolidWorks proficiency level

	Novice	**Advance beginner**	**Competent**	**Proficient**	**Expert**
Dreyfus definition	Have little or no experience. Need step-by-step process to complete a task.	Has basic knowledge. Can work. Cannot troubleshoot.	Has conceptual knowledge and can troubleshoot.	Understand larger conceptual framework. Self-improvement is possible. Can decide actions from experience.	Source of information and knowledge. People who write books and articles. About 10 years of experience.
SolidWorks skill	Has just started using SW and aware of basic functions like extrude, revolve, cut loft and sweep	Can build simple and basic models. Not aware of advance functions and surface tools in SW.	Fair knowledge of tool and features. Capable of creating new forms and using advance features.	Can combine surface and solid modeling tools. Can develop new strategies and multiple ways to achieve challenging details. Can work with configurations.	Knows tool thoroughly. Can create any form and detail, animate and analyze. Can shift between different software. People who create/ test/ teach SW.

Chapter Summary

The chapter elaborates on the gap in the literature and marrows down the research direction. It illustrates the process of deriving the research question. The main research question is defined as*; how does use of CAD affect creative exploration during the idea generation stage of product design*?

The design of the research study section argues the quantitative versus qualitative research approaches in this context. The research uses a qualitative approach to generate rich, in-depth understanding. The primary methods employed are observation and interview. The chapter reviews the methods and outlines the methodology for each study in brief. The detailed description of the methodology for each study is elaborated in respective chapters.

Further, it interprets the Dreyfus model of skill acquisition in terms of Solidworks knowledge for participant selection. Table 3.1 shows the summary of the skill levels interpretation as per the Dreyfus model considered for classifying participants in the study.

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Chapter 4
Pilot study with design students

After having identified the research gap in previous chapter, a pilot experiment was designed to understand the role of CAD in the initial phase of design and its impact on design decisions.

Researcher taught a course of 3D modeling to postgraduate students of product design. During the course conducted in 2013 observations were made about the changing behavior towards the 3D modeling software in students. It invoked the curiosity and inputs from other faculty members were sought regarding the change in student's approaches, representations and capabilities. As the institute provideseducation license of SolidWorks 3D modeling software to students, almost all the product design students had installed the software on their laptops and used it extensively for various class assignments and design projectsh

This chapter elaborates the pilot study framework and findings from the study. The findings further helped formulate the next study.

4.1 Aim and objective

The aim of this study was to seek answer to the main research question - "How does use of CAD affect the explorations during idea generation stage of product design?"

Objective of the study was to understand the student's approach towards inclusion of CAD in the early idea generation phase of product design and how it affects their

explorations. What are the enablers and barriers that CAD introduces when used in the early phase of design.

4.2 Study framework

The study incorporated a class exercise of designing a kettle. This was chosen as it is a simple and familiar product and explorations would mainly be on 3-dimensional form of the product. The functional requirement of the product was simple and minimal and it provided vast scope for formal explorations.

4.2.1 Design Brief

A utensil manufacturing company wants to introduce kettle as their new product. The kettle is to be used on a gas/electric stove. You are required to produce as many ideas as you can to present to the marketing team with minimum of 3 options.

4.2.2 Duration and expected outcome

Participants were given 3 hours of time to create ‘good enough’ representations (in form of quick sketches and quick renderings) of their ideas.

They were asked to make three to five non-identical ideas. In the literature (Tovey and Owen 2000), it was noted that excessive use of CAD hampered the lateral exploration in the early phase. Lateral exploration in the early phase of design is an important and essential requirement for creative idea generation. Hence, one of the guidelines coming from the literature was to ensure and enforce multiple ideas while designing (Tovey and Owen 2000, Bono 1970). Therefore, it was made mandatory to generate more ideas to ensure lateral thinking.

They were also told to keep a track of time they spent on each sketch, model and render by just entering the start and end time in the chart given to them.

4.2.3 Participants

10 students in the first year of their Master of Design in industrial design course participated in the study. All of them had a bachelor degree either in engineering or in architecture.

The experiment was conducted during the module of course titled as “digital modeling for product design”. Convenience sampling (O'Leary, 2010) was used as a selection method for participants. All the participants were in the class and were taught CAD modeling software by the researcher. This made their knowledge of tool at par with each other and they all were trained in the same tool. All the participants were student of industrial design and were in the same semester.

4.2.4 Data collection

The doodles and sketches along with the 3D models and renders made by the participants were collected at the end of the exercise. The tables in which participants mentioned the time they spent in modeling and in sketching were also collected. Observations were made during the exercise, which was noted down.

A group discussion was conducted after the session. A group discussion was preferred over interview as the CAD exercise was held as a group in the class. Researcher believed that it would be best to collect the participant’s feedback immediately after the CAD exercise. The group discussion allowed participants to respond to each other’s points and talk on the key issues raised. It helped them recall their experiences and respond. Group discussion helped researcher identify and deduce the common experiences among participants.

4.2.5 Analysis

The models and sketches were documented. For analysis purpose, the times taken for making the doodles and for making models were also compared. Their sketches were compared with the models to see if the intended forms could be achieved or not and how these differ. Though, it is important to reiterate that the study does not intent to compare the CAD with sketching but is trying to understand the role of CAD in a scenario where all the tools coexist.

Participants presented their ideas and models to the group at the end of the exercise and discussed their experiences. These presentations helped understand their approaches and thought process. Group members raised questions and shared their views. Notes taken during their presentation and interaction were used for analysis. Findings were derived by analysing the observations made during the exercise, notes of the presentations and discussion and their sketches and CAD models.

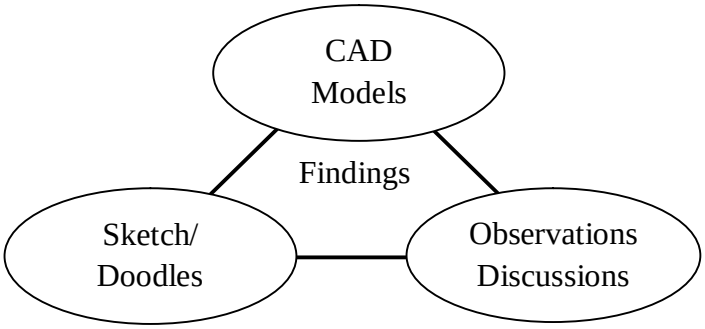
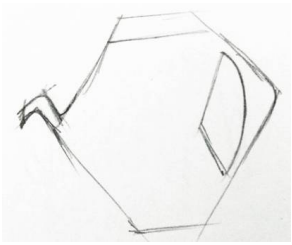
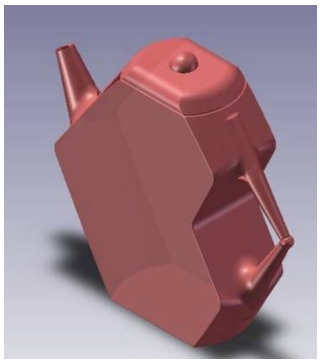


Fig 4.1: Content used for analysis

An example of the comparison and researcher's reflection for one participant, are shown in table 4.1. The detailed outputs by all the participants and their comparisons are shown in Annexure I.

Table 4.1: The comparitive analysis of a participant's output

Intent	Output	Reflection
		- Difficulty in drawing an organic form in perspective is visible - The idea remained unfinished. Organic forms require more time and efforts to explore.
 	 	- Handle in the sketch was more usable as compared to the one in the model. - Participant mentioned that he got carried away with the command while making the handle - The bottom sketch shows the difficulty in drawing the perspective view. - Participant proclaimed his lack of sketching skills and mentioned that CAD renders make him feel more confident about presenting his ideas.

Intent	Output	Reflection
		- Attention to usability missing. Output and intent are on the same lines, so it cannot be claimed that the lack of modeling skills clouded rational thinking.
		- A cork texture applied to body. Participant mentioned getting excited by the choices of colours and textures available and chose the one he liked without any rationale behind. - No consideration for usability given to the design of handle and spout. Still it cannot be claimed that the thinking was clouded by the use of CAD tools as the sketch itself has no usability considerations. What may still be noted here is that the finished rendering that is generated by CAD gives participant a confidence to present such ideas.

4.3 Pilot study design task results

This section reports the ideas created by all the participants. 9 out of 10 participants started with making rough sketches and doodles. Few of them made a chunk of doodles before selecting few to start modeling. One participant started directly with modeling.

3 participants produced well defined realistic ideas through CAD outputs whereas all the remaining participants stayed with the conceptual and not well defined models. The time was acknowledged as a constraining factor by the participants. One participant made 5 models, 5 participants created 4 models each, one produced 3 models and 3 participants could create only 2 models in the time available. The images of their models are shown in the following pages.

CAD output of Participant-1

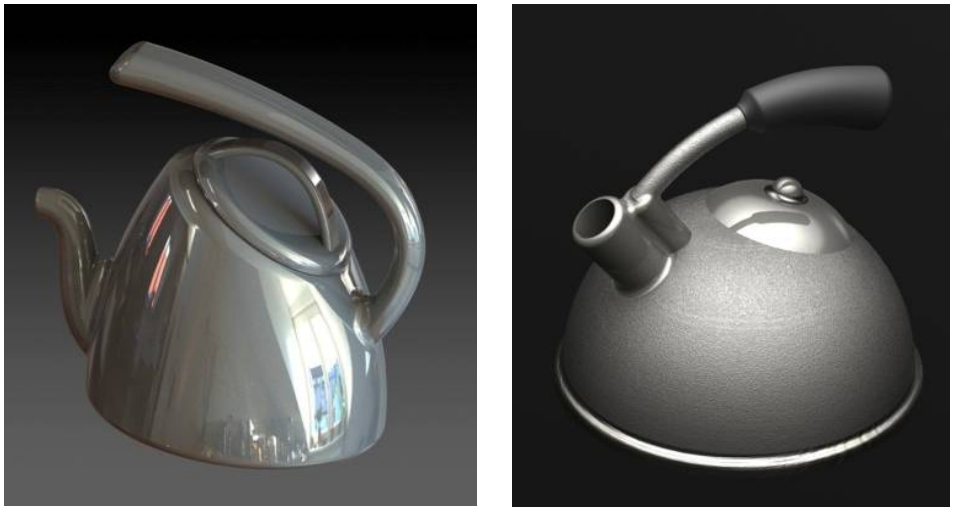


Fig 4.2: Two CAD models created by participant-1

Participant-1 created many sketches and spent a considerable time in exploring the forms. Though, he created CAD models of only 2 ideas shown in figure 4.2, he

ensured that the ideas are well defined and rendered well with realistic finishes. He stated falling short of time to explore other ideas.

CAD output of Participant-2

Fig 4.3: Four CAD models created by participant-2

Participant-2 started exploring his ideas directly in CAD. He was the only participant among all who did not create a single sketch. During the discussion he mentioned that the ideas were in his mind and he could clearly visualize them. He prefered to directly replicate the ideas on CAD as he was not confident sketching them. CAD provided a platform where he could comfortably interact with his ideas and did not feel that it could interfere with his thought process. His CAD models are represented in figure 4.3.

The first two options that he explored (as shown in figure 4.3) remained incomplete and he decided to move on to explore other two ideas instead of finishing the first two options. He stayed with the basic forms but explored the colours and textures and produced well defined ideas.

It could not be established whether idea was thought of before he started modeling or he actually explored and formulated idea while modeling or was it partially planned and partially explored on CAD? When asked, participant was unable to articulate his thought process and gave a vague answer.

CAD output of Participant-3

Fig 4.4: Four CAD models created by participant-3

Participant-3 showed no consideration for usability of the ideas. He felt overwhelmed while exploring colours and textures and got carried away while assigning textures to the ideas. He specifically faced problem creating organic form in the first idea (shown in fig 4.4). He left the idea and moved to creating other ideas. It could not be established whether he left the idea because of the frustration and unability to create a challenging form or because of being unable to articulate what the final product should be.

CAD output of Participant-4

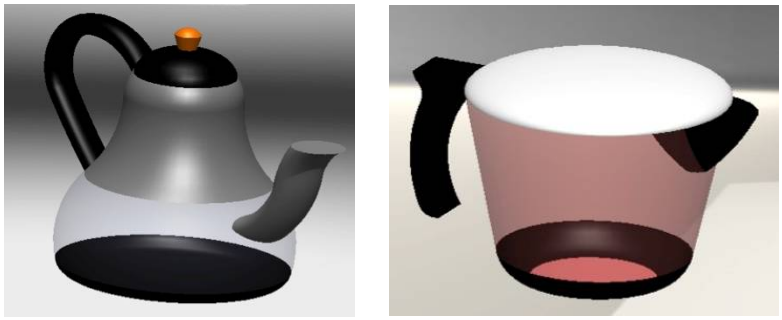


Fig 4.5: Two CAD models created by participant-4

Participant-4 created two and a half ideas in CAD. The third model could not be completed due to time constraint. The participant explored transparency option to enhance the visual appeal of the ideas and illustrate hollowness. Student faced limitations in achieving the intended form and refined the ideas while making the models. The spout details in first idea shown in fig 4.5 were compromised for the ease of modeling. However, the handle details in the 2nd idea (in fig 4.5) were improved through iteration to enhance the usability. The design features that were found easy to make were improved through iteration but the difficult to make features created frustration and were compromised.

CAD output of Participant-5

Participant-5 explored two ideas, one inspired from geometric forms and other from organic forms. The ideas produced were not well-defined and most time was spent on exploring modeling strategy. The organic form (shown in fig 4.6) was very challenging to create and participant spent most of the time in trying to create this form. Upon asking about the usability aspect of the idea, participant mentioned that he was more concerned about being able to create a certain form than working on the usability of the idea.

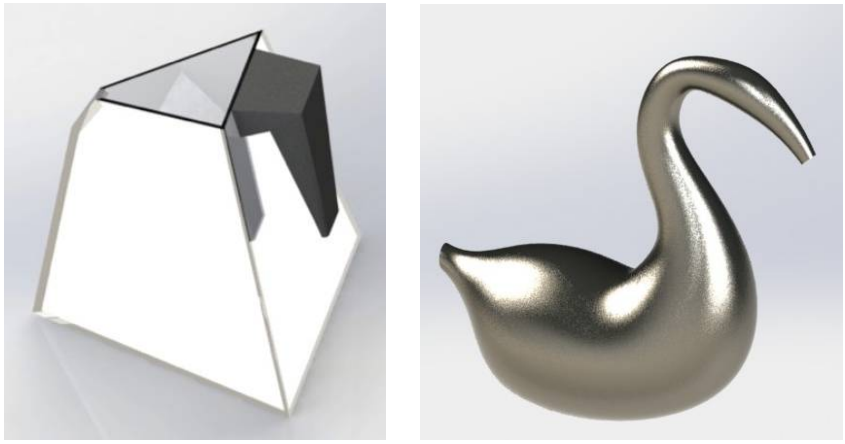


Fig 4.6: Two CAD models created by participant-5

CAD output of Participant-6

Participant-6 created 5 different ideas. She stayed with simple forms but created divergent ideas. She faced problems in creating the spout and could not achieve the intended form. The limitation of tool proficiency was visible in her outputs. Her CAD representations are represented in figure 4.7.

Fig 4.7: Five CAD models created by participant-6

CAD output of Participant-7

Participant-7 found CAD modeling helpful in visualizing 3-dimensional forms that were difficult to express through sketches. He specifically stated that communicating through a CAD model is more effective and easier.

Participant-7 preferred to explore forms through surface modeling and missing volume is visible in the models (shown in fig. 4.8). The ideas are vague and usability is questionable. The participant spent most of his time in achieving unique and novel forms through different command options like twist and sweep with curves.

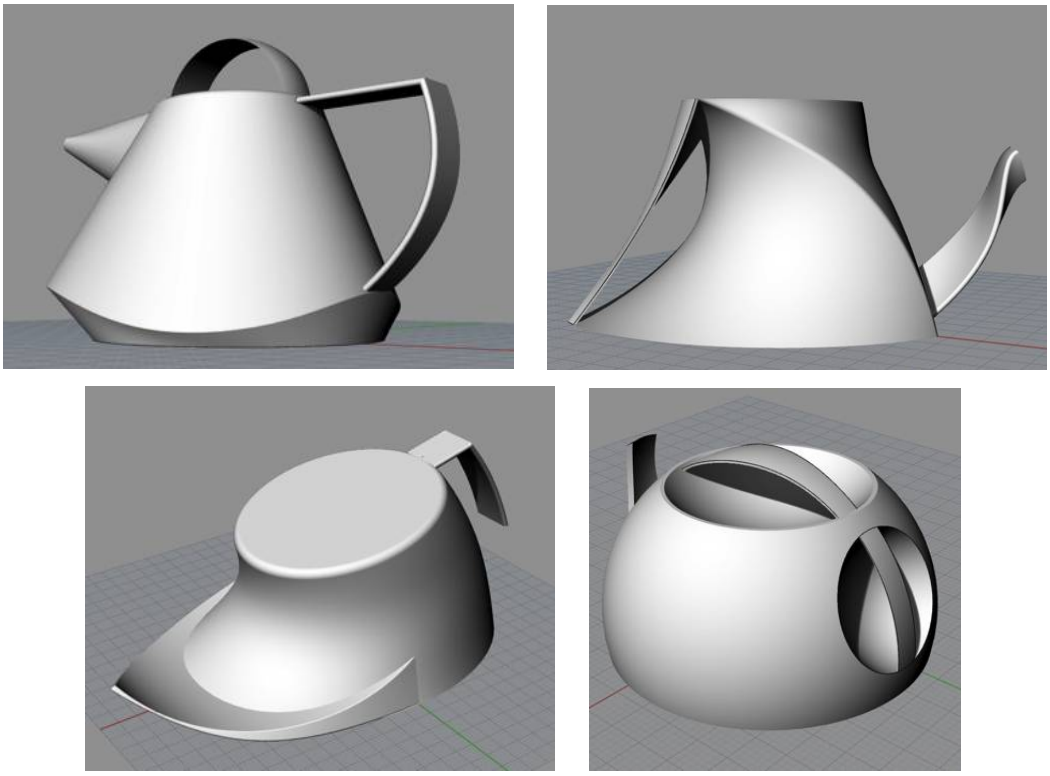


Fig 4.8: Four CAD models created by participant-7

CAD output of Participant-8

Participant-8 explored the ideas based on different expressions. He indicated that using CAD modeling helps him overcome the limitations of his sketching and physical modeling skills. He further stated, *'once the model is ready I can choose my views and create any number of images. I do not have to worry about proportions and angle of perspective'*. His CAD output is shown in figure 4.9.

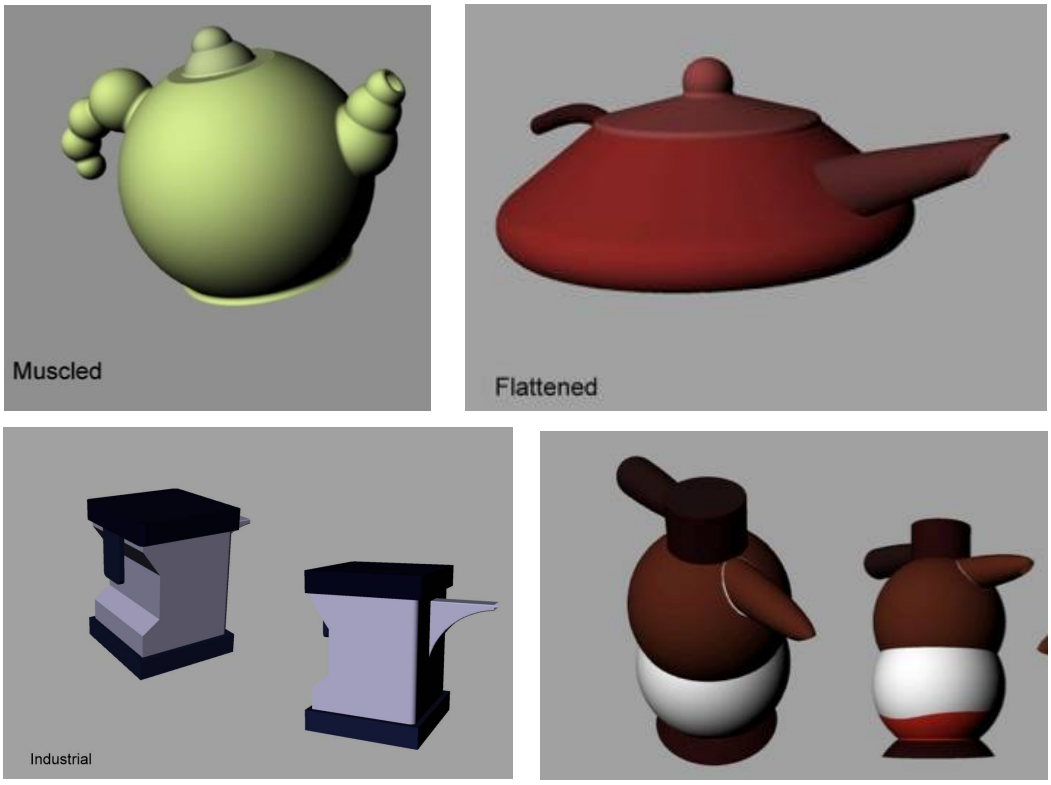


Fig 4.9: Four CAD models created by participant-8

CAD output of Participant-9

Participant-9 spoke about exploring the rough forms through CAD. He admired how making a 3D form in CAD aids spatial visualization and communication. Participant explored irregular and challenging forms. He spent considerable amount of time sketching curves that can be used for creating 3D forms and did not have enough time to finish his ideas. He maintained the roughness even in the 3D models to communicate initial ideas stage. His CAD outputs are presented in figure 4.10.

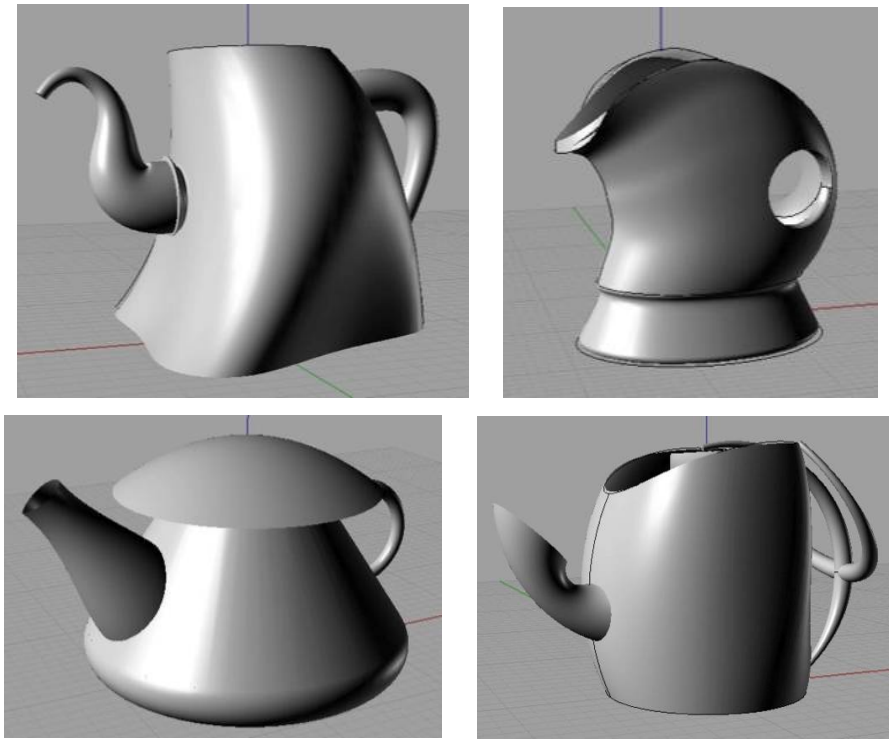


Fig 4.10: Four CAD models created by participant-9

CAD output of Participant-10

Participant-10 had difficulty expressing his ideas through the sketches. Even with 3D models he stayed with the basic forms and depended on the commands he was comfortable with. The limitation of modeling skills is visible in the outputs (shown in fig 4.11). He was very hesistant in trying new commands on his own and did not work towards improving his skills.

Fig 4.11: Four CAD models created by participant-10

4.4 Findings and discussion

- The participants used CAD software in the initial exploratory phase of design even when they themselves were not sure about the idea they wanted to explore and develop. The use of CAD for exploring rough forms was evident in the study and an example of same can be seen in fig 4.12. Students feel CAD helps them articulate their ideas and aid spatial visualization.

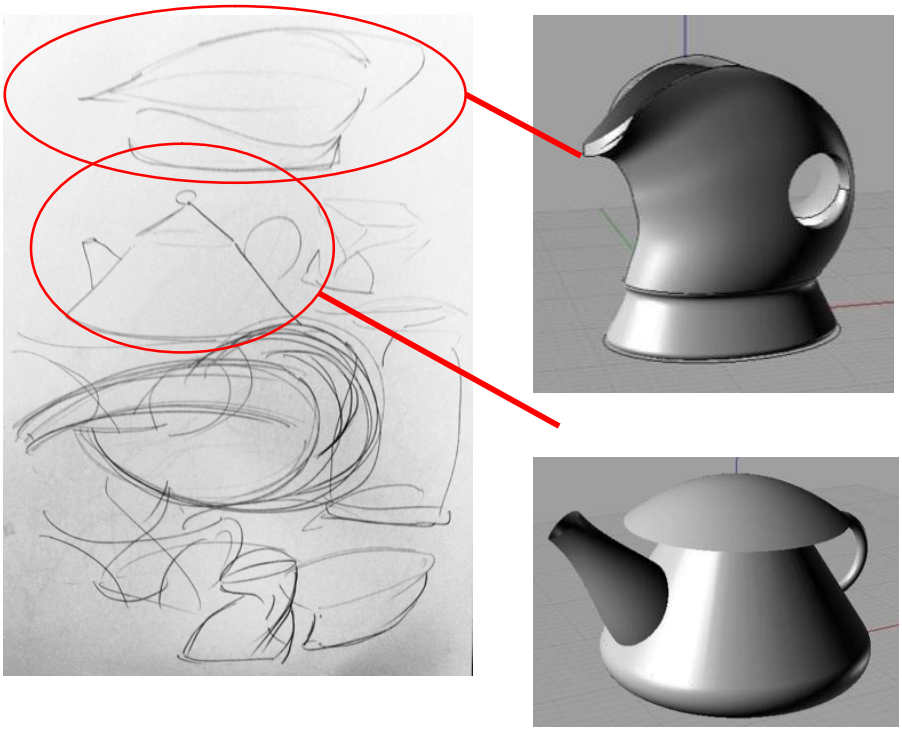


Fig 4.12: Rough sketches and rough forms explored by participant-9

- The use of CAD for exploring initial ideas was noticed not only in the study but also in other courses. Prof. A. G. Rao who conducts the course of "studies in form" mentioned in a discussion how the students have changed over the years. Many students today prefer to present their ideas in the digital format instead of sketches. He expressed his concern about students presenting mediocre ideas through impressive representations. When students were asked to reflect on this point they mentioned that CAD renders, even if rough, gives them confidence. It brings students weak in sketching at par with other students in class and all the representations are judged for the quality of their ideas and not sketching skills. This made students weak in sketching rely heavily on CAD for their presentations.

- 9 out of 10 students preferred to record their ideas in form of doodles before starting with 3D modeling. They mentioned that doodling the ideas give them a starting point. CAD is not a quick tool in recording the thought and

needs investment of time to explore even rough ideas. Using the sketch/doodle as the recording tool also provided participants with an opportunity for further refinement in the idea while modeling.

- One student started his ideation directly on computer. He stayed with the simple and symmetric forms as shown in figure 4.3. Based on the output it cannot be established if his ideas were limited by his modeling skills or not. Participant acknowledged that he could visualize the ideas in his mind and directly replicated those in CAD. However, the difficulty in articulating and establishing the thought process while modeling was realised.

  It was realised that since the form that he created in CAD looked finished, he moved to the next idea. Though his ideas were diverse yet the iterative nature of the design exploration and refinement was found missing in his approach.

- Proficiency level had a direct impact on the ideas produced and presented. Literature shows that if the proficiency levels are not good, it can cloud the thinking of designer (Robertson and Radcliffe 2009). It was observed that the focus of some students shifted from designing to executing while working on the challenging forms as visible in figure 4.13.

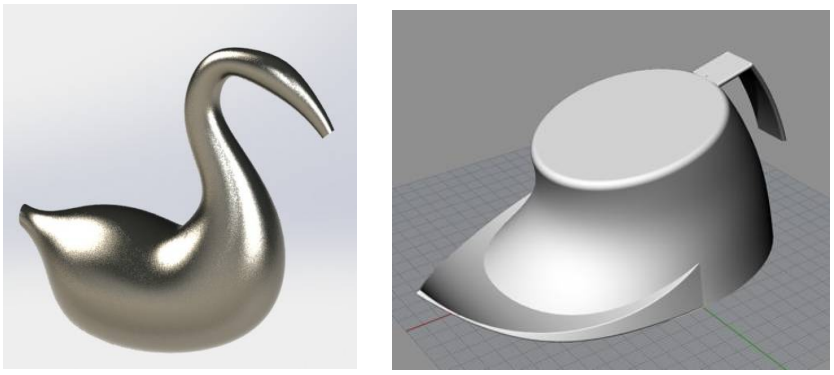


Fig 4.13: Challenging forms made by participant-5 and participant-7

- Most of the participants stayed with the basic shapes that were easy to produce. When the intended form could not be achieved participants compromised on the form.

Fig 4.14: Participant-6 compromised on the spout form

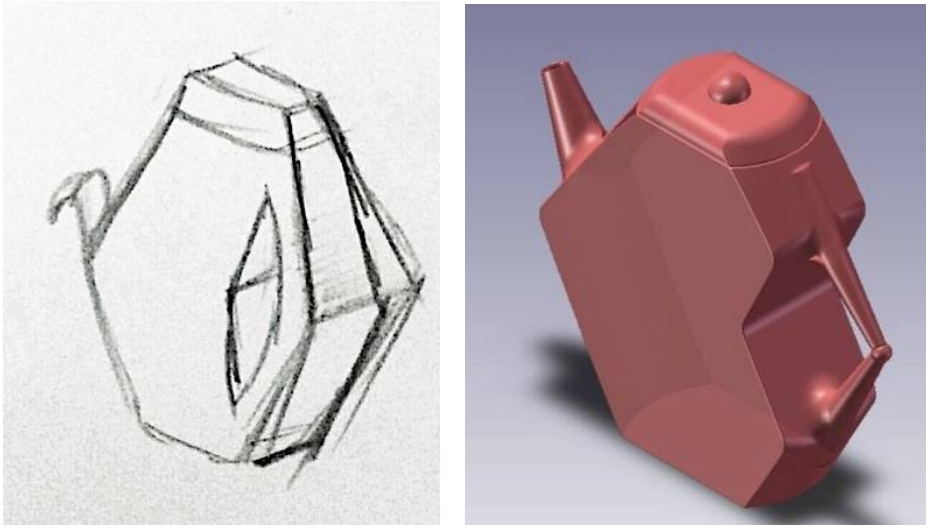


Fig 4.15: Intent and output from participants-3

As can be seen in the figure 4.14 and 4.15, the models created by students are different from the intended ideas. In the example shown in figure 4.15, participant mentioned that he was unsure of the handle and it was not merging with the form so he created a different handle. Similarly, in the example shown in figure 4.14 the participant faced difficulty in creating the spout and left the design with what she could create. She stated, *"...this was just not merging the way I wanted, so I left it"*. This effect was noted with 5 students in the exercises.

- Participants acknowledged that CAD representations aid their spatial visualization. Three participants mentioned that they had problem visualizing

a 3D form and making a CAD model helped them defined form better and brought in clarity. In the example shown in figure-4.16 participant-7 specifically mentioned that he was finding it difficult to articulate and sketch the idea in whole and finally making a 3D model helped visualizing the form clearly.

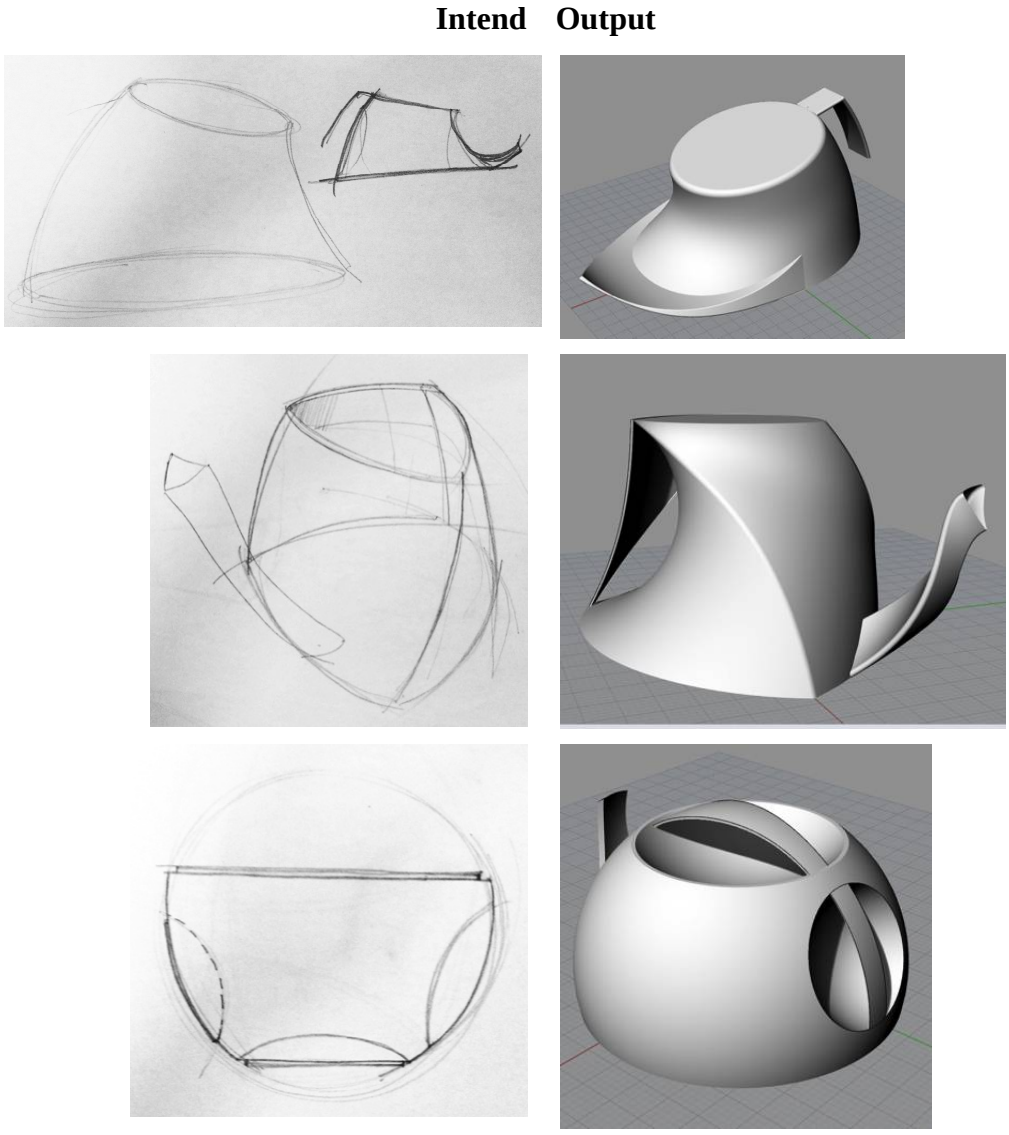


Fig 4.16: Intent and output by a participant-7

- An interesting observation was made related to the shift in thinking process. *Loft* command was one of the basic commands taught to participants. The doodles shown in figure 4.17 depict how participant planned to produce a form using two different cross-sections and the center guideline. However,

he did not explore the idea further yet this shows how 3D modeling can affect the way designers may explore the form consciously or unconsciously.

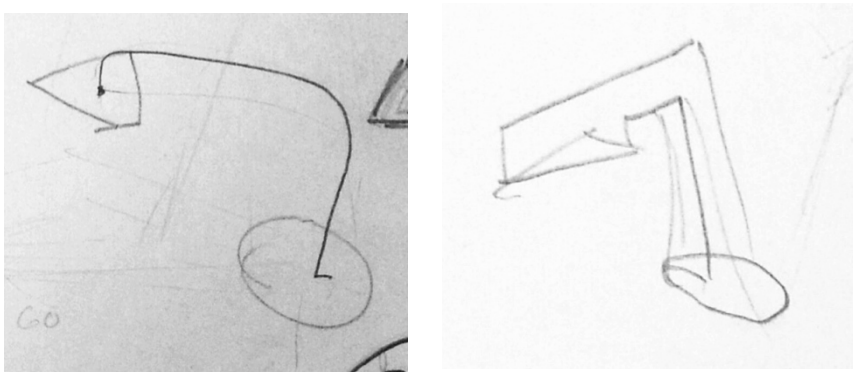


Fig 4.17: Doodles by participant-5 exploring form imagining CAD commands

- In almost all the case it is visible that the ideas changed while being translated from sketch to 3D model. This proves that the exploratory dialogue between the design and designer continues during CAD modeling process and new-age designers do not have any hesitations in exploring their designs on computer screens.

- A major limitation faced during this study was the unavailability of video/audio recorded data that could have helped make this study richer. The researcher heavily depended on the extensive notes made for the analysis. Conducting a group session did not allow understand and analyse each participant's approach in-depth. Giving due consideration to these limitations would help define the next study better.

Chapter summary

This chapter reports the method and findings from the first pilot study. The study was conducted with the 10 post graduate students of industrial design. A timebound design task was carried out that involved 3D CAD modeling. The aim of the study

was to understand how CAD is used in the early phase of design exploration and what are the enablers and barriers it proposes.

The data collection method included notes of observations made during the task, the sketches and models made by participants, notes made during their presentations to the group and from group discussions. The analysis was done by comparing their outputs with their intentions and understanding their though process from their presentations. Notes from group discussion and observations aided the understanding.

This was the 1st pilot study. The limitations faced during this study were inability to study the individual approach and process of the participants. This helped formulate the next study for a more in-depth understanding.

Chapter 5
Pilot study with design professionals

This pilot study was conducted with professional designers with 3-5 years of experience with one person at a time. This allowed qualitative study and analysis on the individual approaches of the participants. The chapter reports the objective, methodology, and findings from this study.

5.1 Aim and objective

The aim of this study was to understand how the use of CAD affects the idea generation process in the early phase of product design. The objective of this study was to explore the answers for the following research questions:

RQ1. How does CAD position itself in the idea exploration stage of the design process?
RQ2. What advantages does CAD offer to the designer, if used in the early phase of design?
RQ3. What limitations does CAD impose on the designer's way of thinking?

5.2 Study framework

The study was based on qualitative observations and semi-structured interviews with participants. Three proficient CAD users and 2 competent users with experience of 3-5 years were chosen for this qualitative study. All of them use SolidWorks 3D

modeling software on a daily basis for their work and have developed a good understanding and command over the software.

The study was conducted in two phases. The first phase of the study was conducted with 3 Solidworks certified product design professionals. They were assigned a design task to be performed in 60 minutes. Later it was realized that 60 min was too little to probe if use of CAD hampers lateral thinking. Therefore, for the next phase, the time was revised to 3 hours. Also, the design brief was simplified for the second phase. During both the phases, participants were required to generate ideas for the problem given and were allowed to use sketching and modeling as per their convenience.

The design task, data collection, their design output, and analysis method are elaborated in the subsequent sections.

5.2.1 Design task and brief

A) Design task for 1st phase

After a lot of brainstorming the design task was defined for a familiar object with unfamiliar users. It was important to define the user to get comparable results and channelize participant's thinking in a certain direction. The reason for choosing a familiar object was to ensure that the participants are aware of the functionality and purpose of the product. To make them think differently an unfamiliar user was defined. The task given to them was as follows:

Design Brief:

Design a bread toaster to be used by a visually challenged person.

- It should be safe and easy to use
- It should be able to toast a minimum 2 pieces of bread at a time.

The size and model of the bread are provided. You need not work on the internal detailing of the circuit, heating element or other technical components at this stage. The ideas/concepts have to depict the considerations for the user.

Generate as many different concepts as you can in 60 minutes.

Your concept should consider:

- Interaction of user with the product for
- Putting and taking out bread
- Operating convenience
- Overall form due to the above consideration

B) Design task for 2nd phase

The design brief for the 1st phase had more usability related issues. The participant's focused completely on solving the problem. Formal explorations were absent in their outputs. Also, due to time limitations, all the participants only created a single solution and lateral exploration was missing. To overcome these limitations the design brief was revised for a simpler product that would require form-based explorations and have basic functional requirements. This was to ensure that participants do not spend too much time on problem-solving and spend maximum time in exploring the ideas. The task does not require any assembly or multiple

components to be made but it will require the participants to have an idea of size and proportions.

After some brainstorming on products for formal explorations, "spoon" was chosen as an object for a redesigning task. The reasons for choosing a spoon as the product were:

- It is a simple and known product
- It allows unlimited formal explorations and functionality is easy
- It is a tricky form and will require a certain level of skills to model
- Can be geometric or organic in form
- The same base model can be tweaked to create multiple options

Design Brief:

A 5-star restaurant is launched and they wish to have a unique cutlery collection that is exclusively used by them. You need to design an elegant, classy and unique dinner spoon to be used by the restaurant. At this stage, you are not required to design other cutlery.

You are required to present as many ideas as possible to the client so that they can choose the design based on which the rest of the cutlery will be developed and produced.

Spoon will be in stainless steel and can have other materials added to it for aesthetic purposes.

Three different spoons for understanding the sizes and proportions are provided.

The design brief was given to participants, on a printed sheet with a declaration stating that the data collected will be used only for academic research purposes. No information or ideas generated by participants will be used for any commercial purpose. All the personal information of the participants will be kept anonymous.

5.2.2 Duration and expected outcome

A) Duration for 1st phase

The time given for the toaster design task was 60 min from the time the participant is ready to begin. The time taken to explain the purpose and set up of the study as well as reading the design brief was not included in this time. Participants were free to take any breaks, if needed and pause the experiment. However, no participant opted for the break.

B) Duration for 2nd phase

In phase-1 it was realized that the time given to participants was too less. No lateral exploration could take place. Even though participants were asked to make as many ideas as possible they all could make only one idea each. Therefore the time in phase-2 was increased to 3 hours plus a 15min break in-between. Participants were required to create as many ideas as possible.

Initially, the plan was to do 2 exercises of 3 hours each with a lunch break and two small breaks. The idea behind this was to simulate one full working day for the designer. But it was realized that it will become strenuous for the participant and thus one session of 3 hours with one design exercise was decided for.

With participant-1 the video recording stopped in between during the exercise for 10 min as camera battery drained out. The camera was replaced as soon as it was

realized. For participant-2, the exercise was broken into 2 sessions of 90 min due to the availability of time and sessions took place on 2 consecutive days. He also mentioned that when a brief is received, he spends a day brainstorming the ideas before actually start generating CAD models. Breaking of the session over two days helped recreate a real-life scenario for him.

5.2.3 Participants

'Knowing who might hold the answer to your question and how you will open up opportunities to gather information from them is fundamental to collecting credible data' (O'Leary, 2010).

It was realized that the participants should have good knowledge of CAD to avoid misleading findings influenced by their lack of CAD skills. Therefore, proficient CAD users who use CAD regularly for their work and through all the phases of the design were invited and recruited for the study. They were invited on different dates to avoid any overlap. Since they did not know each other there was no apprehension about them disclosing the design exercise to each other. They all were in the range of 3-5 years of experience. This sampling method is known as purposive sampling or handpicked sampling (O'Leary, 2010).

In phase-1 three proficient users were invited to participate. All three of them were SolidWorks certified professionals. Since they were certified professionals it ensured that they are all proficient user of the software and their proficiency would not affect their design ideas.Their work experience ranged from 3-5 years.

In phase-2 of the study, two product designers who are competent users of SolidWorks software were invited. The software tool was kept the same for all the participants. Both the participants had 4-5 years of experience of working as product designers and were using SolidWorks software for more than 5 years.

5.2.4 Data collection

Appointment from the participants was sought in advance for an experiment. They were introduced to the design task on the scheduled day. Participants were provided with papers, pencils, an eraser, a ruler and a desktop computer with SolidWorks software (SolidWorks version 2013-14) on it. They were allowed to sketch and model in the order of their convenience.

The whole exercise was video recorded with a digital camera placed on a tripod. The camera angle was set to record the activities on the screen without interfering with the participant's movement. Free desktop recording software Webinaria was also installed to capture the activities on the desktop. This software did not work properly in two cases and camera recording was used for the analysis purpose.

After the design task, interviews were conducted with the participants. The interview was semi-structured and was voice recorded in an informal setup with coffee and snacks. It was kept semi-structured to have more flexibility in asking questions and an informal setup could ensure more open and free responses.

In phase-2, a questionnaire was shared with the participants before the design task, over email. This questionnaire was used as a qualifier for the participant. Its purpose was to gather enough knowledge about the respondent to discover whether s/he is suitable to be a participant for the study. They were requested to email back the filled questionnaire.

5.2.5 Analysis method

Researching within design activity involves an attempt to interpret and describe a designer’s thinking, acts, and behavior while using CAD. Qualitative research allows the researcher to be descriptive, reflective and interpretive while attempting

to describe and understand the actual instances of human action and participant experiences (Fischer (2006) as cited by Musta'amal, 2010). Therefore, the approach considered for this study as well as for the research was qualitative in nature.

The data used for the analysis is the visual data recorded during the design exercise and verbal data from the interviews. Protocol analysis as a method was considered earlier but it was realized that thinking about ideas and making computer models are tough and asking the designer to think-aloud while doing this tough task will disturb them and their thinking process (Won, 2001).

In this study 'candid non-participant structured observation' method was employed. For Candid observation, the participants were made aware of the purpose of the study and data collection method in advance and their consents were sought (O'Leary, 2010). This was also an ethical requirement. The researcher was not part of the experiment and was unobtrusive during the experiment. The structured observation involves scheduled sessions in a formal setting (Guthrie, 2010).

The complete design task was video recorded. Video recording facilitated microanalysis of the complete experiment. The video was reviewed frame-by-frame and transcribed. The transcribed data made the analysis process more effective and increased the probability of capturing significant moments. In phase-2, both the participants used the first 40-45 minutes to think about ideas, the time frame considered for analysis was from the time participant starts modeling until 180 minutes.

The various study parameters were identified through the literature as shown in figure 5.1.

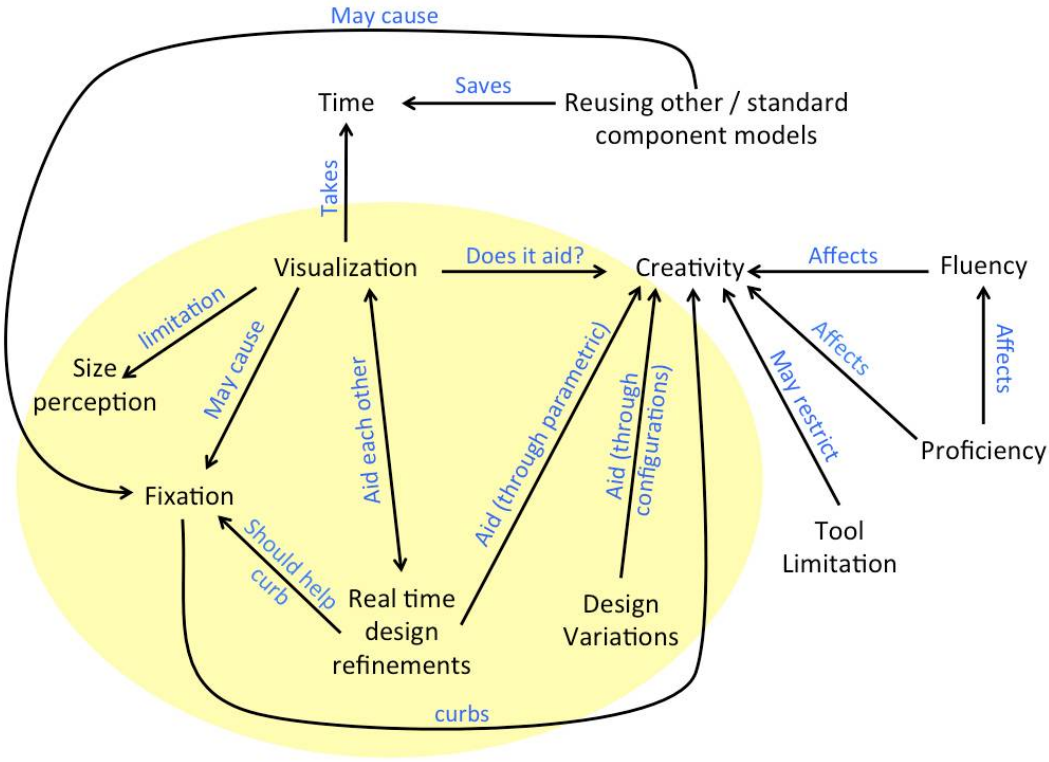


Fig 5.1: Study parameters

The tool used is SolidWorks and the experiment was conducted with proficient users. All participants were given the same time. This helped eliminate tool limitations, proficiency, fluency and time as the variables. Creativity in the study is a dependent variable. Thus, the purpose of this study is to identify the advantages CAD offers when used during the idea generation stage of product design. Identify and analyze the limitations that CAD may impose on the process of exploration.

The occurrences of study parameters- fixation, circumscribed thinking, effective visualization, interaction in 3D space and design changes/variations were mapped onto the transcription. Annexure-II illustrates the transcribes and mapping of study parameters for all the particpants.

Circumscribed thinking is caused when tool or proficiency limitations cause the design decisions to change from what is intended to what can be made (Robertson and Radcliffe, 2009).

Visualization is one of the most important properties of CAD. All the users interviewed so far acknowledge this as an important reason for them using CAD in the idea generation phase. It allows them to visualize their ideas in 3 dimensions. Researchers like Robertson and Radcliffe (2009), Hanna and Barber (2001), Won (2001) have also acknowledged visualization as a very strong advantage that CAD offers.

Fixation occurs when the designer is reluctant to make changes in design (Robertson and Radcliffe, 2009). This can occur because the designer develops a reluctance to make changes either because a lot of detailing has gone into making a model or making the change will cause lots of error to resolve or it might require a lot of work. It can also occur due to a preconceived image of the product being developed. The illusion of completeness caused by realistic visualization can also hamper the further exploration.

On the contrary, a 3D visualization may trigger more ideas. Designers after making a base model can use that to create multiple options. Many design refinements and intermediate design decisions (when the model is being made) are taken visually while creating an initial idea, as nothing is pre-defined. This is defined as Design changes due to visualization (DC) or visual triggers.

In phase-2, the time spent on designing, modeling and exploring how to design was also mapped. Time spent on the design was coded as ‘D’. It signifies the time when design decisions were being taken while making the model. Modeling coded as ‘M’, was a continuous process from 45 min to the end of the exercise. Code ‘EM’ represents exploring model making. It signifies the time the user spent trying to

figure out how to model a particular form/feature. More time spent on exploring means, more difficult the form/feature was to make. If certain form/feature takes too long to make or is very difficult to create, the designer might end up changing the same or simplify it. Robertson and Radcliffe (2009) mentioned that at times time pressure forces designers to generate intended designs in the easiest possible way. CAD tools may never match the imagination of designers and they might, in turn, limit their designs to what is easy to make (Robertson and Radcliffe, 2009).

Looking at the computer screen does not give clear ideas about sizes unless kept against a reference. Many a times it is difficult to understand the size of a grip or handle or the overall form. This is termed as a problem of size perception.

The complete transcribed data with the mapping of parameter occurrences for all the participants is attached as Annexure-II. In the tables shown in the annexure-II, the filled block shows the occurrence of the effect.

After the design task, candidates were requested to reflect on their experience and explain their concepts. A semi-structured interview was conducted that covered questions related to their design approach, how CAD finds its place in the process, advantages and limitations of CAD. The interview guide is presented in Annexure-III. The participant's responses were voice recorded and transcribed for the analysis. Excerpts from the interview responses are given in Annexure-IV.

5.3 Pilot study design task results

This section documents the results of the design exercise created by the participants. In phase-1, all three participants came up with completely different ideas and showed very different approaches. Though they were asked to make as many ideas as they can, all of them could make only one idea in the given time of one hour. In phase-2, both the participants explored many ideas in doodles but faced difficulty in

creating these in CAD. None of them could achieve the desired results. All the outputs are explained in the following pages.

5.3.1 Design exploration by participant-1:

Design task: Toaster for visually impaired
Duration: 60 min

Participant-1 did not deviate much from the common bread toaster design of two parallel compartments. He kept the heating compartments parallel but introduced a step to help visually impaired user to distinguish (figure 5.2). He also introduced slight projection on the three sides of the bread slot to act as a guide and stop bread from slipping back (figure 5.3).

Fig 5.2: Parallel slot toaster with step designed by participant-1

Fig 5.3: Projections around bread slot to stop bread from slipping back

On/off button is placed on the front surface and a thumb depression is provided on both the sides for orientation and grip, as can be seen in figure 5.2.

The symbols II and I are provided for two compartments. A power symbol is provided near the power cord. All the symbols including on/off are raised from the surface to be identified by touching them (figure 5.4).

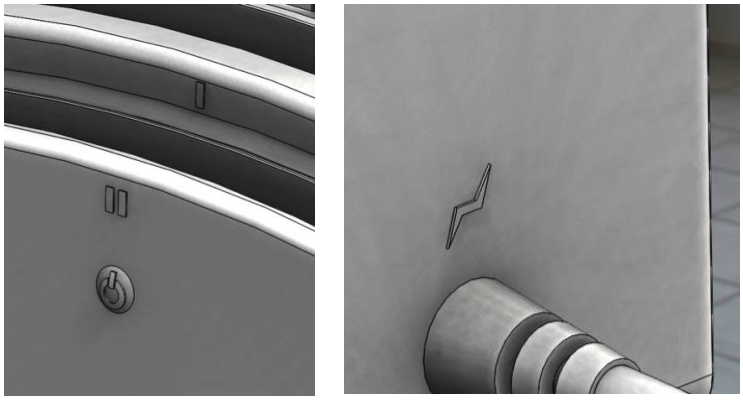


Fig 5.4: Raised symbols for identification by touch

A projected thin section handle is provided on the backside of the toaster for carrying and locating (positioning) purpose as can be seen in figure 5.2 and figure 5.5.

Fig 5.5: Handle for carrying and locating purpose

For the purpose of visualization the model was kept in the kitchen background and few colours and appearances were tried (figure 5.6).

Fig 5.6: Toaster in the kitchen environment by participant-1

5.3.2 Design exploration by participant-2

Design task: Toaster for visually impaired
Duration: 60 min

The participant stayed with two parallel heating compartment feature of commonly available bread toaster but introduced a separate lid for taking out hot toasts. He

made lid and body as separate parts and brought them together in assembly file. The open and closed toaster is shown in figure 5.7.

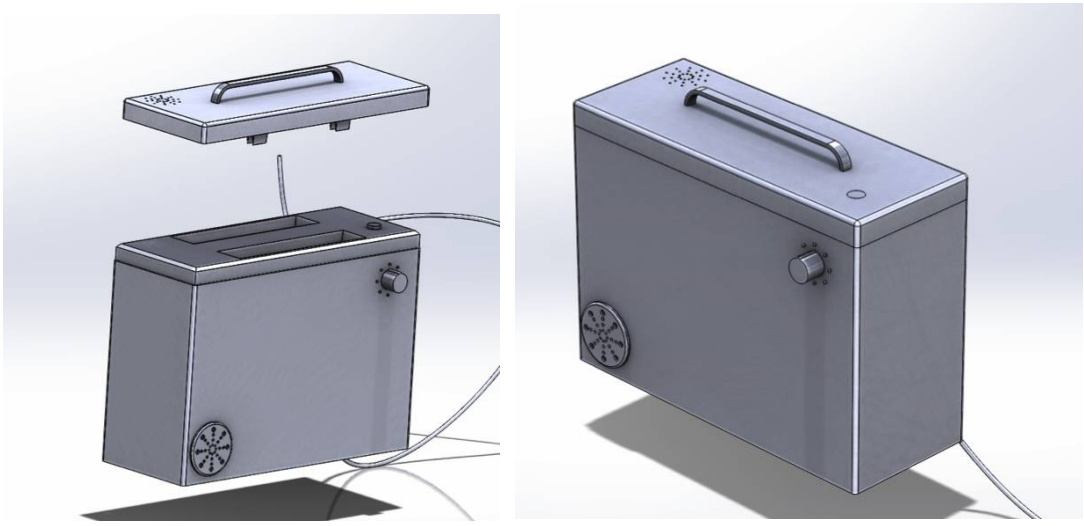


Fig 5.7: Toaster with lid in open and close position by participant-2

Bread slots have been given generous chamfer to guide the bread into the slot (figure 5.8). The on button is placed on the top surface and gets activated when the lid is placed on top (figure 5.9). Timer knob has projected graduations and extended pointer that can be detected by touch (figure 5.9). A speaker to give auditory feedback is also provided at the bottom corner as can be seen in figure 5.7.

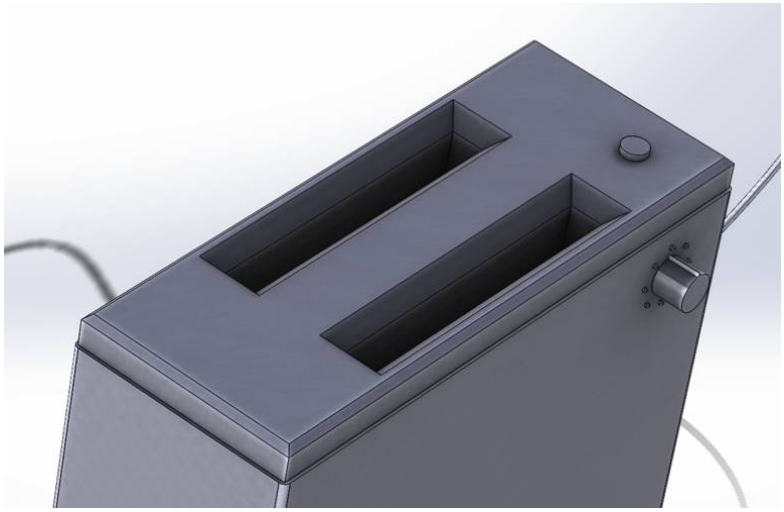


Fig 5.8: Chamfer near bread slot for ease of ingress egress

Fig 5.9: On/off button on top and raised pointer and graduations at knob

The lid has been provided with a handle to facilitate lifting and steam escape holes (figure 5.10). Steam escape holes will also provide olfactory feedback to the user. The underside of lid has four clips to hold the toasts lightly and pull them out when ready (figure 5.11).

Fig 5.10: Steam escape holes on lid for olfactory feedback

Fig 5.11: Clips on lid to hold bread

5.3.3 Design exploration by participant-3

Design task: Toaster for visually impaired
Duration: 60 min

Participant-3 adopted a different model of heating the bread. He came up with a concept in which bread lay flat on a platform and is heated by the heating elements placed on top and below the platform. The bread slides into the heating chamber from the top with the help of a slide provided near the opening. Once the bread is done, the hinged platform rotates and bread slide out from the bottom opening. A small on/off button is provided at the bottom corner and certain controls that participant intent to make could not be completed due to time constraints and are depicted by a cylindrical projection on the top corner. The approach adopted by the participant was more time consuming and hence in spite of having good proficiency he fell short of time.

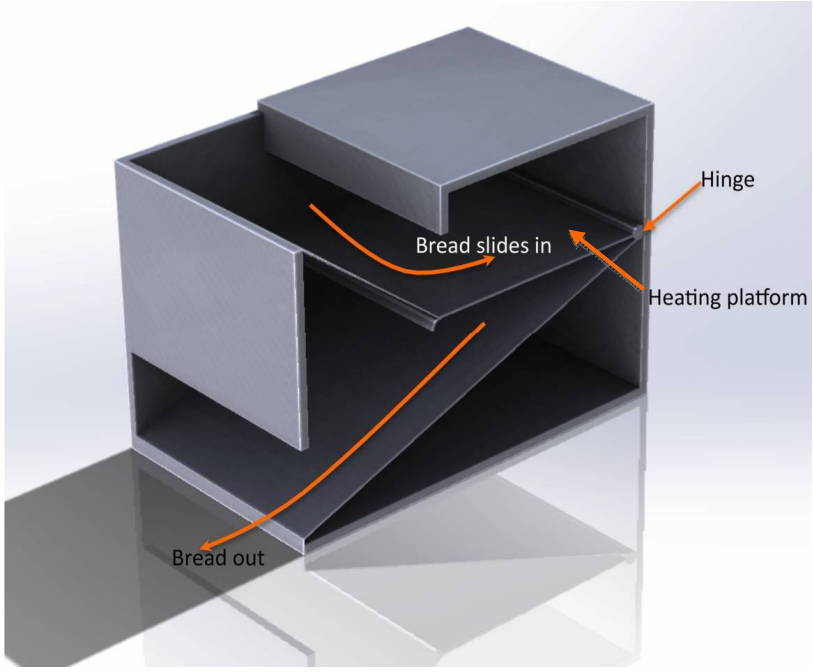


Fig 5.12: Cross-section of the idea by participant-3

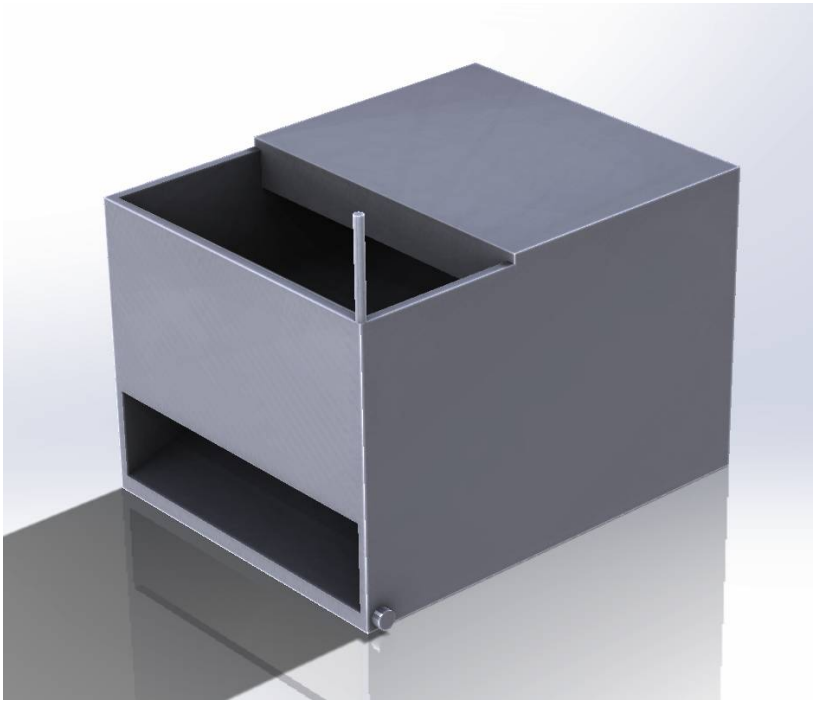


Fig 5.13: Basic structure of the idea by participant-3

5.3.4 Design exploration by participant-4

Design task: Spoon design
Duration: 180 min

The participant explored various ideas on paper through small doodles and sketches for the first 45 min. Most of the sketches depicted either the top or the side profile. He used keywords as elegant, classy and unique for exploration. The sketches are shown in figure 5.14.

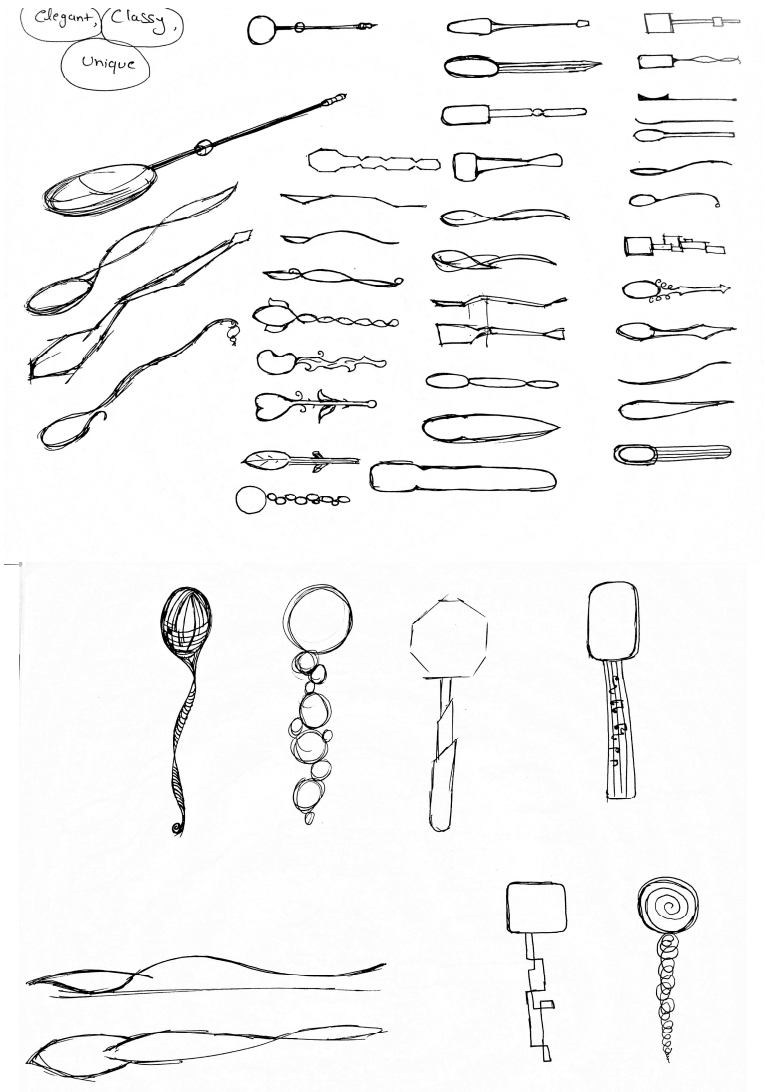


Fig 5.14: Various doodles with keywords by participant-4

After 45 min, the participant started modeling on computer. The images of the models created by him are shown in figure 5.15.

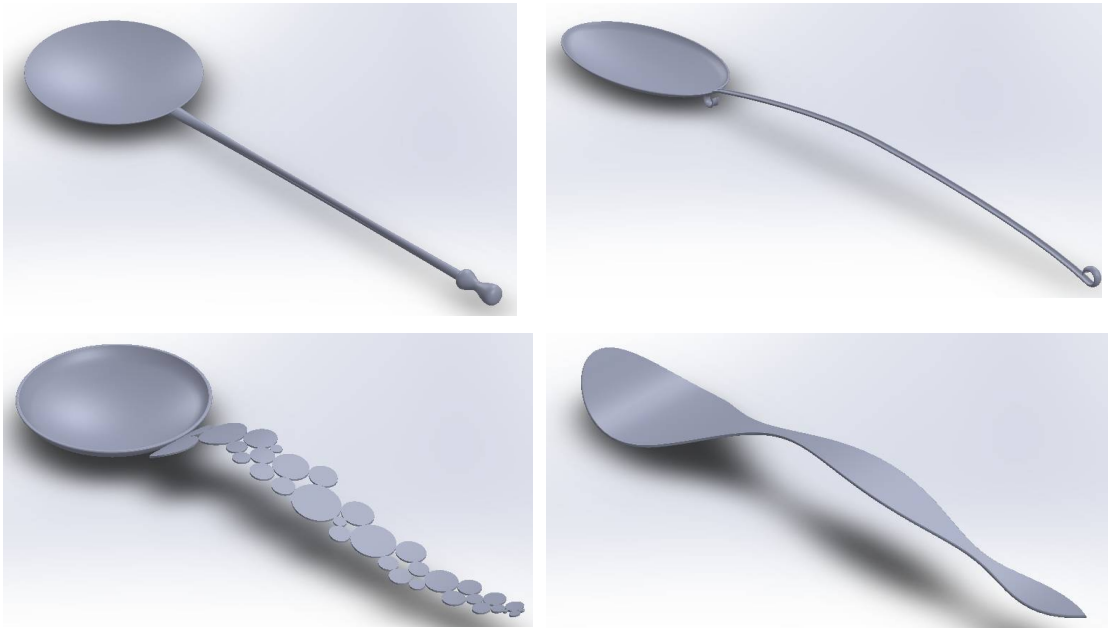


Fig 5.15: Images of CAD models made by participant-4

5.3.5 Design exploration by participant-5

Design task: Spoon design
Duration: 180 min

Participant-5 also spent the first 40 min in sketching and thinking about ideas. He sketched a set of top profiles, a set of side profiles and spoon end profiles and numbered them all (figure 5.16). His approach was to use permutation and combination to come up with multiple ideas.

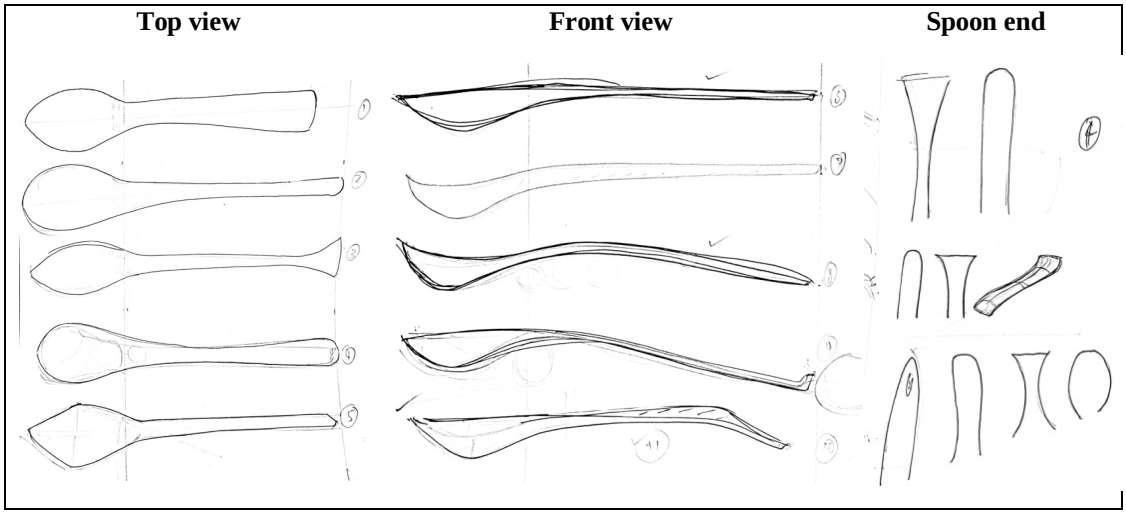


Fig 5.16: Top view, front view and spoon end profile doodles by partcipant-5

He struggled while modeling and the outputs of the modeling exercise are shown in figure 5.17. He had marked his skill levels at a competent user. He had been using the SolidWorks software for 7 years for the various design projects. However, making an organic form with smooth curves as required in the form of a spoon was found to be extremely challenging. He mentioned that none of the models meet his expectation and represent his design idea accurately.

Fig 5.17: Images of CAD models made by participant-5

5.4 Analysis summary

This section outlines occurances of all the study parameters noticed in video transcripts and interview transcripts.

About participants:

- All 5 participants were working as product designers and developers and had a work experience of 3-5 years. One of them was a freelance product consultant, 2 were working with design consultancy and 2 with industry.
- Participants 1, 2 and 3 were also SolidWorks certified professionals and were proficient users of the software. Participant-1 was using the software for the past 5 years and participants 2 and 3 for the last 4 years. Participants 4 and 5 were also the users of the same software. They ranked themselves as competent users. Participant-4 was using the SolidWorks software for the past 4 years and participant-5 for approximately 7-8 years.
- The other 3D modeling software that the participants have used are: Pro E, AutoCAD, Ansis, Catia, Solid Edge adn Rhino.

Design process and approach

During the design exercise, participant-1 had a top-down approach. It means he started by making a block and carved the idea from the block. Participant-3, 4 and 5 used a bottom-up approach i.e. they built each part of the model gradually. However, participant-2 combined both approaches. He created a block to make the main body and then created other parts to finally assemble them in assembly. CAD tools today, allow users to develop their own approaches and are flexible enough to facilitate the same. It is important for tools to provide enough flexibility so that the mind can be free for creative exploration. A tool should not impose a particular approach or method of working on designers and allow them to explore their modes

of working. The tools are evolving at a very rapid rate to make them suitable for all the stages of design.

Participants 1 and 2 did not explore the idea before beginning with modeling. Participant-1 made a sketch but it was of the commonly available toaster for reference purpose. Participant-2 mentioned that he had the image in his imagination and directly started exploring the idea in CAD. Both of them showed slight fixation with the image of the commonly available toaster. On the contrary, participant-3 spent first 20 minutes in planning and exploring idea and came up with a novel idea. Participant 4 and 5 too spent 40-45 minutes doodling their ideas before selecting ideas for CAD modeling.

During the interview, 3 participants mentioned that their starting point is always rough sketch on paper or on digital sketching medium which may further be used in the background for CAD modeling. Only one participant (participant-2) mentioned that for him it does not matter whether he starts on CAD or paper, it is the same for him. Participant-1 stated it depends on the brief and the starting point. It may start with a layout or existing model in case of a redesign project and from brainstorming for a new project. But all the participants mentioned that they use CAD during the idea generation stage when the ideas are still being explored and are not frozen.

Once participants started modeling their ideas it resulted in unidirectional exploration. All the participants in phase-1 showed convergent thinking. The changes and explorations took place in small parts around one basic idea. In phase-2, divergent thinking took place in quick sketches and then the participants moved to CAD. Participant-1 mentioned during the interview that when he is asked to make multiple concepts, he makes one model and uses different configurations to create options to save time. In SolidWorks, configurations allow the values of certain features to be changed in the same model as well as the addition of new features on the base model. This feature is excellent for formal refinements and vertical

exploration but not so much for lateral explorations as this will not lead to completely different ideas and concepts will be slight variations of each other.

One interesting observation was made when participant-3 made a rough model first without any consideration for fillets, formal refinements or separate parts and then tried making a proper model afterward. He could not finish the refined model due to time constraints. But it signifies how CAD is being used for making rough ideas in the initial design phase. During the interview while explaining the importance of rough CAD models, participant-4 stated, *"it (CAD model) is something in-between a 2-D sketched idea and a 3-D physical prototype. It is a 3-dimensional model that I cannot touch but still see it from all the angles*". Participant-5 also shared "*I have never been strong in sketching. To me sketching is like doodling. It (rough CAD model) helps to figure out basic ideas and proportions in the very early part of the project*". He further added that the rough models are created for making decent representations. In the initial phase lot of detailing and realistic renders are not required. Basic models that can help understand the different views and proportions and volumes are enough.

Fixation

Fixation takes place when the designer has a very strong preference for certain compositions or forms or features. This may occur due to strong precedence causing certain mental images of a product or as a result of personal preferences. The main reason is the unwillingness or inability to think beyond a certain image. Fixation can also take place if a designer spends too much time on an idea and gets attached to the idea, causing unwillingness to start afresh.

Participant-1 and participant-2 both showed fixation with the image of existing common bread toaster with two parallel vertical compartments. They both started by making a basic structure similar to commonly available two parallel slot toaster. It

served as the base model until the end around which they worked on to modify the same to adapt to the needs of the visually impaired user.

Participant-3 spent the first 15 minutes sketching and exploring the idea. He came up with a novel idea and in this case fixation took place after the rough model was made and he did not explore it further even though he had some time available.

Fixation was not noticed with participant-4. Participant-5 kept referring to the spoons provided while modeling and tried to replicate the bowl part. The design exercise was of a simple product in phase-2 and did not require much of detailing and assembly of various components. Fixation was not clearly evident in this exercise.

Circumscribed Thinking

Circumscribed thinking takes place when CAD tools impose certain limitations on the user. On the contrary, it may also occur when the user ends up introducing unnecessary details after achieving a higher level of proficiency (Robertson et al, 2007). The parameter is correlated with the proficiency of the user. In phase-1, the task given resulted more in functional exploration and could not probe the effect of circumscribed thinking fully. Hence, phase-2 design brief required more of formal exploration to provide a deeper understanding of this effect.

Participant-1 showed the evidence of circumscribed thinking while creating fillet around the thumb depression on the sidewall. He recreated the fillet with a lesser radius when he faced difficulty with the larger radius. Though, it can also be classified as a design decision take visually and not so much of circumscribed thinking. Towards the end, he created a small handle, which was unnecessary and unthought-of. It was introduced at the last moment without a careful thought.

Participant-2 did not show clear evidence of circumscribed thinking but he stayed with the most basic forms of cuboids and cylinder that are easy to model. When he was asked about the reason for his cubical form, he mentioned that form could be anything. It can be changed later as well. While working on the concept he had a certain idea in mind and was working towards developing it. Participant-3 in spite of having explored the basic functional idea did not try a new form while creating a new part file.

Circumscribed thinking was clearly visible in the participant-4's approach. He compromised at multiple instances when he could not create the intended form. While explaining the challenges faced during the given design task he stated, "*in every model, I could not make what I imagined. The neck detail could not be made the way I wanted and then I had to resort to 'jugaad'*". This is a clear example of circumscribed thinking. Design in this case was affected by the tool and proficiency limitations of the designer. During the interview he was asked if he ever changed his design because making it was difficult or not possible. He answered affirmatively and added if a lot of time is spent on a model and the intended design is not attained then a change is introduced to complete the design in order to justify the time spent on it. He mentioned, at the idea generation stage the ideas are not frozen and this gives him the flexibility to accommodate what is envisioned and what is possible to model by making compromises if needed.

Participant-5 could not create even a single complete idea. He also mentioned that he was committed to certain commands and as a result could not produce the desired results. He could not think of other commands or a different approach to create the intended design. He also recounted during the interview, "*there was a time when all my ideation used to happen on CAD and almost nothing with pen on paper. I realized that I couldn't do it anymore as I could think only what I could model*".

As the circumscribed thinking was most evident in phase-2, a time map of activities related to design decision making (D), modeling (M) and struggling or exploring

ways to model (EM) for participant-4 and 5 was made (shown in figure 5.18 and 5.19).

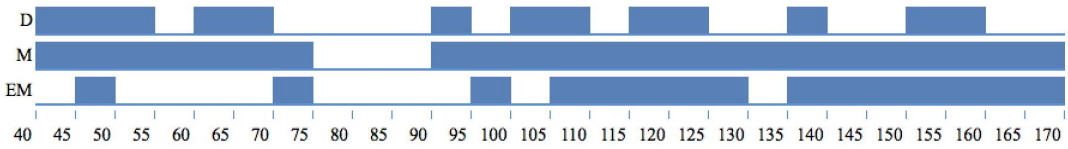


Fig 5.18: Time map for participant-4 showing time for design decision, modeling and exploring modeling method

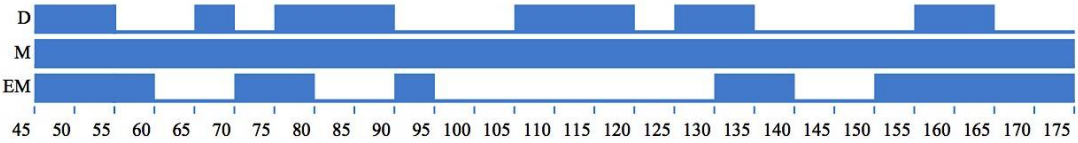


Fig 5.19: Time map for participant-5 showing time for design decision, modeling and exploring modeling method

The time for analysis starts from 45 minutes for participant-4 and from 40 min for participant-5 when they started activities on CAD. There are times when the participant was only performing the modeling work and was not taking any design decisions. Also, a substantial amount of time was spent trying to figure out the ways to model the intended design. This is not just the extra time that making CAD models of initial ideas demand but if it is too much, it may cause boredom and/or frustration in the user that might adversely affect the motivation and in turn creativity of the designer (Robertson and Radcliffe, 2009). As a result, the participant may end up compromising on the intended design and only create what they are comfortable with. In the long term, this may become a practice unconsciously. Participant-2 spent a lot of time trying to create the intended design and could not create the model till the end and finally gave up. He mentioned how frustrating he felt and mentioned this as a completely unexpected experience. He had been using 3D modeling for many years and rated himself as a competent user of the same. He found creating organic irregular forms as challenging. This shows that designers might get used to making certain kind of product forms over a period

of time and consider themselves as proficient/competent users but in reality, they might not have moved from being advanced beginners.

Effective visualization

Today CAD tools provide various options to aid visualization like zoom, sectional views, background images, colors and textures, various viewing angles, walk-through, and real-time changes. The effectiveness was evident as all three participants used multiple options to help them visualize their idea better.

Effective visualization is evident in all the cases throughout the exercise. There was no one period or section specific to this effect. It was spread over the entire task.

Participant-1 took most of the decisions about the placement and form of various features based on the visual feedback from the model. He also used kitchen background for the effective and in-context visualization of the final concept. Participant-3 extensively used sectional views to develop all the internal details of his concept. Participant-2, 4 and 5 also took many decisions on various features based on the visual feedback provided by the model in real-time.

All the participants used to zoom and rotate options extensively throughout the exercise that provided them with rich visual feedback. Even during the interview, all of them identified visualization as the most important advantage CAD offers. It allows them to interact with the idea in three-dimensional space while developing and communicate the same to others. Participant-3 even mentioned that in spite of his education in engineering and his work experience he finds it difficult to visualize an idea in 2D. He needs to make 3D to able to understand the complete assembly of his machines. He further added that sometimes realistic renders are used for catalog purposes much before the real product comes into existence. Animations exploded

views and renders are used for client presentations and eliminating the requirement of making prototypes in early stage.

Participant-4 mentioned that "*sketch is like a shadow of what I have in mind. Whereas, a 3D CAD model is closest to what I am thinking*". He added that a CAD model is something in-between a flat 2-D sketch and a physical 3-D model. It is a 3D model that cannot be touched and felt but visualized. Participant 4 and 5 strongly supported that visualizing an idea in 3D trigger newer ideas.

Another interesting finding from the interview was that the participants feel more confident about the ideas when they are made in CAD. Participant-4 mentioned that it helps him overcome his limitations of sketching skills and he can visualize and present the ideas that he cannot sketch. Participant-5 stated, "*to see how something would look in different angles I would rather make a model then create sketches from different angles. Also with my sketching skills, perspective views will not be very accurate*". Participant-3 also preferred CAD models for any client presentations.

Interaction in 3D space

CAD interface allows a user to move and place various components and parts in a virtual space. It helps them understand their relations and take decisions accordingly.

Participant-1 decided the position of most of the features by moving them in 3D space and taking a visual judgment on it. Participant-2 had the most extensive interaction in 3D space. He kept switching between parts and assembly and tried the interaction of various parts with each other. He shifted the location of the switch and introduced steam escape holes after the role-play with assembly. This helped him extensively to develop the idea further. Even during the interview, he mentioned that

the 3D visualization and assembly allow him to imagine the complete sequence of operations. Role-play or enacting usage scenarios is an important tool for creative exploration. By facilitating this CAD can engage designers in an exploratory interaction with their designs and aid creativity.

Participant-3 had a different approach as compared to the other 2 participants and did not have much interaction between various parts. Similarly, participant-4 and 5 did not have different parts and did not require interaction between separate components. Participant-4 shared during the interview how CAD helps to understand parts interconnection, fits, interferences and sequence of assembly-disassembly from the maintenance point of view.

Design changes / Iterations

Iterations are the core principle in the design process and hold great importance in idea generation. Design changes or iterations are closely associated with effective visualization. In all the cases design changes occurred as a result of effective visualization.

With the participant-1 design, variations took place only in fine-tuning of features.

For participant 2 major design variations inspired as a result of effective visualization and component interaction in 3D space. For example, change of pins to clips; a different pattern for speaker holes and positioning of on/off button, all these resulted due to effective visualization and visual feedback from component interaction in assembly.

Participant 3 had a well-defined idea, to begin with. Still, after creating a small bread exit he changed the feature completely for the user convenience.

Participant-4 made divergent ideas and did not work towards the iteration of the same ideas. However, many design decisions were taken and changes while making the model.

Participant-5 could not complete his models and design changes were constantly occurring as an attempt to reach the desired form. During the interview he mentioned that making a rough model helps with iterations and design refinements. The base model can be used as an underlay to explore further.

Size perception

Though visualization is identified as the biggest advantage CAD offers, it also has a limitation. It is difficult to gauge the sizes by looking at the screen.

The problem of size perception was evident with participant-3. He took the help of a ruler to understand the physical size and volume of the part he was creating. From looking at the screen and being able to zoom in and out on any feature could not give an actual idea about the size in reality.

Participant-5 kept measuring the reference spoons while modeling. Participant 4 and 5 acknowledged the limitation of size perception in CAD. During the interview, participant-4 gave an example of a handheld product that he was working on where he faced the problem of size perception, as it was difficult for him to understand the real-life size and grip and other aspects of design by looking at the screen. He quickly moved to physical mockup making with expanded polystyrene to resolve this problem. Participant-5 mentioned that he tries to zoom the part he is designed to almost actual size by keeping a scale near the screen and tries to visualize the part in real life. An idea that emerges from this is having a scale as part of the display window and in-built articles for size reference may help overcome this limitation to a certain extent.

Other points

2 participants identified flexibility to use standard components and parts from other files as an advantage. A lot of time and effort can be saved by this.

Participants 3 and 5 mentioned that 3D printing even a rough CAD model can help understand the volume and proportions and save efforts of making physical mock-up models.

Participant-4 cited an incidence where he kept trying to create certain features and failed every time. Eventually, he forgot the feature he was trying to create. The cognitive load during model making sometimes can be so overpowering that it may deter certain ideas.

Participant-4 also identified 'lack of gravity sense' as a limitation. He mentioned things works differently in the real-world with gravitation force acting on it. He further added that materials have different flexibility/softness/ hardness according to the thickness and length of the part and its understanding completely depends on the designer's experience with particular material as it cannot be sensed in CAD.

5.5 Findings and discussion

RQ1. How does CAD position itself in the idea exploration stage of design process?

All the participants shared that they use the CAD modeling tools in the early phase for various reasons. It allows them to understand proportions, volume, and scale. 3D CAD aids spatial visualization and allows usage of standard parts making the exploration process faster.

The process and inclusion of CAD in it depend not only on the personal preference but also on the stage at which brief is received. Participant shared that in a redesign project when there is an existing CAD model, the exploration may start from that CAD model. Whereas, for new project participants preferred first registering their thoughts in the form of rough sketches and then explore those further in CAD.

In the initial exploration phase, CAD modeling is used as 3-dimensional rough sketches. It helps participants to comprehend their ideas better. Keeping them in the background and exploring further on top of basic block models help the participant achieve better representations and overcome the limitations of their sketching skills.

All the participants prefer to use rough CAD models over sketches for presentation purposes. It boosts their confidence levels while communicating the ideas to others.

However, it was noticed that the use of CAD modeling in the initial phase may support vertical exploration and formal refinements but might not be supportive of lateral exploration. The point needs to be probed further. Lateral thinking is an essential requirement in the early idea generation phase.

RQ2. What advantages CAD offers to the designer, if used in early phase of design?

Visualization

Visualization was identified as the most important advantage by all the participants. CAD software incorporates multiple tools to aid visualization like zoom, pan, rotate, section, color, background environment, transparency, texture, and even magnifying glass. It not only allows the user to observe the geometry from different angles but also allows focusing and developing even the smallest details.

During the study, various design decisions were made through visual judgment. One participant (participant-2) used the Cad interface to enact a small role-play that further helped him refine his idea. Through the role-play, he not only could enact the sequence of operations but could also check the interaction between the various components. The flexibility and instant visual feedback facilitated by the CAD interface can enrich the experience of design exploration.

It was realized that the interaction in 3D space and design iterations were facilitated by the visualization and hence are considered under the same heading.

Communication

Participant-4 stated, "sketch is like a shadow of what I have in mind. Whereas, a 3D CAD model is closest to what I am thinking". All the participants prefer rough CAD models over sketches for communicating with the clients and other people. CAD helps them comprehend their ideas better and communicate without ambiguity.

Presenting the ideas through CAD models aid their confidence levels. Since the idea is better comprehended and it can be checked for fits, interferences and other detailing aspects, CAD modeling brings in more clarity in communication.

One participant even mentioned that the CAD rendered images and animations are used for catalogs and other communication purposes even before the actual product is made. This helps the presentation to clients much more effective.

Other advatages:

CAD models can facilitate 3D printing and rapid prototyping saving a lot of time and effort.

Further, the usage of standard components and models from other files can facilitate faster development of the product and reduces the chances of errors.

RQ3. What limitations CAD impose on the designer's way of thinking?

It was interesting to notice that 3 out of 5 participants could not think of the limitations imposed by CAD during the interview. It could be because it has become an integral part of their design process or because the advantages are so strong that it overpowers the limitations. All these 3 participants were the proficient users of SolidWorks. Since their proficiency levels were high it does not affect their outputs. Additionally, they all enjoy the modeling process. These could be various reasons why they could not think of any limitations. However, the limitations identified through literature and explored through the study are as follows:

Circumscribed Thinking

Circumscribed thinking occurs when a designer compromises on the intended design feature due to tool or proficiency limitations (Robertson and Radcliffe, 2009). This was evident in the phase-2 of the study where the ideation required formal exploration. The candidates faced difficulty in creating the intended form and one participant mentioned resorting to 'jugaad' to finish the model. During the interview, participants shard their past experiences where they compromised on the design for the ease of creating a CAD model.

In phase-2 both the participants rated themselves to be the competent users of SolidWorks software and had been using the same software for 5 years and more. Yet, they faced difficulty in creating their designs and finally could not achieve the desired results. This shows that the number of years does not ensure proficiency and users do not attain the next level of proficiency unless they are pushed or are motivated. The participants had created their comfort zone and a certain approach to

model making. The task required them to produce forms they were not used to taking on a regular basis.

When the proficiency levels are low and a challenging task is faced a lot of time was spent in trying to explore the ways to create a certain model. If the efforts and time spent on this are more it can create frustration and boredom, further hampering the motivation and creative exploration. As a result, the user may subconsciously start exploring the designs that they are comfortable in modeling.

Size perception

Perceiving the sizes, flexibility, textures, softness or hardness by looking at the screen is difficult. While designing participants were constantly referring back to the ruler to define dimensions. Participant 4 and 5 also shared their experiences where they need to always have a rough mock-up made in thermocol or 3D printed to ensure the sizes. Sometimes, the CAD model is zoomed closer to actual size on the screen to understand its dimensions in reality.

CAD provides the user with a virtual 3 dimensional model of the geometry they define and help them visualize it. Some in-built library of the standard items of a customizable ruler on the screen can help enhance their design experience.

Fixation

Fixation in the study was noticed when two participants first created the base model of the toaster and then worked around it. They were fixated to the existing image of the toaster. However, fixation was not noticed in the approaches of other participants. Can CAD cause fixation could not be answered through this study.

Chapter summary

The chapter illustrates a pilot study done with professional product designers. The study was conducted with one participant at a time. It helped establish a systematic way of analyzing the design activity and drawing observations. The video recording of each session was transcribed by writing down each activity supported with images. The study parameters were mapped onto this transcript. It was a lengthy process requiring an extensive amount of work but allows the researcher to understand the design activity and the participant's approach in depth. The analysis is drawn from the analysis of the audio-visual data of the design exercise and the interviews with the designers.

The chapter discusses the study framework, outcomes of the design tasks, analysis, and findings.

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Chapter 6
Final interview study

The pilot studies done with product design students and professionals helped investigate the role of CAD in the early idea generation phase. However, the study was conducted in a controlled environment and does not represent the real-life working scenario. To draw richer insights and validate the findings from the pilot studies semi-structured interviews were conducted with product design professionals. The one-on-one interviews were done with practicing professional product designers allowed gathering rich in-depth data that highlights the role of CAD in the current practices and its advantages as well as limitations. This chapter reports the details of the interview guide, analysis method, and findings.

6.1 Introduction

To compare the findings acquired from the small number of participants through the design exercises, semi-structured interviews were carried out with the professional product designers. Conducting one-on-one interviews allowed the researcher to gather rich data as designers could reflect on their practices and recall and share their experiences through various cases. The participants were contacted through personal contacts and references from other participants. The selection criteria required them to be trained and practicing product designers who should have knowledge of SolidWorks and use it as one of the software tools.

The interview guide was prepared based on the findings from the previous experiments. A brief introduction to the field of study was given to the participants

while seeking the appointment. The interview sessions were voice recorded with their permission and later transcribed for analysis purposes. The pilot session with 3 designers was conducted first and with minor amendments, the remaining 22 interviews were conducted. Total of 25 interviews was conducted and used for analysis purpose.

6.2 Study framework

The study was based on the qualitative analysis of the data collected through semi-stricture interviews with professional product designers. The section elaborates on the study framework.

6.2.1 Objective

After the pilot study with professional designers, it was realized that CAD can be very supportive for the vertical exploration but may hamper the lateral exploration. Also, for less proficient users CAD modeling can cause cognitive load that can hamper the design outcome. The objective of this study is to find the answer to the following research questions through the experiences of practicing designers:

RQ1: How does CAD position itself in the idea exploration stage of the design process?
RQ2: What advantages CAD offers to the designer if used in the early phase of design?
RQ3: What limitations CAD impose on the designer's way of thinking?
RQ4: Does using CAD during idea generation results in more vertical exploration and hinders lateral exploration?
RQ5: How does CAD affect the design outcome because of its intervention?

6.2.2 Data collection method

Interviewing is defined as ‘a method of data collection that involves researchers seeking open-ended answers related to research questions, topic areas and themes’ (O'Leary, 2010). It is a conversational practice in which knowledge is produced through the interaction between interviewer and interviewee (Brinkmann cited by Musta’amal, 2010). It is a process of guiding a conversation to get information from the participant (Guthrie, 2010). The interview process can be used to get in-depth information and better perspective of certain issues (Patton, 2002). It can help get information about participant’s opinion, feelings and knowledge (Patton, 2002).

Interview was selected as the study method to seek rich in-depth information from participants. Semi-structure interviews ensure that the data collected is comparable while providing enough flexibility to collect open-ended responses. All the interviews were conducted one-on-one by the researcher in an informal setting and were voice recorded using a digital audio recorder.

The language of interview was English. However, during interaction some participants used Hindi and English mixed as language of communication.

6.2.3 Interview guide

The interview guide was prepared based on the findings from the previous study and were grouped to answer the specific research question. Table 6.1 explains the interview questions and how they address the research questions.

Table 6.1: Interview guide for final study and research question that it addresses

Q. No.	Research Question	Question
1	This section was designed to acquire the demographic information about the participants and also act as a warm-up session for before the main interview questions begin.	What is your job profile?
2		What type of projects have you been working on?
3		Does it require you to ideate new ideas and represent?
4		What tools you use during early idea generation stage?
5		Which software you use and how long you have been using these?
6		Can you rate your proficiency on the scale a. Novice – Just started b. Advance beginner – have basic knowledge of the software and can build basic models c. Competent – Fair knowledge of software. Can create new forms using advance features. d. Proficient – can combine surface and solid modeling, use advance features and configurations and come up with multiple methods to achieve same model and select the most appropriate one. e. Expert – more than 10 years of experience. Can teach and test software

Q. No.	Research Question	Question
7	RQ1: How does CAD position itself in the idea exploration stage of design process?	When and how do you use CAD in your ideation generation process?
8		Designers use rough doodles and refined sketches, quick and dirty mockups and prototypes, in their design process. Have you in your experience ever used rough modeling and refined modeling?
9	RQ2: What advantages CAD offers to the designer, if used in early phase of design?	In your opinion, what are the advantages CAD tools offer when used during idea generation stage?
10		Does presenting a CAD representation make you more confident about your idea? How and why?
11		Does making a CAD model help you get more clarity on the design idea? Why?
12		Did you ever have a discovery due to CAD modeling?
13	RQ2: What advantages CAD offers to the designer, if used in early	Does CAD visualization trigger more ideas or induce a feeling of completion leading to finishing of ideation?

Q. No.	Research Question	Question
14	phase of design? **OR** RQ3: What limitations CAD impose on the designer's way of thinking?	Literature says that CAD can make designers less hesitant to try different alternatives. However, making CAD models take substantial amount of time and may lead to fewer ideas. What is your experience?
15	RQ3: What limitations CAD impose on the designer's way of thinking?	Literature mentions instances where due to detailed models made in early exploration stage, and illusion of completeness curtailed further exploration. Sometimes, due to time spent on modeling there is a hesitation to explore fresh ideas. Have you ever experienced obstruction or premature fixation to certain ideas in the early phase of design due to CAD modeling?
16		CAD interface can help designer handle products scaling from micrometer to 100s of meters. Yet, it was realized that looking at the computer screen it is difficult to gauge the size and feel of the design. Have you ever experienced something like that? How do you ensure the size / grip / feel of the product you designing results as intended?
17		What are the limitations of CAD tools when used in idea generation stage?

Q. No.	Research Question	Question
18	RQ3: What limitations CAD impose on the designer's way of thinking? RQ5: How does CAD affect the design ideas because of its intervention?	During the experiments done earlier, it was noticed that people drop certain ideas and / or compromise on certain formal aspects when the 3D model is difficult to make. This was particularly noticed in cases of designs having organic or fluid forms. Can you recall any such experience? What is your strategy when faced with such situation?
19	RQ4: Does using CAD during idea generation results in more vertical exploration and hinders lateral exploration?	Does using CAD in early stage of idea generation result in more vertical exploration and curb lateral exploration?
20	RQ5: How does CAD affect the design ideas because of its intervention?	Does the act of CAD modeling ever create frustration or boredom? Did you ever drop an idea because you would be required to model it?
21		Do you ever experience that the act of CAD modeling takes away the thinking from designing to modeling? Sometimes when the idea is challenging to create in 3D, the attention gets diverted to exploring ways to make it and more time is spent in that instead of taking design decision. What is your view on that?

Q. No.	Research Question	Question
22	Conclusion and wrap-up	Would you like to add anything else from your experience? Can you recall any peculiar experience that you had related to CAD modeling, any failure or success?

6.2.4 Study participants

27 participants were interviewed during the study. 3 participants were interviewed first for the pilot and after the analysis of those, 24 more participants were interviewed. For the analysis, only 25 interviews were considered and two interviews were dropped. 2 interviews that were not considered as part of the study were of design engineers and not of product designers and thus they did not meet the participant selection criteria.

All the interviews considered for analysis were of participants who studied and are practicing product designers. As the study is focussed on the idea generation phase of product design, it was ensured that the participants are working as product designers and had education supporting their work.

All the participants interviewed used SolidWorks as one of the tools. Their proficiency levels were either advanced beginners or competent or proficient users. Novices and experts were not considered for the study.

The specific guidelines to identify a suitable participant left the scope of search very narrow. Only four female participants could be found who matched the selection criteria and all the other participants were male.

All the interviews were conducted one-on-one by the researcher. Three interviews were conducted through video calls using Skype with the participants based in Bangalore and remaining interviews were conducted in person at Mumbai and Pune regions.

6.2.5 Interview analysis

The process of qualitative data analysis can be arduous. All the interviews were transcribed verbatim. The analysis of the transcribed data needed to lead to a deeper understanding of the approaches and processes adopted by the professional product designers and help find the answer to the research question. The amount of data can look intimidating. Therefore, it was essential to subdivide the data and categorize it to draw inferences from it. Coding the data helps achieve it and has an important role to play in analysis. Coding, coding schemes, and retrieval of coded data are key tools of qualitative data analysis (Silver &Lewins, 2018).

Electronic methods of coding data have been in practice amongst researchers. The researcher is required to create codes and decide what to retrieve and collate but the program can help retrieve the data and allow changes in the codes assigned much faster. It facilitates faster and comprehensive searches as compared to the manual process. Different software programs to assist qualitative data analysis were explored. These included MaxQDA, QSR NVivo, Atlas.ti, and HyperResearch. After going through reviews and webinars, MaxQDA was selected for the analysis purpose. The reasons for choosing it were the availability, affordance, and usability of the interface. An education license for the software was bought and used for this study. MaxQDA is a software program used for qualitative and mixed-method data, text and multimedia analysis. It is developed and distributed by VERBI Software based in Germany. The input data can be in rich-text format (RTF), word file, and video or image format. The data can be coded and grouped for the analysis purpose. The software was learned by watching the tutorial webinars.

First, the transcribes were written in Microsoft Word. A sample of the interview transcribe is shown in Annexure-V. Word files (*.docx format) of all the transcribes were uploaded in MaxQDA in a new project. For coding, the data had to be read and selected line by line and assigned a code. All the responses were coded with 2 different sets of codes. The first set was based on the question number from the interview guide. This helped to club the responses to a particular question from all the participants and get an overview.

The second set was a more in-depth analysis of the responses where the occurrences of different parameters were mapped onto the responses. This allowed the responses to be broken into smaller sections and club them together. Figure 6.1 illustrates the coding system used for the analysis purpose. The main categories of demographics, limitations, advantages, design process and thinking and approach were already decided before the analysis. The sub-categories developed along with the analysis during the pilot. The first 3 interviews were considered as the pilot and were transcribed and coded. Afterward, 22 more interviews were conducted making a total of 25 interviews for analysis. The numbers on the right-hand side in figure 6.1 show the occurrences of responses pertaining to that particular category/sub-category. More than 25 occurrences signify that a participant mentioned about a certain experience or concept more than once in the interview. The participants were grouped in 3 sets as per their proficiency levels. The sample of retrieved data after coding is given in Annexure-VI.

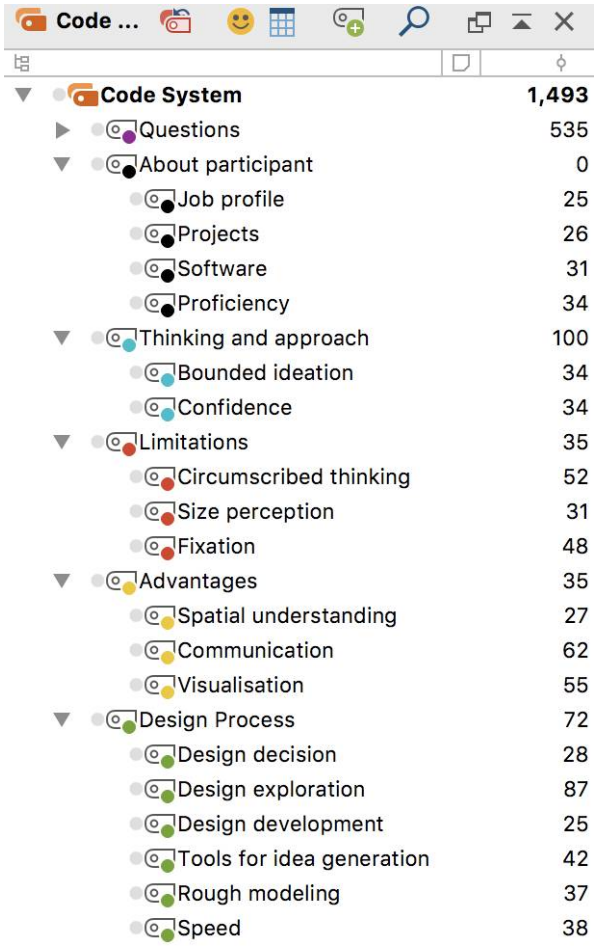

Fig 6.1: Codes and occurances used for analysis in MaxQDA software

After the extensive process of coding was done, the data could be retrieved for each category/sub-category in Excel or PDF or RTF file types. These files assembled the extracts from the interviews related to a particular code. These chunks of information helped derive findings from highly focussed data. All the responses were also categorized in 3 different groups as per their proficiency levels of proficient, competent and advanced beginner level. This helped understand the correlation of different study parameters with proficiency levels of participants.

6.3 Analysis and findings

This section documents the findings from the analysis concerning research questions and the demographic information about the participants.

6.3.1 Information about participants

The first 6 questions in the interview guide were to collect information about the participants. These included the software they use, their skill levels and the tools that they use during the early idea generation phase. The question related to the kind of projects they are working on and does it require them to present it to higher management were used as qualifiers for the participants. It was important to ensure that the participants were practicing product designers. All the respondents had more than 2 years of experience in SolidWorks software. The only reason to have SolidWorks as a common software among all the participants was to ensure certain uniformity in their experiences. However, after the interviews, it was realized that most of the designers use multiple software in practice.

Out of 25 participants interviewed 4 were female product designers and 21 were male designers (figure 6.2).

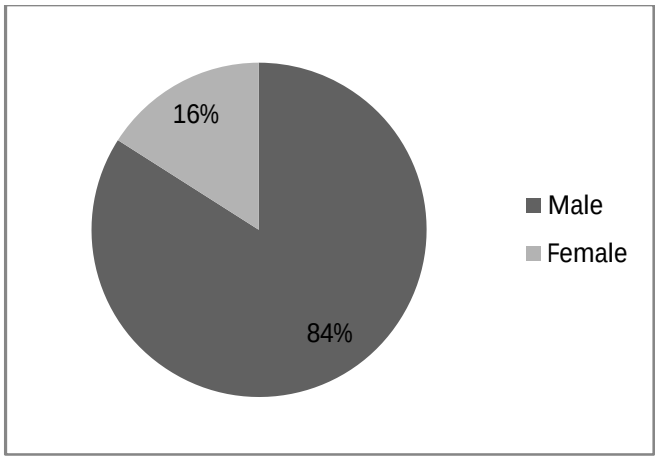

Fig 6.2: Gender ratio of participants

Except for one participant who had done his bachelor in design in product design, the remaining participants had a post-graduate degree in product design from different institutes. 16 participants had an undergraduate degree in engineering, 6 in architecture and 3 in design (figure 6.3).

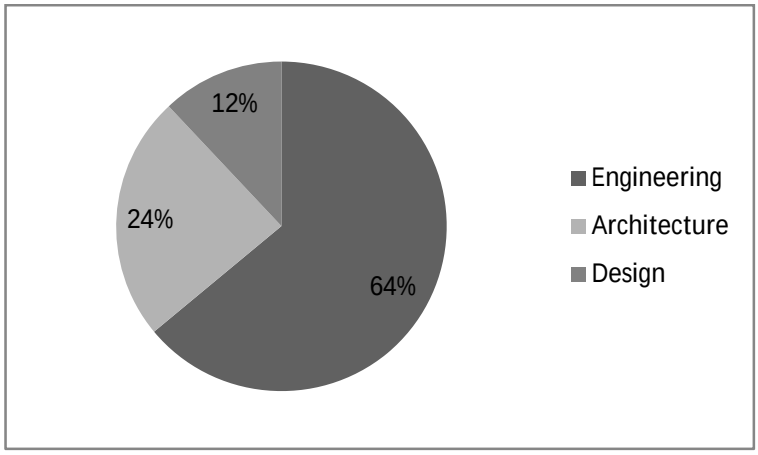

Fig. 6.3: Undergraduate background of participants

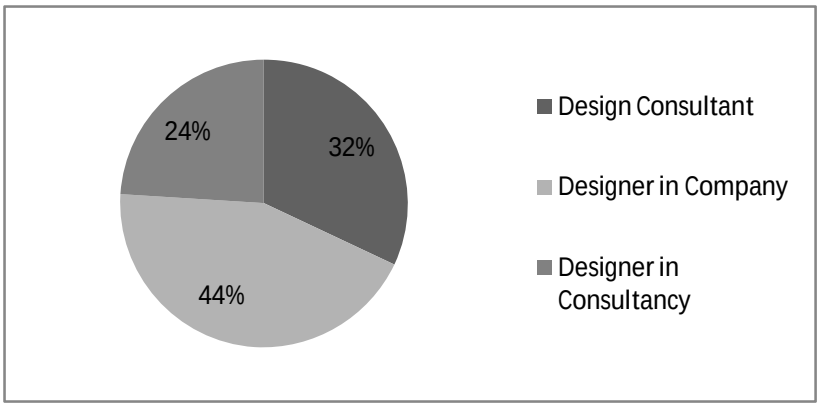

Fig. 6.4: Work profile of participants

As shown in figure 6.4, eight participants were freelance consultants. Two of them are also teaching Product Design in design institutes and are working on different projects as consultants. The clients define the projects they would be working on and require them to present their ideas directly to decision making management and vendors. They are also required to communicate the ideas to the engineering teams.

11 participants were working in different companies and are required to work in teams and also as individuals. They work on the brief provided by the company towards the company portfolio. Most of these participants mentioned that a considerable percentage of their projects include re-design projects.

Remaining 6 participants were working with big design consultancies where the clients define all the projects and the domains keep changing. There they use the strength of their teams and rely heavily on the skill sets of colleagues.

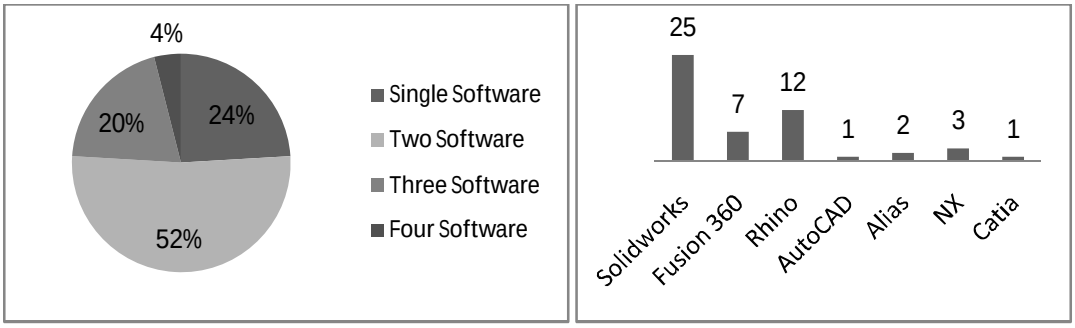

Fig 6.5: Software used by participants

Except for 6 participants, all other people interviewed use more than two 3D modeling software (left side graph in figure 6.5). 13 participants use two software, 5 use three software and 1 participant used four different 3D modeling software. It was ensured that all these 25 participants use SolidWorks as one of the software (right side graph in figure 6.5). The other most common 3D modeling software amongst product designers was found to be Rhinoceros with Fusion360 becoming popular rapidly. Designers mentioned that they prefer a combination of surface modeling and solid modeling software, parametric and non-parametric software. More flexible software support the exploratory phase but parametric solid modeling software helps in 3D printing and presentation and communication of ideas.

Upon enquiring their proficiency of 3D modeling, 12 participants were found to be in the category of advanced-beginner, 7 were competent users and 6 were proficient users with 3 among them being certified professionals (figure 6.6).

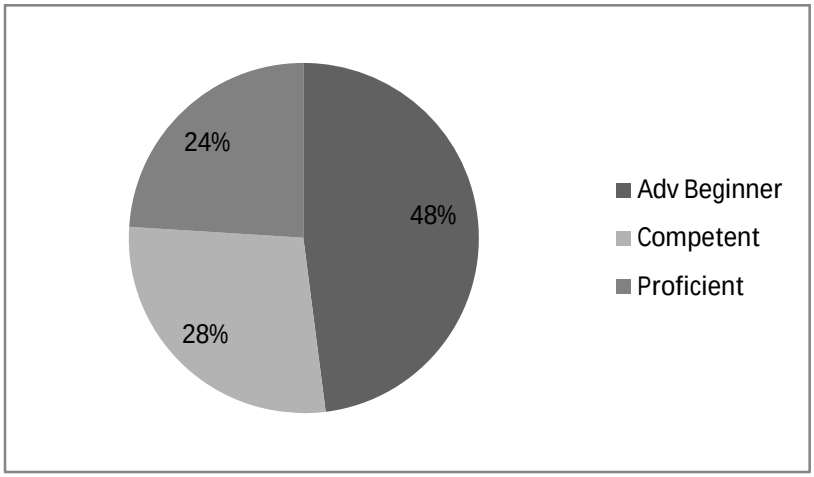

Fig. 6.6: Proficiency levels of participants

6.3.2 Research Question-1: How does CAD position itself in the idea exploration stage of design process?

To understand how CAD positions itself in the design process and how designers work in the environment with multiple tools, 3 specific questions were asked. During the warm-up session, a question on tools participant uses during their ideation process was asked to understand their working environment and available tools. The next question required them to reflect on their design process and how they use different tools in the early idea generation phase. The third question probed the concept of rough 3D modeling and its existence. The importance of doodling or low-resolution sketches and quick-and-dirty models is established in the process of design. On the same lines, it was important to explore the concept of rough 3D modeling. During the pilot study, it was realized that participants create rough models just to visualize the volume or interaction of components or just to understand the rough form in three-dimensional space.

The tools used by designers in the ideation phase include sketching (manual and digital), 3D modeling and physical models making (manual, laser cutting, and 3D printing). With the tablets becoming popular 3 participants mentioned the use of tablets for the initial sketching. All the participants mentioned that the sketching is

mostly in the form of doodles or low-resolution representations. It serves the purpose of registering the thoughts. Notes and keywords are also used for the same purpose.

Further, four participants mentioned that they use the 3D CAD model printouts as the base to sketch and explore ideas. Two participants mentioned that they use their doodles in CAD background for making the model. One proficient participant mentioned that he sometimes sketches directly in the CAD interface and then convert it to 3D. This highlights how designers are integrating CAD with other tools in their process. It helps them overcome the limitations of a single tool. A participant mentioned, "CAD is a tool and sketching is a skill". He furthered the thought by explaining how the rough block models in the background help him overcome the limitations of his sketching skills and achieve a decent and proportionate perspective sketch.

The participants having access to 3D printing use CAD modeling extensively even for rough models. However, other participants mentioned that they keep shifting between rough paper/ Styrofoam/ clay models, sketching and 3D CAD models.

To understand the role of CAD in the initial design process participant's responses to the question were grouped. Narratives from participant responses to other questions also help elaborate on their process and were considered for understanding the whole process. A total of 72 descriptions were found in 25 interviews unfolding their design process. Further, the responses were grouped in 3 sections, Advance beginner, Competent and Proficient users, as per their proficiency. It was realized that their proficiencies had an impact on their approaches.

Proficient users had a more positive attitude towards the inclusion of CAD in their exploratory phase. All the proficient users mentioned that they use CAD for idea explorations extensively. A participant mentioned, *"designers should not get limited*

by the tools but should be able to function with whatever tools are available to them". The proficient designers showed more confidence about exploring their ideas with CAD tools and mentioned that rough sketching and CAD modeling is usually used in parallel. One of the participants mentioned that there are times when he would directly sketch in the CAD interface and move into 3D modeling.

The advanced beginners and competent user groups expressed the need for a certain level of clarity before starting their explorations on CAD. They keep iterating between sketching, 3D modeling, and physical modeling but the thought process starts with rough sketching. Especially the Advance beginner group finds it difficult to start exploring directly on CAD.

However, the process differs when it is a redesign project or a time-bound project with a very tight timeline. Participants with different proficiency levels shared that if the brief is very narrow and constraints are well defined, the project starts from either building or acquiring the existing models of the product to be redesigned. If a version of the product exists then the explorations start from the CAD models of the existing product either by directly changing the model in CAD or by sketching over the images of it and then further modeling the selected options. If it is a new product with a very narrow brief the explorations start by building the block model of the internal components.

A competent user explained how in the company, all the parts of a product are saved as separate CAD files and in the new product many of the components are required to be kept the same as standard / existing components. Having CAD models help speed up the process and define the exploration space more concretely. Another Competent user mentioned that today all the standard components and readymade parts that one would require to be procured are available online in STL or IGES formats. This further helps define the exploration space and constraints, speeding up the design process in-turn.

The CAD in idea generation is used for making rough 3D models to a great extent. 10 out of 12 advance-beginners, 5 out of 7 competent users and all the 6 proficient users mentioned that they use CAD for rough modeling in the initial phase. The main purpose stated for rough modeling was to visualize in 3D, get an idea about the proportions and volumes and understand the spatial relations between various components. The approach for making rough models include basic block models without any details of joining or assembling or just an enclosed volume within surfaces that may or may not be stitched. The thought behind the rough models is to get a quick visualization and render for representation purposes. One participant mentioned that the rough model facilitates vertical exploration where one can save it multiple times or copy-paste to create different features on the same base model. This helps create a variety of iterations much faster. Though, before reaching this base model, the lateral exploration is done through rough sketching and selected ideas are further taken for exploration in 3D CAD models.

The participants who do not use rough modeling as a part of their process mentioned the reason as it to be a time-consuming process and the time should be spent in making a detailed, well thought of design output. They mentioned that explorations can always be in 2D but making a rough and fair model would mean more amount of time is spent in modeling and less in design. Yet, a majority of participants were found to be using CAD for rough visualization.

6.3.3 Research Question-2: What advantages CAD offers to the designer, if used in early phase of design?

Four questions were asked to understand if CAD in the ideation phase could aid the design process and the advantages it offers. The first question was a straightforward question on what are the advantages of using CAD in the idea generation phase of product design. This helped accumulate their thoughts on the topic without any prompt. Further two specific questions were asked if the use of CAD adds to their confidence and brings in clarity of thoughts. The next question enquired if they ever

had a discovery due to CAD. This question helped people recollect their experiences and share a particular incidence. This was to understand if CAD could bring in any specific kind of advantage that other tools might not offer. Apart from these 4 questions, 2 more questions were asked to understand wherein certain aspects of CAD are beneficial or constraining. The first question inquires if visualization facilitated by CAD help trigger more ideas or does it lead to fixation. The second question was asked to understand if CAD helps create multiple options by making them less hesitant to experiment or whether it leads them to create lesser options because of the time and efforts required to make CAD models. Visualization and communication were identified as the biggest advantages CAD offers.

6.3.3.1 Visualization

One advantage that every participant mentioned in different contexts is "Visualization". The CAD interface provides multiple tools like zoom, rotate, pan, transparency, and section-view to aid visualization. The changes being made in the model are visible instantly and it allows the various proportions and alternatives to be explored rapidly. Many participants mentioned that it helps them visualize the volume and mass in the right proportions and from all the possible angles. Certain views like bottom view for large products or close up view of a 0.8mm probe might not be easy to see in real life and CAD interface can help handle the complexities and different scales of the products. A participant also mentioned that looking at different sections could help get more ideas and lead to discoveries.

CAD can help visualize complex forms and ideas that are difficult to sketch. It helps designers overcome the limitations of their sketching skills. A participant mentioned that the ideas in mind are always in 3D but he makes 2D orthographic sketches while externalizing them. Certain features like large curvature surfaces, transparency and textures are found to be difficult to express through sketches or would require a considerable amount of time. However, CAD can facilitate this with a command.

The CAD visualizations are closer to reality; it eliminates ambiguity and makes representations more comprehensible.

The CAD models can help understand the spatial relations between different components and how they interact. Checking for interferences, understanding the space utilization and various movements are few more added advantages. CAD visualization can also aid explorations in cases where making quick mock-ups are not possible as in extremely large products and very fine and precise designs. A participant also mentioned that working in 3D with CAD interface could improve one's spatial visualization and help them practice more complex 3D forms even before making them.

6.3.3.2 Communication

The next most prominent advantage of CAD was recognized as communication. The communication is facilitated by the visualization. It helps remove ambiguity, brings clarity and helps communicate the design idea to all the stakeholders. Many participants asserted that it helps bridge the gap between designers and the technical team, higher management, vendors and other stakeholders. The participants discussed that a 3D model is closer to reality and discussing the idea in 3D leads to better and constructive discussion and feedback, further facilitating collaboration. It is easier to explain the complex details through a digital model. CAD allows you to make the changes during the discussion and reflect on these. It leads to faster decision making. The physical model is also favored but since making physical models is more time consuming and instant changes cannot be done in those, digital models are preferred particularly in the early phase of design. Digital models also enable collaboration and discussion amongst the globally disbursed team.

Participants with limited sketching skills feel more confident about their ideas while presenting them in 3D CAD models. A participant stated, "Sometimes good ideas

get rejected because you could not communicate it well. Presenting a nice render makes a difference". Another participant mentioned, "My low-level digital models are more convincing than my sketches". Nearly all the participants felt that it is easier to discuss ideas in low-resolution sketches and keywords with other designers as they can visualize them but the same cannot be expected from other stakeholders and an absence of a clear model may lead to miscommunication.

The 3D CAD models and rendered images have become an unsaid norm in the design industry today for presentation and communication purposes.

6.3.3.3 Other advantages

A participant mentioned, *"Sometimes until you model something you don't think I could have done this"*. Another participant narrated an incidence where he was working on the design of earphones and during CAD modeling he executed some cuts unintentionally while trying to achieve the intended form. This resulted in a more attractive form and the team decided to stay with it for the final product. One participant specifically suggested that it is difficult to imagine transitional forms and forms achieved by the interference of multiple shapes. CAD can help discover unique ways of exploring forms and assist designers in spatial visualization. Many participants shared their experiences of discovery in terms of form or function or detailing while CAD modeling. One can conclude that CAD can encourage designers to expand their exploration space.

CAD aids designers become more confident about their ideas. Some participants expressed that their confidence level advances because of better visualization and communication that CAD can facilitate. Some mentioned that checking for interferences, understanding assembly and constraints and all the design aspects of the idea makes them feel more confident about it. If the design brief has constraints of weight, volume, internal component sizes, material or anything else, CAD can

help designers check the ideas in the initial phase itself and explore around these, making the process much faster and effective. *"At the sketching stage, you tend to lose out on some basic detailing work. Doing a 3D model makes the idea more comprehensive. You do not miss out on things. You can see the idea from 360 deg. 3D models give a more assured idea"*, stated a participant.

Today a lot of standard component details are available on the Internet along with their CAD files. These can be downloaded and used directly in the files. This further assists designers and save their time in working out the mundane details.

How CAD can assist designers in their process depends a lot on their proficiency. Proficient users mentioned that it assists them to explore much faster and helps create multiple options. CAD can eliminate the need for physical prototypes in the exploration stage and if needed can facilitate 3D printing or rapid prototyping. This saves a lot of time spent on physical prototyping. Further, since multiple options can be explored on the same base model, it allows designers to spend more time on designing.

6.3.4. Research Question-3: What limitations CAD impose on the designer's way of thinking?

Two questions in the interview guide were intended as transitional questions from RQ2 to RQ3. These questions tried to understand if CAD aided visualization can facilitate further exploration or lead to fixation and if CAD helps designers become less hesitant to try multiple alternatives. The succeeding three questions were directed on soliciting inputs on the limitations imposed by CAD. The first question required participants to recall if they ever faced fixation to a specific idea due to early detailing or excessive time spent on CAD modeling. The subsequent question probed into the limitation of size perception. During the previous experiments, it was realized that participants faced hindrance while defining and gauging the sizes

of products/product features by looking at the screen. The next question asked about the limitation they face while working on CAD in the early idea generation phase. Another question was an overlap between RQ3 and RQ5. The researcher requested participants to recall any experience where they compromised on the design/design feature because it was difficult to model in CAD. Though there was a hesitation in the beginning if participants would answer this question honestly or not, surprisingly all the participants very openly shared the cases where they compromised on their design due to the limitations of their CAD skills. The limitations as identified through the interviews are described below.

6.3.4.1 Fixation

The 48 responses that were linked to fixation were further grouped in 3 sets as per the proficiency of the respondents. The possibilities of differences in the responses based on their proficiency and experience could not be ruled out. However, after compiling all the responses, it was realized that the proficiency did not influence their responses and it depended on their processes and approaches.

Many participants believed that clearer you see the ideas, lesser the interpretations and more the feeling of moving towards completion. Looking at the computer screen does not trigger more ideas and requires designers to go back to the drawing board to find fresh thoughts. Seeing an idea in CAD can lead to fixation due to the realistic and complete visualization. However, other reasons that were quoted causing fixations include the level of details achieved in the early phase and time-crunch. If one starts detailing during the early exploration phase, it can cause the designer to get fixated to these features with reluctance to make changes. A participant also asserted that once you start detailing then all the explorations move in a particular direction. There is always a hesitation to start from scratch after having spent time and effort in that particular direction.

The availability of time also plays an important role. With the deadlines approaching one tries to move more towards the completion rather than spending time in the search of new ideas. However, 3 designers expressed the contrary view. They mentioned that if you come up with a better idea and it requires more time, then one has to invest that time in it. Going ahead with a mediocre idea is never a choice.

The use of rough modeling helps avoid fixation due to early detailing. It was found to be a common practice amongst the participants. Participants mentioned that when the goal of modeling is to only explore different directions and one does not get attached to it, it is easier to move away from it.

Some participants who move to 3D modeling only after achieving certain clarity on the paper stated that once they move to 3D modeling there is already a commitment to the idea. At this stage, they do not like to make major changes in their designs. Only one participant mentioned that seeing the ideas in CAD encourages him to create more ideas. It does give him a sense of completeness, which he finds very satisfying.

The 3 design consultants specifically mentioned that presenting a CAD model to the client can get them fixated to the ideas and they feel the project is over. As designers they are aware of the stage the project is in and in the initial phase, the renders of the models are purposefully made to look sketchy for presentation. This helps them convey that this is the exploratory stage and avoid design decisions getting influenced by the realistic renderings.

6.3.4.2 Size perception

Practically all the participants agreed that they have faced the problem of perceiving sizes on the screen. Many narrated incidences when their design turned out dimensionally inappropriate or un-ergonomic and this was realized only after the

prototypes were made. One participant narrated an incidence where he was designing a pastel-mortal set and after 3D printing, the design needed to be scaled down considerably. Another participant described the incidence, *"Once I was redesigning an electronic lock and after making sketches I moved to 3D modeling to create a mock-up for 3D printing. I calculated the size of buttons based on the keypads that we use and all but after designing, the gap between the buttons was so less that the person with thicker fingers would end up pushing 2 buttons. That could have been avoided if we first cut out some cardboard pieces and tested it with different people to find out what would be a suitable gap. So when you can zoom-in you might not realize the actual sizes. We spent 2 days in CAD modeling and one day in 3D printing and all those 3 days work was wasted with no results".*

In the case of a redesign project, the reference products or structures are available for understanding and gauging the sizes. Though in a new product design brief, the issue is more evident. A participant mentioned, *"if you were designing a pen you would always refer to 10 other pens before deciding the size and for finding the most comfortable size. If you are designing something new, then you have to make a physical model using thermocol or clay or other material".*

Most of the participants mentioned that they make quick and dirty mockup models using soft materials or 3D print the design to ensure the sizes. One participant mentioned that he zooms the design on the screen to approximately actual size and then tries to gauge the size by putting his hand against it. Use of ruler while designing, making 1:1 drawing and keeping blocks of Styrofoam or paper cutouts also were found to be common in practice.

One participant mentioned having mannequins and some standard products like a matchbox, credit card and simple ruler in his material library. He places these objects in the models while rendering to provide the right perspective and idea about the size. Another participant mentioned the use of mannequin in her renders, especially for furniture products. She mentioned that if the render is not put in a

relative perspective, it could look completely different and distort the design. More with the time and experience of working in a particular field one's ability to gauge the dimensions improve.

6.3.4.3 Circumscribed thinking

Circumscribed thinking occurs when a designer compromises on form or feature of the design due to the limitations of skill or software. As the phenomenon is proficiency dependent, all the responses were divided into 3 sets of proficiency levels.

All the participants in advance beginners set acknowledged that a compromise on the design occurs due to their proficiency levels. The effect is more prominent in the formal explorations. Organic forms are difficult to create and designers do not hesitate to simplify the forms for the ease of CAD modeling. A participant stated, *"...I'm saying if they (engineers) can leave it because they can't manufacture it. You have to leave it because you can't model it. It's the same theory"*.

Making a CAD model cannot be avoided and the design phase resulting in a CAD model of the selected idea is a common practice in the industry today. Many participants mentioned that presenting a CAD model or the rendered image of a CAD model is the norm. A participant shared, "I know a friend who designs only what she can model. She is a very hands-on person but she is in a place where modeling and rendering is a benchmark of good work. And she is not great at it or enjoys it. So she designs keeping in mind that she has to model it later". Later, a separate interview was conducted with her and she confirmed that she does not enjoy modeling and would not push herself to achieve exactly what she has in her mind in a CAD model. *"Something close enough is good enough"*, she said.

Since time is a constraint, a participant said, "I would rather have more doable ideas than waste time on finding out how to make one particular idea". Lateral ideation is an important part of the ideation phase in the design and if CAD takes up too much of mental space, it can hinder the thought process. In today's fast-paced industry, it is important to deliver on time. Participants expressed that sometimes compromises on the form are made to achieve the deadlines and deliver on time. If a form is too complex and it cannot be delivered within the time available then investing efforts in it is useless and one would rather settle for what can be made in the available time. A participant cited an incidence where he hid the sketches of the ideas that he could not make.

The users with lower proficiency levels require more time to create a particular model and that means the chances of circumscribed thinking are higher in this group. Some participants seek help from their colleagues who are good at modeling to achieve the desired form, but these are specific to the people having team members with expertise available. As explained by Dreyfus the largest population of any skill is the Advance Beginner group and people stay at this level unless they are required and driven to enhance their skills. However, during the interviews, it was discovered that many people found CAD modeling interesting and were self-motivated to enhance their skills. Having better CAD skills added to their confidence levels. However, these participants were very few.

Competent users also acknowledged the occurrence of circumscribed thinking. A participant mentioned, "No matter how much you know but there is always something you do not know. Every time I face such a situation I ask someone who knows. During a project, there was a particular curve that I could not get and since we had to 3D print the model it was essential to create a good model. So I asked a friend to make it in software and give it to me. But if that is not possible then yes people compromise on design because it is just not happening. It is very common". Advance beginners and competent users both suggested combining different software to help them achieve the desired results. The participants who use multiple

software mentioned that creating surfaces in more flexible software like Rhinoceros and further using it to trim the solids in parametric software like Solidworks, help combine the best of different software and overcome their limitations.

A participant working as a consultant shared that for complex designs, after achieving a close enough 3D model the design is given to the digital designers for further work. Digital modelers are experts in 3D modeling, simulations and creating animations and they produce the final deliverables. But this can happen only after the ideation phase is over.

Circumscribed thinking can also result when a designer gets driven by the way the model looks and his/her whole attention diverts into achieving the desired form. Another participant mentioned that sometimes you discover something new and because you can create certain kinds of things, one tends to deviate from the design brief. In such cases, critical details may be missed. A participant shared an experience, *"...working on a particular kind of safes for US-based client that demanded a lot of security. The material for this was really strong and the door itself was very heavy. So the hinges required for this had to be strong to take the load of the door. I was not good at mechanical simulation at that time. I was more focused on how to make it look appealing and pleasing. After the prototype was made the hinges tore like paper. That was a very big limitation".*

Proficient users had a more positive approach towards the inclusion and use of 3D modeling tools in the early idea generation phase. A participant who enjoys 3D modeling and is a certified professional shared that many times he thinks of form in terms of commands. This helped him improve his skills and now looking at any form he can define how it would be constructed in 3D software. All proficient participants agreed that as their skill levels improved, the compromises made in design decisions reduced. Still, a participant stated, *"In the back of my mind software is always playing a role in the way the forms will emerge. It happens and it should happen. Where will you get the 100% representation of what you are seeing in your*

head? Even for manufacturing, it changes. Even for tooling if you cannot give a certain radius you do not give". Two more proficient participants agreed that the tool could dictate the form one creates.

6.3.4.4 Other limitations

Participants expressed how CAD renders could influence design decisions. The way renders are made can direct attention to certain features and create false impressions. Three participants shared their concerns about how sometimes the senior management takes decisions based on the way CAD renders look. Two participants described that the clients perceive rendered ideas as final ideas and they intentionally make ideas look sketchier by editing the renders in Photoshop. Clients have to be continuously made aware of the design stage the project is in. A participant narrated, *"...if I have to make 5 CAD models and I have put the time in 3 and then due to time constraints I pay less attention to remaining 2 or drop them or not do justice to them. Now those 3 look better than the other 2. So we end up choosing from the 3 because they look better. So it has an impact on decision making"*.

6.3.5 Research Question-4: Does using CAD during idea generation results in more vertical exploration and hinders lateral exploration?

Following the previous questions (RQ2, RQ3) about the advantages and limitations that designers face during the ideation phase, RQ4 was designed to examine and explore the influence of CAD, specifically in the lateral and vertical aspects of design during idea exploration phase amongst the designers. The design process emphasizes the importance of lateral and vertical exploration in the initial phase of design to solve a problem at hand.

It was found that CAD is more influential and supportive in the vertical exploration process, irrespective of the proficiency level of the designer. The designers find CAD as an effective tool for the validation and refinement of the idea in a vertical manner. A participant shared his experience, "if you see the speaker concepts I made directly in CAD, there is not much variation. They are derivations of each other. All the speakers more or less belong to the same family. Whereas in glucometer case we made very different sketches and then moved to CAD that was derived from these sketches, so they looked very different". In other words, CAD is found more useful in the focused (advanced) phase of design, where the constraints are clearly defined.

Two participants mentioned that CAD is useful in vertical exploration in terms of styling aspects of design. It is easier to explore the results of incremental changes or variations of certain features in CAD. For example, exploring different colour combinations, trying various textures, refining and changing certain corner radii or chamfer, are much easier in CAD. The majority of the designers identified CAD to be more useful for vertical exploration in the advanced stages of design when manufacturing and material constraints are defined and the design direction is established.

Sketching/doodling is found to be more popular for the lateral exploration process. 'Flexible' and 'swift' nature of sketching is found to be the most indispensable influencers in the lateral exploration process. The approach also depends on the scope of the brief. A participant stated, *"...it is a new project then it is easier to go crazy and explore all the directions. In a redesign project you know you cannot go too far and you start directly in 3D and then do iterations"*. Two more participants shared if the brief is narrow it is easier to start with the 3D modeling whereas, for a broad brief many different directions are explored and a considerable time is spent before starting CAD modeling. Participants shared that in such cases, the time and effort required for creating a model from scratch leads to making only selected ideas in CAD. Speed of CAD modeling cannot match the pace of thoughts. Also, CAD

cannot support the scattered nature of thoughts since making a CAD model requires focused efforts.

Some participants however shared few ways in which they include CAD in lateral exploration. One of the respondents mentioned the use of the digital sculpting tool during the lateral exploration phase, which is less constraint-based, compared to the standard CAD tools. Two other participants mentioned the play approach in CAD as the lateral exploration tool to come up with variations in Form and Styling aspects of design. One participant mentioned the use of block models (less-detailed models) as lateral exploration techniques in the CAD environment.

Overall, CAD is well accepted as a tool for vertical exploration and formal refinements. It seems to be less supportive of lateral exploration and is far from matching the speed of thoughts.

6.3.6 Research Question-5: How does CAD affect the design outcome because of its intervention?

The focus of the study is the early idea generation phase of design. The design outcome in this question refers to the output of idea generation phase. RQ5 was designed to understand the effect of CAD on designer's thinking and how it affects their approach. While the previous research questions focused on the advantages (RQ2), disadvantages of CAD (RQ3) and the influence of CAD in lateral and vertical exploration (RQ4) in the ideation stages of design, RQ5 inquires the effect of CAD on the designers' fundamental approach- 'the conceptual strategy & structuring of design process', and the thinking- 'the active process of decision making at every stage', while using CAD as a tool in the overall design process.

Three questions were asked to find out how CAD influences designers' thinking while working on the design and in turn how it affects the final output of the design

process. The first question addressed two research questions RQ3 (limitations of CAD) and RQ5. It required participants to share if they compromise on the design for the ease of CAD modeling. This explored the occurrence of circumscribed thinking. The next question focused on understanding if the efforts required for CAD modeling can create boredom and frustration leading to dropping of certain ideas. The last question was designed to understand if the process of CAD modeling could shift the attention of the designer from designing to modeling, affecting the design outcome.

6.3.6.1 Design approach

It was interesting to find out designers need ambiguity in the ideation process, where the lack of clarity (low-resolution ideas/ less defined solutions) has a positive impact on the initial idea generation and design conceptualization process.

The majority of designers across proficiency levels mentioned that the fuzzy definition of ideas aid in the avoidance of fixation on that idea, both from the designer's and client's perspectives. One of the respondents mentioned, "*clients looked at the prototype and said that it is different from the concepts shown earlier*". This was the result of the client's fixation on the initial ideas where the client was not aware of the required changes that happen during the design evolution.

To keep the approach more open, designers who use CAD in the earlier stages of design rely on block models or less detailed models. The most preferred strategy amongst the designers to achieve the lateral approach is through sketching or through 2D software. As mentioned earlier in RQ3, 10 out of 12 Advance beginners, 5 out of 7 competent users and all the 6 proficient users mentioned that they use rough CAD modeling in the initial phase.

This is evident in one of the designer's responses *"when you sketch you can go in any direction. But in 3D modeling, you only refine ideas. So when we start a new project we go crazy and do a lot of doodling but for a redesign project we start with the basic building block and then refine it"*.

To conclude on the effect of CAD on the design approach (the conceptual strategy & structuring of design process), the responses indicate that the higher definition visualization of CAD in initial stages of design leads to fixation in design approach and design communication. Designers who use CAD in earlier stages prefer less detailed block models to keep open-approach to design.

It was observed that once the designers strategize their approach towards the larger goals of the design, they start working towards the selected concepts. This is the phase where iterations, refinement, validation and proactive design decisions take place.

6.3.6.2 Thinking

The responses for RQ5 informed that amongst designers, the term 'Thinking' covers two main aspects of the design process here i.e. Visual thinking (Formal aspects) and Functional thinking (technical aspects) that have a direct impact on the final output. Interestingly, the aforementioned 'less-effective' CAD tools in the idea exploration phase are found to be an essential tool in the 'Thinking' process. It is found that the designers prefer to eliminate the 'ambiguity' factor and move towards the higher definitions in their design for faster development, bringing clarity, enhancing their confidence and communication.

a) Visual Thinking

20 respondents mentioned that they find CAD to be an effective tool for visualizing complex form transformations and cross-sections. Remaining 5 respondents belonging to the advanced beginner level find CAD visualization to be time-consuming due to their proficiency level.

As mentioned in RQ2, CAD can help visualize complex forms and ideas that are difficult to sketch. It helps designers overcome the limitations of their sketching skills. A participant mentioned that the ideas in mind are always in 3D but he makes 2D orthographic sketches while externalizing them. Certain features like proportions, volume, large curvature surfaces, transparency, and textures are found to be difficult to express through sketches or would require a considerable amount of time. However, CAD can facilitate this with a command. The CAD visualizations are closer to reality; it eliminates ambiguity and makes representations more comprehensible. Majority of the designers find that CAD tools help them validating the aesthetic aspects of design through quickly manipulating the curves and transformations.

However, in RQ3 it was evident that many designers compromise on the formal aspect of the design for the ease of modeling. Combination of multiple software and seeking the expert help are some of the strategies adopted to minimize this effect.

b) Functional Thinking

This is where the designers find CAD to be irreplaceable. When it comes to the functional aspects of design, the responses mention that CAD is an effective bridge between design and engineering. Validation of volumetric and mechanical (technical) appropriateness of design is found to be more effective in the CAD environment than the other alternatives.

In the interviews, 12 designers with a higher level of proficiency in CAD cited the influence of CAD in the thinking process in terms of tolerances, mechanical interferences, the spatial relationship between components and manufacturing constraints. This is because proficient designers are more involved in the manufacturing stages of design due to their experience than the beginners.

Five of the designers mentioned that they build virtual assemblies of standard parts that are available in the CAD libraries. This is found to be time-saving in terms of error corrections and other manufacturing constraints.

Chapter summary

The final study involved interviews with professional product designers. The interview guide was drawn from the findings from pilot studies. The semi-structured interviews conducted one-on-one in an informal setting allowed designers to reflect on their practices and share their experiences. The interview data were coded and further analyzed with the help of MaxQDA software. The findings from the study helped answer the research questions.

The chapter discusses the objectives of the final study, study framework, analysis method, and coding scheme. It also shares the experience of using MaxQDA for analysis. Further, the chapter discusses findings drawn from the study and how it answers the research questions.

A sample interview transcribe is presented in Annexure-V. Sample of retrieved coded data is presented in Annexure-VI.

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Chapter 7
Consolidated findings and discussions

The chapter discusses the findings from the literature review, pilot studies and the main study with respect to the research questions. It also separates the new findings from the findings that confirm the literature.

7.1 Revisiting the research question

The purpose of this research was to investigate how CAD is used in the idea generation stage of product design and to identify the enablers and barriers that it triggers. The idea generation stage is the most fluid stage in design where thoughts are not concrete and the mind needs to be free to wander into the problem-solution space in search of new ideas. Any tool that may demand too much of mental space can affect the idea outcomes.

The literature establishes the use of CAD in the concept development stage. It is an excellent tool where ideas are already defined and needs development and prototype testing. CAD supports prototyping through CNC machining, rapid prototyping, and 3D printing. It supports simulations to check the ideas for failures and optimization. However, very little literature was found discussing the use of CAD in the fluid idea generation stage especially in the discipline of product design. Today, presenting ideas through CAD models and renders has become an unsaid norm in the product design industry.

Most of the literature that discusses the use of CAD in the early stages of design compares it to conventional tools like sketching and physical modeling. Today, the design environment is not about sketching and physical prototyping versus CAD. Rather it is a mixed-media environment that includes sketching, digital sketching, quick mock-up making, 3D scanning, digital model making (CAD) and CAD supported model making. Based on the resources available a designer evolves his/her working methodology. Thus, this study focuses on the use of CAD in the idea generation stage in a mixed-media environment.

This led to defining the main research question as,

"How does use of CAD affect creative exploration during idea generation stage of product design?"

To answer this question, it was further broken into five smaller research questions. These are:

RQ1: How does CAD positions itself in the idea exploration stage of the design process?

The question tries to establish an understanding of the mixed-media environment and how CAD positions itself in the design process with a focus on the early idea generation phase. The question was designed to understand how and when CAD is used in the idea generation phase.

RQ2: What advantages CAD offers to the designer if used in the early phase of the design?

RQ2 focuses on identifying the advantages (if any) that CAD may offer in this context. Whether it enriches the ideas or assists the thought process or adds any value to the process and outcomes for the designer.

RQ3: What limitations CAD impose on the designer's way of thinking?

It tries to understand the limitations of using CAD in the early idea generation phase. Whether it restricts the thought process or curbs the exploration space or has a negative impact on ideas.

RQ4: Does using CAD during idea generation results in more vertical exploration and hinders lateral exploration?

RQ4 probes a very important question of lateral versus vertical exploration. The design process emphasizes on having lateral exploration in the early phase of design to ensure that all the possible directions of solution-space are explored. Lateral exploration is essential to the creative idea generation process. The question tries to understand whether CAD is supportive to lateral exploration as well as vertical exploration or not.

RQ5: How does CAD affect the design outcome because of its intervention?

RQ5 was designed to understand the effect on the ideas as a result of a mixed-media environment involving CAD. However, after the study it was realized that the question is answered through RQ2, RQ3, and RQ4, making it redundant. Before the final study, the researcher felt that other questions would focus on CAD and the process of designing and modeling whereas RQ5 would focus specifically on the result of the process. However, the other questions not only covered the process but also the results derived from the process. Thus, for this section on findings and discussions, this question is eliminated.

7.2 Answering research questions

The following sections discuss the findings for the 4 research questions.

7.2.1 Learning addressing RQ1: How does CAD position itself in the idea exploration stage of design process?

The initial phase of design is highly creative and fluid. Multiple ideas are visualized, externalized and evaluated at this stage and based on the analysis further iterations are done. An idea could be holistic or in pieces.

In the pilot study with students and professionals, it was evident that most of the designers use keywords and doodles to record their thoughts. In the spoon exercise with one professional, he had a mix-and-match approach where the ideas were broken down in terms of elements. The ideas for spoon handle and ideas for spoon bowl were explored separately in the form of low-resolution sketches and designers tried to bring them together in the model. The ideas that were realized in the CAD model, whether explored directly or doodled first and modeled later, were all holistic. It was interesting to see the approach that was adopted while exploring ideas using low-resolution sketches and keywords differed completely while exploring ideas in CAD. The approach in CAD was more towards making holistic ideas through rough or not-detailed models. It was fascinating to note that while CAD modeling the designers looked at ideas as a whole or in total while during sketches he allowed segmented exploration.

Even in the final study designers discussed the use of doodles, keywords, and notes to record their thoughts and further 3D modeling for defining and representing their ideas. The tools used in the mixed-media environment include sketching (manual and digital), 3D modeling and physical models making (manual, laser cutting, and 3D printing). Designers today are integrating CAD with other tools to overcome the

limitations of a single tool. The use of CAD models in the background for sketching or sketching directly in the CAD environment are some of the ways of combining different tools. 3D printing and creating rough CAD models to visualize the volume is also a common practice.

The proficiency of the designer has a direct impact on their approaches. The proficient users are more comfortable and confident about exploring ideas directly in CAD and may work on CAD and rough sketching in parallel. In the pilot study as well, the designers who started exploring their ideas directly on CAD were proficient users. On the contrary, most of the advance-beginner users mentioned the need for having some starting point and basic clarity of idea before proceeding to CAD modeling.

The approach and inclusion of CAD in the process also depend on the vastness of the brief. A redesign project could start with the model of the existing design or the skeleton. A project with narrow brief and clearly defined constraints may start by building a block model of internal components. Timeline available for a project can also direct how soon a designer would start defining the ideas in 3D. A more open brief and relaxed timelines provide designers more time to explore different possibilities before having to define ideas. Another aspect is whether the brief requires functional-thinking and problem-solving or it needs formal exploration only. The definition of exploration space available defines the way CAD would play a role in the idea generation. In a narrowly defined exploration space, one can start by building up the internal components in CAD and put those together before exploring the formal aspects of it. Whereas, in an open brief and problem-solving situation one might start exploring the various possibilities and CAD may enter the ideation stage much later once a certain direction is selected.

Rough CAD modeling in the initial phase of design can help understand the proportions and volumes and comprehend the spatial relations between various components. Iterations can be created using the base model in a short time and with

less effort. Use of same base model, options to execute iterative work with one command can reduce the workload of the designer.

However, the other perspective found during the study does not support the use of rough modeling in the initial phase of design. Some participants expressed that the time required to create a model is so much that they would prefer to create a CAD model only after a certain level of clarity is achieved. Though this was not a common opinion it does provoke an interesting point to the type of software designers are using. CAD software that can allow quick explorations with a more intuitive interface can change this perception.

7.2.2 Learnings addressing RQ-2: What advantages CAD offers to the designer, if used in the early phase of design?

Literature defines visualization, communication, and collaboration as the advantages that CAD offers at all the stages of design. The study helped define how these advantages are realized in the early idea generation stage. The other advantages identified in the study were increased confidence, achieving better clarity, enhanced understanding of spatial-relationships between various components, quick representation and improved ability to handle complexities. Designers also revealed that the use of CAD for form explorations could lead to certain discoveries and help generate newer forms.

7.2.2.1 Visualization

Visual thinking and externalization of ideas play the key roles in the idea exploration phase. CAD interface provides an array of tools to enhance the visual experience. It allows a designer to view an idea in three-dimensions, look at cross-sections, zoom-in or out, rotate, pan and adjust the transparencies. The changes

made on the model are instantly visible and changing values provide instant visual feedback. It facilitates designers to take the design decisions visually.

CAD can assist in visualizing complex forms that are difficult to sketch. It assists designers to overcome their sketching skills. It was found during the pilot experiment and was confirmed through the interview study that designers weak in sketching rely heavily on CAD to represent their ideas. Certain features like large curvature surfaces, transparency and textures are found to be difficult to express through sketches or would require a considerable amount of time. However, CAD can facilitate this with a command. The CAD visualizations are closer to reality; it eliminates ambiguity and makes representations more comprehensible.

The CAD models can help understand the spatial relations between different components and how they interact. An interesting incident of role-playing in the CAD environment was observed during the pilot experiment. Checking for interferences, understanding the space utilization and various movements are few more added advantages. CAD visualization can also aid explorations in cases where making quick mock-ups are not possible as in extremely large products and very fine and precise designs.

7.2.2.2 Communication

Communication of ideas is facilitated by the effective visualization aided by CAD representations. Even with rough models CAD removes the ambiguity from the representations and adds more clarity to design. The participants in the pilot experiment as well as in the final study identified communication as a key advantage. It helps overcome the limitations of language, allows one to make real-time changes and facilitate decision-making. CAD representation help communicate their design ideas more effectively to higher-management and technical teams. As mentioned by many participants, the CAD representations have become an unsaid

norm for presentation and communication in the industry. The physical model is also favored but since making physical models is more time consuming and instant changes cannot be done in those, digital models are preferred particularly in the early phase of design. Digital models also enable collaboration and discussion amongst the globally disbursed team.

7.2.2.3 Other advantages

CAD representations help remove ambiguity and overcome the sketching skills of the designers. Many students, as well as professional designers, emphasized that communicating through CAD representations make them feel more confident about their ideas. Some designers expressed that bad representation can lead to the rejection of a good idea, hence it is essential to represent the ideas nicely and CAD is a very effective tool for the same.

During the pilot experiment, it was noticed that some students who are not very fluent in English also rely on CAD representations as an effective representation does not require elaborated explaining. Good visual representations can eliminate the limitations caused by the lack of fluency in the language of communication.

CAD was also found to be supportive of exploring new ways to create forms. During the pilot study, students were observed exploring certain transitional forms in terms of CAD commands. In the final interview study, participants mentioned various instances where they discovered certain forms only because of using CAD as a tool. A participant also stated that CAD helped him enhance his spatial visualization overtime through practicing complex form transitions. CAD can help designers expand their exploration space.

How CAD can assist designers in their process depends broadly on their proficiency. Proficient users mentioned that it assists them to explore much faster and helps

create multiple options. CAD can eliminate the need for physical prototypes in the exploration stage and if needed can facilitate it through 3D printing or rapid prototyping. This can save a lot of time spent on physical prototyping. Further, since multiple options can be explored on the same base model, it allows designers to spend more time on designing.

7.2.3 Learnings addressing RQ-3: What limitations CAD impose on the designer's way of thinking?

Circumscribed thinking was identified as the biggest limitation imposed by CAD. Few more limitations like fixation, size perception, time requirement, software limitations, and cognitive load were also found as limitations during the study.

7.2.3.1 Circumscribed thinking

The evidence of circumscribed thinking was not only visible in the pilot experiments but also was widely acknowledged in the final interview study. It occurs when a designer compromises on the form or a feature of design due to proficiency or the tool limitations. The occurrence of circumscribed thinking is more evident in designers with lower proficiency levels for apparent reasons. Participants mentioned that they would prefer to spend more time in exploring realizable ideas than spending time on exploring how to create one particular model.

The CAD is very supportive in exploring the functional aspect of design. It can bridge the gap between design and engineering. However, it is very supportive in exploring and representing formal aspect as well but the extent to which this can be done depends a lot on the proficiency of designer.

During the pilot experiment the students were trying to finish the assignment and professional designers did not have any commercial commitment. The nature of

design exercise was more experimenting so participants spent more time exploring and when they could not achieve the intended form, they left it. However, in professional projects, the designers must achieve a certain level of finesse. They are required to deliver the design and hence if they cannot make it, they are willing to change the direction.

CAD programs also have limitations and might not support the exploration of certain forms in an intuitive way. Most of the participants were found to be using two or more CAD software in practice. Designers combine different software as one of the strategies to overcome this limitation.

7.2.3.2 Fixation

During the pilot experiments, it was difficult to probe into fixation due to CAD representations. The main reason was the time-bound design exercises and the non-requirement of any commercial commitment. Therefore, the questions were included in the final study to understand if the CAD representation can lead to fixation or not.

Many participants believed that clearer you see the ideas, lesser the interpretations and more the feeling of moving towards completion. Looking at the computer screen does not trigger more ideas and requires designers to go back to the drawing board to seek fresh thoughts. Seeing an idea in CAD can lead to fixation due to the realistic visualization. However, the absence of ambiguity in representations was also appreciated as an advantage for communication purposes. This explains that till the purpose of representations is to record a thought and interaction is limited to the designer with him/herself the ambiguity in the representations is appreciated. When the representations are required to be communicated to someone else a clearer and unambiguous depiction is preferred.

Other reasons that can cause fixation were cited as a certain level of details achieved in the early phase of design and time-crunch. After having spent a considerable amount of time and effort in a particular direction there is a hesitation to start afresh. Furthermore, if a certain level of detailing is achieved, designers can get committed to these. Many participants agreed that the way model looks could make them feel committed to certain ideas.

The use of rough modeling helps avoid fixation due to early detailing. It was found to be a common practice amongst the participants. Participants mentioned that when the goal of modeling is to only explore different directions and one does not get attached to it, it is easier to move away from the same.

Some participants who move to 3D modeling only after achieving certain clarity on the paper stated that once they move to 3D modeling there is already a commitment to the idea. At this stage, they do not like to make major changes in their designs.

It is not only the designers, but the clients may also get fixated to certain ideas due to the realistic nature of the representations. The way CAD models are rendered they may direct the focus in a certain direction and influence design decisions. It was found that the designers purposefully make the renders look sketchy using Photoshop to help them convey to the clients and higher management that the ideas are in the exploratory stage of the design.

7.2.3.3 Size perception

During the pilot experiment, it was observed that designers were referring to the ruler while defining the dimensions on the screen. In the final study, practically all the participants agreed that they have faced the problem of perceiving sizes on the screen. Participants narrated various incidences where the design turned out to be unergonomic or out of proportions and this was realized only after prototyping. On

one hand, where the CAD interface can assist designers to handle very small to very large scale on the other it may cause issues of understanding the physicality of these sizes.

Additionally, the project brief and previous experiences have a role to play in this context. A redesign project has reference products for understanding and gauging the sizes whereas; a new project needs to be continuously evaluated at various stages through prototyping and true-scale drawings.

Designers shared different strategies that they employ to overcome this limitation. The strategies include keeping rough blocks of Styrofoam or other soft material and ruler handy. For communication purposes and putting the correct perspective, many designers use the material library with mannequins, human-hand and small known products like credit cards or matchbox. They use these reference models next to their designs for rendering and communication purposes. Sometimes the model is zoomed close to the actual size on the screen, which is gauged with the help of a ruler, and designer can put his/her hand or a reference material against the screen to understand the size.

This presents the possibility of a new feature in 3D modeling software. If one can zoom to print size in 2D software, why a 3D modeling software cannot have the same feature? The modeling window can have a ruler feature in different measuring units. The software can come with a material library with inbuilt models that can be used for reference. Multiple opportunities can be explored to minimize this limitation.

7.2.3.4 Other limitations

Many designers use two or more software to assist them to achieve the desired results. Learning and achieving certain proficiency in each software requires

investment in terms of time and effort. There is no common interface or modeling strategies between various modeling software and there is a hesitation in moving from one software to another as it requires the designer to move out of their comfort zone.

Extra work and time need to be invested in making the representations look sketchy to communicate the initial phase of design. The use of rough modeling in the initial phase was evident. If the software can support the sketchy rough modeling and sketchy representations and further allow the same files to be developed into the more detailed design concept, it will save time and efforts of the designers.

Another limitation identified was the time required to create each model. This can lead to fewer ideas to be generated, which is not favorable in the initial phase of the design.

When making a CAD model, the designer is more focused on the holistic view of the design and the focus keeps shifting between the modeling strategy and design decisions. The shift is more when the designer is not a proficient CAD user. Also, continuous failure to create something can lead to boredom and frustration. Though not many users acknowledge rejecting certain ideas due to boredom but some designers at advance beginner level agreed that it may cause frustration. However, if the design needs to be delivered it has to be made and feeling bored or frustrated cannot be used as an excuse, cited a participant.

7.2.4 Learnings addressing RQ-4: Does using CAD during idea generation results in more vertical exploration and hinders lateral exploration?

CAD is an excellent tool for refining and exploring ideas vertically. It was found to be very supportive of vertical exploration irrespective of the proficiency level of the

designer. It has proven to be very useful at a slightly advanced stage where the idea has been shortlisted and refinements are required to be done.

CAD is also beneficial for repetitive work like creating arrays and tessellations. It can help explore multiple combinations and positioning of different elements and try alternate colors, textures, transparencies and other surface finishes. It can reduce the efforts and time required for trying such alternatives and doing repetitive work.

However, it is not found to be flexible enough to support lateral exploration. Further, the time required to create separate models from scratch can lead to fewer alternatives. If the same components or the base model are used to create alternatives the CAD can facilitate faster exploration. However, this would lead to more vertical results. On the contrary, if different ideas need to be generated as separate CAD models the time required would be more and might lead to fewer alternatives. Since only the selected alternative might be taken further, there can be a hesitation to invest the same amount of time and efforts in the alternatives.

7.3 Summary of key findings

1. CAD is used in combination with other tools in the initial design phase. It is one of the essential and integral tools in the process of design including early idea exploration stage.
2. Rough CAD models are created to understand spatial relations, volume, and proportions in the initial design phase. Rough models also help designers to not get attached to the idea and avoid fixation. If the advance level of detailing is achieved in the initial phase of ideation, it can cause reluctance to deviate from the idea resulting in fixation.
3. Designers who lack sketching skills rely heavily on CAD modeling for presentation purposes. Rough models support communication and aid confidence in presentation.

4. Proficient users are more comfortable exploring their ideas directly on CAD and including it in the early stages of explorations. Whereas, advance-beginners prefer to achieve a certain level of clarity in ideation before moving to CAD modeling.
5. The vastness of design brief and exploration space also influence the role CAD plays in the ideation phase. When the exploration space is narrow the designer might start with a CAD model. On the contrary, for an open brief, the explorations start with brainstorming and searching different alternate direction before starting with CAD modeling.
6. The advantages were identified as visualization, communication, collaboration, increased confidence, more comprehensive idea, quick representations and improved ability to handle complexities. CAD models can help understand the spatial relations and interaction between different components. It eliminates ambiguity and makes representations more comprehensible. CAD can support exploring products where making quick physical models are not possible as in extremely large and very fine/small and precise designs.
7. Circumscribed thinking, fixation, perceiving sizes, time requirement, and cognitive load were identified as limitations caused by integrating CAD in the early idea generation phase.
8. Circumscribed thinking was identified as the biggest limitation. Professional designers are under pressure to deliver designs with certain levels of finesse. If the design is too difficult to model, designers compromise and simplify it to make it easier to model. Some participants also mentioned that they would only generate the ideas that they can model. The limitation is highly depended upon the proficiency of the designer. Many designers use more than one CAD programs to cope with this limitation.
9. Many participants believed that clearer you see the ideas, more the feeling of moving towards completion causing fixation. The commitment to certain ideas can also be caused by time and efforts invested in making it and the way the model appear. The CAD renders can also be created to direct the

attention towards a particular feature and influence decisions. Realistic renders can also cause fixation in clients. The renders need to be touched up to look sketchy to communicate about the initial exploratory stage which in turn requires extra efforts and time invested.

10. On one hand, CAD allows the users to handle a vast range of dimensions (from very large to very small), on the other looking at the screen it is difficult to comprehend the actual size, grip, volume and texture of the design. Participants identified this as a limitation of the tool.
11. CAD is a very supportive tool for vertical exploration. It can save a great amount of time in creating variations of an idea. However, it is not very supportive of lateral exploration. Creating completely different options would require more efforts and time.

Chapter summary

The chapter brings together the findings from two pilot experiments and the final interview study and tries to comprehend them concerning research questions. The research questions are revisited and the rationale behind the question is explained. The findings are summarised to answer each question based on the studies conducted. In the end, a summary of key findings are presented.

Chapter 8
Conclusion and Research contribution

The chapter concludes the work carried out as a part of this research, a summary of research contributions and suggestions for future work. The qualitative enqiry helped in removing the ambiquty and apprehensions for the use of CAD in the early stages of product idea generation .

8.1 Research contribution

The findings of this study highlight how CAD finds its role in idea generation stage in the context of product design. The idea generation stage is the most fluid stage in the process of design, where ideas are explored in various directions. CAD tools today are an integral part of a product designer's environment. Therefore, the study focused on studying the implications of using CAD during the idea generation stage in conjunction with other tools.

The findings reinforced that ignoring technology in the design process is not necessary and with the right approach and considerations it would be a winning proposition The digital modeling and digital sketching tools have become an integral part of the design process, even in the early exploratory stage. Designers today use multiple tools in combination, and one needs to understand the advantages and limitations of this mixed-media environment in the process of design.

8.1.1 Contribution to Design research

The research helped evolve a qualitative research methodology to understand the designer's approach through design tasks and rich, in-depth interviews. The pilot study conducted with professionals helps understand ways to interpret and analyze a design activity. The video recorded and desktop recorded design activity was transcribed and narrated step-by-step, and occurrences of study parameters were visually mapped onto the same. The study also used multiple sources of data i.e., CAD models, sketches, video recordings of design session and audio recording of interviews for the purpose of analysis.

Additionally, to classify the participants based on their proficiency levels, the Dreyfus model of skill acquisition was used. This was deciphered for the *SolidWorks* proficiency levels based on their certified exam levels. This can help other researchers to translate other skills in terms of proficiency levels for their study.

Further, the interviews helped to collect rich data as it allowed the designers to recall their past experiences, quote instances from their on-going projects, and reflect on their practices. *MaxQDA*software was explored for coding and analysis purposes. The study elaborates on the process for the same.

8.1.2 Contributions to design pedagogy

The young designers must be made aware of the limitations and advantages of tools they use. Students rely on the software to represent their ideas neatly with a concern to secure their grades. A teaching strategy on how to develop and teach a design methodology that would inform students about the scopes of various tools they use and help them develop their design methods would help create better and more aware design professionals.

Students are not only taught skills, but they are trained to be able to think out of the box. Most of the design exercises focus on producing the end results. The research contriubutions can inspire the development of tools that would help students record their thoughts while developing an idea and help in mitigating the disadvantages by remedial measures.

8.1.3 Contributions to design practice

The study informs the current practices and various strategies adopted by the designers to overcome the limitations. It helped understand how designers accommodate CAD in their exploratory process in combination with other tools like sketching and physical modeling. It strengthens the view that CAD has become an integral part of the design environment and is extensively used even in the idea generation phase of design. It can make designers more aware of their processes and help them develop it further to maximize the results. The research area was focused on product design as much literature was found related to Architecture and Engineering, but very less data was available related to product design.

The study informs designers that their proficiency has a significant impact on their approaches, and it is essential to accommodate a system to work towards improving one's abilities consciously continuously. Dreyfus's model of skill acquisition mentions that most of the users of any skill are at the advance-beginner level, and they do not move to the next level unless required or driven (Honken, 2013). The barriers that designers need to be aware of and be cautious of are circumscribed thinking, fixation, limitations of size perception and design decisions led by the realistic renders.

The study revealed that CAD is an excellent tool for vertical exploration and design refinements. If the design brief is narrow or requires variations of particular concepts, CAD can assist the designer in achieving multiple options through

incremental changes. However, CAD was not found to be very supportive of lateral exploration. Lateral exploration is vital in the idea generation stage. The speed of CAD modeling cannot match the speed of thoughts. During CAD modeling designer's focus keeps shifting between the modeling process and design decisions. When the design is challenging, considerable time is spent on exploring ways to create the intended form. More time spent on this may lead to frustration and boredom or circumscribed thinking. Especially with pressure to deliver, the less proficient designer is bound to compromise on the design to perform. This raises a big concern and needs to be addressed in the process.

On a positive note, CAD can aid visualization and communication. It helps boost the confidence level in the designer and make ideas more understandable. CAD interface has various tools to support visualization and can help improve spatial visualization in the designer over time. It can handle complexities and scales with ease and help designers communicate the same to the other team members or stakeholders. The visual representations eliminate ambiguity in presentation, help overcome language limitations and make communication more comprehensive.

Seldom CAD can also lead to discoveries. Participants shared their experiences where some designs were the result of accidental discoveries resulting because of particular CAD command or a mistake. The use of standard components or material libraries can aid the development process. Further, 3D printing and rapid prototyping reduces the efforts required in making the prototypes leaving more time for designers to spend on designing.

8.1.4 Contribution to CAD software

CAD is not recognized as a creative tool. Instead, it is said to have a negative impact on creative exploration. The study establishes the extensive presence of CAD in the design process in practice with various limitations and advantages that it offers.

However, the tool still does not align with the thinking and the working strategies of designers. Understanding the limitations faced by designers can help developers achieve better CAD programs that align with the requirements of the designers in the early idea generation phase.

8.2 Limitations of the study

This research was based on the qualitative study of the designers through design tasks and interviews. This limited the number of participants that could be involved in the study. The pilot study with design students had 10 participants. Whereas, pilot study with professionals employed 5 participants. The process of analysis was extensive, iterative, and in-depth. Transcribing interviews, transcribing videos to record each step, and analyzing these with CAD models and sketches was very strenuous. However, the data that it provided was rich and extensive.

Further, the interview study was conducted with 25 participants. The interview durations vary from 30 min to an hour. The lengthy transcribes provided rich narratives that high-lighted many vital points and led to interesting findings. Yet, a limitation in order to generalize the results is evident and opens up the possibility for future scope.

In order to achieve comparable results, it was ensured that all the participants use SolidWorks 3D modeling software as one of the tools available. The study could not cover the variety of 3D modeling tools. This was one of the limitations faced that also made it challenging to find the participants.

8.3 Future scope for research

The study tries to plug the gap in the literature by providing inputs on the approaches, design methods, and limitations and advantages of CAD in the early

phase of product design from the designer's perspective. It opens up many areas of further research.

Since the study was based on qualitative analysis, the results were not quantified. Future studies can further the work by quantifying the research to generalize the findings. Also, it was ensured that all the interview participants use SolidWorks as one of the tools. The 3D modeling software employed for the pilot study was also SolidWorks. A more comprehensive study can be done employing different 3D software and comparing them for the suitability for designers in the idea generation stage.

Designers were found to be using different software for different requirements. Tools can dictate the design language of the ideas generated. Research on why and how the software is selected can be undertaken to identify the selection criteria further. This can also help develop one comprehensive CAD software that could address all the needs of a designer for exploring his/her ideas.

It was found in the study that designers do not hesitate to change the design for the ease of modeling. Their proficiency levels had a direct impact on their ideas, limiting their exploration space. The problem would be more prominent in their early stages of using a particular software. Research on how to curb this limitation and support further learning to enhance the proficiency level of the designer would enhance the user experience of the tool.

Dimensions and proportions are important even in the early stage of design. Various features like providing ergonomic data, clear ideas about the actual sizes, multiple strategies to create the same form, a more intuitive interface that can interact with designer and product library, can be developed and tested to understand how the creative explorations can be supported. The features should allow designers to spend

more time on thinking and less on developing strategies to create a model or on finding mundane data.

The study establishes a method to conduct qualitative research in the field of design. Similar research in the various fields of design like fashion, interior, communication, and craft can be undertaken to find the similarities and dissimilarities in the practices. This can further inform pedagogy and software development for such areas.

8.4 Reflection on the journey

The research helps understand how the design approach is evolving with various tools being used in conjunction and how the approaches differ based on the vastness of brief. It highlights the concerns raised by the limitation of using CAD in the exploratory phase of design. The research also highlights the advantages of using CAD as a tool in idea generation. The researcher does not favor or oppose the use of CAD in the fluid phase of design but is just trying to investigate the role it plays in this phase.

This research had been an enriching journey that has helped broaden my perspective as a designer. Through this journey, I learned the rigor of research, which has complimented my reflection on design practice. As an academician, it has deepened my understandings and has brought a systemic and disciplined approach in my thinking further enriching the pedagogy.

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Annexure-I

Pilot study with design students

This annexure outlines the outputs by all the 10 participants.

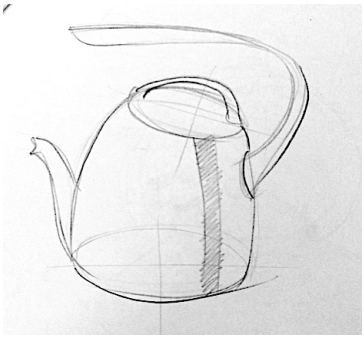
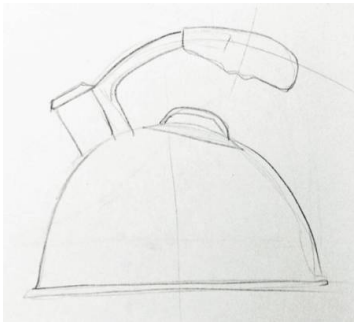
Participant-1

Average time taken for each sketch – 3 – 4 min

Average time taken for each model – 45 - 55 min

Explorations:

Table 9.1: Designs produced by participant-1

Intent	Output	Reflection
		Design refinements at feature level took place. Overall idea remained same. Reflections on the surface, material property helped convey design intents well
		Metallic finishes and different textures used for the body and lid with plastic grip could communicate the designer's intent well in this case. Small changes while modeling made the design more refined.

Other sketched ideas by participant are shown in figure 9.1.

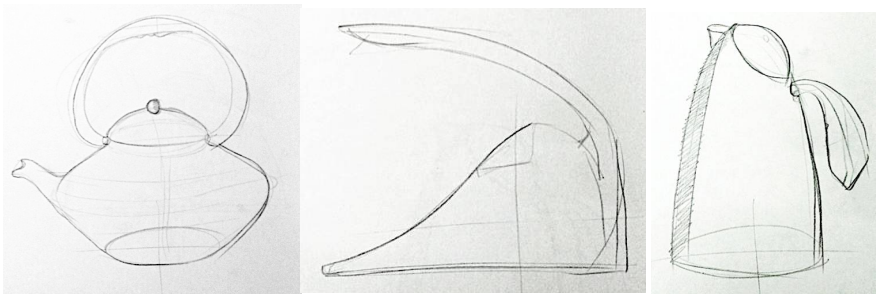


Fig 9.1: Other ideas recorded in form of quick sketches by participant-1

As can be seen in the sketch in the center, the cross-section and overall form of the product are not conveyed well in the sketch. Participant fell short of time and could not attempt to explore the form in 3D for that option. Exploring the textures and material finishes helped him get a realistic image of the idea.

Participant-2

Average time taken for each sketch – none
Average time taken for each model – 30 – 35 min

Explorations:

Fig 9.2: Designs produced by participant-2

Out of all the participants this student was the only participant who did not sketch and started exploring his ideas directly on the computer. He mentioned that ideas are in his mind and he can visualize them and directly replicate on computer. The question here is *whether idea was thought of before he started modeling or he actually explored and formulated idea while modeling or was it partially planned and partially explored on CAD?*

It may be noted here that to him CAD provided a platform where he can comfortable interact with his ideas and did not feel that it can / does interfere with his thought process. The first two options that he explored (as shown in figure 9.2) remained incomplete and he decided to move on to explore other two ideas instead of finishing the first two options.

Form wise; he stayed with basic and simple to produce forms. Since the form looked finished, student moved onto the next form without exploring the initial idea in more depth and make further refinements to it. This could also be because of the time constraint and cannot be proved completely as premature fixation, though it does indicate towards it. The iterative nature of design was missing in his approach.

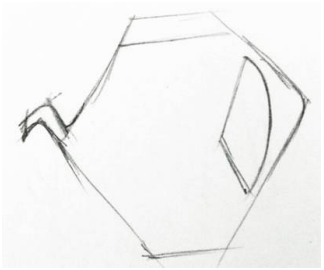
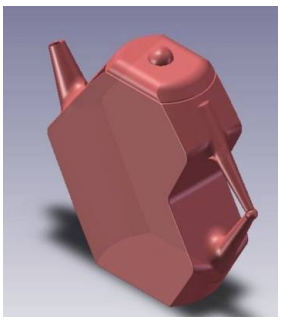
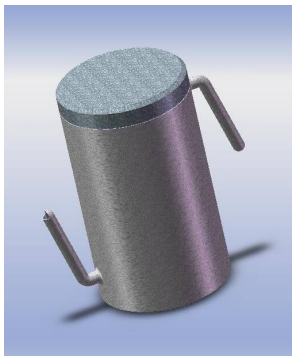
Participant-3

Average time taken for each sketch – 2-5 min
Average time taken for each model – 45 min

Explorations:

Table 9.2: Designs produced by participant-3

Intent	Output	Reflection
		Difficulty in drawing an organic form in perspective is visible The idea remained unfinished. Organic forms require more time and efforts to explore.

Intent	Output	Reflection
 	 	Handle in the sketch was more usable as compared to the one in the model. The bottom sketch shows the difficulty in drawing the perspective view. Participant acknowledged the ease of creating multiple views from different angles as an advantage. Participant proclaimed his lack of sketching skills and mentioned that CAD renders make him feel more confident about presenting his ideas.
		Attention to usability missing. Output and intent are on the same lines, so it cannot be claimed that the lack of modeling skills clouded rational thinking.

Intent	Output	Reflection
		A cork texture applied to body. Participant mentioned getting excited by the choices of colours and textures available and chose the one he liked without any rationale behind. No consideration for usability given to the design of handle and spout. Still it cannot be claimed that the thinking was clouded by the use of CAD tools as the sketch itself has no usability considerations. What may still be noted here is that the finished rendering that is generated by CAD gives participant a confidence to present his ideas.

Considerable changes took place while translating a 2D sketch into a 3D model. Question that arises here is, *are these changes intentional or accidental or result of circumscribed thinking?*

None of the ideas that were produced by this participant showed any considerations for usability. *Is this an example of circumscribed thinking? Are tools driving designer's decision so much that they are not applying their logics? Or is this just a rough exploration without any considerations for usability?*

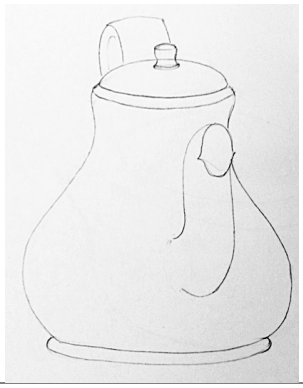
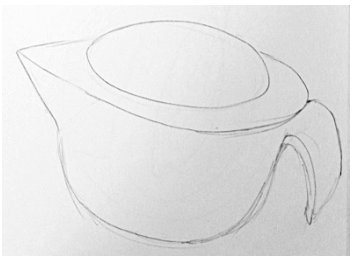
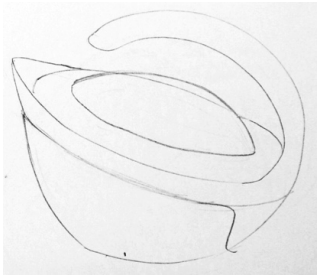
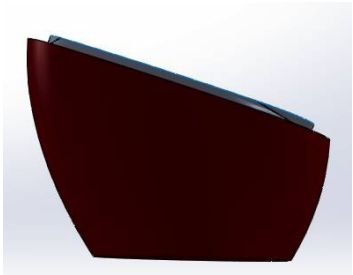
Another important observation is that the participant's sketching skills were weak and CAD provides him with a platform where he could communicate and express his ideas more confidently. *Are students using CAD to compensate the skill they lack (in this case sketching skill)?*

Participant-4

Average time taken for each sketch – 4 - 6 min + 20 min for initial thinking
Average time taken for each model – 45 min

Explorations:

Table 9.3: Designs produced by participant-4

Intent	Output	Reflection
		The hollowness and formal refinements are missing in the 3D image. It is visible from the image how proficiency level of participant affected the design outcome
		Design refinements are visible. Design iterations carried out. Excessive use of colors and material property visible.
		Incomplete form. Participant fell short of time and found the form little challenging to explore.

Other sketches by participant are shown in figure 9.3. The sketch on left does not convey the overall form of the product well and both the sketches show partially thought of ideas.

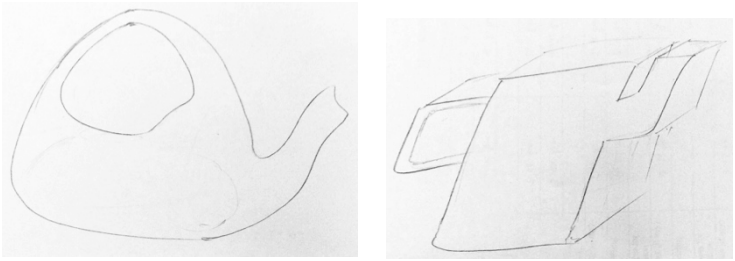


Fig 9.3: Other ideas recorded with sketch by participant-4

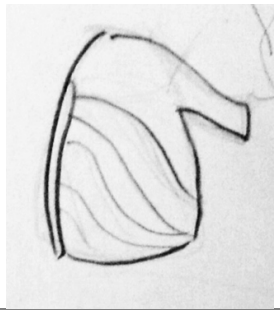
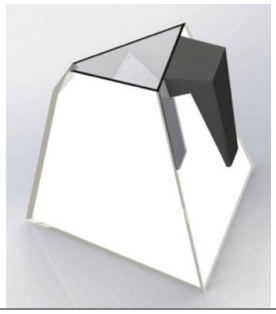
It is visible that proficiency level of the participant has a direct impact on the ideas produced. Also, when the tools provide more opportunities like usage of colors, transparency and textures, it causes an excitement. Sometimes, user may get driven by this excitement and try to exploit these features by over-using them. This is another example of circumscribed thinking where user ends up introducing unnecessary details.

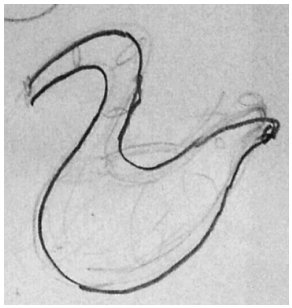
Participant-5

Average time taken for each sketch – not logged
Average time taken for each model – not logged

Explorations:

Table 9.4: Designs produced by participant-5

Intent	Output	Reflection
		The design completely changed from sketch to model.

Intent	Output	Reflection
		The design does not look like a kettle and its usability may be questionable but particpant used CAD to explore rough form and wanted to explore organic forms in CAD.

Other ideas by participant are shown in figure 9.4.

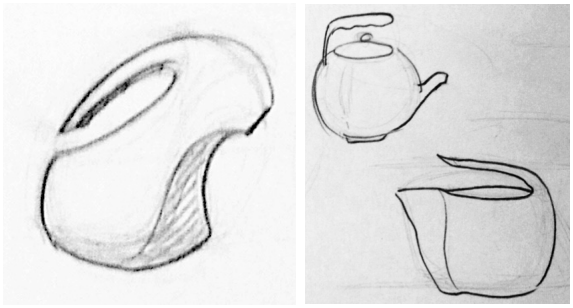


Figure 9.4: Other ideas recorded in sketch by participant-5

Participant made extremely small, thumbnail like doodles. That probably saved him time but showed the lack of confidence in making clear sketches. He also used CAD to explore rough forms that may not look like the end product.

Another interesting observation was the shift in thinking process. *Loft* command was one of the basic commands taught to students. The doodles shown in figure 9.5 depict how student planned to produce a form using two different cross-sections and the center guideline. However, he did not explore the idea further.

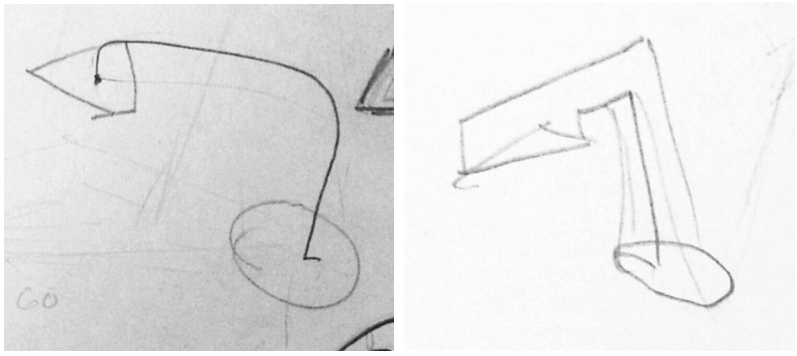


Fig 9.5: Loft command used for visualizing a new form by participant-5

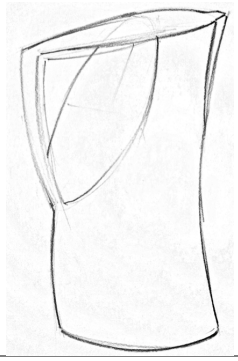
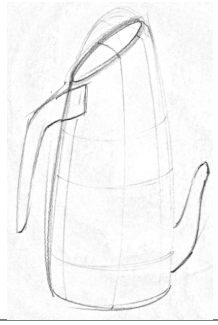
Participant-6

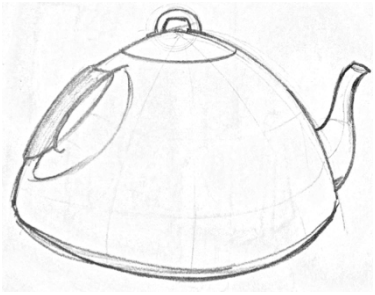
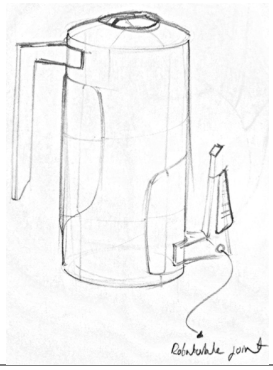
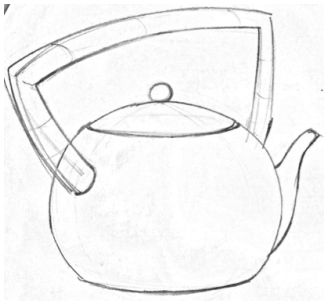
Average time taken for each sketch – 3 – 6 min

Average time taken for each model – 20 – 25 min

Explorations:

Table 9.5: Designs produced by participant-6

Intent	Output	Reflection
		Minor changes in design from sketch to model but overall idea remains same. Rough exploration without any hollowness and seprate parts
		Minor changes Attention to usability missing The flaring at spout end could not be made Solid one piece

Intent	Output	Reflection
		Similar but refinements missing due to proficiency limitations Faced problem in creating spout More defined than the previous models
		Attention to usability missing Effective translation from sketch to form
		Spout does not flush the way it was sketched. Compromised on design due to modeling skill limitation

This participant stayed with simple forms that were easy to create. From the images above it is visible that the proficiency level affected the outcome while modeling complex features like spouts and handles.

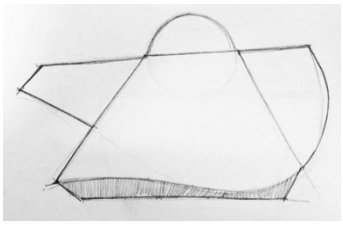
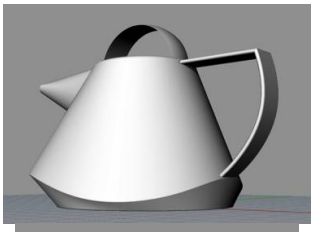
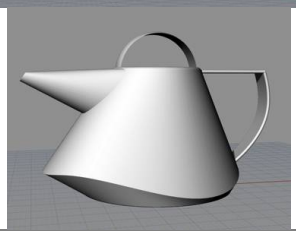
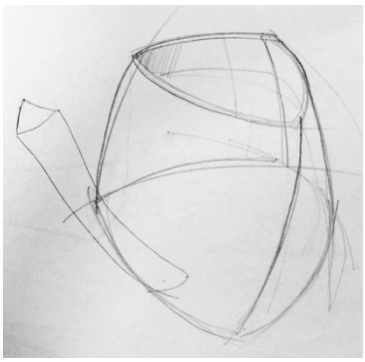
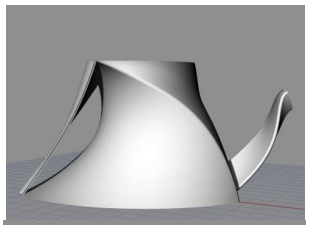
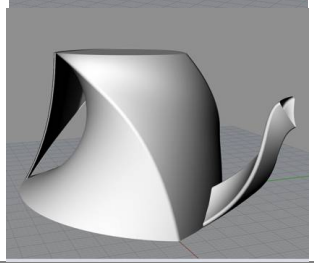
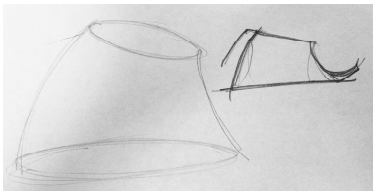
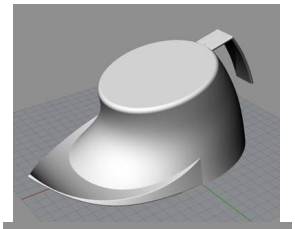
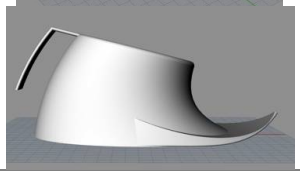
Participant-7

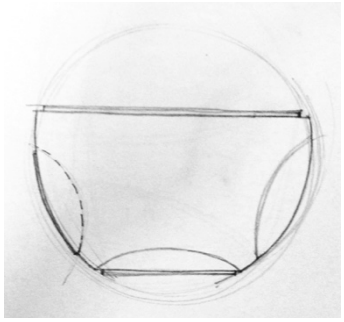
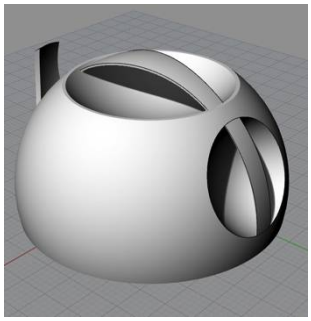
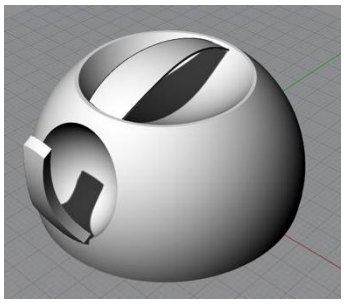
Average time taken for each sketch – 5 min

Average time taken for each model – 30 - 35 min

Explorations:

Table 9.6: Designs produced by participant-7

Intent	Output	Reflection
	 	Participant found 3D form as more communicative as compared to sketch
	 	In this design participant faced diffciculty in visualizing the final form and sketching it (as described by him). This participant had good sketching skills. He felt that he could express and explore his design well through the CAD model
	 	Another example of a form that was difficult to visualize in 2D and was only partially defined before CAD modeling.

Intent	Output	Reflection
	 	Explored largely in 3D while modeling. All the forms explored were rough ideas and were not defined as complete products. 3D CAD models could support participants in exploring the rough initial ideas. The merging of spout with the body was missing. Participant mentioned that it was just a sketchy idea and he was only placing the different components.

Do 3D CAD explorations help desiners visualize and define their ideas better? Does 3D visualization aid their creativity?

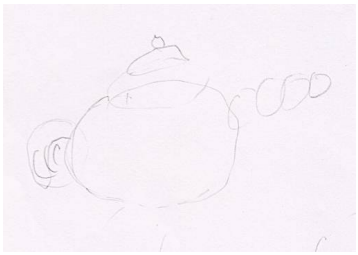
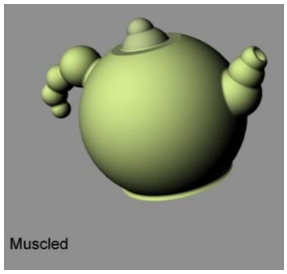
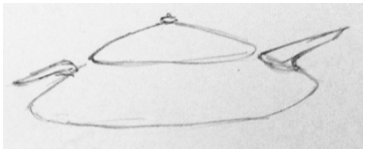
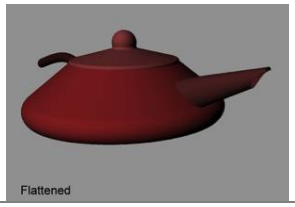
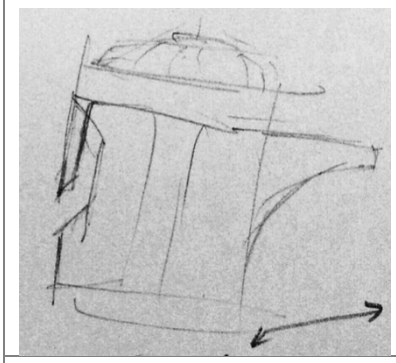
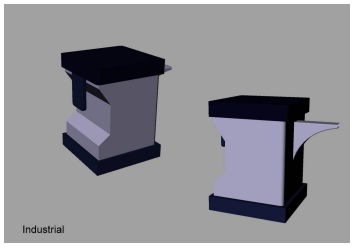
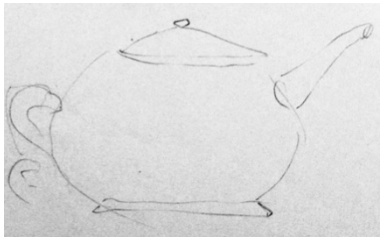
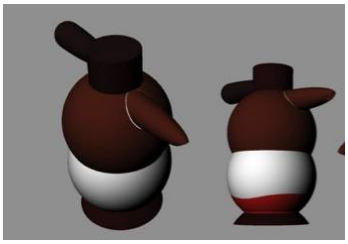
Participant mentioned that certain forms are difficult to visualize in sketches and he finds it easier to explore them in 3D, but sketching provides a starting point.

Participant-8

Average time taken for each sketch – 3 - 4 min
Average time taken for each model – 30 min

Explorations:

Table 9.7: Designs produced by participant-8

Intent	Output	Reflection
		Considerable changes from sketch to model. Design iteration took place Use CAD to compensate for sketching skills
		Usability considerations missing
		Sketch is not communicative and is used only to record the thought Design iteration occured
		Completely changed from sketch to model. Design iterations occured

During a conversation participant mentioned, *'once the model is ready I can choose my views and create any number of images. I do not have to worry about proportions and angle of perspective'*. This also indicated that designers who were

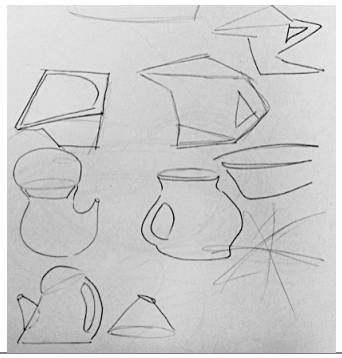
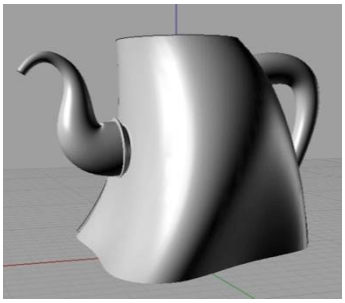
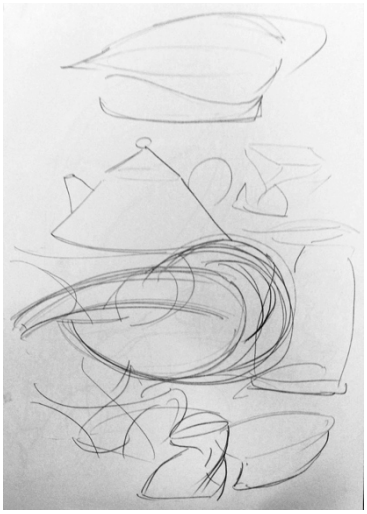
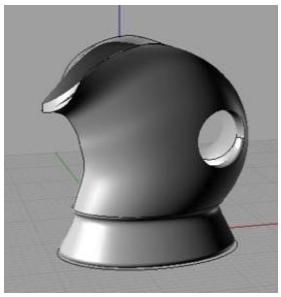
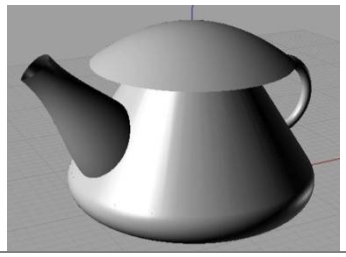
not very good with sketching skills used 3D modeling as a tool to overcome their limitations.

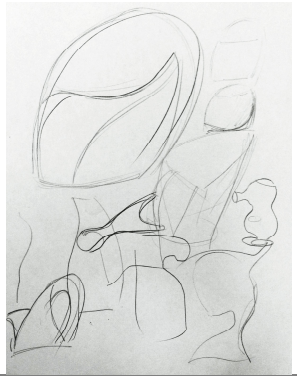
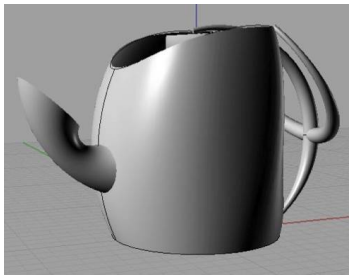
Participant-9

Average time taken for each sketch – not logged
Average time taken for each model – 30 min

Explorations:

Table 9.8: Designs produced by participant-9

Intent	Output	Reflection
		Many doodles and not clear which he used as starting point Incomplete design Used CAD to generate rough forms
	 	Explored more challenging forms Rough modeling to articulate the form

Intent	Output	Reflection
		CAD used to explore rough forms and surface Usability consideration missing

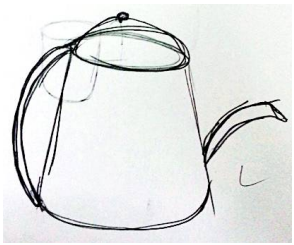
In this case participant spent continuous time doodling the lines and forms after which, he started with the modeling. He spent considerable time thinking about the problem before he began converting those lines into 3-dimentional forms. However, the thinking continued and he did not finish any idea to the level of complete product idea.

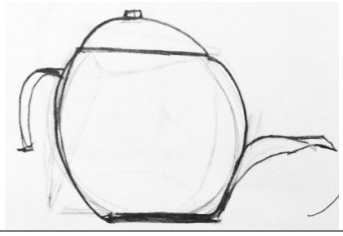
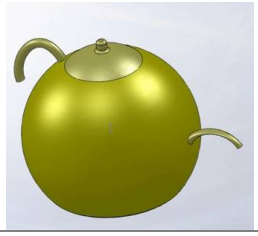
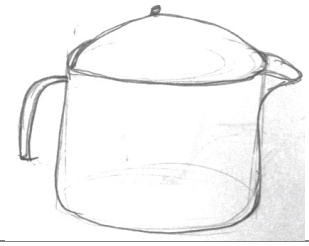
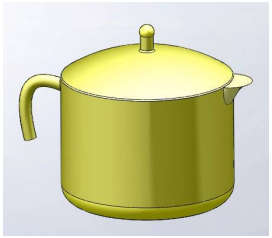
Participant-10

Average time taken for each sketch – 4 min
Average time taken for each model – 30 min

Explorations:

Table 9.9: Designs produced by participant-10

Intent	Output	Reflection
		Sketch does not communicate design intent.

		Weak representation The proportions are unappropriate and consideration for usability is missing
		Basic form. Solid rough model.
		Incomplete idea Attension to usability missing

In spite of being an architect this participant lacked the sketching skills and even while making a 3D model he stayed with the very basic forms. The proportions in his ideas even in 3D models look unappropriate and design decisions lack rationale.

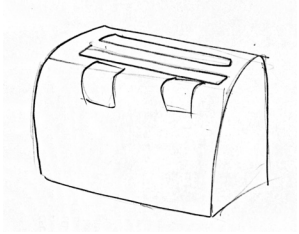
Annexure-II

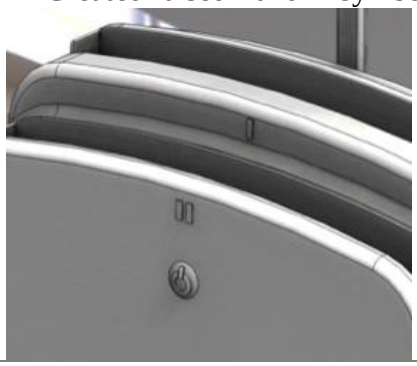
Pilot study with professional designers

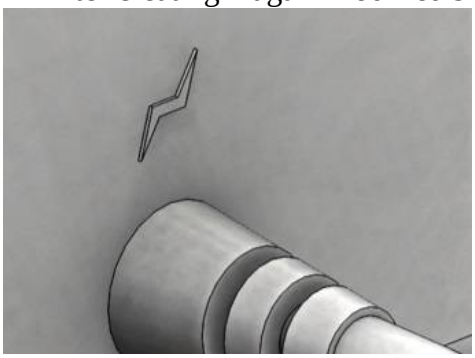
The annexure documents the process by all 5 participants and visual mapping of the occurances of the study parameters on the process.

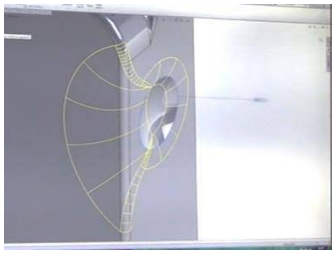
Participant-1

Approach analysis

Fixation	Circumscribed Thinking	Time (in min)	Journey	Effective Visualization	Interaction in 3D space	Design change/ Variation
		0-5	- Read assignment - Sketched reference toaster  - Started with modeling			
		5-10	- Created basic block with draft and fillet on front face - For 1 min looked at sketch to compare the shape of section 			

Fixation	Circumscribed Thinking	Time (in min)	Journey	Effective Visualization	Interaction in 3D space	Design change/ Variation
		10-15	- Rolled back above fillet and created step in block - Fine tuned fillet value based on visual feedback for both the steps 			
		15-20	- Created cuts for bread slot - Realized block thickness was less so went back and changed it - Rolled back to provide draft			
		20-25	- Rebuilt the model and observed - Created raised I and II symbol 			
		25-30	- Created round on/off button - Decision on positioning taken visually - Drew on/off symbol on it			

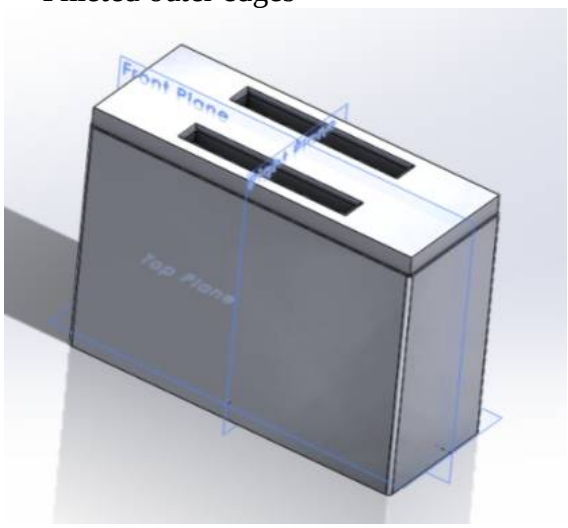
Fixation	Circumscribed Thinking	Time (in min)	Journey	Effective Visualization	Interaction in 3D space	Design change/ Variation
		35-40	- Created raised power symbol near cord - Decision on size and shape taken visually first and then defined - After creating – again modified slightly  - Created a power cord			
		40-45	- Created depression in side wall - Created another plane - Changed the plane of sketch for depression to new plane - Modified sketch for bigger depression and added fillet on circumference - Changed values of diameter, depth and fillet radius few times			
						

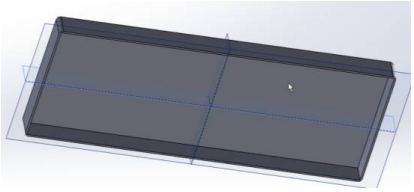
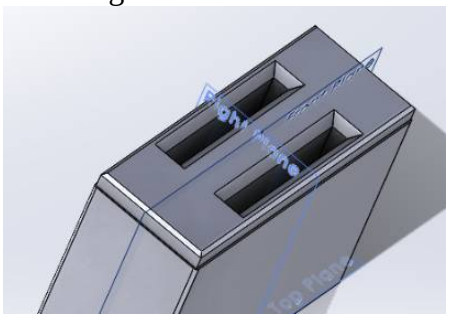
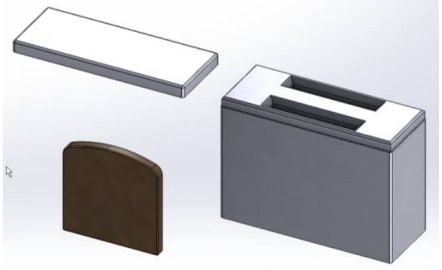
Fixation	Circumscribed Thinking	Time (in min)	Journey	Effective Visualization	Interaction in 3D space	Design change/ Variation
		45-50	- Few dimensions went wrong so redefined  - Mirrored feature on other side - Zoomed in and out while thinking about next step - Tried colour variations - Observed and thought for some time - Created projection on the edge of upper bread slot 			
		50-55	- Removed appearance - Modified back projection - Created projection on the side edges of upper bread slot - Switches on appearance again			
		55-60	- Created projections around the 3 edges of lower bread slot in much lesser time as compared to upper slot - Filleted edges of projection - Filleted inside edges of bread slot - Added small handle in the back - Added kitchen environment in background - Tried few colour variations and finished 			

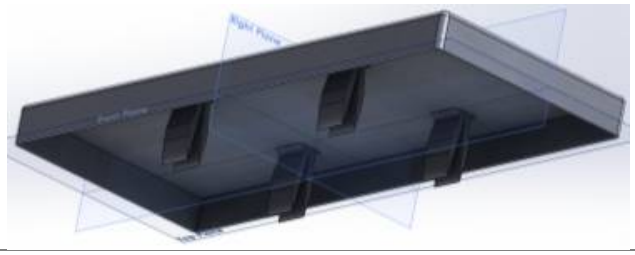
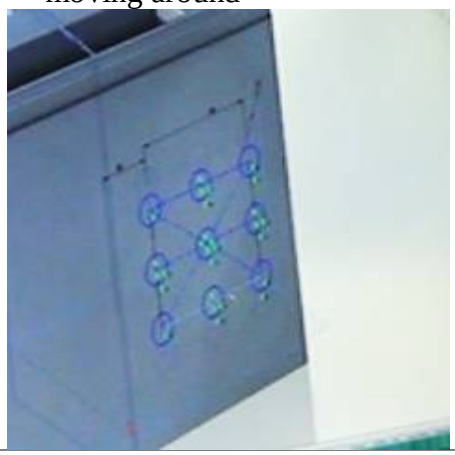
Other Observation: Some of the decisions on form and draft were driven by the engineering and manufacturing constraints that participant had in mind His focus was to create raised symbols and surfaces to provide tactile feedback to visually impaired user.

Participant-2

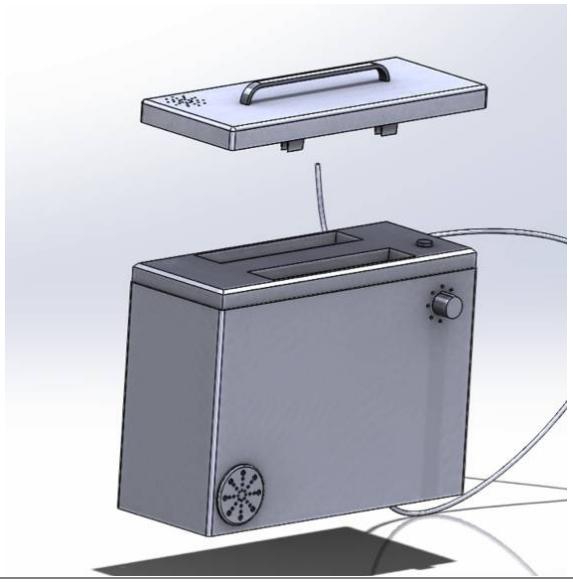
Approach analysis

Fixation	Circumscribed Thinking	Time (in min)	Journey	Effective Visualization	Interaction in 3D space	Design Change/ Variation
		0-5	- Thought for 2-3 minutes - Checked bread size - Sketched a rectangle with 2 slots			
		5-10	- Created a block with two slots and capped the bottom - Filleted slot edge - Created recess by making thin cut - Filleted outer edges  - Rotated the model, saw from all the sides while thinking			

Fixation	Circumscribed Thinking	Time (in min)	- Journey	Effective Visualization	Interaction in 3D space	Design Change/ Variation
		10-15	- Created a sketch by copying edges on the top surface - Copied this and pasted in new file - Created thin walls and capped the top to create lid  - Went back to body file and deleted fillet from bread slot edge - Added chamfer and checked visually for suitable value - Chamfered top edge of body - Changed the chamfer value  - Saved body and lid file			
		15-20	- Switched to Lid file - Filleted outer edges of lid - Opened assembly file - Placed body, lid and bread in assembly  - Deleted bread and aligned body and lid and saved assembly - Basic block ready – sat back and looked at assignment sheet for a minute. - Returned to lid file			

Fixation	Circumscribed Thinking	Time (in min)	Journey	Effective Visualization	Interaction in 3D space	Design change/ Variation
		25-30	- Deleted pins - Opened lid file - Created four rectangular projections and cut them to make clips - Visually altered the shape of clips			
		30-35	- Modified clip shape again - System crashed and had to be restarted - Clips were not saved			
		35-40	- Opened assembly and created sketch on lid for reference - Recreated clips for one side - Mirrored for the other side 			
		40-45	- Moved cap up-down in assembly to check the alignment and insertion - Sat back to think for a minute - Opened body file and created a rectangular array of circles on front face of body and positioned by moving around 			

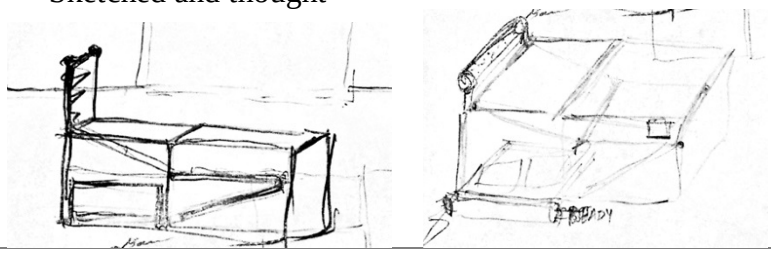
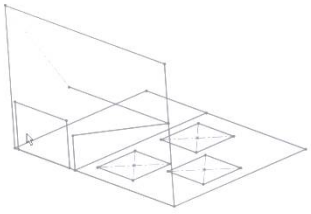
Fixation	Circumscribed Thinking	Time (in min)	- **Journey**	Effective Visualization	Interaction in 3D space	Design change/ Variation
		50-55	- Placed bread in toaster and later aligned with lid - Moved lid with bread in and out of toaster  - Returned to body file and deleted on/off button from front face - Recreated on/off button on top surface			
		55-60	- Created a circular knob on front face - Created small circular projection with fillet near knob - Created pointer on circular knob - Created array of small circular projections around knob to complete timer   - Changed holes pattern on speaker			
Extra 5 min were given to compensate for time lost during system crash						

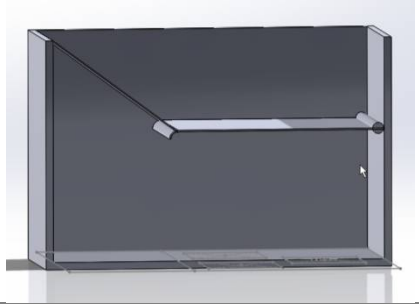
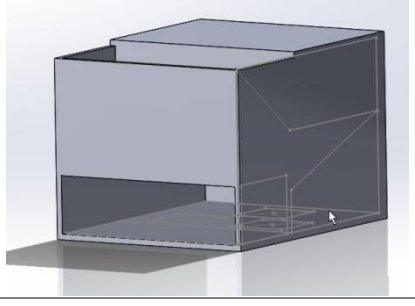
Fixation	Circumscribed Thinking	Time (in min)	- **Journey**	Effective Visualization	Interaction in 3D space	Design change/ Variation
		60-65	- Returned to assembly - Positioned lid in close position - Opened cap and created array of holes for steam escape  - Created small wire in body file using spline and a circle - Returned to assembly – moved lid up-down - Reduced the height of on/off button that was projecting out from lid in closed condition - Task finished 			

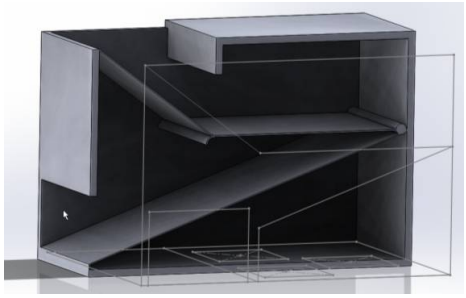
Other Observation: Little role-play in assembly lead to many changes in design during the task. He explored complete design on CAD. All the decisions and design changes took place while modeling.

Participant-3

Approach analysis

Fixation	Circumscribed Thinking	Time (in min)	Journey	Effective Visualization	Interaction in 3D space	Design change/ Variation
		0-5	- Sketched a bit, sat back and thought			
		5-10	- Sketched and thought			
		10-15	- Sketched and thought 			
		15-20	- Started with *SolidWorks* - Started making section drawing			
		20-25	- Changed section drawing to plan - Changed drawing plane to top plane - Started with section drawing in front plane 			
		25-30	- Took ruler few times in hand while defining dimensions to understand approximate physical size - Created a block - Again used scale to understand size - Shelled into open hollow box			

Fixation	Circumscribed Thinking	Time (in min)	Journey	Effective Visualization	Interaction in 3D space	Design change/ Variation
		30-35	- Created top slide using section drawing as reference - Created heating platform using section drawing as reference - Observed using sectional view and reduced thickness of slide and heating platform - created cylinder to depict hinge 			
		35-40	- Created cut at bottom left corner - Rotated model and thought for a minute - Created top cover with small flange  - Deleted bottom cut - Created larger cut on side wall for taking out bread 			

Fixation	Circumscribed Thinking	Time (in min)	Journey	Effective Visualization	Interaction in 3D space	Design change/ Variation
		40-45	- Opened section view - Created bottom slide  - Created a reference line - Rotated and thought			
		45-50	- Opened a new part - Created a hollow block with capped ends using first model dimensions as reference - Kept moving between new part and first model - Created top opening in new part			
		50-55	- Measured bread exit slot dimension of first model - Created cut in the new model with changed height - Filleted edges of new part - Changed appearance - Measured angle of entry slope from first model			
		55-60	- Created slope in new part - Saved file - Opened a new file and created a cylinder for hinge - Realized time was getting over so stopped with making separate parts to create assembly - Created a small button on front surface and a cylindrical projection to depict controls on top edge 			

Other Observation:

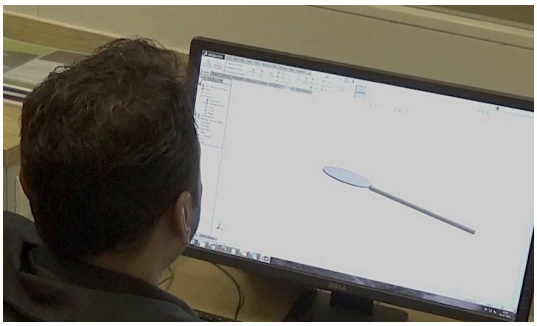
- Size perception was noticed as limitation in the beginning and participant used ruler to approximate dimensions.
- He created a rough model to visualize his idea before trying to create a final model.
- He was the only participant who planned his idea almost completely before modeling.

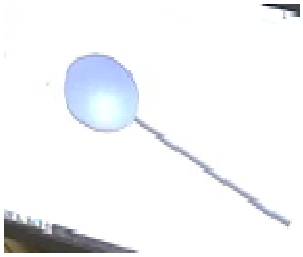
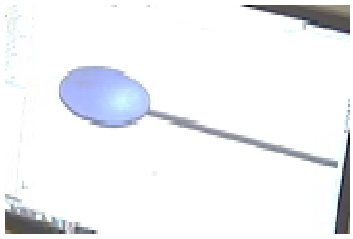
Formal exploration of Spoon design task

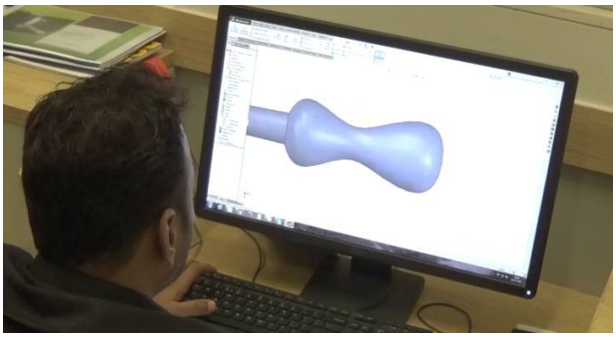
Codes:

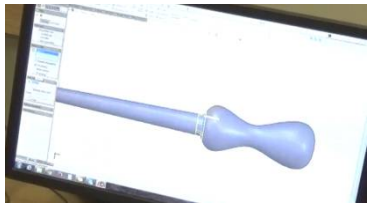
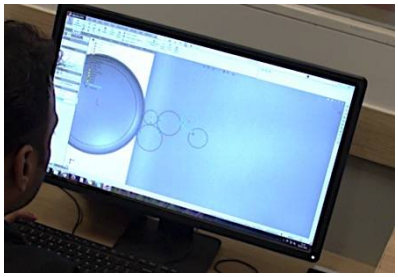
- Working on design idea – D
- Modeling– M
- Exploring how to model - EM
- Changed design due to tool/ proficiency limitations – Circumscribed thinking – CT
- Visualization – zoom, rotate, and look around – V
- Fixation – did not make changes due to errors, left it due to excessive detailing – F
- Design changes due to visualization, further exploration due to 3D visualization – DC
- Difficulty in perceiving size - S

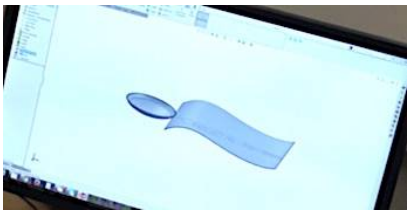
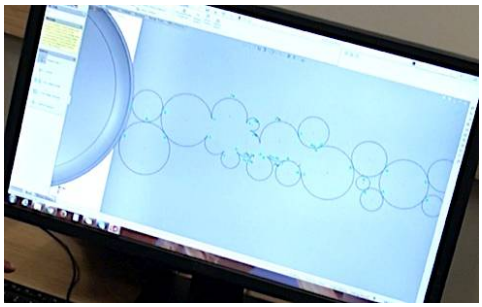
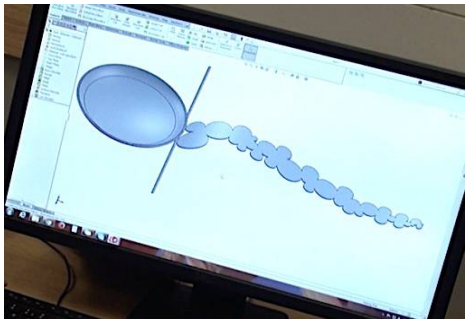
Participant-1

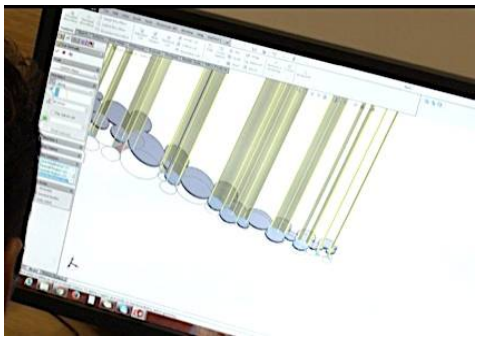
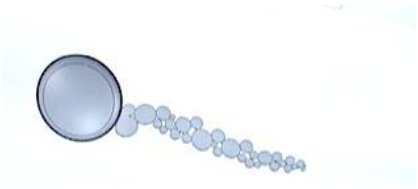
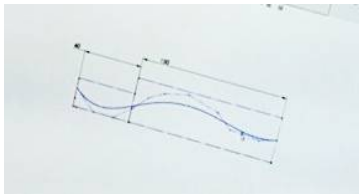
Time (in min)	Journey	D	M	EM	V	CT	F	DC	S
0-5	Sketched ideas Thinking and brainstorming time This time frame not to be analyzed – consider as a thinking time.								
5-10									
10-15									
15-20									
20-25									
25-30									
30-35									
35-40									
40-45									
45-50	Opened *SolidWorks* Spread all the sketches in front – to decide which one to make Used a ruler and given reference spoons and measured all 3 spoons Made a circle in the top plane Extruded circle Rotated the model and tried to figure out how to form a spoon Created a cylinder to form the handle of spoon Looked at it with confusion  Switched between different tabs (solid/surface/..) to explore how to create intended form								

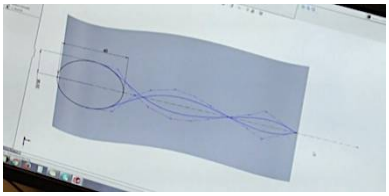
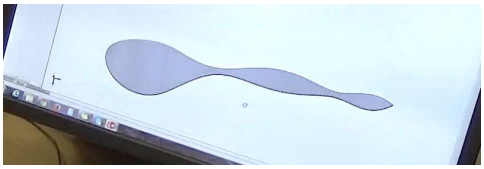
Time (in min)	Journey	D	M	EM	V	CT	F	DC	S
50-55	Kept looking at the various features to find an appropriate command								
	Created bowl using dome and shell command								
									
	Deleted cylindrical handle								
	Deleted shell as it was creating an edge around bowl								
	Sketched handle cross-section and deleted								
	Struggled to create handle								
55-60	Created a new cross-section for handle in the center of bowl								
	Tried loft with 2 cross-sections, reviewed then cancelled								
	Created another cross-sectional sketch								
	Tried loft with 3 cross-sections and reviewed								
60-65	Combined handle and bowl bodies								
									
	Looked back at the sketch								
	Changed the sketch plane for handle centerline								
	Created an end profile sketch for handle								

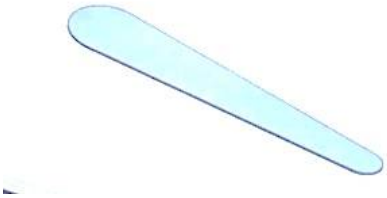
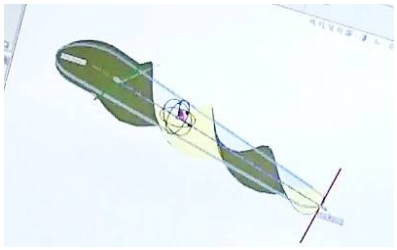
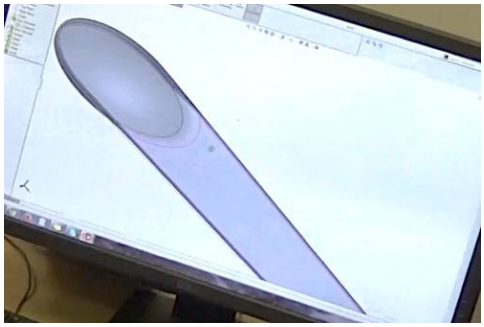
Time (in min)	Journey	D	M	EM	V	CT	F	DC	S
65-70	Rotated the profile sketch to create end of handle  Spent time rotating the model and observing the form  Measured diameter of bowl Created edge fillet Rolled back before combine command and copied the outer surface of bowl Rolled down and created an offset surface with the copied surface Went up and down the feature tree and changed few parameters Uncombined handle and bowl Changed dimensions of end and mid cross-section of handle The end profile projected out so changed the sketch further to match the new cross-section. Rotated, adjusted views and zoomed-in and out a lot during this time 								

Time (in min)	**Journey**	**D**	**M**	**EM**	**V**	**CT**	**F**	**DC**	**S**
70-75	Tried creating fillet at the end of the handle, faced some problem, refined the sketch twice Created the fillet  Saved spoon-1 Spent time rotating and observing the form Did not look like the sketch at all Opened a new part file Went back to sketches to decide which one to make Made an ellipse in the top plane								
75-80	Created elliptical surface Created one more sketch to define depth of bowl Tried creating surface with that as guiding curve Failed Deleted earlier surface and trimmed the ellipse in half and created a surface for half bowl Tried to mirror but kept on choosing feature to mirror and it did not work								
80-85	Failed to mirror Tried offsetting surface, cancelled Lost few minute recording Created the bowl and a curved surface								
85-90	Started making circles on the flat surface  Adjusted the diameters and positioning of circles visually Tried to extrude cut the surface with circles								

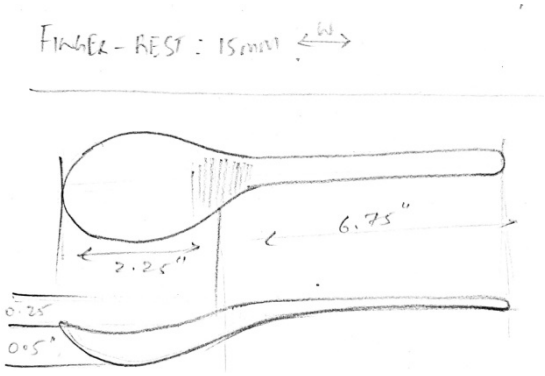
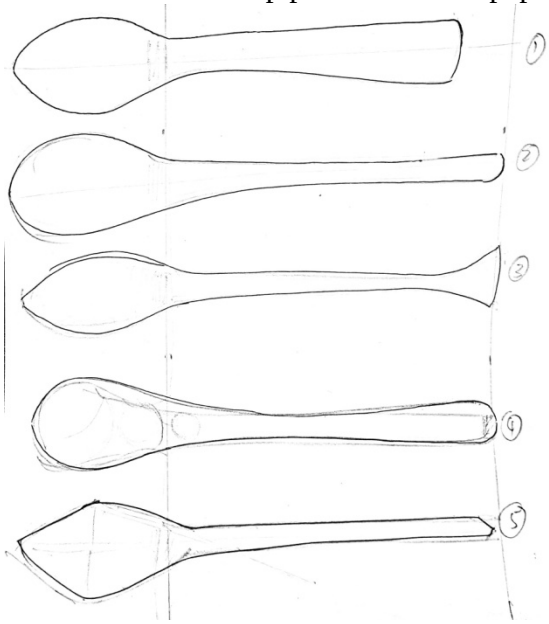
Time (in min)	Journey	D	M	EM	V	CT	F	DC	S
90-95	Cut could not be made so extruded cylinders from circles Rolled back and offset the curved surface to make a curved solid  Tried to trim with circles – did not work Thought for a while and tried extruding again – got an error message and cancelled Realized need for a closed profile and started trimming circles  Made changes in sketch as required								
95-100	- Trimmed with new profile  - Readjusted the profile and position of cutting profile - Cut the extra line visible near the neck								
100-105	- Created sketch to define circle lines								

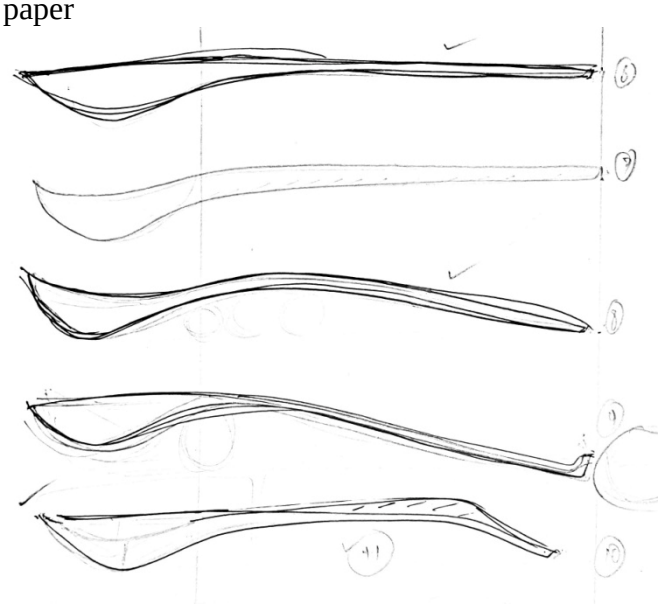
Time (in min)	**Journey**	**D**	**M**	**EM**	**V**	**CT**	**F**	**DC**	**S**
105-110	- Worked on sketch to define circles - Created small fillets to avoid zero thickness corners								
110-115	- Continued working on sketch								
115-120	- Continued working on sketch - Cross-checked sketch several times								
120-125	- Created cut in handle using new sketch  - Cut gave error - Reexamined sketch and rectified errors - Created the cut  - Observed the form for a while and saved spoon-2								
125-130	- Opened a new file - Created defining box - Created spline to define profile  - Adjusted the curve								

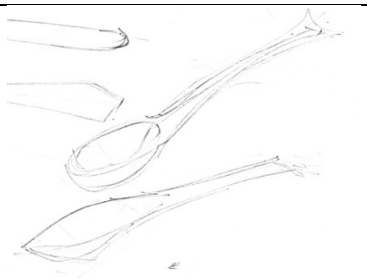
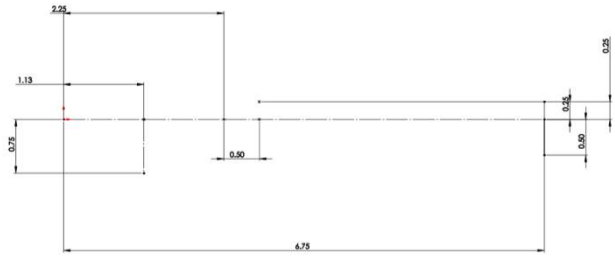
Time (in min)	Journey	D	M	EM	V	CT	F	DC	S
130-135	- Extruded surface from curve  - Created top profile sketch in top plane - Experienced some errors in defining spline 								
135-140	- Tried trimming surface - Zero thickness error occurred - Rolled back and replaced surface with curved solid - Tried to extrude cut with top profile – faced rebuilt error - Realized the problem in top profile sketch - Started refining sketch								
140-145	- Refined sketch								
145-150	- Made more adjustments to the sketch								
150-155	- Deleted the sketch and started making it again - Created half profile and mirrored it - Trimmed curved solid with new profile 								
155-160	- Filleted the top edge with variable fillet - Filleted the bottom edge - Saved file - Opened new part file - Created a sketch – deleted it - Started making another profile in top plane								

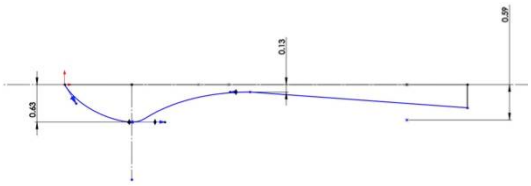
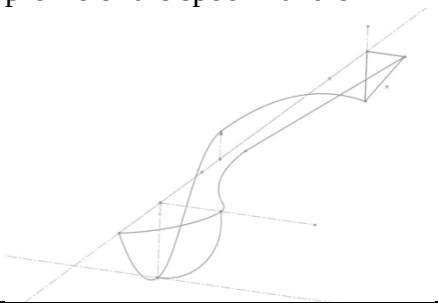
Time (in min)	Journey	D	M	EM	V	CT	F	DC	S
160-165	- Created a sketch and extruded  - Looked into the list to find the right operation to use - Tried twist and cancelled								
165-170	- Tried twisting handle again cancelled  - Created dome at the bowl end and filleted - Changed fillet value - Created fillet on the outer bottom edge								
170-175	- Tried shell, encountered error - Changed thickness and created shell  - Cancelled shell - Tried changing the first profile sketch and almost all the consecutive commands gave error - Deleted everything - Started again by sketching and extruding a circle - Created dome to form the bowl - Filleted bottom edge and shelled - Filleted top edge and saved file								

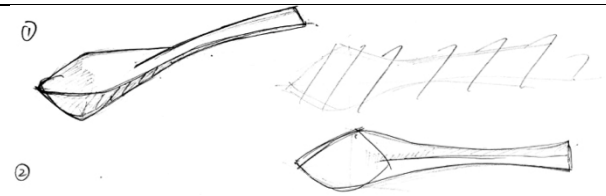
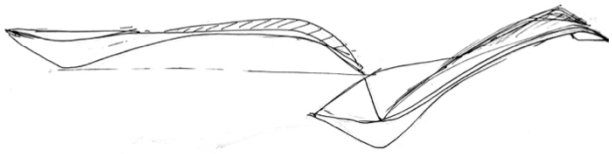
Participant-2

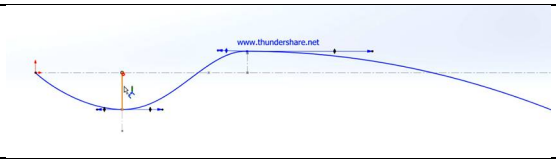
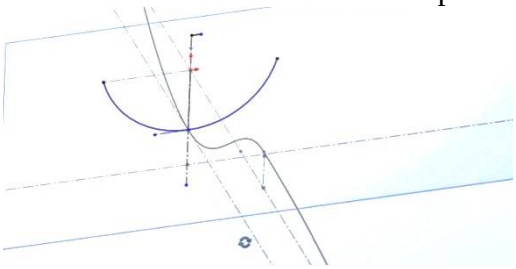
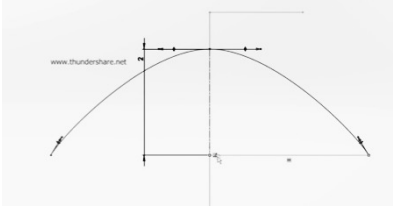
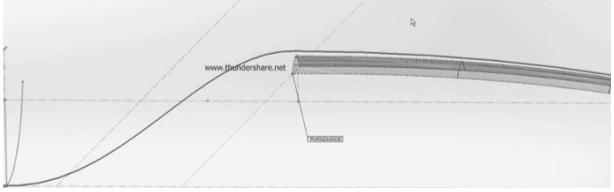
Time (in min)	Description	Remark	D	M	EM	V	C	F
Session-1								
0-5	Goes through the design brief Writes keywords Refers to spoons and checks grip and sizes Writes down reference dimensions							
5-30	Checks other spoon dimensions with a scale Writes down some more dimensions Creates a reference sketch  Sketches different top profiles on one paper 	It is important to have an idea about dimensions before starting to model. So first defined the basic dimensions. Kept the approach modular. Sketches top profiles and side profiles separately so that can generate more forms by mix-and-match.						

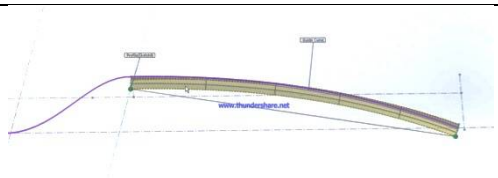
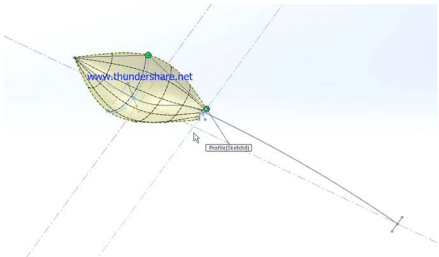
Time (in min)	Description	Remark	D	M	EM	V	C	F
	Sketches different side profiles on another sheet of paper  Relook at the brief Sketches some more profiles Refer backs to spoons and check the grip for different types of handle							
30-40	Sketched different end profiles for spoon  Tries to sketch rough 3D forms	The modular approach continues.						

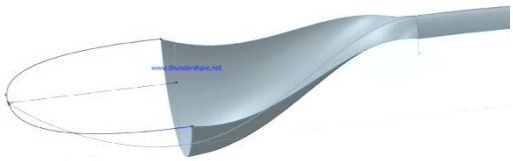
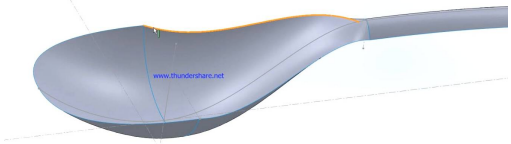
Time (in min)	Description	Remark	D	M	EM	V	C	F
		Finds sketching 3D forms challenging. Uses Sketch-up pro to create sketches sometimes for quick representation. Uses manual sketching just for doodling the ideas.						
40-50	Start by creating guidelines to define basic dimensions  Goes back to measuring spoon	Keeps switching between sketch and screen while defining dimensions						
50-55	Taking reference from the guideline sketch, start another sketch to create side profile Uses 'spline' to create the profile curve. Struggles in the beginning to get the curve right. Goes back and creates another sketch to define points Creates profile using the points from reference sketch to define 'spline' 	Reference sketch help maintain the overall dimensions All the decisions related to the curvature of the profile sketch were taken visually						
55-	Measure spoons again for top profile dimensions	Keeps switching						

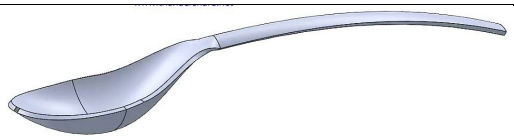
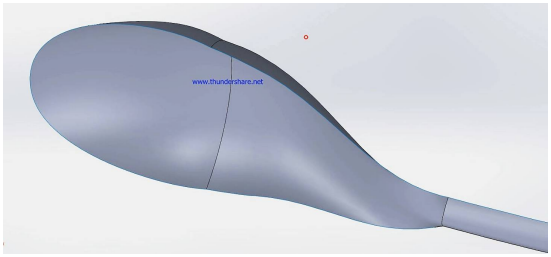
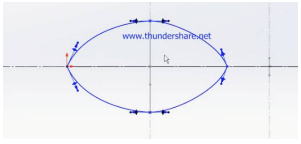
Time (in min)	Description	Remark	D	M	EM	V	C	F
60	Start sketching top profile Pauses sketch, measure spoon, go back to sketch and define dimensions	between profile sketch and spoon measuring						
60-65	Uses Spline to create top profile Takes the decisions about the curvature visually Keeps referring back to spoon for dimensions of the bowl part	Keyboard is used for 'shift', 'ctrl' and 'esc' and to enter numeric values. No keyboard shortcuts were used.						
65-70	Changes dimensions and adjust curvature visually to get a smooth curve  Creates a reference plane Defines curve in the new plane for cross section of spoon bowl. Creates another plane and sketch to define the end profile of the spoon handle 	So far only single line curves are used for defining the form. No thickness is considered.						
70-75	Tries using surface loft command Does not get desired results Changes parameters and try again Does not get desired results Goes back to sketching and tries to sketch a 3D spoon to get clarity on the overall form	Trying to create only half spoon form						
75-	Sketches 3D spoon	Just using the						

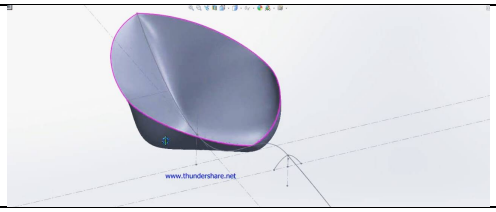
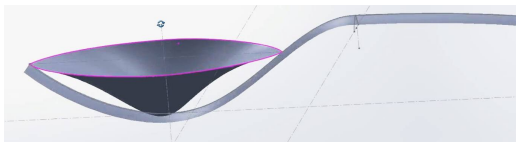
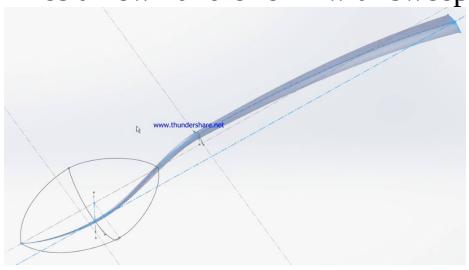
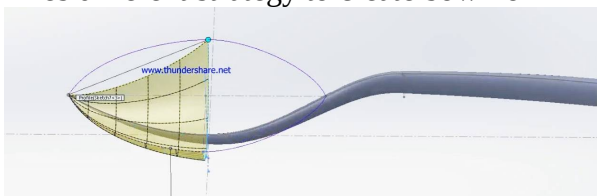
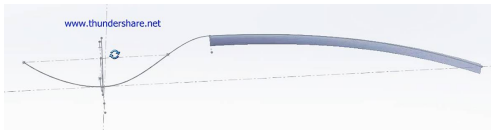
Time (in min)	Description	Remark	D	M	EM	V	C	F
80		side and top profile, was not clear about the overall form of the spoon. When could not achieve a proper form by computer, started sketching to understand the intended form						
80-85	Returns to the profile sketches Sketches 3D forms again after selecting some profile sketches 							
85-90	Tries to do more sketching Times gets over Mentions that in a normal mode he usually sits and thinks and would like another session for modeling. Wraps up and takes the break							
The session for the day gets over and participant decides to return next day for modeling session. He mentioned that usually when brief comes he would sit and do some brainstorming and then starts modeling either towards evening or next day. Due to some other commitments participant decides to come next day instead of continuing post lunch.								
0-5	Revisit sketches Opens file made in previous session Deletes spoon bowl part of the front profile curve Redraws it and adjust the curvature and tangencies visually	All the profile curvature decisions were taken visually						

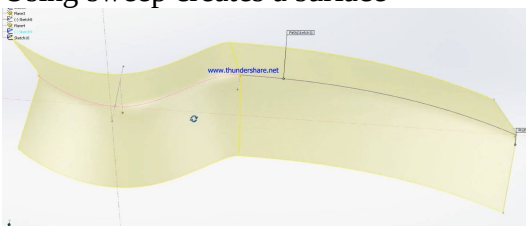
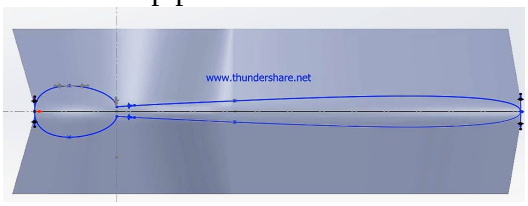
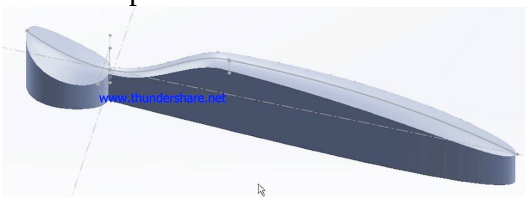
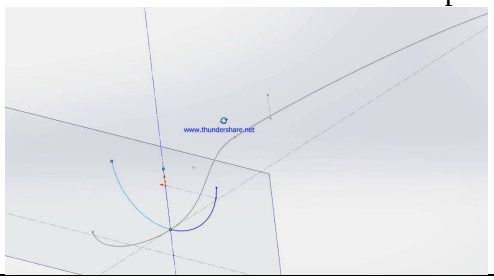
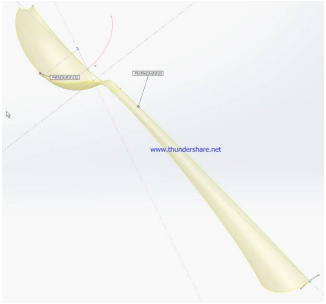
Time (in min)	Description	Remark	D	M	EM	V	C	F
								
5-10	Keeps adjusting the curve visually by pulling spline handles Deletes the handle end profile Deletes bowl cross-section							
10-15	Sketches a new cross-section for spoon bowl  Creates new reference planes							
15-20	Creates cross-section for the end of neck and start of handle Deletes and recreates using different commands  Creates another plane	Uses multiple commands to create a simple curve that could have been made in single command						
20-25	Creates handle end profile Tries to create complete form using surface loft but gets an error Tries to create handle but realizes that the surface is not meeting the guide curve  Moves cross-section curve to match the profile curve Tries to create complete profile Gets and error so creates only handle	Uses lot of construction lines to create profiles Uses spline instead of curves for profiles						

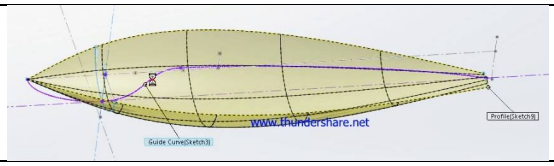
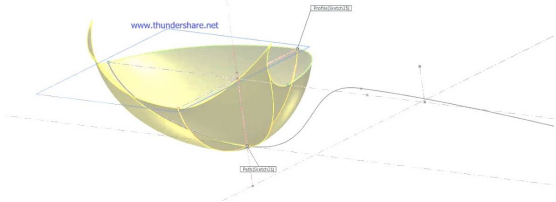
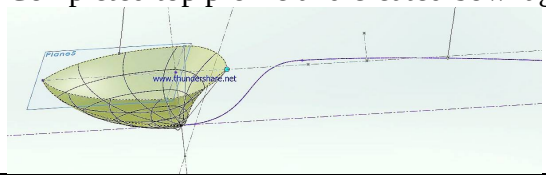
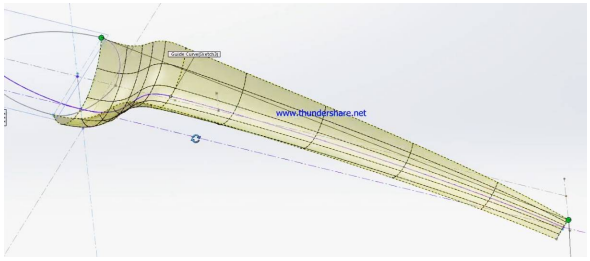
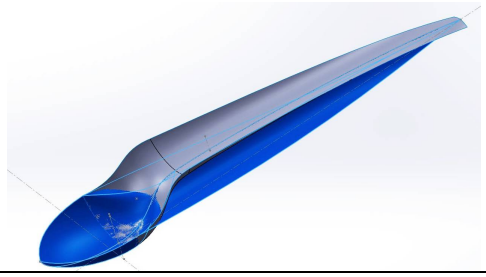
Time (in min)	Description	Remark	D	M	EM	V	C	F
	 Deletes the surface created Tries to create complete spoon using single loft command  Loft gives error and fails							
25-30	Tries to create half spoon but fails Creates the neck portion first using loft command  Tries to create handle but gets error Deletes the neck surface Creates same again Copy and create guide curve for handle in separate sketch Using loft creates handle 	Creates the portion with form transition first. Ideally should have created it later to achieve the continuity in form Does not use tangency option while creating loft to get formal continuity						
30-35	Creates loft to complete the bowl Tries option of tangency and curvature to get smooth form	Participant didn't realize that for loft command he will need 2 profiles						

Time (in min)	Description	Remark	D	M	EM	V	C	F
	 The absence of end profile resulted in above form Deleted commands to remove the front portion Created sketch to define the bowl form  	Because the portion where the formal transition takes place was created first, the tangency in the top view could not be achieved						
35-40	Creates front portion using loft and new profile  Rotates and observes the form  Realizes the discontinuity in form Creates a curve and trims the surface 							
40-45	Tries two different thicknesses and defines thickness							

Time (in min)	Description	Remark	D	M	EM	V	C	F
	 Tries to fillet the edges, gets error and leaves it Uses surface fillet to fillet bowl Creates fillets on the bottom edge							
45-50	Saves file and creates a copy with another name Deletes all the commands leaving sketches Undo all changes Deletes thickness							
50-55	Changes the profile curve for the bowl front part and encounter error  Tries variations to resolve error Deletes it and starts creating a new curve Tries different curves Deletes Creates a curve and surface is recreated 	Does not result in smooth transition						
55-60	Checks model from various views Deletes the complete form Creates a new sketch to define bowl profile  Creates a surface using fill command but gets a distorted surface	Takes the formal decisions visually Tries a new approach to create spoon form						

Time (in min)	Description	Remark	D	M	EM	V	C	F
								
60-65	Deletes the surface Tries loft – fails Tries sweep  Creates bowl  Deletes bowl Deletes handle	Spending more time on trying to find ways to create the desired form then creating it Trying new ways to create forms						
65-70	Tries a new handle form with sweep  Tries different strategy to create bowl form  Command did not work Trims the handle 							

Time (in min)	Description	Remark	D	M	EM	V	C	F
70-75	Using sweep creates a surface  Sketches top profile  Extruded profile and trimmed surfaces  Deleted all the surface	Trying a new approach again Could have created a spoon form from this but discarded the idea						
75-80	Refines profile curve Creates a cross-section curve for spoon bowl 	Going back to the same method						
80-85	Created half spoon with two curves  Cancelled Tried loft and cancelled							

Time (in min)	Description	Remark	D	M	EM	V	C	F
								
85-90	Created a new curve and tried to create bowl form  Resulted in non-uniform shape Deleted Completed top profile and created bowl again 	One more new method tried						
90-95	The bowl did not shape up so tried to form handle first  Tried creating loft for creating bowl but it added a random surface 							

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Annexure-III

Interview questionnaire and interview guide for Pilot study with professionals

A structures interview questionnaire was share with participants before the design task over email. This questionnaire acted as the qualifier for the selection of candidates. Post design task, a semi-structure interview was conducted one-on-one and was voice recorded. Interview guide used for semi structured inteview and pre-study questionaaire are shown below.

Pre-study questionnaire

Declaration: The data collected will be used only for academic research purpose. No information or ideas generated by participants will be used for any commercial purpose. All the personal information of the participants will be kept anonymous.

Dear Participant

Thank you so much for participating in our experiment and helping us in our research. The purpose of study is to identify the advantages and limitations CAD brings when used in the idea generation stage of product design.

Before we begin with our little design task, request you to kindly answer a few questions below to help us gain few insights.

- Qualification:
- Job responsibilities:
- Since when are you working in design and research?
- Years of experience in 3D modeling:
- Years of experience using *Solidworks*:

- How would you rate your *Solidworks*proficiency level: Beginner/ Competent / Proficient / Expert?
- Which other software you use?
- When a new design task is given to you, what is your usual approach?
- How do you start generating ideas?
- What are the various stages of the work in which you use CAD?
- What are the other tools you use during idea generation stage? (Like sketching, group brainstorming, etc.)
- Do you use CAD during idea generation stage where your ideas are still vague?
- If yes, what are the advantages of using CAD in idea generation stage?
- Have you experienced any limitations while using CAD? What are those?
- Do you ever feel that making a CAD model restricts your thinking and all the attention gets diverted into process of making the model?
- If no, why not?

Post-study interview guide

Declaration: The data collected will be used only for academic research purpose. No information or ideas generated by participants will be used for any commercial purpose. All the personal information of the participants will be kept anonymous.

- Can you please describe the thought process and approach on what you did today?
- In the pre-experiment questionnaire you mentioned that CAD modeling diverts your attention from designing and affects thinking process. Still you use CAD for idea generation, why?
- Does it ever happen that you intent to make something else but you are unable to model it, so you change the design?
- The changes caused due to usage of CAD are intentional or un-intentional?
- How many ideas did you create for today's design task?
- Where the ideas free-flowing or you experienced any limitations in getting new ideas? What limitations did you experience?
- Do you ever use CAD for your form explorations?
- Did you feel any limitations imposed by CAD while generating ideas today?
- Which features of CAD were helpful in generating ideas?
- How CAD can be helpful? Does it help you get more ideas?
- What was the biggest challenge you faced in the exercises?

- Does using CAD for idea generation boost your confidence or it makes you nervous?
- What is that one feature you would want in your “dream-CAD-tool”?
- Any advantage other than visualization?(added during interview)
- Any other insight or feedback you would like to give?

Annexure-IV
Interview excerpts from
pilot study with professionals

Annexure documents excerpts from the participant interviews from pilot study with professionals.

Years of experience using *Solidworks*:

- Participant 1 – 5 years on 3D modeling and 6-7 years on 2D
- Participant 2 – 4 years
- Participant 3 – 3.5 years on 3D modeling and 5 years on 2D
- Participant 4 - 4 years
- Participant 5 - Approximately 10 years

How would you rate your *Solidworks* proficiency level: Advance-Beginner/ Competent / Proficient / Expert?

- Participant 1, 2, 3 - Proficienct
- Participant 4, 5 - Competent

Which other software you use?

- Participant 1 – Pro E, Auto CAD, Ansis
- Participant 2 – AutoCAD, 3D Max, Photoshop, CorelDraw
- Participant 3 – Catia, SolidEdge, Pro E, Space Claim, Key creator, AutoCAD
- Participant 4 - Pro-e, CATIA, CREO, Coral Draw
- Participant 5 - Adobe Illustrator, Adobe Photoshop, Autodesk Sketchbook Pro, Keyshot

When a new design task is given to you, what is your usual approach?

- Participant 1 – Mostly make a layout drawing and adopt bottom-up approach. If there are standard parts I use them from library or previous models. But for given exercise I had top-down approach. Usually we are required to make 3 concepts and present it to management for approval. Many times I make one base model and make different configurations or save as separate files to create variations.
- Participant 2 – to me sketching on paper or starting directly on computer is same. Sometimes I doodle; sometimes I directly start with making a drawing on computer.
- Participant 3 – I first sketch using a tablet and sketching software sketch-pro. Then take this sketch in AutoCAD and make a 2D layout. This 2D drawing is taken as a reference for making model in 3D. Sometimes, I also place sketch directly in background for 3D modeling.
- Participant 4 - sketching /ideating/CAD modeling - mockups - prototypes - CAD modeling/detailing - manufacturing
- Participant 5 - Problem setup – context definition, user definition, client expectation (may not be same as user), vague enough / precise enough design brief definition. Clearly define product scope and deliverables. Understand the brand feel / client thoroughly. Research closest existing solutions, broaden solutions as required (1 level or 2 levels parallel solutions as well). If necessary based on "similar usage / action, but different application" approach (for example studying a mine stone crusher to design a pepper mill). Understand the constraints (development budget, time available to work on project, available vendor quality, manufacturing volume, product cost, scope). Mood Board + Ideation based on all this. Grouping, Gravity filtering of ideas. Concept generation, client feedback, basic prototyping if necessary. Concept detailing, advanced prototyping (mockups, functional etc.). Detailing + manufacturing input

What are the various stages of the work in which you use CAD?

- Participant 1 – Use CAD for all the stages- starting from concept generation, creating walk through and animations for presentations to detailed engineered concept and FEA analysis.
- Participant 2 – For all the stages
- Participant 3 – after a basic sketch is ready, 3D modeling is used for concept development, visualization, renderings, animation, creating instructions for assembly lines, various analysis purpose, etc. Sometimes realistic renders are used for catalogue purpose much before the real product comes into existence. Animations, exploded views and renders are used for client presentations and these eliminate the requirement of making prototypes.
- Participant 4 - Ideation, part assembly visualization, mechanism testing, motion analysis
- Participant 5 - To visualize sketched geometries in 3D ISO, volume flow from different angles. To 3D print for checking fit, form and function, also to use as a physical prop while talking to vendors, getting feedback. To create models for "sexy" renders – either exaggerated or to show product in idealized "typical" usage scenarios. Product detailing for manufacturing, drawing generation, tooling, etc.

What are the other tools you use during idea generation stage?

- Participant 1, 2 and 3 mentioned only sketching as other tools used in initial stage. Participant-3 does sketching also on computer. This helps overcome limitations of his sketching skills and allows quick changes.
- Participant 4 - sketching/ mockup building/ paper models
- Participant 5 - Dirty sketches (lots of lines, wasted paper, only understood by me), Brainstorming, role-playing, vocalization of ideas.

Do you use CAD during idea generation stage where your ideas are still vague?

- All the participants agreed to using CAD in early idea generation stage

What are the advantages of using CAD in idea generation stage?

All the participants mentioned Visualization as the one of the most important advantage. It allows them to interact with the idea in three-dimensional space while developing and communicate the same to others.

Participant-2 mentioned that the 3D visualization and assembly allows him to imagine the complete sequence of operations and he did a role-play exercise with assembly model while developing the concept of toaster.

Participant-3 mentioned the importance of animation, exploded views and realistic renderings.

Participant-4 - It helps to create and visualize the parts which dimensions/ function are yet to defined. I start with fix and known part and assembly build around it. simultaneously checking mechanism and appearance/form, it also helps to understand parts interconnection and sequence of assembly- disassembly from maintenance point of view.

Participant-5 - To understand volumes and proportion clearer from different angles. Time taken to sketch different angles may take too long for me or may not be accurate, as I may not capture the form correctly in perspective on paper from different views. To understand edge treatments better (radii, chamfers, etc), more complex form transitions, manufacturing - Although this is usually during later stages, sometimes the “overall” mood / stance / “10-ft read” of the product can be greatly affected by this and hence would be important to easily see variations with a basic volume in CAD.To generate basic volumes to act as underlays for sketching, especially when whatever is being designed needs to fit with other things around it.

Have you experienced any limitations while using CAD? What are those?

- Participant-2 could not think of any disadvantages.
- Participant-1 mentioned system requirements as limitations.
- Participant-3 time requirement is a limitation. It may be looked at as advantage and disadvantage both.
- Participant-4
    - I always keep mannequin in to assembly to get the scale judgment while Modeling.
    - Materials has different flexibility/softness/ hardness varying according to thickness and length, its completely depend on your experience with particular material, can't sense in CAD.
    - 'lack of gravity sense' it's actually a one of the Point of reference in real world. things works differently in real world in gravity.
    - Can't sense the Interrelation between parts e.g. fits and tolerances/tightness and looseness.

- Participant-5 - Mainly it’s the limiting effect of “design only what you can model”**.** Time taken to model details can be high, so generally only used when ideas have reached a minimum level of clarity through basic models / sketching / etc.

Do you ever feel that making a CAD model restricts your thinking and all the attention gets diverted into process of making the model?

All the participants other than participant-4 mentioned that initially they faced cognitive load while learning but now they do not have to think about the tools and it does not require any conscious efforts. Participant-4 feels that it does affect the thinking process.

You mentioned that CAD modeling diverts your attention from designing and affects thinking process. Still you use CAD for idea generation, why?

Participant-4

- That gives me a freedom to visualize my idea. That is something closest to reality. I can quickly make and see my idea.
- When I translate a sketch into a 3D model, things change. I have something on paper but when I start modeling it something else comes up. Then I can explore what if I do this how will it affect the design.

Does it ever happen that you intent to make something else but you are unable to model it, so you change the design?

- Participant 1 - Sometimes
- Participant 2 and 3 - have not experienced this
- Participant 4 - Many times. Idea does get driven by what can be made or what I can make on CAD. I try to make what I sketch on paper, as I want to see that, but since I have invested so much of time trying to make a model, I need to justify that and then I start making adjustments. If there is a particular feature in the design that is not happening or I can't model it, then I may change that.
- Participant 5 - There was a time when all my ideation used to happen on CAD and almost nothing with pen on paper. I realized that I couldn't do it anymore as I could think only what I could model.

How many ideas did you create for today's design task?

- Participant 1, 2 and 3 - only 1
- Participant 4 - 20 on paper and 5 on CAD.
- Participant 5 - many on paper but not a single satisfactory one on CAD

Where the ideas free-flowing or you experienced any limitations in getting new ideas? What limitations did you experience?

- Participant 3 - I experienced the limitation of time
- Participant 1 and 2 - I was focussed on finding solution. Time went too fast.
- Participant 4 - I had no problem when I was generating ideas on paper. I focused on what should be the shape of the spoon, and then how the handle should look like, then what motifs can come on it. After that I moved to 3-D form of it. That is when I started modeling. Till I was sketching I was thinking only in one dimension, either top view or side view. *I had a 3-D view in my mind but I won't be able to sketch it* so I started modeling.
- Participant 5 - Idea was to split the whole form in 3 sections - bowl, shaft and ending. Wanted to try mix and match based on sketches and then generate them here. Came up with a sci-fi concept last minute which was completely unintentional. Features that I thought would work did not work. Wanted to use loft between 3 sections and a center line but that did not work.

Do you ever use CAD for your form explorations?

- Participant 1 - I would crate a base model and refine that further
- Participant 2 - Sometimes
- Participant 3 - I need to visualise the ideas in 3D. So i prefer to use 3D modeling
- Participant 4 - Yes, I do use CAD for form explorations as well. Mostly during form exploration, I get a basic 3-D form idea and then I make it on CAD and then play around it. It is something in-between a 2-D sketched idea and a 3-D physical prototype. It is a 3-dimensional model that I cannot touch but still see it from all the angles.
- Participant 5 - Not as such for form. But to see how something would look in different angles I would rather make a model then create sketches in different

angles. Also with my sketching skills perspective views will not be very accurate. I also use sketchup-pro sometimes to create quick sketches.

How CAD can be helpful?

- Participant 2 and 3 - Other advantages include design validation, interference detection, reduced physical load and faster development.
- Participant 1 - to visualize design alternatives
- Participant 4 - it boosts my confidence. I know if it will work or not when I make a CAD model. Especially in assembly, a 2D sketch does not communicate well. After making a CAD model I can be sure if things will work or not.
- Participant 5 - I have never been strong in sketching. To me sketching is something like this (points towards doodles). It helps to figure out basic ideas and proportions in very early part of project. Once I have little clarity then I start developing concept, not in very details but a rough model. I would leave out small details like radii, holes, texture, etc. I would create a rough model that would look decent on a render. It is not that if you create a good detailed model and make it look complete and realistic, it is done. In past, we have done complete redesign even after showing realistic renders.

Annexure-V

Interview transcribe - Final study

All the interviews for the final study were voice recorded and transcribed. A sample transcribe for one participant is presented in this annexure.

Interview Transcribe sample: for one participant

Q. What is your job profile?

A. Product Designer

Q. What type of projects have you been working on?

A. Basically electronic accessories, household accessories like switches, switch accessories, door bells, spike guards, smart switches, fans, all electrical accessories.

Q. Does it require you to ideate new ideas and represent?

A. We have to re-design as well as design from scratch and present the ideas to management.

Q. What tools you use during early idea generation stage?

A. Start with doodling, keywords and post-it. We dont make detailed sketches. After doodling we move to SW. We start with basic form in SW. Then either will keep improving that form or looking at it if i get a new idea then makes another file. But then the whole process is very iterative and is in 3D modeling.

Q. Which software you use and how long you have been using these?

A. SW only for last 5 years

Q. Can you rate your proficiency on the scale?

A. From Product designer’s perspective I am a proficient user. I'll always find a way to make it in SW. If it is not possible to make it in SW then will take help of Rhino. But for detailing and all SW is required also it is easier for engineer if Ii give him a SW file.

Q. When and how do you use CAD in your ideation generation process?

A. We only do initial doodles. We dont detail any idea on paper. Immediately after doodling initial thoughts we move to 3D mdoeling. And iterations are done in 3D model.

Q. Designers use rough doodles and refined sketches, quick and dirty mockups and prototypes, in their design process. Have you in your experience ever used rough modeling and refined modeling?

A. Yeah. Certain ideas you just want to explore roughly in 3D for visualisation purpose, it helps. Ideas that you are not able to draw or visualise. In 2D it is not very clear. 3D provides a mass. You can always go back to sketching after rough 3D modeling for further ideas and detailing.

Q. In your opinion, what are the advantages CAD tools offer when used during idea generation stage?

A. You get a wholistic visualization. Visualizaion.

Q. Does presenting a CAD representation make you more confident about your idea? How and why?

A. In a way. It gives you a clearer picture of what you are trying to make.

Q. Does making a CAD model help you get more clarity on the design idea? Why?

A. Yes. But it restricts the creativity. Your ideas get limited in numbers.

Q. Did you ever have a discovery due to CAD modeling?

A. Once or twice. But that happens during sketching also. Once you make a dirty mockup the entir form is something else. Sometimes on paper the idea looks nice but when you give dimensions and all and make a mockup model or a 3D model it looks entirely different. And then you have to make a lot of changes. It basically gives you a feeling of volume that you can work around. Now with these new programmes where you can sculpt in 3D and it gives you basic 3D form that you can furtherr refine, one can make multiple ideas in much lesser time. These days it is easier to make multiple options. Rhino is also very flexible. SW does not give you that kind of flexibility. In rhino in one file I can put 5 different options but in SW I'll have to make 5 different files.

Q. Does CAD visualization trigger more ideas or induce a feeling of completion leading to finishing of ideation?

A. Potter while working on a pot can go on stretching it pushing it and exploring various options. For designer also it should be same. After making the base model designer should be able to think beyond it. I feel as a designer if you want to do lateral explorations the new-age tools actually allow you to do that much faster. You can make 3D sketches on ipad now and in google sketch up. Now making 3D has become much easier. Now VR will also come. Interfaces are changing and may be next gen computers will come with VR.

Q. Literature says that CAD can make designers less hesitant to try different alternatives. However, making CAD models take substantial amount of time and may lead to fewer ideas. What is your experience?

A. Ideas come all the time even while making 3D models. You always visualize in 3D. So everytime an idea comes you note it down for future concepts. I might write an idea on post-it and put it on my wall and then work on it in 3D later. So it is an iterative process. You can focus on one thing if you want to but ideas keep coming. So it does not depend on whether you are working on 3D.

Q. Literature mentions instances where due to detailed models made in early exploration stage, and illusion of completeness curtailed further exploration. Sometimes, due to time spent on modeling there is a hesitation to explore fresh ideas. Have you ever experienced obstruction or premature fixation to certain ideas in the early phase of design due to CAD modeling?

A. If you start detailing a particular idea and just keep thinking about it then the idea is dead. Nothing new comes up. You will explore only in a certain direction. Starting from scratch creates hesitation. You have to completely start afresh to work on a different concept.

Q. CAD interface can help designer handle products scaling from micrometer to 100s of meters. Yet, it was realized that looking at the computer screen it is difficult to gauge the size and feel of the design. Have you ever experienced something like that? How do you ensure the size / grip / feel of the product you designing results as intended?

A. This happens. Once I was working on the produc interface and designed and positioned all the buttons and then when i zoomed out and kept it on the screen approximately in actual size then i realized those were really small. You cannot visualise the actual size. It happens while sketching as well. Unless you make a physical model you do not feel the actual size. So I try to zoom it to the actual size while designing.

Q. What are the limitations of CAD tools when used in idea generation stage?

A. Restricts the number of ideas that are produced. It is subjective as well. Sometimes you dont need many ideas because it has to be delivered in a week.

Q. During the experiments done earlier, it was noticed that people drop certain ideas and / or compromise on certain formal aspects when the 3D model is difficult to make. This was particularly noticed in cases of designs having organic or fluid forms. Can you recall any such experience? What is your strategy when faced with such situation?

A. It happens. Rhino deals with complex surfaces whereas in SW you get accurate results. So I make surfaces in rhino and take it to SW and then work further on it. But still there are limitations.

Q. Does the act of CAD modeling ever create frustration or boredom? Have you ever dropped any idea to avoid modeling it?

A. When someone else has made a design or product and I only have to replicate it and create a render of it then it is very boring and frustrating. When you are not doing anything creative then it is boring.

Q. Does using CAD in early stage of idea generation result in more vertical exploration and curb lateral exploration?

A. Yes. When you sketch you can go in any direction. But in 3D modeling you only refine ideas. So when we start for a new project we go crazy and do lot of doodling but for a redesign project we start with the basic building block and then refine it. So when you have more freedom and it is a new project then it is easier to go crazy and explore all the directions. In a redesign project you know you cannot go too far and you start directly in 3D and then do iterations.

Q. Do you ever experience that the act of CAD modeling takes away the thinking from designing to modeling?

A. Sometimes when the idea is challenging to create in 3D, the attention gets diverted to exploring ways to make it and more time is spent in that instead of taking design decision. What is your view on that? This has happened. We dont sketch much. We mostly 3D model more. It is about how it should be and not about how it is model. But it is all about visualising. Even during modeling you are continuously taking decision on how it should be.

Q. Would you like to add anything else from your experience?

A. SW is not good with surfacing and once I had to make a curved form and I was trying to extract some curves but then it didn't comeout the way I wanted so I dropped the idea. I could have made that in Rhino but then learning Rhino would also take time.

Q. Any thought on features you would like to have in the next version / upgrade of your CAD programme?

A. VR based 3D sketching. It would be like sculpting. The interface will shift from mouse and keyboard to more intuitive VR controls.

Annexure-VI

Retrieved coded data

All the interviews were coded using MaxQDA. A sample retrieved data for code-rough modeling is shown below.

Retrieved data for Code: ROUGH MODELING

Document name	Segment
Pilot interview 3 - rewritten	Yeah I do rough modeling sometimes. Yeah. So I do like these quick models where I don't know how, like I told you how it's going to be made and It is just to see like, Okay, I'm looking okay in proportions and all. Once it is really okay then I'll probably take it out and then detail it. it has to stand it has to take load. It has to it has to do all of that. So then you have to think of the construction and everything so yeah, I do a little bit of rough modeling.
Pilot interview 3 - rewritten	That's why I don't do it. I don't make my first models very detailed. I just make them like you can see? Looks fine? Then only I ll go on. Rhino allows you to just put things together and you have a make shift arrangement. But in solidworks you need to add values and all and define it. It is a lot of work to do.
Pilot interview 3 - rewritten	I don't know for me I don't I start with rough modeling. So when I start with rough modeling, I try to do as different as possible. Once you've decided on it anyways when I will start detailing it and narrowing it down I

	will be in that vertical exploration. So i don't i try to not do it in the beginning unless I have been given restrictions. If I am given restriction like there is a box of this by this and make it look nice somehow then I'll just do that I'll put constraints to it and explore. Because the brief itself is so narrow. But otherwise I try to make like one blue sky idea and one on mother earth and the one below and then I see like you know where is your interest and then I'll probably go in that direction. Sometimes I've just gone crazy when models because I just learned new things to do on the model so I've just made stuff which I know is not clearly mood or might not get approved but just for the fun of it. You know that this looks like gothic or this looks like a machine and I go crazy when you're not investing time and material and when you when you learn when it's not like. Like when you have the time and you just are in like it's like a preset you take a break.
Pilot interview 2 - rewritten	Actually it happens all the times. There are 2 files, one which you can allow to get dirty and have errors in it but there is a parallel file that is developing for final production and detailing. That is the fair modeling. You want to do a trail you do not copy-paste and name all the elements so that someone who receives the file can also understand it. So the concept very much exists in reality. Manner of giving commands is still very technical. It does not allow rough modeling. Even rough models are pretty fair.
Pilot interview 1 -	It is there in practice. Crude initial models with random fillets, without refinements, etcexist. It helps specially to

rewritten	understand the massing and proportions.
Pilot interview 1 - rewritten	I have had many bad experiences with clients who thought the rendered idea is the final idea. We used to make renderings look sketchier in Photoshop. Or make a model and take it in sketch-up and make look it rough.
190727_001	It definitely exist. I start with skeleton model which mostly has blocks of the internal components and then i sketch over it. Then again i quickly do a rough model just to see how the shape will look visually. it is easier to visualise in 3D CAD model.
190715_001	I have not yet done rough 3D modeling. But new software are coming up where for a given dimensions it can generate multiple options and like rough doodles you can quickly make rough 3D models, volumetric models.
190713_001	No. Rough is in 2D. One major reason is also the availability of 3D software licenses in office as these are more expensive we cannot have many licenses. So i have become better in Photoshop rendering using stylus and tab.
190612_001	Yes. Rough is used for volumatric study. for example, i was working on a project where i used rough modeling to see how big is battery, camera, pcb and other components so that i can design the package around it. For placements of various components and for the overall size.

190526_002	Very much. Pretty much all the designs go through this rough and refined phases. In my design process, I make a lot of rough models during the concept generation phase. Once the concepts are finalised, again refinement of the same goes through the refinement stages, more often with files saved as versions.
190526_002	It depends. While CAD gives a lot of ideas, I have found myself caught up in making many manyiterations which are incomplete in actuality. I overcame this habit by becoming more disciplined with my file management and time management. CAD works best when there is more focus on the work- this is my learning!
190526_001	Yes, I do make quick dirty protos to check with the ergonomics and form factor possibilities of the idea.
190526_001	If someone is good at detailing then he/she may not spend time constructing whole model in CAD. To get a gist of what he/she wants, he/she may create a crude CAD models to check with form and other physical aspects of product.
190525_001	I dont think so. It takes a lot of time when you are trying to generate or develop something in 3D. If you are trying to create random forms then it is a different thing. But if you are trying to delelope the products of daily use, instead of spending much time in developing 3D models it is better to test the viability of the design with a physical model. Physical models can be made with very basic profile drawings done in autocad then model can be made with foam or MDF.

190524_001	If anything has to be done over-night then you do a rough 3D model without adding any details. Just to get the basic form right. Suppose you want to put a screen on glucometer so use a jpeg screen and put it in keyshot. Even the buttons can be added as texture in keyshot.
190519_001	Yeah. Certain ideas you just want to explore roughly in 3D for visualisation purpose, it helps. Ideas that you are not able to draw or visualise. In 2D it is not very clear. 3D provides a mass. You can always go back to sketching after rough 3D modeling for further ideas and detailing.
190428_001	Yes, every project doesn't go without it. So I can just pick any project, I used a very rough model at times, surface model tha, getting back on board that this is the direction which we can take, is this fine, we showed it to the engineers also. So the sketch also gives clarity on feasibility, so you can show the sketches to your senior management, senior management if they understand so well, was very rough 3D model done in a day, it helps them to understand also ki ok, fine or no, we cannot go with this kind of shape because it needs this kind of investment which is not possible. An engineer can give you some directions. When they start give you some direction that if you go into this kind of form, we may need collapsible tool or we need to have some xyz things, you can not give a texure here or you can give it here. You need to have a shape for some purpose, you need to give a gap here which you have not shown in the sketch then yeh model mein to tum wohdaloge, the sketch which is shown in the model and realise how it

	looks, there are so many things that happen in the sketch, so it is an advantage there.
190428_001	Bahot jyada hota hai. (I do a lot of rough modeling)
190427_001	I was very comfortable with 3D models, but there were many models that I used to save as draft because to reach to a very detailed and final one, I had to create many files, which were very....so for eg. Maine ek fillet de diya, phirbaad main, I feel, areyiskoaurekalagtarike se karnachahiyetoh instead of going back, I used to keep that as an option, so this can be one of the another design option as well, let it be a draft one..so then moving ahead, whatever mistakes I have made in that, so this would be an improved version, which I had ...I mean you build onto something, right?...Pehleek plain lo, phirek sketch lo, phir 2D ko 3D banao, 3D mein...give the radiuses to everything, and then you realisesareyiskotohaurek step easy bhikarsakatethey..So in the later part, the second one, I also want to do detailed one, I used to skip those process and then jump to a very different way of doing it, so those models were also saved as rough. So for me, rough and detailed one exists in this way.
190427_001	So 2D was very easy for me, 3D I will do a rough one, which will give me an idea keyeh rhino meinkaisebanega, fatafat I will go and make it in rhino, because it was giving me a very clear idea, a crisp idea. I used to experiment more on radiuses over there, fillets, radiuses, exclusions and all. Detailing of course. Then for a presentation purpose if I want to sketch a very

	confident line, print data, I will put it on tracing, I will fatafatdo a very confident line or whatever it, because to create something presentable it was very easy for me. So I used to do that and again I come back. So it was my jugaad, I don't know, for other people it might be very different, It was my jugaad, I used to do that way.
190420_001	Absolutely. There are times where we shall present 80 block models to the client out of which 5 will be taken forward. then we do the secodary model. Making CAD models also give me edge. If client wants to see any idea in physical form then i can quickly 3D print the same and showcase. Rough block modeling is always useful to mill / 3D print / present. It speeds up my design process. 3D printing has become so accessible and easy today.
190419_005	Yeah, so generally the sketch is more of an idea. Then when I get into 3d like designing everywhere in 3d its, not like general translation. So just to give you briefing there has been in different organizations there is a push to share your sketch directly with a digital modeler or some who is going to take that sketch ahead. So its part of the design process. Design matures when you are defining it. Design is not over when it comes to 3d modeling, so its part of designers domain. And there is modeling because you are doing changes here and there and creating ideas, it's a part of the process. And eventually, you convert into better surfaces and quality and sort of what direction to take. I generally prefer doing that in a separate file otherwise its get very messy.

190419_005	I think it actually depends on the software, because Rhino has that issue that fiest you have to finish your entire model then you will go to edge finishing and you also have to save one raw model without any egde finishing that is ridiculous.
190419_004	I use CAD more for vertical explorations and not for lateral explorations.
190419_003	ya. It does. KyukiwahiBolrahahun, sketch me kabhikabhi workshop me jaake banana aasan ho jatahaikai forms, koi forms 3d model me banana asan ho jatahai. Kabhikabhi 3d model me banake, phatak se uska drawing leke workshop me jake, bhaiyaItnabana do, nahitohkhudjake, depends. So sometimes that is time saving making 3d model, random phatak se karke, im not saying detailed 3d model. For presentation, last me we do that. so, that is different. Rendering keliye. Ye hua form ka.
190419_003	Ya it does. It does. I told you na sometimes I have to check something so I go to rhino open it go to 2d and make only a sketch We do filleting and all when we are going to present it or later stage me, when we are ki production me ab ye final Jane Walahai what should be the fillet, what should be..we think in that detail. Ye thodajyada ho rahahai, ye thodakamkarnachahiye. Wo detail baad me kartehain. Lekin functional product hai tab. Jab aesthetic hai to starting me hi banate time hi variations banatehain hum uske. Jyada fillet se aisadikhega, kam fillet se aisadikhega. Usmewahi start rehtahai. But ya, it does

	exist.
190419_002	We first break the brief into parts and generate ideas for each part through brainstorming in terms of keywords and quick sketches. We select few ideas and either takes it on CAD or directly prototype through quick and dirty mock up. If the idea is simple to make then making quick mock up is good. For complecated idea we do a block / rough 3D model in CAD and then we did laser cutting for making prototype. We designed the concept for acrylic laser cutting. Basically, when I'll use CAD and what my approach will be is based on my prototyping method.
190419_002	Yes like I said. We do the rough modeling to make quick models
190419_001	Initially I always use rough 3D modeling just to see if the concept will work. It will be like a block model. After the idea is confirmed then I do refinements and detailing.
190417_001	Through conceptual models I am looking for a good rendering or to get quick 3D proportions of the idea, till that point. So these I never give out as final models. These are only for me.
190417_001	One can always make rapid surface models that do not have perfect geometry but is quick and sketchy. If you know the limitations of the tool then you can work around it. But someone who is not aware to limitations can fall pray to these kinds of things. There is always a temptation to add thickness, fillets and small details in

	the idea and then you get trapped in it.
190223_006	Rough modeling happens in we are working on new platform projects that are entirely new product. That will definitely involve a lot of rough modeling. That are for the explorations of volume and sizes. Whereas, if i am doing something time bound then i would directly do the final model. It is all time dependent.
190223_005	irst with sketching we show the limitations and possibilities on a page. Once that is clear, then we show the aesthetic part through models. For aesthetics 3D modelling is easier because it is very easy to manipulate radius and the fillets. For that modelling software is easy. The initial detailing does not require detailed workout. Just to express what is your idea.
190223_005	In sketching I've only done rough work. I also used to make quick models with papers and foam-board, thermocol that is just to give the initial idea. That how the product is going to perform, and how it will look, the volume and that. But for the detailed design, I always use software. That's my comfort zone. I'll say.
190223_004	I use a lot of rough modeling to get the basic form to use as base and move to refined models only after I have shortlisted few ideas. Mostly after I get into CAD I do not go back to sketching. Whatever changes are required those are done in CAD itself.
190223_003	I most probably go towards the final form rather than doing rough ideas. For that I'll use sketches.

Retrieved data for Code: CIRCUMSCRIBED THINKING

The interviews were also grouped based on the proficiency of the interviewee. The following section demonstrates the retrived data for 'Circumscribed thinking' code for different proficiency levels.

Code: Circumscribed thinking
Participant: Proficient users

Document name	Segment
Pilot interview 1 - rewritten	We would start defining a form in terms of commands. This was like a game but then it increased our proficiency and confidence.
190727_001	Initial stages it is difficult. As you start developing your own ways it becomes easier. Your proficiency will dictate how good or bad your concepts are. It is relative. Depending on the proficiency designer might get constraint by the software or use it to come up with newer forms and finishes with the software.
190727_001	It depends on time available and your capability. A beginner will always compromise and get constraint with what can be made. It happened with me in the earlier years. At this stage your designer sensibility has to play a major role. The better you get with your skills, lesser the compromises that you make. You understand how the software has to be used to achieve what you want. There is good compromise as well. You might create a form where PCB is coming out, and then you

	quickly change it to accommodate the components. The instant feedback that comes from the 3D model allows you to explore more constructively and focused and can result in good compromise as well.
190727_001	Yes. It happens. It also depends on the approach of designer. I try to draw a balance but then there is always a time constraint. In the back of my mind software is always playing a role in the way the forms will emerge.
190526_002	Yes. We face this situation while making the end-caps for the aluminium sections. The sections are straight and we use the end-caps as fluid-accent elements to break the monotony. Some of the curves in sketches look great, but when we try to make it in CAD, it becomes very difficult to match the integrity of the curves and surfaces in CAD. To overcome this problem, we often tweak CAD parameters to reach the desired design.
190420_001	I have seen this happening with my team and they will try to convince you just because they could make it using a certain set of commands. So if we face such a situation we make a mock-up and then 3D scan it. We do reverse engineering. We extract form from the point cloud data. But still we do have to compromise on form sometimes 15-20% due to other limitations but yet we are able to achieve organic forms in our products to a great level when required. Any tool has its limitations. So

	we have alias experts and we have solidworks experts and we do not insist on using one tool from start to end. We use the strengths from various tools. That is how we try to acheive what we want rather than compromising on what we can get.
190417_001	Your vocabulary or tool will dictate the kind of form you generate.
190417_001	It is not powerful enough yet. It is just a matter of how many features you know and how good you are at it. It is a well known thing that people will make a sketch and then try to model it and if it does not turn out to be exact then they tweek it to account for the tool. So design gets modified as per the tool. Happens regularly.
190417_001	It happens and it should happen. Where will you get the 100% representation of what you are seeing in your head? Even for manufacturing it changes. Even for tooling if you cannot give certain radius you do not give.
190223_006	If constraints are clear then i might go for an outline sketch. I also do modelling just to get the feel of volume. Sometimes you get biased by the tools so i try to avoid it initially.
190223_006	In my case, the conversion is not 100%. There are always few unresolves things with form or idea. Then later you have to compromise. Since it is a compromise it does not add to my confidence.

190223_006	It is very subjective to what you are working on. It does take more time specially if you are trying to achieve exactly what you sketched. Then it will lead to lesser ideas.
190223_006	What happens, in product design you design a product today and it goes into tooling tomorrow. Not like automotive industry where you can keep refining the form for a long time. So you tend to compromise because there is no time. At times you want to explore some tactile pattern and it is very lengthy to create in model. So my strategy is you can't get if you can't make. so I take the help from other software or colleagues.

Code: Circumscribed thinking

Participant: Competent user

Document name	Segment
190715_001	No matter how much you know but there is always something you do not know. Every time I face such situation I ask someone who knows. During a project, there was a particular curve that I could not get and since we had to 3D print the model it was essential to make a good model. So I asked a friend to make it in another software and give it to me. But if that is not possible then yes people compromise on design because it is just not happening. It is very common.
190612_001	Yes. I was planning some fluid design inspired from bio-mimicry and tried for days to create it but it didnot work.

	Finally we compromised in form. It happens a lot.
190525_001	If you start modeling at an early stage you might focus more on that model and eventually you will add more and more details to that model. Over time you do nont get back to if this idea will work on not but you end up detailing it more.
190525_001	Yes inertia settles in and you just modify the same idea and try to arrive at some result rather than going laterally.
190525_001	One major limitaiton is with all zoom-in and zoom out, you do not realise if the dexterity required for a handheld product is achieved or not. Secondly, you can put any colour swatches and combinations without realising what kind of products will be available from vendors. Instead of using a physicl material board you are using a virtual material board original results may be drastically different. Other limitation is we do not get an idea about the tactile feel of the material.
190525_001	When I was a student, all my explorations were limited by my knowledge of the software. Now when I see my students working on products that require organic form, limited use of CAD actually results in geometric form. It does not match the product semantics for that category of products. Our knowledge of software hinders the kind of design we produce.
190525_001	Once I was working on a particular kind of safes for US based client that demanded a lot of security. The material for this was really strong and the door itself was very heavy. So hinges required for this had to be really strong to take the load of the door. I was not good at mechanical simulation at that time. I was more focued on how to make it look appealing and pleasing. After the prototype was made the hinges tore like paper. That was a very big limitation.

190428_001	there really has been instances where I have been persuaded XXXX to just leave the mouse, just leave the keyboard, just sit and think ki tum kya karna chahte ho yaar, exactly kya? Don't let you 3D model to constraint riding a form, toh hota hai woh immediately in a glance na, in just few seconds realise, you will realise that this really not what she wants to do. And it really happens that way and then you have to be there haa, because this generation needs little bit of, thoda paper pen ka jarurat hai, to teach them to help them out.
190419_004	Usually what happens if a design is hard to make in CAD I will give it to someone else, we have digital designers over here. When I am doing it I take it as a challenge and most of the times I end up making something very near to the original design. I don't alter the design as it is shortlisted and it has to look good. In extreme cases I will give it to the digital designers and get it done.
190223_005	Ya, ya. Possible. It happens with me also. In that case I generally don't show that detail. I tell people that this is the overview. These corner details will improve in future. Because for doing that I'll need more time. So this corner detail will not be exactly the same as it is looking like here. So if it difficult for them to imagine then I do it on paper.
190223_004	CAD can make designers lazy. CAD is still more manageable and you can always go back to your model and review it. But once you start rendering then your focus shifts to colour texture and lights and how well it looks etc… You might completely overlook the functional aspects or flaws or mistakes. More than CAD I think keyshot is towards completion.
190223_004	Yes I do that. I used to drop ideas if I cannot make it on CAD. But sometimes it is otherway round as well. I can probably make it in CAD but cannot sketch it. Like in case of safe I

	wanted a curved surface with a very large radius. It was not visible in sketch but in CAD it was clear. So it helps visualization.

Code: Circumscribed thinking

Participant: Advance beginner user

Document name	Segment
Pilot interview 3	I think sometimes for people like me who are not very good at modeling and who wouldn't push themselves to do it right like this is what it is in my head I have to make it like this. Sometimes just complaining and then you change the idea to make it easy to make.
Pilot interview 3	Because it is just too complicated and you're trying and you're trying and deadlines coming in and you feel it is not so bad. It just gets selected also. So for example, if you put five things and the one you really wanted to do is just too complicated model not modeled it well it is the same as sketching you weren't able to sketch it out with the other ones gets selected because it looks much better. The same happens in the model because you didn't model it as well as you could say, and it's just like gone.
Pilot interview 3	Yes I do! totally. Like it was very difficult to me I'll be like forget it. Like let's not do this. like if I have time I'll try it. I ask people for help but you know what happens is invariably the system is such that even on the people on top of

	you are going to tell you to leave it because they know you won't be able to do it in that time. so you don't take somebody else's help to get it done. We don't have anybody like a 3d modeler or someone in our office who can do the models for you. If you can't do it and even if you model it if we can't manufacture it is going to drop it, right? I'm saying if they can leave it because they can't manufacture it. You have to leave it because you can't model it. It's the same theory. like it's the same application because the time is the restriction but I so that's why when I have a little free time I try and learn modeling and I try and do it.
Pilot interview 3	Even I will have to detail it out, figure out how to make it. But if you were stopping at the initial stages, not because of the design but because of the model. and I know a lot of people who do that. a lot of designers, a lot of them. I know that designers have a thing where your skill set just like you're sketching is not good. You're not a good designer, you can't model well you're not a good designer you can't render well you're not equivalent to being a good designer. And when you take it a direct proportion then obviously you have to do it.
Pilot interview 2	I know a friend who designs only what she can model. She is a very hands-on person but she is in a place where modeling and rendering is a benchmark of good work. And she is not great

	at it or enjoys it. So she designs keeping in mind that she has to model it later. But it also depends on material. You may go wild while modeling but if the material doesn't support that then it does not make sense.
190713_001	I have faced this. But with me I also had a team that had people who were expert so I would use their expertise in doing such thing. It is not my expertise.
190524_001	Because later i only face the problem and if i am not able to deliver then it is of no use so I go for Bauhaus style and keep it simple and as neutral as possible.
190524_001	I do not go for organic form. I am not ashamed of it but your outputs are skill dependent.
190524_001	Sometimes, I hide some sketches because I cannot deliver those. If you pitch it by mistake and it gets approved and then you cannot make it, it becomes an issue. Even the design engg questions it. So I settle for things that are doable for me as well as for design engineer. I would rather have more number of doable ideas than waste time on finding about how to make one particular idea. You make a dirty 3D model, give it a dark background and focus on the feature that you want management to pay attention to. Like for a particular curve, I'll give it glossy texture and give lighting in the render in a way that the curve gets highlighted. Also put it at an angle from which it looks nice. Then when you sit with design engineer certain

	changes always take place. I mostly do the dirty modeling and depend on design engineer for detailed model.
190519_001	It happens. Rhino deals with complex surfaces whereas in SW you get accurate results. So I make surfaces in rhino and take it to SW and then work further on it. But still there are limitations.
190519_001	SW is not good with surfacing and once I had to make a curved form and I was trying to extract some curves but then it didn't comeout the way I wanted so I dropped the idea. I could have made that in Rhino but then learning Rhino would also take time.
190427_001	At the very initial phase, I had faced that. So in Simbi, that was for my graduation project or something, I had to give arrival assignment task, so initially they asked me to sketch something. So I sketched something very organic. Later on I realised that I won't be able produce it then actually changed the shape.
190419_005	It has happened like more than once that I have discovered something while working on 3 d models. But I have never gone with it. It's as a backup to try on later. During the beginning when I was new to Rhino. At that time dependency on software was higher than. So software sometimes designs for you and sometimes it makes what you needed it for. Initially, these accidents used to happen more then as I gained command over the software I

	started getting what I planned for.
190419_005	Yeah many times it happens and it's really shamefull to tell that i have changed my design because earlier one was tough to make in model. So, that would also come under limitations of software.
190419_003	Hota hai. Hota hai. Haan usko kabhi aise use nahi kiya maine. Ki haan ye aise nahi hota lekin aise mil gaya. Lekin mujhe Wahi chahiye tha. Aisa hai. Toh woh ho jata hai kabhi kabhi.
190419_003	Haan back of mind sometimes I agree with this point sometimes when you sketch only you think of so many things ahead like arey model Iska nahi banega, so you try to make it simpler. So you imagine that. That is a problem. So even I try to do that ussey simple yet beautiful. I try to do that. Which is possible. But sometimes the form is really good then we have to, we have engineers, we have digital people who can help us.
190419_002	Not actually. But recently I worked on a handle using push-pull kind of commands and there it really worked. So I had a sketch and it was really complex. I tried to model it but it didn’t work out. Then I tried this push-pull and made something which looked good.
190419_002	So I was facing problem in making the handle so I used push-pull. But it does not give you exact form. It gives you something closer to what you wanted to make. Then you compromise and feel content with what you

	could make.
190419_001	Yes this happens. And we ask the team to modify the form so that it can be made. It also depends on how expert the user is.
190223_003	I sometimes get stuck with that one primary form that I make first. There is a large volume and I might refine that but I am not going to make an entirely different form. For that I ll have to make an entirely new model. If I am making another model then I might miss out on the explorations that I could have done on the primary model. The volume there also could have been adjusted.
190223_003	Initially it used to happen. It is usually easier to create geometric forms in 3D. But now that I have gained experience and I am fairly good at it, I am fine with creating organic forms.

References

- Abdelhameed, W. (2007). *Visual Design Thinking in the Design Process as Impacted by Digital Media.* Retrieved from ftp://ftp.forum8.co.jp/Forum8lib/pdf/VRsymposium /Bahrain-4.pdf
- Albert, A., Chakravarthy, B. K., & Dirk, S. (2001). Collaborative Environment for Concept Generation of New Products. *Exploring Emerging Design Paradigms.* South Korea: ICSID.
- Aldoy, N. N. (2011). *An investigation into a digital strategy for industrial design education.* Loughborough, UK: Loughborough University.
- Allen, J., & Kouppas, P. (2012). Computer-Aided Design: past, present, future. In S. Garner, & C. Evans (Eds.), *Design and Designing: a critical introduction* (pp. 97-111). New York, USA: Berg.
- Athavankar, U. (1990). Thinking Style and CAD. *Proceedings of Conference on Design Research* (pp. 109-116). Compiègne, France: University of Compeigne.
- Atilola, O., Tomko, M., & Linsey, ,. J. (2016). The effects of representation on idea generation and design fixation: A study comparing sketches and function trees. *Design Studies , 42*, 110-136.
- Bilda, Z., & Gero, J. (2005). Do we need CAD during Conceptual Design? *Computer Aided Architectural Design Futures* , 155-164.
- Bono, E. D. (1970). *Lateral Thinking: a textbook of creativity.* Word Luck Educational Press.
- Bramston, D. (2009). *Basic Product Design 01: Idea Searching.* Switzerland: AVA Publishing SA.

- Brown, P. (2009). CAD: Do computers aid the design process after all? *Intersect* (2), 52-66.
- Carroll, M., Cavagnaro, L. B., & Goldman, S. (2012). Design thinking. In S. Garner, & C. Evans (Eds.), *Design and Designing: a critical introduction* (pp. 20-31). New York: Berg.
- Chakravarthy, B. K. (2009). *Collaborative new product concept management: A flexible model for innovation.* Delhi: IIT Delhi.
- Chakravarthy, B. K., & Karpe, R. (2004). Collaborative Model for Entrepreneurial Innovation. *Cumulus Conference.* Oslo, Norway.
- Clare, A. (2009). *The development of three-dimensional computer-aided design modeling strategies and an investigation into their impact on novice users.* UK: Loughborough University.
- Cooley, M. J. (1977). Impact of CAD on the designer and the design function. *Computer-Aided Design , 9*, 238-242.
- Coyne, R. D., Rosenman, M. A., Radford, A. D., & Gero, J. S. (1987). Innovation and creativity in knowledge-based CAD. *Expert Systems in Computer-Aided Design* , 435-465.
- Creswell, J. W. (2011). *Research Design* (3rd ed.). New Delhi: SAGE Publications India Pvt Ltd.
- Cross, N. (2005). *Engineering Design Methods: Strategies for Product Design* (4th ed.). Chichester, England: John Wiley & Sons, Ltd.
- Garland, K. (1964). *First Thing First.* Retrieved March 5, 2018, from Design is History.
- Gero, J. (2011). Fixation and commitment while designing and its measurement. *Journal of Creative Behavior , 45* (20).

- Gibson, K. (2000). Divergent and Convergent Thinking with CAD. *Journal of Design Communication* (2).
- Guthrie, G. (2012). *Basic Research Methods: An entry to Social Science Research* (4th ed.). Sage Publications India Pvt Ltd.
- Hanna, R., & Barber, T. (2001). An inquiry into computers in design: attitudes before - attitudes after. *Design Studies , 22*, 255-281.
- Honken, N. (2013). Dreyfus five-stage model of adult skill acquisition applied to engineering lifelong learning. *120th ASEE Annual Conference & Exposition.* Atlanta.
- Hunt, A. (2008). *Pragmatic Thinking and Learning.* Raleigh, North Carolina, USA: The Pragmatic Bookshelf.
- Ibrahim, R., & Rahimian, F. P. (2010). Comparison of CAD and manual sketching tools for teaching architectural design. *Automation in Construction , 19*, 978-987.
- Ingram, J. (2012). Models of design and models in design. In S. Garner, & C. Evans (Eds.), *Design and Designing: a critical introduction* (pp. 69-81). New York, USA: Berg.
- Jonson, B. (2005). Design Ideation: the conceptual sketch in digital age. *Design Studies , 26*, 613-324.
- Kulogun, N., & Asasoglu, A. O. (2010). Indirect expression as an approach to improving creativity in design education. *Procedia Social and Behavioural Sciences* (9), 1674-1686.
- Lawson, B. (2002). CAD and Creativity: Does the computer really help? *Leonardo , 35* (3), 327-331.
- Lawson, B. (2006). *How designers think* (4th ed.). Oxford, UK: Architectural Press.

- Lee, S., & Yan, ,. J. (2016). The impact of 3D CAD interfaces on user ideation: A comparative analysis using SketchUp and Silhouette Modeler. *Design Studies* , 52-73.

- Liu, X. Y., Li, Y., Pan, P. Y., & Li, W. Q. (2011). Research on computer-aided creative design platform based on creativity model. *Expert Systems with Applications* , 9973-9990.

- Lubart, T. (2005). How can computers be partner in the creative process: Classification and commentary on the special issue. *Human-Computer Studies , 63*, 365-369.

- Luchs, M. G. (2016). A brief introduction to design thinking. In M. G. Luchs, K. S. Swan, & A. Griffin (Eds.), *Design Thinking* (pp. 1-11). New Jersey: John Wiley and Sons.

- Lupton, B. (n.d.). *The effects of computer aided design (CAD) on design education.* Retrieved August 23, 2013, from Barry Lupton: http://barrylupton.com/the-effects-of-computer-aided-design-cad-on-design-education/

- Mckay, A. (2012). Designing Design. In S. Garner, & C. Evans (Eds.), *Design and Designing: a critical introduction* (pp. 50-62). New York, USA: Berg.

- McKim, R. (1980). *Experiences in visual thinking.* Brooks/Cole.

- Milton, A., & Rodgers, P. (2013). *Research methods for product design.* London, UK: Laurence King Publishing.

- Milton, A., & Rodgers, P. (2013). *Research methods for product design.* London: Laurence King Publishing Ltd.

- Murthy, S. R., & Mani, M. (2012). Design for sustainability: The role of CAD. *Renewable and Sustainable Energy Reviews* , 4247-4256.

- Musta'amal, A. H. (2010). *An empirical investigation of the relationship of CAD use in designing and creativity through a creative behavior framework.* PhD Thesis, Loughborough University, UK.

- Musta'amal, A. H., Norman, E., Mohd, K. J., & Yahya, B. (2012). Does CAD really encourage creative behaviours amongst its users?: a case study. *Proceedings of 4th Regional COnference on Engineering Education and Research in Higher Education.* Malaysia.

- O' Leary, Z. (2011). *The essential guide to doing your research project.* New Delhi: Sage Publications Indian Pvt Ltd.

- Oxman, R. (2006). Theory and design in the first digital age. *Design Studies , 27* (3), 229-265.

- Pietsch, S. M. (2000). Computer visualisation in the design control of urban environments: a literature review. *Environment Planning , 27* (B), 521-536.

- Qin, S. F., Prieto, P. A., & Wright, D. K. (2008). A novel form design and CAD modeling approach. *Computers in Industry , 59*, 364-369.

- Robertson, B., & Radcliffe, D. (2009). Impact of CAD tools on the creative problem solving in engineering design. *Computer-Aided Design , 41*, 136-146.

- Sequin, C. H. (2005). CAD tools for aesthetic engineering. *Computer-Aided Design , 37*, 737-750.

- Shih, Y. T., Sher, W. D., & Taylor, M. (2017). Using suitable design media appropriately: Understanding how designers interact with sketching and CAD modeling in design process. *Design Studies , 53*, 47-77.

- Silver, C., & Lewins, A. (2018). *Using software in qualitative research.* Retrieved July 10, 2018, from https://study.sagepub.com/using-software-in-qualitative-research/student-resources/step-by-step-software-guides/maxqda-11-6

- Sonmez, M. (2013). Creativity and solid modeling. *Procedia - Social and Behavioral Sciences* , 169-173.
- Stappers, P. J., & Hennessey, J. M. (1999). Computer-supported tools for the conceptualization phase. *Proceedings of the 4th International Design Thinking Research Symposium on Design Representation*, (pp. 177-187).
- Stuart, M. D. (2008). Design Thinking and Design Innovation Scotland. *Proceedings of 2008 International DMI Education Conference.*
- Tovey, M. (2002). Concept design CAD for the automotive industry. *Engineering Design , 13* (1), 5-18.
- Tovey, M. (2012). The passport to practice. In S. Garner, & C. Evans (Eds.), *Design and Designing: a critical introduction* (pp. 5-19). New York, USA: Berg.
- Tovey, M., & Owen, J. (2000). Sketching and direct CAD modeling in automotive design. *Design Studies , 21*, 569-588.
- Ulrich, K. T., Eppinger, S. D., & Goyal, A. (2009). *Product Design and Development* (4th ed.). New Delhi, India: Tata McGraw Hill Education Private Limited.
- Walther, J., Robertson, B. F., & Radcliffe, D. F. (2007). Avoiding the negative influence of CAD tools on the formation of student's creativity. *Proceedings of the 2007 AaeE Conference.* Melbourne.
- Wergles, N., & Muhar, A. (2009). The role of computer visualization in the communication of urban design - a comparison of viewer responses to the visualizations versus on-site visits. *Landscape and Urban Planning , 91*, 171-182.
- Wojtczuk, A., & Bonnardel, N. (2011). Designing and assessing everyday objects: impact of externalization tools and judge's backgrounds. *Interacting with Computers , 23*, 337-345.

- Won, P. H. (2001). The comparison between visual thinking using computer and conventional media in the concept generation stages of design. *Automation in Construction , 10*, 319-325.

- Xiuzi, Y., Hongzheng, L., Lei, C., Zhiyang, C., Xiang, P., & Sanyuan, Z. (2008). Reverse Innovation Design - an integral product design methodology. *Computer-Aided Design , 40*, 812-827.

- Zboinska, M. A. (2019). Influence of a hybrid digital toolset on the creative behaviors of designers in early-stage design. *Journal of Computational Design and Engineering* , 675–692.

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List of conference papers

- Battula, Chakravarthy K., and Purba Joshi. "Role of CAD in Product Innovation: A case study approach." *GLOGIFT 10.* Tokyo, 2010.
- Joshi, Purba, and Chakravarthy K. Battula. "Articulating the Phenomena of Creative Exploration of Design Students: Representing Ideas through Computer-aided Design and Its Effects on the Creativity of the Design." *Design Principles and Practices.* Rio de Janeiro, 2016.
- Joshi, Purba, and Chakravarthy K. Battula. "Study of the effects of Computer-Aided Design in the early phase of product design: an exploratory study." *Design Principles and Practices.* Chicago, USA, 2015.

Published papers

- Joshi, Purba, and Sharmila Sinha. "The Effect of Idea Representation Techniques on Design Decisions During Idea Exploration Phase: An Exploratory Study of New Product Design." *Smart Innovation, Systems and Technologies* (Springer) 2, no. 66 (2017): 567-576.
- Joshi, Purba, and Sharmila Sinha. "A design inquiry into the role of design process in fostering creative exploration of ideas and concepts: an exploratory study of design projects of students." *Proceedings of the 21st International Conference on Engineering and Product Design Education (E&PDE 2019).* Glasgow: https://doi.org/10.35199/epde2019.6, 2019.

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