Retracing Spatial Design Processes:

Developing a Pedagogical Tool for Architecture

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ABSTRACT

RETRACING SPATIAL DESIGN PROCESSES:
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Over the recent decades, contemporary architecture and its design processes have witnessed rapid digitization - owing to the advent of Computer-Aided Architectural Design (CAAD) tools. However, these tools for the architectural discipline have yet to holistically accommodate the intuitive, “messy” and collaborative nature of its ideation processes. These creative processes of architecture students and novice practitioners have either been flattened or neglected while enforcing conventional CAAD tools with inflexible interfaces. However, students can benefit from experiential learning in design studios with tools that support and facilitate their reflective design processes. These tools could intuitively assist in brainstorming design concepts from inspirational stimuli while simultaneously documenting these thought processes and ideas through interactive design databases. Hence, given the continued adaptation of the architecture discipline with digital design strategies, tools that help in dynamically recording and tracing the evolution of design thinking and making processes can help better validate and reflect on their corresponding conceptual designs.

This research is an investigation into the ongoing gap in the interactive documentation of the ideation processes in architecture education such that they could promote reflective design learning among architecture students while generating ideas for the built. This gap is attributed to the various challenges and limitations of existing CAAD tools such as the rigidity of their interfaces and lack of holistic support for collaborative design works. The research explores a digital design tool for students and novice practitioners that has the ability: (1) to record and trace the concepts and design ideas generated during creative brainstorming sessions, (2) to provoke reflective design thinking and making through proposed design modes and, (3) to facilitate collective contribution to these designs. Through experimentation with these criteria, the proposed tool is investigated for its potential to bridge the gap in reflectively communicating and collaborating on design proposals during the conceptual design phases in architecture education and practice.

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FOREWORD

This thesis is based on my background in architecture school which has given me many insights on design thinking and professional practice in the discipline that has grown so socio-culturally complex over the years, making it harder for novice practitioners to “fit in”. I reflect that the open-ended and ambiguous nature of architecture and design education has made it difficult to find the “right way” to be trained and better equipped for the real-world challenges in skill building and contributing to each of our communities of practice. However, more and more global economic trends have compelled the field of architecture to rethink the ways in which it addresses the gap between academics and practice through advanced technological interventions that promise augmentation of our design skills and services.

As an architecture student that entered the world of design research to find answers or even possibilities of holistic knowledge exchange in the discipline, my research position is one of constant oscillation between the roles of a curious onlooker and an aspiring studio instructor. Assuming the former role, I question my ideological biases and personal experiences of architecture school (including an 8-month Office Training) which have shaped my worldview of the Architecture, Engineering and Construction (AEC) industry. However, I believe this research can better inform me for the latter role I hope to take up in the near future, positioning myself to share and grow in an organic yet holistic manner amongst younger generations of creatives in the field.

However, the digitization of architecture as a service has been further propelled by several historical moments including the disruptive pandemic that we find ourselves in. This has gravely affected creative collaboration amongst design team members whose foundations of peer interaction and coordination have primarily been built through physical movement within the stimulating spaces of design studios in architecture schools. In this event of the crisis that has socially distanced many communities of design practice, the “interwebs” of remote yet virtual human interaction have been both a saving grace as well as an eerie awareness to the norms of architecture and design of the future. While one might argue that these ‘workarounds’ irreversibly damage conventional modes of instruction and practice, this research is relevant now more than ever in contributing to the resilience showcased by the socio-cultural disciplines through digital interventions that embrace and overcome their systemic flaws in unexpected ways.

Therefore, it is essential to draw inspiration from the traditional practices of architectural thinking and making that are often messy and divergent explorations of possible solutions to the problems at hand. Consequently, I set the chapters of this research by respecting these alternating modes of *Reflecting* and *Making* in order to illustrate the temporal and spatial nature of design thinking and creation. I navigate through incremental theoretical and practical investigations in this research by iteratively switching my positions between an outsider *Reflecting* on the discipline and a student immersed in the design process of *Making*. Hence, this thesis is written with the intended portrayal of the flow of reflective design practice which is the primary focus of this research.

I urge readers to approach this thesis with an open mind in order to inform and realign architectural pedagogy for healthier integration of digital tools in the complex processes of design thinking and making. It is commonplace to see senior architects and designers overwhelmed by the apparent decline in quality of conceptual designs in projects for the future, but these worries can be confronted and addressed agonistically at the cusp of training to draw out plans that redefine architecture practice in the long-term. Therefore, I expect novice instructors and facilitators of design learning to be accomplices in this quest to nurture values of self-reflection and inclusive collaboration amongst students and enthusiasts who would eventually venture into real-world problem-setting and solving experiences fueled by holistic knowledge exchange.

Firdous Nizar

Table of Contents

List of Figures

Introduction - Design Thinking and Tools in Architecture

Background and Current Scenario

Architectural education has seen multiple redefinitions in structure and content over the years as its counterpart, the architecture profession and practice, has been relentless in its developments. Whether they mark progress or decline, the enterprises of architecture and engineering schooling have been constantly put under the microscope for its theoretical instructions which are linked almost directly to their practical applications in the built environment. However, the legitimacy of architectural pedagogy continues to be questioned in light of those enthusiastic design practitioners who were either self-taught through experiential learning by taking up a series of odd apprenticeships or imbibed with generational craftsmanship (Marchand 2006; McGuickin 2016). These instances position professors and studio instructors of contemporary institutions to rethink their roles in influencing newer generations of creative thinkers and makers.

Over the years, the complexity of the design process and its non-conformity to a fixed set of rules that can be enforced unequivocally, pedagogues have moved to the background as facilitators that share their personal experiences of design but ‘give some space’ to their students to find out their own methods. Nonetheless, it is an ongoing negotiation of values and ideologies between the instructors and the students as they build confidence to showcase their skills in critical and reflective thinking and experimentation through design (B. Smith 2017). Furthermore, architecture design education pushes students to read, travel, observe, sketch and document the dynamic built environment in order to cultivate cultural sensitivities over their tacit knowledge for their own design explorations.

Unfortunately, due to the ambiguity of this challenge, there is an uneven distribution among the students in their levels of engagement to the design process that comes closest to meeting the quality standards of the practicing industry. While this ensures the successful integration of those ‘top’ students who acknowledge the tensions in their relationships to the instructors and the institution in delivering their design proposals, several other students are evidently ‘left out of the loop’, particularly in design studios, where they succumb to the expectations of self-nurtured reflection and creation amidst socio-cultural diversity and its inherent conflicts. At these junctures, the pedagogy often fails to address the differences in theoretical frameworks and design methodologies amongst such students, often owing to the institutes' one-size-fits-all approach to design research and education for social services such as architecture.

However, these apparent disagreements from the students are turning points that question the status quo and reshape the paradigms of architectural education. If these crossroads are missed by the communities of education as well as practice, it becomes increasingly difficult in the long run to regain the financial and intellectual investments of the students, instructors and the institutions. Due to the multidimensionality of architectural design that mandates the development of various 'metacognitive' skills such as "analytic reasoning, intuition and creative expression" (Kavousi, Miller, and Alexander 2019) of authentic, abstract yet practical ideas, the educational parameters that impact the instruction of design processes should be debated and calibrated at a pace that is economically and culturally viable for the architecture, engineering and construction (AEC) industry.

One such methodological dimension of architectural design education that undergoes constant revisions is the 'design studio'. Philippe Crowther in "Understanding the signature pedagogy of the design studio and the opportunities for its technological enhancement" (2013) defines the design studio as "a unique pedagogical format" that has been widely adopted in the curricula of design fields because it is key in providing "an important environment for collaborative learning" (Crowther 2013). Through partially structured educational strategies such as 'experiential learning', design studios are observed as an appropriate mode of instruction to students who learn design techniques through hands-on experimentation and creation of proposed solutions to given design problems (mostly hypothetical).

In most institutions, the students work on several graphical and verbal descriptions of their design ideas in between individualized weekly feedback sessions with their respective project mentors who are often the sole instructors of the studio. As illustrated by Donald Schön in *Educating the Reflective Practitioner: Toward a New Design for Teaching and Learning in the Professions* (1987), much of the experiential learning by the students takes place through the dialogue with the instructors that trigger and deepen their perceptions of the built environment while eliciting suitable design actions that attempt to address the issues discussed (Schön 1987).

As design studios are structured to simulate the real world practice environment of the industrialized profession of architecture, most institutions across the globe adopt very similar strategies of implementing design studios as their primary mode of engaging students with skill building tasks of brainstorming and presenting conceptual ideas for assessment. These design studios are delivered as semester-long academic courses where students develop their designs through drawings and models, and which "typically culminates in a public presentation of the design project, referred to as a crit, at which time it is assessed by a jury of academics" who are usually external to the institution (Crowther 2013; Al-Qawasmi 2005).

However, unlike art and craft studios where liberal expression and projection of the student's personalities and individual worldviews are encouraged during the design process (Taylor and Ladkin 2014), design studios in architecture, design and planning foster more collective critique and action on projects with direct or indirect value additions to industrial applications that benefit larger communities (Park 2020). From the theoretical perspectives of accessibility, ownership, scale, legislation and management of resources, the students are given deeper insights into the multifaceted nature of architectural design in parallel to fundamental training in both analog and digital design tools.

This basic training in technique and design principles are typically given in the initial years of architecture school (1st, 2nd and part of 3rd year) where they use the tools "to address simple design problems on smaller sites" (Park 2020). Consequently, the projects worked on by students in 'upper-level' studios (4th and 5th year) increase in their complexity and scale with further elaborate constraints and deliverables. A conventional studio is, therefore, a suitable setting for problem-based knowledge exchange through iterative and dynamic experimentation, peer-to-peer interaction and sharing of tools, equipment, materials and speculative ideas. Key principles of effective communication and collaboration with other students and studio members are imparted through the course of the studio projects such that they learn to build on each other's ideas as a design team (Al-Qawasmi 2005).

Design Thinking and its Applications in Architecture Design Studios

This phenomenon of idea generation and exchange in teams is known as 'design thinking' and its process is one that emerges in a generative manner as the designers reconstruct their realities through actions that are "responsive, opportunistic and reflective to the design state" (Dorst and Dijkhuis 1995). The term 'design thinking' was first coined by Peter G. Rowe, architecture professor at Harvard University, in his pioneering book, *Design Thinking* (1987). He argued that while the design process can be observed from multiple perspectives, one can study "what the designers do and how they undertake their tasks" through fundamental and practical forms of inquiry which enables them to shape their perceptions of dwelling and settlement (Rowe 1987).

Furthermore, he states that design thinking is concerned with the process of *making* through "rather private moments of 'seeking-out', on the part of the designers, for the purpose of inventing or creating buildings and artifacts." In these moments, designers alternate between two iterative phases of (1) *divergent* data collection and brainstorming that widen their perspectives and, (2) *convergent* decision-making actions that narrow or 'frame' the given design problem (T. Brown and Katz 2009). As seen in Figure 1, during both phases, an ideal design thinking process constitutes the simultaneous application of the designer's 'interior situational logic' to the identified problem informed by several theoretical modes suited to the task of choice-creating and choice-making for the specific project.

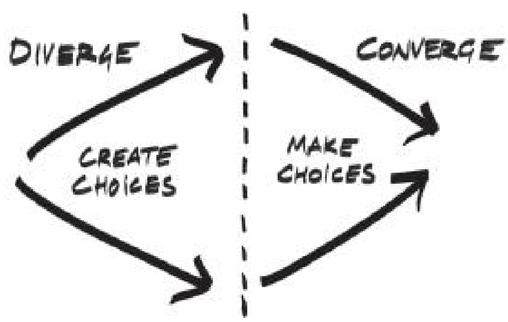


Figure 1: Divergent and Convergent Design Thinking (Brown and Katz 2009)

Due to the ambivalent nature of this method of inquiry, it can be concluded that there is no one 'right' way to undertake design thinking through a rational step-by-step technique as different designers have different styles of constructing meanings of the problems at hand in order to propose relevant solutions (Rowe 1987). Furthermore, Rowe observes that these variations in design thinking styles emerge from 'individual quirks' in addition to the given problem's physical and socio-political constraints that influences the 'unfolding' of the design process for the built environment. Therefore, one can argue that the prevalent structure of the design thinking process is a 'back and forth' oscillation between two positions of the designers as they incorporate their subjective opinions and prejudices into their 'tentative proposals' while adhering to their expert knowledge of technical dimensions of the fabrication process.

Additionally, design thinking as an approach implemented in studio pedagogy draws inspiration from Gabriela Goldschmidt's framework of *design cycles* of "seeing-as" and "seeing-that" as well as Masaki Suwa and Barbara Tversky's definition of with cycles of *focus shifts* and *continuing thoughts* (Goldschmidt 1991; Suwa and Tversky 1997). Therefore, the design education paper, "Modeling metacognition in design thinking and making" (2019) by Shabnam Kavousi, Patrick Miller and Patricia Alexander propose that design studio instruction should encourage students to nurture this metacognitive reflection of the process of design with design focus shift cycles (Kavousi, Miller, and Alexander 2019).

In doing so, students can attain the necessary experience of a 'reflective practice' through the pedagogical self-investigation on one's own thought process during the design process. As a result, they can be better equipped to monitor and analyze their 'situational actions' that were either successful or unsuccessful which is essential in learning how to design. These in-situ judgements, as illustrated by the studies of Donald Schon in *The Reflective Practitioner* (2008), are key to helping students overcome 'design blocks' and generate ideas when confronted with the 'aha-moment' of inspirational stimuli (Schön 2008).

However, it is not sufficient to produce a myriad set of design ideas for a given problem as students are expected to showcase well-developed designs for studio evaluation and final jury. Here, design thinking can enable students to make feasible decisions on macro- and micro-level design strategies, resource management (including time until *deadline*) and quality of project outcomes. By testing out various strategies while 'consciously or unconsciously monitoring the outcomes' lead to a holistic design learning method for students in architecture studios. Hence, this self-awareness of their own design strengths and weaknesses through the design thinking process positively influences and complements the physically stimulating and socially collaborative environment of the architecture design studio.

Impact of Digitization of Design Tools in Architecture Studio Pedagogy

Rapid industrialization on a global scale has resulted in a drastic shift to digital technology in the learning environments of architecture design. Subsequent advancements in the multi-disciplinary applications of information technology increased the dependence of architecture education on digital tools to train their students for the practicing communities that had readily adopted these tools (Gross and Do 1999). Despite this widespread digitization, Jamal Al-Qawasmi in "Digital media in architectural design education: reflections on the e-studio pedagogy" (2005) argues that the impact of *e-studios* on the quality of design education's structure and delivery has not been investigated deeply, particularly in the instructional format of design studios (Al-Qawasmi 2005). He attributes this gap in our current understanding of these tools to the fact that existing literature reviews on the subject are rather polarized into two broad categories of *instrumental* and *critical* such that neither of them provide constructive insight into the positive potentials of digital tools in design studios.

While the former view associates digital design media as 'value-free tools', the latter view challenges the 'bias of the media' and their negative implications to architecture education (Robbins and Cullinan 1994; Piotrowski 1998; Lawson 2006). Therefore, in order to address this gap through a more balanced analytical framework, Marshall and Eric McLuhan introduce the 'law of media' through four elements of comparison: (1) intensify/enhance human abilities, (2) nullify certain abilities or cultural practices, (3) revitalize abilities or practices neglected in the past, and (4) reversal of performance when "pushed beyond their limits of potential" (McLuhan and McLuhan 1999). By applying McLuhan's law of media, one can acknowledge both the enhancing as well as inhibiting forces that affect the integration of digital technologies in design studios (Al-Qawasmi 2005).

According to Al-Qawasmi's research, when used as tools for design thinking and making compared to their typical applications in presentations, digital tools revealed several qualities that enabled a ‘fluid-thinking mode’ amongst design students in relation to their analog counterparts in design studio environments. These qualities were the increased degree of (1) integration of design ideas, (2) interactivity or responsiveness of immediate design changes made, (3) reflection and (4) immersion (Al-Qawasmi 2005). He observed that the resulting smoother design flow of students using digital tools as their sole design mediums ensured quicker generation of larger quantities of design artefacts with greater complexity. In addition to fluidity of the design process, e-studio environments also enabled a redefinition of the design learning process beyond the physical boundaries of the architecture studios as students were now able to continue their interaction with peers and instructors via emails and discussion forums. Moreover, the e-studio tool made inspection of student work by the instructors more feasible in terms of time and ease of communication through remote access “without having to meet in the studio space” (Al-Qawasmi 2005).

Using digital tools, students displayed greater independence and self-awareness with regards to their design process where they were stimulated to produce more amount of visual information essential to communicating their conceptual designs. This increase in stimulation was associated with the enhancement of peer-to-peer interaction not just through the interface of the digital tool but also through movement between their individual physical spaces in the design studio. Through these interactions, students were able “to discuss shared problems and solutions, to evaluate designs and how they did things, and sometimes to see what other students were doing...Students tended to draw on each other’s knowledge through the sharing of resources and artefacts, which is expected to have positive learning effects” (Al-Qawasmi 2005). Consequently, the digital design tool played an integral role in facilitating proposed solutions from students that were ‘beyond their current skill levels’ in comparison to the time and effort put by them using analog design tools.

Context and Assumptions

Nonetheless, as mentioned earlier, the implementation of digital technology in the design thinking and making process in architecture education leads to a realization that it is “not a value-free neutral tool that produces objective realities...it fundamentally alters the way in which students envision and describe architecture…(through) aesthetic values and their perception of the built environment” (Al-Qawasmi 2005).

Socio-cultural Practices

This research acknowledges the socio-cultural complexity of the learning process in architecture design studios. According to activity theory studies on the dynamics in design studios, institutional infrastructure as well as teaching faculty act as mediators along with the design tools and artefacts used by students such that their learning and development "cannot be analyzed in isolation of the socially and artefact-mediated context" (Engeström 2014). Jean Lave and Etienne Wenger in *Situated learning: legitimate peripheral participation* (1991) emphasize that the community of practice, particularly in a design studio, is a social context of practicing and learning where the students instructors and external resources teach each other through shared exercises of meaning-making (Lave and Wenger 1991). Therefore, the propositions made in this research need to be mindful of the community of practice who may or may not adopt new methods/tools depending on the enhancement or facilitation of their existing practices or their abilities to change and align to their differences from ongoing limitations in practice (Tuomi 2006).

According to Lave and Wenger's research in peripheral participatory aspects of design learning, students in their initial years of architecture education as well as intern/entry-level practitioners in a new work environment take on a gradual process of peer interaction and socialization which is an essential 'first step' in establishing themselves in the community of practice (Lave and Wenger 1991). These interactions along with digital tools and environments enable them to stay motivated with positive learning effects as they wander around between individual work stations to discuss shared problems and design proposals (Al-Qawasmi 2005; Kavousi, Miller, and Alexander 2019). However, depending on the cultural context of the institution, students may not be encouraged to move around freely as instructors believe this may be distracting to their design process and workflow. As a result, the socio-culturally ideological biases of the instructor may promote or disrupt peer interaction which is observed as an integral learning experience for collaborative design practice in the AEC industry.

Actors and Agents

Students

In order to explore and propose alternative characteristics that define a holistic design learning environment in architecture studios, students are expected to have acquired a basic level of maturity and skills in navigating through a design thinking and making process. Depending on the design maturity level, they would be able to propose solutions to advanced design issues within physical and/or virtual mode(s) of collaborative design environments (Al-Qawasmi 2005). However, virtual environments that are newly introduced to architecture and design students take a significant 'time lapse' in 'getting used to' as students may encounter confusions and starting troubles in developing essential skills and techniques in designing digitally. Hence, students need to be given ample time in aligning the flexibility of their design processes to freely switch between conventional, physical design studio environments and virtual workspaces.

One of the major challenges of incorporating digital design processes in the design studio is that students go through the stressful process of outputting their design proposals to a suitable presentation format as each has their own "rituals and constraints" (Al-Qawasmi 2005). The extra time needed to test-print, set up design data for projection in compatible layouts, etc. can negatively affect the student's design process. However, this can be addressed through evolving hybrid CAAD tools that combine direct haptic feedback and interaction with the digital designs without having to print onto hard copies for mark-ups and evaluation. Subsequently, popular graphic tablets with touch displays such as iPad, Wacom Cintiq, MS Surface Pro, etc. have paved the way for more digital design explorations that encourage sustainable methods of design learning in architecture studios.

While design tools can enhance the workflow of several students, they also have the potential to disrupt the same. In several investigations, researchers conducting protocol analysis on students using digital design learning environments have reported some 'distracting' effects of digital tools on students who are less focused in their design processes. These arguments are supported by observations such as the use of presentational gimmicks, ‘dazzling colors and incorrect use of line values’, weak design intentions and practices blamed on ‘technical difficulties’ of the digital medium and so on (Al-Qawasmi 2005; Kavousi, Miller, and Alexander 2019). Additionally, students with lower design confidence also tend to personify these tools and their implications in the design process through “incorrect or immature decisions they made, as if the computer was their invisible partner” (Al-Qawasmi 2005).

This highlights the fact that the learning attitude and self-esteem of students is crucial in implementing digital design tools and methods in their workflows without misusing the extends beyond their intended applications in the design studio, as predicted by McLuhan’s law of media (McLuhan and McLuhan 1999). Nonetheless, through continued practice with computers in the design process will ensure students’ familiarity and growth of design skills in the virtual learning environments. Consequently, the tactile and cognitive incoherence experienced by students while using physical hardware such as the mouse and keyboard to flesh out their design ideas “will tend to disappear and intuitive digital design will become the core experience” (Al-Qawasmi 2005).

Instructors

As mentors vital to facilitating the learning curve of digital methodologies in design thinking and making processes, instructors face many challenges that promote or hinder a deeper integration of digital design tools. Firstly, verifying the ‘authenticity’ and ‘legitimacy’ of students’ work done through digital interfaces increase the workload of instructors during virtual evaluation sessions. In certain instances, students could claim complete authorship over the designs that were otherwise plagiarized from various sources such that they become less discernible “due to the absence of characteristic touches that distinguish one student’s work from another” (Al-Qawasmi 2005).

Secondly, students tend to produce larger amounts of design data while exploring proposed solutions on digital design tools that empower greater conceptual complexity. This jeopardizes the time available to instructors as institutions that adopt these new digital tools assume the continuation of conventional schedules of design reviews and evaluations that have been conducted over many years when traditional tools were in place. Therefore, due to increased quantity and complex abstraction of the design artefacts produced, instructors can be skeptical of the digitization of design studios as they are unable to meet the demands of holistically reviewing student work (Al-Qawasmi 2005).

Jurors

The role of jurors have not been researched to the extent of those of students and instructors in the design studios in architecture schools as there exists very less literature around the same (Anthony 1987; Graham 2003; Webster 2007; Utaberta, Hassanpour, and Usman 2010). However, the master's thesis of Elizabeth Marie Graham titled 'Studio design critique: student and faculty: expectations and reality' (2003) sheds some light on the structure of architectural design juries and the system that promotes/hinders design learning in students. According to her research, a design jury consists of an immediate dialogue between a juror or a panel of jurors and a student who presents their design work in a short period of time (Graham 2003). This jury setting can occur either in a closed or open presentation format with fellow students, instructors, alumni and other external experts (see Figure 2). The jurors are typically brought from outside the institution to provide unbiased feedback to the students' designs but can be guided by internal faculty members, teaching assistants, practitioners and sometimes even clients of public projects.

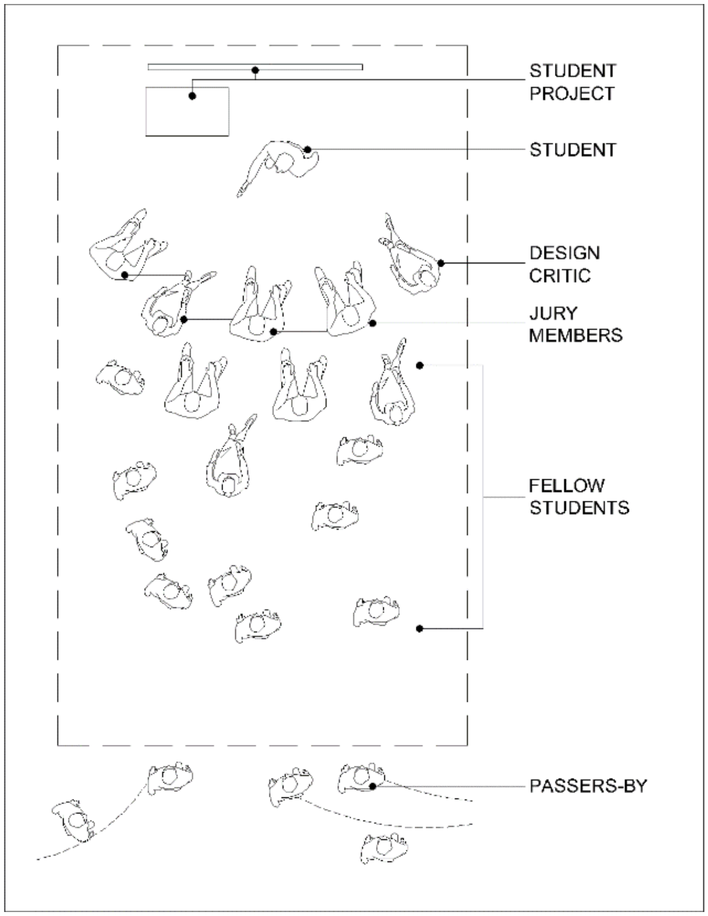


Figure 2: Typical Layout of a Design Studio (Doidge, Sara, and Parnell 2007; Graham 2003)

The above layout is inspired by the French Ecole des Beaux Arts in the nineteenth century which mandated juries as an evaluation system of students' design processes where jurors would decide the pass or fail 'fate' of the students through written feedback and direct comments (Anthony 1987; Graham 2003). Due to the negative connotations of jury systems on the educational values of students as they are infamous for harsh criticism, research has been emerging questioning the relevance of jurors in the design learning process of the students. Although instructors face several instances where they intervene and defend the ideas of the students 'under attack', they continue to rely on jurors and the jury system as the 'primary vehicle' to judge the progress of students through verbal and graphical debates on the design proposals.

The juror's role is, therefore, to participate in the professional development of the students into novice practitioners for the near future through constructive criticism of areas of improvement in their design concepts (Anthony 1987). However, through digitization of the design studios, conventional formats and practices of desk critiques have been 'heavily displaced' with more remote discussions through forums and virtual markups of design documents uploaded by students (Al-Qawasmi 2005). Nonetheless, the jurors are now less intimidating benefactors to the growth and development of the design students through well-mediated and documented critical review sessions.

Physical, Virtual and Economic Infrastructure

The teaching and learning flexibilities of physical infrastructure in design studios are directly related to the extent of intellectual and financing investment by the architecture education institute. As a result, the architecture design studio is a physical space that is visibly distinct from traditional classrooms due to its omnidirectional furniture configurations as well as instructional informality (Crowther 2013). Here, the aim is to promote a pedagogy that is flexible through movable furniture that welcome freedom of movement and peer interaction, drafting tables that are personalized by the students, larger areas for model-making, pin-up walls and panels for final presentations and so on. However, in addition to flexible physical infrastructure, the integration of digital interfaces have gradually been mandated by several communities of practice owing to the experiential learning demands of the AEC industry (Piotrowski 1998). Nonetheless, these digitized design learning spaces could pose a threat to the economic infrastructure of architecture schools who may be pressured to 'keep up with the trends' as they constantly upgrade as well as maintain these environments built to simulate real-world design practices.

Research Question, Hypothesis and Objectives

Current 'messy and divergent' conceptual design processes in architecture learning environments are documented without structure such that students and instructors are unable to keep track of the origins and evolutions of their emerging designs. Poor documentation of the proposed ideas and strategies brainstormed by the students could restrict their creative reflection by undermining the process of flexibly 'retracing' the version histories of the design objects. Design learning environments, particularly architecture design studios, can be vital in training students and novice practitioners for design practice as they simulate real-world practicing communities in the AEC industry. In a conventional architecture project, schematic design (SD) phases are run primarily on iterative brainstorming with clients which are crucial sessions for architects to gather relevant design principles that steer the course of the project moving forward. As these sessions get information-heavy and rely almost solely on verbal discussions, architects and designers rely on various design tools, methods and techniques in order to capture and document the design principles for future reflection, communication and collaboration with other peers.

Hence, this research proposes the hypothesis that architectural pedagogy can positively benefit from rethinking their conventional digital design tools and modes which can help students situationally learn both the communicative as well as collaborative facets of spatial design thinking and making. The research seeks to reimagine traditional processes of conceptual design in architecture education by investigating new design technologies that can potentially answer the question: How does dynamic documentation and tracing of the evolutions of design proposals promote design reflection and collaboration in students and novice practitioners during architecture studios? From this perspective, the research explores the development of a more engaging and educational CAAD tool interface for virtual as well as physical design learning environments that can recreate a real-world collaborative design practice and encourage the students to build on each other’s ideas inclusively while exploring all potential design alternatives.

The objectives of this research are:

1. To study existing tools and methods used for communicating and collaborating spatial design concepts in architecture design studios
2. To investigate conventional design tools and practices in the AEC industry
3. To propose design modes for CAAD tools that help train students on conceptual design methods through practice-based simulations
4. To experiment with an educational interface for CAAD tools that documents and keeps traces of design thinking and making processes
5. To generate design principles for future CAAD tool developments that focus on reflective and collaborative design learning environments in architecture pedagogy

Methodology

This research alternates between two main phases that resemble the design process: *Making* and *Reflecting*. While the *Making* phase is primarily based on research-through-design approach which includes development research, quasi-experimentation and comprehensive prototyping methodologies, the *Reflecting* phase runs in parallel through qualitative focus group research, user and usability research, and speculative design fiction. This methodological framework grew in an organic and generative manner through the course of this research as is common with most explorations on educational HCI technologies for the social sciences such as architecture and design theory and practice (Mattelmäki and Matthews 2009).

Making

This phase is based on 'development research' methodology (Van Den Akker 1999; Reeves 2000; Richey, Klein, and Nelson 2003; Wang and Hannafin 2005) which was first introduced as 'use-inspired basic research' by Donald Stokes *in Pasteur's Quadrant: Basic Science and Technological Innovation*(1997). According to Stokes, a research's agenda can be placed within a matrix consisting of 4 quadrants where each cell represents whether or not the researchers are either concerned with 'seeking fundamental understanding' or the 'practical uses' of their findings (see Figure 3(a) and 3(b)). Stokes argues that French chemist Louis Pasteur falls in the quadrant 2 which is ideal for the development of new and emerging technologies (Stokes 1997).

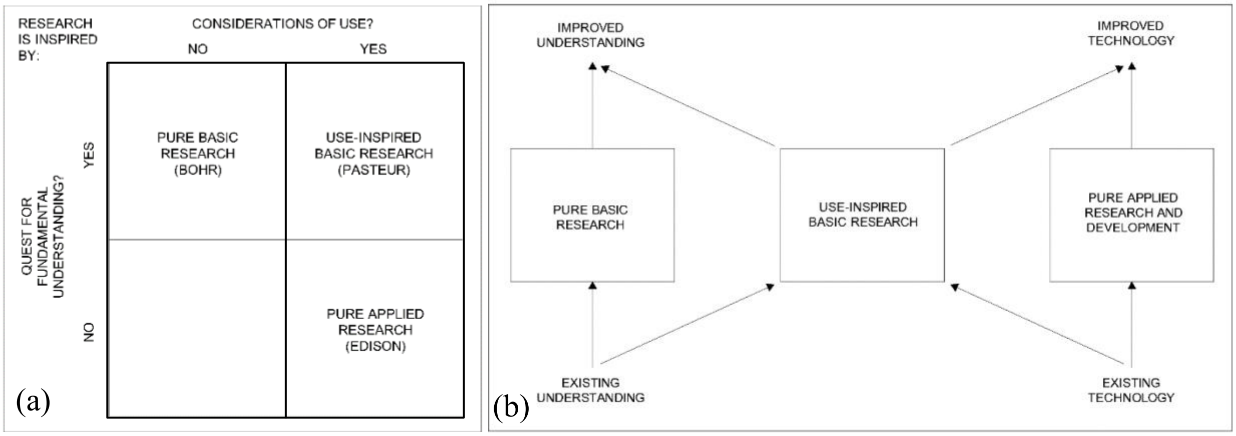


Figure 3: (a) Quadrant Model of Scientific Research, (b) Revised Dynamic Model (Stokes, 1997)

In 1999, Jan van den Akker in 'Principles and Methods of Development Research' (1999) outlined the characteristics of development research as a methodology which can be applied to those complex problems which have only very few theoretical foundations available to support the design and development of innovative solutions (Van Den Akker 1999). Similar to Stoke's argument, van den Akker proposes that development research can be used to do not just pure basic research but also explore practical applications for practitioners dealing with pedagogical problems. Development research typically begins with a literature review or expert consultation followed by systematically documented interactions with the intended users through prototyping and testing which ultimately produces principles in the format of heuristic statements for future developments (Van Den Akker 1999; Wang and Hannafin 2005). He advocates that the iterative process of approximation and prototyping cycles through interactions with the concerned practitioners is essential in creating effective interventions that cannot be addressed with just theoretical explorations (Van Den Akker 1999).

According to Thomas Reeves, development research is applied by those researchers with dual objectives of addressing issues in teaching, learning and performance of practitioners "while at the same time constructing a body of design principles that can guide future development efforts" (Reeves 2000). He validates the necessity of development research in educational technology innovations as it involves long-term observations on situated learning of target users, appropriate features in 'multimedia learning environments' as well as tests of the proposed models and products with these users. In Figure 4, he illustrates the process of development research which has greater value than conventional empirical research when proposing advancements in instructional technologies (IT) as it involves collaboration among the researchers, instructors (practitioners) and students for context-specific results (Reeves 2000).

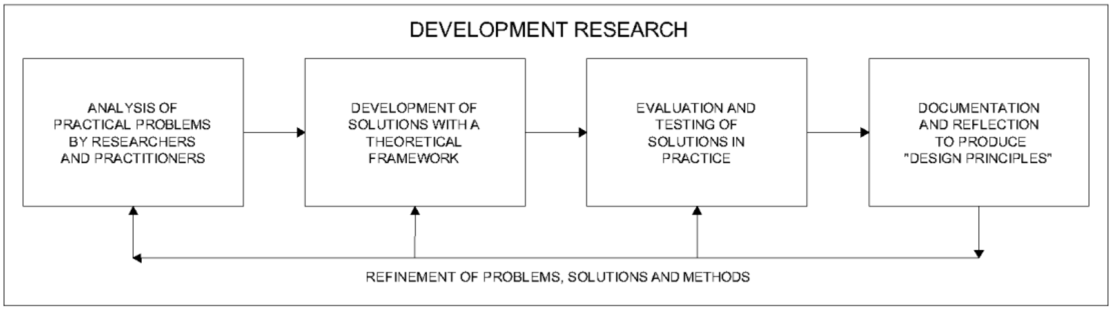


Figure 4: Process of Development Research (Reeves, 2000)

Therefore, the research adopts development research which is further validated by Rita Richey, James Klein and Wayne Nelson as a methodology that addresses "not only formative, but also summarize and confirmative evaluation" (Richey, Klein, and Nelson 2003). This research aims to 'serve as a vehicle for stimulating new research' and can be identified as a Type 2 development research as it addresses a generalized context of design, use and development of larger system models than just products in local contexts as seen in Type 1 research scenarios (Richey, Klein, and Nelson 2003). In this type of development research, a greater variety of research methods can be employed, including qualitative experimental and quasi-experimental techniques in order to propose new models for designers, developers, evaluators, researchers, theorists, learners, instructors, but most of all, educational institutions (A. L. Brown 1992; Shadish, Cook, and Campbell 2001; Richey, Klein, and Nelson 2003; Ross and Morrison 2003; Mattelmäki and Matthews 2009).

The methodology of development research is supported with multiple iterative and comprehensive prototypes (Houde and Hill 1997; Gil-Garcia, Pardo, and Baker 2007; Mattelmäki and Matthews 2009; Wensveen and Matthews 2015) as critical and reflective investigations throughout the course of this research. According to Stephanie Houde and Charles Hill in "What do Prototypes Prototype?" (1997), prototypes are built in order to create different representations that help researchers think about and communicate several design options and intended interactions that tackle 'open design questions', especially in computer artefacts (Houde and Hill 1997). This research is particularly concerned with the genre of 'implementation prototypes' that attempt to address important technical questions of how a new functionality might actually be put to work feasibly by its potential users while gaining their feedback on its performance issues. “Comprehensive prototyping attempts to take into consideration the most important elements early in the process…(and) as a research strategy is able to recreate the context more realistically and obtain better and more accurate data about the features of the technology and the characteristics of the organization in which it is going to be deployed” (Gil-Garcia, Pardo, and Baker 2007).

Reflecting

This phase is based on research through design approaches that seek to draw insights from the *Making* phase in order to inform it back again with clearer research goals. In 2014, Richard Krueger in *Focus groups: A practical guide for applied research* observed that focus groups are applied as a qualitative data collection method for research that seeks to explore and capture perceptions and personal thoughts about current issues, products, services and so on (Krueger 2014). In this research, focus group research brings together architecture students and researchers in order to test and validate an existing theory, the collaborative dimensions framework, in relation to the proposed design tool so as to reflect on those dimensions that are relevant to the architectural design learning environments. The focus group is used to carefully plan and make informed decisions about a product or theory’s applications by gaining more understanding from shared and inclusive discussions “where stories could be told and that in turn sparked others to remember and describe their stories” (Krueger 2014). This method allows the research to assess user’s needs, conduct further surveys with larger sample sizes, improve existing paradigms in the proposed tool’s research and evaluate its outcomes.

After the focus group, the research switches back to *Making* phase where it explores more prototypes before coming back to *Reflecting* phase to formulate a 5-minute online survey for expected users (architecture students and novice practitioners) by employing ‘user research’ and ‘usability research’ methodologies (Schumacher 2010). These methods draw upon many social science disciplines such as behavioral sciences, engineering, computer science, architecture, etc. and evolve through the time period of the research demanding new tools and technologies of gathering user feedback. “However, user research per se is not about a technology or a method; it entails learning about the evolving user needs and user capabilities” (Schumacher 2010). Hence, usability research is a form of ethnographic research that gauges the behavioural aspects of users with direct or indirect interactions proposed products which helps identify competitors in the existing market. This research attempts to combine both qualitative and quantitative inputs on these behaviours through the online survey as "the bedrock of ethnography is the combination of informal and formal observation" which ensures lesser levels of user bias when providing feedback to the ongoing research (Schumacher 2010).

Finally, this phase actively contributes to development research in Making by applying 'speculative design' and 'design fiction' methodologies (Dunne and Raby 2013; Lindley and Potts 2014). While design fiction is a 'narrower genre' that deals with imaginary designs with a scientific approach that is primarily geared toward future technology, speculative design aims for alternative realities through imagination which stems from problems questioned in current scenarios (Dunne and Raby 2013). These are identified as 'professional imaginations' for design through stories that enact socio-cultural norms and values with plots and characters closest to reality. However, these fictions arise from the design so that the researcher can visualize "the kind of society that would have produced them, its values, beliefs, and ideologies" (Dunne and Raby 2013).

Joseph Lindley and Robert Potts in 'A machine learning: an example of HCI prototyping with design fiction' (2014) proposes practical applications of design fiction in order to gain technical insights for the design and development of a HCI platform. According to them, design fiction is one of many prototyping techniques that facilitates conversations about near futures to find out user preferences and the systems in place (Lindley and Potts 2014). In order to work effectively, the design fiction's context must be relatable to both the researcher as well as the target audience such that the proposed technological design can fit in 'believably'. However, "speculative design, prototypes, and design fictions only exist to provide the provocation necessary to forge a 'discursive space'. It is from that discursive space that design insights emerge" (Lindley and Potts 2014). Hence, this research applies design fiction in the form of storyboarding to visualize an engaging narrative that helps evaluate potential user application scenarios of the proposed design tool.

Contributions to Design Research

The research proposes a rethinking of the status-quo conventional design processes taught to and learnt by students in architecture design studios. Primarily, the explorations in this research seek to instil virtues of iterative reflection and inclusive collaboration in students' flow of design thinking and making. The proposed framework focuses on refining 6 key design 'modes' that are commonly observed in conceptual phases of the design process, particularly in an architecture education institution. These design modes are: (1) Audio, (2) Precedent, (3) Sketch, (4) Concept, (5) Massing, and (6) Walkthrough. By integrating all these design modes that are traditionally available across multiple design software, the research explores the impact on design flow and collaboration by introducing flexibilities in time management as well as documentation of the otherwise 'messy' and 'divergent' conceptual design process.

Furthermore, the proposed 'reflective and collaborative' design process framework encourages deeper design learning of students who would benefit from fluid and iterative design thinking and making that collectively exchanges and builds on each other's ideas while exhausting all possibilities right from the beginning. This ensures that students learn to not just extract better design principles to further their proposed solutions but also cultivate an experiential sensitivity toward sustainable design processes in the AEC communities of practice by saving on additional intellectual, temporal and, most importantly, financial resources that are usually invested in later phases of design projects where design changes are far more cumbersome. Therefore, the proposed framework is explored through a digital design learning tool, *Retracer*, that seeks to take on a more 'active' role of facilitating creative brainstorming sessions in conceptual design phases where students are encouraged to 'trace' and 'retrace' their design processes for reflective and collaborative design thinking and making.

Through an integrative and highly interactive interface that is focused on haptic and immersive modes of human-computer interaction, *Retracer* is envisioned as a portable and remotely accessible design studio space for students and novice practitioners. This can enable smoother and intuitive design workflows as they can readily access and review their previous design data within the virtual environment as though they are stepping back into their physical design workstations with a history of all their previous design explorations. However, these older iterations are not presented ‘as they were last left’ by the design team, but through a hierarchical structured design database within the tool that ensures the investigation of more design versions and alternatives to address the same design problems. Hence, *Retracer* is the creative contribution of this research-creation thesis to the larger ‘design *for* design’ research community that seeks to reimagine existing methods, tools and techniques of conceptual design process in architecture education and practice.

Reflecting - Communication and Collaboration in Architecture

Relevance of Communication in Architecture

In contemporary communities of architecture design education and practice, the tendency is to focus solely on the clarity of visual communication processes, overlooking other sensorial tools and methods used to convey spatial ideas in a more balance and effective manner (Ingold, 2013). While analog tools such as hand sketching, sculpting, storytelling, etc., retain the authenticity of thinking and making designs through hands-on interaction with material artefacts (Pallasmaa, 2009), digital tools such as AutoCAD, Revit, etc., stay on par with leading architectural, engineering and construction innovations by ensuring smoother translation and communication of designs in the multi-disciplinary industry (Yiannoudes 2016).

Typically, the schematic design (SD) phase as defined by the American Institute of Architects (AIA) is observed to cover 15-20% of the total project time where architects and designers listen and collaborate with clients using images of previous projects, hand sketches, models and so on while communicating the relationships between each of the proposed spaces (Fontan 2016; Chintis 2019). In this phase, multiple conceptual designs are constantly run by the clients who will be expected to engage with the designers in order to give their insights that would assist in the refinement of some designs as well as the elimination of some others. During this period, it is evident that practitioners need to create an understanding with their clients through listening and observing but also explain the necessary concepts to them in order to produce meaningfully designed spaces that meet their expectations. Unfortunately, due to the limited time and lower consultation fees that this phase demands, it is often rushed through without a holistic and fluid design thinking process that gets the most ideas across so that changes can be limited in further phases that need more temporal and financial investments (Safin, Leclercq, and Blavier 2008).

Therefore, communication is an integral part of architecture which can be defined as the transfer of experiential data and design knowledge from one participant in a project to all its stakeholders. However, due to the ambiguity of the 'steps' to be followed in the initial phases of design projects, students and novice practitioners are always at a dilemma when picking their medium/tool to work with at any stage of the design. Hence, the research investigates three main aspects of communication that govern the design learning, thinking and making process in architecture education as well as practice: spatial perceptions, verbal communication and visual communication.

Spatial Perceptions

According to current research in architecture pedagogy and practice, there is an ongoing communication gap between various stakeholders: architects, engineers, designers, policymakers, clients and occupants. This gap can be seen as a result of their fundamental differences in spatial perception at their cognitive level (Montello, Grossner, and Janelle 2014). At present, the design processes in architecture use tools such as sketching, model making, collaging, storytelling, digital drawings, etc., in combinations that have not yet been very successful in bridging this communication gap (Pallasmaa 2009). In this research, a vast theoretical framework of phenomenology in architecture and design is consulted for the investigation of various communicative aspects of designer's perceptions of the world around them and their embodiment in the spatial design process.

In order to perceive spatial environments, Maurice Merleau-Ponty writes in *Phenomenology of Perception* (1962) that we need to stop and observe the world around us more closely for deeper meanings as we are so caught up in our lives, and this happens only when we have managed to extricate ourselves from it to achieve consciousness of the world. The research attempts to adopt the metaphor of building our perceptions of the world around us like "a house is built with bricks, (such that) a mental chemistry is invoked which fuses these materials into a compact whole" (Merleau-Ponty 1962). In this regard, the spatial perceptions and aesthetic intuitions of an individual designer are more influential to their conceptual models of reality than its formal qualities. These perceptions are brought to life "only through the medium of a subject who traces out and sustains them; and pass from spatialized to spatializing space" (Merleau-Ponty 1962).

Most architectural schools adopt a tone of technical rationality to a field of design that has many more facets to the production of space, place and identity arising from critical reflections of the student's lived experiences. Merleau-Ponty argues that technical "empiricism is a kind of mental blindness that is least able to give an inclusive account of experience while reflection on the other hand embraces empiricism's subordinate truth and assigns to its proper place" (Merleau-Ponty 1962). Through the theory of phenomenology of perceptions of space, he observes that architecture's mathematical process of planning from the bird's eye view or 'God's eye perspective' could not grasp the 'finite' nature of bodily experiences within the spaces designed. Alternatively, he proposes that designs should comprehensively communicate various 'existential' embodiments of the space such as "affect, memory, kinesthesia and other felt relations" from multiple positions within the same space that accommodate the student's pluralistic imaginations of livability (Merleau-Ponty 1962).

Juhani Pallasmaa in The Thinking Hand (2009) observes that the skill most vital for an architectural designer is “to turn the multi-dimensional essence of the design task into embodied and lived sensations and images” (Pallasmaa 2009). This skill can be built as students go through the process of ‘sensorial reflection’ which leads to a ‘capacity of empathy’ for lived experiences within the built environment. Hence, design studio pedagogy can be informed by this theoretical framework that seeks to build a holistic science of design by weaving multiple narratives of space, place and identity facilitated by architecture and design. “Unlike the critic and the philosopher, the architect must embrace the contradictions between perception and logic, the slippage between architectural intention and realization, and the unpredictability of the future's judgement upon the acting present, and "resolve" or con-fuse these aporias through his/her personal imagination” (Holl, Pallasmaa, and Pérez Gómez 2006).

Verbal Communication

In 1995, Walter Wendler and Julie Rogers in ‘The Design Life Space: Verbal Communication in the Architectural Design Studio’ observed that design teaching and learning processes in architecture studios are dependent on sharing creative ideas primarily through verbal communication “before they have been fully documented” (Wendler and Rogers 1995). They propose a ‘design life space’ which is defined as the shared ‘psychological-intellectual realm’ by instructors and students in order to reflect and collaborate on their design ideas (see Figure 5). This space is observed as a rich, complex, expansive and accessible mental space that helps identify the given design problems and facilitates the design development (Wendler and Rogers 1995).

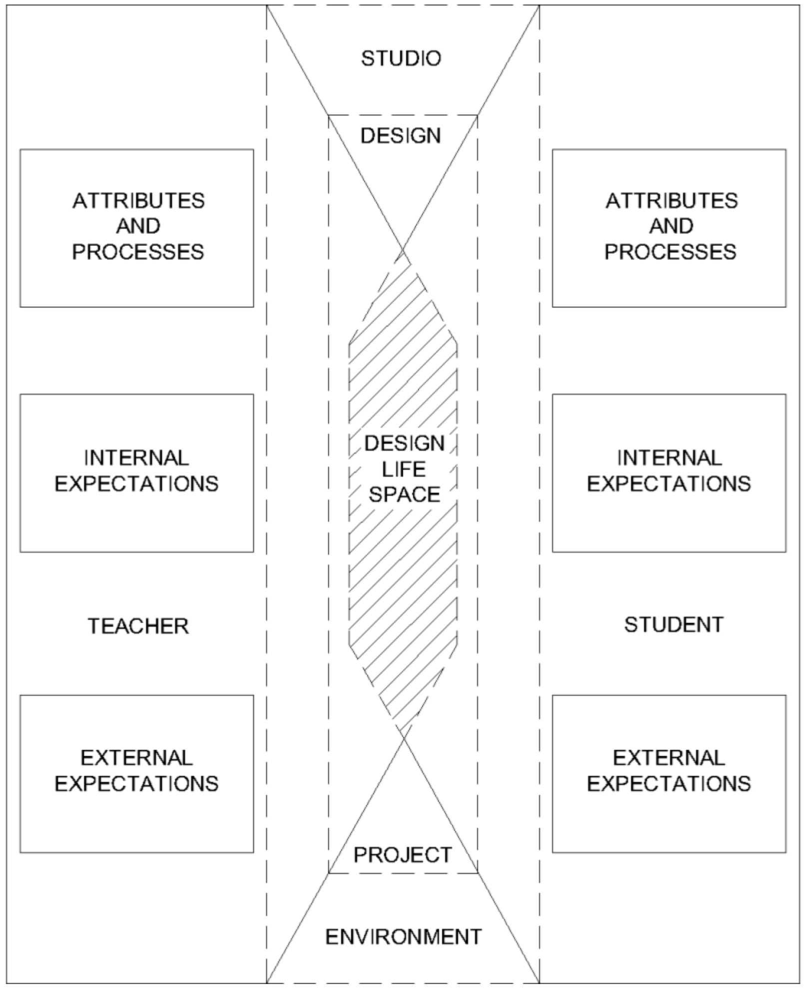


Figure 5: Model of a Design Life Space (Wendler and Rogers, 1995)

Wendler and Roger's model suggests that the design life space can take on a dual role of 'individual' as well as 'shared' spaces whenever students and peers explicitly present their design thought processes. However, not all vocalization of spatial ideas are accepted readily as the instructor and fellow students superimpose their thoughts on the issues as well (Wendler and Rogers 1995). According to their research, 'the act of specifying' gives dimensions to the design life space such that the design goals are extracted within the confines of this space that is now starting to take shape. These specifications and internalizations of spatial perceptions through verbal and gestural debates can allow individualized learning objectives for the project to be cultivated (Wendler and Rogers 1995). Through 'naturalistic and interactive' dialogue, realistic pedagogical goals are mutually agreed upon by the instructor as well as the student as they make the design relationships and their meanings more verbally explicit. This creates an understanding and promotes effective communication among apparently cryptic conversations, “so that each individual can better ‘see’ what another ‘sees’...(although) the dialogues reveal that, in the design studio, communication with others occurs at an in-depth and often abstract level” (Wendler and Rogers 1995).

Visual Communication

Edward Tufte in *Envisioning Information* (1990) argues that two-dimensional ‘flatlands’ of the paper and digital screen pose various challenges of graphical communication on architects and designers when they attempt to convey three dimensional perceptual worlds. They face struggles while communicating these dimensionally complex worlds which often have graphical representations that are “undifferentiated, unlayered surface results, jumbled up, blurry, incoherent, chaotic with unintentional optical art” (Tufte 1990). This is because these spaces and their situated navigation brings implicit and explicit reasoning of spatial qualities that are ‘invisible’ such that they cannot be portrayed efficiently on flat surfaces to external readers of these images.

While developments in architectural representation techniques were made since the 15th century Renaissance through the invention of perspective geometry using handheld tools and mathematical problem-solving, architects and designers have slowly but surely explored ‘enterprising methods’ in order to capture and narrate “more abstract multivariate information not residing in our three-space reality” (Tufte 1990). Often, these practitioners are confronted with ‘overwhelming quantities of data’ which makes it intellectually tedious to immediately communicate layered complexities in the presentation of spatial information. As a result, the visual display of a concept as a whole constructed from several parts is facilitated by systematic strategy of placement of information in accordance to their levels of detail to produce more clarity (Tufte 1990).

For example, a two-dimensional and isometric aerial view of a city’s landscape can be ‘condensed, slowed and personalized’ through the interplay of macro- and micro-information such as the addition and subtraction of textures, line-weights, shades, labels, color highlights and so on. Similar data displays that seek to capture and simulate reality can be “universal, rooted in human information-processing capacities and in the abundance and intricacy of everyday perceptions…(as they) can report immense detail, organizing complexity through multiple and (often) hierarchical layers of contextual reading ” (Tufte 1990). Therefore, through the technique of ‘layering and separation’ of key components of the spatial data, lesser unintended ‘confusion and clutter’ of the structured display of information can lead to fewer instances of faulting viewers for their incomprehension.

Another challenge faced by designers is that the layers of information can become obstructive to visual perception of the readers as they go through flattened representations of space on dynamic digital displays in comparison to their static paper counterparts. “There, all sorts of unplanned and lushly cluttered interacting combinations turn up, with changing layers of information arrayed in miscellaneous windows surrounded by a frame of system commands and other computer administrative debris” (Tufte 1990). It is here that Tufte advocates the skillful use of color through ‘proportion and harmony’ as annotations on the diagrams made such that they establish relationships between each of its information layers.

Finally, communication of graphical simulations of the built environment is not a passive endeavour which is unidirectional in information transfer. The reader, often the designers themselves, respond to these visual flatlands in order to decipher and make sense of the data displayed through qualitative and quantitative comparison and reasoning. This dialogue is dependent on the mindful arrangement of ‘small multiples’ of the designs within the eye-spam so as to ensure “uninterrupted visual reasoning” (Tufte 1990). Through the breakdown of large amounts of graphical data into smaller multiples, designers have more freedom to experiment with the framing of the right sets of these multiples rather than making modifications to their individual content. This is particularly useful in the conceptual design process where designers exhaust multiple design variations of the same ideas through sketching, sculpting, etc, so that they can rearrange, compare, retain and eliminate them based on their relevance in tackling the given design problems (Atilola, Tomko, and Linsey 2016).

Relevance of Collaboration in Architecture

Architecture is inherently a socio-cultural practice of collective imagination and sustenance of shared and livable built environments for human as well as non-human members of the society.

This is directly reflected on the design process where collaboration is an integral part of bringing together a wide range of unique and apparently conflicting values and ideas along with individual expertise in the industry (van Bakergem and Obata 1993). Through cooperative sharing of personal experiences throughout the course of the creative process, designers ‘expand their knowledge base’ as each of them bring new insights leading to shared discoveries that positively benefit the project’s outcomes. This informative collaboration is facilitated by the collective construction and maintenance of a common design database that allows individual contributors to stay motivated while working with other team members and their subjective differences.

Also, the embodied and experiential nature of the design process demands open and neutral spaces for collaboration amongst architects and designers from different knowledge bases. Depending on the group dynamics while working collectively across multiple projects that promote or hinder socio-cultural ‘bonding’, these spaces can often be messy and disorganized despite a coherent understanding that emerges from constant debates and cognitive mappings. These group sessions are key in dividing the workload of navigating through the chaotic pattern of the initial design phases as the “spatial location and organization of information sources is created with surprisingly efficiency” (van Bakergem and Obata 1993). This leads to a ‘collaborative effort’ in building and sharing a “project-specific memory which will guide and influence decisions throughout the course of the project.”

Collaborative Dimensions Framework

While it is not possible to holistically codify all the underlying characteristics of ‘good’ collaborative practices in architecture and design, the ‘collaborative dimensions framework’ by Sabrina Bresciani in “Visual design thinking: a collaborative dimensions framework to profile visualizations” (2019). Her research investigates seven traits of the visual interface of design tools such as templates, charts, etc. that facilitate collaboration and co-construction of knowledge: (1) structural restrictiveness, (2) content modifiability, (3) directed focus, (4) perceived finishedness, (5) outcome clarity, (6) visual appeal, and (7) collaboration support (Bresciani 2019).

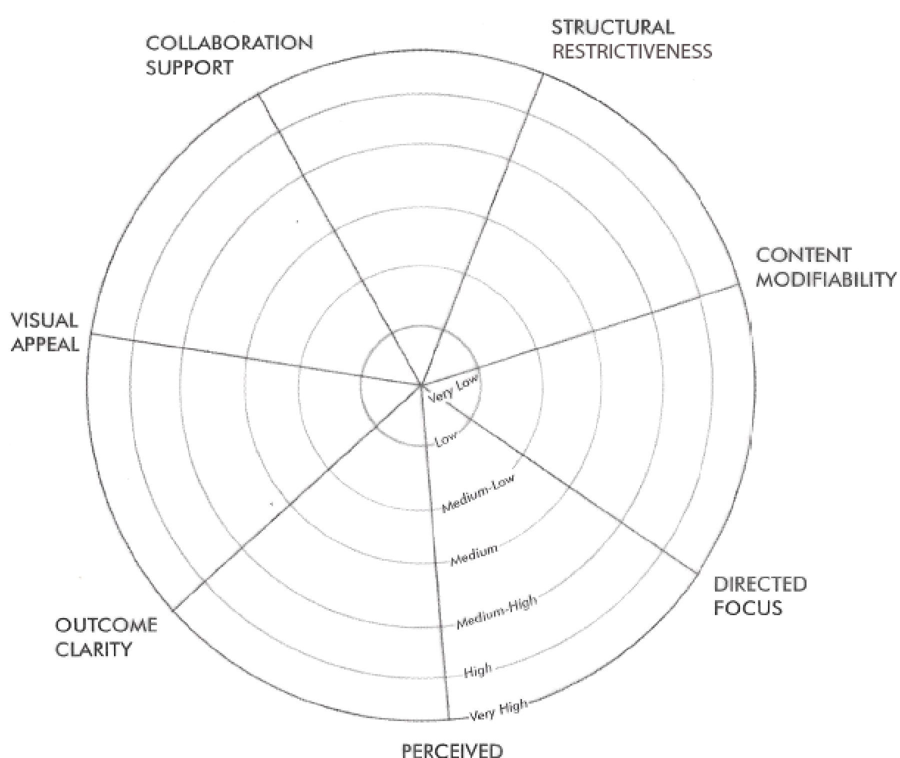
According to the framework, in order to support idea generation in a collaborative design meeting, it is essential to follow and maintain a flexible layout of visual composition of the design data "which does not need to be clear nor beautiful" (Bresciani 2019). However, to provoke swift and effective decision-making practices, the visual format needs clarity in terms of project-specific criteria that promote consensus on the design proposals discussed. As a result, the framework prompts communities of design learning and practice to be more conscious of the effect of their visualization formats on not only the creative outcomes but also the socio-political and cultural dynamics amongst the collaborators and co-designers. Using the framework's dimensions, designers can collaborate with 'non-designers' as they provide guidelines to the design thinking process that is easily comprehensible but crucial in capturing relevant concepts from business and management standpoints of practice-based design research.

As discussed earlier, the 'non-linear' iterations of design thinking processes make it all the more pertinent to apply the collaborative dimensions framework as it allows flexible adaptations 'intuitive visuality' of the dynamic and demanding 'co-evolutions of problem and solution spaces' (Dorst and Cross 2001). According to the research of Masaki Suwa and Barbara Tversky in "What do architects and students perceive in their design sketches? A protocol analysis" (1997), architects and designers are self-aware of the potentials of 'external' visual representations such as sketches, graphs, and hand-written reminders to assist in their design thinking processes not just as 'memory aids' but also as vital mediators that expand or constrain group understanding and solving of various design problems (Suwa and Tversky 1997). In fact, the social dynamics of their collaborative design activities, particularly sketching, have been observed to support shared reasoning and documentation of critical design data by acting as a 'visible graphic memory'.

In the research of impacts of data visualizations in design thinking processes, one of the key formats is the 'mind-map'. Vasilije Kokotovich in 'Problem analysis and thinking tools: an empirical study of non-hierarchical mind mapping' (2008) investigates the application of non-hierarchical mind mapping in order to frame the design problem for holistic analysis before providing appropriate solutions. This research suggests that novice practitioners in the design community find this more of mind mapping to be essential in their design processes as they were able to follow expert designers in their strategies of converging their unstructured ideas.

Similarly, Martin Eppler and Sebastian Kernbach in 'Dynagrams: Enhancing design thinking through dynamic diagrams' (2016) advocated the use of interactive and dynamic diagrams or ‘dynagrams’ for design thinking and making collaboratively “as they provide law encoding, representational guidance, and the generation of new understanding” (Eppler and Kernbach 2016). In this instance, design data visualizations take on structural and interactional flexibility as they can be altered or extended to share and record experiences, conduct scenario explorations and analyses that lead to productive conversations and constructive decision-making processes. Additionally, the formats of these visualizations are defined as boundary objects in reference to the term first coined by Susan Star and James Griesmer as they have certain levels of plasticity that welcomes pluralities in identities within a community of learning and practice (Star and Griesemer 1989).

Consequently, the Collaborative Dimensions of Visualization framework proposed by Bresciani (2017) observed that culturally diverse design groups found visual templates with appropriate collaborative constraints beneficial to the design thinking process (Bresciani 2019). They argue that these processes are undertaken through the sequential steps of cognition, communication and collaboration. Therefore, the seven proposed dimensions traverse across these three steps which are laid out on a continuous spectrum of design actions and interactions (see Figure 6). The first dimension, *structural restrictiveness* is defined as the extent of guidance or constraint imposed by visual templates on the design data and process. Based on practice-based empirical research on live brainstorming sessions within design teams, Bresciani observed that a low structural restrictiveness was appropriate for the initial divergent phases of the design process whereas a higher structural restrictiveness proved beneficial to decision making and convergence of design ideas.



The second dimension is *content modifiability* which determines the extent to which several parts of a visual composition can be changed over the course of the design process (Hundhausen 2005). The extent of modifiability depends on the group's design goals during a particular collaborative session where high levels of modification can enhance peer interaction and low levels can provoke second thoughts before making design decisions. As a result, digital collaboration environments in opposition to pen and paper mediums of design have greater flexibility in content modification, storage and sharing amongst teams. The third dimension is *directed focus* which helps the team concentrate on the levels of emphasis of different concepts that are very relevant to addressing design problems such as goals, objectives, design principles and so on. In this regard, lower directed focus creates more ambiguity that welcomes divergent design thinking of several derivatives and alternate design ideas (Atilola, Tomko, and Linsey 2016)

The fourth dimension, *perceived finishedness* deals with those features of a design visualization that make it appear finished or unfinished in presentation to design collaborators. This dimension has the potential to invite or deter participants from suggesting more ideas to the proposed design artefacts. For example, a sketch can be considered as a visual format with lower perceived finishedness due to its rough and abstract lines that welcomes more conscious additions/modifications by others in the design team (Bresciani 2019). Due to this reason, sketches are heavily researched and promoted for their potential in supporting positive group dynamics and creativity during the design thinking and making processes. The fifth dimension, *outcome clarity* is the ability of graphical design representations to be clear and easy to comprehend by the most number of design team members without additional descriptions. This dimension helps the team monitor the level of abstraction or complexity of design proposals such that it promotes either macro- or micro-level decision making. To illustrate, storyboarding can be seen as a visual template having higher outcome clarity as it leads to swift correlation of concepts but "may lead to oversimplification" .

The sixth dimension, *visual appeal*, is an aesthetic judgement of the visualizations such that they are either pleasing or unattractive to other team members. Evidently, those representations with higher visual appeal coerce collaborators to be engaged and motivated as they contribute more ideas to further its design complexity (Bresciani 2019). The seventh and final dimension is *collaboration support* which endows power to the visual design data and its supporting frameworks to manipulate the flow of the design thinking process. Using this dimension, collaborative ventures can inclusively track individual participant's contributions to the overall progression of design reflection, production and documentation (Eppler and Kernbach 2016).

User Feedback on Collaborative Dimensions Framework

Inspired by this framework, a focus-group of architecture students and researchers were convened in order to discuss the relevance of each of these dimensions in the realities of learning and practice in conceptual design processes. The goal of this group reflection was to gauge the 'sweet spot' of the proposed design tool by incorporating user feedback on the radar graph adapted from Bresciani (2019) (see Appendix a). However, during the workshop, the complexity of the radar graph as well as the definitions of the collaborative dimensions took a considerable amount of time and effort in explanation as the definitions provided by Bresciani's research showcased greater correlations between each of them, making them dimensions that are not mutually exclusive in their measurability. Nevertheless, this qualitative survey was put to the test as it helped formulate an average region of favourable values of each of the dimensions (see Figure 7) while discerning those dimensions of collaborative design visualization that are significant to conceptual architecture design in education as well as practice.

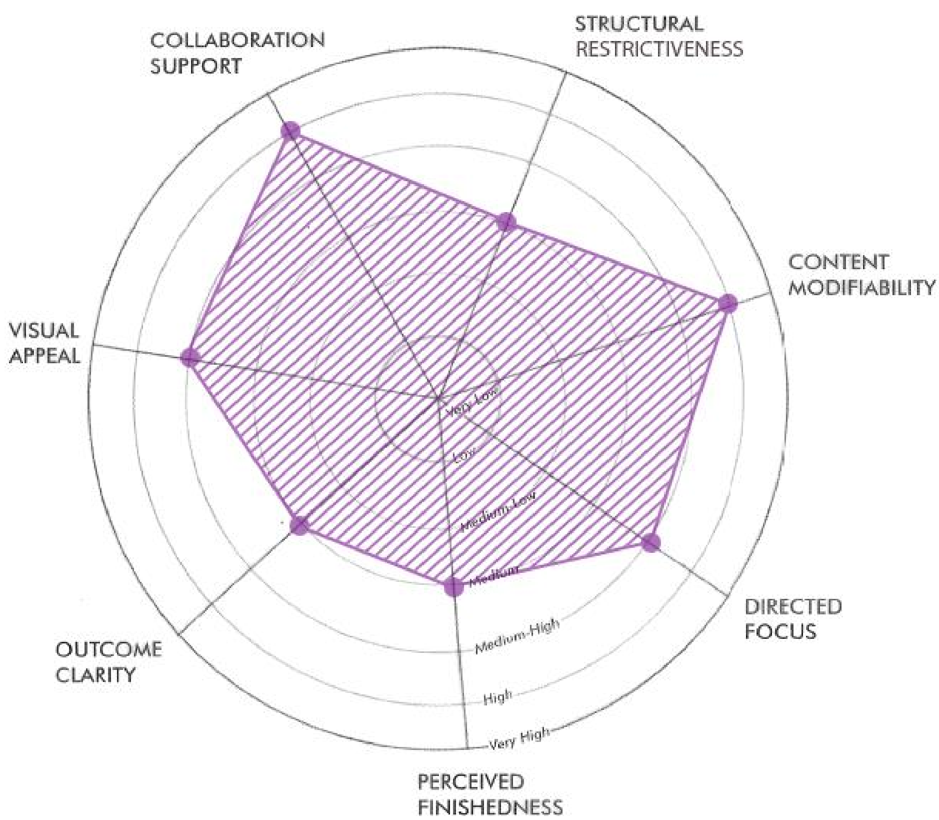


Figure 7: Average radar graph of focus-group survey with Collaborative Dimensions Framework (Bresciani, 2017)

The given figure is an average of the 7 responses from graduate architecture and design students where each of the dimensions were rated on a spectrum of *very low* = 0 and *very high* = 6. It can be observed that *structural restrictiveness* was voted *medium* (=3) which indicates the preference of a balanced visual template that is not too open yet not too constrained. *Content modifiability* was rated *high* (=5) which validates Bresciani's argument that more allowance for design changes in earlier phases can positively benefit the design process. The third dimension, *directed focus*, was rated medium-high (=4) where very low represents divergent mode of thinking and very high represents convergent mode of thinking. This implies that the design visualization can be slightly inclined toward convergence as this promotes rapid decision-making practices during design collaborations.

Perceived finishedness and *outcome clarity* were both voted *medium* (=3) which suggests that designers prefer a moderate level of detail during design explorations such that it conveys the concepts without appearing too vague or too polished as to discourage further inputs from peers. The sixth dimension, *visual appeal* was rated *medium-high* (=4) which implies that the aesthetic attractiveness of the design artefacts can be of an above-average quality although lesser priority while brainstorming further ideas. Finally, *collaboration support* was rated *high* (=5) which indicates that designers rely on the interactive and inclusive features of the visual template which can facilitate recognition of individual design interventions in collective design thinking and making sessions.

Based on these observations, it can be argued that the more the structural restrictiveness through constricting visual templates, the more the directed focus toward common design goals as these dimensions are directly correlated. Also, dimensions of perceived finishedness and outcome clarity need to be maintained at a visual equilibrium in order to facilitate smoother communication of design ideas to culturally diverse groups without losing out on every individual's participation. Furthermore, during the discussions that followed the survey, the group agreed on the view that visual appeal is not an essential dimension that gravely impacts the design process in architecture, particularly in the conceptual design phases even though it was scored at 4 out of 6. Finally, the high ratings for content modifiability and collaborative support highlight that these two dimensions are the most relevant to measure while proposing and developing design thinking tools for architecture education and practice.

Reflective Communication and Collaboration in Studio Pedagogy

Thus, combining the theoretical insights that emphasize the importance of communication and collaboration in architecture design learning environments, specifically design studios, the research proposes a reiteration of their conventional definitions through the theories of 'reflection-on-practice' and 'backtalk cycle' as well as the empirical perspectives of the 'science of design' of space and 'scientific rationality'. Studying the tensions between these frameworks would enable the research to enhance the 'tacit knowledge' of students in conceptual design phases by encouraging them to actively trace the evolution of their design proposals through reflective design thinking and making of the built environment.

Typically in a design studio, students are expected to tackle the given design situation through several iterative strategies that are reflective and conversational in nature such as "drawing/modelling, interpreting the consequences of the drawing act and making moves to a new design situation" (Al-Qawasmi 2005). However, in order to adopt these theoretical models which can liberate architectural design such that it embraces the pluralities of spatial experiences, these perceptions are not readily discerned by the architecture students at the onset of their training. As a result, the educator builds his instructions upon the student's 'tacit' or innate understanding of space through a generative knowledge exchange process. Michael Polanyi in *The Tacit Dimension* (2009) states that "we can know more than we can tell" and this knowledge enables the recognition and validation of the student's conceptual models of the world around them. "While tacit knowledge can be possessed by itself, explicit knowledge must rely on being tacitly understood and applied. Hence, all knowledge is either tacit or rooted in tacit knowledge. A wholly explicit knowledge is unthinkable" (Polanyi 2009).

One of the main focuses of this research is the theory of 'reflection-on-practice' which was first introduced by design philosopher, Donald Schön in *The Reflective Practitioner: How Professionals Think In Action (1983)*. According to Schon, reflection-on-practice occurs when the designer commits to a progressive and conversational relationship with the design process such that their reflections of the materials they use, the strategies they follow and the outcomes they wish to produce serve as key decision-making points that govern future designs (Schön 2008). In his interview with John Bennet in "Reflective Conversation with Materials", *Bringing Design to Software* (1996), Schon revealed the notion of a 'backtalk cycle' where both designers and users alike continuously project and redefine the meanings of products through listening and observing how they were designed and used. According to him, the reflective practitioner looks back at the design task that they just completed or are currently working on and "may criticize tacit understandings that have grown up around repetitive experiences of designing" (Schön and Bennett 1996).

Similarly, the theory of 'making' by anthropologist, Tim Ingold in *Making: Anthropology, Archaeology, Art and Architecture* (2013), encourages learners to not be fixated on preconceptions that cloud observations by 'feeling forward', confronting and questioning their certainties of the world around them. These ongoing reflections as the designers work with their hands is described as the process of anticipation of following design strategies or 'moves' to solve the problems that emerge from the simultaneous act of making (Ingold 2013). Thus, he argues that thinking and making are two sides of the same coin that propels innovation during the design process. "We cannot make the future, however, without also thinking about it. What then is the relation between thinking and making? To this, the theorist and the craftsman would give different answers. It is not that the former only thinks and the latter only makes, but that the one makes through thinking and the other thinks through making" (Ingold 2013).

However, in contrast to these intuitive theories on design thinking and making, the research seeks to investigate the contemporary paradigm of 'the science of design' by Horst Rittel in *The Reasoning of Designers* (1988), in architectural education where there the objectives are: "First, to further develop the theories of design, to learn more about the reasoning of designers. Secondly, it should pursue empirical inquiries into how plans come about, and what the effects of plans are in comparison with what they intended. Finally, on this basis, it should look for tools to support designers in their work. The human mind is fallible. Methods should be sought to amplify its abilities, even if it's only to keep us from falling prone to our idiosyncrasies" (Rittel 1988).

Furthermore, Herbert Simon in *Sciences of the Artificial* states that "the apparent complexity of our behavior over time is largely a reflection of the complexity of the environment in which we find ourselves" (Simon 1969). According to him, the act of designing is to convert current undesired situations into a preferred one by reflecting on the changes that arise from changing the state, i.e, solving the problem. In architecture discipline, much of the focus has been on the artifact rather than the larger ecosystem that they interface and distinguish as inner and outer environments (Simon 1969). Simon then concludes that only when the inner is in harmony with the outer, does the artifact serve its purpose. Hence, this holistic thinking, listening, observing and reflecting that is mindful of the larger systems in place are essential in architecture and design education.

The research is also aware of management skills that are essential for novice designers to have a 'control' of their creative reflections during the messy and divergent conceptual design process. In this regard, 'reflective process control' is a pedagogical theory that focuses on the decision-making abilities of students during their problem-solving explorations (Kavousi, Miller, and Alexander 2019). Presented as a subcategory of metacognitive design thinking in studio pedagogy, the theory proposes the exercise of control of students on three main areas of their learning process: idea generation, situational action and the design environment. Idea generation and situation action control for design development involves students to build their planning skills as they constantly reflect on the project brief as well as their instructor's suggestions through iterative reading and design regulating strategies based on past experiences (Kavousi, Miller, and Alexander 2019). Lastly, control of the design learning environment is done by students when they rearrange their settings that stimulate the progress of the design thinking and making process such as task and resource organization, data documentation and reducing clutter of their workstations.

Making - Tool Proposal

Design Tool Trends in Architecture

Traditionally, students are trained in design studios to emulate the professional services that practicing architects provide to the construction industry such as client interactions with collaborative efforts in ideating the schematic designs (SD) of their projects. Similar to the methods adopted by the architects to interact with clients quickly and efficiently, students are instructed to use very minimal and easy to access analog tools for their conceptual designs such as: pen/pencil sketches on tracing paper, quick study models with paper/card sheet, "play-doh" sculptures, card games, preference forms, charts with field notes and so on. These analog design tools help in swiftly incorporating and communicating design constraints and needs while observing and collectively brainstorming various possibilities of the desired spaces by hand. This hands-on approach of students with design tools to dynamically document and reflect verbal and non-verbal narration of spaces through stylized hand drawings highlights the foundationally tactile nature of architecture as a discipline.

However, major socio-cultural and economic reforms took place that redefined several professional practices including architecture which underwent irreversible changes in the format of its design processes. Handheld tools and subsequent techniques slowly but drastically moved to the periphery of the architecture, engineering and construction (AEC) industry's strategies in delivering their services to governing bodies as well as the general public. While the transition to digital tools, particularly computer-aided design (CAD), saw pushback from many leading designers and theorists, industrialists saw several advantages of their implementation from the standpoints of time and resource management that continue to revolutionize the AEC industry. In fact, the introduction of CAD in the 1960s "made life much easier for architects, the biggest advantage being the amount of time saved by not having to keep making drawings manually, incorporating changes in the various stages of design and detail" (cite). Therefore, it is imperative to revisit the history of the integration of CAD technologies in the ideation and development of the built environment in order to rethink its applications for the future, both in pedagogy as well as practice.

By late Renaissance, a surge of developments in rational thinking in the fields of mathematics and engineering occurred in parallel to the emergence of Capitalism which deeply influenced the tectonics of construction of large-scale structures such as churches, bridges, fortresses and so on. In an effort to simplify and mass produce the hand-drafting of graphical representations of infrastructure, the roots of modern day technical drafting methods can be seen in the development of 'descriptive geometry' by Gaspard Monge, an 18th century french mathematician through his seminal work, *Application de l'analyse à la géométrie*. By approaching problems of construction through geometric calculations, he introduced the graphical method of using "two planes of projection at right angles to each other for graphical description of solid objects" which is now called the 'orthographic projection' in engineering drawing.

In the early 20th century, even after major advancements were made in these representational techniques through the invention of the drafting machine by Charles H. Little, it was not until the Second World War that a sudden transition to digital design tools were made. During the war, large investments were made in order to simplify the process of design drafting in the automotive and aerospace industries. As a result, during the 1960s, the development of real-time computing and interactive graphics in the automation of engineering design was heavily researched at Boeing, Ford, Citroen, MIT, and GM. Finally, in 1963, Ivan Sutherland wrote a computer program named SketchPad (or Robot Draftsman) during the course of his PhD thesis at MIT titled, "SketchPad: A Man-Machine Graphical Communication System" (cite). The distinctive feature of the tool he developed was that it allowed the designer to interact with their computer graphically through a light pen directly on the screen in order to draw, move and change the virtually designed objects. This interface pioneered both the development of what is now known as CAD as well as further research into human-computer interactions (HCI).

However, large scale application of CAD tools in the AEC industry was witnessed in the 1990s with Autodesk launching AutoCAD which was readily adopted by architectural and engineering firms everywhere owing to contemporary advancements in computational hardware. Furthermore, when personalized computers became increasingly affordable and accessible, this marked a widespread integration of CAD training in many architecture and engineering programs across the globe. However, these software remained in the background as they weren't used in the earlier phases of brainstorming on design ideas even though they have apparently triggered the extinction of hand-drawn sketches (Shah 2015). Nonetheless, conventional architectural drawings have been taken to levels of complexity never possible by human mental cognition and computation as digital designs afforded more experimentation and validation of their constructability in real-life scenarios. The integration of CAAD tools in the design process of most communities of learning and practice have enabled them to stay in the competitive market of the AEC industry.

Therefore, it is imperative for this research to take a closer look at the existing 'market' of CAAD tools and their inherent characteristics that make conceptual or schematic design representations generated from within each of their interfaces differ in their communicative and collaborative qualities. In agreement to McLuhan's law of media, Neil Postman in *Technopoly: The Surrender of Culture to Technology* (1993) argues that "embedded in every tool is an ideological bias, a predisposition to construct the world as one thing rather than another, to value one thing over another, to amplify one sense or skill or attitude more loudly than another" (Postman 1993).

AutoCAD and AutoCAD Architecture

AutoCAD is a CAD software that is popular among architects, engineers and construction professionals to draft, annotate and design two-dimensional and three-dimensional drawings of floor plans, sections, elevations and other orthographic projections of the building designs. The software was developed and marketed by Autodesk as a design tool that can speed up the design process and produce specialized and automated outcomes. A subset of AutoCAD was also released specifically for the architecture discipline, AutoCAD Architecture, which has gained traction on account of ready-to-use 'design blocks' representing walls, stairs, windows, etc which are intended to reduce time and increase productivity during the design process.

In *Mastering AutoCAD Architecture 2010* by Paul Aubin, the two CAD interfaces are compared and likened to the applications of a handsaw (AutoCAD) and a power saw (AutoCAD Architecture) to cut wood. Although this indicates that there is a sharper learning curve in AutoCAD Architecture compared to AutoCAD, he argues that the power saw can cut more wood in less time with better results provided the user knows how to handle its functionalities properly (Aubin 2010). “Success in completing most tasks requires a combination of understanding of one’s goals, ample time and planning, and access to the right tools. Although knowledge and planning are critically important, having the proper tool for the job can often determine the overall success or failure of a given undertaking” (Aubin 2010).

However, in AutoCAD Architecture, the conceptual design process is primarily based on a three-dimensional model which acts as an abstract representation of a building’s design using basic blocks with planes, volumes, groups and slices. This direct three-dimensional approach is proposed as an efficient means of identifying design intent at earlier stages of the design process such that they can be ‘reused’ as digital models to add on more details in later stages (Aubin 2010) without them being ‘throw-away’ models as expressed by concerned users in several CAD community forums.

SketchUp Free and SketchUp Pro

SketchUp is a CAD application that specializes in 3D modeling with a simplistic interface that is accessible to many disciplines such as architecture, interior design, landscape architecture, engineering, film and video game design. There are two versions available—*Free and Pro*—based on the software package’s pricing and corresponding features. While the Free version promotes open web accessibility of the models from anywhere for a wide range of audience, including hobbyists, Pro version “broadens this even further by providing layout and documentation abilities and other professional oriented tools” (Schreyer 2013). As a result, SketchUp has a loyal user community that vouches for the tool’s ability for ensuring easy visualizing of ideas and concepts while traveling, collaborating and illustrating on-the-go. On account of this global following, recent CAD tools in the market ensure compatibility of their designs with basic SketchUp models as their features are light-weight during initial design phases.

The software can be observed as a success on account of its minimal layout with greater clarity and hence, a lower learning curve. “Students and professionals take easily to SketchUp, and, before long, some of them produce very detailed building models and professional-grade renderings" (Schreyer 2013). The founders and developers of SketchUp are aware that not many people are professionally trained in hand-made 3D sketching and sculpting skills which could affect their chances of communicating the intended design ideas. This drove them to create an easy-to-understand user interface that allows for quick and effective '3D sketching' during early design stages as the name suggests (Schreyer 2013).

Rhino and Grasshopper

Rhinoceros3D or "Rhino" is a 3D modeling CAD software developed by Robert McNeel & Associates that employs free form surface modeling using NURBS (Non-uniform rational B-spline) mathematical models to produce complex shapes and mesh geometry with ease. With an open source code, Rhino is a modular digital tool that enables users to freely customize their modelling workspace and create their own commands to generate dynamic 3D representations of their design ideas. Although the tool has a wide collection of plugins that are geared toward improving presentation skills of practitioners through realistic renders for design communication, Rhino is also used for very basic prototyping iterations that are compatible with new 3D printing technologies for large-scale commercial projects. Since most designers prefer form-based explorations of building designs in conceptual design phases, the computational power of the tool focuses on providing a seamless experience that is closest to conventional hands-on methods of modeling such as sculpting clay, carving wood, or chiseling marble (Bachman 2017).

The interface of the tool promotes both two-dimensional as well as three-dimensional iterative explorations of design concepts as the workspace incorporates multiple viewports that enable the designers to view the model from different vantage points while making the models. Documentation of design progress is primarily visual as Rhino allows users to capture various design 'states' of the model through 'snapshots'. Protocol analysis on design studio projects, where students are allowed to use Rhino and similar NURBS-based modelling tools, observed that they created various formal transformations that "transcended several essential issues such as constructability, materiality, or the cultural and economic context" (Al-Qawasmi 2005; Guidera 2009).

In addition to Rhino's features, Grasshopper is adopted by novice practitioners as an add-on 'visual scripting platform' which allows them to 'code' and generate parametric 3D models with simple graphic modules that bypasses the necessity of learning a programming language (Bachman 2017). This platform enables designers to have greater control over the process of customization of formal qualities of the spaces that are imagined during the conceptual design process in architecture. However, this additional design interface can be intimidating to beginners who wish to explore more flexible and free-flowing volumes in their building designs as the workflow is unfamiliar in relation to conventional 3D modelling software (Bachman 2017).

Revit and FormIt

Revit is a 'building information modelling' (BIM) software developed by Autodesk for architects, designers, engineers (structural, mechanical, electrical and plumbing) and contractors to create detailed design documents for construction. The software enables users to add a 'fourth dimension' of metadata such as market prices, physical properties, etc. to each three-dimensional component that represents real-world building materials and prefabricated modules used in contemporary built environments. By adding this layer of information to a 3D building model, the design project is made planning and management-friendly in terms of budget calculations, energy and load simulations, and so on that provide valuable insights for the design process even before the project is built (Dzambazova, Demchak, and Krygiel 2008). Through 'intelligent elements' that represent walls, floors, windows, etc, Revit enables users to conceptualize design spaces at a faster pace than most conventional CAAD tools, making it popular among well-established AEC firms with large-scale projects.

Owing to its rapid adaptation in the practicing communities, students are encouraged to work directly with Revit even during initial design phases although it is designed to facilitate the construction phases of architectural design. Additionally, Revit has structured and centralized documentation of design iterations as well as flexible workspaces that allow for local and remote collaboration with fellow designers (Dzambazova, Demchak, and Krygiel 2008) . Although the initial learning curve is steep, the software promotes a dynamic workflow that is supported by realistic renderings, cut-aways, panoramas, site documentation that are essential for multidisciplinary collaboration. “The immediate 3D design visualization of the building and its spaces improves understanding of the building and gives you the ability to show a variety of design options to all members of a project, at any moment...That information can then be used to make decisions earlier in the design process, reducing risk and cost overruns (as) the change management required by CAD is a tedious and error-prone process that requires diligent project management and lots of red lines” (Dzambazova, Demchak, and Krygiel 2008).

However, students using Revit face the design challenge of ‘over-developed’ models during early design phases (Fuhrman 2017). As it is relatively quicker to create models with multiple layers of graphical and textual information in Revit, Autodesk introduced FormIt as an add-on to Revit which is marketed as a conceptual BIM tool that encourages collaboration on more abstract spatial formations through real-time massing models and energy analysis. FormIt is yet to receive a widespread user base (Keskeys 2017) as its interface provides tools that bias the design thinking process and flattens the often 'messy' and 'divergent' nature of conceptual design phases. Nonetheless, the key to generating design models that are not too detailed yet provide adequate visual communication on Revit is “up to the user to exercise the control needed to keep the model simple, yet informative” (Fuhrman 2017).

3dsMax

3dsMax is a 3D ‘artistic’ modeling software developed by Autodesk that is popularly used for film animations, game designs and realistically rendered walk-throughs in architectural design. *Foundation 3ds Max 8 Architectural Visualization* (2006) by Brian Smith argues that 3dsMax’s modeling power enables architects and designers to create 3D models on “just about anything you can dream up” (B. L. Smith 2006). Users can create compound design objects using primitive splines, shapes and meshes which provide high levels of editability. The software recommends a workflow that begins from two-dimensional designs that are created in external 2D CAD software such as AutoCAD and imported into

3dsMax's interface to convert them into 3D visualizations with materials, textures, lighting effects and so on.

The proposed workflow enables the creation of alternative 3D models by other collaborators who can refer to their original details in the 2D CAD drawings (B. L. Smith 2006). Using mesh and poly objects, precise and fluid building forms are generated for peer-to-peer design communications as they are "easy to work with and manipulate" (B. L. Smith 2006). However, due to its complex and less intuitive user interface in comparison to modeling tools like SketchUp, students and practitioners have observed a very steep learning curve and have limited their use of 3dsMax in the conceptual design phases of architectural design projects. They tend to use this CAAD tool in the post-production stages of their projects when photorealistic renders need to be produced for public presentations.

Adobe Photoshop and Illustrator

Adobe Photoshop and Adobe Illustrator are graphic editing softwares developed by Adobe Inc. to generate two-dimensional digital images in a large array of disciplines, particularly in the visual arts and design domains. Although not commercially promoted as an architectural design tool, Photoshop and Illustrator have gained more traction among students and practitioners as key presentation tools in conceptual design processes. With recent developments in post-modernist schools of thought that promote design ideation techniques such as 'collages', hyper-realistic 3D models of spaces are being replaced by 2D graphical representations of space with illusions of depth and volume through the clever use of colors, line weights, backgrounds and foregrounds (Jacob 2017). These vibrant compositions of color and shape that speculate alternative imaginations of built space that leans toward quick and informal formats of artistic expression more than technical formulations of broad ideas in the design process (Hogrefe 2015).

With greater accessibility to image databases, students can explore alternate forms of communicating spatial ideas through open manipulation of visual content and establishing relationships between seemingly disparate parts to create a narrative whole. "Within Photoshop, however, we can explore images at a forensic level, slicing, masking, and smoothing the joints between things. And that smoothness means the possibilities of remix and mash-up become infinitely more nuanced. Rather than a thing made up of parts, the parts become an indivisible graphic whole" (Jacob 2017). Nevertheless, technical rationality can be employed when adding ergonomic templates such as human figures in architectural visualizations, among other annotations such as grids, labels, numerical data, etc.

Morpholio Trace

Morpholio Trace is a mobile CAD application developed by Morpholio targeting architects and design practitioners who have access to touch-enabled graphic tablets such as the iPad Pro in order to facilitate an intuitive digital design experience from conventional techniques (Potuck 2018). Released in 2015, the application has made a swift integration into the design workflows of many architects and students who can quickly put together design mockups with the fluidity of hand-drawn sketches on touch screen interfaces. As it is developed for the iPad, Morpholio Trace is an exemplar design tool for this research as it seeks to augment the creative design process by supporting portability, accessibility and simplicity of ideas 'while thinking with your hands' (Potuck 2018). In this regard, although Morpholio Trace is the closest to the proposed design tool in the research, its pedagogical implications are yet to be explored as it is primarily marketed for design professionals working on real-world architecture projects. Moreover, the iPad and Apple Pencil devices are not currently student-budget friendly and as a result, may lead to additional financial investments in an already expensive architectural education scenario worldwide.

Users of Existing CAAD Tools and their Experiences

The users of CAAD tools in conceptual design phases of the architecture design process are students, studio instructors, practicing architects and planners. However, as mentioned in the Introduction, the scope of this research focuses on architecture students and their design processes using CAAD tools as a reflective and collaborative design interface. The studio culture consists of a back and forth between the students and the instructors where they iterate and refine the design concepts presented in each consultation (Schön 1987). However, the transitional phase between these consultations and their own conceptual design ideations is often a critical juncture where the students are burdened with intense mental and cognitive reflection of their one-to-one discussions with the instructors. In addition, students face stressful design processes that are encumbered by various constraints and submission mandates as stated by the design briefs given to them by the instructors at the start of the studio projects.

There are four levels of interactivity with CAAD tools such as: "(1) interaction with a free form (paper-based non-digital) representation, (2) interaction with digital constructs, (3) interaction with a digital representation generated by a mechanism, and (4) interaction with digital environment that generates a digital representation" (Oxman 2006). The corpus of CAAD tools addressed in this research falls primarily in the second level of design interaction: *digital representation construct*. Based on a key reference of this research, "The impact of computer aided architectural design programs on conceptual design in an educational context" by Huda Salman, Richard Laing and Anna Conniff, students tend to use a single CAAD tool throughout their conceptual design process (Salman, Laing, and Conniff 2014). However, observations from their design protocol analysis reveal that higher rates of design interaction transitions occur when the students use multiple CAAD tools to propose the same design solutions. The students who took part in the experiment by Salman et al. remarked that their design ideas were largely influenced by the unintended stimulus received from the CAAD tool interfaces while 'actively designing the solutions.'

Through their protocol analysis it can be observed that the student's design experiences moved away from traditional modes of abstraction while communicating ideas in the conceptual design phase, namely, verbalizing or 'thinking aloud' of the ideas along with gestures. Here, it is interesting to note that those students who adopted multi-CAAD design protocols while alternating swiftly between 2D and 3D digital representations found more freedom to vocalize and consequently analyze their ideas through self-reflection. However, existing CAAD tools such as AutoCAD restrict the student's design thinking and making strategies to a predominantly solution-oriented process with lesser attempts at analysis or reflection of the solutions.

While these can be attributed to the novice level of design expertise exhibited by most students in architecture and design studios (Kruger and Cross 2006), the technical and 'finished' interface of present CAAD tools motivate a solution-driven approach than a problem-driven approach. Nonetheless, user interactions observed in multi-CAAD protocols by the students such as zooming in and out of the proposed solutions while switching between multiple interfaces indicate a greater tendency for macro- and micro-level inspection and analysis of the designed entities by the students (Salman, Laing, and Conniff 2014).

In most cases, in order to inform the conceptual design process, the student struggles to gauge every last memory of the discussion with the instructor and this can be an erroneous method of documenting raw and vibrant spatial concepts. It is here that the digitization of architectural design processes needs to step up as the human-machine interface affords beyond-human capacities of documentation while also accommodating analog and tactile human skills of subjective value reflection and judgement.

Proposed Tool Design Principles

Hence, this research adopts a critical approach to current design practices in order to rethink the tools that facilitate communication and collaboration of design ideas with others. In a studio setting, students get 'comfortable' with combinations of design tools that enable them to communicate ideas and strategies in the conceptual design phase in a way that suits their individual skill sets. Whether collaborating with larger student teams or designing 'solo' under the supervision of the instructors, these tools and their design interfaces affect the students' design processes in terms of speed, flexibility, levels of abstraction, but most of all, documentation.

The protocol analysis done by Salman et al. observed "speedier shifts of design intention" of the students as this may be related to them employing a multi-CAAD protocol where they move across multiple CAAD tools to develop their designs (Salman, Laing, and Conniff 2014). This illustrates that the multi-CAAD protocol could be more efficient in the conceptual design phase where the ability to generate larger quantities of ideas and alternatives through creative and flexible brainstorming without being fixated at any one design intention. Hence, the multi-CAAD workflow which allows rapid transitions between design intentions during the conceptual design process can be adopted as one of the design principles for the design tool proposed through this research. This principle is addressed in the research of the proposed design tool through rethinking the user interface of existing CAAD tools and introducing multiple panels with different modes of working on the same design intentions, i.e., a multi-CAAD tool rolled into one interface.

However, these multi-CAD interfaces can become crowded very quickly along the course of the brainstorming process and the critical ‘parts’ of the whole problem need to be made more visible in the digital collaboration space (van Bakergem and Obata 1993). This visibility influences ‘serendipitous connections of disparate associations’ in a virtual project environment where it is essential to keep track of personal as well as collective design inputs. Keeping in mind that CAAD tools have promoted the redefinition of synchronous and local collaborative activities into asynchronous, long distance creative interactions (Achten 2002; 2003), the user interface should ensure the least amount of hidden graphic and textual information that is otherwise lost in a labyrinth of information that is largely overlooked during the process (van Bakergem and Obata 1993). Thus, with the additional support of a digital ‘library’ that is intuitively generated by the machine, participants can freely collaborate and even bring others up to speed on the evolution of the designs through the course of the project.

Based on van Bakergem and Obata’s research, the research seeks to tackle the principle of visibility by exploring the visual framework of the proposed tool’s interface through virtual simulation of a physical ‘situation room’ as seen in architecture and planning communities of practice (see Figure 8). This can be observed as an intuitive data visualization strategy that helps eliminate the apparent randomness through effective organization of relevant information in a three-dimensional digital model, which is not to be confused with Building Information Modelling (BIM) systems. Instead, these virtual situation rooms assist in building a shared understanding of the team’s design goals and principles in the earlier phases of design when much of the design thinking process is divergent and hard to document (van Bakergem and Obata 1993). As a result, this collective space is envisioned in the proposed tool’s environment in order to provoke ‘pinning-up’ of individual contributions of students in larger group design projects.

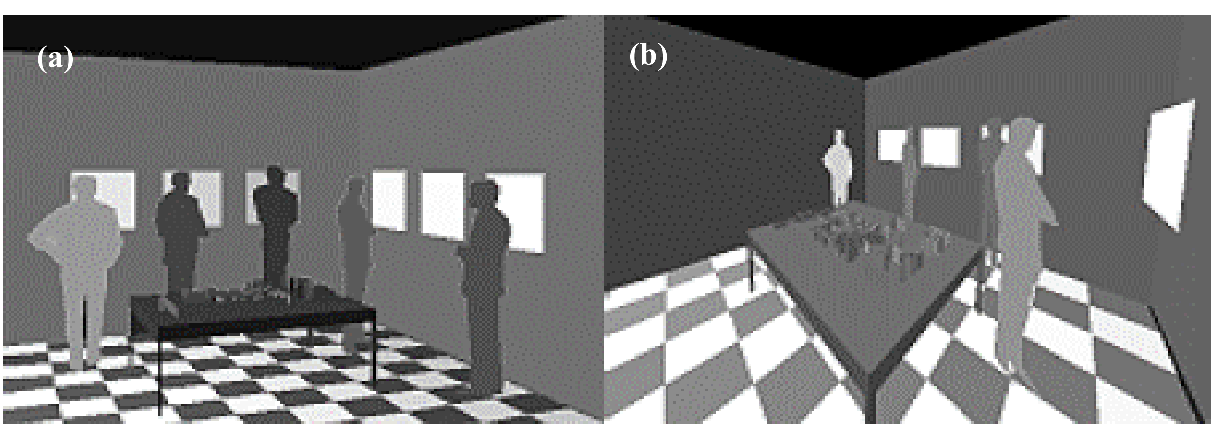


Figure 8: Virtual Situation Room with Full-scale Site Model: (a) normal view (b) perspective view of participant

The application of this principle can enable the curation of a historical collection of reference images and other relevant information such that it addresses issues of accessibility and modifiability for all the collaborators involved. “New items get posted over the course of the project, and the space changes character as the project matures” (van Bakergem and Obata 1993). Diagrams such as sketches and basic CAD drawings can be integrated into this design database for future analysis of the underlying concepts, principles and the quality of the proposed solutions by the team. This is analogous to building on each other’s ideas as the design progresses in a generative manner facilitated through the ‘on-the-fly’ chronological mapping of these ideas onto the virtual model, supported by annotations from designer’s as well as user’s verbal discussions and gestural visualizations. However, as Tufte (1990) argues, analytical reasoning in the design thinking process is facilitated by data collections only when they are effectively composed at the eye-level of the collaborators who are working on the two-dimensionality of the digital screen. Therefore, conventional models of textual labels for design data are replaced with three-dimensional forms and icons that are legible and does not require additional narratives on the design artefacts they are linked to.

Version Control and Data Documentation

In 1986, R. H. Katz, M. Anwarrudin and E. Chang published a conference paper titled, *A Version Server for Computer-Aided Design Data* which impacted computer-aided design communities by introducing the concepts of version control and hierarchies of design objects in better equip designers to iterate freely on innovative solutions (Katz, Anwarrudin, and Chang 1986). Through the implementation of a common “version server”, this research team at UCB was successful in organizing and maintaining hierarchies and versions of designs (or portions of designs) evolved in the process. The server also facilitated collaborative workspaces where these versions were shared in a controlled manner for team approval on the updates made to the main archives. By tracking the evolution of the design objects through mapping their version histories, the research observed that the structure of these historical mappings are similar to a tree’s structure where the branches represent both design derivatives as well as alternatives (see Figure 9).

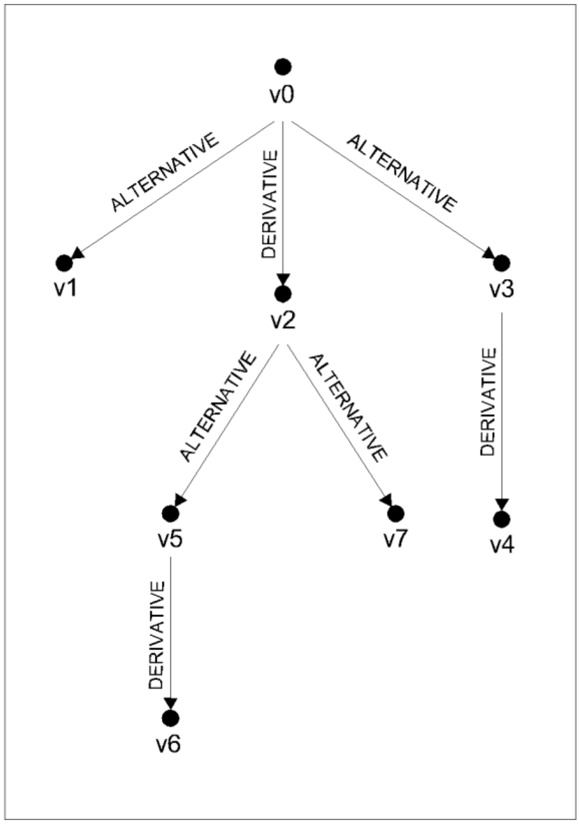


Figure 9: Version Plane mapped with Design Alternatives and Derivatives (Katz, Anwarrudin and Chang 1986)

Although this is an improvement as it acknowledges alternatives that can arise from the design process, it still assumes a progressive and unidirectional ideation that does not backtrack to refer and merge older versions into newer versions. Also, the tree structure of design versions assumes a constant multiplication and divergence of the design histories while, in reality, there are points in the process when several previous versions combine or converge to form a new version (Brown 2008). Based on this phenomenon, we can then speculate that the version plane is not a tree but a web of interrelations across old and new versions at the designers' discretion.

As discussed in Introduction, design thinking processes are often a progressive interplay between divergence and convergence of ideas. Consequently, keeping track of numerous versions of these design ideas is crucial to the constructive evolution and progression of the design process with the help of some 'control mechanisms'. A 'currency indicator' is one such mechanism proposed by Katz et al. where the designers can explicitly set any of the previous versions as a 'currency', i.e., default version from which to brainstorm new derivatives. Figure 9 illustrates this mechanism which enables the design teams to control the version evolutions as well as shift design foci and intentions from any point within the same collaborative sessions.

Furthermore, Katz et al. proposed the mechanism of 'dynamic binding' that is "most useful during exploratory phases of design, "when alternative new versions are being evaluated" (Katz, Anwarrudin, and Chang 1986). Through the implementation of dynamic binding, the designers can analyze the pros and cons of previous design versions and specify those versions that need to be 'bound' together in order to converge to a new design version. Therefore, this research acknowledges the necessity of version mapping and control of design ideas in the conceptual design process by proposing a "graphical browsing capability of top of the design database" (Katz, Anwarrudin, and Chang 1986). The proposed CAAD tool features an exploratory interface called the 'condensed blocks room' that simulates the evolution and sedimentation of design ideas throughout the design process and permits students to closely inspect their design strategies and solutions.

In this interface, however, the extent of content modifiability needs to be monitored as students can generate large amounts of design data in very short spans of time but proceed to 'destroy' their traces if they do not feel confident with them (Al-Qawasmi 2005). This could prove counterintuitive in the documentation of design evolution which assumes the storage of all versions without imposing any judgement on their value-addition to the larger problem-solving process (T. Brown and Katz 2009). Although these judgements on the part of students could be overcome with clear instruction that highlights the relevance of holistic documentation in design thinking process, some students can be deeply immersed that they tend to save some relevant ideas for future but 'lose records' of several others which can prove detrimental to the development of designs in later stages (Al-Qawasmi 2005).

Workspaces

As discussed earlier, the proposed design tool in this research integrates a three dimensional interactive interface that simulates a virtual 'situation room' that gives the appearance of a collaborative work environment that is now portable and remotely accessible (van Bakergem and

Obata 1993). The metaphor of the room can be applied to de-clutter the ideation space where the walls of the room now provide two-dimensional planes to ‘pin-up’ or project various design objects through the course of the project. While situating themselves in the model, the individual designers are encouraged to zoom in and out, rotate and span across the walls where they can browse the design data with intuitive ease while also switching between private and semi-public workspaces within the same interface (Katz, Anwarrudin, and Chang 1986).

Therefore, the room represents dynamic workspaces that increase in complexity of the information displayed through the use of layers and separation as Tufte proposes to ensure smoother communication and subsequent collaboration (Tufte 1990). This enables the team to zoom in and out of their design evolutions and re-enter these tracings from any point of the conceptual phase, creating new branches of alternatives that can be worked on in separate individual and/or shared workspaces. Furthermore, students can reap the benefits of working in an integrative mode that is flexible in its spatial boundaries to be able to transition between different mental states required for design thinking and making (Al-Qawasmi 2005). This in turn motivates students to alternate between macro-level and micro-level strategies as they refine their design ideas within these spaces whose privacy settings within the larger workspace can be altered organically along the process.

In addition to the representation of the physical space of the design studios, the research also explores the application of avatars and color labels that assign unique identities to the design collaborators. “Each team member might have a representative surrogate in the model which would link to critical commentary on the project or any contributions from their personal experience...these figures could be assigned any function and act as an agent to help the designers reveal information...These scale figure agents are expected to become a useful tool in the evolution of information spaces” (van Bakergem and Obata 1993). Thus, these virtual characters are proposed as mediators in the collective workspaces so that each student creates personally relatable design personalities as they interact with one another in order to grow and evolve in their learning process.

Proposed Design Modes

This research proposes a framework that acknowledges 6 key design 'modes' that are commonly observed in conceptual phases of the architectural design process, particularly during openly speculative and collaborative projects among students and instructors in design studios. These design modes are: *(1) Audio, (2) Precedent, (3) Sketch, (4) Concept, (5) Massing, and (6) Walkthrough* (see Figure 10). Given that architecture is a discipline that sustains itself through socio-culturally complex interactions with key stakeholders such as clients, mentors and collaborators, the *Audio* mode is considered a central 'verbal' mode of design thinking and making. Once spaces are visualized through these verbal ideations, design thinking moves onto non-verbal and visual modes of design that gradually increase in their level of detail and complexity in brainstorming spatial designs.

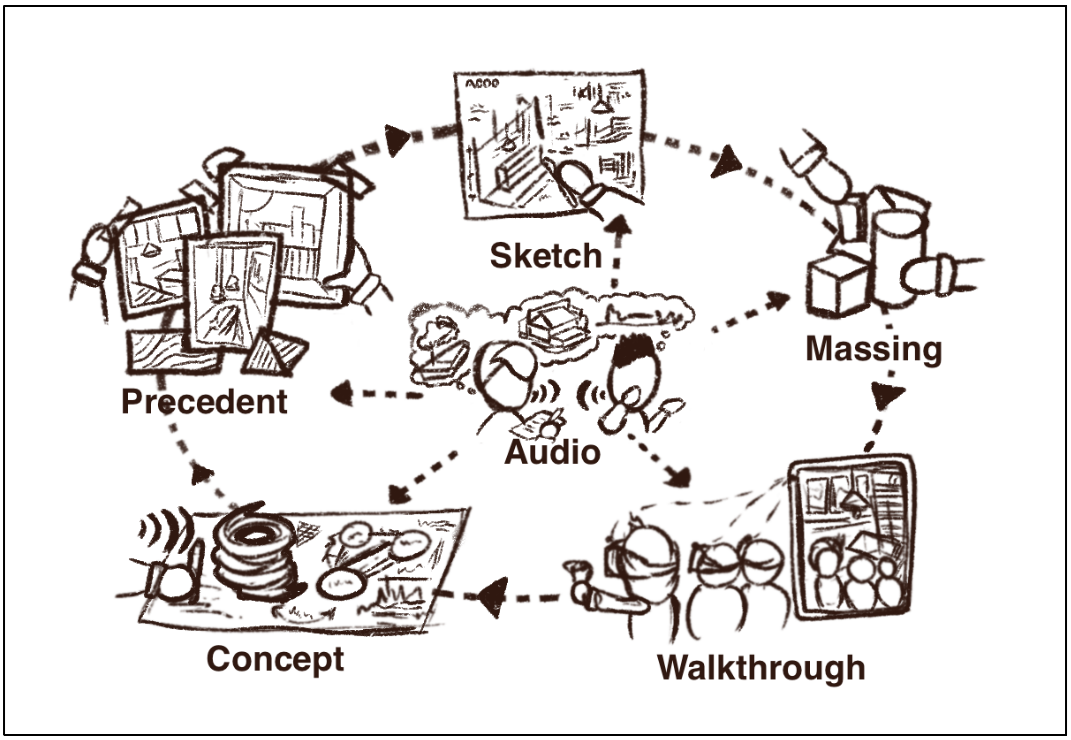


Figure 10: 6 Proposed Design Modes: Audio, Sketch, Massing, Precedent, Concept and Walkthrough

In this manner, *Concept* is the design mode that focuses on analogical reasoning that is key in extracting and imparting new meanings, concepts and design principles for conceptual architecture design. Once the themes and principles have been brought to light, the *Precedent* design mode is an integral portion of the design process where the designers seek out external sources or 'stimuli' for design inspiration which can include literature reviews, case studies of existing projects, contextual studies of the design site, building regulations and so on.

Sketch is a one of the most vital components of the creative design thinking and making process in architecture education and practice that empowers quick and iterative visualizations that investigate compositions, proportions, light and so on. *Massing* is the design mode where designers play with different configurations of three-dimensional design artefacts, either virtual or physical, through solid-void investigations that provide 'form' and 'mass' to the proposed built environments.

Finally, *Walkthrough* is an immersive visualization of the design space that enables the designer to get data related to embodied and experiential qualities of the built environment and its surroundings. In this mode, designers move through physical and hypothetical spaces in a 1:1 scale that promotes intuitive design explorations such as sequential site photos, time lapse videos, short documentaries, etc, which can be further augmented with in-situ observations and field notes through GIS, AR or VR technologies.

Audio

> Transcribing and note-making software that convert recorded or real-time audio into text for future reference has been used more frequently by students as they enable effective recollection of complex design concepts discussed with their instructors. In this case, the transcription tool can also be considered as a CAAD tool as it later informs the design drawings and representations made by the students. This highlights the significance of integrating 'speech-to-text' transcription features in conventional CAAD tools as it allows for a holistic documentation of the design process that includes verbalization of the ideas and strategies worked on (Wendler and Rogers 1995). Hence, by offloading the tedious task of note-taking during creative brainstorming sessions, the students can actively 'think-aloud' and vocally ideate through multiple iterations of design concepts and stimuli with lesser inhibitions and hindrances of process documentation (Al-Qawasmi 2004; Goucher-Lambert and Cagan 2019).

Therefore, this research proposes a design tool that incorporates active transcription of verbal design actions by the students and instructors during studio consultations as well as group projects with large student teams. The proposed CAAD tool acknowledges vocalization of design ideas which are critical in supporting the creative and reflective potential of architecture students as they mentally navigate and visualize the process (Wendler and Rogers 1995). These verbal design thinking actions by the students can be seen as equivalents to quick and earnest sketches by the architects in professional practice as they design spaces based on clients' inputs and other project constraints (Goldschmidt 1991). The audio and textual data extracted and stored from these creative sessions are similar to quick and rough sketches in the conceptual design process that allow one to see the origins and the multiple directions that the designs can evolve into.

Sketch

Sketches are most popular among architects and designers as they are used as problem-solving and communication facilitators in addition to being memory aids that complement other diagrammatic representations essential for the design thinking process (Suwa and Tversky 1997). However, this facilitation is often limited in conventional digital design tools that do not offer flexible and tangible interactions with the graphical interface leading to recent pen-based design sketching options (Kramer 1994; Gross 1996). According to Mark Gross in 'The Electronic Cocktail Napkin—a computational environment for working with design diagrams'(1996), most of the available CAAD tools automatically rectify the free-hand shapes drawn which may deter fluid generation of ideas in the conceptual design phase by limiting the visual imagination of the designer (Gross 1996). As a result, architects and designers "still turn to freehand sketches for naive concept-forming" (Suwa and Tversky 1997). This is particularly evident in novice practitioners when their sketched marks on paper trigger a dynamic meaning-making exercise with the underlying representation that emerges conceptually and "free from unnatural constraints that conventional design tools would impose" (Kramer 1994).

Hence, sketches can facilitate the design process in a conversational manner as it triggers the designer to revisit their conceptual models of reality in order to generate more ideas through visual design thinking (Goldschmidt 1991). Similarly, Vinod Goel in *Sketches of Thought* (1995) promotes free-hand sketching as the perfect venue for exploring design ideas as they possess the dual nature of being dense and ambiguous at the same time (Goel 1995). Masaki Suwa and Barbara Tversky in 'What do architects and students perceive in their design sketches? A protocol analysis' (1997) argue that a sketch is a pictorial device that allows designers to create interrelations between graphical entities to create meanings and concepts and consist of (a) emergent properties, (b) spatial relations, (c) functional relations, and (d) background knowledge (Suwa and Tversky 1997).

These interrelations are made through 'lateral' and 'vertical' transformations of design intentions into conceptual ideas which are facilitated by hand sketches in a naturalistic manner (Goldschmidt 1991; Goel 1995). The lateral designing promotes the exploration of alternative designs from the same base conditions while vertical design can dive deeper into the base design to flesh out further details. Therefore, the proposed design tool seeks to accommodate this indispensable design mode of sketching by acting as a perceptual interface that encourages users to respond to certain aspects of the visual schema while 'reading-off' those ideas that increase the quality and productivity of their designs (Suwa and Tversky 1997).

Precedent

In this proposed design mode, students can access design precedents or case studies that are crucial to gaining creative insights before or during their exploration through sketches and 3D models. These inspirational stimuli are essential as it allows students to reflect on design proposals through analogical reasoning (Markman et al. 2009). Kosa Goucher-Lambert and Jonathan Cagan in 'Crowdsourcing inspiration: Using crowd generated inspirational stimuli to support designer ideation' (2019) conducted several experiments with design students where they observed that "near stimuli improve the feasibility and usefulness of designs solutions, while far stimuli improved their uniqueness" (Goucher-Lambert and Cagan 2019).

Therefore, through their research findings, it is evident that one of the proposed CAAD tool's design principles is to be supportive to designers by providing appropriate stimuli "at the right moment" (Goucher-Lambert and Cagan 2019) such that the tool's interface can facilitate analogical reasoning and analysis by the design students. However, according to the protocol analysis by Salman et al., students using popular CAAD tools such as AutoCAD and SketchUp barely performed design actions such as 'refer' and 'inspect', both of which are associated with the analysis of the given design problem and the proposed solutions (Salman, Laing, and Conniff 2014). This lack of referring to other designs as well as inspection of the solutions through the existing CAAD tools can be related to their interface which does not include these analytical and reflective features of reference/inspection. This can be observed as a limitation of existing CAAD tools which has been addressed by the features of the proposed research tool through the integration of the 'Precedent' mode. This proposed design mode would allow students to seamlessly refer to external sources of design inspiration from within the tool's interface.

Concept

As a design mode that immediately follows and complements the Precedent and Audio design modes, Concept is envisioned as a convergent design mode that incorporates diagrammatic representations of design principles, spatial layouts, activity mappings and so on which are extracted from the former two modes. This design mode depends on multiple levels of abstraction of design ideas discussed collectively in order to reject inherent assumptions but also expand those knowledge boundaries that are relevant to the design problem (Larkin and Simon 1987; Ward 2009). This conceptual expansion is observed as a pervasive activity by designers in order to analogically derive new instances by outlining existing well-defined domains of knowledge. Parts of a diagrammatic whole that defines a design problem are typically indexed by location on a plane with topological and geometric interrelations (Larkin and Simon 1987). Some examples are adjacency matrices that help designers to spatially program built environments in architectural design. Such diagrams make relevant design information explicit and easily recognizable that otherwise remains implicit in other design modes such as Sketch and Massing.

Additionally, research has been done on 'dynamic' diagrams and their effects on the design process in a collaborative setting through three mechanisms: representational guidance, diagrammatic free ride and law encoding (Eppler and Kernbach 2016). While the first mechanism makes diagrams more conversational in nature, the second mechanism enables designers to find new ideas at a glance and the third mechanism reminds them to adhere to pre-existing design norms. Therefore, the Concept design mode ensures the formulation of 'dynagrams' that act as fluid and stimulating boundary objects for creative collaboration on design ideas.

Massing

This design mode enables designers to compose and manipulate three-dimensional masses that represent livable spaces in architectural design projects. Through simple push-pull interactions with the geometry, massing is an efficient design thinking and making process that is hands-on in its approach while reflecting on balanced proportions of solids and voids to give 'form' to the proposed spaces. Each massing element is connected with adjacent elements in a way that generates a coherent architectural configuration by establishing relations with its situated context (Akin and Moustapha 2004). Although these design moves critically affect the external features and identities of the architectural spaces in conceptual design phases, massing is also essential in discerning the designed building's environmental impacts through 'shoe-box' energy simulations (Samadi, Qamaruzzaman, and Fadzil 2010). As a result, popular CAAD tools such as Revit have laid emphasis on conceptual massing models at the onset of construction projects that mandate energy-efficient building designs as one of the core design principles. However, massing as a spatial design method does not occur in isolation and is dictated primarily by schematic diagrams and sketches created in Sketch and Concept modes which already influence decisions made three-dimensionally. Hierarchical relationships among massing parts to the whole building mass enable designers to divide the project up in manageable sections for distributing detailed design tasks among team members (Akin and Moustapha 2004). In this manner, an ill-structured problem can be broken down into tangible and specialized parts so that each designer can work individually to derive spatial programs and vice versa ('form follows function' or 'function follows form').

Various regulating elements such as horizontal and vertical axes, section cuts, mirror planes and so on make massing one the most intuitive design processes (Chen, Bowman, and Laidlaw 2009; Sun et al. 2013) that is equivalent to the art of sculpting clay. More and more, these models have become key graphical representations in architectural communication and collaboration activities as they simulate the potentially livable spaces closer to reality in comparison to sketches, 2D CAD drawings, mood boards, etc. Recent building information modelling (BIM) paradigms have also highlighted the impact of layering real-time data on materials, structural loads, etc. in order to provide a holistic platform for collaboration with the least design changes and risks that may occur in later stages of the construction process. Consequently, the proposed design tool incorporates Massing as a design mode that emulates real-world architecture and design practices for students in design studios as it allows for rapid prototyping of proposed solutions and testing their impacts on an urban scale before committing them permanently into the built environment.

Walkthrough

This design mode allows students working in teams to increase their degree of involvement in the collaborative design process through the use of generative design tools that are compatible with virtual reality or augmented reality (VR/AR) and geo-referencing technologies (like GIS). Through this intimate and immersive interaction with the digital design objects, the students can navigate through the embodied qualities of the proposed site and freely move through conceptual representations as though they were already built in their desired locations (Al-Qawasmi 2005). Walking through the intuitive site documentation and in-situ field notes in a 1:1 scale supported with sequences of images or short video segments that simulate dynamic movement through the proposed solutions superimposed on the experiential data of existing conditions such as favorable views, courtyards, pathways, etc (van Bakergem and Obata 1993). In this regard, film animations can be seen as predecessors of AR and VR technologies that are still relevant digital visualizations tools to communicate and collaborate on conceptual spaces for the built environment.

Reflecting - Design Workflow

Design studios have physical environments that often encourage divergent and messy design thinking and making practices amongst students and instructors such that documentation of their ideas can become cumbersome. This struggle of recording dynamic design processes can be seen when students participate in open ideas-only architecture competitions which are often held at an international scale. As a result, the proposed design tool in this research can be applied to conceptual designs in competition entries that are speculative and futuristic in design proposals. Depending on the student's tacit and explicit design knowledge and skills, the six proposed design modes can be approached from any entry point through flexible combinations of two or more modes at the same time. For example, a student who is confident with their researching and sketching skills can work simultaneously on Sketch and Precedent modes as their corresponding interfaces will be placed side-by-side within the larger interface of the proposed design tool. These chosen design modes can be paused or terminated in any combination, at any point during the brainstorming session in order to pull up and work on more mode interfaces such as Massing, Concept, etc. This ensures the fluidity of the design process that is conventionally lost due to manual switching across separate digital tools for each design mode.

Storyboarding Expected Users

Figure 11: Feature image of 'Retracer' Storyboard with 3 characters: Sasha, Aang and Hari

Given that ideas-only competitions can be unique and challenging with never-before-seen design constraints, existing precedents and literature may be limited to effectively kick start the design process. According to Jane Darke in 'The primary generator and the design process' (1979), a conceptual design process on complex problems begins on a conversational tone rather than interrogational as designers do not have direct and explicit task lists to produce swift design outcomes. "Rather they have to find a way of reducing the variety of potential solutions to the as yet imperfectly- understood problem, to a small class of solutions that is cognitively manageable" (Darke 1979). These smaller groups of objectives are defined as 'primary generators' which are often arrived at by designers through their 'strongly-valued and self-imposed' subjective design decisions which may or may not have undergone a 'process of logic'.

However, these primary generators result in design proposals which have clarity in their base conditions which can be moved forward or eliminated through the design process. Through intuitive design data documentation and tracking of the primary generators of design solutions, their evolutions can be effectively communicated and justified to a wider audience, particularly competition juries, where the graphical proposals cannot contain all of the intended verbal descriptions from the designers. Therefore, the proposed design tool can be employed in converging to the primary generators of complex design thinking and making activities that are encountered during architecture design competitions.

A storyboard with three characters, Sasha, Aang and Hari, were developed in order to visualize the subjective judgements that may showcase potential deviations from the intended method of application of the proposed design tool. While Sasha is a teaching assistant and an active design representative of the local community, Aang is a studio design instructor who advocates frequent hand sketched designs and Hari is a 3rd year architecture student who is always keen on learning new and trending 3D modelling software. Hari approaches Aang to collaborate on a design competition that requires divergent brainstorming of ideas for a sustainably fabricated outdoor pavilion that implements local materials and craftsmanship. Intrigued by this proposal, Aang requests Sasha to join the team as she has professional connections with local artisans who have previously worked with her on public design projects. However, due to frequent clashes in course schedules, the three of them design remotely from the comfort of their homes and meet twice in a week during lunch breaks to consolidate their design approaches.

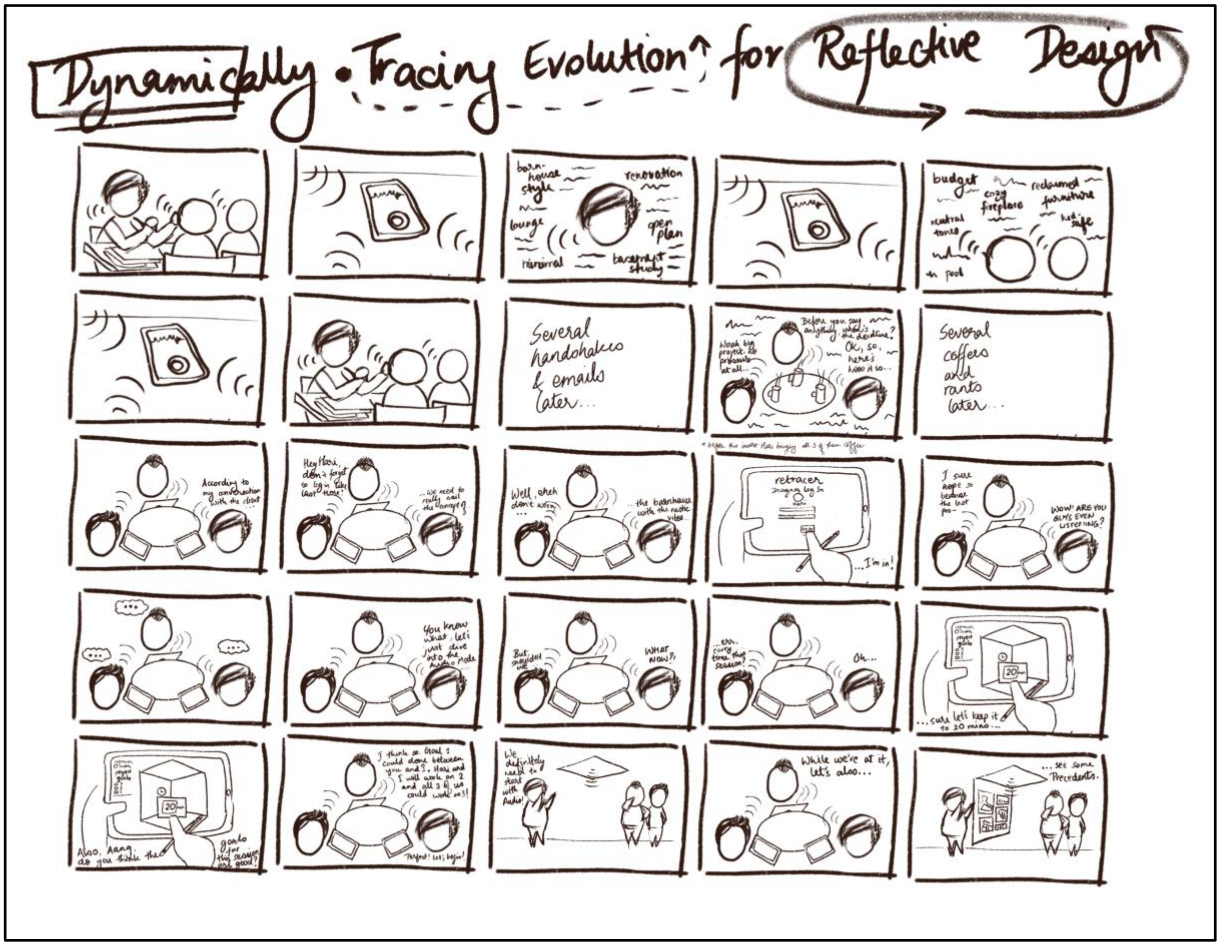


Figure 12: Rough development of 'Retracer' Storyboard

During their design sessions, each of them open their touch devices with the proposed design application installed for ease of design documentation and collaboration. Sasha often brings audio recordings of her discussions with interested craftsmen and inserts them into Audio mode in order to generate design principles in the Concepts mode. In the meantime, Aang adds relevant literature research and a few images of the proposed site in the Precedent mode while using Sketch mode to markup the site map in multiple iterations to determine the pavilion's strategic location in the urban landscape. Under the guidance of Aang, Hari explores several digital models of the pavilion within Massing mode based on the site markups provided by Aang in the Sketch mode. Sasha keeps referring back to the condensed blocks room within the application in order to browse through the ideas generated so far and provide valuable feedback on the design direction most appropriate for the socio-cultural fabric of the local community. Although they hesitated to work within the same design mode walls at first, dividing the work among them and working cooperatively, they quickly moved into a single interface as they felt comfortable in the evidently conversational design flow where all three of them would collaboratively observe, discuss, sketch and sculpt their proposed solutions.

Prototyping Proposed Workflow

Based on the storyboard, this research explores a digital tool for architecture students, instructors and novice practitioners in learning environments such as design studios as the tool takes on the role of a design brainstorming facilitator. This design application is developed for touch-enabled graphic interfaces that are handheld, such as the iPad, where virtual design workspaces can be accessed either locally or remotely depending on the collaborators' preferences. Figures 13 to 17 illustrates the key wireframes of the proposed design tool that enabled this research to incorporate the theoretical reflections of studio pedagogy and its user's preferences.

Design collaborators each log in to the digital tool with their individual credentials. Next, the team leader initiates either a new design session or resumes an existing session by adding the team members and their identities. A prompt asks the team to enter three key design goals that would help divide the work among them and steer the decision-making processes during the session. The team is then led to the condensed project room with stacked clusters of building blocks that each represent previous design sessions, colored based on individual contributions.

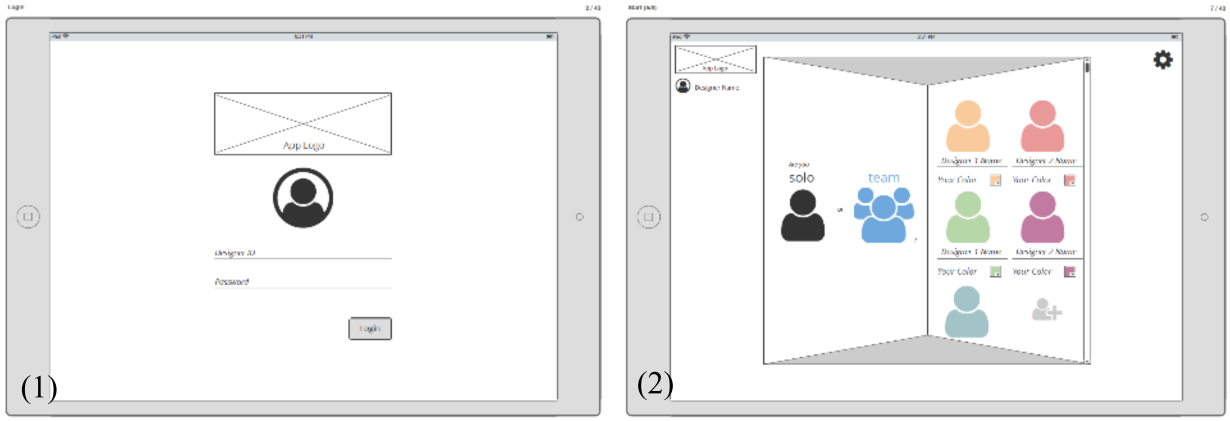


Figure 13: 'Retracer' Wireframes – (1) Individual Designers Log-In to the App and,, (2) enter their Design Team Details

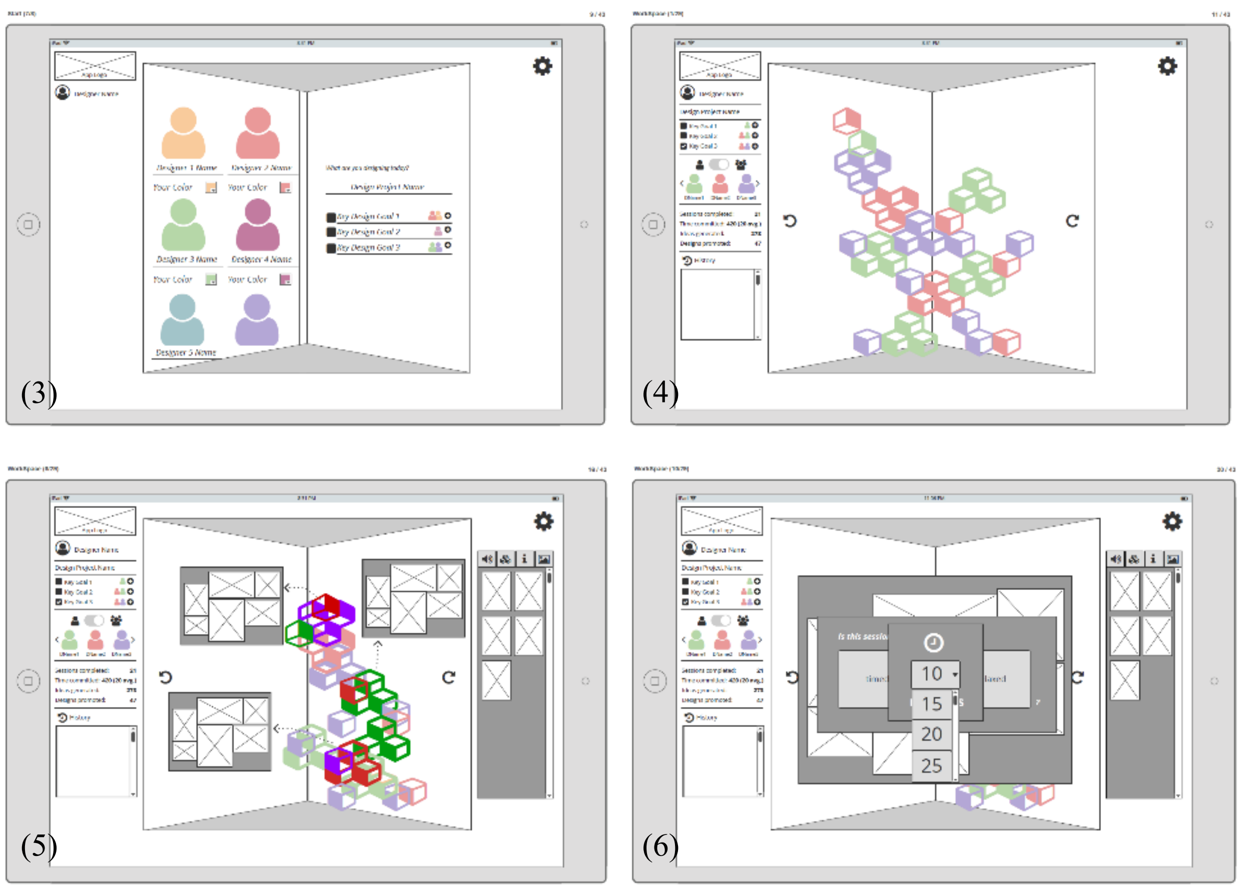


Figure 14: 'Retracer' Wireframes – (3) Managing Key Design Goals, (4) Condensed Project Room, (5) Session Block Clusters and their corresponding visual summaries (collage), (6) Choosing desired minutes in a timed design session

The design team can pick their desired cluster of blocks to work on and choose to time the session or keep it relaxed as this can motivate them to explore and generate larger quantities of alternate design ideas within shorter timeframes. The application then displays a summary of the selected session's ideas in the format of a collage. Additionally, the interface prompts the team or individual designer to select their preferred modes of designing in order to kick start the design thinking and making process within the particular session.

Suggested Workflow 1: Sketching and Massing

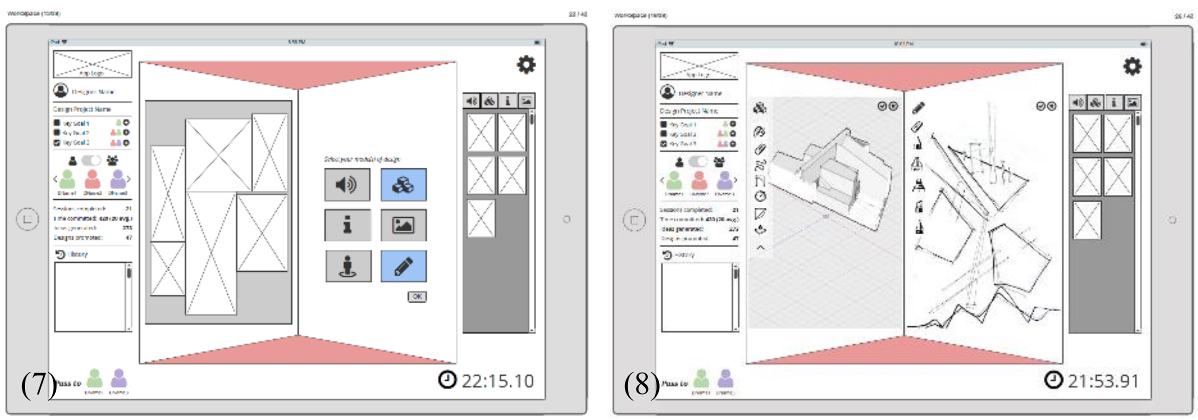


Figure 15: 'Retracer' Wireframes - (7) Selecting Sketching and Massing of Suggested Workflow 1, (8)Working on Sketching and Massing design mode walls in the same workspace

The first suggested workflow combines Sketching and Massing design modes within a single interface, which is popular in CAAD tools that support 2D as well as 3D virtual ideations of the proposed spaces. However, within the proposed application's interface, the designers have the option to link their sketches to translate into 3D models or leave them as orthographic sketches that retain certain levels of ambiguity for future proposals. Sketching and Massing mode walls each have their tools for drawing lines, curves, planes and sculpting spatial volumes using basic geometry such as cubes, spheres, cylinders, etc.

Suggested Workflow 2: Audio, Concept, Precedent

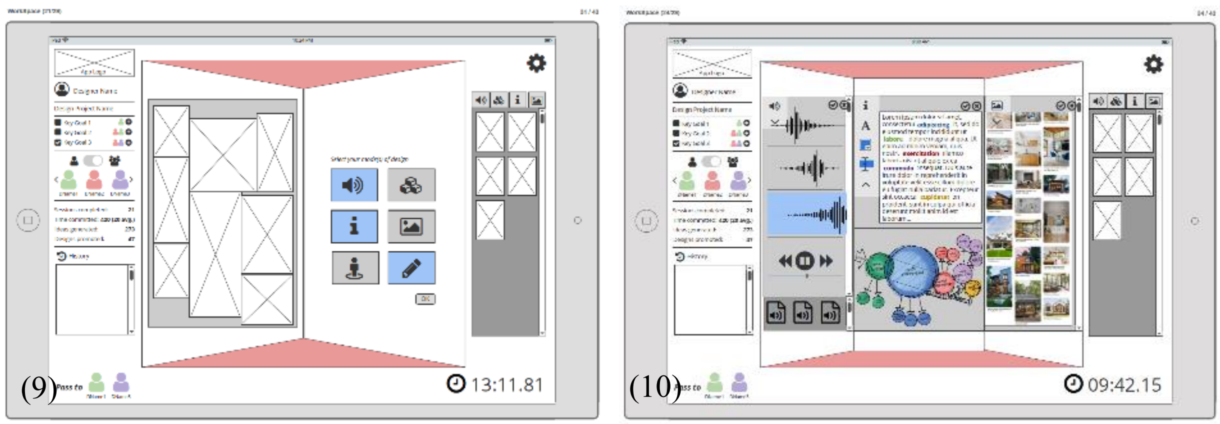


Figure 16: 'Retracer' Wireframes - (9) Selecting Audio, Concept and Precedent of Suggested Workflow 2, (10) Working on Audio, Concept and Precedent design mode walls in the same workspace

The second suggested workflow combines Audio, Concept and Precedent modes of design within a single interface which is particularly useful during pre-design phases of data collection from clients, policies, previous design projects, and so on. Voice recordings of important design discussions can be played in the Audio mode to activate textual transcription of key ideas in the Concept mode interface which can then be highlighted for keywords to be mapped into schematic diagrams such as bubble diagrams, adjacency matrices, activity mappings and so on. Parallelly, the case studies and site details displayed in Precedent mode can help extract key ideas from the other two modes.

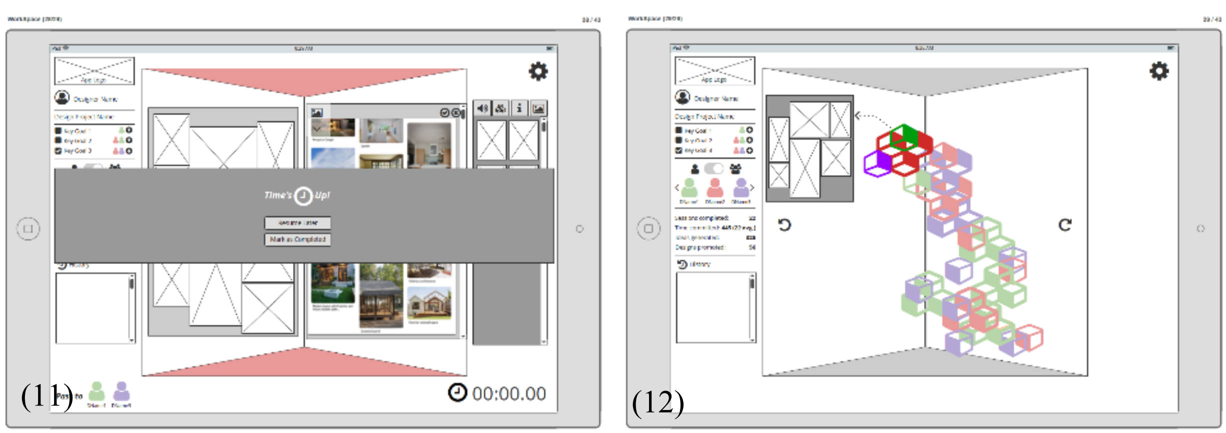


Figure 17: 'Retracer' Wireframes - (11) Prompt that freezes a timed out design session, (12) Condensed Project Room updated with new design session block clusters

In the case of a timed design session, a prompt blocks the design interfaces as soon as the timer runs out and asks the design team to resume the session for a later time or mark the session as completed. Back in the condensed project room, newer blocks are clustered to form a visual feedback of the design progress made so far. This dynamic project overview using the metaphor of stacked building blocks encourages further generation of ideas until the design team is satisfied with the quality of the designs proposed.

User Feedback on Proposed Workflow

The proposed framework of reflective, collaborative design modes and workflow was put to the test through an online survey hosted on the Google Forms platform (see Appendix b). This survey was generally timed in under 5 minutes and was conducted as part of the 'user research' methodology that focuses on three potential users of the proposed design tool: students, instructors and novice practitioners. Although the design studio environment also includes jurors and jury systems, these roles are assigned differently in different architecture school contexts. For example, some schools do not reveal jurors' identities until the day of the final presentations and are typically external to the institution. However, juries are ideally composed of seasoned practitioners who may not directly benefit from the educational aspects of the design tool proposed in this research but play the roles of mentors for junior designers.

The survey contains a total of 15 questions which are divided into two sections: (1) General Information with 6 questions and, (2) Design Workflow with 9 questions (see Appendix b). The survey was conducted with 21 participants where 47.6% (=10) are Architects, 33.3% (=7) are Architecture Students, 9.5% (=2) are Design Students, 1 Designer and 1 Intern Architect (who is also an Architecture Student). It is interesting to note that 42.9% (=3) of the Architecture Students are teaching assistants with at least 2 years of experience. Similarly, 30% (=3) of the Architects are currently teaching with an experience of at least 3 years. While 40% (=4) of the Architects can be identified as novice practitioners with work experience of 0-3 years, 20% (=2) of them can be identified as near-seasoned practitioners with 5-15 years of work experience.

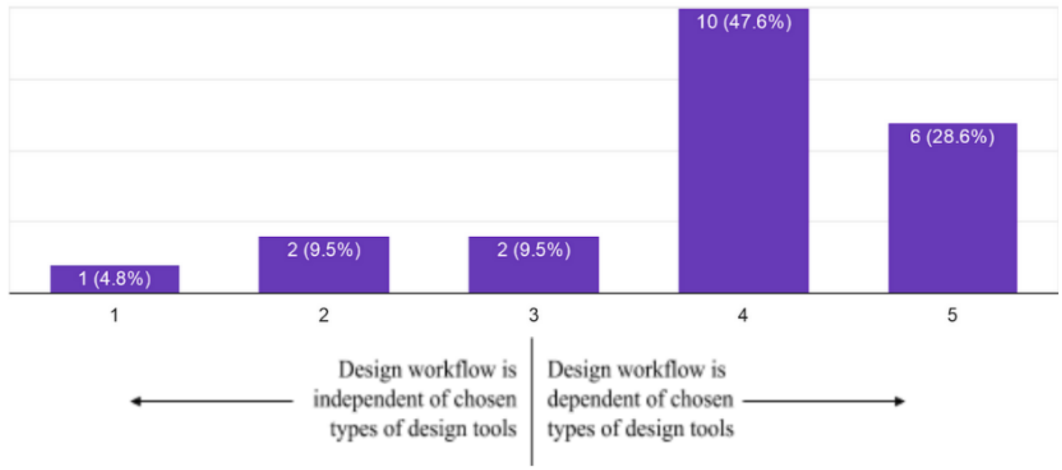


Figure 18: User Feedback Survey - Results of Section 1 Question 5

On the question, *Do you think the type of tools you design with can affect the speed and quality of your design workflow?*, which is evaluated on a spectrum of 5, 47.6% (=10) voted the value of 4 and 28.6% (=6) voted the value of 5 where 5 is equivalent to the response, *Yes, very much (design workflow is largely dependent on the right choice of types of design tools)*. This indicates that 16 out of 21 participants (=76.2%) believe that types of design tools affect the speed and quality of their design workflow. Out of these 16 members, it is interesting to note that most of the '4' rating was given by practicing architects (=6) and all of the '5' ratings were given by architecture and design students and interns.

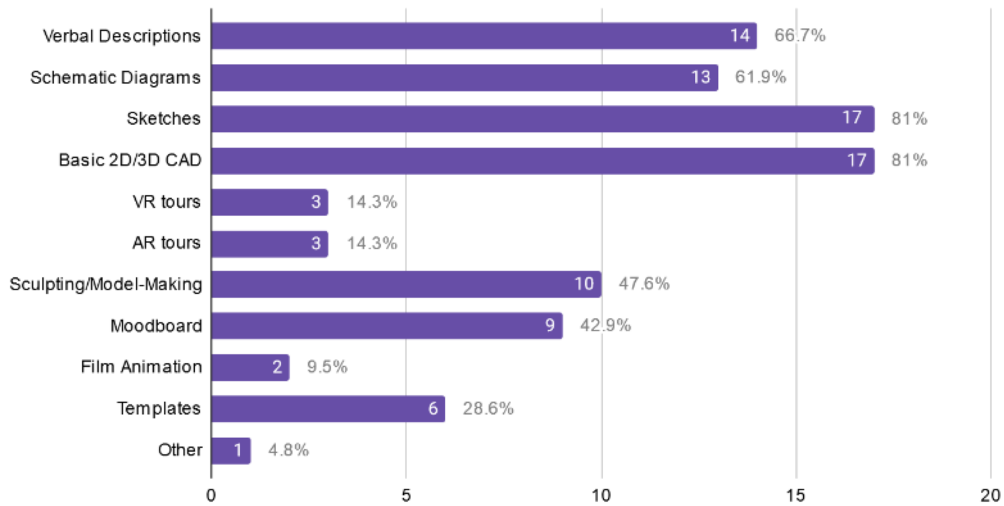


Figure 19: User Feedback Survey - Results of Section 1 Question 6

Sketches and *Basic 2D/3D CAD drawings* were chosen as the most preferred types of design tools/methods for architectural design with 81% (=17) votes each. *Verbal Descriptions* followed as the second-best type of design tool/method with 66.7% (=14) votes and *Schematic Diagrams* took third place with 61.9% (=13) votes. It is interesting to note that *Sculpting/Model-making* got 47.6% (=10) votes where 60% (=6) votes were made by Students (Architecture and Design).

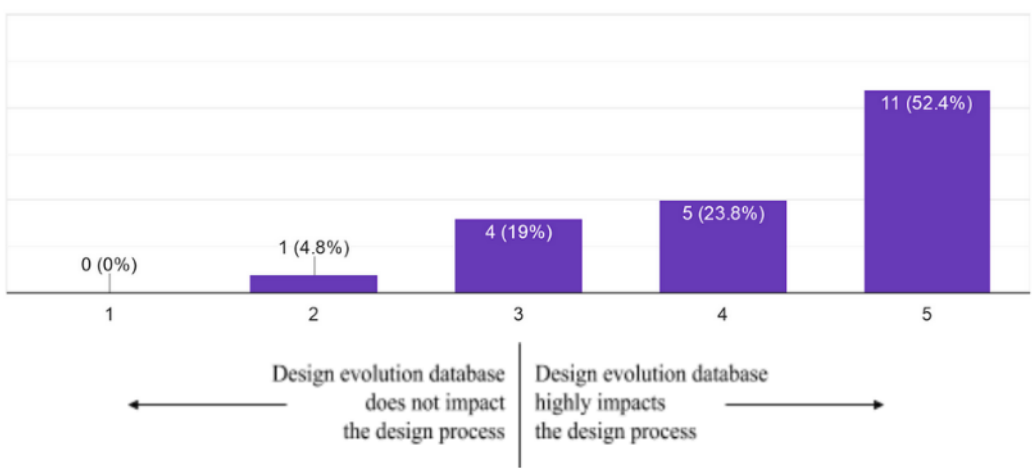


Figure 20: User Feedback Survey - Results of Section 2 Question 1

Out of 21 participants, 11 (=52.4%) of them marked 5 on a spectrum of 1 to 5 for the question, *Do you think it is important to have a database of the evolution of your design ideas in order to generate more?*, where the value 5 represents the response: *Yes, very necessary as a design evolution database highly impacts the design process*. This indicates that the majority of the survey's participants find the maintenance of a comprehensive design database essential to the progress of their design processes by helping them generate more ideas.

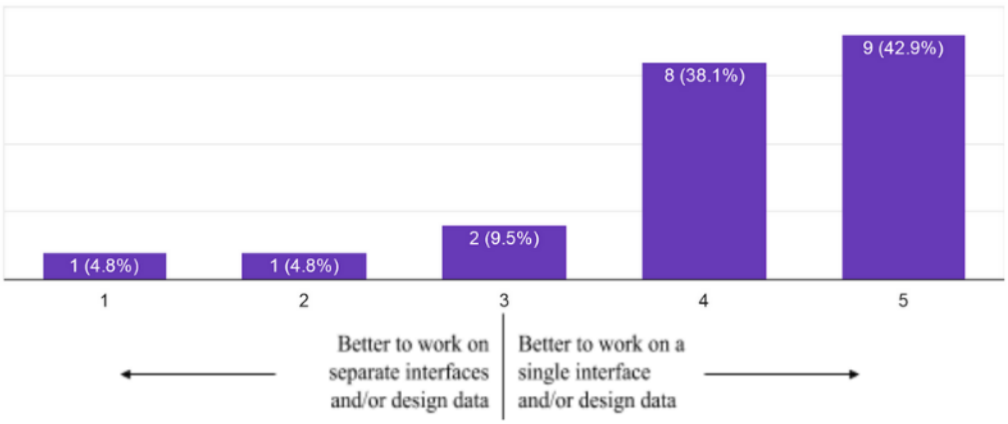


Figure 21: User Feedback Survey - Results of Section 2 Question 2

Similarly, for the question, *While working collectively, do you think it is necessary for all the collaborators to have access to a single interface that allows simultaneous generation of ideas?*, the response was almost unanimously valued at 4 and 5 on a spectrum of 5 where the highest value corresponds to the answer: *Yes, very necessary as it is better to work on a single interface and/or design data while working collectively*. This validates the popularity of a collaborative workflow over a cooperative workflow within the same design teams and environments.

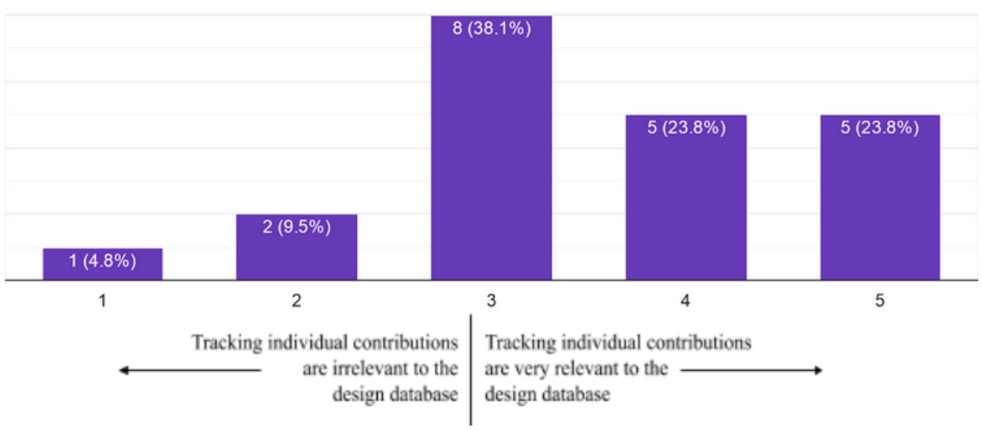


Figure 22: User Feedback Survey - Results of Section 2 Question 3

Garnering a neutral response valued at 3 by 38.1% (=8) participants, the question, *Do you believe it is necessary to track individual contributions of a collective workflow in the design database?*, showcases a slight resistance toward tracking individual design interventions in a larger team's design workflow. Values 4 and 5 were voted by 23.8% (=5) participants each on the spectrum with 5 representing the need for tracking individual contributions.

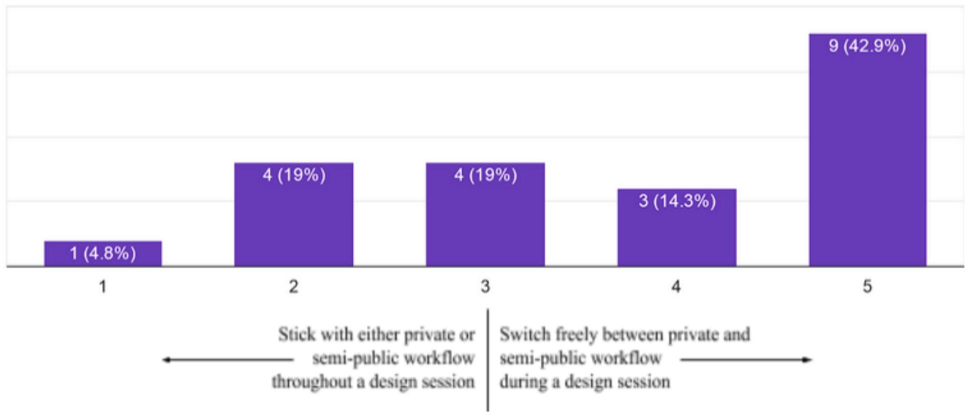


Figure 23: User Feedback Survey - Results of Section 2 Question 4

The question, *Within an ongoing design session, do you think it is essential to switch freely between individual (private) and collective (semi-public) design workflow?*, got rated at a value of 5 by 42.9% (=9) on a spectrum of 5 where the right extreme corresponds to the answer: *Yes, it is very essential to switch freely between private and semi-public workflow during a design session*. 8 (=38.1%) participants voted for values 2 and 3 which indicates that there is an inclination to the other extreme of the spectrum which represents the response: *No, it is better to stick with either private or semi-public workflow throughout a design session.*

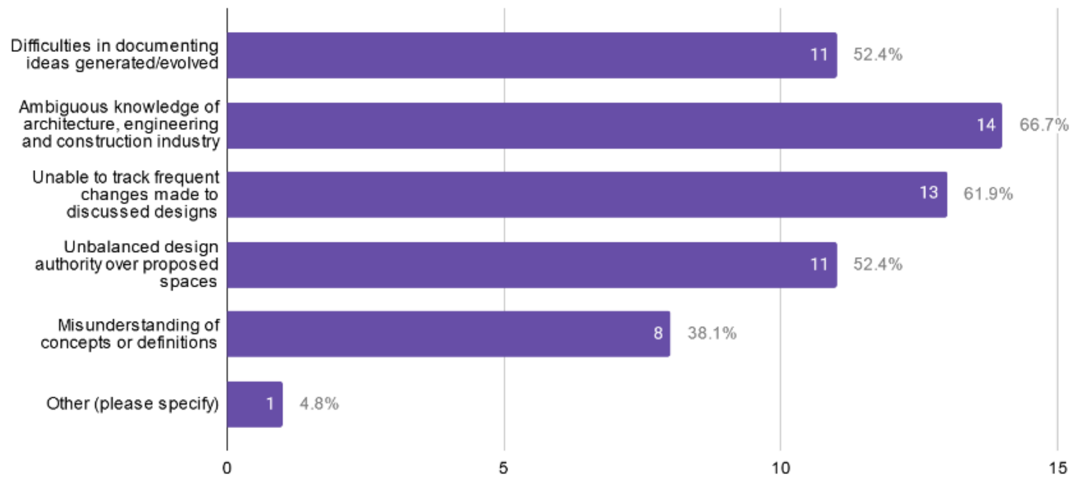


Figure 24: User Feedback Survey - Results of Section 2 Question 5

Ambiguous knowledge of the architecture, engineering and construction industry was ranked the highest with 66.7% (=14) votes as the most difficult challenge faced during collaborative design sessions. This was followed by *Unable to track frequent changes made to discussed designs* at 61.9% (=13) and *Difficulties in documenting ideas generated/evolved* as well as *Unbalanced design authority over proposed spaces* at 52.4% (=11) each. It is interesting to note that an Architect with practicing experience of 5-15 years supplemented the design challenge which is prominent in the AEC industry: *Difference in levels of experience of various team members*.

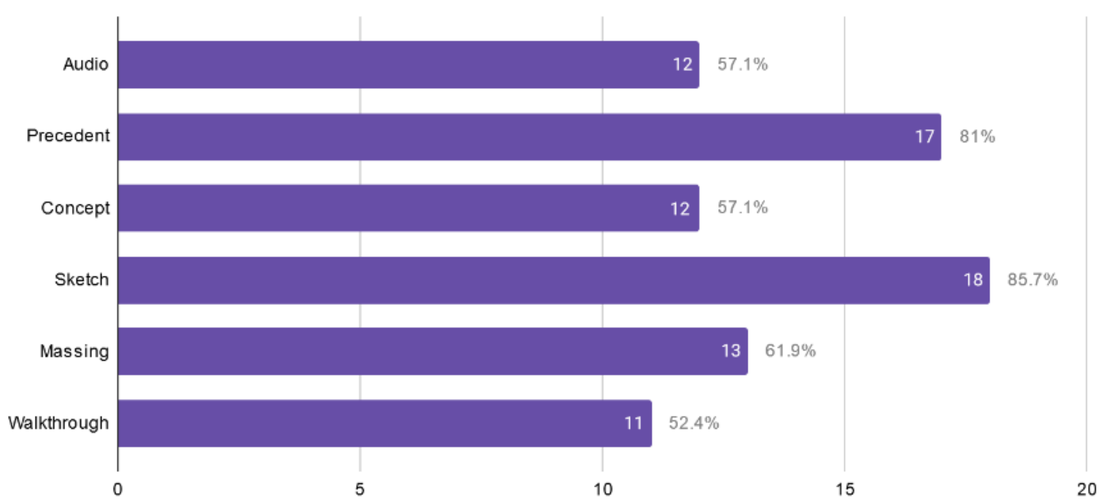


Figure 25: User Feedback Survey - Results of Section 2 Question 6

Out of the 6 proposed design modes, *Sketch* mode ranks as the most preferred design mode with 85.7% (=18) votes followed by *Precedent* mode with 81% (=17) votes. The next most preferred design mode is *Massing* mode at 61.9% (=13). *Audio* and *Concept* modes received 57.1% (=12) votes each which indicates a correlation between these modes and validates the relevance of Suggested Workflow 2. Finally, *Walkthrough* mode received 11 (=52.4%) votes which highlights that the majority of the participants identified this as a relevant design mode even though AR and VR technologies are yet to be implemented on a global scale in architecture education and practice. It is important to note that no additional design modes were supplemented by the participants using the 'Other' option, which validates research findings that identified and proposed these 6 key design modes prevalent in the conceptual design process in architecture.

Also, the participants shared their preferred conceptual design workflows using the proposed design modes with some interesting deviations. The most common workflow is: *Precedent/Audio —> Concept —> Sketch —> Massing*. This indicates that, depending on the role of the designer and the nature of the project, the conceptual design process almost always begins with *Audio* and/or *Precedent* modes of design which is immediately followed by schematic layouts and design principles extracted in *Concept* mode. 57.1% (=12) participants observed their design workflows consist of pairings of *Concept* and *Sketch* design modes to 'materialize ideas' for effective communication and collaboration while staying relatively ambiguous. Most importantly, *Massing* design mode was unanimously observed as a successor of *Sketch* mode in their design workflows which took on both analog study modelling as well as precise digital 3D modelling to further design ideations and client collaborations. *Walkthrough* was observed by 38.1% (=8) participants which indicates that AR, VR or film animation formats of design are yet to gain popularity as a prevalent mode of conceptual design in architecture. Lastly, few of the participants suggested 'Documentation' as a design mode in itself to consolidate their design processes which highlights the necessity of design databases in future developments of design tools in architecture education and practice.

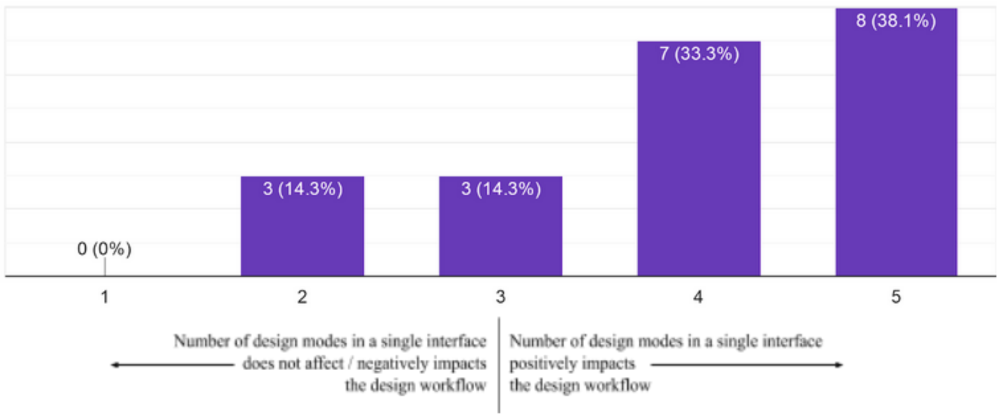


Figure 26: User Feedback Survey - Results of Section 2 Question 8

For the question, *Do you think having ALL the design modes in a single interface benefits the design workflow?*, 71.4% (=15) participants gave 4 and 5 valued ratings on a spectrum of 5 where 5 represents the response: *Yes, having all the proposed design modes within a single interface positively impacts the design workflow*. This validates the user interface of the proposed design tool with the possibility of including all 6 design modes in multiple combinations within a single design session's workflow.

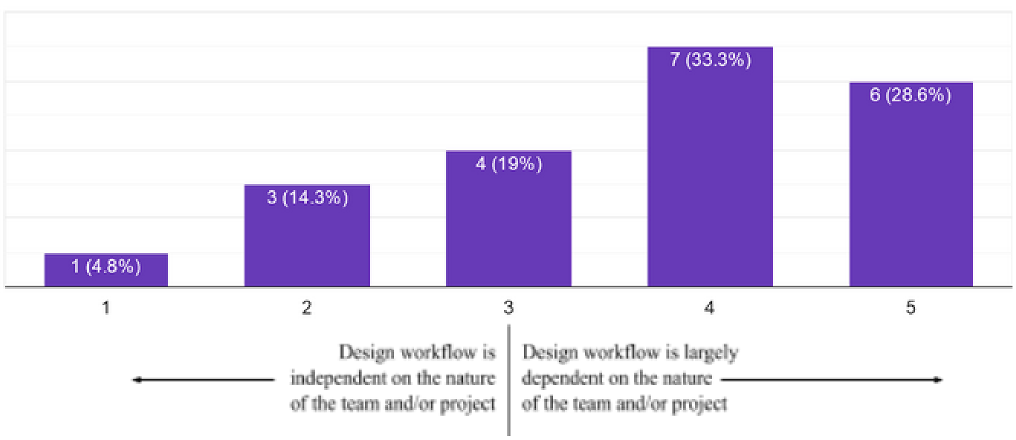


Figure 27: User Feedback Survey - Results of Section 2 Question 9

Finally, for the question, Does the workflow pattern alter based on your design team and/or project constraints?, 33.3% (=7) voted 4 and 28.6% (=6) voted 5 on a spectrum of 5 where 5 represents the response: Yes, the design workflow is affected/altered as it is largely dependent on the nature of the design team and/or project. This highlights that the majority of the participants felt that their design workflow is greatly influenced by the socio-cultural forces that hinder or promote healthy and productive team dynamics during collaborative design activities.

Key Takeaways for Proposed Design Tool

The user feedback survey was conducted to identify the feasibility, scope and limitations of the proposed design tool, modes and suggested workflows for conceptual design processes in architecture. The target audience for this user research were primarily architecture and design students, novice practitioners and instructors who are often licensed architects with at least 2 years of work experience in the AEC industry. Findings and follow-up discussions with participants have resulted in a positive reinforcement of the design tool's framework which is based on reflective and collaborative design processes within digital design learning environments. The survey was structured in an interrogative tone that seeks to clarify some assumptions on conventional design methods in existing communities of practice before introducing the proposed framework. As a result, the first section collects general info as a prerequisite and warm-up before asking '*Do you think…*' questions in the second section with ratings on a spectrum of 1 to 5 in order to gauge user reactions on the proposed design workflow while ensuring the least amount of socio-cultural bias from the participants.

Results indicate that the progress and productivity of conceptual design workflows are dependent on (1) types of design tools, (2) methods of process documentation, (3) segregation and flexibility of workspaces, (4) project constraints, (5) socio-cultural and professional dynamics among design team members and (6) openness to adopt hybridized modes of design collaboration and communication. As the proposed design tool seeks to increase design accessibility and facilitate rapid design thinking and making processes, questions on the relevance of maintaining an interactive design database, working collectively on a single interface with all design modes and, moving freely between individual and collective modes of design were validated due to their prevalent ratings on the right end of the spectrum. However, intermediate values (2, 3 and 4) on the spectrum were not labeled and this may have created some ambiguity in the responses received.

The 6 design modes, *Audio, Precedent, Sketch, Massing, Concept* and *Walkthrough* were well-received by students and practitioners alike who appreciated the opportunity to reflect on their preferred as well as conventional modes of conceptual design ideation. Although design modes such as *Sketch*, *Massing* and *Walkthrough* were direct in their respective applications in architectural design, *Audio*, *Precedent* and *Concept* design modes were observed as broad categorizations with multiple design methods that overlap across their boundaries. For example, *Precedent* mode was defined as a design mode that includes site surveys, photos, climatic analysis, etc. clubbed along with mood boards from case studies, previous projects, material catalogs and so on. This may create discrepancies in the observations made on conventional design protocols in popular architecture firms where site documentation is done during a 'pre-design' phase before the conceptual/schematic design phase (Chintis 2019). Nonetheless, the user feedback survey has greatly influenced the user interface of the current iteration of the design tool's prototype and has created a network of participants who would be willing to contribute further feedback for future developments which could involve hands-on workshops and testing, primarily among architecture and design students.

Making - Tool Design and Development

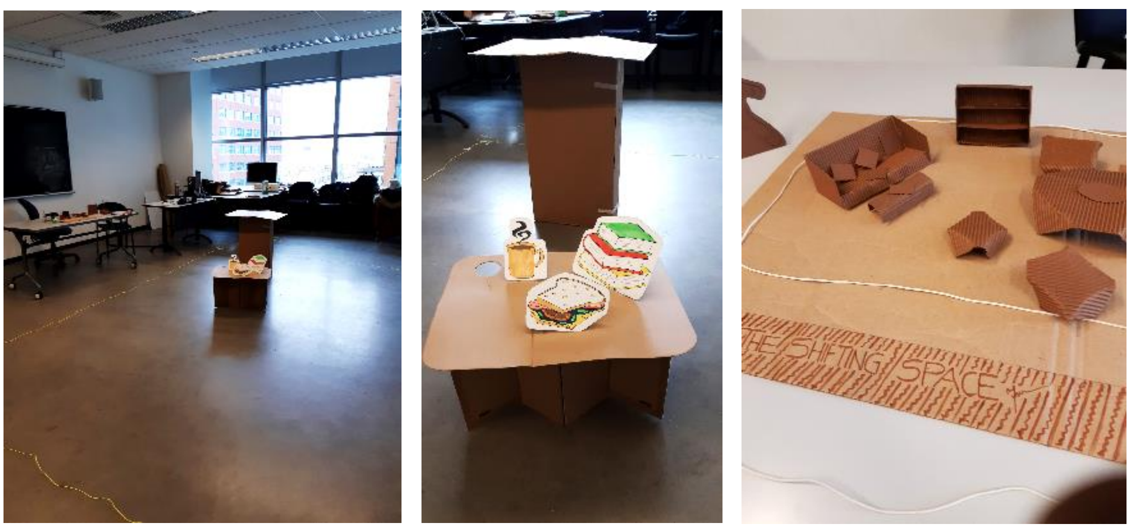
The proposed design tool underwent a total of 4 design iterations in the span of 2 years: (1) The Shifting Space, (2) MindBlocks v1 (Arduino), (3) MindBlocks v2 (AR), (4) Retracer App. These iterations have been cumulative design making ventures that covered speculation, prototyping, and testing before developing the current iteration of the design tool, Retracer.

Speculating Spatial Interactions in Design

A creative exploration of the impacts of scale on the design process of the built environment, *The Shifting Space* was an open and interactive experimentation setting that encouraged the audience to step into the hypothetical boundaries of their day-to-day activities within the spaces most frequented by them in their households. This spatial recreation of their conceptual models of these spaces was done by inviting the audience to rearrange mockup cardboard furniture made in 1:1 scale within a 3 x 4.5 m area marked by rope. Based on literature that ascertain the impacts of furniture layout in the configuration of residential spaces and subsequent distribution of activities within them, the experiment was set up to explore the dynamics of people defining meaningful relationships with their immediate surroundings by interacting with the formal and functional qualities of the lived spaces. This hands-on inquiry was also conducted as a speculation of intelligent, flexible and shape-shifting residential spaces, both in physical form and function, which adapt to the changes that are dictated by the ever-evolving spatial perceptions of their occupants.

Using cardboard as the primary material for interaction, the set-up sought to instill a feeling of delicate respect for our immediate surroundings as humans and start a discourse on anthro-spatial narratives and their implications to imposing meaning as architects and designers of our own living spaces. The audience was also asked to fill in surveys before and after their interactions with the spatial mockups. However, due to limitations in resources, the mockups were limited to basic volumes that could be interpreted as a coffee table, TV stand and so on. Furthemore, the intended set-up was presented in the form of a 1:10 maquette made of cardboard that also emulated the intended interactions within the actual 1:1 conception of the same. After its presentation to fellow design peers, this speculative exploration was confronted with its inherent assumptions such as the

Figure 28: Photographs of The Shifting Space set-up with cardboard mock furniture and rope boundary



effect of interactions between people
in a community on the spatial configurations as well as the limits of physical and material interactions to accommodate intangible cultural values and meanings to space.

Prototyping Tangibility and Hybridization in Design

The advent of digital and multimedia platforms has made spatial design much more flexible in conceptual experimentation. Tangibility of design tools and their impact on cognitive learning of spatial formations in architectural design was explored through the prototyping of MindBlocks, a platform that hybridizes analog and digital interfaces in the design process. The prototype featured ‘intelligent’ building blocks based on Arduino that would act as physical representations of their corresponding digital blocks such as walls, floors, furniture, etc. and used by architects and designers alongside conventional CAAD interfaces (see Figure 30(b)). MindBlocks was developed as a conversational design tool that promotes co-design and bridges the communication gap between designers and ‘non-designers’ who have varied levels of spatial aptitude and visual depth perception.

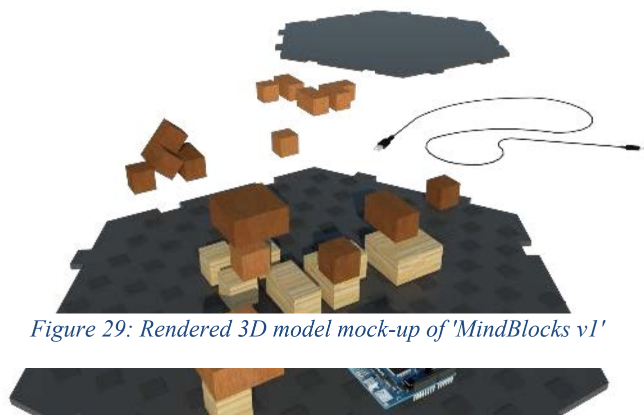


Figure 29: Rendered 3D model mock-up of 'MindBlocks v1'

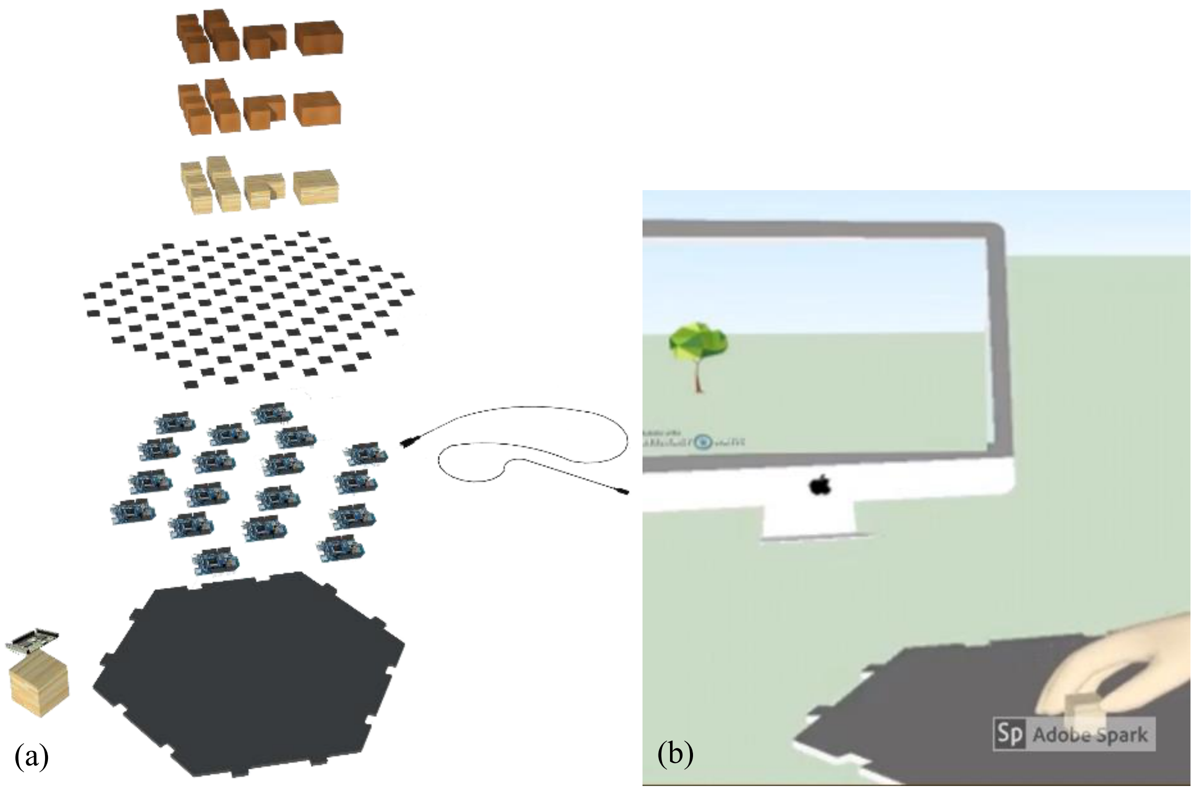


Figure 30: (a) Axonometric View of 'MindBlocks v1' and its components, (b) User demo of 'MindBlocks' featuring its physical building blocks and digital design software

MindBlocks was designed as a playful construction kit which consists of a set of physical hardware in the form of stackable wooden building blocks and a hexagonal base board to be used along with a software application and a community website (see Figure 31). The 3cm cubic blocks were designed as hollow wooden casings which contained a ‘WinoBoard’ microcontroller each, which are WiFi-enabled miniature derivatives of the Arduino Uno microcontroller, popularly used in product and multimedia design. The base board made of acrylic board and magnets would also embed a central Arduino that would detect the building blocks stacked on it and transfer its digital identity to the computer via a USB cable. Using information relayed by the baseboard’s microcontroller, the MindBlocks software was wireframed as a 3D modelling CAAD interface which would display the block’s ‘true’ digital identity. For example, if one of the building block’s microcontroller contains a unique ID of a tree, on placing it on the baseboard, the graphical representation of the tree would appear on the modelling window in the software followed by coherent audio feedback that confirms the placement of the tree on the virtual site model (see Figure 30(b)).

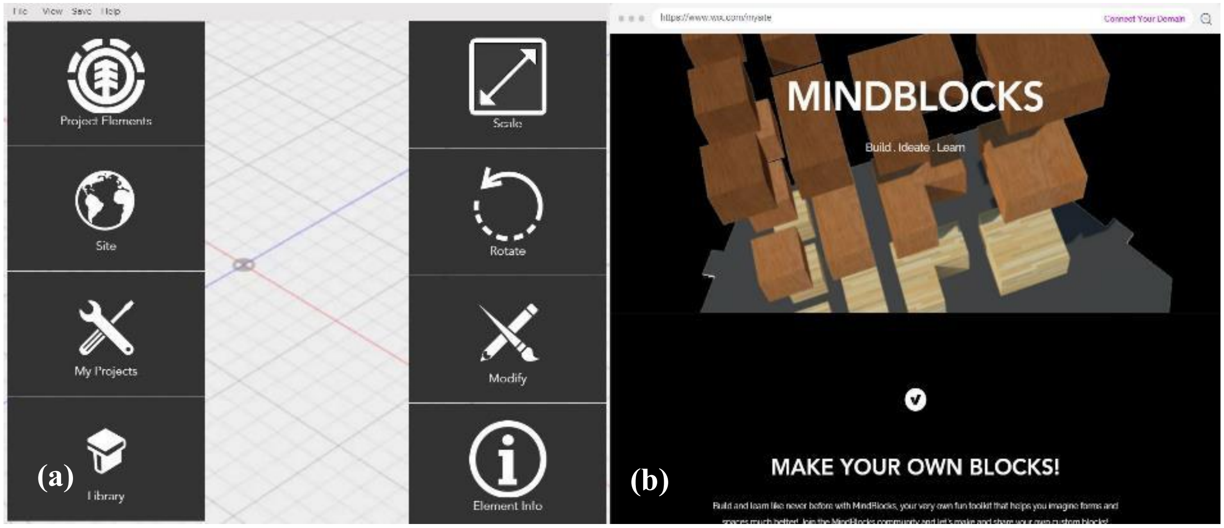


Figure 31: (a) 'MindBlocks v1' digital design software's UI wireframe, (b) 'MindBlocks v1' community website mockup

The physical kit would include different shapes and quantities of the building blocks based on the level of expertise of the users; starter pack for beginners with basic block shapes to advanced kit complete with guides to reprogramming the block's with one's own digital designs using an additional plug-in with the software provided. The software has a simple and easy to comprehend interface with large icons and buttons that represent various functions such as Project Elements, Site, My Projects, Library, Scale, Rotate, Modify and Element Info. The website is designed as a platform to share ideas by designers and makers alike. Custom blocks can be uploaded by users and ordered for manufacture by the MindBlocks team. The blog section of the website would serve as an ideal archive that tracks the growth of the MindBlocks design community that would ultimately inform future upgrades of the kit's design. This design was developed based on smart technology (IoT) and maker culture which provide a much more decentralised format of designing and collaborating as a community through active co-participation. A promotional video and supporting mockups for MindBlocks were also designed in order to present it as a product used primarily in contemporary architectural practice.

The underlying concept of active learning through playful building blocks was well received and appreciated. The implications of the design were broadly discussed and it was felt that the building kit could be applied to various disciplines beyond architecture including game design. Although the hardware used, namely Arduino, in the design concept was questioned and alternatives such as motion sensors used in platforms like Kinect were suggested, the idea of integrating a digital dimension to the simple act of stacking and combining blocks in different configurations was perceived as an effective way of visualizing spatial forms and relations much better than conventional ways of representation that sustain a dichotomy between the analog and the digital. Overall, the scope of the educational aspects of the project was discussed and deemed a promising venture in redefining the political dynamics of conventional design processes, particularly in architecture.

Testing Augmentation in Design

Due to a steep learning curve in implementing Arduino-based building modules as well as other technical limitations, the interactions proposed in MindBlocks were reiterated for a second version which tested the integration of Augmented Reality features in the design tool. The application focused on visual detection of unique patterns on the blocks which were tracked real-time through a camera which can then be augmented with additional layers of information on the user interface. This virtual layering of physical interfaces was explored using the augmented reality software development kit, Vuforia, in unison with the popular game engine platform, Unity3D. As a result, the wooden blocks proposed in MindBlocks could now be hollow or solid blocks without additional electronic devices embedded within them as augmented reality depends on patterns such as QR codes, barcodes, etc. which activate their corresponding virtual objects and information on the screen of the application (see Figure 32).

Figure 32: Rendered collage mockup of 'MindBlocks v2' and its components

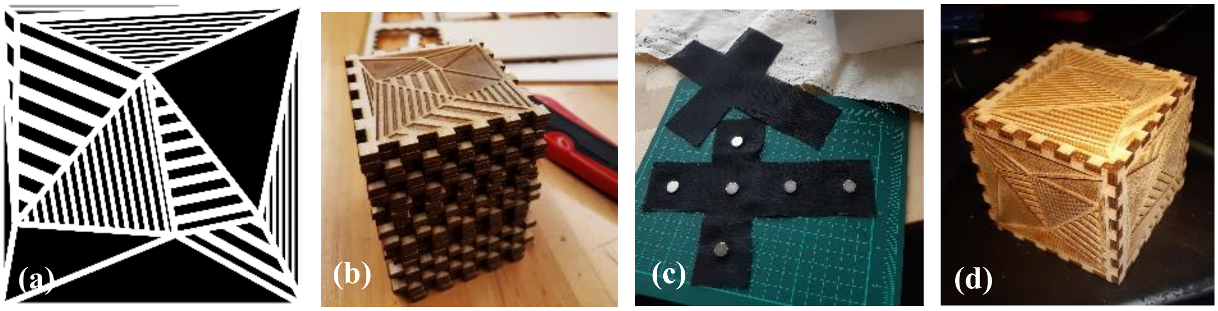


Figure 33: (a) Unique block pattern made with OpenProcessing, (b) Block sides laser-cut and etched with patterns, (c) Magnetic 'spine' of the building block, (d) 'MindBlocks v2' building block assembled

Therefore, a set of unique patterns were designed and generated to be laser etched on each of the 6 surfaces of the cubic wooden blocks which were made from plywood pieces joined together using laser cut dovetail joints that were evenly spaced (see Figure 33(b)). The patterns were randomized using a live-pattern generating code based on p5.js derived from OpenProcessing as hand-made patterns did not ensure unique identifiers and took longer to develop for laser cutting precision. Additional flat packing mechanisms for the block were explored in the form of a flexible 'spine' to unpack the laser cut blocks after use, such as a cross-shaped felt cloth lining with magnets that would snap the individual wooden sides of the blocks in place (see Figure 33(c)).

These prototypes were made with the design intention of making the building blocks unpackable, lightweight and portable for architects, designers and students who would travel more frequently with notepads and basic sketching stationery. Along with these prototypes, six design modes such as Audio, Sketch, Massing, Concept, Precedent and Walkthrough were brought to light through two simultaneous reflections: (1) literature reviews on conceptual design processes and (2) 6 faces of the cubic building blocks which could each hold different patterns that trigger different functionality. For example, revealing one side of the block to the device's camera at a given time would trigger one of the 6 design modes, say Audio, which acts as a prompt for designers to ideate in this mode. Once done, the designer would flip to another side and proceed with a different design mode such as Massing. This was done in order to retain the playful and exploratory nature of the design thinking and making process through elements of surprise where the designers do not have visual cues on which side of the block triggers which design mode.

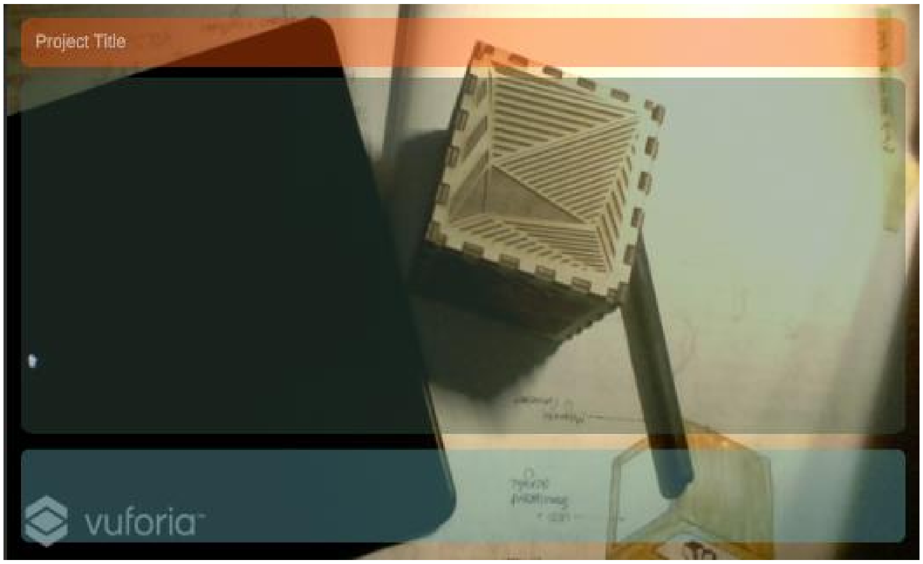


Figure 34: 'MindBlocks v2' digital design software's rendered UI mockup

Additionally, a stronger emphasis was laid on design data documentation methods through the integration of database systems within the application. It is interesting to note that the user interface of the proposed tool witnessed speedier developments and testing during this iteration due to prior knowledge in basic programming languages such as C++, and C# (see Figure 34). Given that Unity3D is a platform that allows a developer to build software applications across a wide variety of devices, the user interface of the proposed design tool was experimented for iOS, MacOS, Windows and Android devices. However, on further reflection with user groups, this iteration was discontinued before user testing owing to the dependence of the design tool on camera quality, lighting levels, etc. to successfully detect the etched patterns on the blocks.

Developing Reflection and Collaboration in Design

The hollow building blocks in the previous iteration have been transformed into a virtual metaphor for the user interface of the proposed digital design tool, *Retracer*, for architecture students in design studio pedagogy. Retracer has been developed in Unity3D as a design learning tool that focuses primarily on tracking and revisiting the traces of a conceptual design's development which has been spatially mapped within the interface in order to encourage more divergence in design thinking and making (see Figure 35). The interior of the building blocks has now been magnified virtually to represent a portable studio space that can be accessed for design reflection and collaboration from any touch device connected to the cloud. The interface of Retracer has been designed through the paradigms of design accessibility (Achten 2002) and human-machine interaction (Al-Qawasmi 2005) for potential users of the application who can log into this application from their respective touch devices and be seamlessly linked back to their individual or collective design ideation spaces.

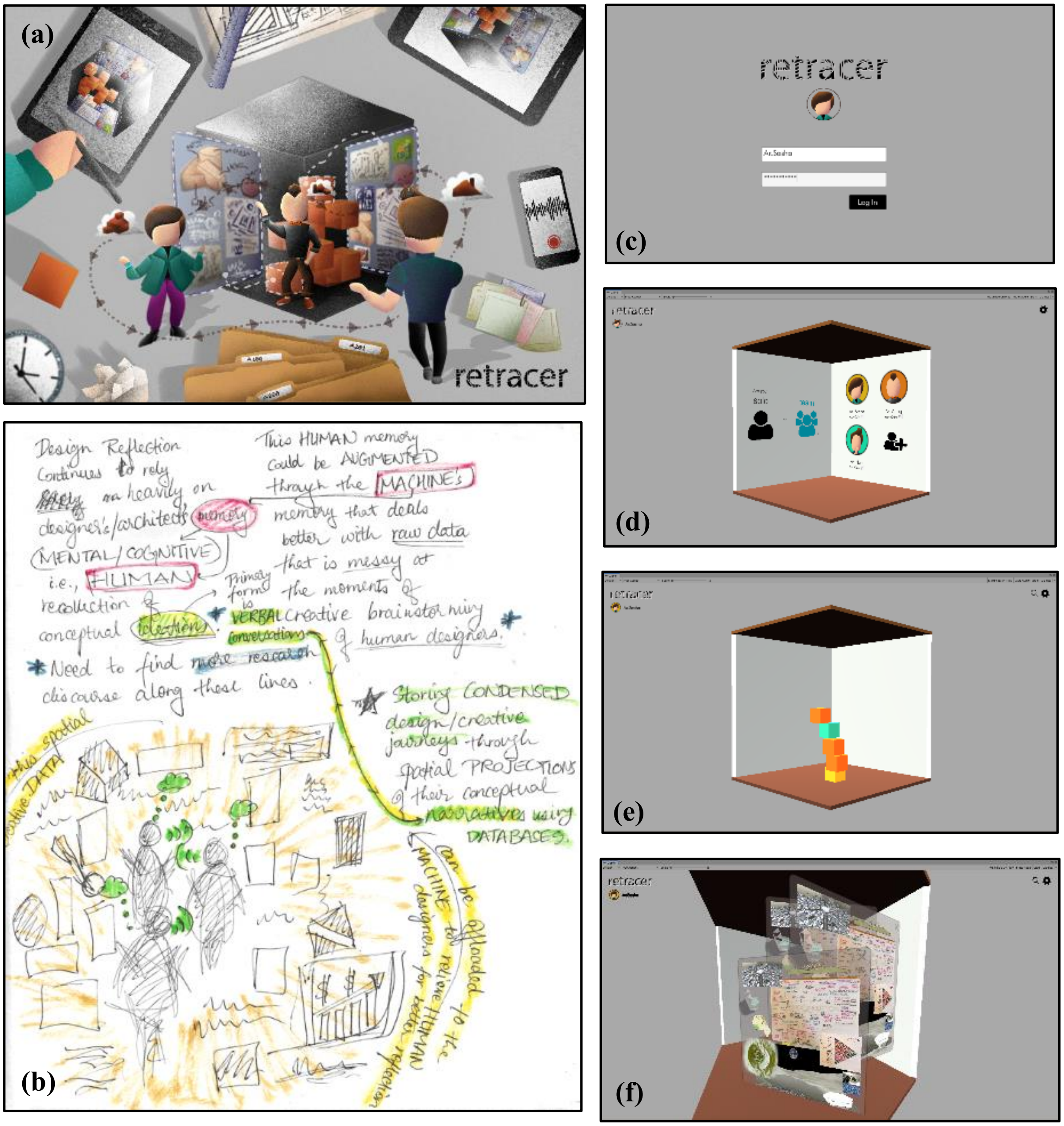


Figure 35: (a) 'Retracer' feature image, (b) Rough sketches and design principles of 'Retracer'; Rendered 'Retracer' digital software's UI mockups - (c) Log-In Portal, (d) Design Team Details, (e) Condensed Project Room with design session blocks, (f) Condensed Project Room with visual summaries opened from the design session blocks

The physical interaction of stacking building blocks has been translated into a Condensed Project room, displayed at the onset of a design session within the software, where each block represents a particular design session with all their corresponding ideas brainstormed and designs generated (see Figure 35 (e)). This was validated through the research conducted on the importance of design data documentation and version control in design reflection using interactive visual browsing of design objects and their evolution histories compared to conventional text-based searches for previous designs. Furthermore, conceptual sketches, plans, models, diagrams, etc. generated for an international ideas-only competition, *Moonception* (see Appendix c) have been used within the prototype of Retracer in order to illustrate the tool's application in the conceptual design process in architectural education.

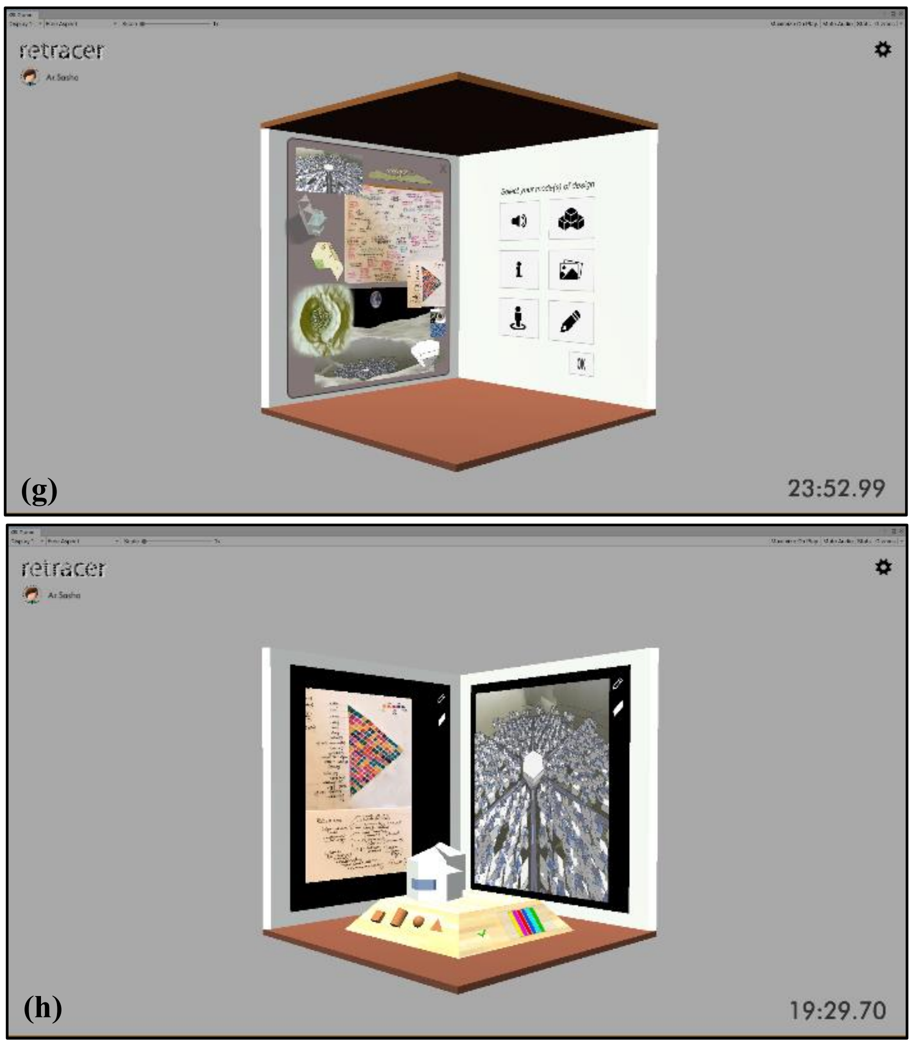


Figure 36:Rendered 'Retracer' digital design software's UI mockups – (g) Design Mode Selection Room, (h) Custom Workspace generated from the selected design modes

The 6 design modes proposed—*Audio, Sketch, Massing, Concept, Precedent* and *Walkthrough*—have been retained since the wireframing of Retracer (see Prototyping Proposed Workflow) as these were implemented in the design process for Mooneption (see Figures 36(f), 36(g) and 36(h)). Two design workflows have been suggested: (1) *Sketch* + *Massing* and (2) *Audio*, *Precedent* and *Concept*. The first suggested workflow has been visualized through Retracer's current development in Unity3D where designers could open two design mode 'walls' and 'floors' in the same 'room', in order to work on *Sketch* and *Massing* modes simultaneously (see Figure 36(h)). In the second suggested workflow, Audio was given more priority in development and testing using Google Cloud Speech-to-Text software development kit. This iteration has enabled the feature of real-time textual transcription of verbal design descriptions during a brainstorming session where conscious efforts at note-taking could hinder productive design flow.

Parallel to this reiteration of the user interface, a focus group survey was conducted to investigate the relevance of the Collaborative Dimensions Framework (Bresciani 2019) to make the software application collaborative in its interactions (see User Feedback on Collaborative Dimensions Framework). Based on this survey, the application's user interface includes integrative tracking of individual designer's contributions for each collaborative activity such as custom avatars and colored labeling of session blocks. Also, given the increasing popularity of touch-display graphic tablets such as the iPad among practitioners of all levels of design expertise, conventional non-design actions such as delegating design tasks to fellow designers have been emulated through swiping interactions that pass on one's work to others within a design session. This accommodates both collaborative as well as cooperative design workflows within larger design teams based on their cultural preferences as a community of practice (Dorta 2009). Although these proposed workflows have not been put to live tests through protocol analysis methodologies yet, the relevance of reflective and collaborative interfaces proposed in Retracer has been positively received and validated through the user feedback survey (see User Feedback on Proposed Workflow)

Conclusion - Implications for Design Research

During conceptual and schematic phases of the design process, traditional modes of communication and collaboration in architecture have been inflexible in terms of intuitive documentation of the designs brainstormed. Design thinking and making sessions are often divergent while generating design proposals and this can lead to messy arrangements of important ideas that are needed for reference while detailing proposed spaces in later design phases. As these sessions get information-heavy and popularly stem from ambiguous verbal conversations with collaborators, architects and designers of all skill levels rely on various design tools, methods and techniques in order to capture and document the designs for future reflection, communication and collaboration with other peers. Furthermore, conventional design studios face several socio-cultural, physical, economic and temporal limitations in holistically integrating digital design teaching and learning environments for the professional development of students and novice practitioners.

As a result, an interactive documentation interface can constructively train architecture students and debutant practitioners who would benefit from experiential learning while tracing and reflecting the history of the designs evolved over the course of the design process. By rethinking conventional tools, methods and techniques in digital conceptual design in architecture, students can situationally learn both the communicative as well as collaborative facets of spatial design thinking and making. Given that architecture education is designed to prepare students for real-world projects in the Architecture, Engineering and Construction (AEC) industry, this research stems from the gap identified in implementing interactive and inclusive digital design environments in pedagogy that stays on par with the industrial standards of practice. Therefore, the question: *How does dynamic documentation and tracing of the evolutions of design proposals promote design reflection and collaboration in students and novice practitioners during architecture studios?*, is addressed through the investigation and reimagination of existing Computer-Aided Architectural Design (CAAD) tools and their limitations.

From this perspective, the research explores the development of a more engaging and educational CAAD tool interface for virtual as well as physical design learning environments that can recreate a real-world collaborative design practice and encourage the students to build on each other's ideas inclusively while exploring all potential design alternatives. Hence, this thesis contributes to the 'design *for* design' research community by (1) studying existing digital design tools, methods and techniques for communicating and collaborating spatial design concepts, (2) investigating conventional design tools implemented in AEC communities of practice, (3) proposing new 'reflective and collaborative' design modes from conventional methods applied by current users of CAAD tools, (4) prototyping an educational CAAD interface that documents and keeps traces of design thinking and making processes in order to train students on conceptual design methods through practice-based simulations.

Making and *Reflecting* are two sides of this research that occasionally diverge into deeper creative explorations only to reconvene and intermingle in a way that cumulatively contributes to the system of digital conceptual design proposed for architecture pedagogy. While the *Making* phase is primarily based on research-through-design approach which includes development research and experimental prototyping methodologies, *Reflecting* acts as a complementary phase that finds design inspiration and validation through qualitative focus group research, user and usability research, and speculative design fiction.

Making

This research experimented a total of 4 different prototypes for the proposed digital design learning tool before arriving at the current iteration titled, *Retracer*. Over the past 2 years, the proposed design tool manifested itself in these iterative prototypes: (1) The Shifting Space, (2) MindBlocks v1 (Arduino), (3) MindBlocks v2 (AR), (4) Retracer App. The Shifting Space was a speculative open-laboratory setting where life-sized furniture mockups were rearranged by participants within a roped 'imaginary' room that represents their favorite spaces in their households. This experiment was done to observe and analyze the impacts of physical and tangible interfaces such as furniture in designing residential spaces where occupants make spatial meanings and relations with the built environment. The second iteration, MindBlocks v1 was an Arduino-based prototype of an interactive design tool that could be used by designers as well as 'non-designers' in order to conversationally design spaces in architecture practice. This prototype featured wooden building blocks embedded with microcontrollers (Arduino Uno and WinoBoard) which made them intelligent components of a hybrid construction kit that makes use of analog interactions to produce quick designs in the digital realm. Stacking these blocks on a central base board which is connected to a computer with the preferred CAAD tool, MindBlocks explored the tangibility and malleability of virtual design objects through physical hand-held blocks in place of traditional mouse and keyboard interactions.

Due to technical limitations, the third iteration, MindBlocks v2 incorporated Augmented Reality (AR) features in order to simplify the hardware and focus more on the user interface of the digital design software. Inspired by the layering of information on physical space as seen in the first iteration, The Shifting Space, as well as the playful building actions in the second iteration, MindBlocks v1, MindBlocks v2 now worked with hollowed building blocks with 6 sides containing unique patterns for augmentation with digital design objects. These 6 sides in parallel to the theoretical reflections on conventional design methods in CAAD tools, resulted in the proposal of 6 reflective design modes, namely, Audio, Sketch, Precedent, Massing, Concept and Walkthrough. However, due to technical dependencies on lighting levels and camera quality in user's devices, this iteration was discontinued for the testing phase of the proposed design tool.

Finally, the current iteration, Retracer, has been developed as an interactive CAAD environment for architectural design learning in studio pedagogy. The proposed design modes as well as the user interface features were validated through the Reflecting phase which included focus group survey on the collaborative dimensions framework (see Appendix a), design fiction storyboarding of expected users (see Storyboarding Expected Users) and user feedback survey on the proposed design workflows (see Appendix b). The hollowed blocks in MindBlocks v2 were translated into the virtual realm as a visual metaphor of a design studio that is on the cloud, portable and accessible from anywhere. Retracer has been developed in Unity3D as a design learning tool that spatially maps design ideas evolved throughout a design process in order to facilitate reflection, communication and collaboration during the conceptual design process in architecture education and practice. The interface of Retracer has been designed through the paradigms of design accessibility (Achten 2002) and human-machine interaction (Al-Qawasmi 2005) for potential users working on touch-enabled devices in their individual or collective design ideation spaces.

The 6 design modes proposed and developed within this iteration are: (1) Audio: Verbal discussions with peers/instructors/clients, etc. that are recorded for design reference, (2) Precedent:

Data collection and review of images (including site), diagrams, literature, etc. that act as case studies and sources of design inspiration, (3) Concept: Idea extraction from Audio and Precedent modes that inform the design principles and concepts for the specific design problem, (4) Sketch: Quick and rough compositions made from perspective or orthographic drawings and other 2D representations (including annotations) of the ideas discussed and generated, (5) Massing: Basic volumetric solid/void explorations of the design ideas with or without site details, labels, scale figures, shadows, etc., and (6) Walkthrough: 'On-the-fly' field notes of site visit(s) transcribed either on paper/device for future manual documentation or using AR and/or VR directly over real-time visual data of the design site such as photos, short/long video segments, etc.

Additionally, two design workflows have been suggested: (1) *Sketch* + *Massing* and (2) *Audio*, *Precedent* and *Concept*. The first suggested workflow has been visualized through Retracer's current development in Unity3D where designers could open two design mode 'walls' and 'floors' in the same 'room', in order to work on *Sketch* and *Massing* modes simultaneously. In the second suggested workflow, Audio was given more priority in development and testing using Google Cloud Speech-to-Text software development kit. This iteration has enabled the feature of real-time textual transcription of verbal design descriptions during a brainstorming session where conscious efforts at note-taking could hinder productive design flow. The relevance of these suggested workflows in architectural education and practice have been validated through the user feedback survey (see Appendix b). Furthermore, conceptual sketches, plans, models, diagrams, etc. generated for an international ideas-only competition, *Mooneption* (see Appendix c) have been used within the prototype of Retracer in order to illustrate the tool's application in the conceptual design process in architectural education.

Therefore, the proposed 'reflective communication and collaboration' framework is explored through the digital design learning tool, *Retracer*, that seeks to take on a more 'active' role of facilitating creative brainstorming sessions in conceptual design phases where students 'trace' and 'retrace' ideas during design thinking and making. Through an integrative, haptic and immersive interface for human-computer interaction, *Retracer* is envisioned as a portable and remotely accessible design studio space for students and novice practitioners. This can enable smoother and intuitive design workflows as they can readily access and review their previous design data within the virtual environment as though they are stepping back into their physical design workstations with a history of all their previous design explorations. However, these older iterations undergo a hierarchical structuring within the tool's intuitive design database that ensures 'enriched perception' (Goldschmidt 1991; Ward 2009) during the investigation of more design versions and alternatives (Goel 1995; Suwa and Tversky 1997) to address the same design problems.

Reflecting

This phase witnessed the construction of a theoretical framework that was fundamental in the proposal and development of 'reflective communication and collaboration' digital design learning systems for architecture pedagogy. Through theories of design 'thinking'(Brown 2008) and 'making' (Ingold 2013), 'reflection on practice' and 'backtalk cycle' (Schön 2008), 'tacit knowledge' (Polanyi 2009), 'design rationality' (Rittel 1988), 'phenomenology' (Merleau-Ponty 1962) and 'embodied spatial perceptions' (Pallasmaa 2009), 'design life space' (Wendler and Rogers 1995) and 'collaborative dimensions' (Bresciani 2019), the proposed tool gained valuable insights on the relevance of active reflection on design traces in the architectural design process.

At the onset of a design studio, students and instructors maintain a loose understanding of the design problems at hand as the student is yet to harness their tacit knowledge base and the instructor is yet to gauge and guide the student for explicit design learning activities (Polanyi 2009; Al-Qawasmi 2004). Hence, an explicit design knowledge base is built through reflection-on-practice where the student listens and responds to the design tasks at hand as well as the moves they make through the process of thinking and making (Schön 1987; Ingold 2013). Complementary to these intuitive modes of design learning, subjective judgements can be backed with logical reasoning and rational decisions made through the empirical science of design that transforms current undesired situations into preferred solutions (Simon 1969; Rittel 1988). Additionally, the research is also mindful of the metacognitive management skills required for novice practitioners to have a 'control' of their creative reflections during the messy and divergent conceptual design process (Kavousi, Miller, and Alexander 2019).

However, conventional design studio environments tend to emphasize individual design interventions for ease of teaching and evaluation which may deter their skills of collaboration with fellow students which is necessary for real-world architectural practice. Collective design thinking and making processes were investigated through a focus-group survey (see Appendix a) that was based on the theory of 'collaborative dimensions framework' (Bresciani 2019). The goal of this group reflection was to gauge the 'sweet spot' of the proposed design tool by incorporating user feedback on a radar graph with all the 7 collaborative design dimensions: (1) structural restrictiveness, (2) content modifiability, (3) directed focus, (4) perceived finishedness, (5) outcome clarity, (6) visual appeal, and (7) collaboration support. This qualitative survey helped formulate an average region of favorable values for each of the dimensions (see Figure 7) that are significant to conceptual architecture design in education as well as practice.

It was inferred that the more the structural restrictiveness through constricting visual templates, the more the directed focus toward common design goals as these dimensions are directly correlated. Also, dimensions of perceived finishedness and outcome clarity need to be maintained at a visual equilibrium in order to facilitate smoother communication of design ideas to culturally diverse groups without losing out on every individual's participation. Furthermore, during the discussions that followed the survey, the group agreed on the view that visual appeal is not an essential dimension that gravely impacts the conceptual design processes in architecture. Finally, the high ratings for content modifiability and collaborative support highlight that these two dimensions are the most relevant to measure while proposing and developing design thinking tools for architecture education and practice.

Another highlight of this research phase is a user feedback survey (see Appendix b) which was conducted to identify the feasibility, scope and limitations of the proposed design tool, modes and suggested workflows for conceptual design processes in architecture. The target audience for this user research were primarily architecture and design students, novice practitioners and instructors who are often licensed architects with at least 2 years of work experience in the AEC industry. Findings and follow-up discussions with participants have resulted in a positive reinforcement of the design tool's framework which is based on reflective and collaborative design processes within digital design learning environments. The survey was structured in an interrogative tone that seeks to clarify some assumptions in existing communities of practice in order to gauge user reactions on the proposed design workflow while ensuring the least amount of socio-cultural bias.

Results indicate that the progress and productivity of conceptual design workflows are dependent on (1) types of design tools, (2) methods of process documentation, (3) segregation and flexibility of workspaces, (4) project constraints, (5) socio-cultural and professional dynamics among design team members and (6) openness to adopt hybridized modes of design collaboration and communication. Questions on the relevance of maintaining an interactive design database, working collectively on a single interface with all design modes and, moving freely between individual and collective modes of design were validated due to their prevalently positive ratings.

Consequently, the 6 design modes, *Audio, Precedent, Sketch, Massing, Concept* and *Walkthrough* were well-received by students and practitioners alike who appreciated the opportunity to reflect on their preferred as well as conventional modes of conceptual design ideation. Although design modes such as *Sketch*, *Massing* and *Walkthrough* were direct in their respective applications in architectural design, *Audio*, *Precedent* and *Concept* design modes were observed as broad categorizations with multiple design methods that overlap across their boundaries. For example, *Precedent* mode was defined as a design mode that includes site surveys, photos, climatic analysis, etc. clubbed along with mood boards from case studies, previous projects, material catalogs and so on. This may create discrepancies in the observations made on conventional design protocols in popular architecture firms where site documentation is done during a 'pre-design' phase before the conceptual/schematic design phase (Chintis 2019).

Future Iterations

It is interesting to note that the user feedback survey has created a stable network of research participants who would be willing to contribute further feedback for future developments which could involve hands-on workshops and testing, primarily among architecture and design students. This is essential in a development research methodology for emerging technologies as the limited timeframe of a master's thesis does not permit extensive interactions to test the proposed tool with potential users. "Development research treatments, by contrast, are likely to last many days, weeks, or months. Rather than requesting permission to come into a classroom or training center for a few hours, instructional technology researchers and practitioners should enter into long term agreements to build prototype solutions together and study them rigorously. Funding agencies, whether government or private, must be prepared to support these collaborations for five years or more to expect useful results. None of these activities will be easy" (Reeves 2000).

An intended dissemination strategy was to set up an exhibition of the research-creation that would allow in-situ participation of potential users in testing the usability of the proposed tool, *Retracer*'s, current prototype. The layout of the exposition was envisioned to simulate the environment of an architecture studio with design tools and infrastructure that recreate the physical environment of collaborative design thinking and making processes. Additional promotional videos and descriptions were outlined for this exhibition which would have opened the discourse of reflective communication and collaboration in architectural design in the local practice scenario of Montréal. Therefore, future explorations of the tool would include community workshops and design charrettes for the proposed tool as the "interrelations that form a community of practice and its norms arise out of shared enterprise and engagement in practice and not some idealized view of community" (Lave and Wenger 1991).

However, presentations of the proposed tool have raised concerns of socio-cultural fabric and ideological biases of architectural design education and practice which is hard to capture in a digital design tool's user interface. "It is often argued that a major disadvantage of digital media is their inability to communicate cultural and symbolic meanings… (and rather) support commodification and globalization of cultures (in) favor of the 'image'" (Al-Qawasmi 2004) As a result, future iterations of *Retracer* would resist the tendency of approaching this problematic from a 'one-size-fits-all' approach and involve several revisions with interested architectural institutions who wish to embed their design identities into the tool's interface. In this regard, various additional features in the proposed tool's interface that localize and situate the design process can be incorporated either based on specific project constraints or overall design visions of the educational institution.

Nonetheless, this research is optimistic in enhancing studio pedagogy in architectural institutions by introducing the proposed design system by being mindful that the integration of "digital media (in design) do not enable without cost or change" (Al-Qawasmi 2005).

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Appendix a:

Focus Group Survey on Collaborative Dimensions Framework (Bresciani 2019)

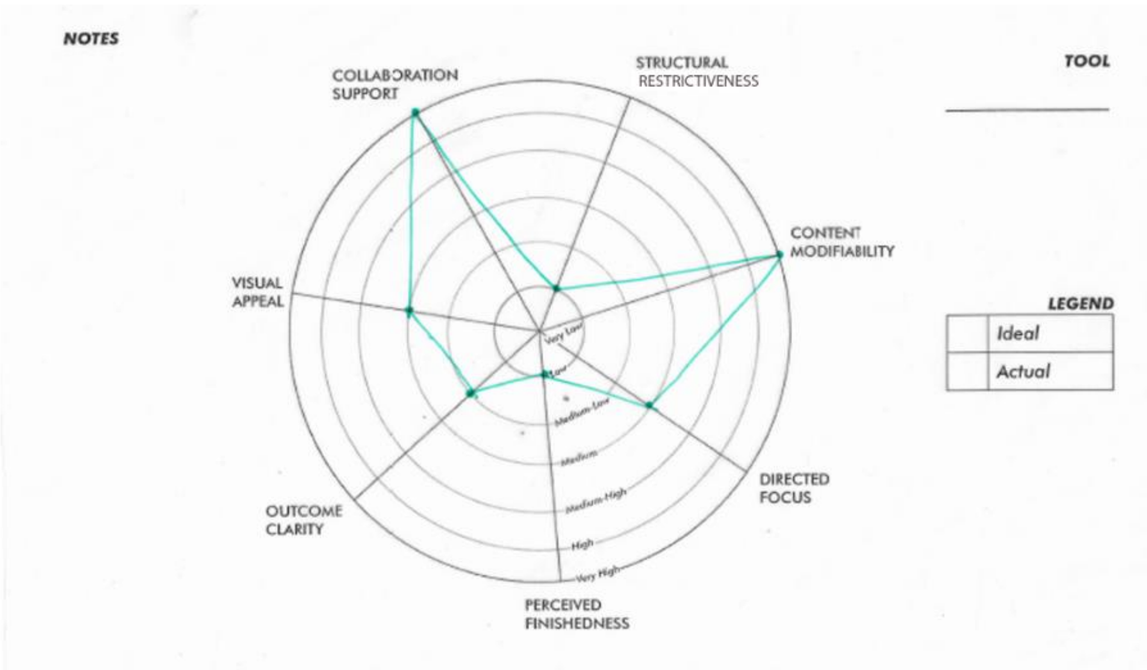

Figure 37: Focus-Group Survey: Radar Graph of Participant 1

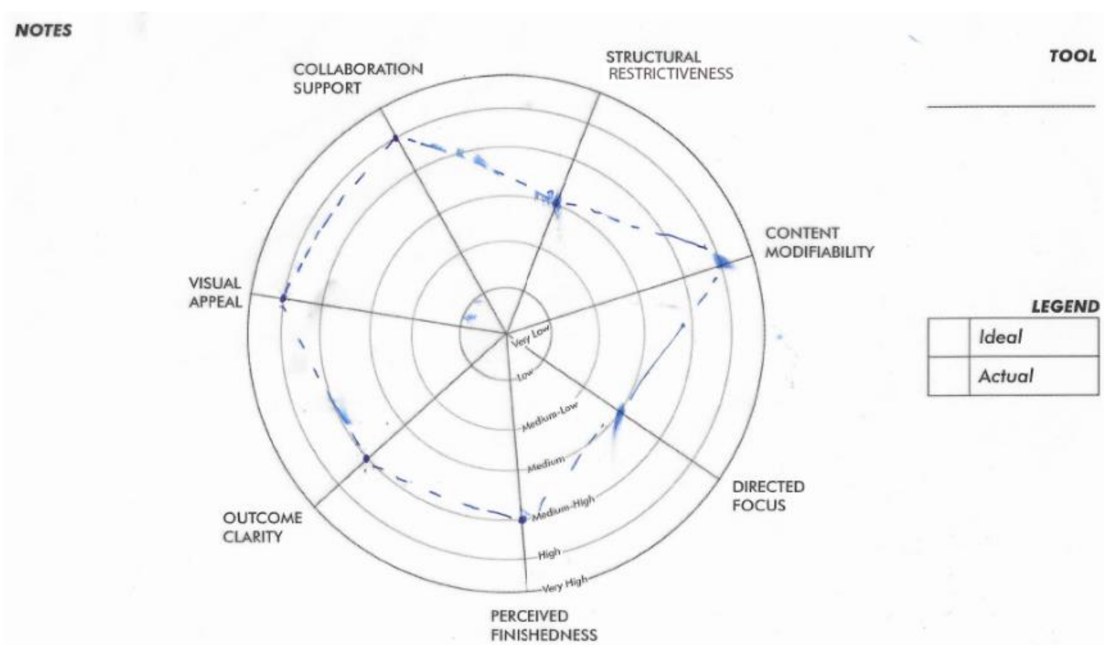

Figure 38: Focus-Group Survey: Radar Graph of Participant 2

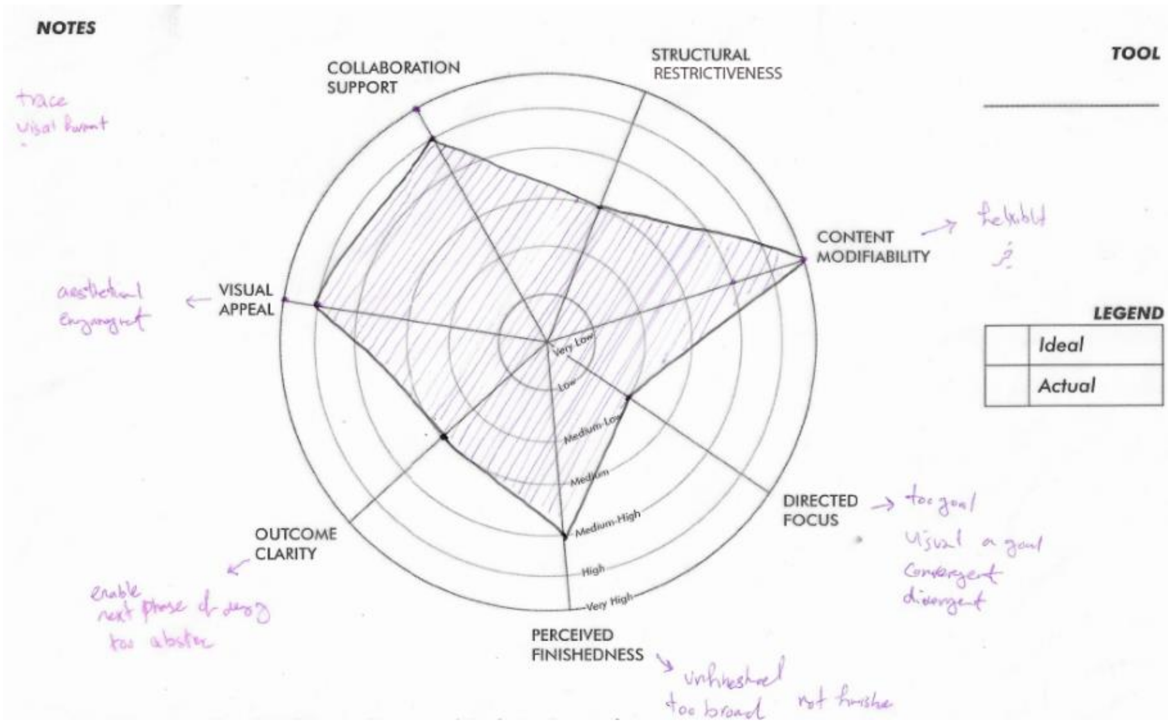

Figure 39: Focus-Group Survey: Radar Graph of Participant 3

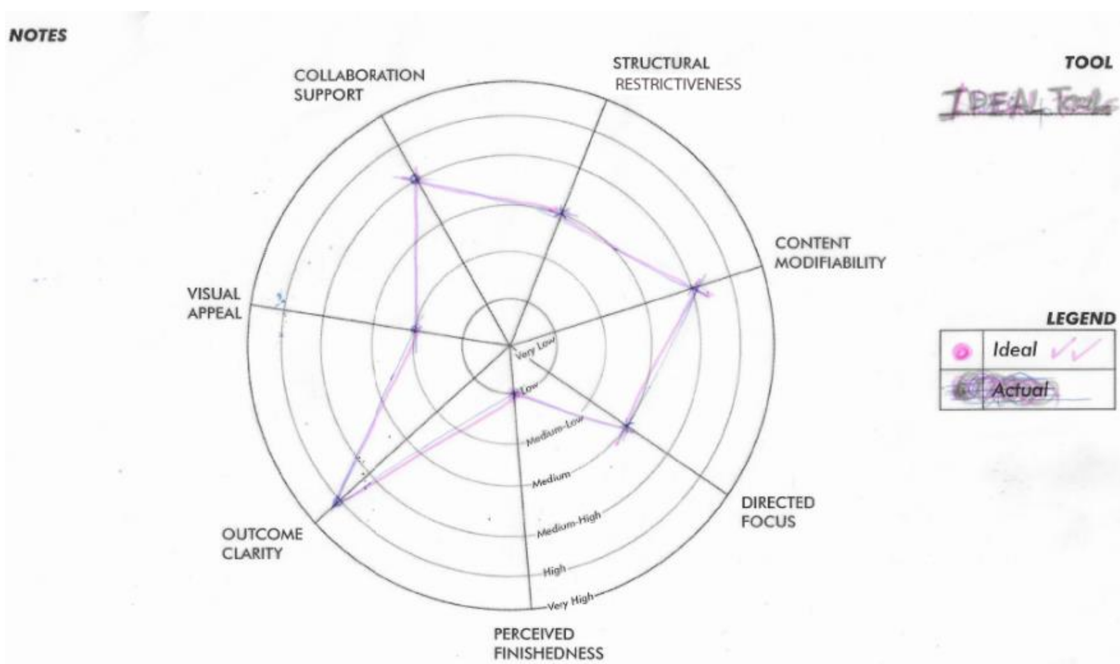

Figure 40: Focus-Group Survey: Radar Graph of Participant 4

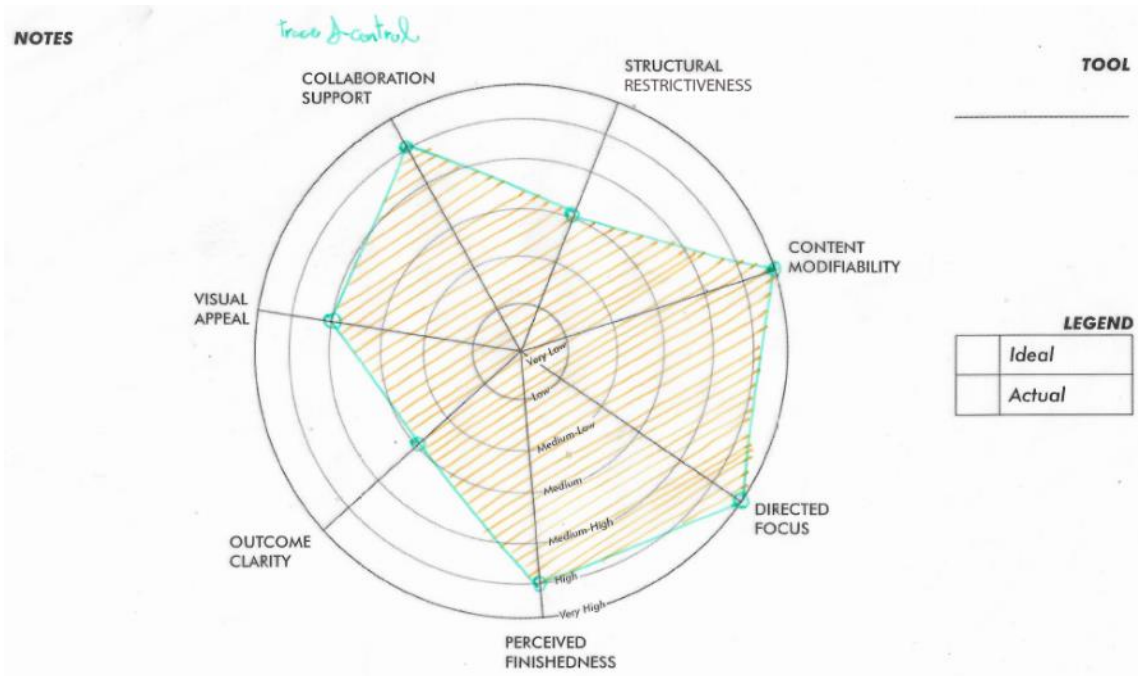

Figure 41: Focus-Group Survey: Radar Graph of Participant 5

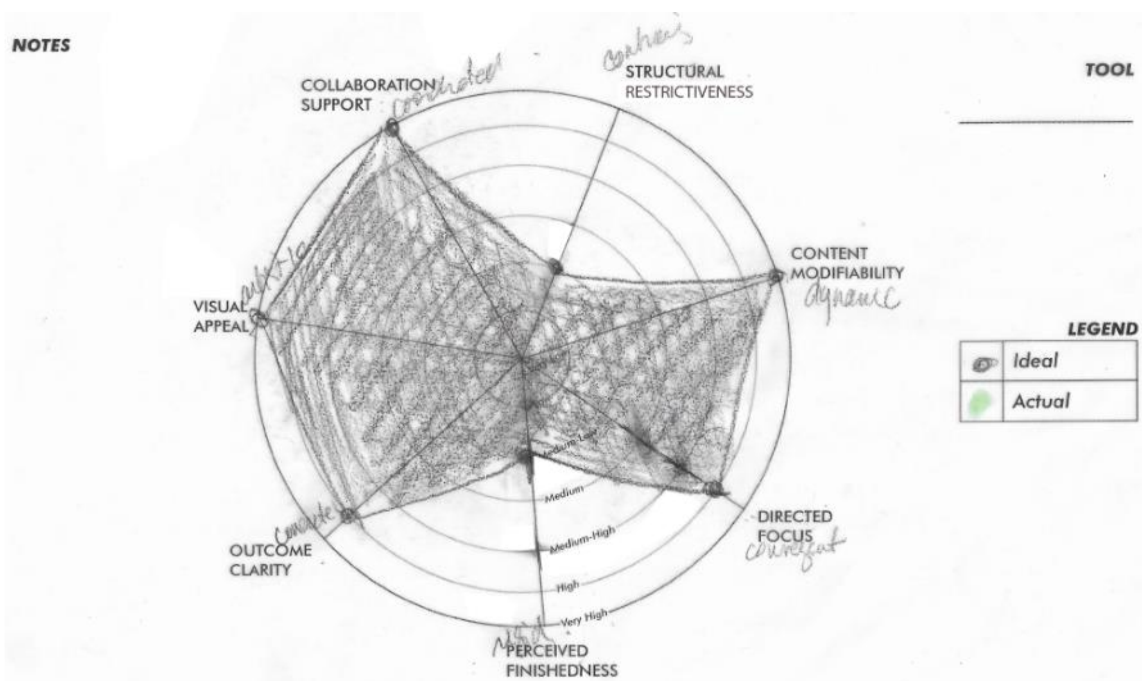

Figure 42: Focus-Group Survey: Radar Graph of Participant 6

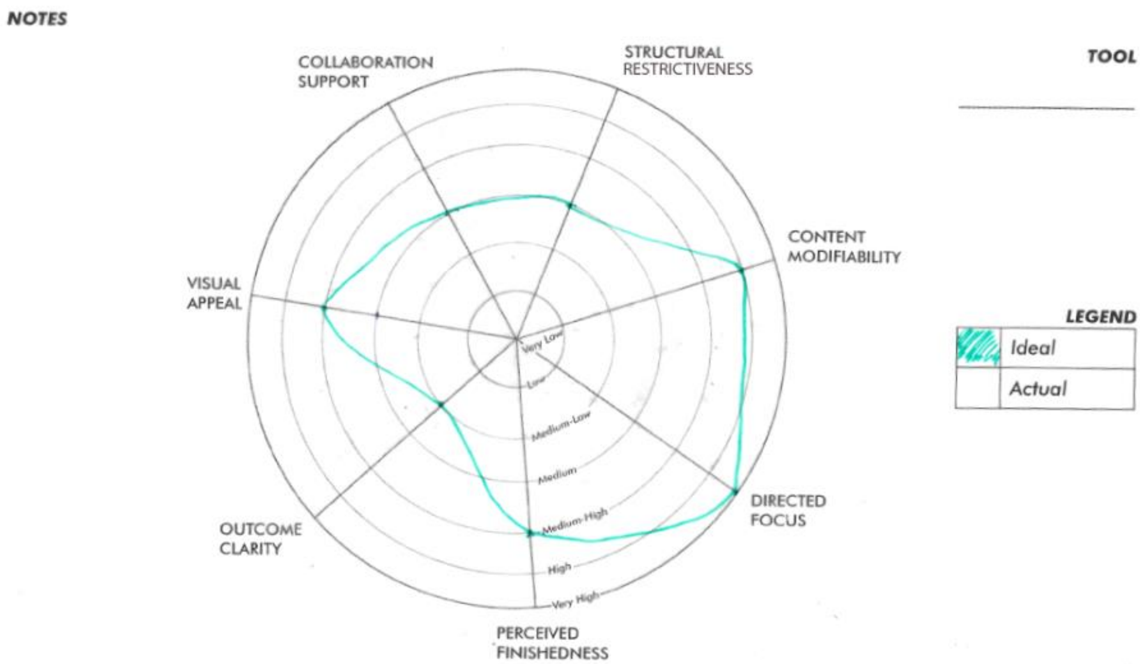

Figure 43: Focus-Group Survey: Radar Graph of Participant 7

Appendix b: User Feedback Survey Questionnaire (Google Forms)

Section 1 - General Information

1. Occupation (Choose only one)
    - Architecture Student
    - Design Student
    - Architecture Educator/Trainer
    - Architect
    - Designer
    - Intern Architect
    - Intern Designer
2. Years of Experience (Choose only one)
    - Studying(undergrad) - 1st/2nd/3rd year
    - Studying(undergrad) - 4th/5th year
    - Studying(master's) - 1st/2nd year
    - Teaching - 0-3 years
    - Teaching - 3-5 years
    - Teaching - 5-15 years
    - Teaching - 15+ years
    - Practicing - 0-3 years
    - Practicing - 3-5 years
    - Practicing - 5-15 years
    - Practicing - 15+ years
3. Do you often design individually or collectively in a design team? (Choose only one)
    - Individual
    - Collective
4. Are you and your clients, instructors, and/or team members situated locally, remotely or both? (Choose only one)
    - Local
    - Remote
    - Both
5. Do you think the type of tools you design with can affect the speed and quality of your design workflow? (On a spectrum of 1 to 5)
    - 1 = Not Really (design workflow is independent of chosen types of design tools)
    - 5 = Very Much (design workflow is largely dependent on the right choice of types of design tools)
6. What are the types of methods/tools that enable your preferred design workflow? (Select multiple)
    - Verbal descriptions of concepts
    - Schematic diagrams such as flow charts, adjacency matrices, bubble diagrams, activity mapping, etc.
    - Quick hand-drawn sketches
    - Basic 2D/3D CAD designs (AutoCAD, SketchUp, 3dsMax, Adobe Photoshop, etc.)
    - VR - Virtual reality tours of previous project models/current project mockups

- AR - Augmented reality tours of previous project models/current project mockups
- Quick sculpting/model-making
- Rough moodboard/catalog with images, patterns, materials, fabrication methods, etc.
- Quick simulations through film animation
- Templates such as ergonomic silhouettes, modular design blocks of furniture, vegetation, etc.
- Other (please specify)

Section 2 - Design Workflow

1. Do you think it is important to have a database of the evolution of your design ideas in order to generate more? (On a spectrum of 1 to 5)
   - 1 = Not Necessary (does not impact the design process)
   - 5 = Very Necessary (highly impacts the design process)
2. While working collectively, do you think it is necessary for all collaborators to have access to a single interface that allows simultaneous generation of ideas? (On a spectrum of 1 to 5)
   - 1 = Not Necessary (better to work individually on separate interfaces and/or design data)
   - 5 = Very Necessary (better to work together on single interface and/or design data)
3. Do you believe it is necessary to track individual contributions of a collective workflow in the design database? (On a spectrum of 1 to 5)
   - 1 = Not Necessary (tracking individual contributions are irrelevant to the design database)
   - 5 = Very Necessary (tracking individual contributions are very relevant to the design database)
4. Within an ongoing design session, do you think it is essential to switch freely between individual (private) and collective (semi-public) design workflow? (On a spectrum of 1 to 5)
   - 1 = Not Really (prefer to stay either in private or in semi-public workflow throughout a design session)
   - 5 = Very Much (prefer to switch between private and semi-public workflow during a design session)
5. What are the challenges you face during these sessions? (Select multiple)
   - Difficulties in documenting ideas generated/evolved
   - Ambiguous knowledge of architecture, engineering and construction industry
   - Unable to track frequent changes made to discussed designs
   - Unbalanced design authority over proposed spaces
   - Misunderstanding of concepts or definitions
   - Other (please specify)
6. Select one or a combination of the following proposed ‘design modes’ that best describes your conceptual design workflow. (Select multiple)
   - Audio: Verbal discussions with peers/instructors/clients, etc. that are recorded for design reference

- Precedent: Data collection and review of images (including site), diagrams, literature, etc. that act as case studies and sources of design inspiration
- Concept: Idea extraction from Audio and Precedent modes that inform the design principles and concepts for the specific design problem
- Sketch: Quick and rough compositions made from perspective or orthographic drawings and other 2D representations (including annotations) of the ideas discussed and generated,
- Massing: Basic volumetric solid/void explorations of the design ideas with or without site details, labels, scale figures, shadows, etc.
- Walkthrough: 'On-the-fly' field notes of site visit(s) transcribed either on paper/device for future manual documentation or using AR and/or VR directly over real-time visual data of the design site such as photos, short/long video segments, etc.
- Other (please specify)

7. Please specify your usual pattern of design workflow using the above design modes. (Short answer)
8. Do you think having ALL the design modes in a single interface benefits the design workflow? (On a spectrum of 1 to 5)
    - 1 = Not Really (design modes in single or multiple interfaces does not affect/negatively impacts design workflow)
    - 5 = Very Much (design modes in single interface positively impacts design workflow)
9. Does the workflow pattern alter based on your design team and/or project constraints? (On a spectrum of 1 to 5)
    - 1 = Not Much (design workflow is independent of the team and/or project)
    - 5 = Very Much (design workflow is largely dependent on the team and/or project)

Appendix c: Conceptual Design Process in International Open Ideas Competition

In July 2019, *Mooncеption* was an international ideas-only architectural competition organized by Volume Zero, a digital platform for architecture design curated by a team of architects based in Mumbai, India. Generating both analog and digital design ideas for this highly speculative design competition served as the perfect venue to critically explore the flow of conceptual design processes as an architecture student doing practice-led research. According to the competition's design brief, the participants were urged to design a human civilization on the Moon to relocate from Earth in the near future (see Figures 44 to 46).

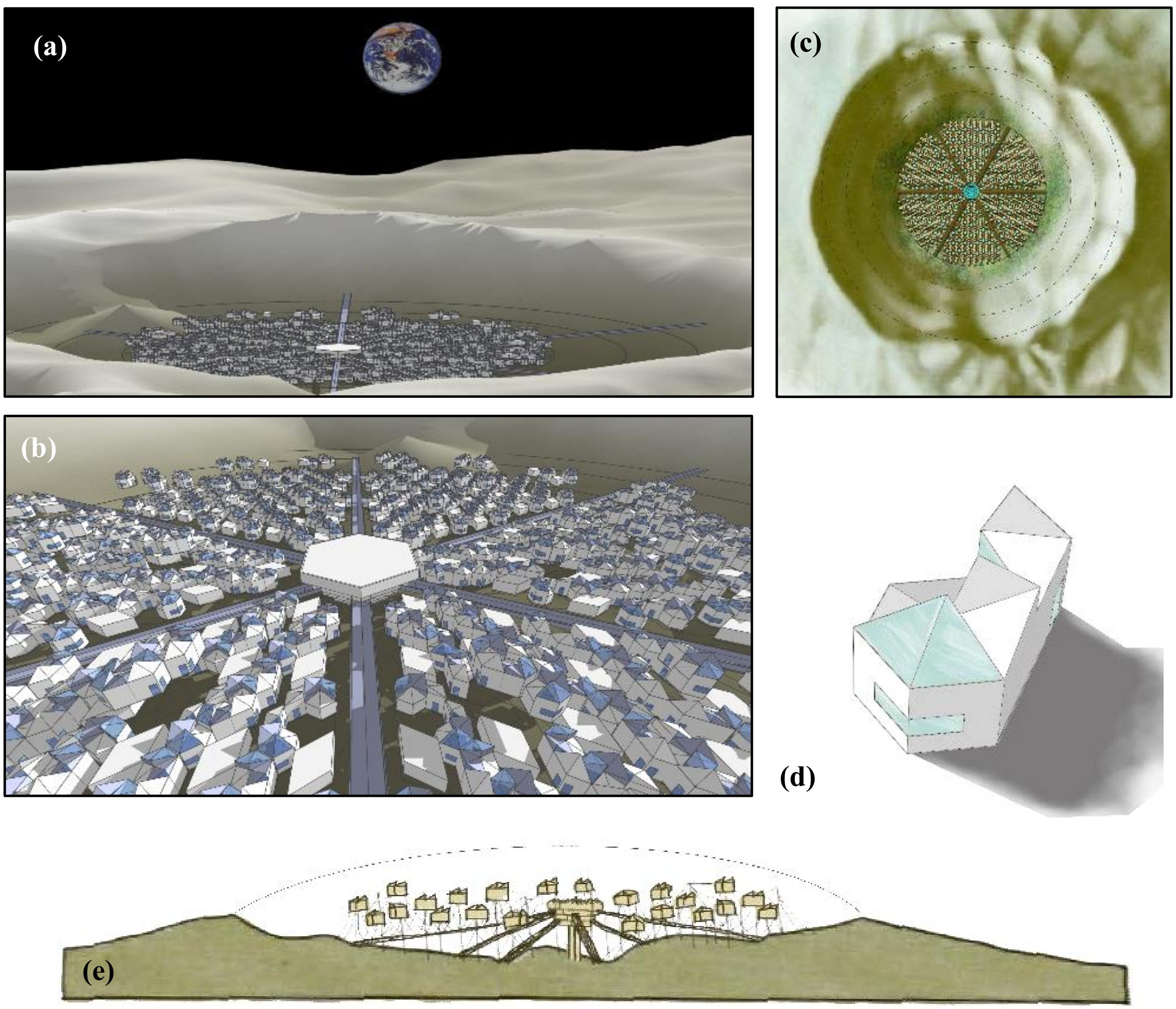

Figure 44: Conceptual designs of ideas-only architecture competition, 'Mooncеption' - (a)Rendered 3D view of proposed habitat on the Moon, (b) Closer isometric view of proposed colony, (c) Site plan of proposed colony, (d) 3D model of one household module, (e) Section of Moon's crater and the proposed colony

This prompt enabled non-linear and divergent design thinking using the 6 proposed design modes (see Figure 45) as it was necessary to rethink the basic spatial livability paradigms on Earth to best suit those on lunar terrain where the relationship between built space and gravitational forces is overwhelmingly apparent. The design exercise was essential in order to navigate through the complexities of a conceptual design process in speculative architecture and trace the path taken across each of the design modes to arrive at satisfactory results.

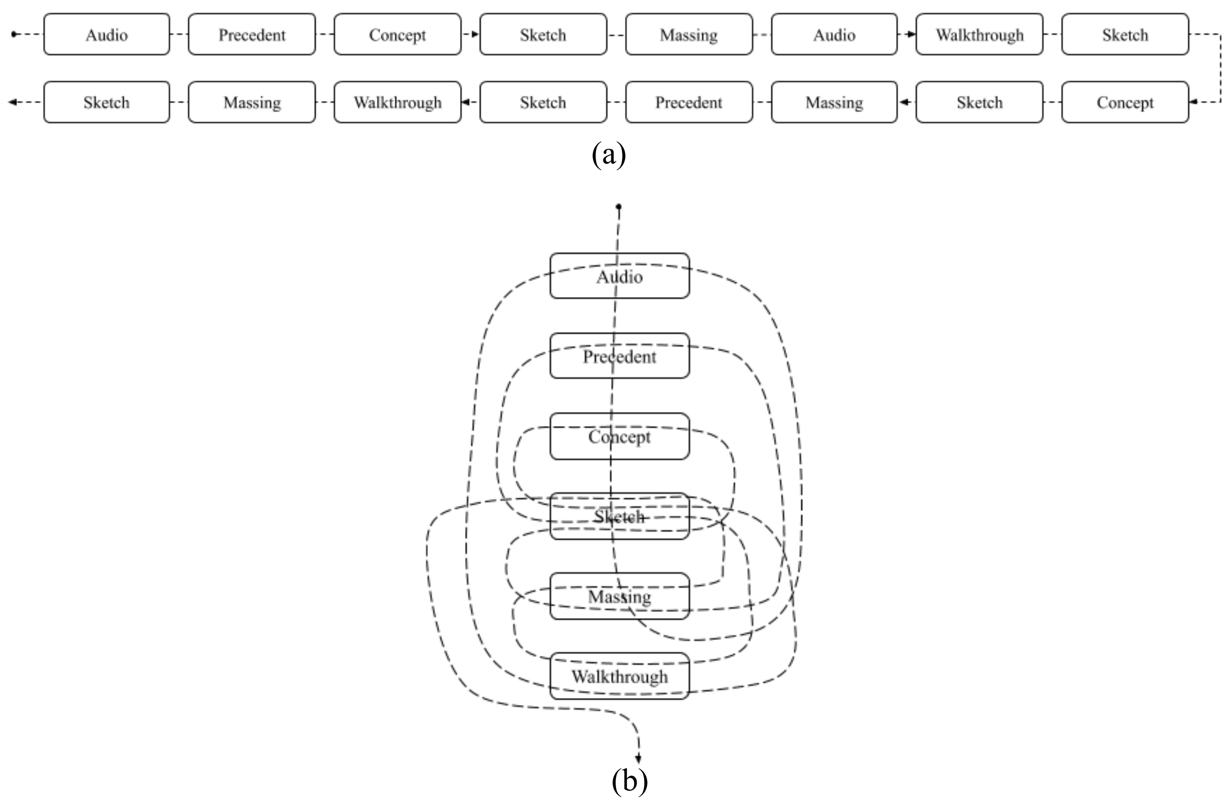

Figure 45: (a) Linear mapping of design modes and workflow during conceptual design process of 'Mooneption', (b) Non-linear tracing of the ame design modes and workflow

Audio, Precedent and Concept modes included research of basic infrastructural elements in spaceships in order to propose self-sustaining spaces in accordance to the competition's prompts using Sketch, Massing and Walkthrough modes. The Lunar Experience and Research Centre was placed at the centre in a radial pattern for the habitat which would be initiated by the first human expedition team of 10 tourists and 5 researchers. The spaces for the program included areas for socializing, resting, cooking, researching, controlled farming, exhibition, storing resources, and experimentation among basic amenities such as areas for sanitation and medical care. These spaces were arranged based on the adjacency matrix derived from one of the Concept design modes during the design process (see Figure 46(f)).

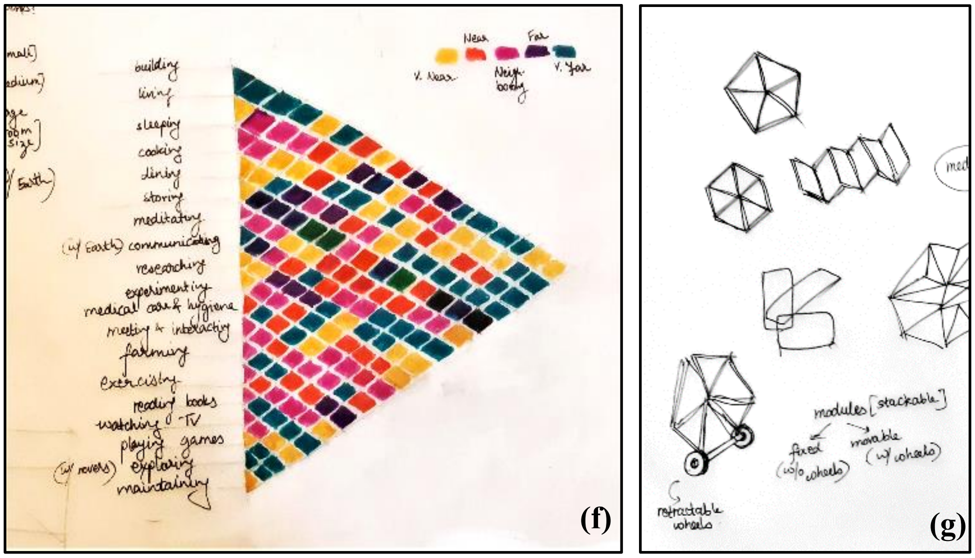

Figure 46: Conceptual designs of 'Mooneption' - (f) Adjacency matrix of the activities identified, (g) Rough sketches of structural framework for individual household modules

The design process was research intensive, digging up and assimilating as much literature on outer space habitation as possible while designing flexible building prototypes within a limited timeframe (see Figure 46(g)). By breaking down the types of drawings required to convey the design, the project took on a reflective approach after brainstorming all possible speculations on habitation scenarios. While it is essential to build a foundation of climatic and material data on the moon, the research was primarily oriented on gaining as much insight on human-moon encounters in the Audio modes through astronaut testimonies from renowned space agencies such as NASA and JAXA. Further into the design process, various socio-cultural assumptions were made while trying to build a utopian of life by defining spatial relations of mutual habitation. However, the future of human habitation severely relies on its designers to envision the most utopian of utopias in order to breathe life to design realities.