EMPOWERING SPACES: CUSTOMIZABLE FURNITURE SOLUTIONS FOR TORONTO'S MOBILE COMMUNITIES

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ABSTRACT

The paper tries to investigate the influence of parametric design tools and digital fabrication to create customizable furniture solutions for Toronto's mobile communities like International Students and Non-resident working class. The recent investigations done in the field of parametric design tools focuses on things like how it makes the designer creative or creating products that are never ideated alongside the end user and their precise needs. The problem is that modularity, multiple purposes and customizability is being brought into the market without bringing the end user to the designing table. The methods used in this paper are based on human centred design approaches of co-design with the end user to create prototypes which can then be analysed by user testing to gather feedback and create iterations to better computational or generative algorithms. This study found evidence that algorithms created for customization of furniture by involving the end user at every step of the stage creates solutions that have intuitive use cases which the intent for was never there. What emerged are customizations that can help produce preferences for the end user at hand to provide agency in their daily activities. The research provided the base of what kind of customizations can be desired by the end user and how a rigorous study can be conducted after this exploratory research to better optimize the algorithms and also the user interface of how the customizations can be done by the end user.

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1. INTRODUCTION

Approximately one-fourth of Canada's international students study in Toronto, and their presence adds to existing diversity on campuses and in communities. International student enrolment in Toronto's public post-secondary institutions has risen dramatically; the number of international undergraduate and Master's level students more than doubled in the City of Toronto's four universities between 2006 and 2015. It also more than doubled in Toronto's four public colleges between 2009 and 2015, growing from 10% of the college student population to 21% for this period (Wayland & Hyman, 2018).

In 2014 the Canadian government under Prime Minister Stephen Harper released its International Education Strategy which set a goal of doubling the number of international students studying in Canada to 450,000 by 2022 (Wayland & Hyman, 2018).

Recent insights highlight that international students in Toronto face significant challenges in finding furniture that meets their needs and aligns with the constraints of rental spaces over other things. This issue is compounded by the housing crisis in Toronto, where student accommodations are often inadequate or overpriced. Shared housing and converted residences are frequently overcrowded and suboptimal for the diverse needs of students, especially international ones who lack the option of commuting from family homes (Lorinc, 2024).

Furniture rental services have emerged as a potential solution for international students. They offer flexible options tailored to temporary housing situations, minimizing the burden of purchasing, transporting, and assembling furniture. Companies like BARD Furniture is one example for furniture rentals but the issue again comes up to the fact that their average plan costs an additional 75 CAD per month which again on top of rent, utilities, food expenses and tuition fees becomes an added expense which everyone cannot pay for 2 to 4 years (BARD, 2024).

Universities and the city of Toronto have yet to make significant progress in addressing student housing needs comprehensively, leaving many to navigate a market ill-suited to their requirements. There is a pressing need for inclusive design solutions that consider the

adaptability, customizability and multifunctionality of furniture for small and diverse rental spaces.

The World is slowly starting to realize how Universal Design does not cater to the needs of every individual in a way that it is adaptable enough to enhance the lives of a diverse group of people. One size fits all is slowly starting to diminish in our vast World filled with countless preferences, ideologies and ways of life. People in todays age and world want everything in a way that does not compromise their needs because they understand the shift in technological advancements has the ability to provide them with that. Everyone will benefit if design is looked from a perspective of one size fits one (Inclusive Design Research Centre, n.d.). Because of this perspective shift, the future of products needs to shift towards customizability where it can be adapted to every individuals need. The world is acknowledging the emerging technologies at such a fast pace. So, why not use it to better our designs. Knowing computational capabilities, understanding how furniture can be made customizable or adaptable by having various iterations available at the movement of a slider (Inclusive Design Research Center, n.d.).

The group of designers and researchers who use this approach call for "one size fits one" solutions over "one size fits all." At the same time, they acknowledge that "segregated solutions" are technically and economically unsustainable. They argue that, at least in the digital domain, adaptive design enables personalization and flexible configuration of shared core objects, tools, platforms, and systems provides a path out of the tension between the diverse needs of individual users and the economic advantages of a large-scale user base. (Costanza-Chock, 2020)

Since the digital world is capable of storing all kinds of data that can enable personalization and the physical world is capable of transforming that data into real objects using digital fabrication techniques like 3D printing and laser cutting, computational thinking and generative algorithms are a good way to create integrated systems where one can work with the physical and digital realm to achieve inclusive and adaptable solutions (Richard & Giri, 2019).

This is where computational design comes in. Computational design is a computer-aided design (CAD) method that uses a combination of algorithms and parameters to automatically compute a product’s structure.

It’s not artificial intelligence (AI) in that the software doesn’t make choices or learn, but computational design can leverage AI techniques and tools, such as generative algorithms, evolutionary optimization, and machine learning, to enhance the design process and create more efficient, innovative, and bespoke solutions.

With computation design, a model is produced by adding numerical values to predefined parameters. The designer does not draw or apply shapes. Unlike traditional static design, a computational design is fluid and dynamic, meaning that it can be continuously altered by inputting new data. Each new piece of data can affect all the other pieces of data by establishing various relationships between the parameters (Lee, 2023).

Based on this background, the purpose of this research is to is to combine adaptability, modularity, customizability, flexibility and multi-purposeness in furniture design using computational tools which can then be digitally fabricated to be used by the end user. The idea is to understand the needs of International Students living in a rental space to ease their lifestyle economically and functionally. The research will aim to create algorithms in computational design tools which can generate 2D or 3D information that can be used for digital fabrication to generate informed design which would give a user the ability to customize the space they live in according to their preferences.

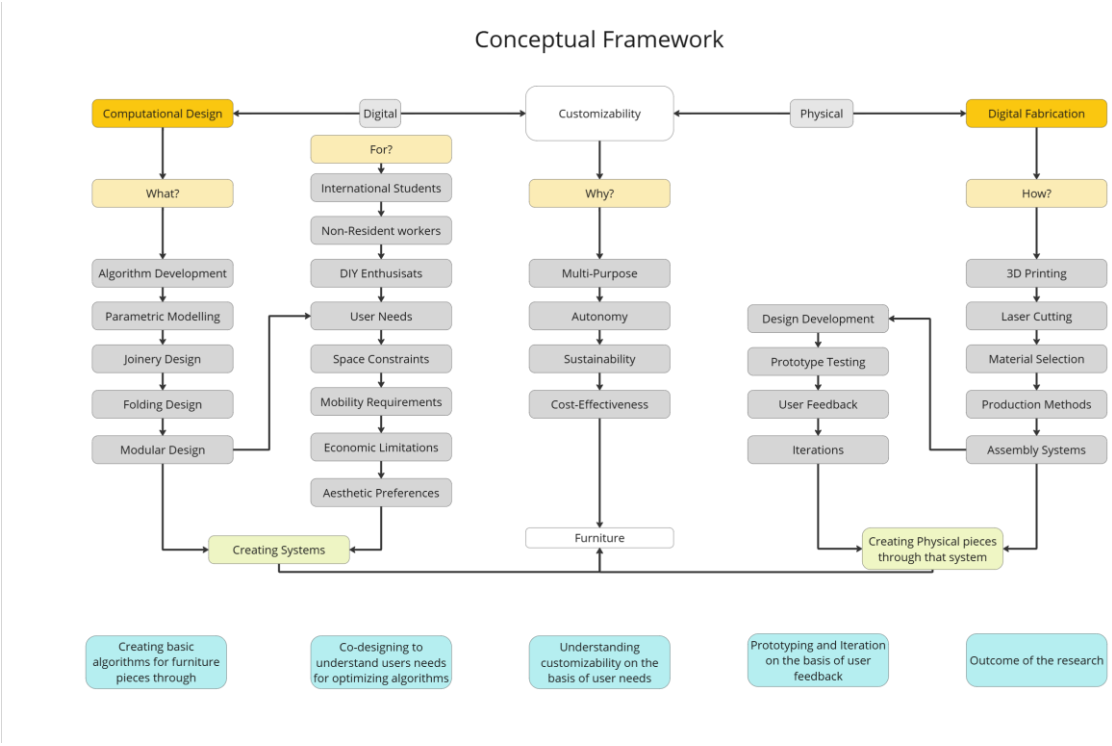


Figure 1 - Conceptual Framework

2. CASE STUDIES

2.1. HUMAN CENTRED DESIGN VS PROJECT BRIEF DRIVEN MODEL

In the field of architecture, interior design and furniture design which spans from macro to micro scales, design education has traditionally adhered to a project brief driven model. In this approach, information about users and environmental context is typically gathered only and the beginning of the design process. This information serves primarily as a background and the design decisions are often guided by the student's or instructor's personal interpretation of the problem. The evaluation stage relies heavily on feedback from peers and lectures without any usability testing. This form of learning maintains a disconnect between designers and the real-world users. Thus, design outputs have often remained as conceptual ideas which are suitable for portfolios, exhibitions or design competitions. These ideas lack tangible social impacts, which limits opportunities for students to critically reflect on the social relevance and real-world applicability of their work. This limits the potential for the students design to make a meaningful contribution to society and the built environment. (Thamrin, Wardani, Natadjaja, & Sitindjak, 2018).

By cultivating a collaborative relationship with local communities, community-based learning puts forth the cumulative nature of design and planning, and highlights relationship building rather than merely goal accomplishment (Hou, 2007). As (Salama & Wilkinson, 2007) put it, 'The most important purpose of community design and participation is not only good buildings and environments, but good citizens in a society.'

(Narenthiran, Torero, & Woodrow, 2022) conducted a mixed-methods study at a large UK university to investigate how students and staff adapted their home environments for remote work and study during and after COVID-19 pandemic. Traditional accessible design often focuses on mobility impairments and the author suggests that the scope should be expanded to include mental health and neurodivergent conditions, thus, emphasizing the need for more inclusive design workspace.

The study distributed a survey to two primary groups which comprised of students and staff (n=60), of which 88% were students and a specialized sample of 15 staff members who identified as neurodivergent or disabled. Participants shared their experiences of modifying their home workspaces, the barriers they continued to face, and features that supported their wellbeing and productivity.

Key findings indicated that majority of students worked from their bedrooms. The dominant factors that influenced the workspace satisfaction included furniture, lighting, thermal comfort and acoustics. For most participants, the lack of separation between work and relaxation spaces negatively impacted mental health.

The authors also asked respondents about changes made in their living spaces over the past year with majority participants selecting furniture. The aim of doing these changes was to become more motivated and concentrated to study and improving their overall work efficiency. This showcases the importance of modular and collapsible furniture where in certain parts can be changed according to changing preferences without changing the whole piece of furniture. For instance, new tabletops with different dimensions or textures can be bought without buying the legs for the table again so that the tabletop can be interchanged.

The barriers that continue to exist within their space were furniture, the participants found it hard to work in the same space they sleep because of no distinction between work and relaxation in addition to not having enough space in furniture to be organised the way they would want which could be another option for customizability in furniture pieces. The participants find furniture and lighting to be the most important to their wellbeing within that space. Next, participants were asked about adaptability and flexibility of their spaces to which participants described their space as not adaptable. This was largely related to the furniture within the space and the limited flexibility caused by fixed room sizes, including issues such as "limited configurations," "using furniture to compartmentalize," and "restrictive space for moving furniture."

Narenthiran, Torero, and Woodrow (2022) highlight that designing for wellbeing is largely absent from existing building regulation documents. A review of these documents found no occurrences of key terms such as "wellbeing" or "mental health." Similarly, terms representing non-visible disabilities, including "autism" and "dyslexia," were also absent, underscoring the

lack of mandatory guidance for non-visible conditions. The study further examined the distribution of "visible" and "non-visible" disabilities—referring to mobility and mental health conditions, respectively—and found that among working-age adults (16–64 years), 42% reported a mental health condition. Notably, the reported conditions did not total 100%, suggesting that many respondents identified with multiple disabilities, thereby reinforcing the need for an intersectional approach to inclusive workspace design.

According to Dixon, Smith, and Touchet (2018), people are disabled not by their impairments or differences, but by the barriers present in society. The barriers can be physical (lack of accessible toilets). It is necessary to overcome these barriers to create equality and offering disabled individuals greater independence, choice and control.

Many Neurodivergent individuals experience sensory sensitivities that affect their interaction with built environments. These sensitivities include hypersensitivity to certain textures, patterns and colors which can lead to discomfort, distraction, or even distress. For instance, high-contrast patterns or visually noisy environments can be overwhelming for neurodivergent students, while specific textures may cause tactile discomfort (Slocombe, n.a).

Thus, a key principle of design is to create spaces where such barriers are removed. One way to achieve this is by offering individual the option to customize the furniture pieces before buying, allowing them to select colors, textures, forms, and dimensions that best support their comfort and productivity. Providing such feature ensures meets the need of the users and caters to maximum productivity in their everyday life in all fronts.

2.2 CUSTOMIZATION

Customization has been part of product design since the beginning of time, initially through hand production and later through machines. Essential goods such as clothing and furniture were made locally to meet the specific needs of individuals and spaces. Craftsmen served as key members of their communities and consumers could easily communicate their requirements directly to the craftsmen. However, the Industrial Revolution changed production and consumption by introducing mass production that were then distributed across the country. Consumers were

exposed to new designs and trends through catalogues and newspapers. Brand name items became popular because they were perceived as advanced in design and trend, but they were no longer tailored for an individual user. (Johnson, 2020). One such example is Sears, they offered prefabricated homes in their catalog in 1894 (Stevenson & Jandl, 1995). In recent times, there has been a growing dissatisfaction with standardized mass produced, and an increased demand for unique, one-of-a-kind goods. The rise of the internet has facilitated direct, immediate communication between customers and producers, allowing customization to re-emerge as a major trend (Johnson, 2020). Furthermore, with the development of digital fabrication technologies, people can customize products on the internet in real time which can then be digitally fabricated at home.

(Flynn & Vencat, 2012) argue that the growing shift towards for personal customization in product design "is so enormous and all-encompassing that it ultimately promises to define the coming decades as powerfully as the Industrial Revolution defined the nineteenth and twentieth centuries." Outside of material goods, society has been adjusting to a more customizable life through businesses such as Netflix, which curate personalized recommendation lists based on users' viewing habits, and Pandora, creates customized playlists for their users.

Current projections indicate that the trend toward a customized economy within the furniture industry will continue to expand. In response to increasing international market competition, manufacturers are expected to increasingly adopt built-to-order models, with customization offering added value to domestically produced goods (Schuler & Buehlmann, 2002). A study by Lihra Torsten, Urs Buehlmann and Robert Beauregard (2008), three experts in the wood furniture industry—found that price is not always the most critical factor for consumers when purchasing new furniture. This research team found that customization, customer service, and delivery times were three of the most important factors in purchasing. When surveying furniture manufacturers, Torsten, Buehlmann and Beauregard found that 21 out of the 23 companies believed that with customization, products could be sold at higher prices. When asked about which types of customization customers appreciate most, they responded by saying that color, finish, and dimensions were the top three factors their customers responded to. Hardware options and a variety of configurations were also viewed as valuable traits (Lihra, Beuhlmann, & Beauregard, 2008). Millennials view themselves as confident, open minded and wanting to express

themselves uniquely through their social media and the products they purchase. They are drawn to distinctive brands that offer products that reflect their own traits and serve as a form of self-expression (Valentine & Powers, 2013).

In ‘Mass Customization: The New Frontier In Business Competition’, Joseph Pine defines mass customization as “a process by which firms in different industries apply technology and management methods to provide variety and customization through flexible production and quick responsiveness.” The goal of mass customization (MC) is to offer enough variety in a company’s product assortment for everyone to find exactly what they want (Pine, 1993).

Besides being able to create unique products that reflect their personal tastes, international students and non-resident working class want to be able to customize products for their own needs. Echoing this emphasis on user-centered design, Dieter Rams, a renowned industrial designer, argues that after quality, usability is the most critical attribute of a product. He asserts that products should be "adaptable to their owners' wishes and changeable when requirements change" (Rams, 1995), further reinforcing the importance of flexibility and personalization in contemporary product design.

As outlined in the introduction, international students are moving to Toronto at an unprecedented rate. Due to rising cost of living, many are moving into smaller living spaces than they had lived in previously. As a result, there is an increasing demand for products, particularly furniture, that can adapt to their changing lives and living spaces. Furniture selection is influenced by the space available and the proportions of the overall living environment. Following the shifting trends and their changing needs, furnishings would be most functional and least expendable if they were designed to be more modular, systemized, customizable, longevity.

3. METHODOLOGY

The aim of this study is to understand the needs of migrants in Toronto like International Students and non-resident working class in the realm of furniture design to better understand how the furniture used in their rental spaces could be better optimized to be customizable according to their varying needs using generative algorithms. The customization for those furniture pieces will be controlled by parametric algorithms created in Grasshopper and the main purpose to gather data on the living preferences of those migrants will be to optimize the algorithms as much as possible so the end user can benefit from them by customizing the furniture pieces according to their living space, preferences and visible or invisible disabilities before buying them. The method used in this study is similar to a study carried out in 2018 titled 'Experiential learning through community co-design in Interior design pedagogy'. The researchers used participatory design by involving the community they were designing for in the design process. Even though the research produced satisfactory results in understanding the communities needs and coming up with a solution that is carefully crafted for them, it remained a one-off solution where the whole process will have to be repeated if it has to be recreated for a similar or another community depending upon their site conditions or dimensions and other factors. So, the additional solution being tested out in this research is the addition of using automation through digital fabrication and parametric algorithms by using results from participatory or cooperative design to be turned into generative algorithms which can be used by a similar kind of end user again and again by choosing customizable options that suit their needs better.

In this study, a mix of qualitative and quantitative methods have been used. The qualitative method of co-design has been used to understand the users better. (Sanders & Stappers, 2008) describe 'co-design' as an activity where the creativity is accomplished collectively. So, the way co-design sessions work is that the researchers, intended users and experts come together and co-operate as participants to come up with creative solutions in the design process (Steen, Manschot, & Koning, 2011). Following a generalized brief feels outdated in the current trends of the world of design so, designers bring the target user and experts together to become a part of

the creative process. (Spinuzzi, 2005) outlined 3 stages of co-design research as shown in Table 1.

Table 1 - Methodology of cooperative or participatory design

S.NO.	STAGE	METHODOLOGY
1.	Initial exploration	• Designers familiarise themselves with users and the work environment. • Ethnographic studies on user site involving designers to empathise with user's daily settings, habits and problems.
2.	Discovery process	• Active interaction between designer-user-expert. • Collaborative setting up of goals, ideas and design concepts.
3.	Prototyping	• Collaborative and iterative shaping of artefacts using various prototypes. • Results are discussed in forms that users can understand and share.

The quantitative method is the use of generative parametric algorithms which can help create multiple iterations of design feedback gathered by just one co-design session. So, the whole idea is to qualitatively create design processes with intended users which can have multiple iterations for different preferences and uses through generative algorithms, hence the customization.

The design process for this study required it to be very iterative so the inspiration was taken from Stanford School of Design which consisted of six stages: understand, observe, point of view, ideate, prototype and test (Carroll, Goldman, Britos, Koh, & Royalty, 2010). The design process can be amalgamated with the 3 stages of co-design identified by (Spinuzzi, 2005) showcased in Table 1. The plan of action while carrying out all the six stages of design processes revolved around the human-centred designed studies.

The first stage of understand-observe initiates with autoethnography by a student researcher who is an International Student to create initial basic algorithms. After that, potential participants are asked to fill an online screening survey on Microsoft Forms which is showcased in Appendix A. The eligible participants sign a consent form which contains all the information of the study. The

participants then answer an online semi-structured interview on Microsoft Forms which can be seen in Appendix B. This is done to prepare the researchers with some information for a fruitful co-design session with the participants. After which phenomenological studies with participants will be done through one-on-one co-design sessions to use criterion sampling to understand their experience with the topic under study. The facilitation guide for co-design sessions can be seen in Appendix C. This allows the researchers to understand how participants who have shared a way of life can vary in their individual outlook or experience towards it (Moser & Korstjens, 2018).

The second stage of point of view – ideation will involve the preferences gathered by understanding every participant's lived experience to be used for optimizing the basic algorithms created during autoethnography or create new ones depending upon the themes emerging from inductively coding the transcripts of every co-design session. These generative algorithms address to the individual needs and preferences of users that standardization cannot address. The need for mass customization is catered by these generative design tools like grasshopper which allows iterations of diversified solutions using automation (Raposo, na). The participants are involved in choosing the most suitable option out of the iterations and customization available at hand in the form of 3D models where the models can be changed in real-time by moving sliders or inputting numbers through generative algorithms.

The final stage of prototyping and testing has all the participants testing the 1:1 scale prototypes created using digital fabrication of their chosen options in addition to providing feedback on the prototypes of other to better understand how generative algorithms can be better optimized to provide suitable customization options for furniture design. This also tells how satisfactory the exploratory research is before delving into a more large scale and rigorous study. Table 2 showcases the strengths of implementing the methodology proposed in this study.

Table 2 - Design Methodology and the expected benefits of co-design with intended users

S.NO.	STAGE	METHODOLOGY & STRATEGY	BENEFITS EXPECTED
1.	**Understand – Observe** (Initial exploration of work)	• Autoethnography a) Student researcher in this study who is an International Student will create basic generative algorithms for furniture pieces according to their preferences and needs. • Phenomenological studies a) Researchers gather information about the intended users through online semi-structured interview about their furniture preferences. b) Researcher and the intended user collaborate in a co-design session to elaborate on the furniture preferences showcased in the semi-structured interview through discussions, sketches, 3D modelling and low fidelity prototyping. c) Researcher takes notes of the participants needs, behaviours and actions.	• Autoethnography will provide this study with a base which can be added upon or altered or optimized better because algorithms work better with multiple iterations. • Researchers gain a thorough understanding of intended users needs, experience and aspirations. • Discovery of qualitative data in terms of customizability for furniture pieces that could be enhanced using generative algorithms.
2.	**Point of View – Ideate** (Discovery process)	• Inductive Coding a) The transcripts of all co-design sessions are coded to create themes and patterns. b) The themes and patterns are visualized into separate flowcharts for every participant for ease of understanding. • Creating generative algorithms a) Grasshopper and Rhino are used by the researchers to create generative algorithms	• Optimization of generative algorithms by adding options of newer participants needs and preferences. • Creation of customizable and adaptable design solutions because of various perspectives.

		wherein design elements of furniture pieces can be customized on the basis of deduced themes and patterns. b) The participants are involved again for feedback on the algorithms and choosing an option to go ahead with the creation of first prototype.	
3.	**Prototype – Test** (Prototyping and Usability Testing)	• Production and Implementation a) The options chosen by the participants will be converted into 1:1 scale prototypes to be used for usability tests. • Usability Tests a) Researchers invite the participants of co-design sessions to use the prototype and provide feedback. b) All the participants can provide feedback on every prototype created to evaluate the effectiveness of design.	• Production of customizable and adaptable furniture pieces based on multiple perspectives. • Understanding the fruits of this exploratory research to get the know how's of a vigorous study in future. • The design output can truly be useful for the community of intended users in giving them customized solutions.

Even though this study has the researcher conducting autoethnography in addition to co-design sessions with intended users, the chances of a potential bias occurring is not possible because the main goal of the research is to create generative algorithms which produce solutions catered to intended user's preferences and needs. So, the more data incorporated of the target audience which the student researcher is a part of, the better the algorithms can be optimized for customizability. All in all, both qualitative methods play a role. The first to create a base and the second to build upon it.

The method used in this research to recruit participants is called convenience sampling method. Convenience sampling method is a non-probability sampling method where participants are selected based on their availability and accessibility rather than random selection (Moser &

Korstjens, 2018). The reason for choosing this method to recruit participants is because of limited time and resources turning the current study into a pilot or exploratory research to test out the viability qualitatively before moving on to conducting a more rigorous and large scale research.

Participants were recruited from OCAD University, the University for whose coursework this research is being done, who were fellow students and alumni. The sample size for this study is 3 participants since the approach for this study is phenomenological. According to (Moser & Korstjens, 2018), the sample size for phenomenological studies requires fewer than 10 interviews when designing a qualitative sampling plan. The study was initially supported to target International Students but the addition of non-resident working class participants is included to understand about life changes that happen after graduating for the students and if the needs and preferences towards furniture in their living spaces still align.

4. AUTOETHNOGRAPHY

4.1. ANALYSIS

The research as outlined in the methodology section began by conducting an autoethnography, answering the same questions that would later be posed to the participants in the form of a semi-structured interview which is in Appendix B. As an international student myself, my experiences and traits will help form the base of the generative algorithms for furniture customization which will be optimized as the research goes on with other participants. I identified a personal need for a collapsible table which can be collapsed to create space in my private room since there is less space to move around after setting up a permanent table for work in the room.

Additionally, my background in architecture influenced the design preferences for this piece. An additional personal trait from architectural background dictated the design of the table to have the ability to incline since I got used to making architectural sheets during my early academic years like that which developed a habit to sketch concepts on a table that is inclined or has a slanted surface. It makes me think and sketch better.

The autoethnography also involved looking into previous research papers which delved into using digital fabrication techniques for creating furniture pieces. The first thing a generative algorithm for customizable furniture pieces demands is the option for changing the basic dimensions which is length, width and height so that any end user can input them on the basis of the space available. Once the algorithms could generate real time 3D models of a basic table structure including tabletop and legs according to the dimensions inputted, the focus was shifted towards integrating the adjustable inclination mechanism.

A particular influential study by (Aiman, Sanusi, Haidiezul, & Cheong, 2020) is a research paper which concludes that 3D printed joints are more stable than expected and being tested to be fully functional where the final prototype could withstand loads up to 730 kg. This research helped in choosing 3D printing as a helpful digital fabrication method for creating generative algorithms for modular joints.

The research moved forward by creating two categories of generative algorithms which could create 3D printable STL files which can be customized based on the length and width of the joint itself in addition to the thickness of the teeth that grab the material. There is also an option to change the material thickness that the joint is holding to change the whole 3D model accordingly. The different categories in the generative algorithm of joints is catering to the differentiation for creation of fixed and hinge joints.

A mixture of fixed and hinge joints allowed the possibility of collapsing the table fully in addition to the ability of inclining at a desired angle as well as you can see in the following photos.

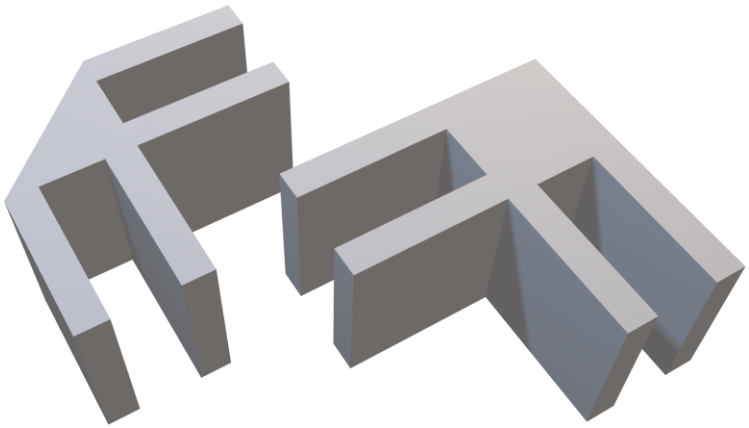


Figure 2 - 3D model of fixed joints creating using algorithms

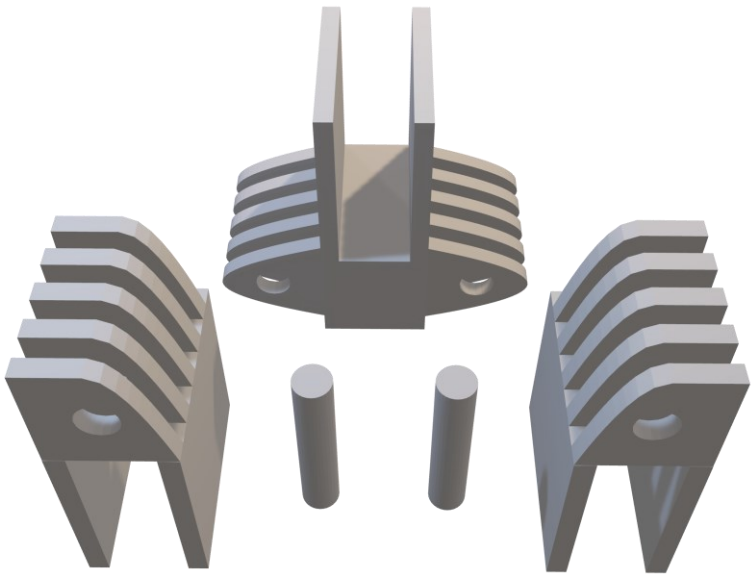


Figure 3 - 3D model of hinge joints created using algorithms

The final step was to create a prototype to test the feasibility of the design. The material chosen for the creation of tabletop and legs was cardboard because of its economical nature, durability and strength when used in the form of a 3-ply construction with alternating truss patterns. The cardboard was laser cut keeping in mind the KERF tolerances of 0.2mm of the machine used which the generative algorithms, which also provide us with a 2D file for laser cutting already account for because they are created in such a way. The material chosen for the 3D printed joints was PLA Basic in colours black and grey. The 3D printed joints were given an infill percentage of 15% for this prototype to save material and test out the durability progressively. The infill percentage is the amount of material present inside the 3D printed object in comparison to air. The tolerances in 3D printing used for inter fitting mechanisms of the joints were 0.15mm.

4.2 RESULTS

The prototype did well in terms of providing a smooth inclinable and collapsible movement to achieve the desired inclination and space saving aspect of the design. The thing that the prototype lacked was the strength to take everyday amount of weight. It wobbled quite a bit and did not feel structurally capable to be used for everyday tasks.

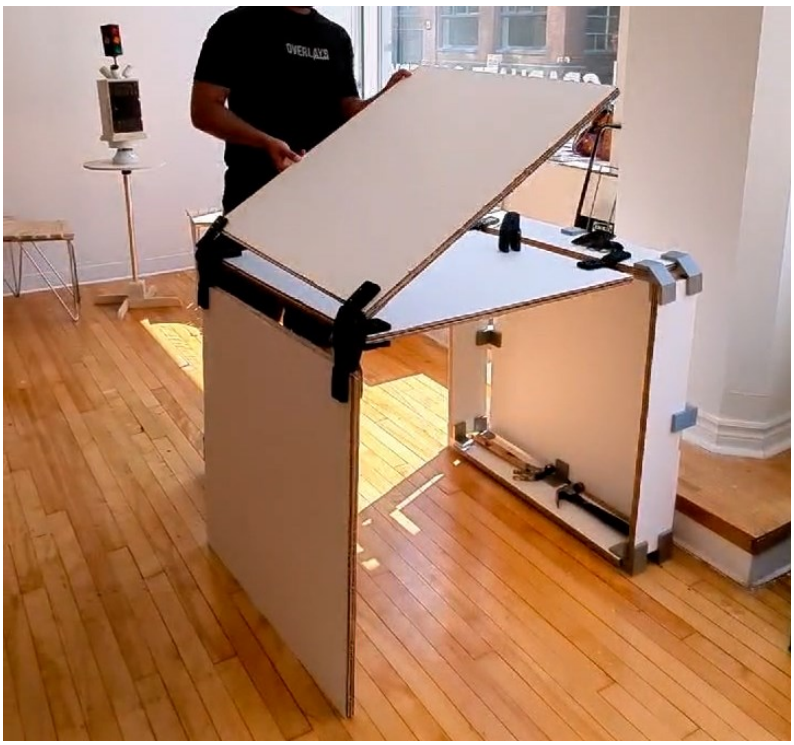


Figure 4 - Prototype created using laser cut cardboard and 3D printed fixed and hinge joints

The reason for the negatives can be attributed to the fact that the joints had very less material in them and mostly air i.e. 15% infill percentage. (Aiman, Sanusi, Haidiezul, & Cheong, 2020) used comparatively bigger infill percentages. So, the next prototypes will be made using bigger infill percentages to test the structural strength.

5. SEMI-STRUCTURED INTERVIEW

The next step in the research was to conduct online semi-structured interview of the 3 participants that fit the study after fulfilling the criteria in the screening questionnaire. Engaging in these interviews before co-design session provided the benefit to the participant of having some prerequisite of thinking over the pain points faced during everyday life which could be alleviated by the topic at hand in addition to the facilitator having some questions which could be used to elaborate on the psyche of the needs of the participant.

5.1. ANALYSIS

5.1.1. PARTICIPANT 1

The first participant expressed their need of a desk which could be used for work, reading and painting.

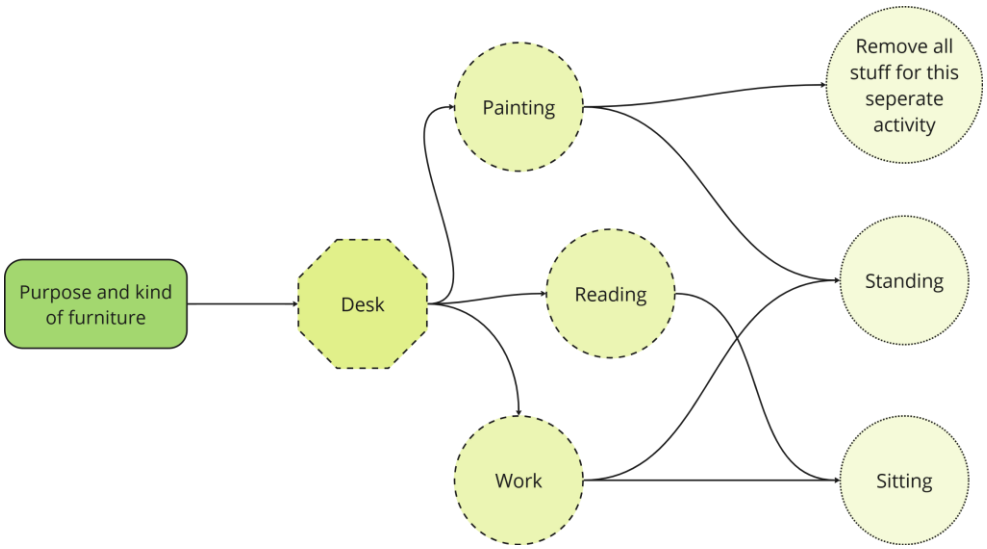


Figure 5 - Flowchart describing purpose and kind of furniture

The location of their preference of furniture was also mentioned by the participant.

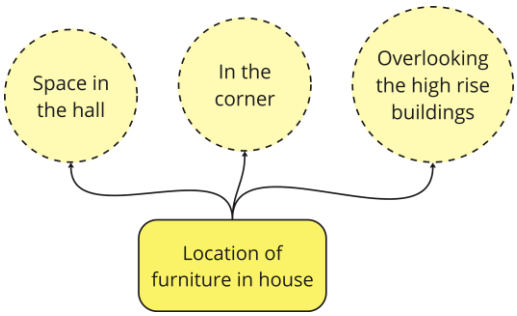


Figure 6 - Flowchart describing location of furniture in the house

The interview also shed light on the multi-purpose and modular features which could make their life easier. They mentioned,

"For multi purpose I think it can be three things:

1. Standing desk

2.Easily movable

3. Good Height in proportion to the chair I own

For modularity:

1. Maybe it can extend when I'm painting as I need a big space then.

2. Some space to keep my stationery

3. Some space where the wires can be hidden or kept together of my various devices."

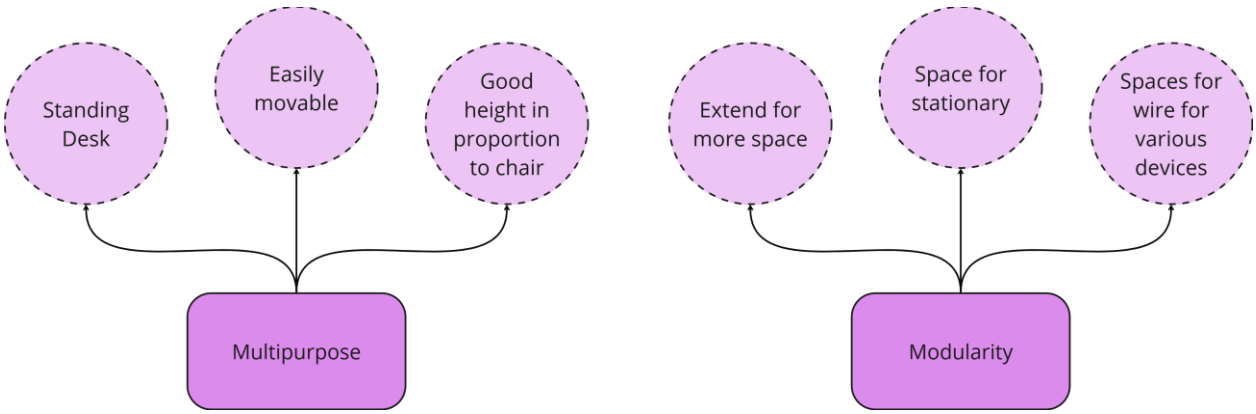


Figure 7 - Flowchart describing the multi-purpose and modular features answered by the participant

The approximate dimensions of the space available for their preferred desk was also mentioned so enough material could be kept for low fidelity prototyping during the co-design session.

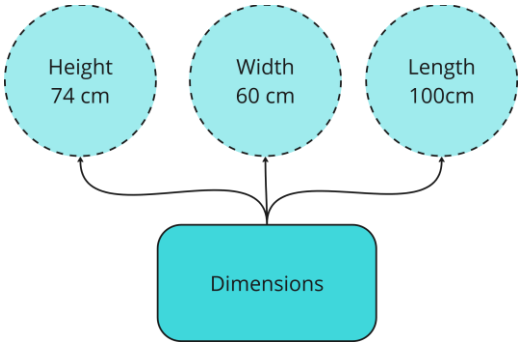


Figure 8 - Flowchart describing the dimensions for the furniture piece answered by the participant

The semi-structured interview also described the characteristic of the participant to prefer their furniture to completely come as a kit which they can assemble instead of owning carpentry equipment and dabbling with making some things themselves at home.

The participant also described a perfect room for themselves where they mentioned,

“Well, a perfect room it can have certain elements which i would incorporate and some colors too like:
1. Big and small plants
2. Carpet
3. 2-3 lamps
4. Queen size bed
5. Dressing table
6. Worktable/ chair
7. A few of my artworks
I think it should all in color sync like pink/ light blue with white furniture. I like light colors with a touch of dark tints through art pieces.”

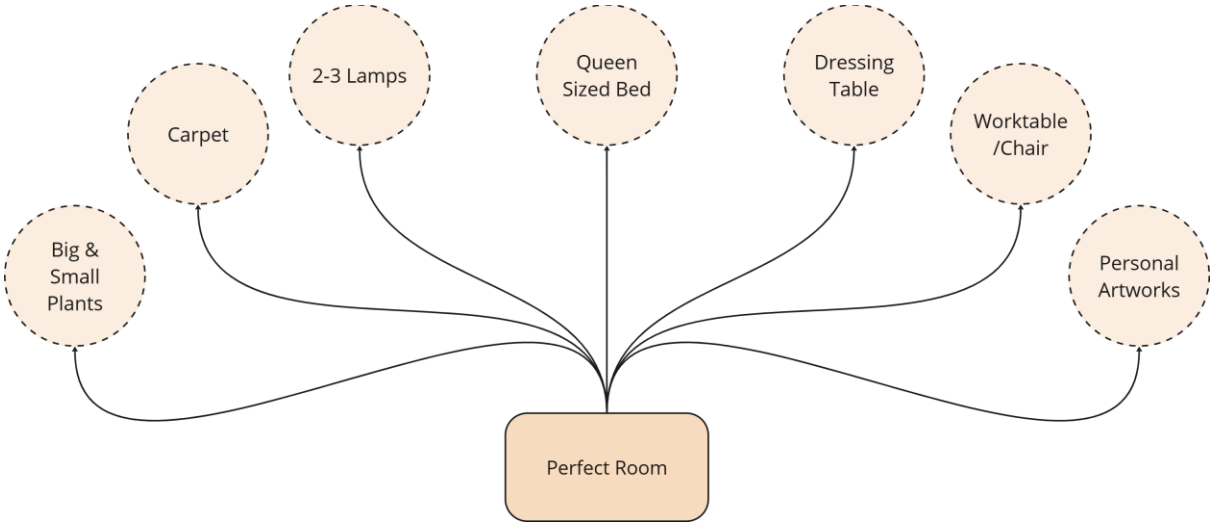


Figure 9 - Flowchart describing the perfect room desired by the participant

Engaging in this interview-based data collection benefitted the researchers in preparing some questions which can be asked during the co-design session to help the participant in elaborating on their preferences and needs which would make the facilitation better. The questions that were prepared are mentioned in Appendix D.

5.1.2 PARTICIPANT 2

The second participant mentioned a detailed list of needs for the perfect furniture they would want. They mentioned,

“ A cozy, multipurpose zone – A place for reading, relaxing, or working.

- Smart lighting integration – Since there are no windows, the furniture should incorporate soft lighting to make the space feel more inviting.
- Storage & organization – A functional yet stylish way to keep essentials without cluttering the room.
- Illusion of openness – Using design elements that prevent the space from feeling too enclosed.

Design Opportunity

- A Wall-Mounted Multi-Use Unit:
- A foldable desk surface that can be stowed away when not in use.
- A vertical bookshelf with open and closed compartments to add character and utility.”

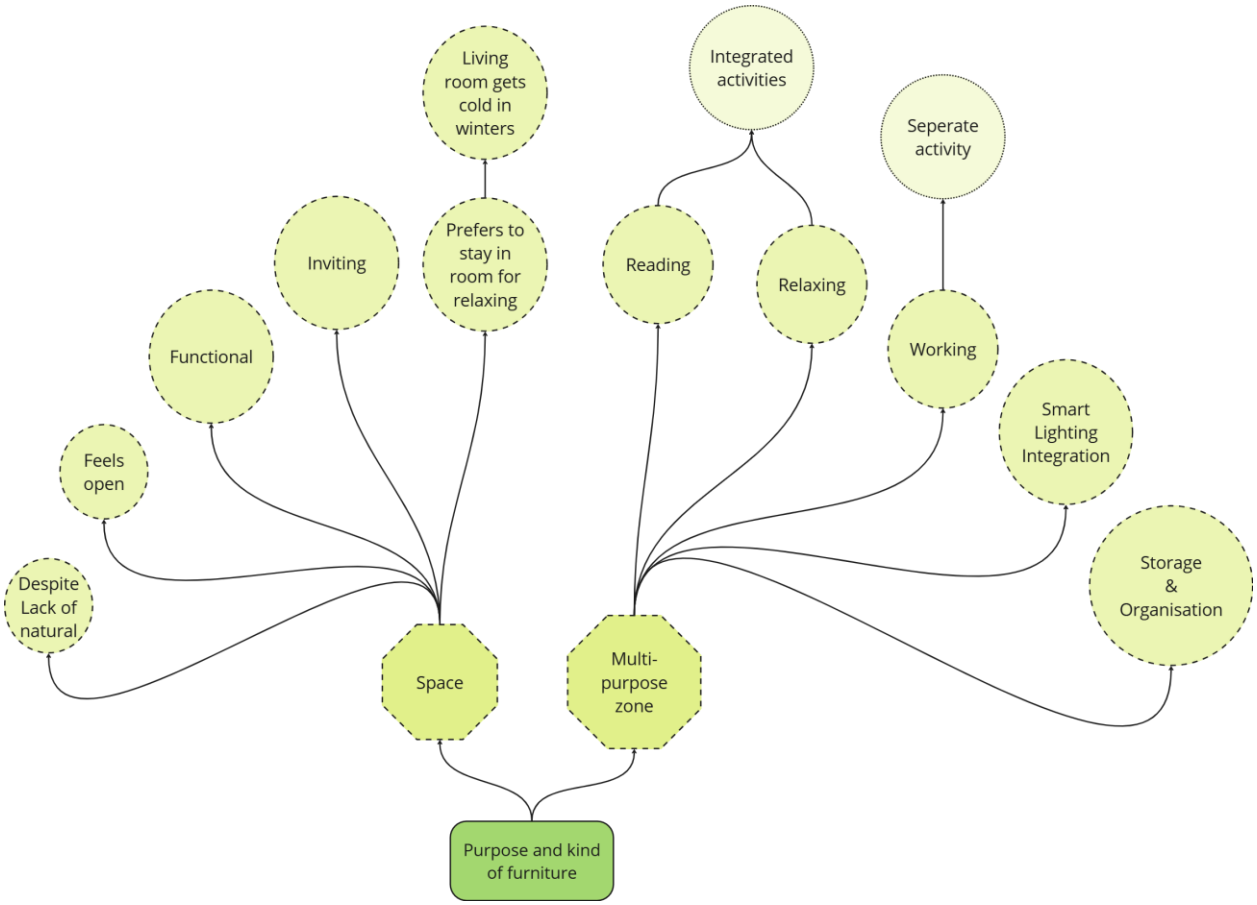


Figure 10 - Flowchart explaining the purpose and kind of furniture required

The participant showcased the need of wanting a whole multi-purpose zone which consisted of a desk and bookshelf wherein multiple activities like reading, relaxing and working could be done in addition to having proper storage and organisation spaces with proper lighting.

The space was in which they would like to do conduct these activities was also described by the participant mentioning, “In a den room with no windows, the biggest challenge is creating a space that feels open, functional, and inviting despite the lack of natural light.”

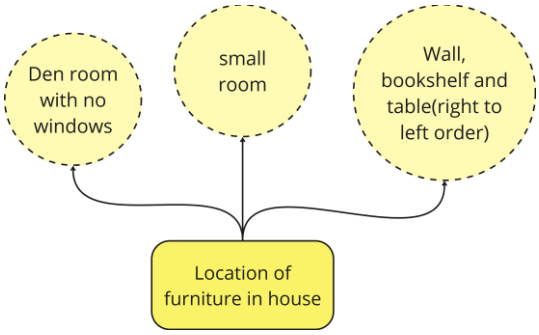


Figure 11 - Flowchart describing the location of furniture in the house

The interview also shed light on the multi-purpose and modular features which would make their life easier. They mentioned,

"Convertible Bench to Lounge Chair → A folding backrest that allows the bench to go from upright seating to a reclined lounge mode for relaxation.
Pull-Out Desk Panel → A compact sliding or fold-out desk integrated into the structure for work or writing, which can be hidden when not in use.
Adjustable Height Tabletop → A lift-top coffee table integrated into the seating, which can be raised for working or dining."

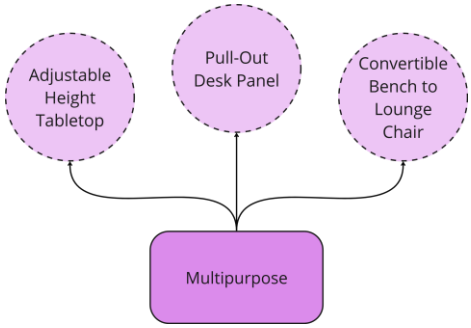


Figure 12 - Flowchart describing the multi-purpose features answered by the participant

The semi-structured interview also described the characteristic of the participant to prefer their furniture to completely come as a kit which they can assemble instead of owning carpentry equipment and dabbling with making some things themselves at home.

The participant also described a perfect room for themselves where they mentioned,

“Theme & Atmosphere
Modern Minimalist with a Cozy Feel – Clean lines, uncluttered space, but still warm and inviting.
Soft, Natural Aesthetic – Inspired by Scandinavian & Japandi design, blending wood, neutral tones, and natural textures.
Multi-Functional & Adaptable – Everything should serve more than one purpose, maximizing space efficiency.

Colors & Materials
Primary Colors: Warm neutrals – Soft beige, light gray, and muted olive green for a calming effect.
Accent Colors: Deep teal or terracotta – Subtle pops of color in textiles or decor.

Ideal Feeling of the Space
A calming retreat where I can focus, create, and unwind.
Everything feels intentional—no excess, but everything serves a purpose.
A balance of tech and nature, keeping it modern yet organic.”

Engaging in this interview-based data collection benefitted the researchers in preparing some questions which can be asked during the co-design session to help the participant in elaborating on their preferences and needs which would make the facilitation better. The questions that were prepared are mentioned in Appendix E.

5.1.3. PARTICIPANT 3

The third and the last participant showcased their need for a portable drawing table. They mentioned how the table needs to be small and portable in addition to having the ability to adjust its angle. They were not able to provide the approximate dimensions of the space because they recently moved and did not have access to measuring tape. They would also like to have their furniture come completely as a kit which they can assemble. They described their perfect room as minimal and easy to organize.

Engaging in this interview-based data collection benefitted the researchers in preparing some questions which can be asked during the co-design session to help the participant in elaborating on their preferences and needs which would make the facilitation better. The questions that were prepared are mentioned in Appendix F.

5.2. RESULTS

The semi-structured interviews gave us a basic understanding of the needs and preferences of the participants on the furniture they require based on the activities they do. This also provided the researchers with the realization that all the participants require in their day-to-day life to have a proper desk space or table space on which they can carry out the multiple activities that they indulge in with the utmost ease. They also like to have proper space for storage and organizations of the things that help them carry out those activities. So, the consensus among the three participants stays around requiring desk space for multiple activities accompanied by proper organisation for the things that help in conducting those activities.

6. CO-DESIGN SESSIONS

The research further carried on to conduct one on one co-design session with each participant. The co-design sessions were an opportunity for the researchers to interact and collaborate with the participants to discuss in detail about their needs and preferences. The co-design sessions were a way to bring the participants into the conceptual building of the prototypes through phenomenological conversation, sketches and low fidelity prototyping.

6.1. ANALYSIS

6.1.1. PARTICIPANT 1

The co-design session conducted with the first participant was audio recorded and transcribed so it can be inductively coded to create themes and patterns based on which the design for their prototype will be evolved. The transcribed file was coded into 8 themes after understanding the patterns which are as follows:

1. Location of furniture in the house
2. Purpose and kind of furniture.
3. Components on the furniture and their characteristics
4. Characteristics of furniture piece itself like shape, colour and texture
5. Dimensions of components on the furniture
6. Participants way of working or likes and dislikes
7. Confusions during the co-design session which were cleared later in the session
8. Visible or invisible disabilities

The conversation in the co-design session began by elaborating on the information mentioned in the semi-structured interview by the participant. The participant elaborated in detail on their needs and preferences pertaining to every theme that emerged from coding the transcript. The initial phases of co-design helped in gathering this information.

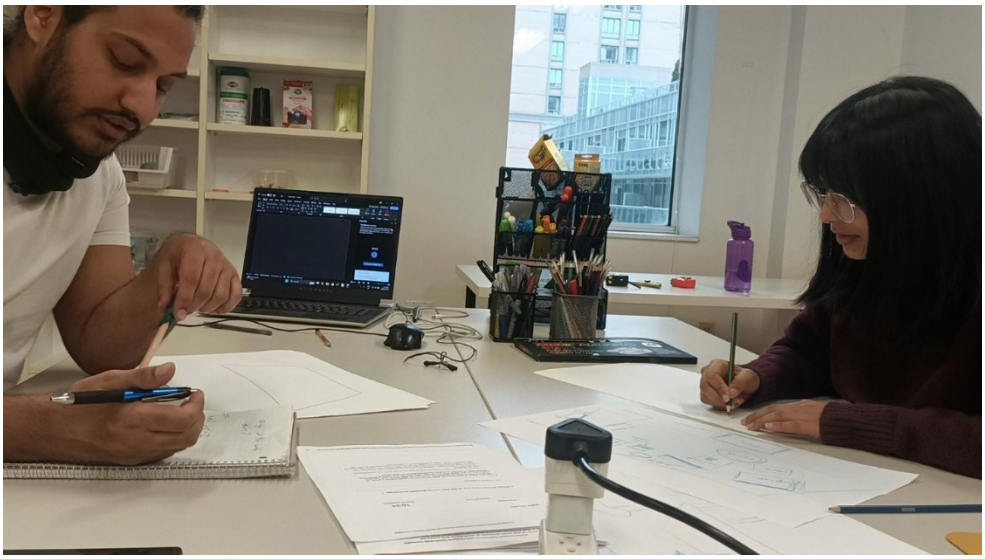


Figure 13 - Photograph taken during the co-design session

The next phase had the participants sketch visuals that will help them understand their needs better. The first sketch made them draw a tabletop boundary and place objects in the sketch that they use everyday and how they place them while doing various activities. This will help inform the shape and form of the tabletop. The discussion dove deep into the psyche of how everything is organized while doing various activities.

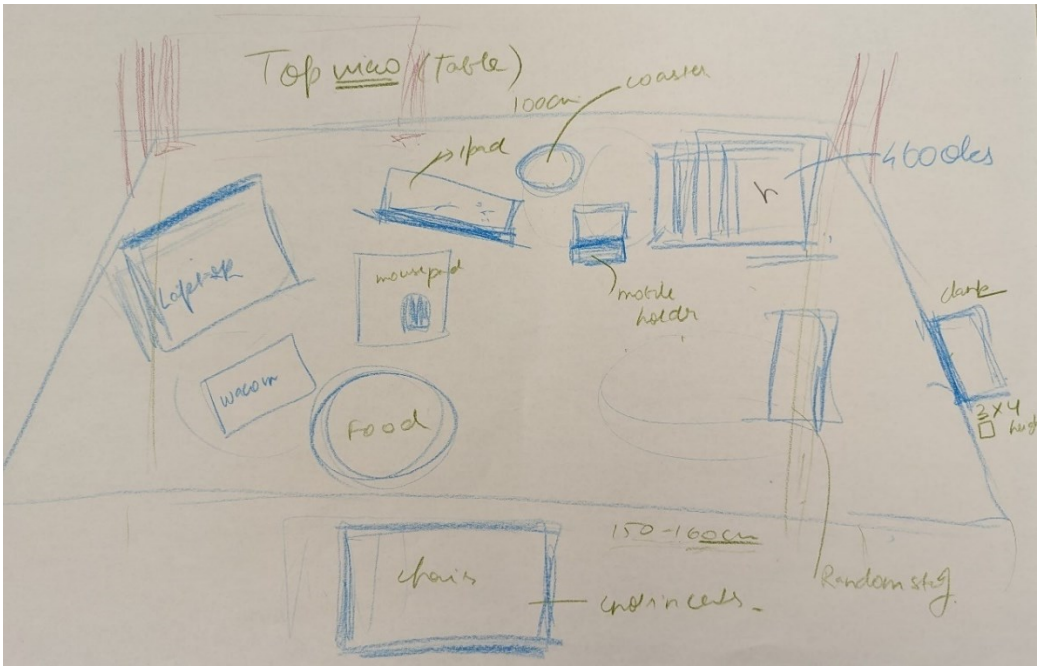


Figure 14 - Sketch by the participant showcasing the top view of table while doing daily activities

This enlightened the session to the fact that the participant does not like their table's top surface to be a square or a rectangle because they always tilt their laptop at an angle while working. So, they want their tabletop to be in a trapezium shape where the agency to place their laptop at a tilted angle exists instead of creating a mental barrier of not being able to do it because they feel the laptop will fall.

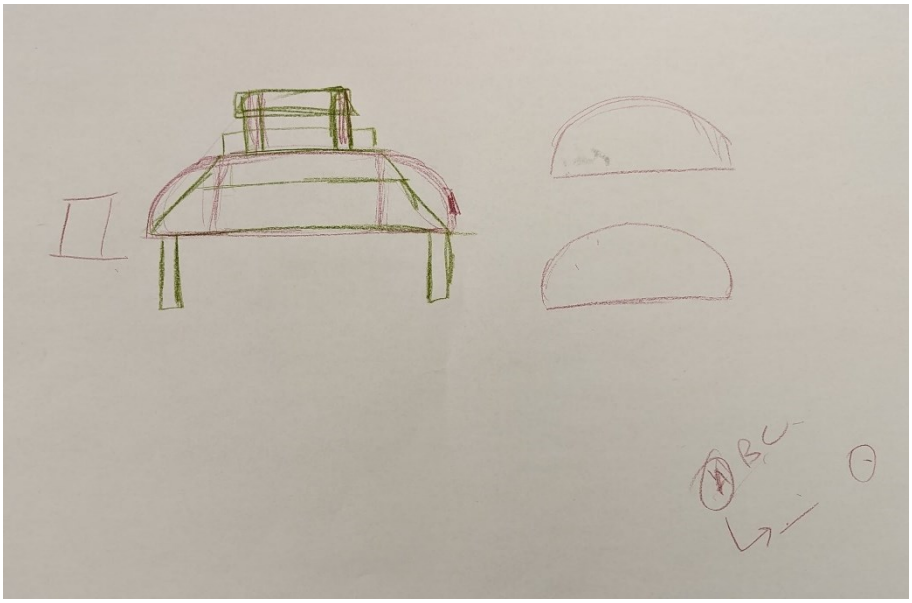


Figure 15 - Sketched by participant to showcase the form of the table preferred

The other thing the sketch helped us figure out is the need of the participant to have a horizontal tabletop book holder to keep a few amount (they mentioned 4) books which they are currently reading. Two other requirements that came up for proper storage and organization were of a wire holder at the back and a penholder which would be clamped to the sides of the table and taken out whenever required. The participant also described how they preferred very basic forms and shapes of their tabletop and legs because they want functionality over aesthetics.

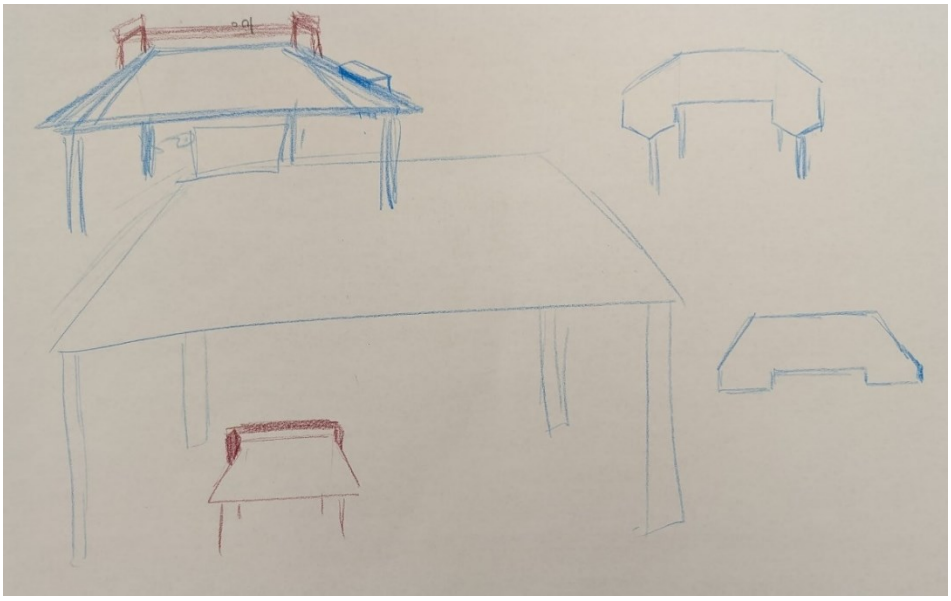


Figure 16 - Sketched by the participant to discuss the forms for table

Another thing that came up was their love for asymmetry. The participant feels asymmetry is visually soothing to them and helps them focus. The co-design session also prompted to ask the participant about any likeness towards particular patterns or textures that help them focus during certain activities. The participant described and sketched very organic forms like Voronoi structures and free flowing protruding textures like the bark of a tree.

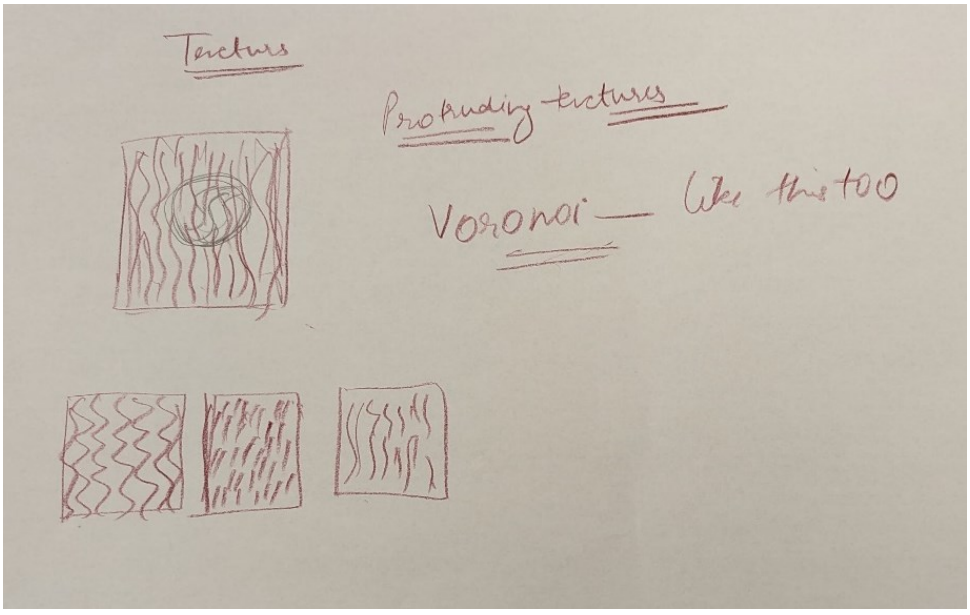


Figure 17 - Sketched by the participant to showcase the organic textures preferred on surfaces

The discussion then further moved on to discuss the preferences and opinions of the participant on laser cutting certain parts and 3D printing the other. The participant showed their preferences on 3D printing the side accessories like book holder, wire holder and pen holder with the organic textures they sketched and laser cutting the tabletop and legs.

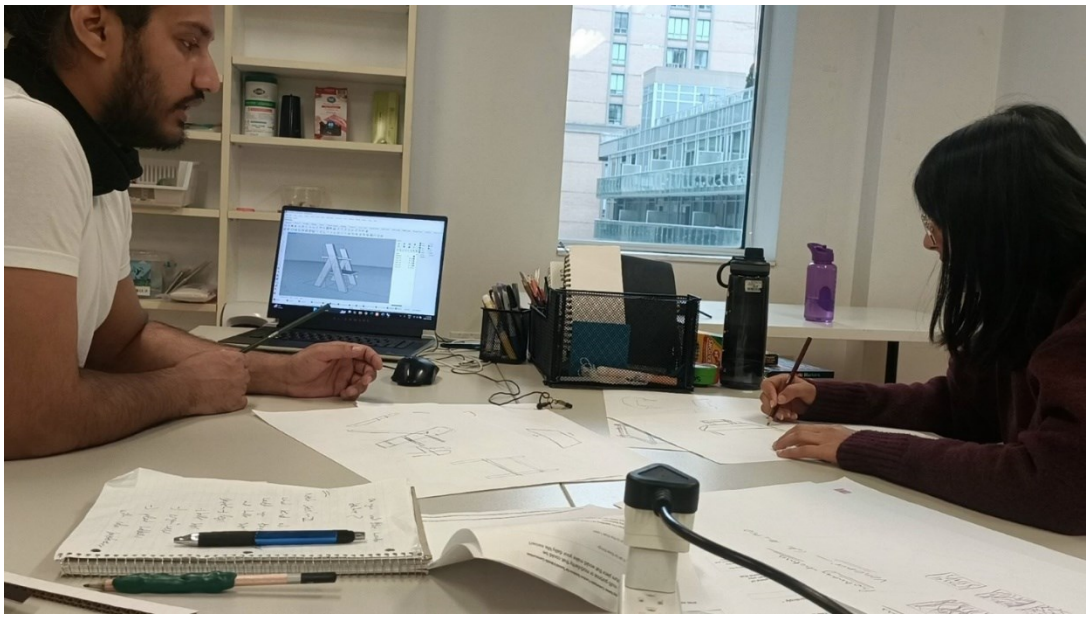


Figure 18 - Photograph of the co-design session

Another trait mentioned by the participant is the utmost likeness towards wanting everything in their furniture piece to be white. They feel that as a painter maybe, they find white colour around them to be non-distracting in addition to it being like a blank canvas on which they will produce their work. It just helps them focus better is what they said. We also made them choose the colour for the 3D printing filament from a physical printing filament catalogue. The participant chose an ivory white PLA Matte material.

The last phase was used to figure out the dimensions for every part of the furniture piece using cardboard and other objects lying around as proxy. Measuring tape was used to figure out the exact dimensions that would them anthropologically.

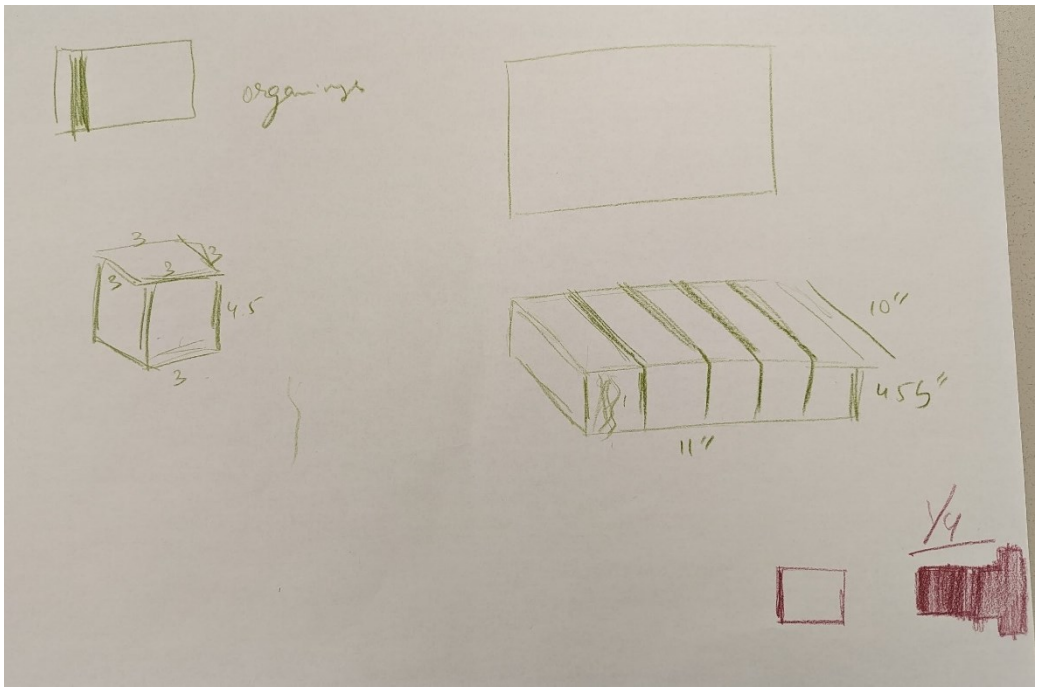


Figure 19 - Sketched by the participant to figure out the dimensions for the organizers

6.1.2. PARTICIPANT 2

The coding themes that emerged from second participant's audio transcript was the same as the previous one. The conversation in the session began by the participant elaborating on the answers given in the semi-structured interview.

The participant described their need of a table that can have adjustable height. They mentioned that they require 2 height levels. One for working at a higher level while sitting only and one at a lower level like a coffee table for relaxing.

They were made to visualize by sketching the top view of their desk while working and relaxing. Their work requires them to use 2 laptops (both 18 inch) accompanied by a lot of printed research papers. They require proper organization and storage spaces that can be taken out to create a table stand as well and put away when not in use.

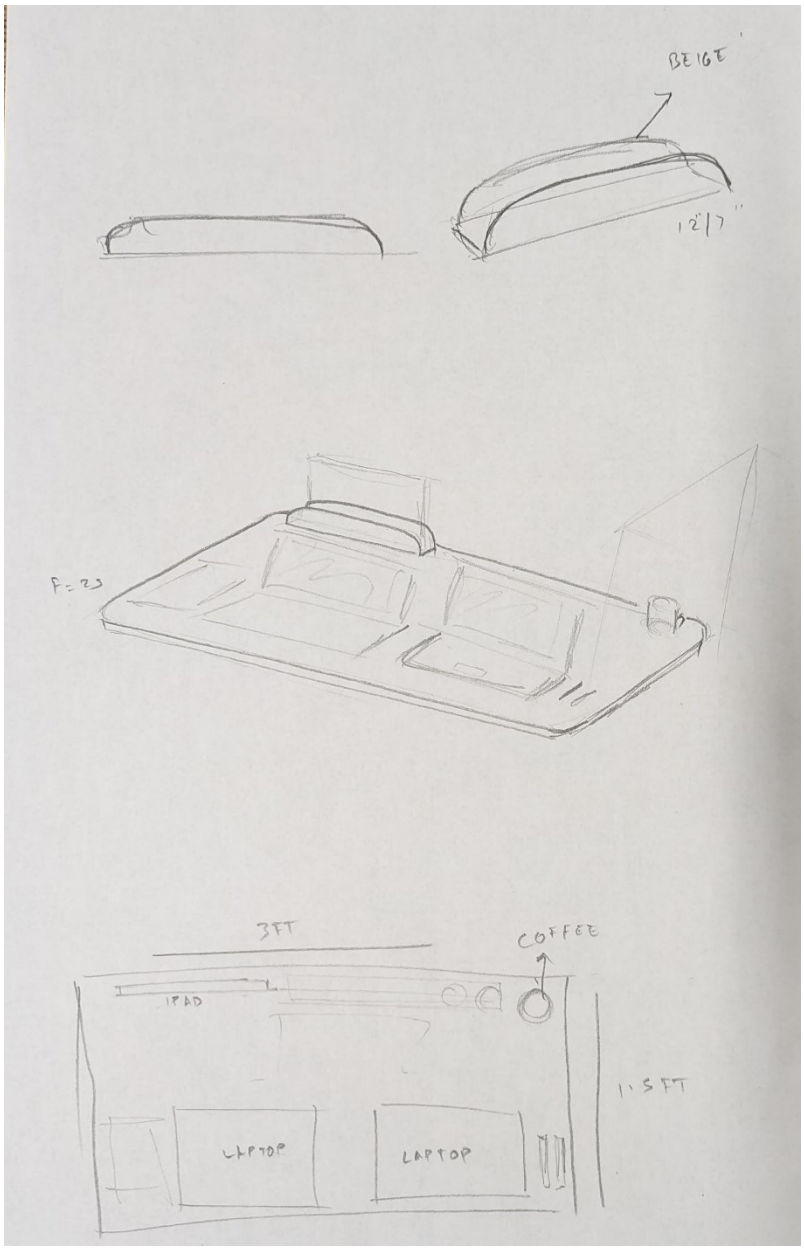


Figure 20 - Sketched by the participant to showcase the top view of table during daily activities

Since they mentioned of a multi-purpose zone in the semi-structured interview, they also required a bookshelf which should be able to fit different kinds of personal items at different levels. They wanted the first level to store their work bag, research papers and boxes holding papers too. The second level should be smaller in height and hold all the electronic devices like laptops, wires, IPad, etc. The third level should be bigger in height to hold décor like plants and candles in addition to papers, diary, sketchbooks and the books they are currently reading for

quick access. Lastly, the fourth level should hold all the remaining books they have which they are currently not reading. They are also a LEGO collector and have a lot of LEGO pieces that they wish to have on display in their room which will also be placed on the top level. The participant wants it to be that way because the top two levels are closer to eye level and perfect for décor.

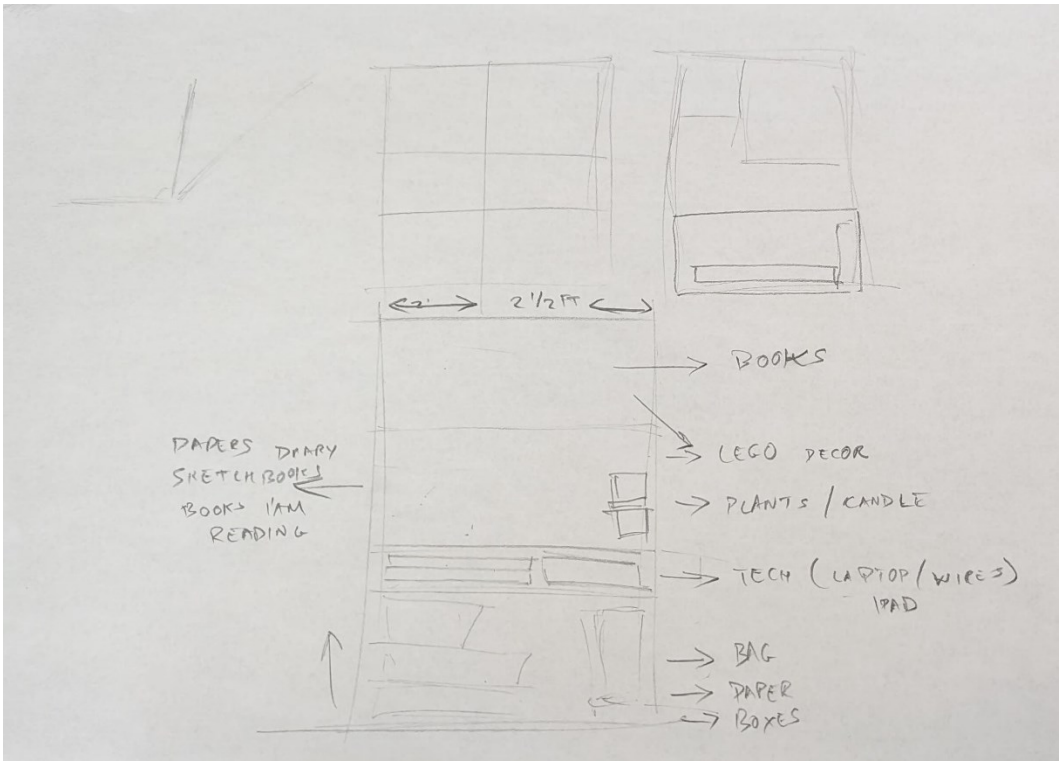


Figure 21 - Sketched by the participant to figure out the form and uses of the bookshelf

They also pondered over the idea of having modular storage bins for displaying books and LEGO pieces which can be interlocked as drawn in the sketch below to have multiple ways of placing it.

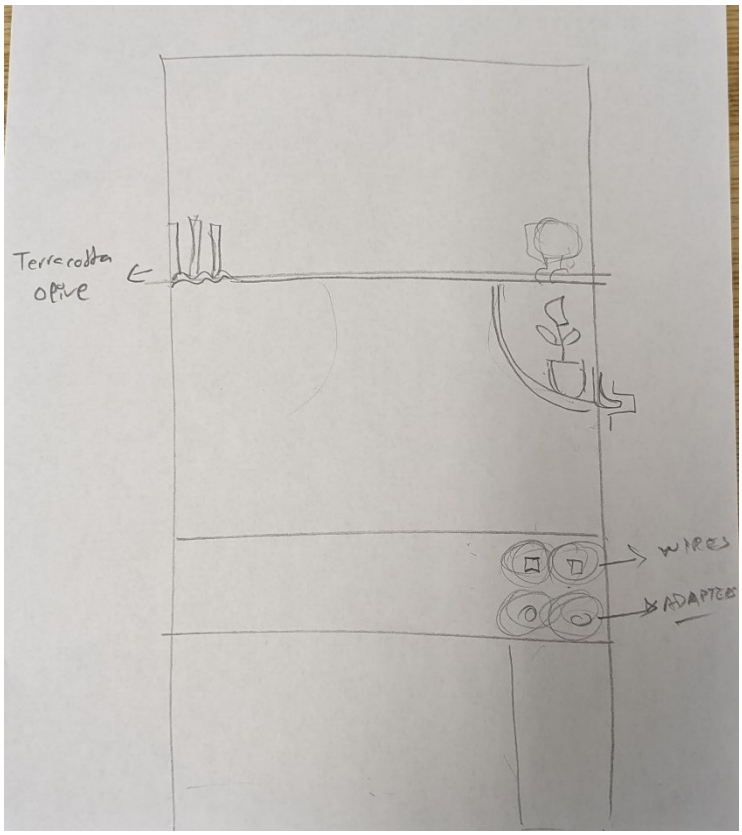


Figure 22 - Sketched by the participant to come up with modular solutions in the bookshelf

They did not seem to want textures or patterns in their furniture. They just wanted smooth and plain textures. Their colour preference varied towards olive, terracotta, teal and beige. This is the reason they wanted their organizers and modular interlocking display to be of those colours. So, 3D printing filaments similar to said colours were chosen from the physical catalogue as follows:

1. Olive – PLA Matte 11501
2. Terracotta – PLA CF 14200
3. Beige – PLA Matte 11800
4. Teal – PLA Basic 10500

The material for the table and lower two levels of bookshelf shelf should be of wooden feel as mentioned by the participant. The participant also mentioned their disability being arthritis due to which they wanted a kind of furniture assembly that would be easy for them to pick up and assemble easily.

The last phase had the session figuring out the exact dimensions based on the anthropology of the participant using cardboard and lying objects as proxy. The last phase also incorporated creating a rough 3D model of the table and how it could have different height levels as shown in the image below.

Figure 23 - 3D model created for the table design during low fidelity prototyping phase of the session

6.1.3. PARTICIPANT 3

The third participant's co-design session also brought forward the same themes after coding the audio recording transcript. The initial phase of the session had the participant elaborating on the answers provided in the online semi-structured interview.

The participant was asked to sketch the layout of the new house they have recently moved in to better understand how they use their space and what spot could the furniture piece they mentioned in the interview can be placed in. They described how they already have a table they like in the living space and how they would like a portable drawing table which they can use while painting or sketching while sitting on the floor which they usually do and lack furniture for that. They also mentioned how they have a corner space in their house connected to their living

room which is used as a storage space hosting a closet. This space is where they hope to keep a portable drawing table out of sight with easy access whenever required.

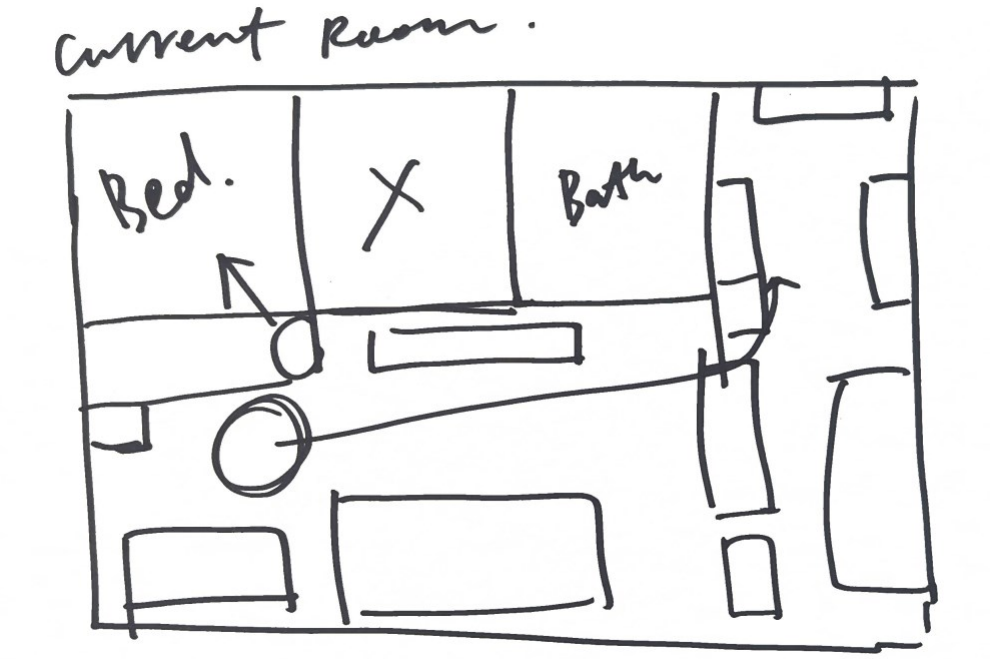


Figure 24 - Sketched by the participant to discuss the layout of their house

The participant then further visualized through sketches as to how they want their table to have the ability to incline at specific angles. This is required since this table is going to be used by them for painting and sketching which sometimes requires them to work on a slant surface for better ergonomics.

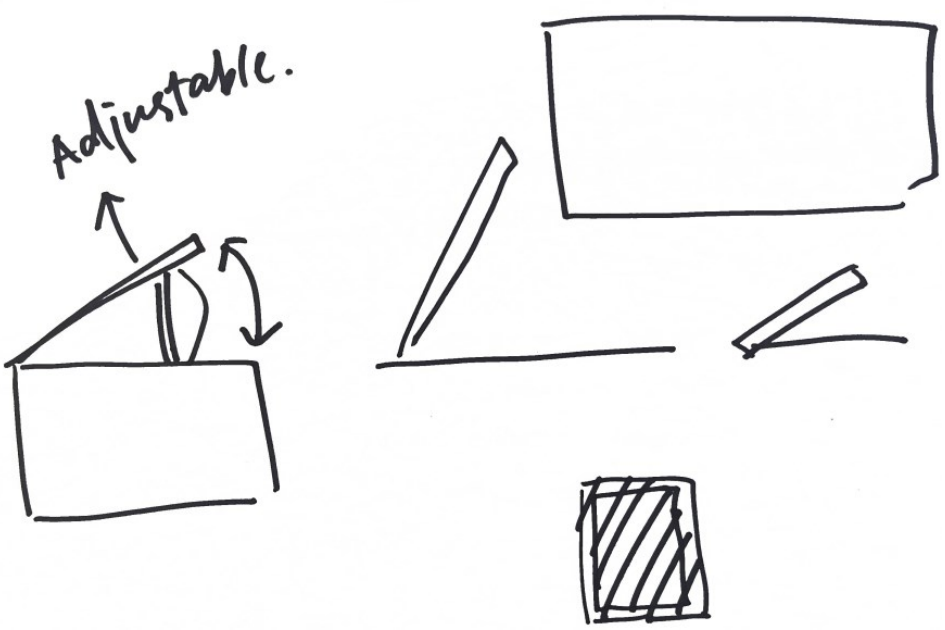


Figure 25 - Sketched by the participant to showcase the features required in portable drawing table

The participant also sketched the top view of the table with the needs and requirements of storage and organization space for paintbrushes and other stationary. The discussion brought forward the idea for the possibility of side organizers too which can be taken out to be put on the table. They also prefer organizers to be at a slant angle for ease of put in and pull out of stationary.

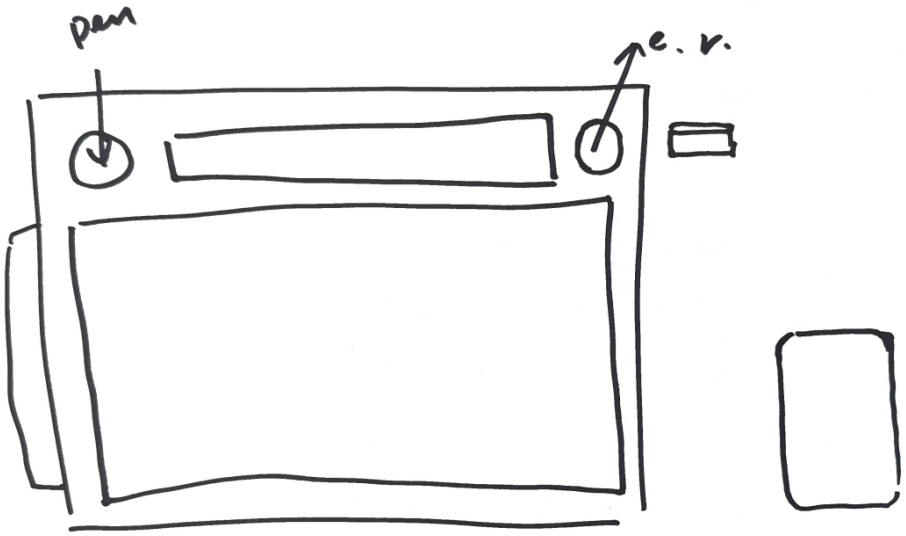


Figure 26 - Sketched by the participant to discuss the top view of the table during daily activities

The participant put forward their preference of wooden texture for laser cutting the tabletop and legs in addition to a grass green PLA matte filament for organizers to be 3D printed. They love the green color found in nature among trees and grass. It soothes them and makes them focus better.

Another idea was discussed wherein they mentioned that they do not paint or sketch while sitting on the floor all the time. They sometimes do that on their existing table too which does not have the ability to incline. So, in that regard, another possibility for the table to be used on the floor and while sitting on the table in addition to standing arise. The participant loved the idea of it ever being possible with some design solution.

The final phase had the session figuring out the exact dimensions using cardboard and lying objects as proxy.

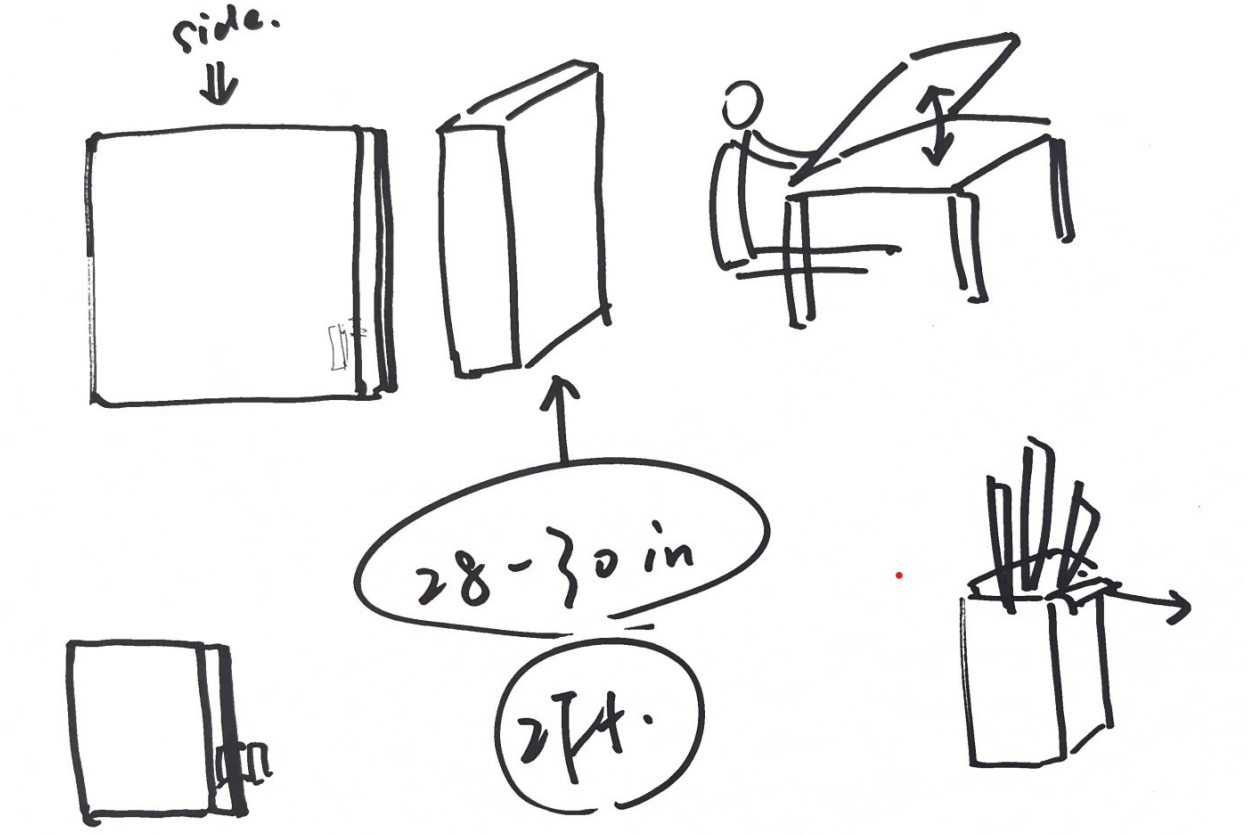


Figure 27 - Sketched by the participant while figuring out the dimensions and the form of the portable drawing table

6.2. RESULTS

The co-design sessions helped the research gather personas of different participants which will optimize the customizations in the generative algorithm based on user informed design challenges. The design concept will evolve to provide better agency to the end user. The generative algorithms can be coded to provide better customizations by removing the pain points faced by the participants in their daily activities. The prototype section will further describe how the preferences, traits, needs, activities and environment discussed by the participants in the co-design sessions helped in providing customizations in the furniture pieces.

7. PROTOTYPING

The prototyping phase had 2 sections involved in this study. The first step was to create generative algorithms that can produce laser cut and 3D printable files when prompted on the basis of the options governing the specifications of the furniture piece. The second phase involved creating real life 1:1 scale medium fidelity prototypes by choosing appropriate materials. These prototypes will then be used to conduct user testing by the participants and provide their valuable feedback.

7.1. GENERATIVE ALGORITHMS

7.1.1. PARTICIPANT 1

Due to the existence of basic algorithms created which could control the basic dimensions of a table by conducting autoethnography, the same algorithms for length, width and height can be applied here. The images for the grasshopper scripts can be seen in Appendix D.

The very first customization to add in order to better optimize the algorithm for this participant is the ability to input the angle of tilt which will govern the trapezium shape of a table instead of keeping it rectangular or square. The customization was achieved by coding the 4 end points of the quadrilateral in the algorithm to stay parallel from the top and bottom but move according to the angle inputted towards opposite directions to form a trapezium shape for the tabletop. This can be showcased in the images below.

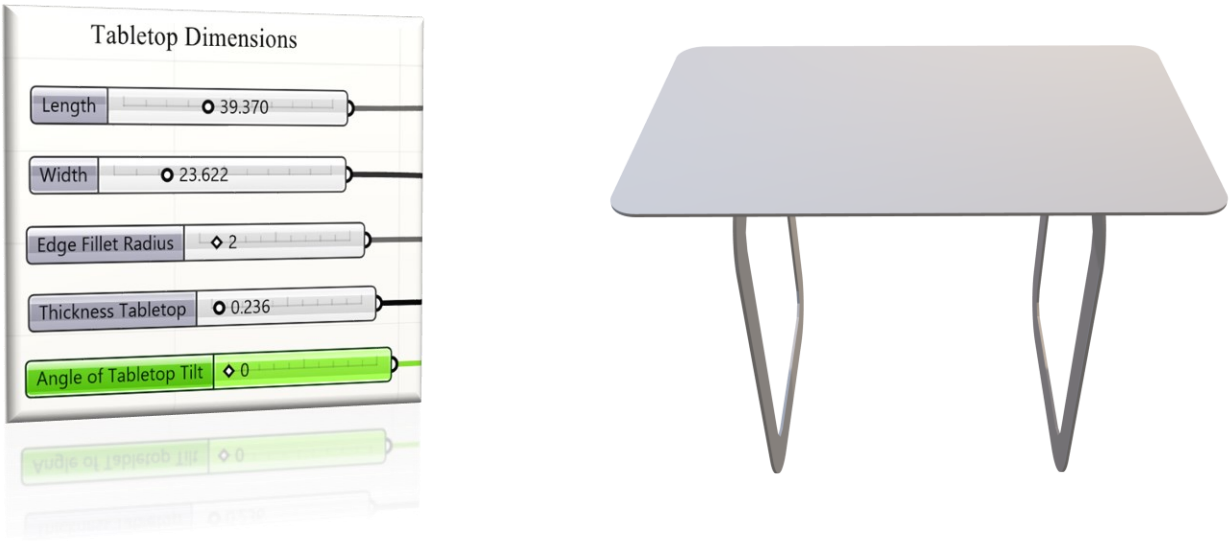


Figure 28 - Customizable options in the algorithm with the real time render of 3D model based on the inputs

Figure 29 - Showcasing how the 3D model is changed based on different inputs

Figure 30 - Showcasing how the 3D model is changed based on different inputs

The participant mentioned that they want basic aesthetics for the table legs as they prefer functionality over aesthetics. They also discussed how very complex forms in the bigger structure distracts them. They require minimalism from the bigger mass. For this reason, a customization option for the table legs to have an offset running around it was added instead of it being a big block of mass. The said customization is showcased in the images below.

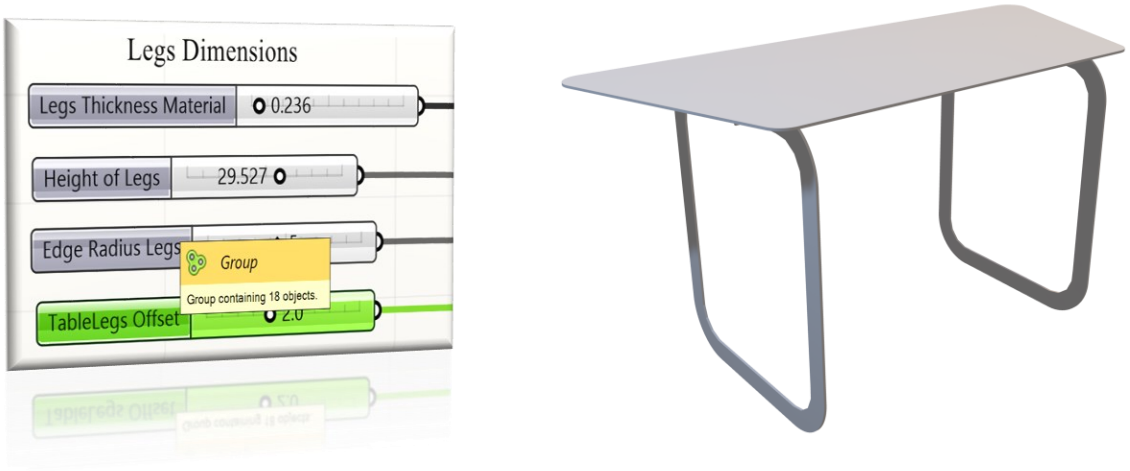


Figure 31 - Showcasing how the 3D model is changed based on different inputs

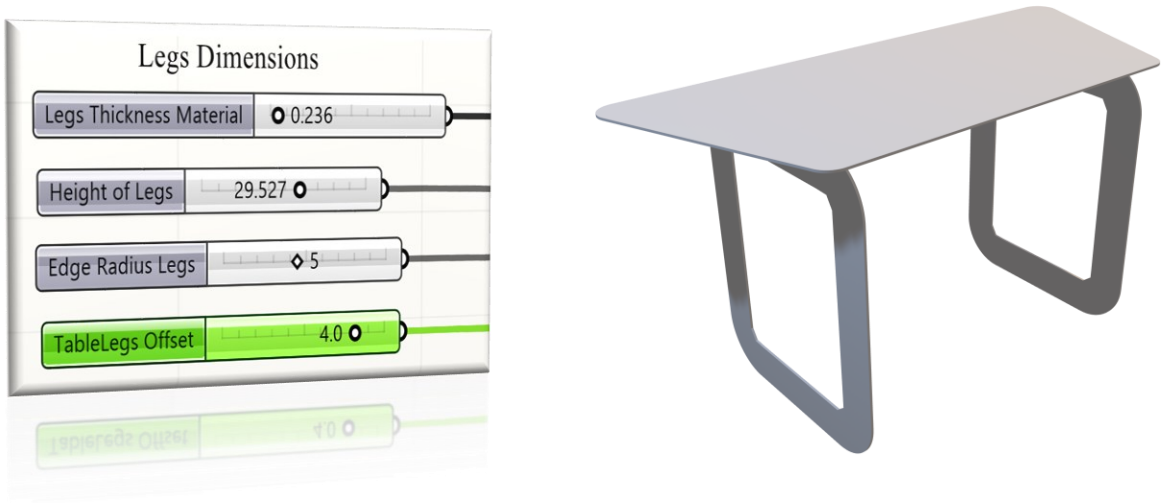


Figure 32 - Showcasing how the 3D model is changed based on different inputs

The next step in the coding of algorithms required us to create an algorithm to create the horizontal tabletop book holder. The algorithm of the book holder was created in such a way so that the form is always asymmetric depending upon the minimum and maximum height inputted in addition to the number of compartments wanted and the thickness of the book ends. The user can also seed random models of the same by just moving the slider and decide what they like. The book holder algorithm also generates an interlocking base wherein book ends can be added or removed at will creating more permutations and combinations of space allocation for different items. The images below showcase it through 3D models.

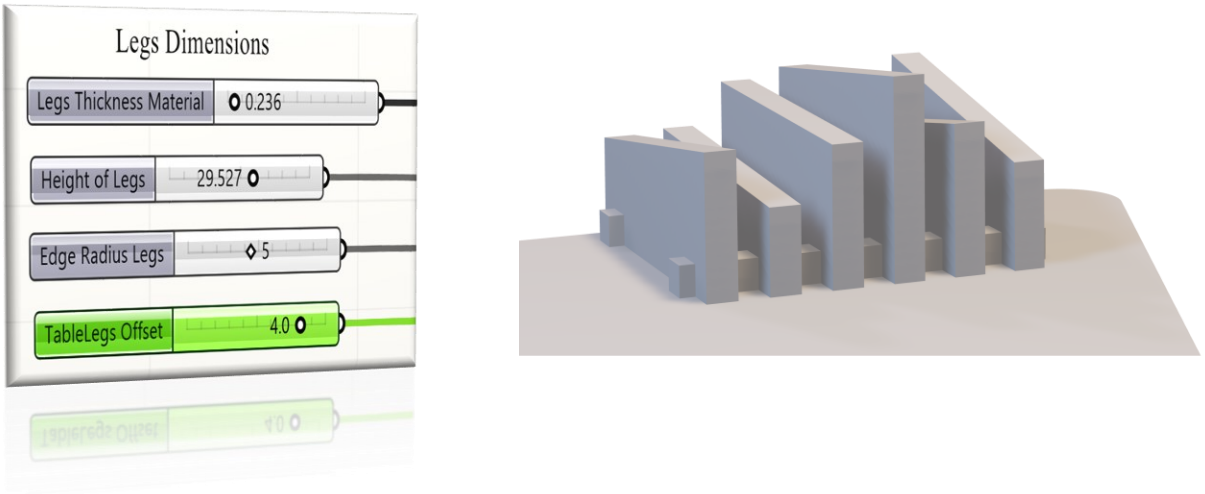


Figure 33 - Showcasing how the 3D model is changed based on different inputs

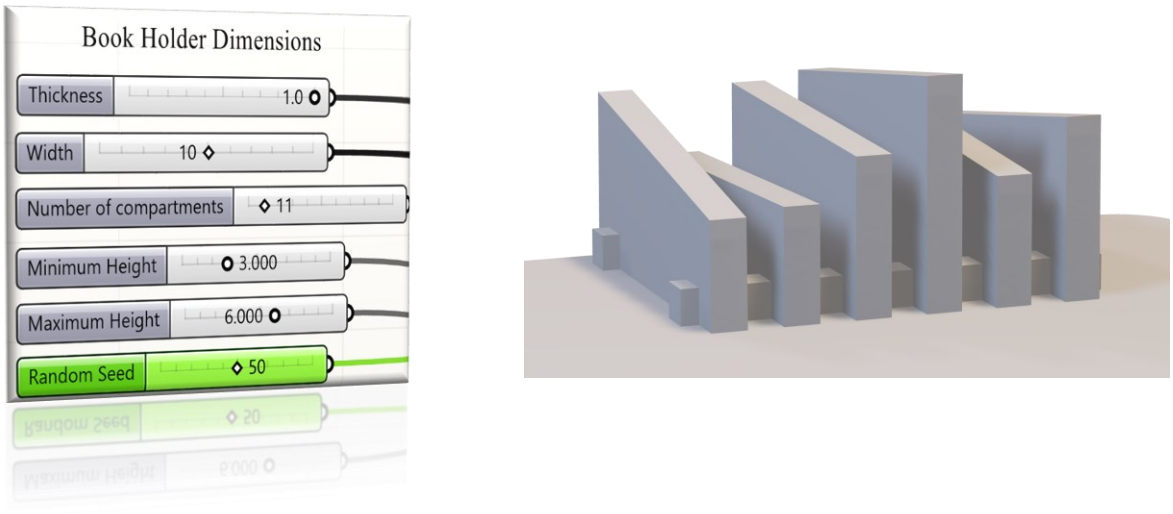


Figure 34 - Showcasing how the 3D model is changed based on different inputs

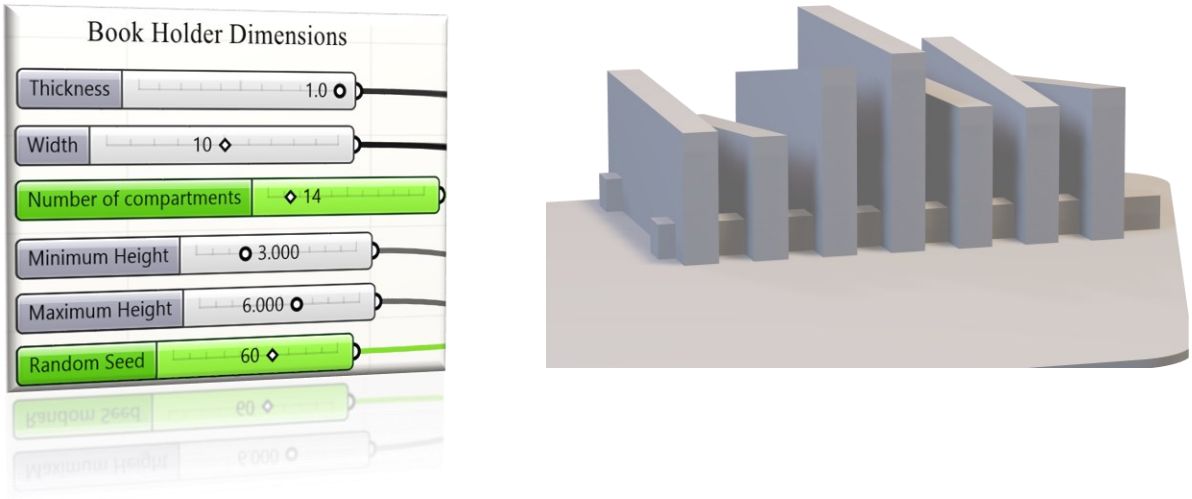


Figure 35 - Showcasing how the 3D model is changed based on different inputs

The next step in the algorithms was to create a customizable pen holder for the purpose of keeping everyday stationary. The pen holder can be customized on the basis of basic dimensions like length, width and height in addition to how much thickness of the table top the clamps will hold.

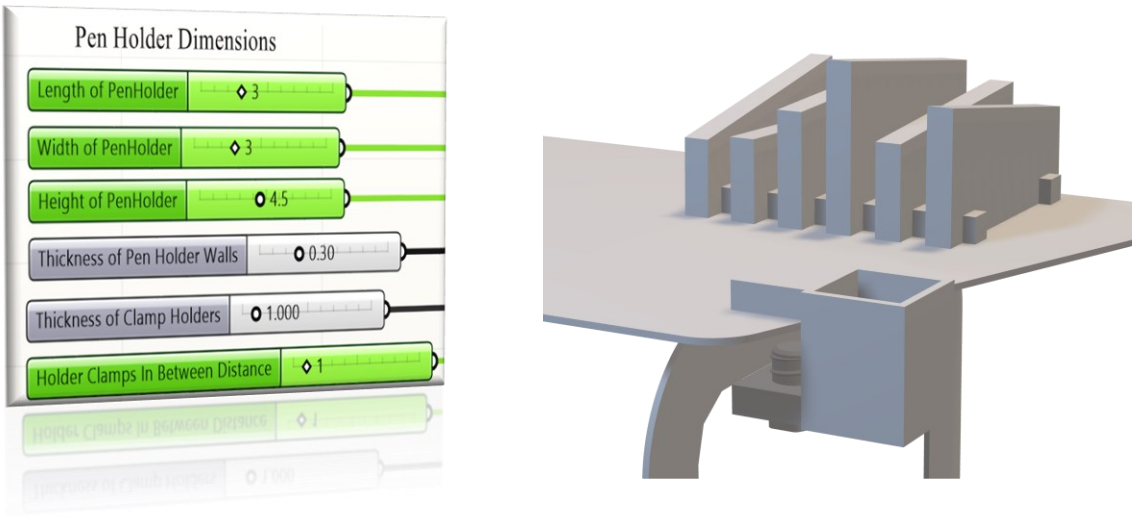


Figure 36 - Showcasing how the 3D model is changed based on different inputs

The next addition in the algorithms was to provide with the option to change textures based on the sketches drawn by the participant in the co-design session. The texture option is only applicable to 3D printed portion of the prototype which will be the pen holder, book holder and the wire holder. It is so because the participant did not want the whole furniture to be of that texture. They just wanted some parts to be that way.

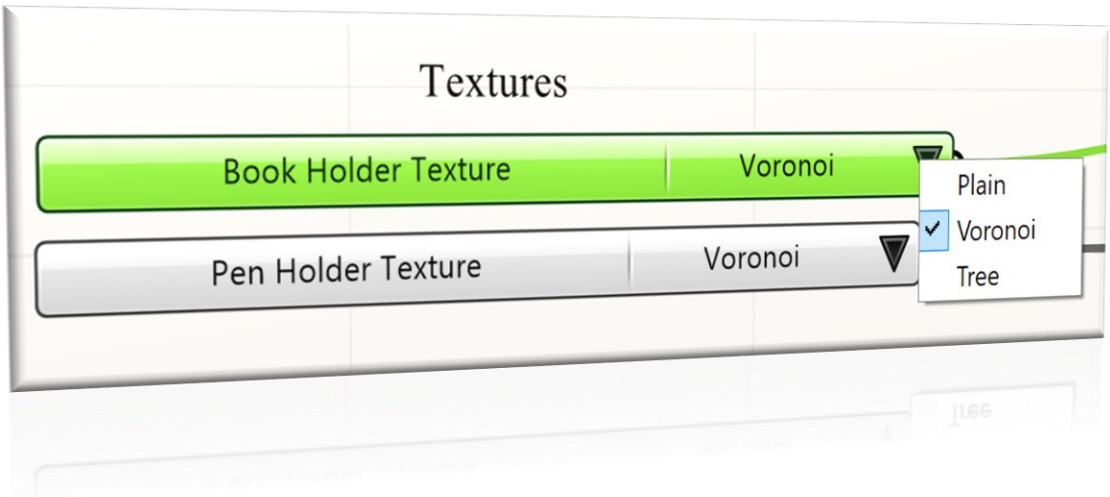


Figure 37 - Showcasing the texture options available in the algorithm

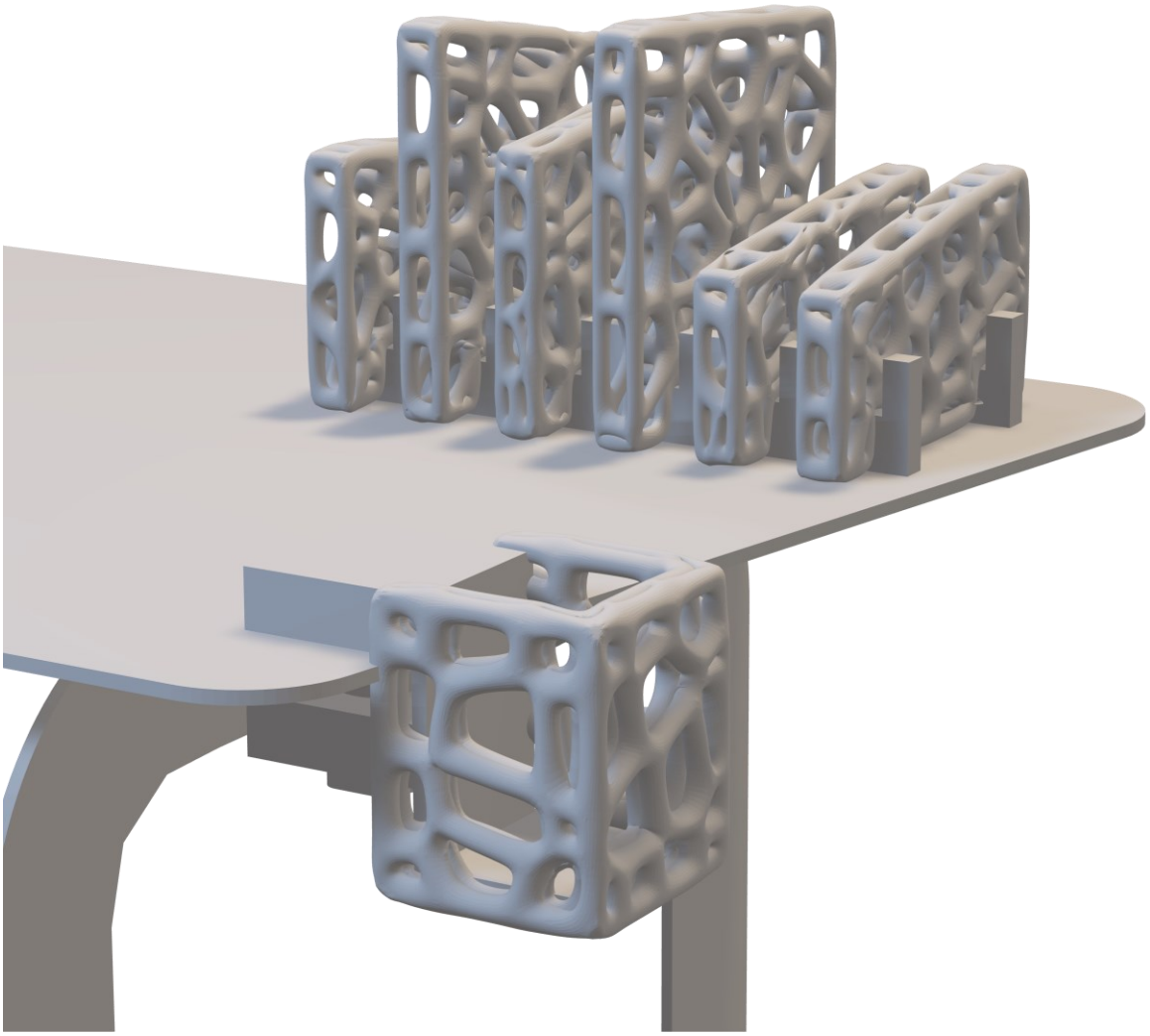


Figure 38 - 3D model showcasing the changes in realtime when different textures are selected

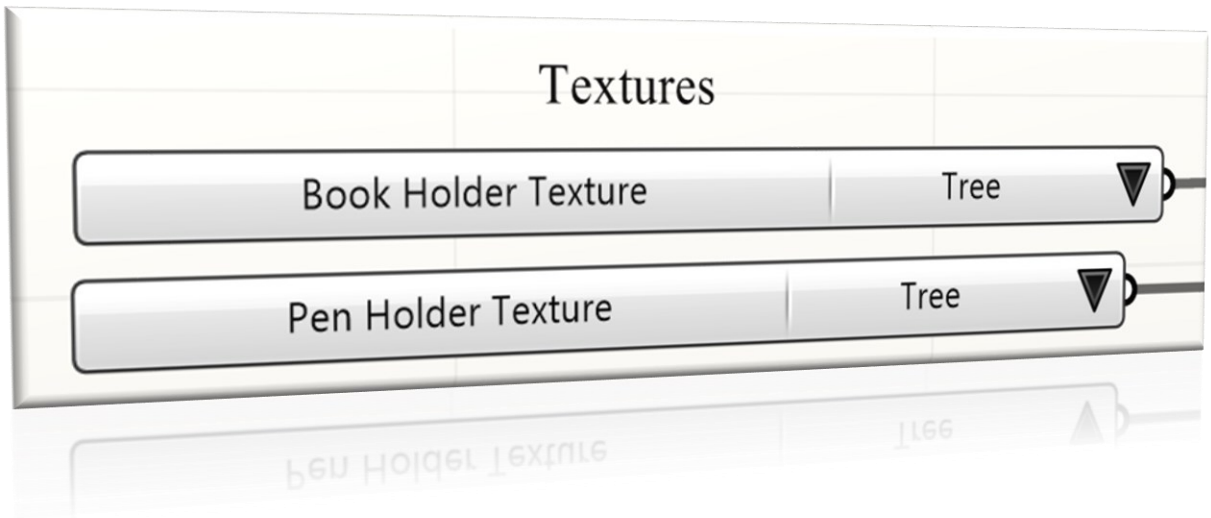


Figure 39 - Showcasing the texture options available in the algorithm

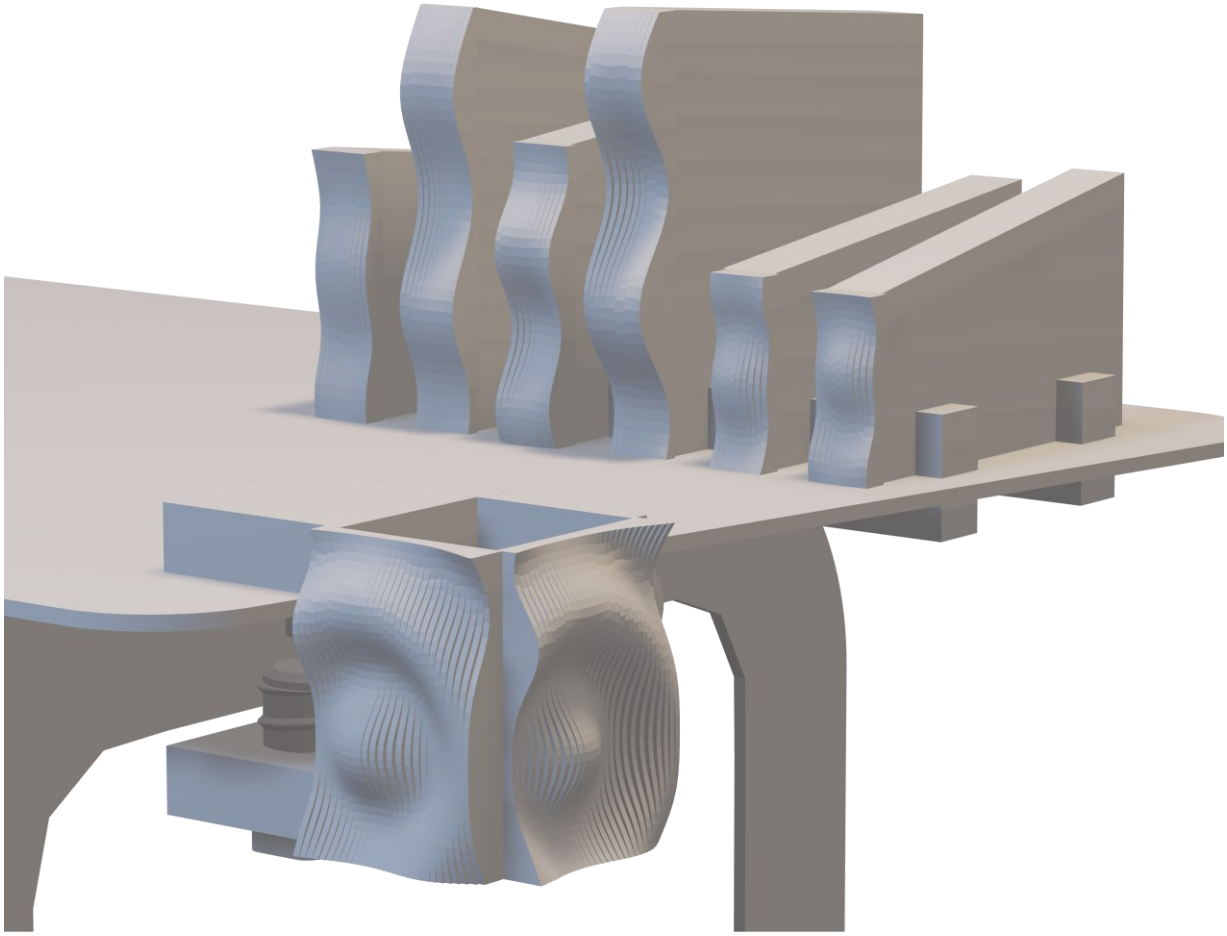


Figure 40 - 3D model showcasing the changes in realtime when different textures are selected

The participant themselves provided with the suggestion to keep them a part of the design process by sending them emails of the progress. This was done so that the prototypes are created after asking their preferences. The participant preferred the Voronoi pattern better and was satisfied with the look of the tabletop and legs. They also mentioned that the wire holder can be of Voronoi pattern, and everything is sufficient to be turned into a prototype for user testing.

The Voronoi texture in wire holder also provided automatic organic spaces in which wires can be held and kept clean.

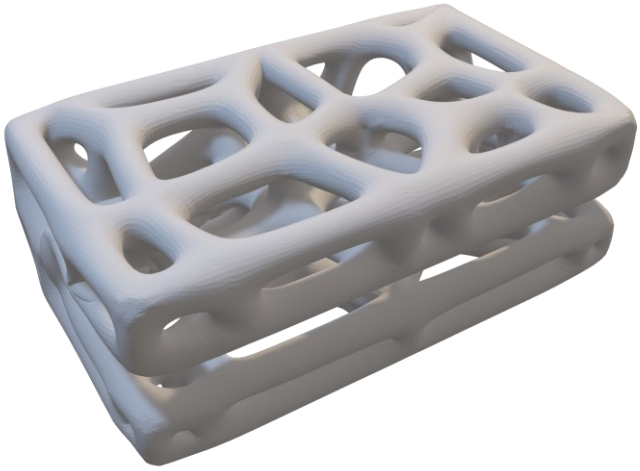


Figure 41 - 3D model showing the wire holder in chosen texture

The algorithms were finally coded to turn the 3D printed objects of the furniture piece into STL files and the laser cut objects into 2D curves. The prototype was ready to be created. The final render of the prototype that the participant found satisfactory is showcased in the image below.

Figure 42 - Final rendered image of the prototype to be created for user testing

7.1.2. PARTICIPANT 3

The participant required a portable drawing table that can be used while sitting on the floor, sitting on the existing table and standing using the existing table. So, the design was conceptualized in such a way that the whole system is working using 3D printed joints and interlocking screwless assembly so the tabletop can be taken out to be kept on the table if the requirement is to sit and paint on the existing table at an inclinable angle in addition to the portable table assembled with legs which can be either kept on the floor to paint while sitting on the floor or kept on the existing table to be able to stand and paint. The images for the grasshopper scripts can be seen in Appendix F.

The algorithm for this furniture allows the end user to customize its basic dimensions like length, width and height. The algorithm also allows the user to change the placement of organizers on the table legs depending upon their preference. The 3D printed joints are customizable too in addition to the shape of the organizers.

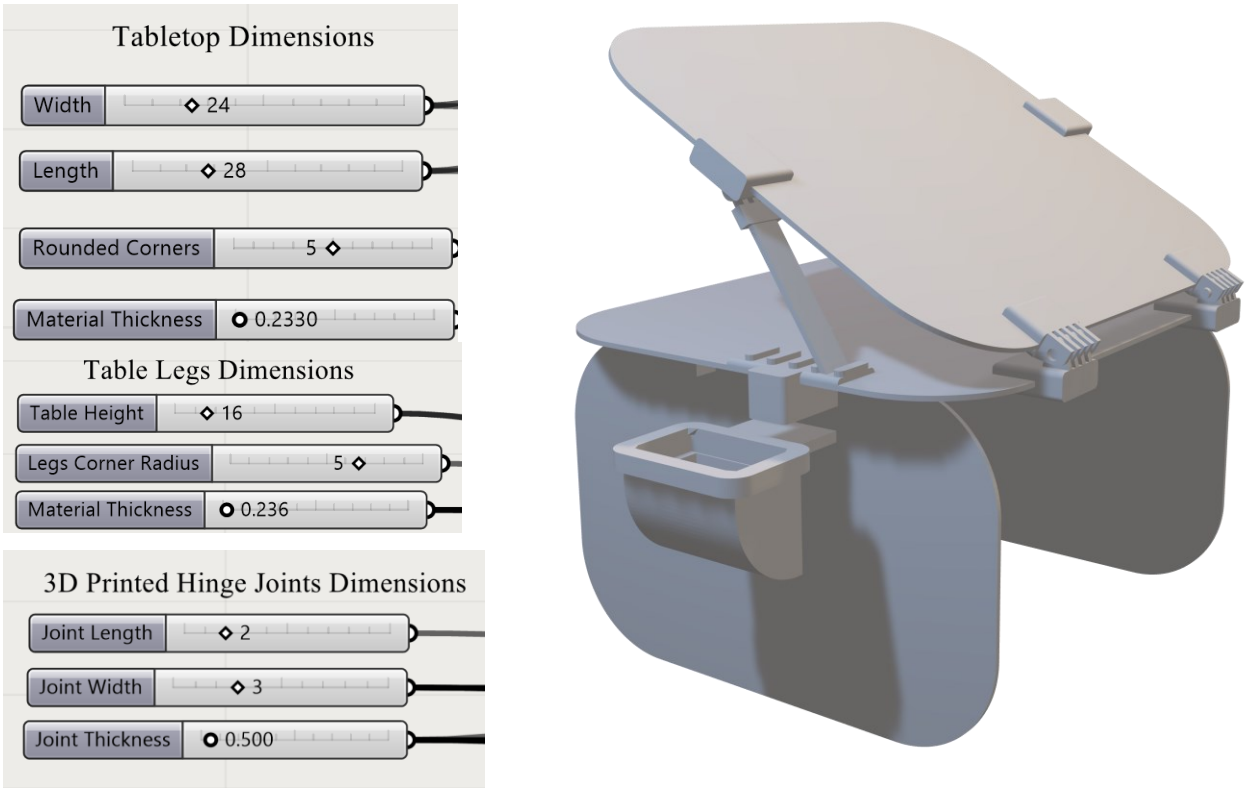


Figure 43 - Showcasing the customization available with the real time render

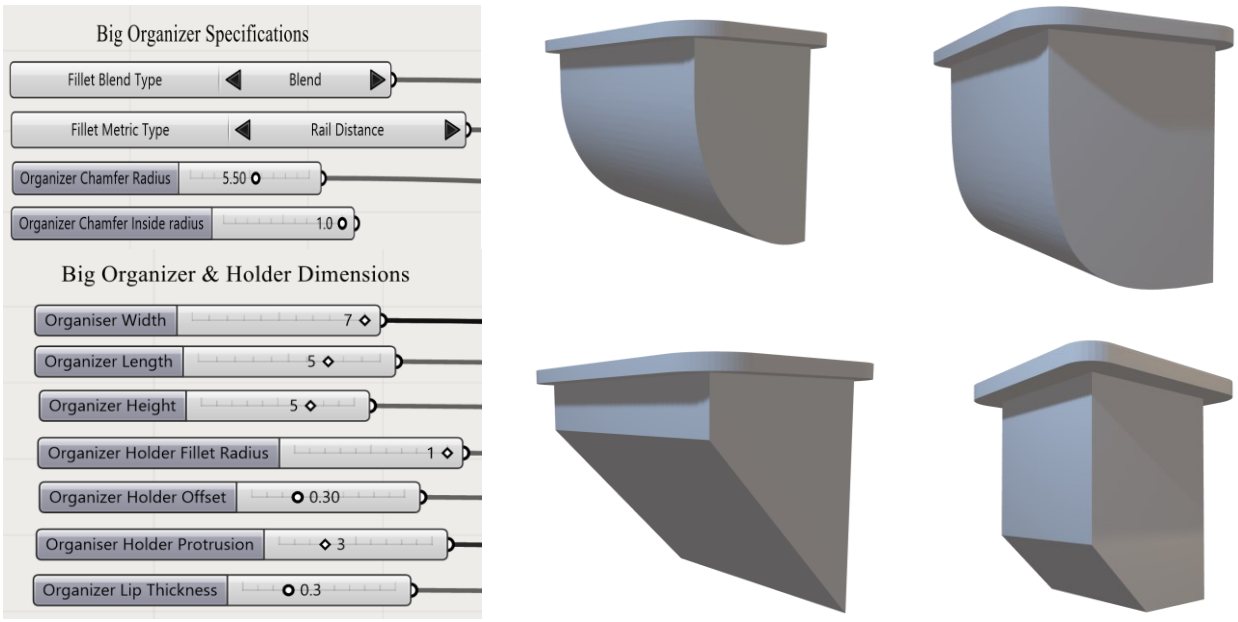


Figure 44 - Showcasing the options in the algorithms to customize organizers accompanying the furniture piece with renders

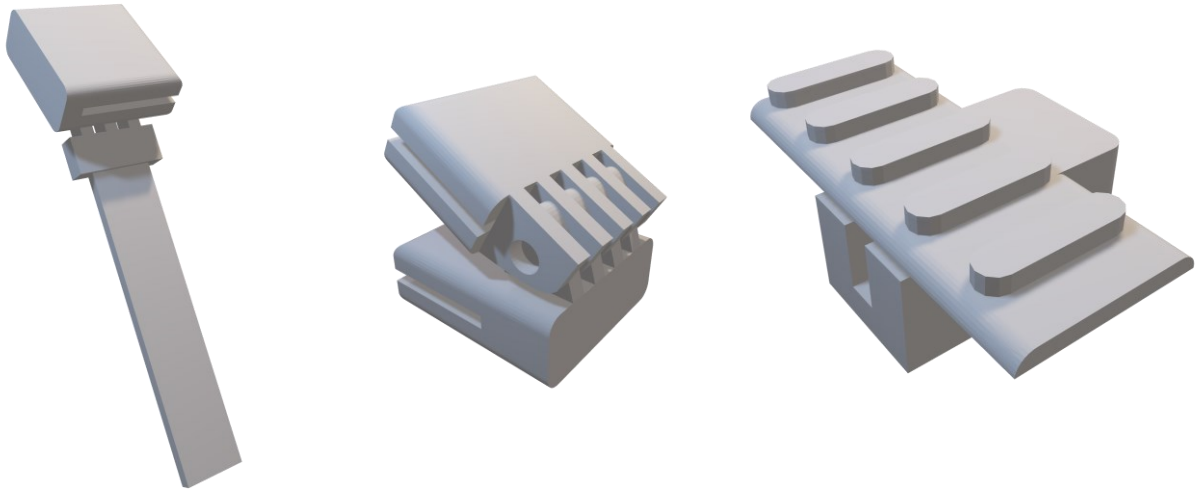


Figure 45 - 3D models showcasing all the different joints that can be created using the algorithm

The final render of the design that will be created as a prototype is in the image below.

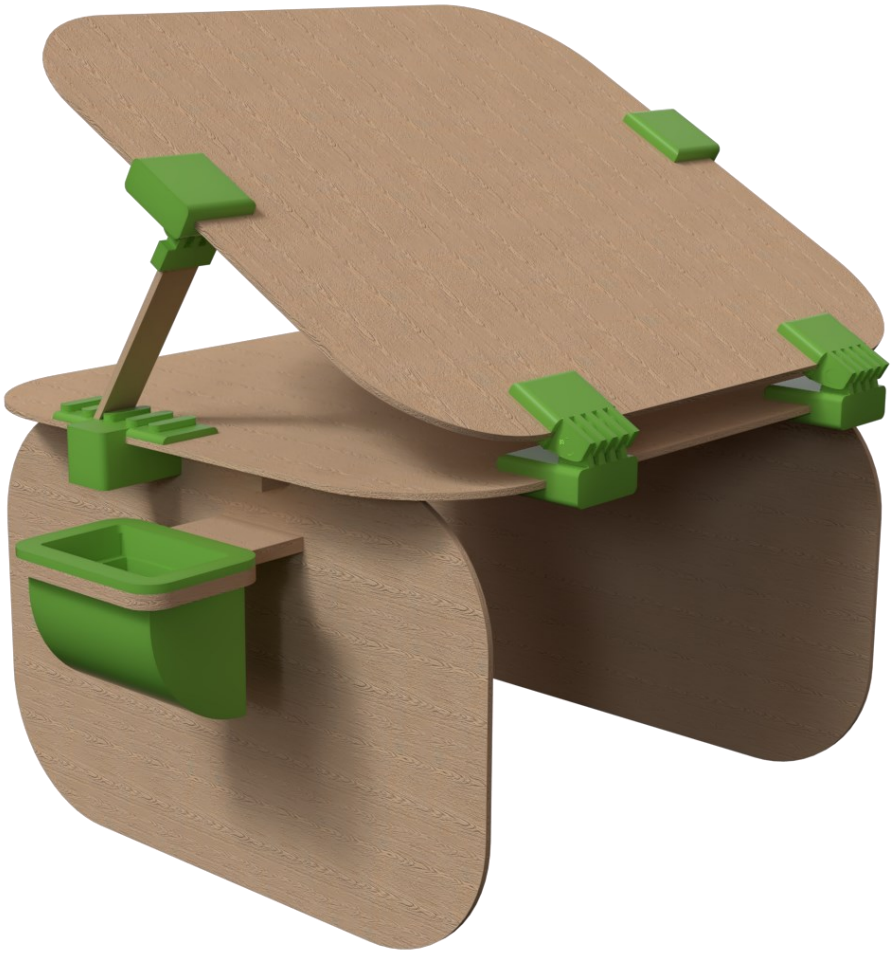
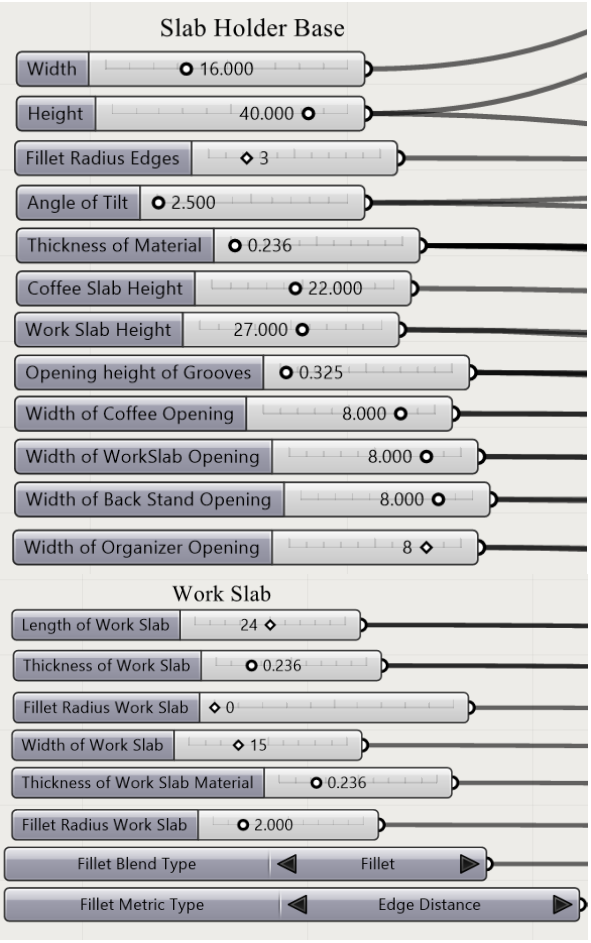


Figure 46 - Final render of the prototype to be created

7.1.3. PARTICIPANT 2

The algorithm generation for the second participant began by evolving the basic geometry created for coming up with a customizable design of a table where the height levels can be changed and set according to the preferred heights for various activities. The coding started by creating a base board in which multiple grooves or openings can be provided at desired heights for the interlocking of different dimensions of slabs as tabletops for different activities. The base board will be attached to a back stand in which the angle of both the things can be controlled

depending upon the space available in the room for depth of the table. The participant only requires levels for two slabs and organizers, so, the algorithm in this scenario has the option to control the height of three slab placements. The customizability of organizers is the same as that in the algorithm of participant 3. The images for the grasshopper scripts can be seen in Appendix E.



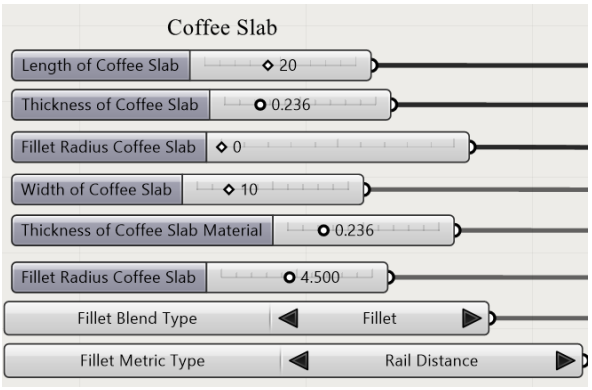


Figure 47 - Showcasing the customization available with the real time render

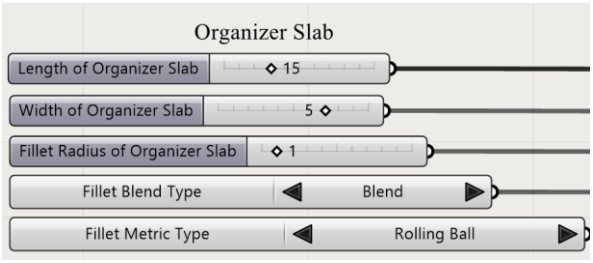


Figure 48 - Showcasing options for customizations

Only the table was created for this participant and not the bookshelf because of time constraints. The participant themselves provided with the suggestion to keep them a part of the design process by sending them emails of the progress. This was done so that the prototypes are created after asking their preferences. The participant was satisfied with the progress so that the prototype creation could go ahead. The final render for the design approved is in the image below.

Figure 49 - Final rendered image of the prototype to be created

7.2. 1:1 SCALE PROTOTYPES

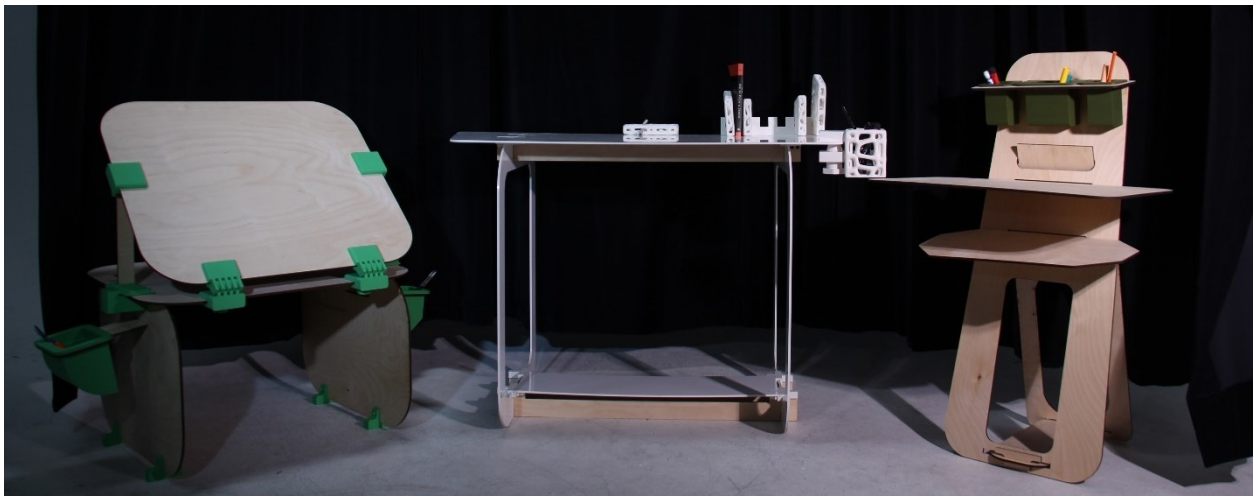


Figure 50 - Photograph of the final prototypes

8. USER TESTING

The user testing helped in providing valuable feedback in two phases. The first phase was to interact with the algorithms to use the slider options or input desired values which would showcase the customization changes in real time on the accompanying 3D model created. The second phase was to use the prototypes created as they would use their furniture while carrying out their daily activities. This was done to mimic the real-world scenario wherein people order things from online and get to see the actual product when it arrives to imitate real reactions and valuable feedback.

8.1. PARTICIPANT 3

The user testing started by making the participant use the customization options in Grasshopper and look at the changes happen in real time in Rhino. The participant provided feedback on how there were too many customization options and how there should be categories of simple and advanced controls in addition to having presets available for all kinds of audience. They mentioned that the user interface should also be visually more informational wherein it highlights the part of the furniture being customized and is near the 3D model instead of a split screen for both features. These things were already anticipated since the participants were made to use customizations in the software the algorithm was created. This was done to understand how to create an informed website interface in future for the end user to be able to customize with ease.

The second phase had the participant testing out the prototype. The participant on first look was very satisfied with the grass green color popping out in 3D printed organizers and joints in contrast with the plywood texture of the tabletop and legs. The participant was surprised by the stability of the prototype in all three purposes of sitting on the floor, sitting on chair and standing. The most stability was observed in the sitting on chair stage of the prototype. The participant was very satisfied by how stable the drawing table is while keeping it on an existing table to use it while sitting on a chair. The participant also liked the ability to take the organizers out of their holds and how they could be kept facing you at a slant angle due to the chamfered and filleted bottoms.

Another thing the participant noticed was how they thought that the scale of 3D printed joints in the 3D model would be too big and obstruct their hands while drawing but it was not the case when the actual prototype was used. So, they raised the need in the customization interface to better understand the sizes by having a human figure too.

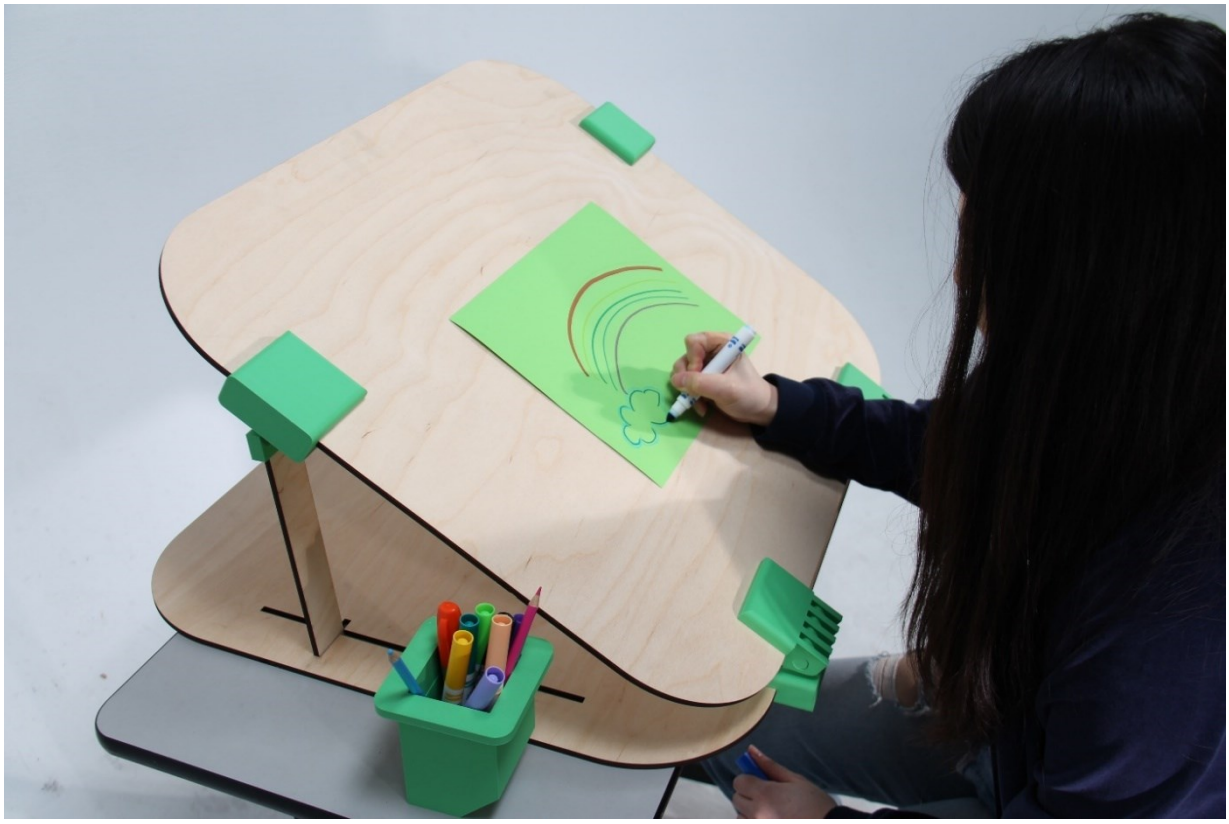


Figure 51 - Showcasing the multi-purpose feature of the table where it can be used while sitting on an existing table to sketch with an inclined surface

Figure 52 - Showcasing the inclining ability of the table

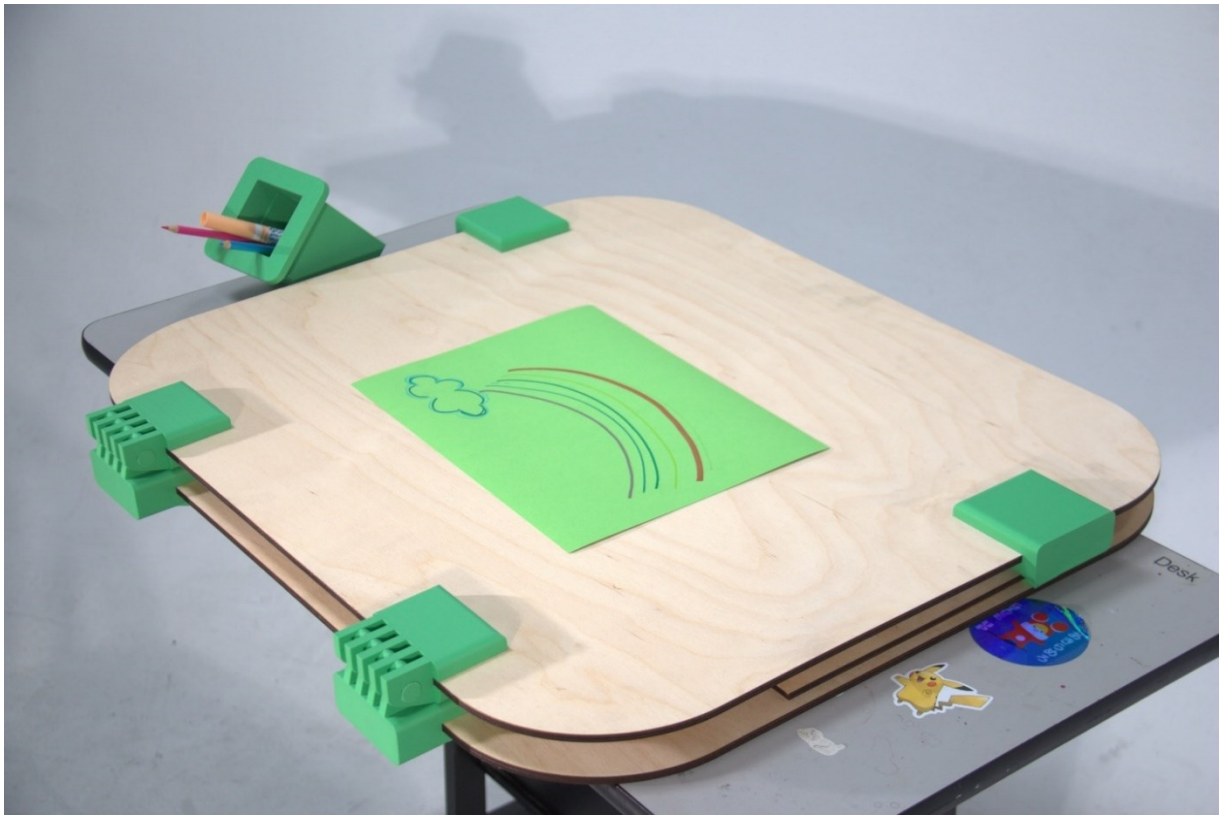


Figure 53 - Showcasing the table in flat position

Figure 54 - Table being used in a flat position with the organizers being kept on it in a way where there is easy access

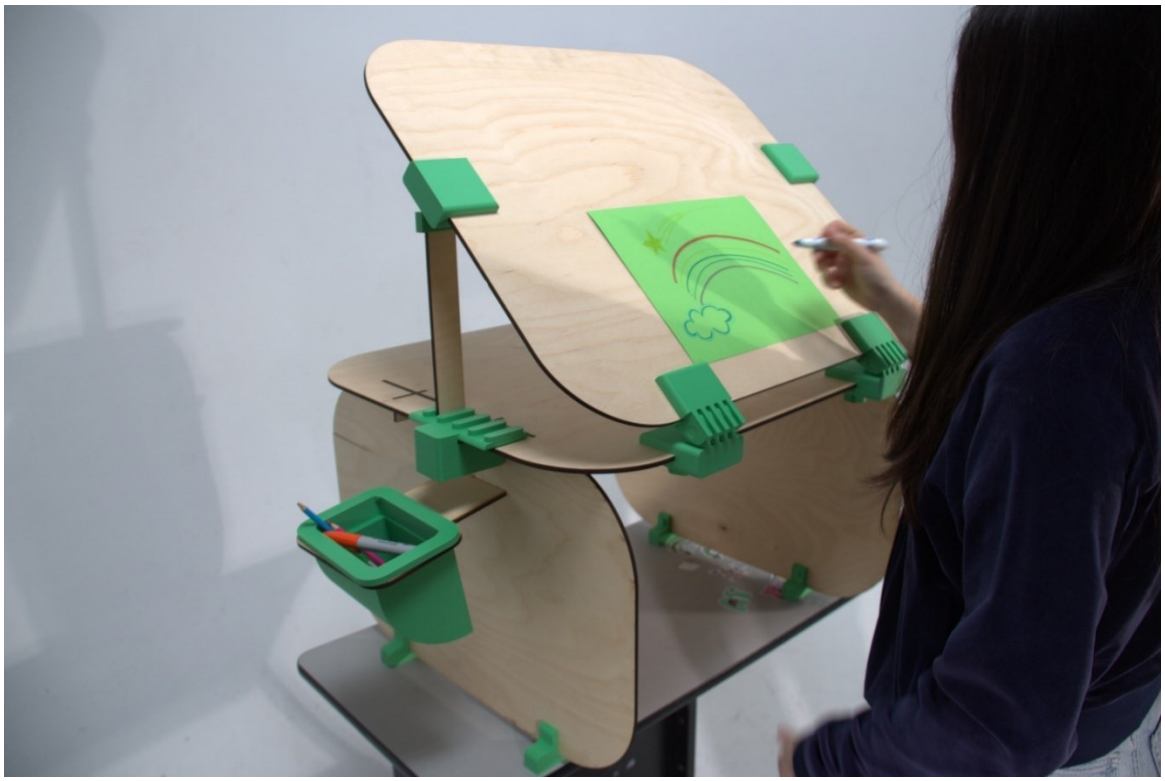


Figure 55 - Showcasing the multi-purpose feature of the table where you can stand and paint too

Figure 56 - Showcasing the multi-purpose feature of the table where you can stand and paint too

Figure 57 - Showcasing the multi-purpose feature of the table where you can sit on the floor and paint too

Figure 58 - Showcasing how the organizers can be easily placed on the table for quick access

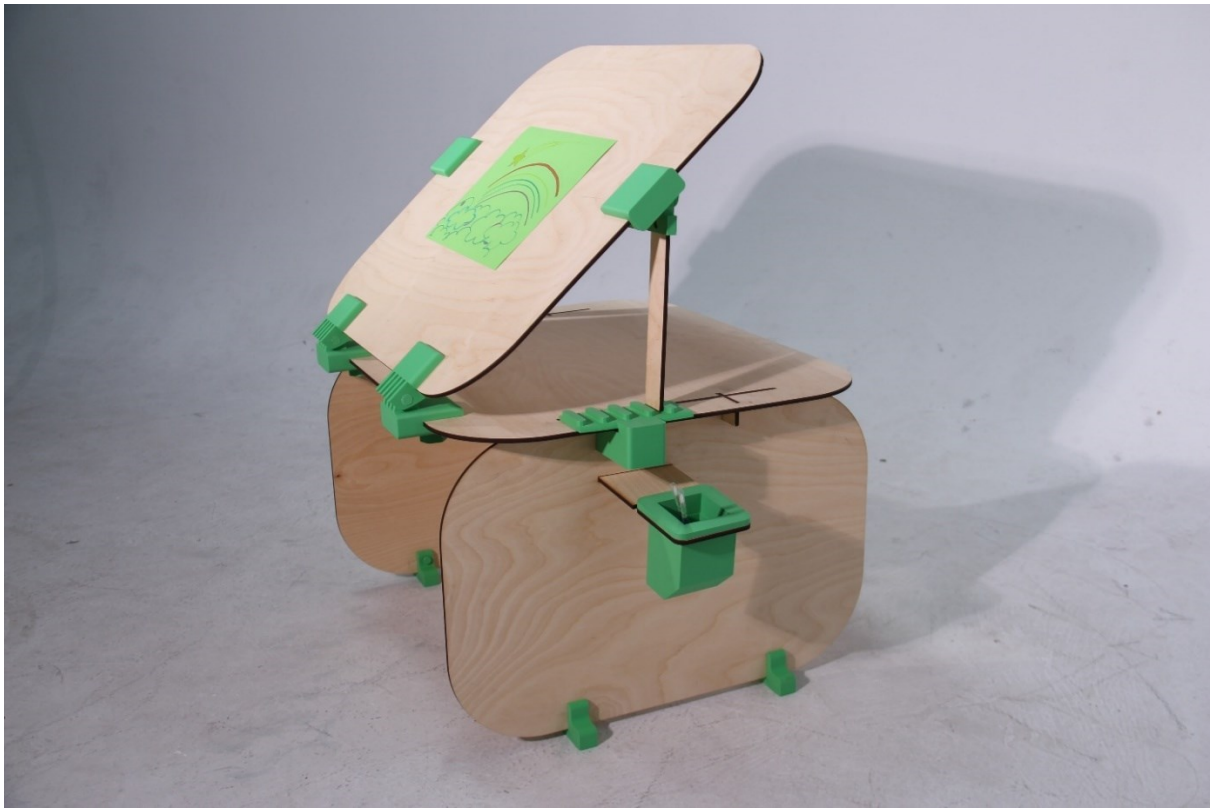


Figure 59 - An image of the prototype

8.2. PARTICIPANT 1

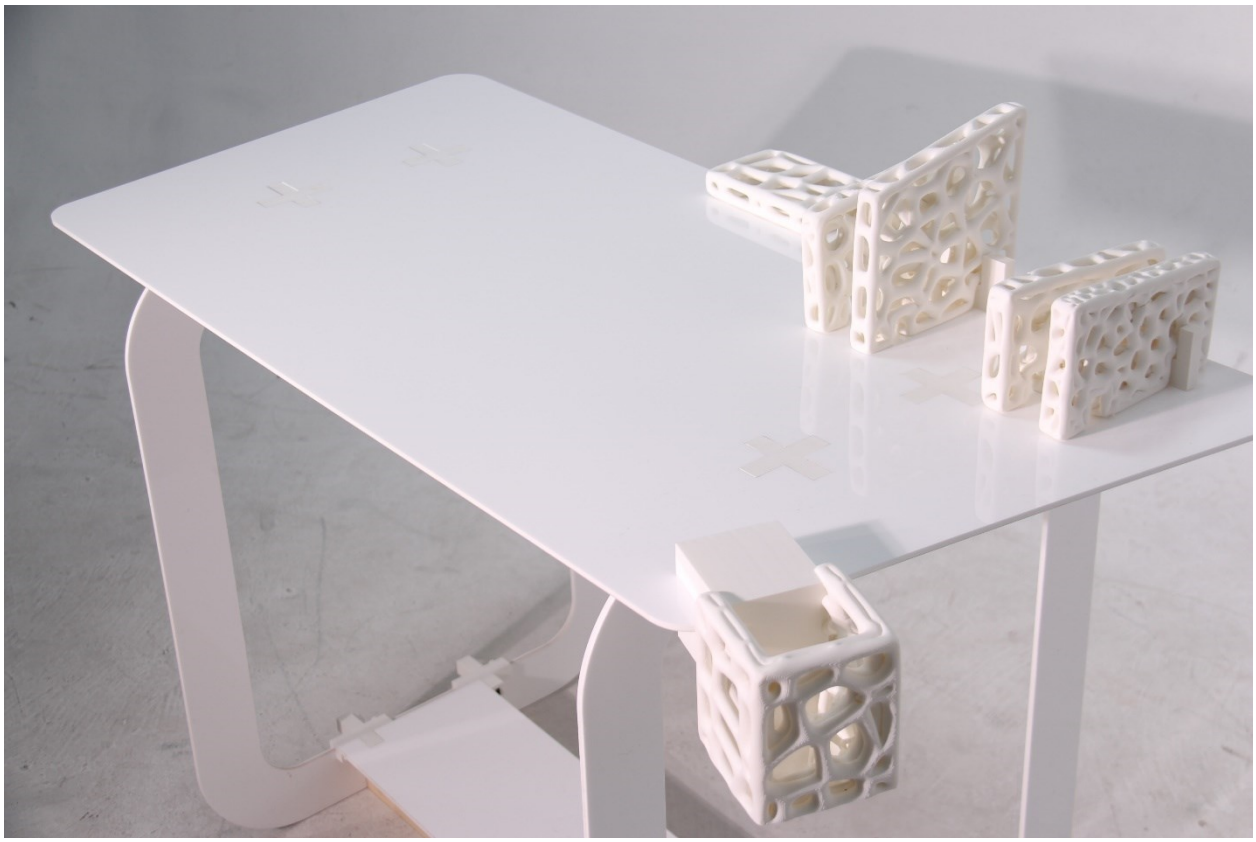


Figure 60 - Photograph of the final prototype with all accompanying organizers and storage

The participant began the user testing by interacting with the algorithms to customize the furniture piece. The feedback provided was the same as the previous participant in the sense that the customizations were too many and the interface was not visually intuitive.

The second phase had the participant interact with the prototype. The participant was very satisfied with how 3D printed Voronoi textured accessories looked and felt. They were mesmerized by all white look that they wished. They used the book holder, pen holder and wire holder the way they would be using it in daily life and were satisfied with the agency it provided. The book holder was not just useful for storing books but also to keep pen drives, rings and pencils in the openings created because of the texture chosen. They found the modular aspect of interchangeable book ends very useful. The wire holder was also better than the one they own is what they mentioned since the wire gets stuck in them and doesn’t fall on the floor when not in use which is not the case in the one they have previously used. The penholder could also be

integrated into the book holder due to both the products modularity if side clamping was not permissible.

The only drawback in the prototype was the side-to-side wobble when pressure was applied. The prototype was stable in back-and-forth motions but side to side stability was not up to the mark.

Figure 61 - Photograph showcasing different permutations of organization and storage

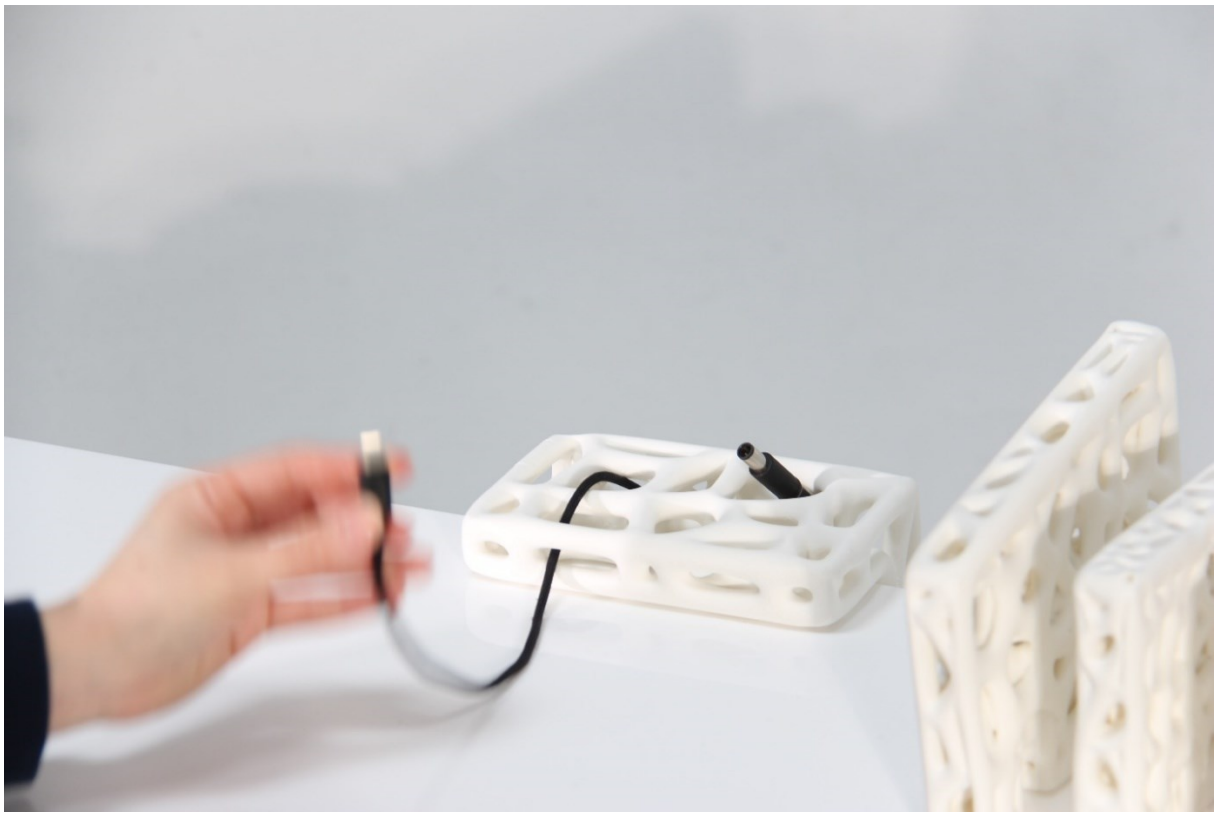


Figure 62 - Photograph showcasing the wire holder in use

Figure 63 - Photograph showcasing different permutations of organization and storage

Figure 64 - Showcasing engagement with the prototype

Figure 65 - Experiential use cases being tested

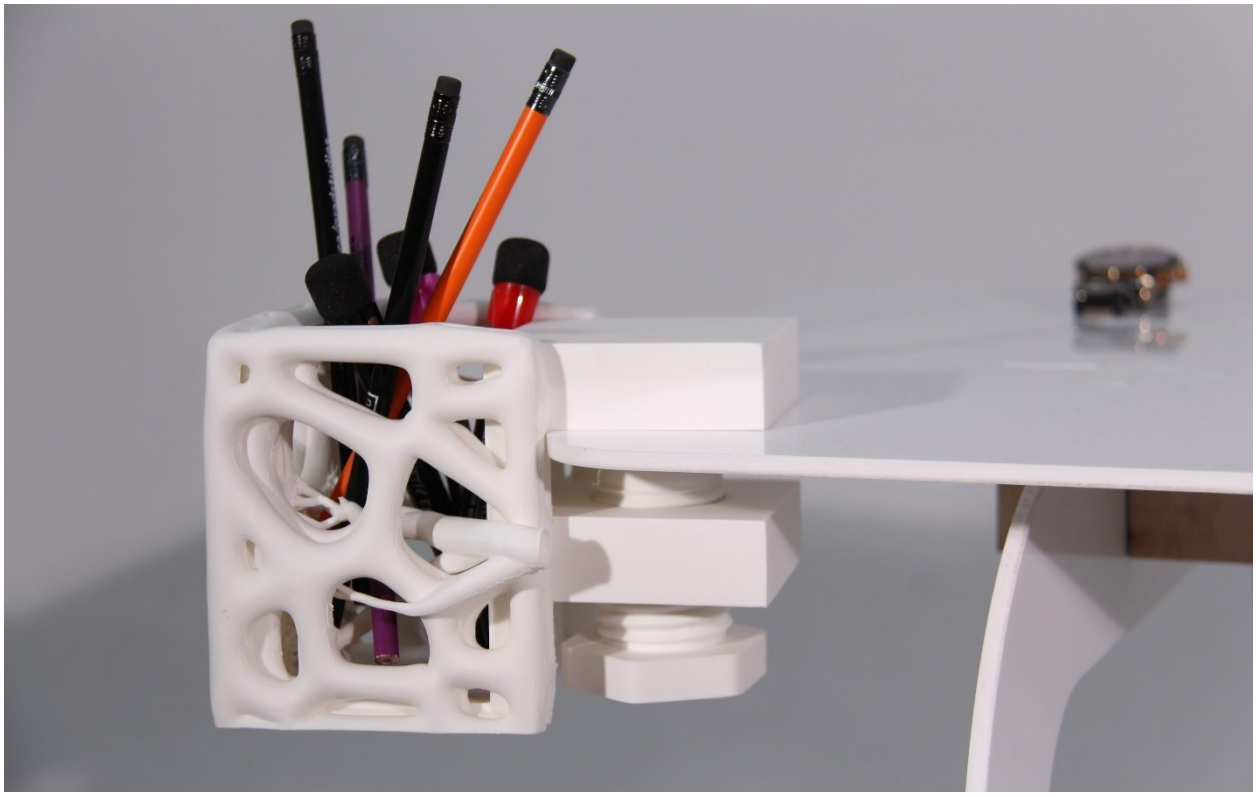


Figure 66 - Showcasing the pen holder with items

Figure 67 - Intuitive use cases being identified like storage for rings

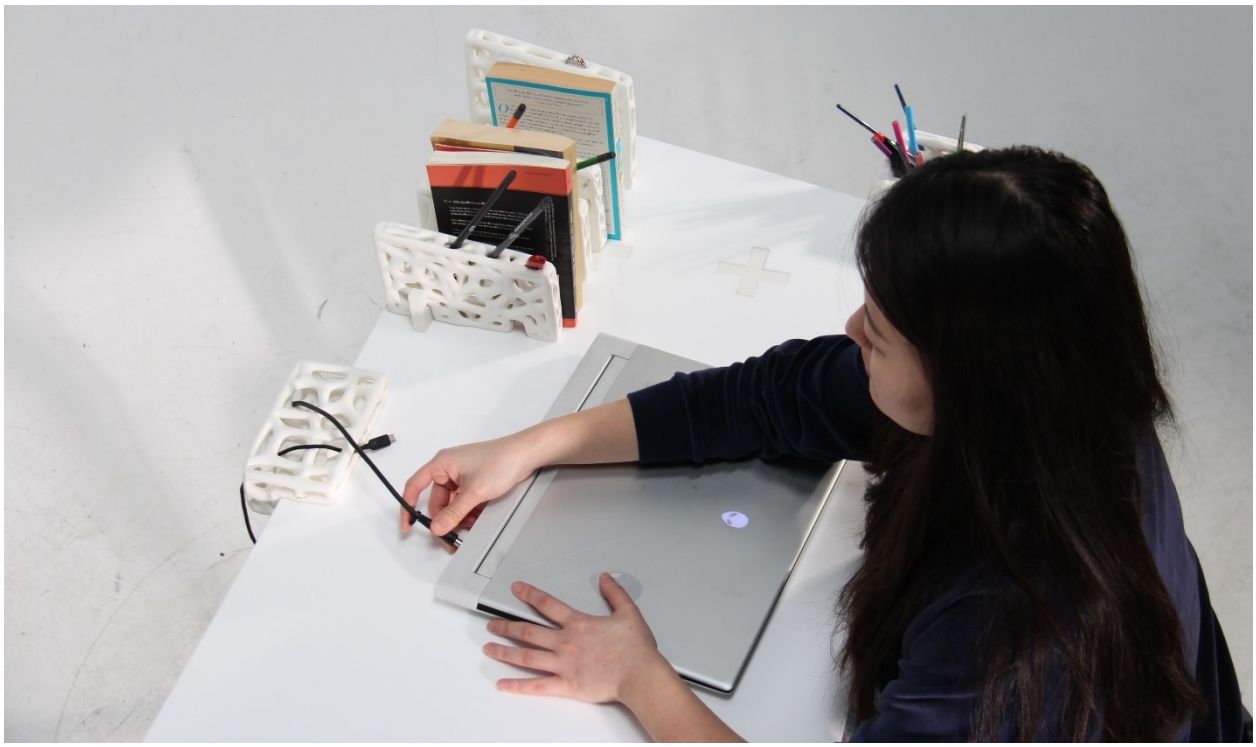


Figure 68 - The prototype being tested for different use cases

Figure 69 - The prototype being tested for different use cases

Figure 70 - Modularity of the organizers of being fitted in one spot

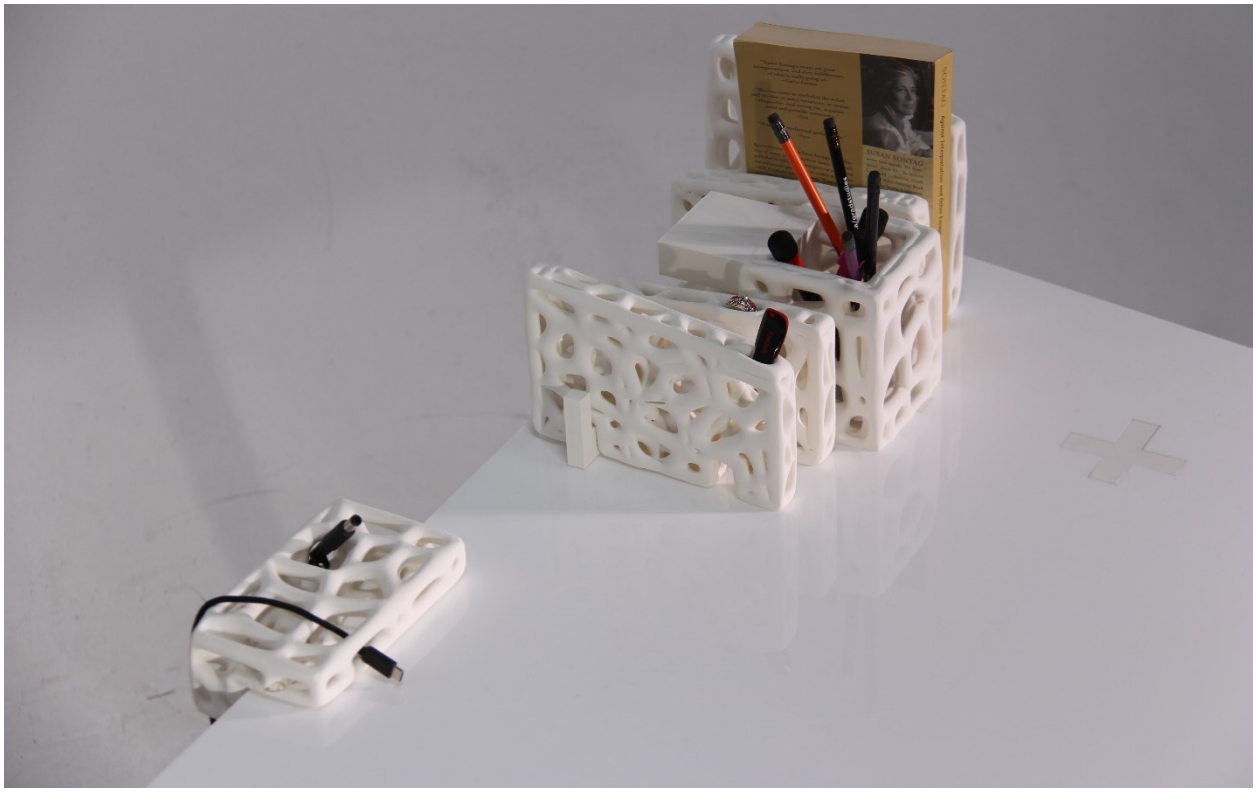


Figure 71 - User testing scenarios

Figure 72 - Image of the prototype in respect to the participants daily activities

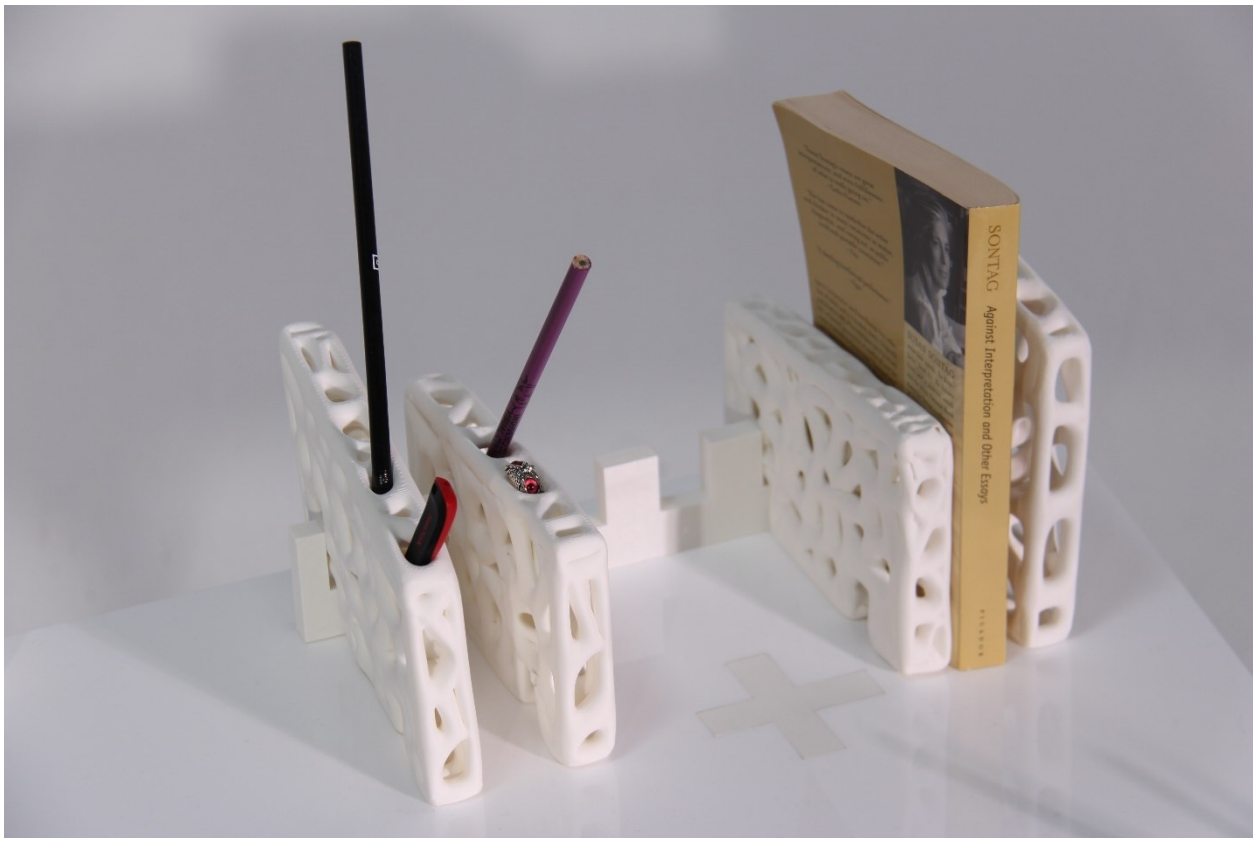


Figure 73 - Multiple use cases for the book holder

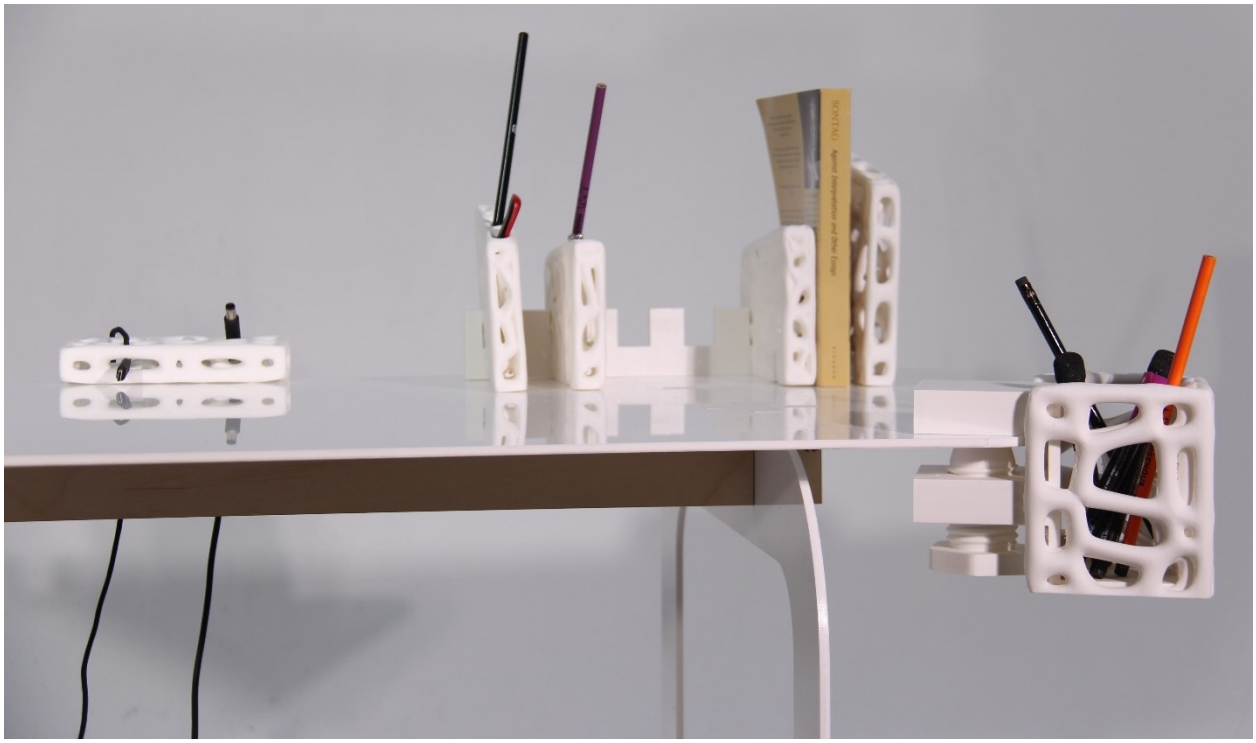


Figure 74 - Showcasing the accompanying organizers

8.3. PARTICIPANT 2

The participant mentioned the same issues as the other two in the first phase of customizing the furniture piece while using the algorithms.

The second phase had the participant testing the prototype wherein they were satisfied with the design considering the less amount of space they have in their room, the furniture provides the perfect way to incorporate multiple heights. They were satisfied with the quality of 3D printed organizers and the way the color looked. Some issues in the prototype were the height was a bit low and the coffee table slab was sinking a bit and was not parallel to the ground. The organizer slab was the same. The working slab was perfectly parallel though. The participant also brought to realization how books can be kept between the organizers on the table itself.

Another thing that the user testing brought to realization was that the participant who suffers from arthritis could assemble the furniture piece easily under 2 minutes.

Figure 75 - The prototype being tested for multiple use cases

Figure 76 - The prototype being tested for multiple use cases

Figure 77 - Image showcasing the prototype

Figure 78 - Image showcasing the full prototype

9. FINDINGS & LIMITATIONS

9.1. AUTOETHNOGRAPHY

- The autoethnography was beneficial in forming the base of algorithms to be able to change basic dimensions of the furniture parts.
- The algorithms were additionally evolved to create fixed and hinge joints as well to provide structural support to multiple permutations of forms desired.
- The prototypes created showcased smooth flow of movement to create movable parts through the use of hinge joints.
- The 3D printed joints showed very less structural stability because the infill percentage, i.e. the percentage of material to air inside of the object printed, was kept at 15%. The infill percentage will be increased in future prototypes.

9.2. SEMI-STRUCTURED INTERVIEWS

- The online semi-structured interviews held before the co-design sessions turned out to be very beneficial to preparing both the participant and the facilitator better for a fruitful conversation where the only goal for the facilitator is to make the participant elaborate more on their psyche of how the design should be without providing any prompts that are random because of a first meeting.
- The interviews concluded that all 3 participants wanted tables with proper organization and storage. It shows how important it is to understand people coming from different professions and cultures into the city of Toronto as international students whose style of working has very subjective tastes.

9.3. CO-DESIGN SESSIONS

9.3.1. PARTICIPANT 1

The first participant shared their pain points as follows:

- Wanting the table tops form to provide agency to their habit of tilting the laptop while working. Squares and rectangles provide a mental barrier against it.

- Invisible disability pertaining to losing focus in case of having symmetrical or coloured objects in sight while working.
- Prefers only white colour probably because of being a painter who wants their work canvas to be white so they can fill in the information. They mentioned it distracted them.
- Believed in functionality over aesthetics evolving the design to have basic forms with a splash of organic textures for storage and organization accompanying the furniture like wire holder, book holder and pen holder.

9.3.2. PARTICIPANT 2

The pain points shared by this participant are as follows:

- Requires a table where the height can be adjusted while sitting on a chair for it to be used for working at a normal height and relaxing like a coffee table height.
- The participants shared about their visible disability of arthritis and how things if needed to be done manually should be lightweight.
- The participant's likeness towards specific colors for storage and organization and wooden texture for table was shared.

9.3.3. PARTICIPANT 3

The pain points shared by this participant are as follows:

- The participant requires a portable drawing table with inclinable top feature and a low height for being able to sit on the floor to paint and sketch.
- The participant loves grass green colour to get a feeling of staying connected to nature.
- The participant already owns a table which does not incline and would love the table to have multiple purposes of sitting on floor, sitting on chair and standing use.

9.4. ALGORITHM CREATION

9.4.1. PARTICIPANT 1

- The algorithm for creating furniture table where basic dimensions can be customized was evolved to generate forms where the angle of the tilt of the sides of the table can

be inputted to create a trapezium shape for building the agency to tilt your laptop while working easily.

- Another script was created where the algorithm can generate random seeds for a book holder which is always asymmetric governed by the parameters of minimum and maximum height, top surface angle tilt range and number of compartments.
- A script for penholder and wire holders was also created with options for customization of basic dimensions.
- Scripts were created to apply textures sketched by the participant during co-design sessions so that they can be applied to the book holder, pen holder and wire holder.

9.4.2. PARTICIPANT 2

- Algorithms were created to design an easel like table consisting of openings to insert your work, coffee and organizer slab based on the height inputted for each.
- The algorithm can also dictate the depth of the easel stand by changing the angle of tilt between the base board and back stand for space adaptability.
- Scripts were created for organizers which could be customized based on basic dimensions and shape having blend, fillet and chamfered edges at the bottom.

9.4.3. PARTICIPANT 3

- The algorithm creation for this table was very similar to the one done in autoethnography. The scripts for basic dimensions, fixed joints and hinge joints remained the same. The only addition was to be able to fillet the edges on the joints for smoother edge feel.
- This algorithm also had scripts for customizable organizers the same as previous one.
- The algorithm also automatically created a screwless assembly for tabletop, legs and anchors for it to be used under multiple purposes.

9.5. PROTOTYPE CREATION

9.5.1. PARTICIPANT 1

- The material used for the tabletop and legs was white cast acrylic of a 6mm thickness. It was laser cut with a KERF tolerance of 0.2mm added in the algorithms.
- The 3D printed book holder, pen holder and wire holder were made with ivory white PLA Matte filament having an infill percentage of 20%.
- The anchors supporting the legs and tabletop were made of birch plywood of 6mm thickness. It was laser cut with KERF tolerance of 0.2mm.

9.5.2. PARTICIPANT 2

- The material used throughout was birch plywood of 6mm thickness. It was laser cut with KERF tolerance of 0.2mm.
- The organizers were 3D printed with dark green PLA Matte filament with infill percentage of 15%.

9.5.3. PARTICIPANT 3

- The 3D printed components were printed with Grass Green PLA matte filament with infill percentage of 50%.
- The laser cut material was birch plywood 6mm thickness with KERF tolerance of 0.2mm.

9.6. USER TESTING ALGORITHMS

- All the participants were asked to interact with the algorithms created on Rhino and Grasshopper to instill a sense of real-world scenario of the customer purchasing something online versus the reaction of actually owning and feeling the product on delivery.
- The participants shared a similar kind of feedback regarding the user interface not being visually interactive and the number of options for customizations being overwhelming.
- The user interface needs to be able to highlight the part being customized with sliders nearby.

- The provision for presets, simple controls and advanced controls was also suggested for different kinds of user moods.
- All the participants mentioned the need for a digital domain where furniture can be bought by applying such customizations. They also mentioned that it should only take 15 minutes max by having maximum 10-15 options for customizations.

9.7. USER TESTING PROTOTYPE

- All the participants were very satisfied with the prototypes. They described them to be exactly what they wanted aesthetically and functionally.
- The prototypes produced use cases that were not intended while designing as well. The intuitive use cases were in line with the persona of the participant and provided a step beyond the intended modularity and multi-purpose features.
- The only drawback found during user testing were minor stability issues like a bit of wobble too much pressure is applied.
- All the participants agreed to wanting such customizations available through a website or an app.

9.8. FINAL THOUGHTS

- The study did not turn out to be just a traditional product design journey, but it was a journey using the principles of inclusive design techniques which are co-creation, co-discussion, use case testing, etc. The theory was about using generative algorithms to customize furniture and digitally fabricate it. The end results were satisfactory based on the user testing feedback. The engagement of the participant with the final prototypes returned valuable feedback containing a lot of positives. The participants loved the fact that they were able to own what they customized with the only drawback being confusion and overwhelm caused due to too many parameters or options to choose from. It was also to do with the fact that they interacted with a back-end interface where the algorithms are created and useful for the people dealing with the fabrication aspect. Nonetheless, the outputs achieved modularity, adaptability and personalization as aspired for the users.
- Credit goes to the whole idea of co-creation or user involvement in the design process, we identified that there was more to the design than what meets the eye. The participants were

able to add their own touch to it during user testing by coming up with personal or subjective use cases that were not intended while designing showcasing the multi-purpose and modular ability of the digitally fabricated output using generative algorithms informed through co-design sessions.

- The field of Inclusive design helps the study reap benefits because of the involvement of the end user at every step of the process. The design evolves into something beyond the furniture use case. It becomes personal like a comrade helping along the way in your daily life, assisting you at every step.
- The goal was to design a customizable furniture solution for participants but if we dive into the micro level of the study, it consisted of designing tables. Since the journey involved a collaborative and creative discussion with them, the output generated is more than a table. It becomes something that they can embody with their personal character and activities. Painters can put paintbrushes, fashion lovers can put their jewellery like rings and other products, etc. So, that's the benefit a user gets in this journey compared to IKEA or current shopping trends where they would have the same products designed without user involvement. The whole design process is adding so many layers of personalization and customization making the output lead to something that was not the intent in a positive way. This is the beauty of the framework followed in the study.
- The user testing brought forward intuitive use cases for all the prototypes which could have only been found by experiencing the product itself by the participant. The intuitive use cases are:
    1. The organizers in the prototype of Participant 3 when taken out could be kept facing the user at a tilt because of the customizations provided for chamfer, blend and filleting the bottom. The intended use of the customizations was aesthetics and smooth bottoms for easy hold. The intuitive use turned out be a pre discussed preference during the co-design session of the participant's liking towards organizers having a tilt for easy access to items.

Figure 79 - Intuitive use cases for prototype of participant 3

2. The book holder in the prototype for Participant 1 was meant intended to be modular in being to create the amount of space required in each compartment for the storage of books. The intuitive use realized during user testing was its ability to hold pen drives, rings, pencils and paintbrushes because of the texture selected which provided additional agency. Another intuitive use was the ability to create enough space using the modular compartments to incorporate the penholder inside if required.

Figure 80 - Intuitive use cases for prototype of participant 1

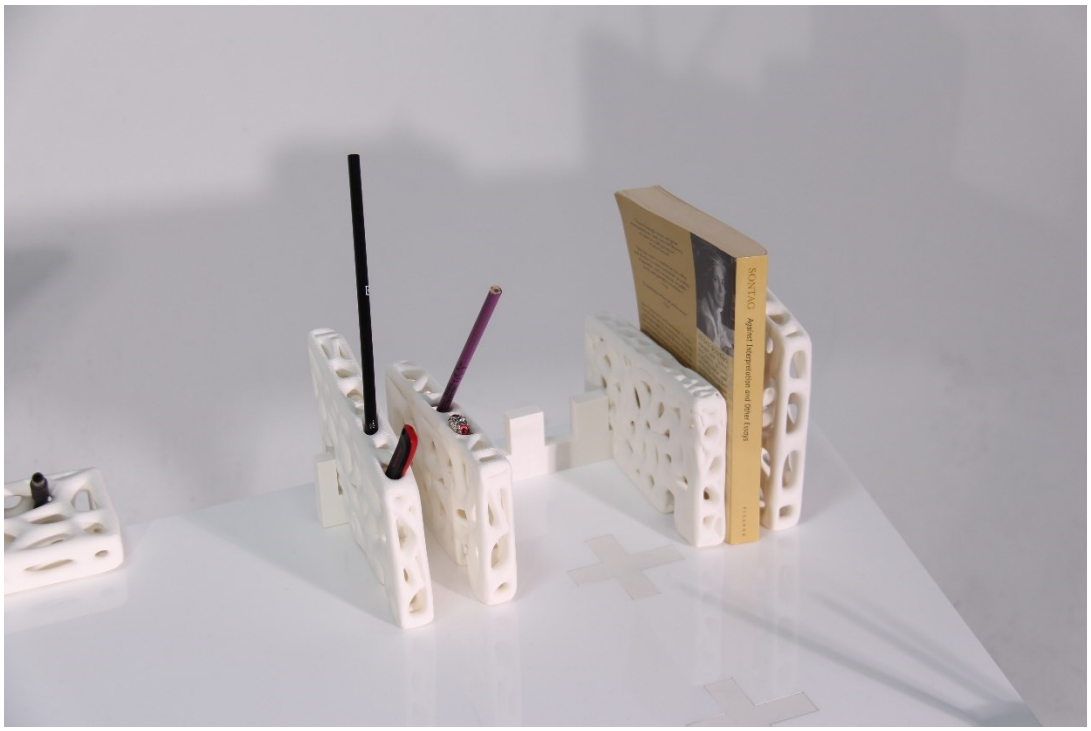


Figure 81 - Intuitive use cases for prototype of participant 1

3. The prototype for Participant 2 was found to intuitively provide space in between the organizers on the table for book and papers for quick access or display.

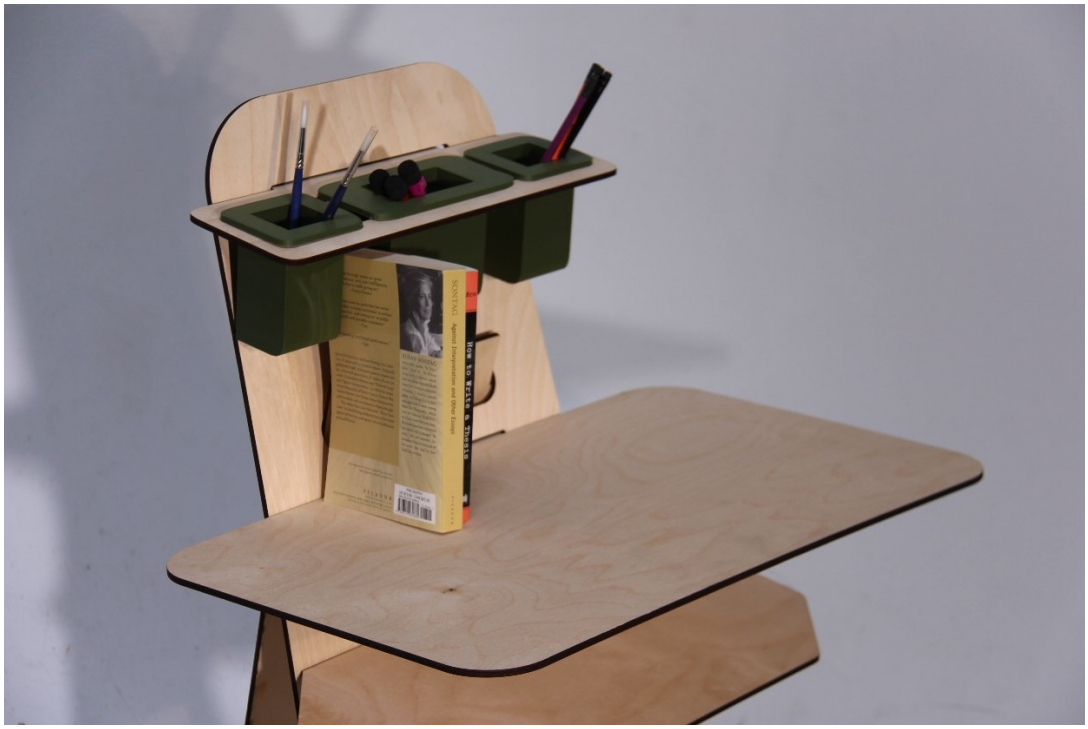


Figure 82 - Intuitive use cases for prototype of participant 2

- If this was an industrial or product design project, the tables will be designed and the algorithms and the output will be displayed at the end but we are going one step beyond where we are talking about the inclusive process where you bring people in the creative process, you conduct user testing to get feedback and the framework can keep constantly evolving.
- So, the algorithm is not just the Grasshopper script. The framework to develop that script which involved collaboration of people and presenting their needs and persona provides 2 layers of adaptability and customizability embedded within.

10. CONCLUSION

The research carried out the methodology described step by step in a proper manner. Starting with conducting autoethnography to create basic generative algorithms of furniture pieces. Then, conducting an online semi-structured interview with eligible participants to understand their needs. Hosting a one-on-one co-design session with the participants to elaborate on their needs on the basis of preferences, needs, traits, environment and activities to bring forth a collaboration to inform design decisions better. The participants were asked for their satisfactory level of the evolution of algorithms before the creation of prototypes as well. And the user testing provided such valuable feedback in the sense that all the participants were happy with how the actual product turned out since it was exactly what they wanted. Some negatives that were seen throughout were the lack of a better user interface while applying customizations digitally and a proper way to understand the scale before actually interacting with the product on the basis of just a 3D render. There were some stability issues as well that need to be looked into. But all in all, the participants were satisfied with the customizations that the algorithm provided on the basis of their personas. All the participants mentioned that they would want the agency to be able to customize their furniture the way we did in the study in real life as well. It provided agency at a very personal level. The research was successful in understanding the psyche of the end users with the help of interviews and co-design sessions to empower spaces into providing furniture that is modular, easily assembled, aesthetic and functional. The research was unsuccessful in providing a better user interface for said customizations and had minor stability issues in the final prototypes.

11. FUTURE POTENTIAL

The next step for the research should be to optimize the algorithms to provide better structural stability in addition to creating a better user interface digitally for customizations based on the feedback provided by the participants. Since this was an exploratory research or a pilot study, more participants should recruited for a rigorous study after sorting out the stability and user interface issues to keep on optimizing the algorithms.

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APPENDIX A: Screening Survey

Table A 1 - Overview of Screening Survey questions and types

S.NO.	THEME	SURVEY QUESTION	QUESTION TYPE
1.	Screening	Is your age between 18-40?	Multiple choice: • Yes • No
2.	Screening	Which of the following languages are you fluent in? (You can choose multiple options)	Multiple Choice: • English • Hindi
3.	Screening	What describes your living status best from the following? (you can choose multiple options)	Multiple Choice: • International Student • Non-resident working visa • General DIY lover living in Toronto or GTA for less than 5 years • Lived in Toronto or GTA for more than the last 5 years • Living on rental basis
4.	Screening	Do you relate to wanting modular customizable furniture in your room which could be cheap and customizable to fit perfectly in that empty space in the room in addition to fulfilling your daily needs?	Multiple choice: • Yes • No
5.	Screening	Are you willing to participate in an online interview (10-15 minutes) leading to a co-design session (1 hour 30 minutes long) to provide instances from your experience of living in your room and what kind of DIY modular furniture would you like that would make your life easier considering a lot of people live in small rental rooms where space is a constraint?	Multiple choice: • Yes • No

6.	Participant Information (only taken if questions 1,4 and 5 are answered yes and at least one option has been checked in questions 2 and 3)	What is your name?	Open ended
7.	Participant Information (only taken if questions 1,4 and 5 are answered yes and at least one option has been checked in questions 2 and 3)	What is your mobile number?	Open ended
8.	Participant Information (only taken if questions 1,4 and 5 are answered yes and at least one option has been checked in questions 2 and 3)	What is your Email address?	Open ended
9.	Participant Information (only taken if questions 1,4 and 5 are answered yes and at least one option has been checked in questions 2 and 3)	What is your age?	Open ended
10.	Participant Information (only taken if questions 1,4 and 5 are answered yes and at least one option has been checked in questions 2 and 3)	Which dates would be best suitable for you to conduct co-design sessions at 205, Richmond Street, Toronto or 100 McCaul Street, Toronto.	Open ended date input option

11.	Participant Information (only taken if questions 1,4 and 5 are answered yes and at least one option has been checked in questions 2 and 3)	Please choose the most suitable time slot. (You can choose 2 options)	Multiple Choice: • 10AM-11.30AM • 12AM-1.30AM • 3.30PM-5PM • 5.30PM-7PM • 7.30PM-9PM

APPENDIX B: Online Semi-Structured Interview

Table B 1 - Overview of Semi-Structured Interview questions and their types

S.NO.	THEME	INTERVIEW QUESTIONS	QUESTION TYPE
1.	Spatial Context and Overall Use (Context regarding location and what kind of furniture they envision for that location)	Can you think of any space in your room which could house a piece of furniture that would be perfect for your day to day needs and can you elaborate on the need and the design opportunity you have in mind that would help us design a perfect furniture piece for that spot?	Open ended
2.	Spatial Changes and Individual use (Regarding specifics changes within the use of the space and if any barriers exist for multiple purposes)	Can you also think of any multi-purpose or modularity that could be incorporated in that furniture piece that would make your daily life easier?	Open ended
3.	Dimension and Scale (To keep enough material available for low fidelity prototype during co-design session)	Would you be able to provide rough dimensions or a relative furniture piece of the design you have in mind to help with keeping appropriate amount of material for co-design sessions quick prototyping phase? Please provide an approximate dimension (length x breadth x height) of your room.	Open ended
4.	Assembly of Furniture (To understand how they like their furniture pieces to be assembled)	Which characteristic describes you best?	Multiple choice: • You would love your furniture to completely come as a kit which you can assemble. • You own carpentry equipment and dabble a lot with making furniture at home yourself. • You have phases and do both the things.

5.	Wellbeing and Aesthetics (To understand styles or colors they like which could be incorporated into the furniture piece)	If you could, describe a perfect room for yourself mentioning the furniture, theme or colours that would be ideal for you to have? This question can help us integrate some parts of your dream room into your current room design to inform the design better.	Open ended

APPENDIX C: Co-Design Facilitation Guide

Table C 1 - Co-Design Facilitation Guide

TIME	ACTIVITY NAME	GOAL	ACTIVITY INSTRUCTIONS	FACILITATOR INSTRUCTIONS	MATERIALS OR TOOLS	SPACE ARRANGEMENT
10 minutes	Introduction	The purpose of the introduction is to make the participant privy of the facilitator's details, aim and purpose of the research study, their consent form details and if they would like to change anything and the rights they have during the whole co-design session.	The participant has to cross check the information we have of them and ask any questions they have regarding the consent form or of the whole research process.	The facilitator must introduce themselves in addition to the aim and purpose of the research. The facilitator also must make the participant go through their consent details before starting the rest of the session.	Screening survey responses, camera to record	Experimental rooms in OCADU Graduate Building for one-on-one session
20 minutes	Furniture requirement discussion	The purpose of this activity is to go through in detail of the answers given by the participant in the online semi-structured interview to understand what they require better.	The participant has to elaborate on the answers given in the semi structured interview for the modular furniture piece they require to be designed that can ease their daily life in their living space.	The facilitator must involve the participant in a dialogue to better understand their requirements. The facilitator will also be prepared of what the participant has in mind in lieu of the responses given in the semi structured interview which will help in going question by question to	Semi-structured interview, camera to record	Experimental rooms in OCADU Graduate Building for one-on-one session

				understand their preferences in detail.		
25 minutes	Designing Furniture	The purpose of this activity is to sit with them and design the components to create a prototype for the furniture piece.	The participant will be given a sheet of paper to sketch, or any other form of digital software's will be available too on the facilitators laptop if that is more comfortable for them to ideate or conceptualize a bit further of what they have in mind.	The facilitator will create a 3D model side by side with them to figure out the rough dimensions for the next activity and to show them a 3D model of what they have in mind.	Paper, pencil, pen, markers, laptop with 3D softwares.	Experimental rooms in OCADU Graduate Building for one-on-one session
30 minutes	Low Fidelity Prototyping	The purpose of this activity is to create a low fidelity prototype with cardboard and 3D printed joinery details in addition to figuring out the dimensions of each component for the prototype.	The participant will be asked to assist by observing the facilitator create a low fidelity prototype with cardboard, paper, 3D printed joints, etc. They can also join in if they feel it could be of help. It will be a collaborative event depending upon the wishes of the participant as to how much they want to be involved.	The facilitator will cut the cardboard pieces and start assembling the components to give a feel of how the final prototype will look like and if any small changes are required.	Cardboard, paper, 3D printed joints, adhesives	Experimental rooms in OCADU Graduate Building for one-on-one session
5 minutes	Wrap Up	The wrap up will include their thoughts on how the session went and if anything could be done to make it better for future co-design sessions	The participant will be asked to give feedback on how the session could have been better so the next co-design sessions are easier to conduct.	The facilitator will ask question on how the session went and if there are any thing the participant found lacking.	Paper, pencil, pen	Experimental rooms in OCADU Graduate Building for one-on-one session

		with other participants. And also, to ask them a tentative date for user testing and feedback for the second iteration if required.				

APPENDIX D: Participant 1 Grasshopper script

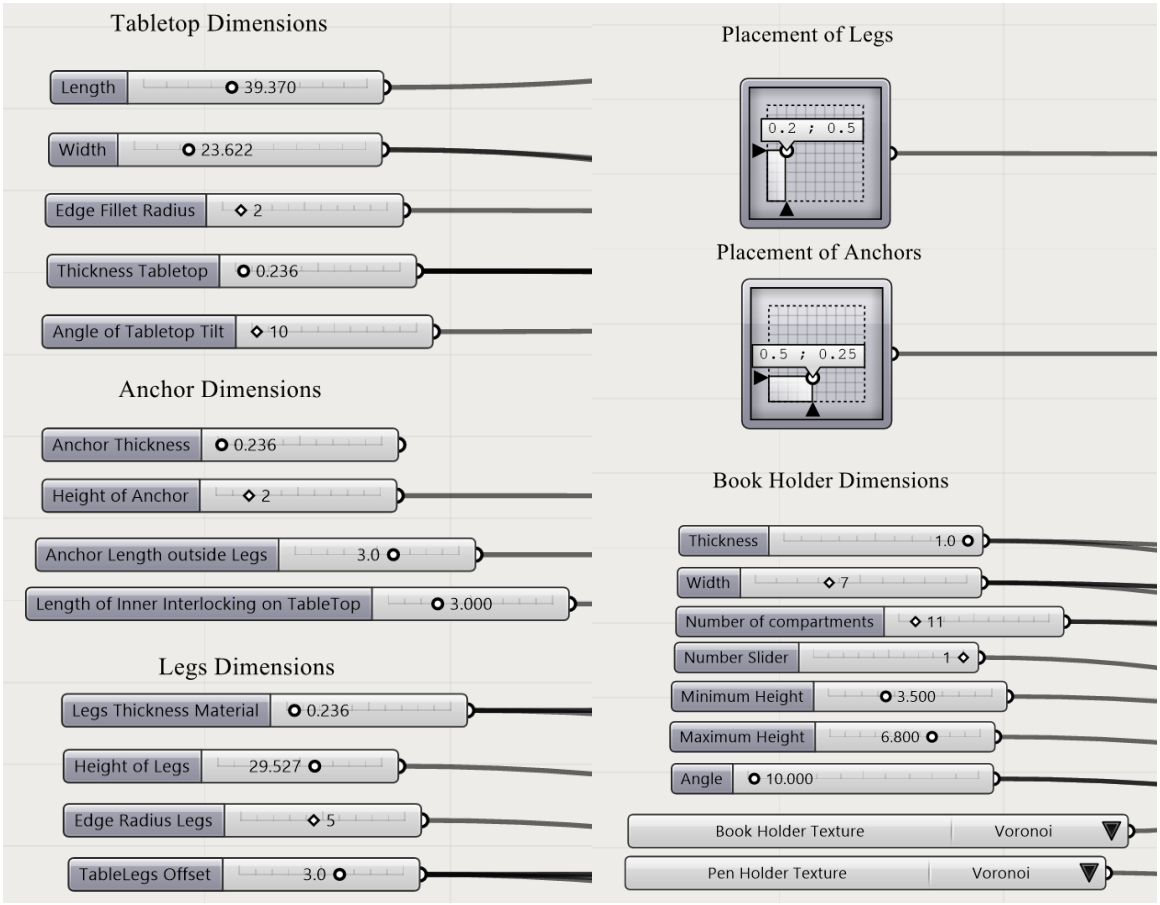

Figure 83 - Showcasing the customizations available in Participant 1 script

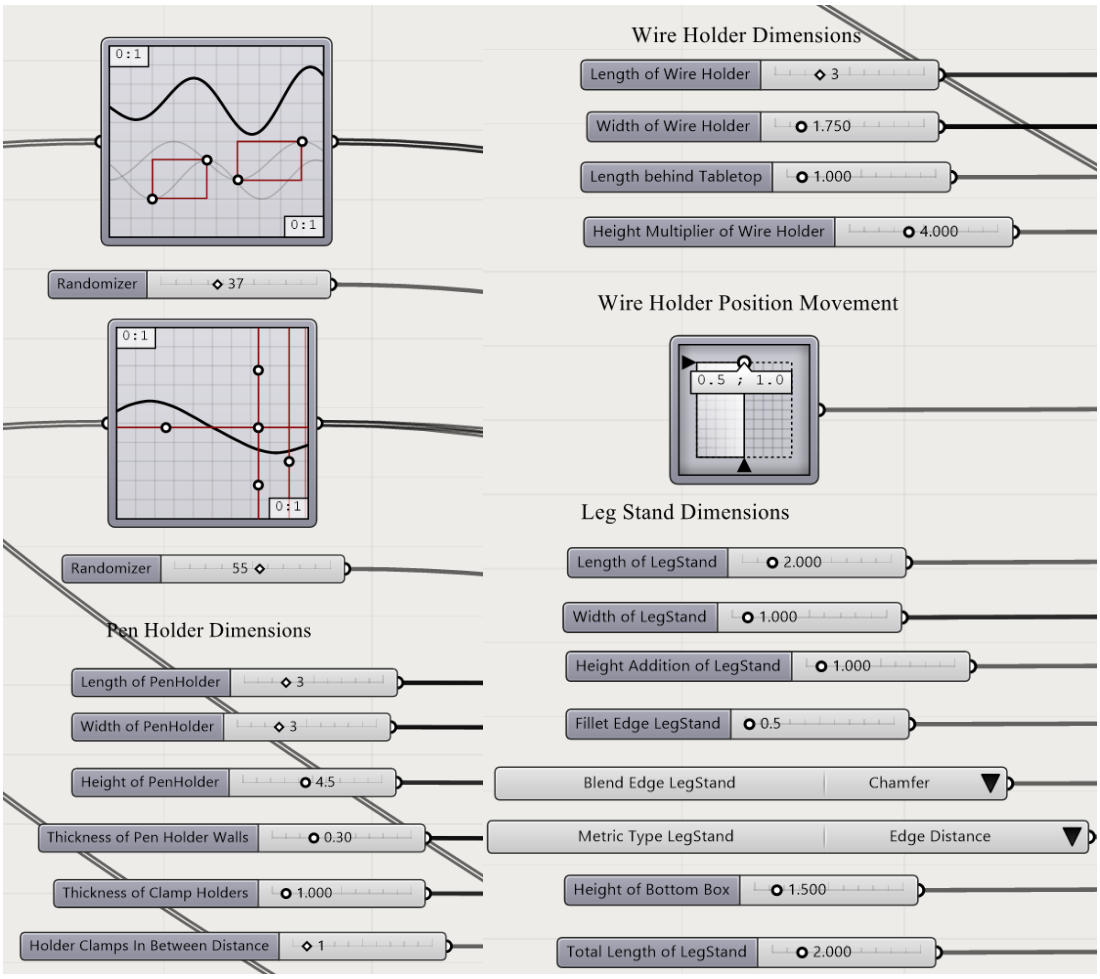

Figure 84 - Showcasing the customizations available in Participant 1 script

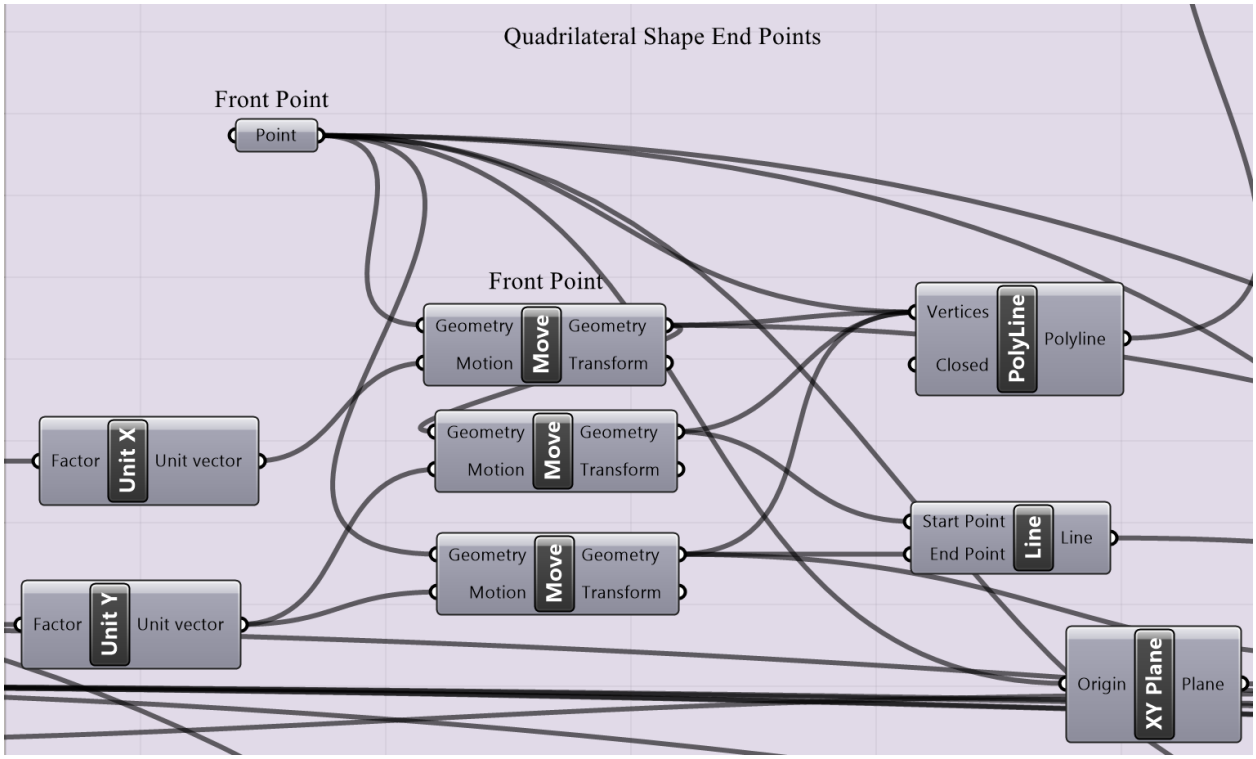

Figure 85 - Script for creating 4 points of the quadrilateral shape of the table

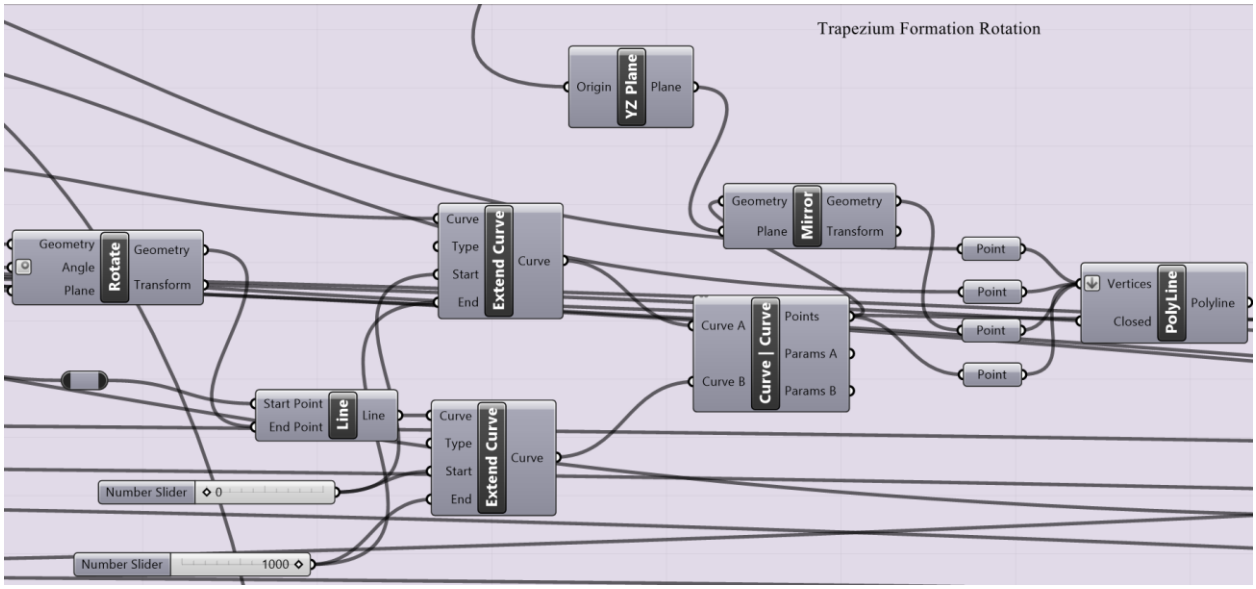

Figure 86 - Script for providing the rotation to create a trapezium shape from the quadrilateral

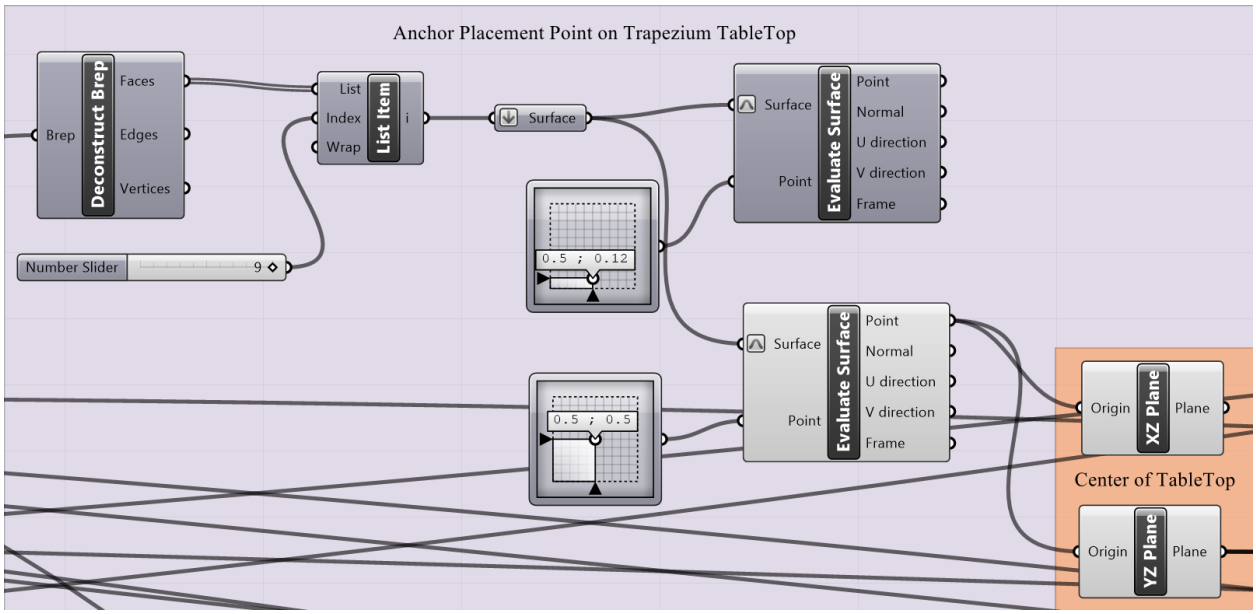

Figure 87 - Script for creating placement points on the table top where the anchor is created

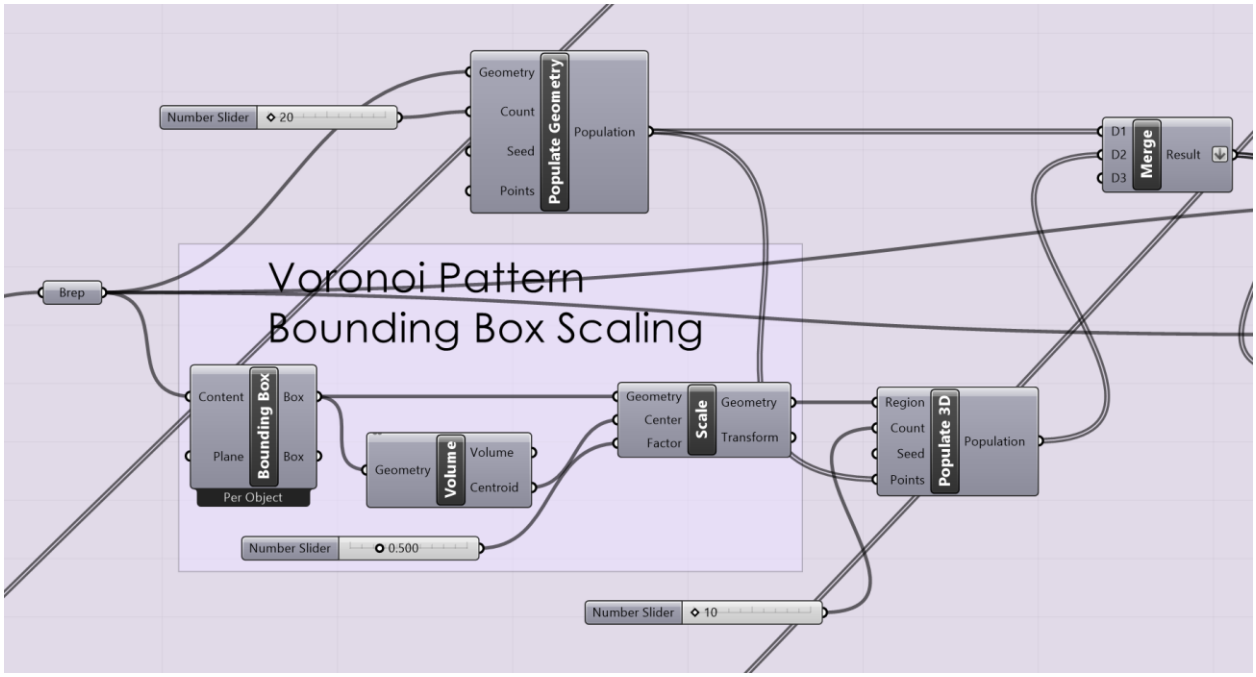

Figure 88 - Script for creating Voronoi texture

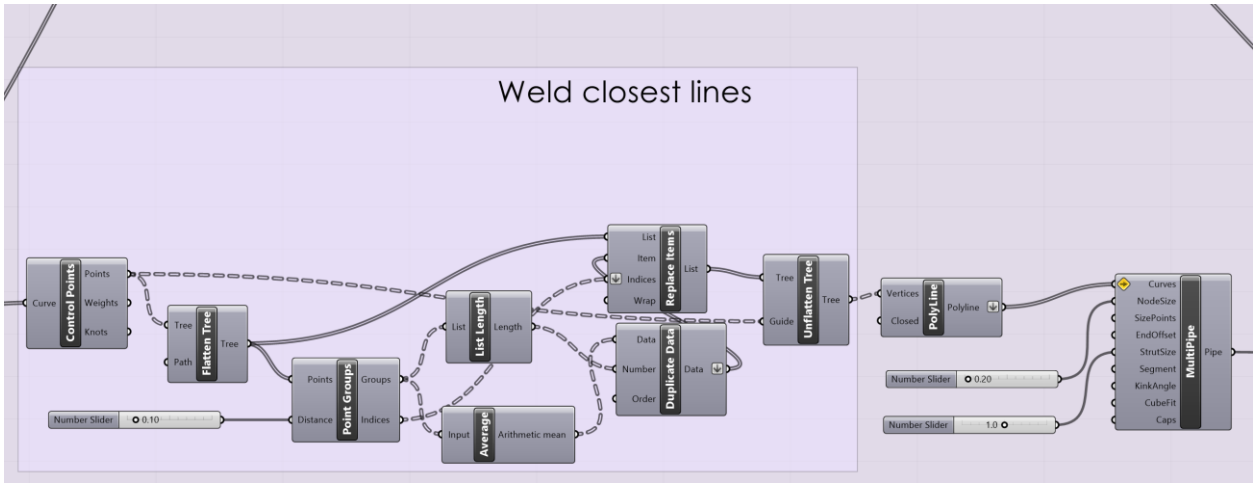

Figure 89 - Script for creating Voronoi texture contd.

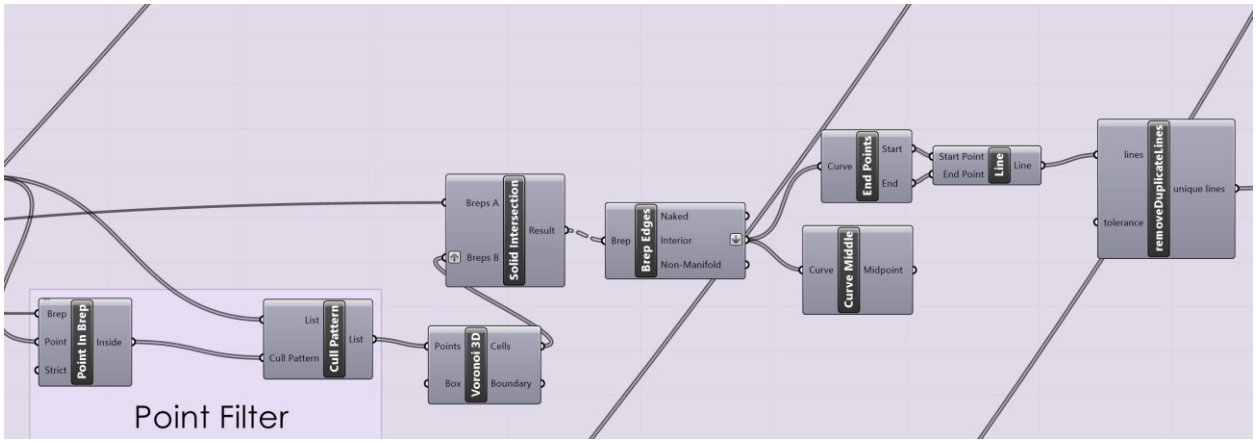

Figure 90 - Script for creating Voronoi texture contd.

APPENDIX E: Participant 2 Grasshopper script

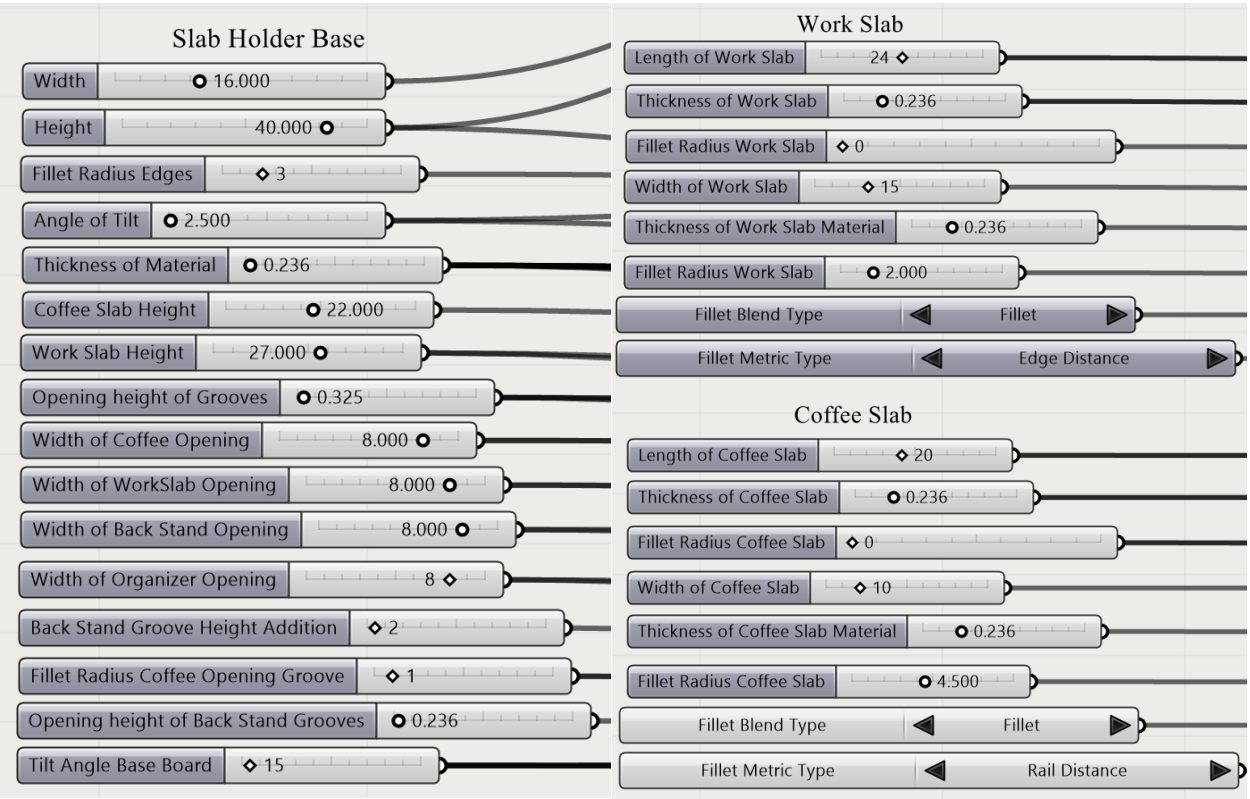

Figure 91 - Showcasing the customizations available in Participant 2 script

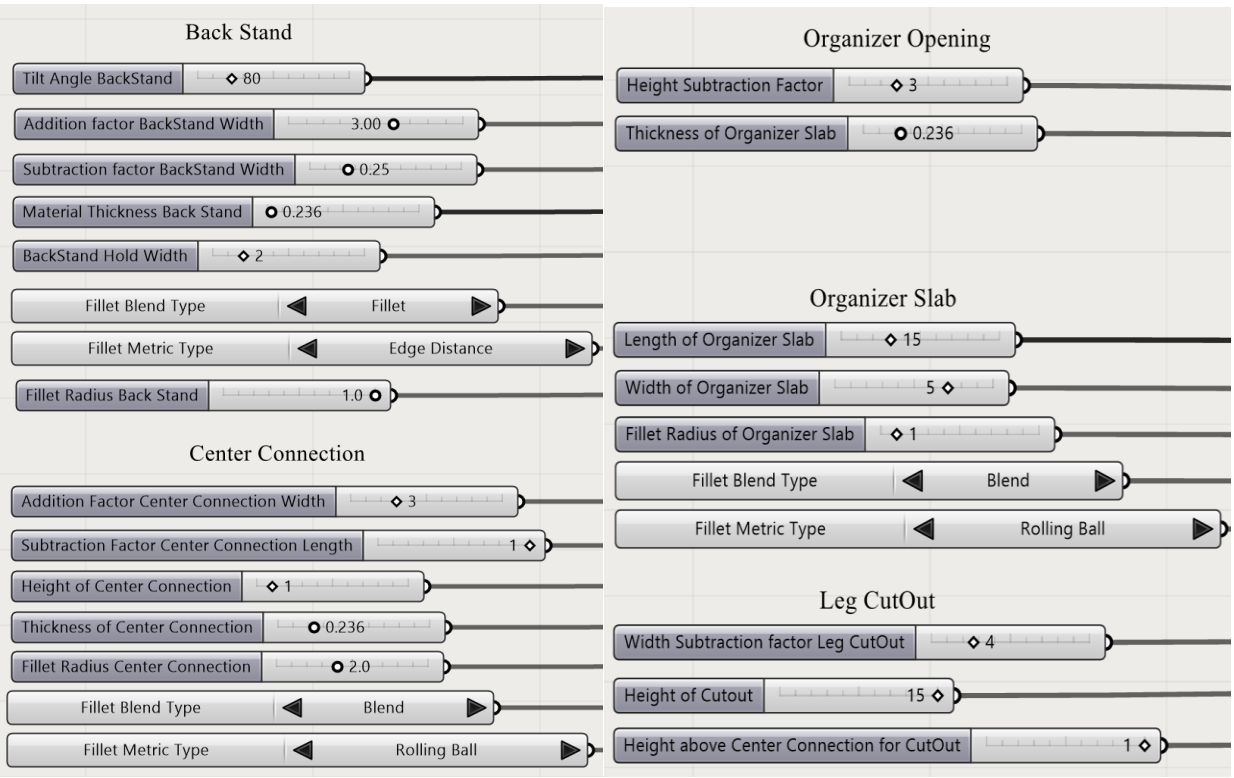

Figure 92 - Showcasing the customizations available in Participant 2 script

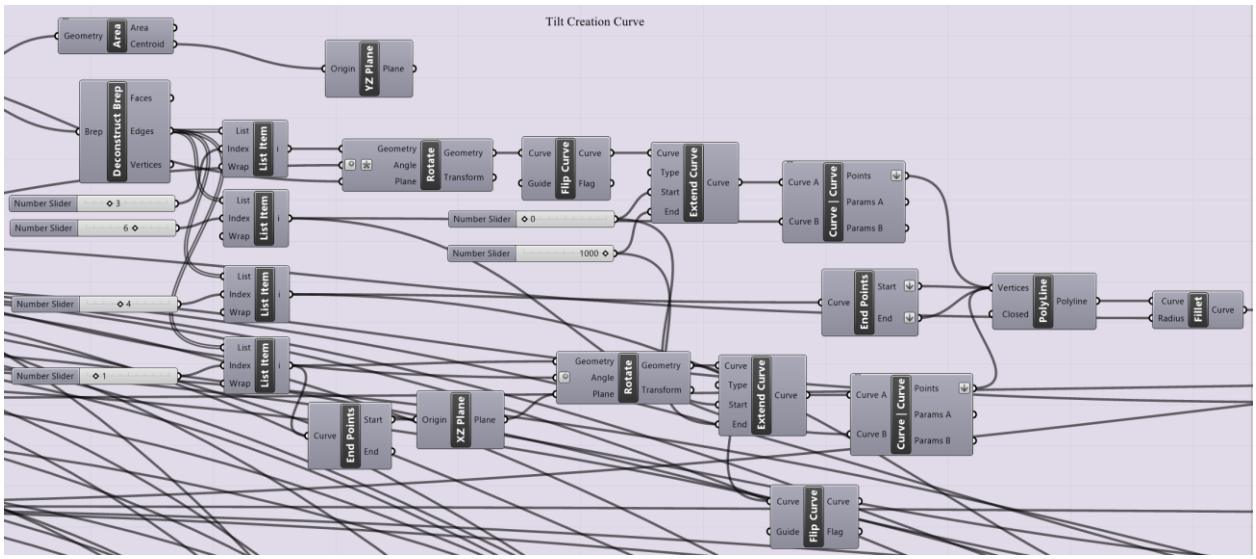

Figure 93 - Script for creating the tilt on the base board

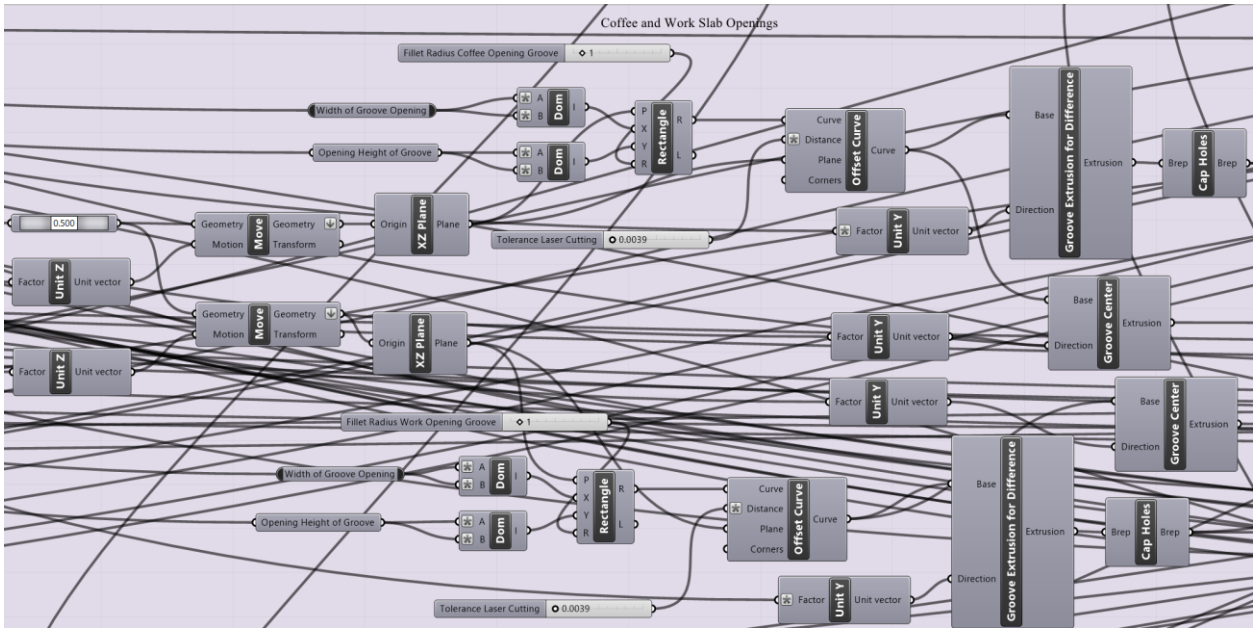

Figure 94 - Script for creating the openings for slabs on the base board

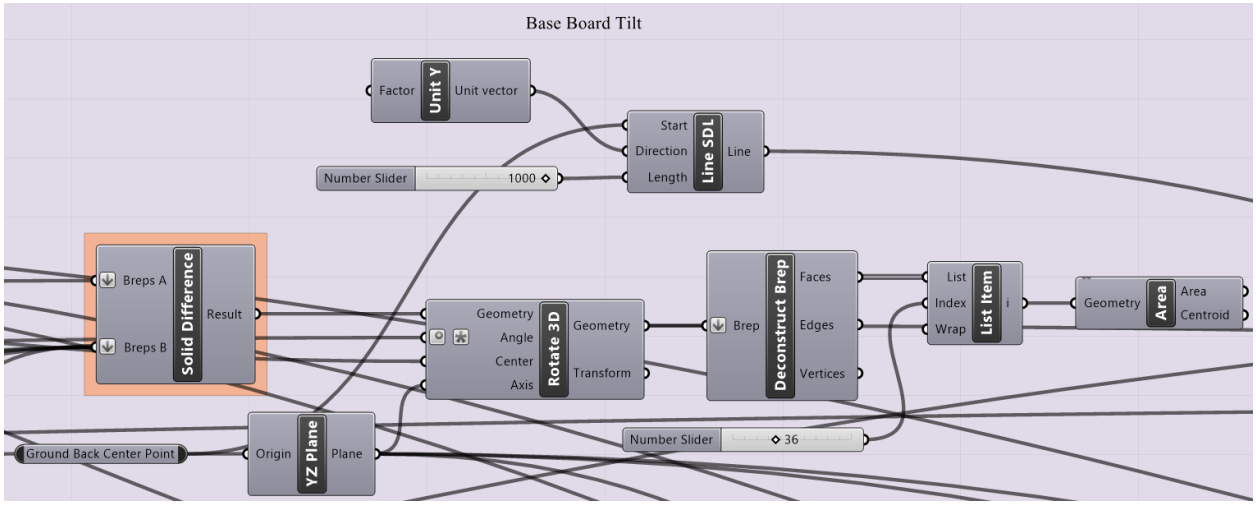

Figure 95 - Script for tilting the base board

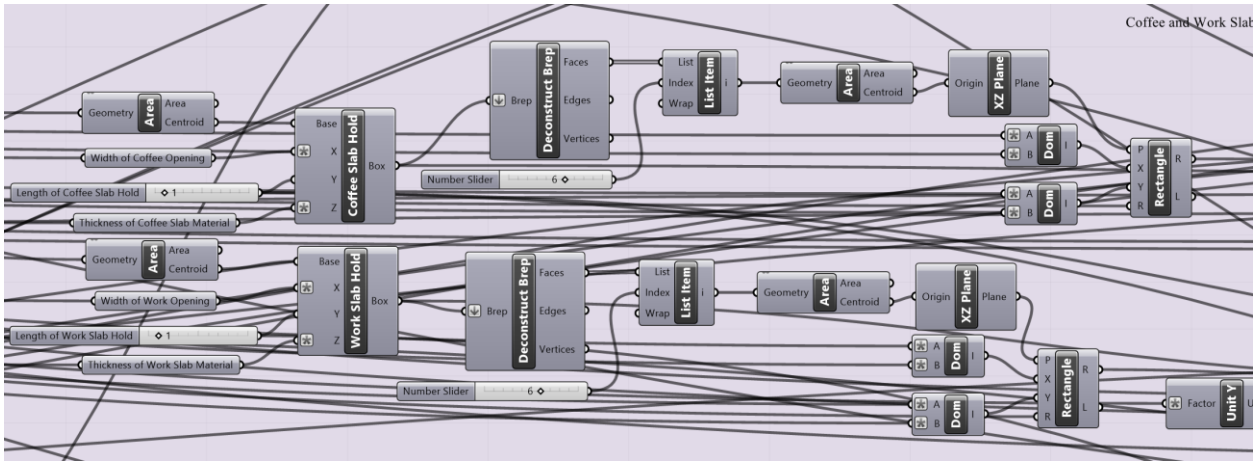

Figure 96 - Script for creating the slabs

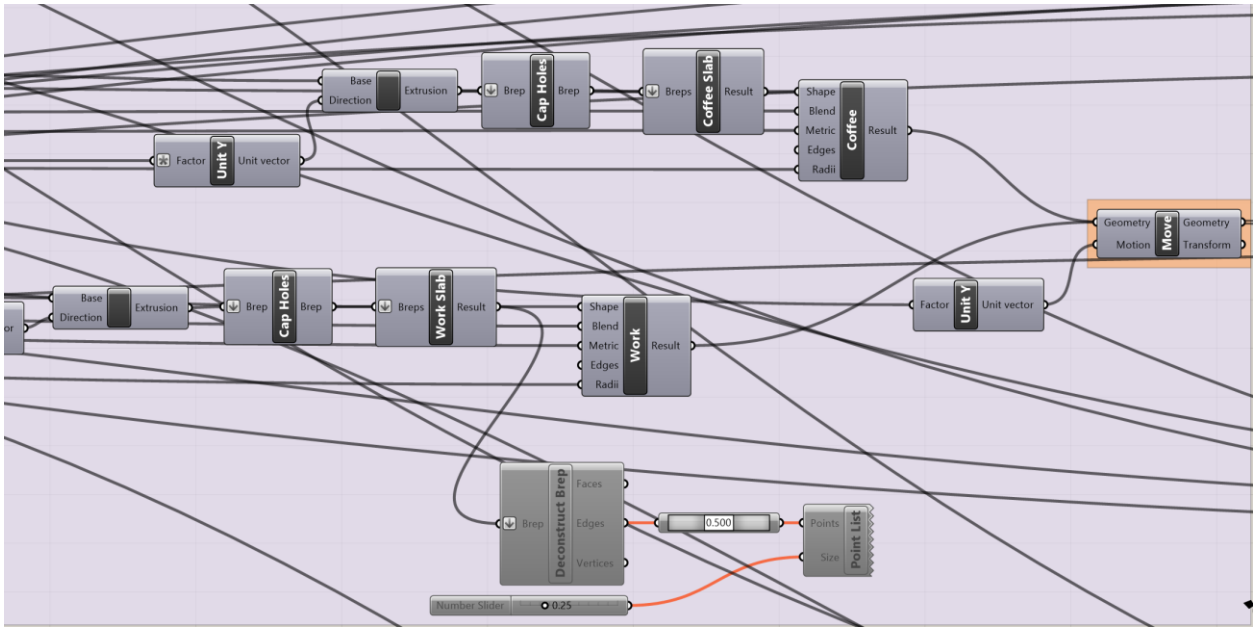

Figure 97 - Script for creating the slabs contd.

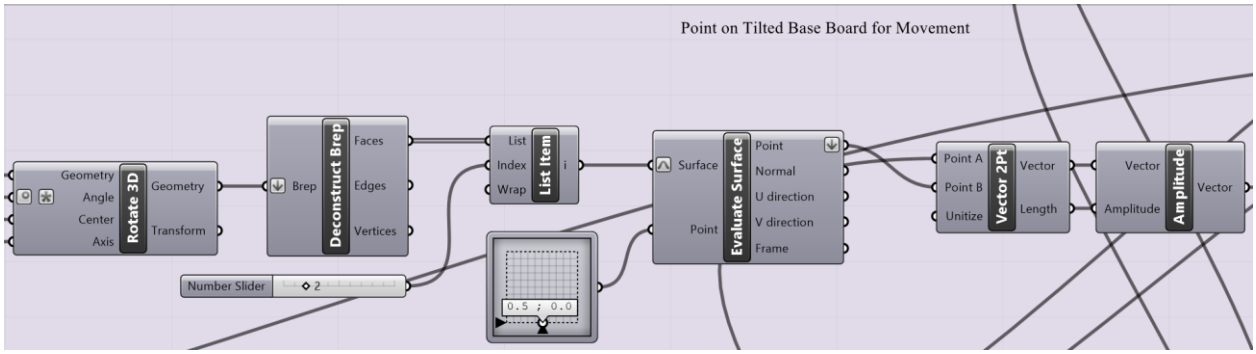

Figure 98 - Script for creating the point from where the model should rotate for the tilt

APPENDIX F: Participant 3 Grasshopper script

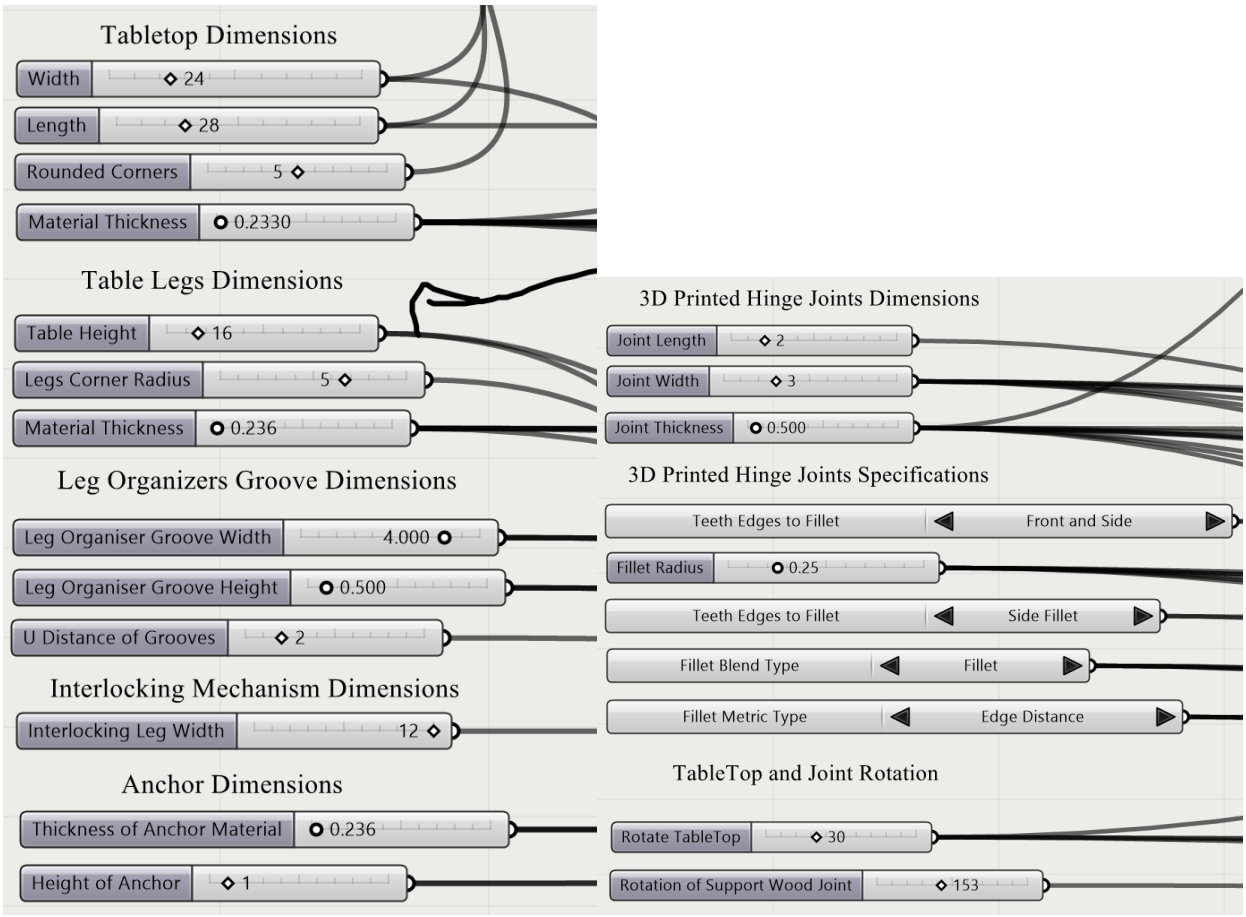

Figure 99 - Showcasing the customizations available in Participant 3 script

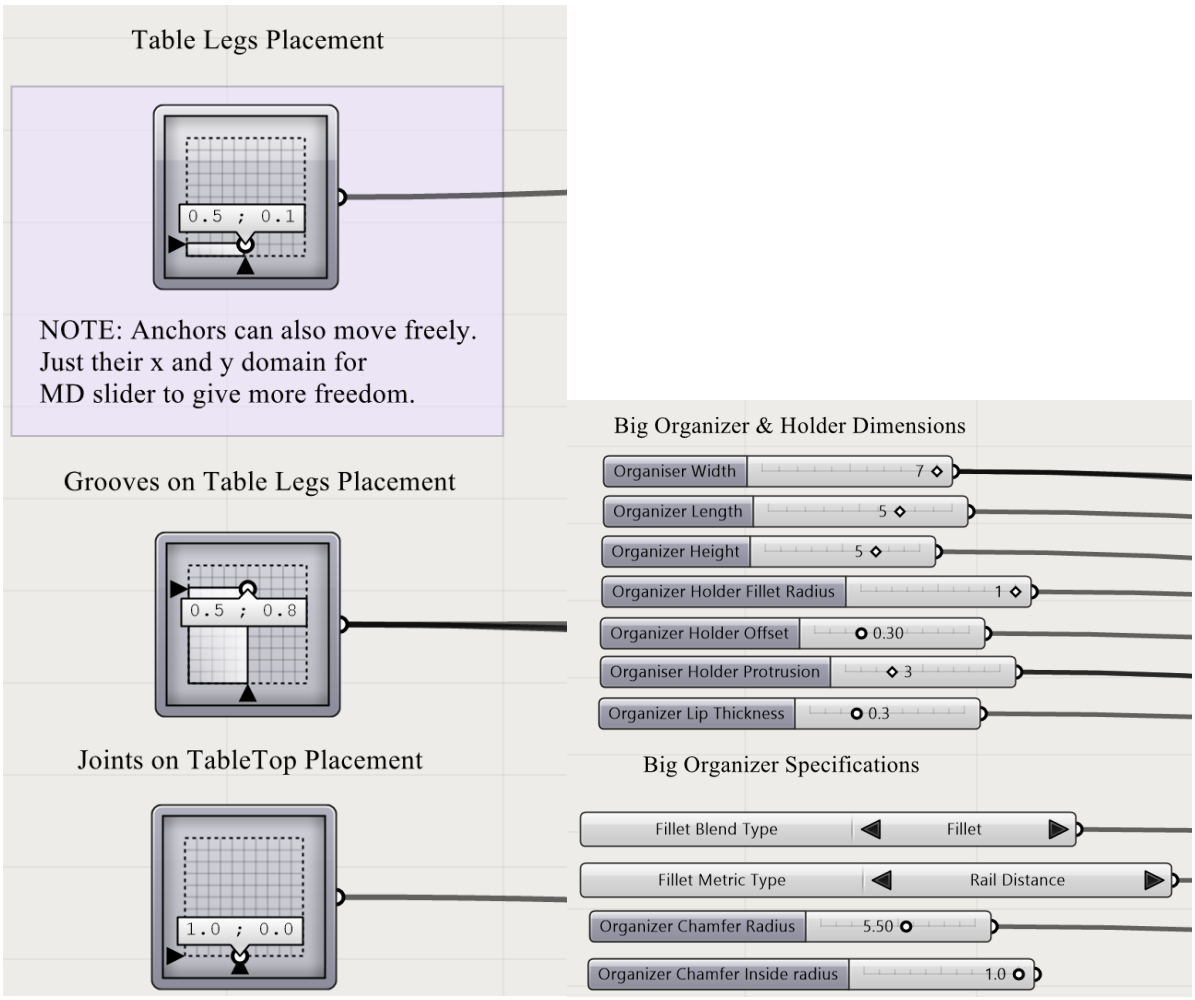

Figure 100 - Showcasing the customizations available in Participant 3 script

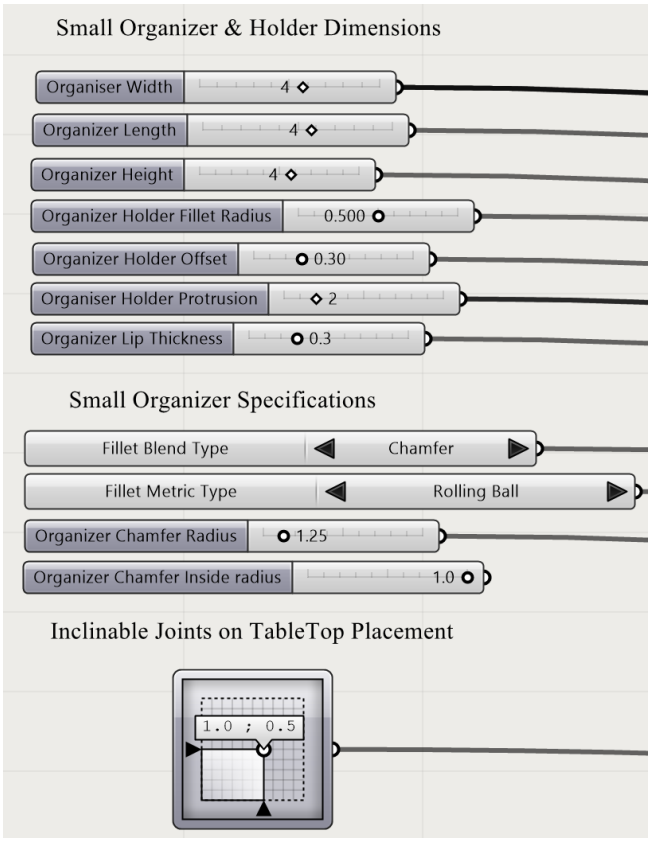

Figure 101 - Showcasing the customizations available in Participant 3 script

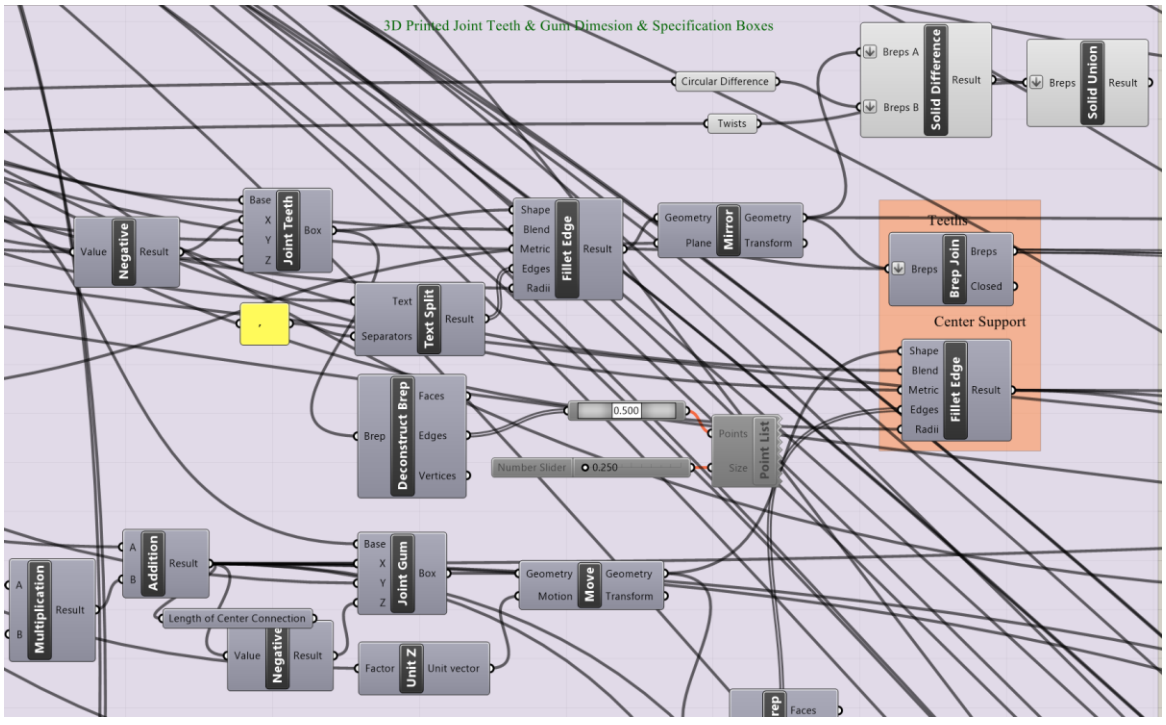

Figure 102 - Script for creating 3D printed joints teeth and gum

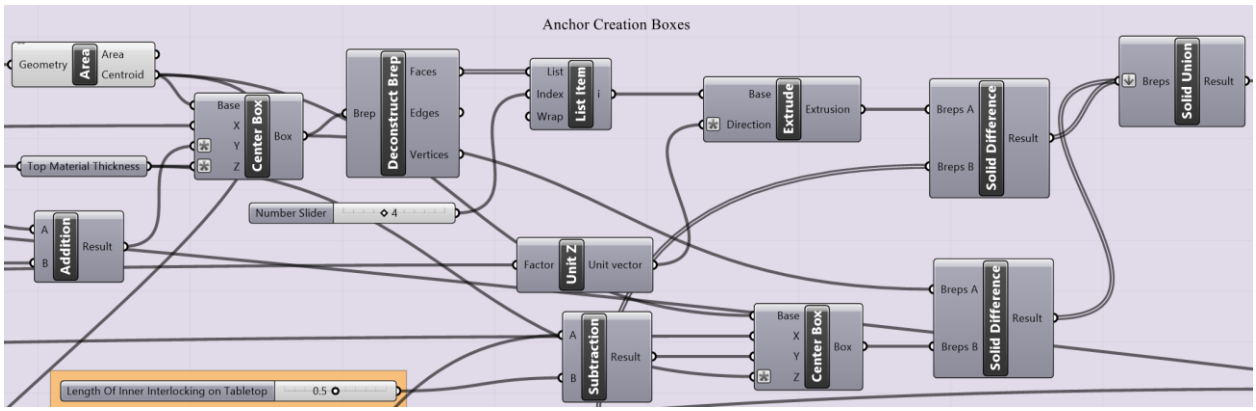

Figure 103 - Script for creating the interlocking anchors

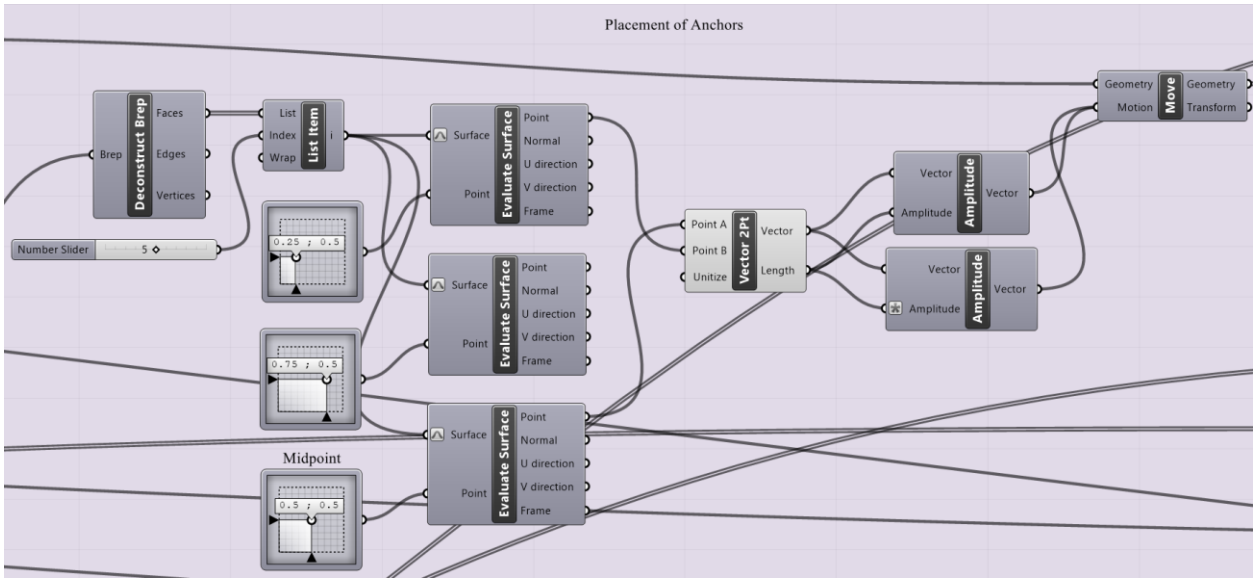

Figure 104 - Script for creating placement points of anchor on table legs

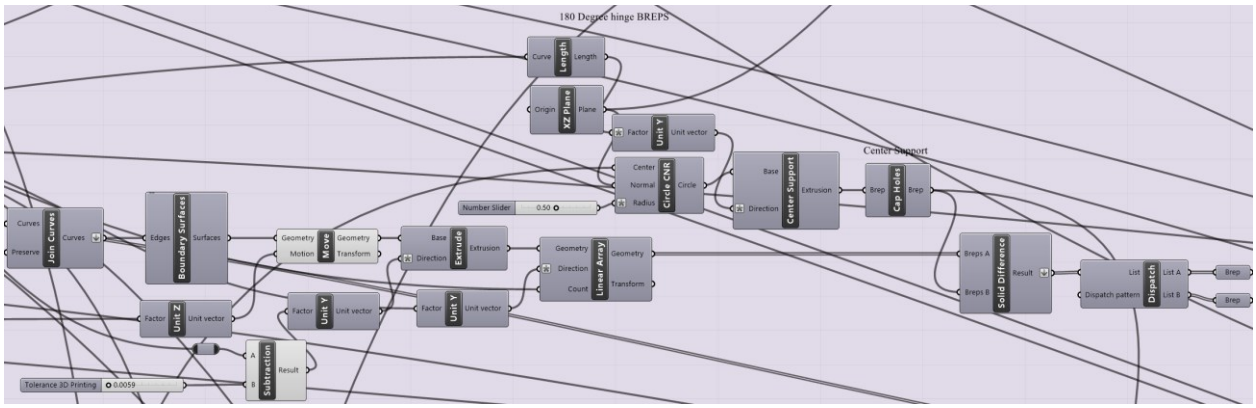

Figure 105 - Script for creating 180-degree hinge joints

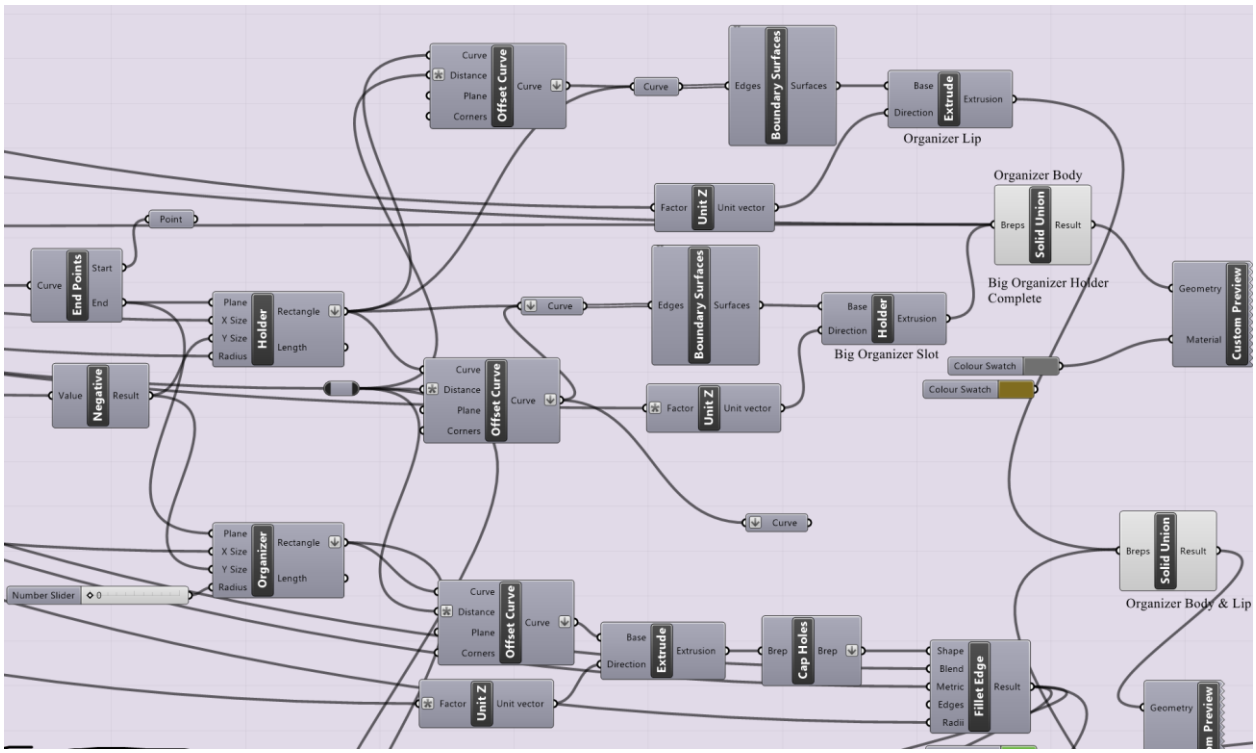

Figure 106 - Script for creating 180-degree hinge joints contd.