

## **Branch: Final Report**

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AR2AA016 1:1 Interactive Architecture Studio



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## Introduction: Site Analysis

MSc2 Interactive Architecture Studio focuses on developing a design solution for the TU Delft University Library. The scope of the project required us to integrate interactive furniture into the library to enhance the space and provide more social and collaborative zones. Our group began the project by investigating the current status of the TU Delft library. We visited the library at various times in the day for a month and documented our observations on what spaces are working well, what spaces are most popular versus underused and how people circulate through the space. In that time we developed a brief questionnaire (Figure 1-4) and interviewed nearly 40 visitors to confirm our findings.

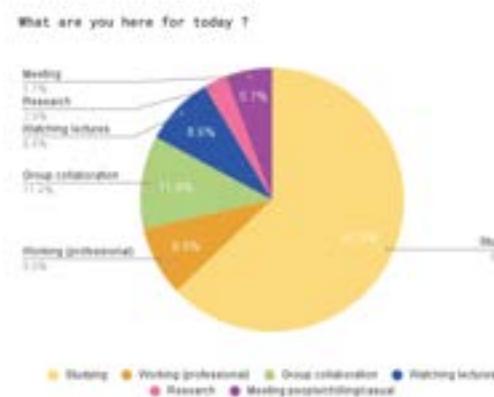


Figure 1

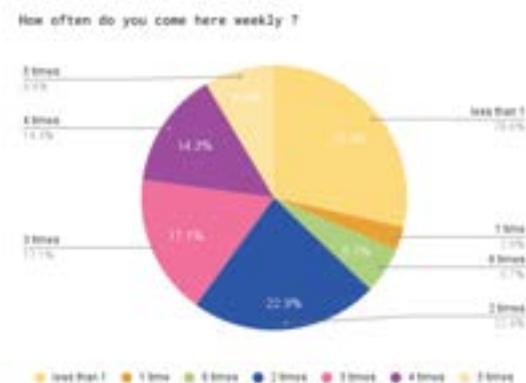


Figure 2

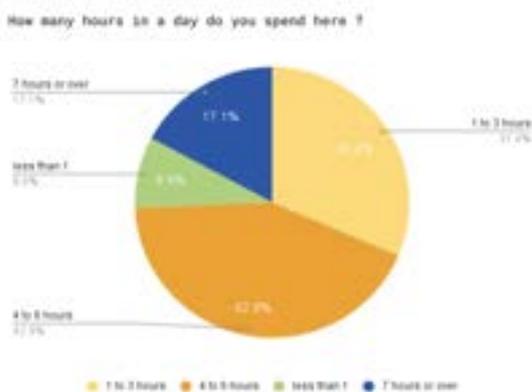


Figure 3

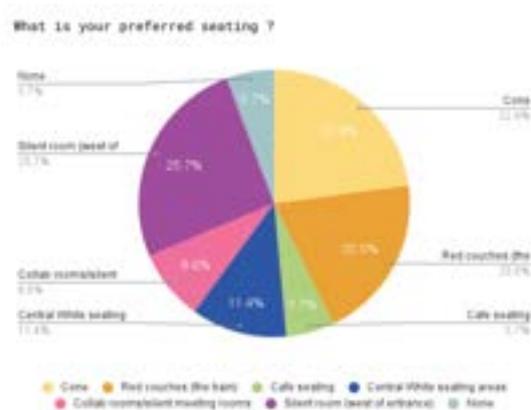


Figure 4

Based on the comments we received from Vincent and the research compiled from our site analysis, we learned that the primary users of the space are students and they mostly come to study. However, the preferred seating of the students varied. We continued on to develop five design drivers: semi-privacy, privacy, meeting spaces, informal seating, and appeal. These drivers guided us throughout the entire design process. We aimed to develop a design that integrated each driver by catering to our four functioning typologies: study, collaboration, chill and exhibit. The intention is to provide the library with flexible spaces that can change their function overtime, accommodating more spaces for studying but also retreats and more engaging informal meeting and lounging areas. The current exhibition space, the "train" seating, and the wellness area were the three potential locations (Figure 5) we sought out to explore and

we chose these zones based on their noise levels and potential for improvement. Once we established the function typologies and locations we proceeded with developing our architectural language for the furniture.

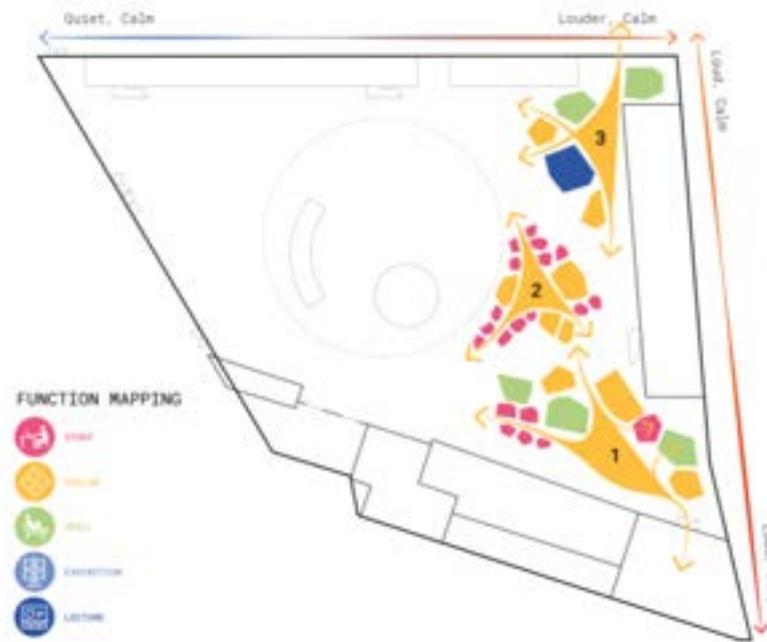


Figure 5

## Conceptual Development

Our concept "Branch", explores the above and below relationship of a playful undulating indoor landscape (Figure 6). The intention is to provide different functioning spaces that can vary in function, and are the structural support for an informal and chill seating area above (Figure 7).

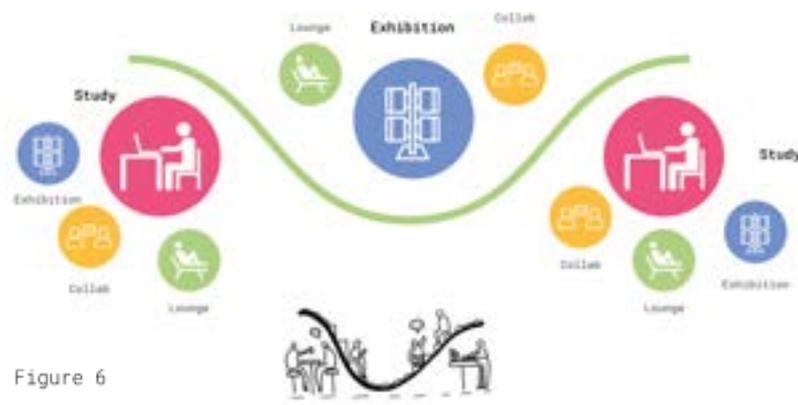


Figure 6

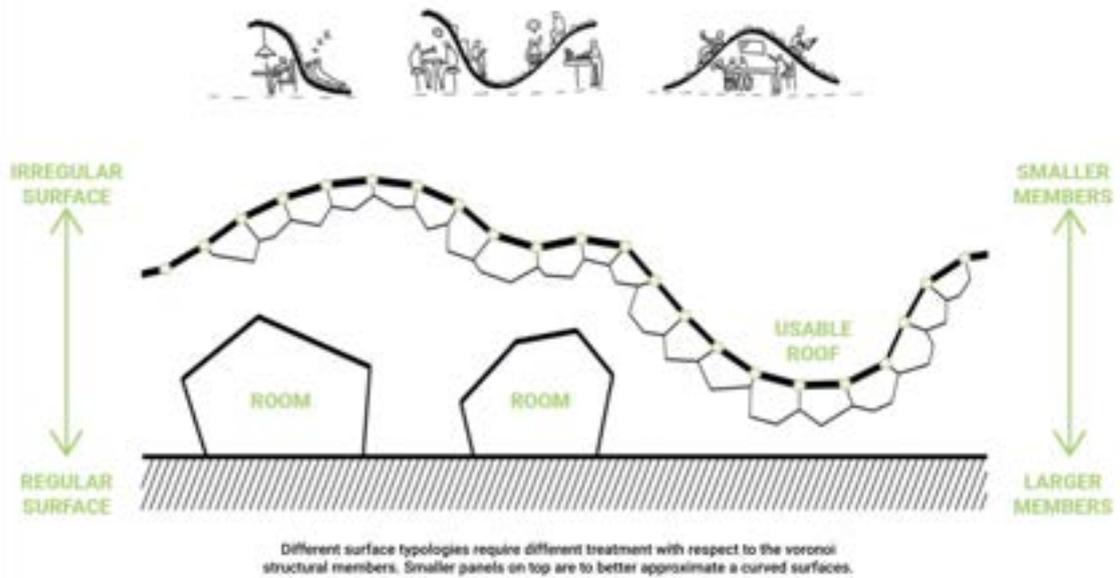


Figure 7

To achieve a structural system that can accommodate our design intention we explored various grid systems and decided on using voronoi geometries due to their scalability and capacity to generate a functioning system out of irregular geometries. While voronois add additional levels of complexity and challenges to our structure, they have proven to function at every scale of our design which has resulted in a unique yet cohesive architectural expression, and an overall unified systematic approach (Figure 8). The benefit of designing with a voronoi system is that the structure can be manipulated, rooms can be re-configured and scaled up or down according to the needs of the space, and the rest of the form will adapt. *Branch* is a literal expression of form following function. With our unified systematic-thinking approach we have been able to transition our concept from points and vectors, to surfaces, to three-dimensional geometries. *Branch* is a re-configurable and scalable system that generates its form from the needs and desires of its users. It is a walkable landscape that provides new capacities for the future usage of the TU Delft library.

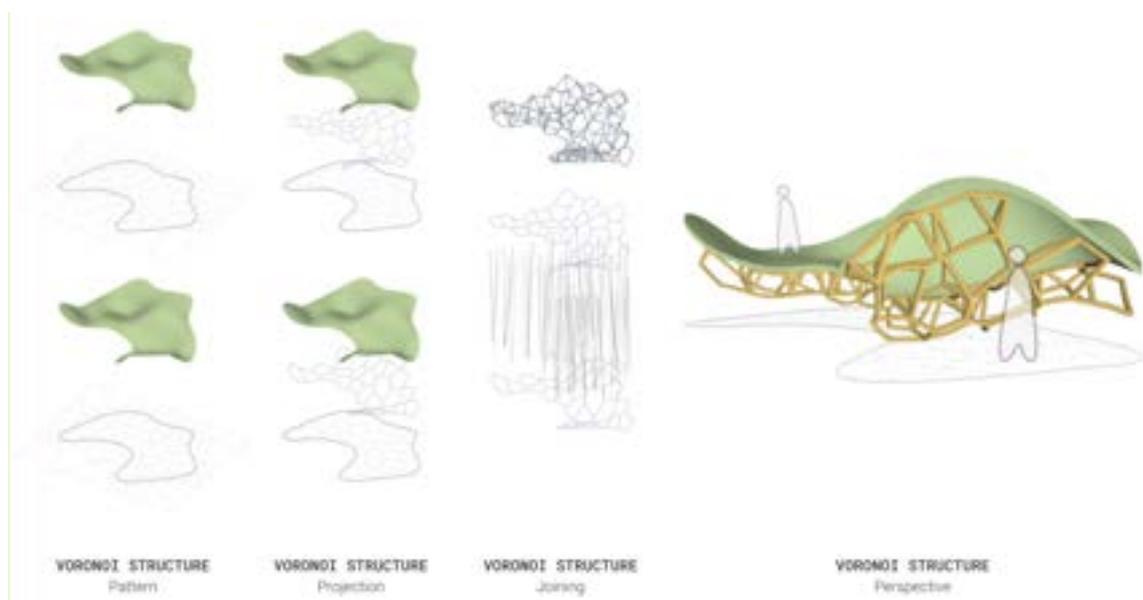


Figure 8

## Design Development

Branch consists of elements ranging between different scales which we have chosen to divide into three different categories: Micro, Meso and Macro.

### Design at 'MICRO' scale

The Micro Scale consists of the structural elements of the architecture. These elements are both used for the voronoi-generated furniture, the voronoi rooms, and the larger structure on top. The primary element type consists of a 3D printed node, a wooden panel and wooden beams (Figure 9), all based on the programmatic need of the project. The typology of each of these elements can be adapted to suit different materials and processes in various settings.

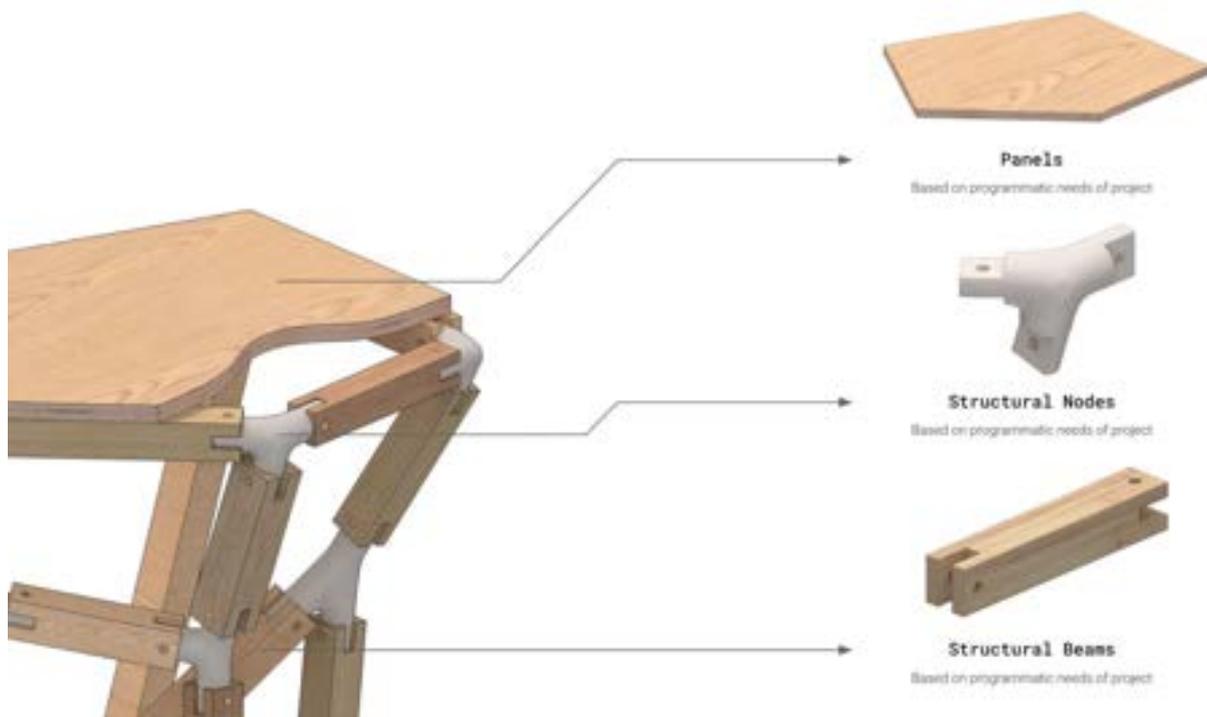


Figure 9

The nodes are not only structural but also hold LED lights that will be activated through pressure (Figure 10). This way it indicates the availability of rooms for better orientation of the library. The wooden panel also comes in different varieties (Figure 11), the solid plywood, the perforated panels, panels with integrated cushions, panels with integrated sockets, and panels with pressure sensors to activate the LED nodes. Although the rooms are only semi-secluded, the perforated panels help with better orientation of activities happening in the library when you are sat inside one of the rooms. Another benefit of these panels is the improvement of light into the rooms. The lack of sockets in the library is a large concern for the users of the library and led us to integrate the socket panel into the structure. The cushion panel will be used for the furniture and the seated stairs on top of the surface. This cushion is 3D printed and the fabrication of these elements will be further explained in the fabrication section.

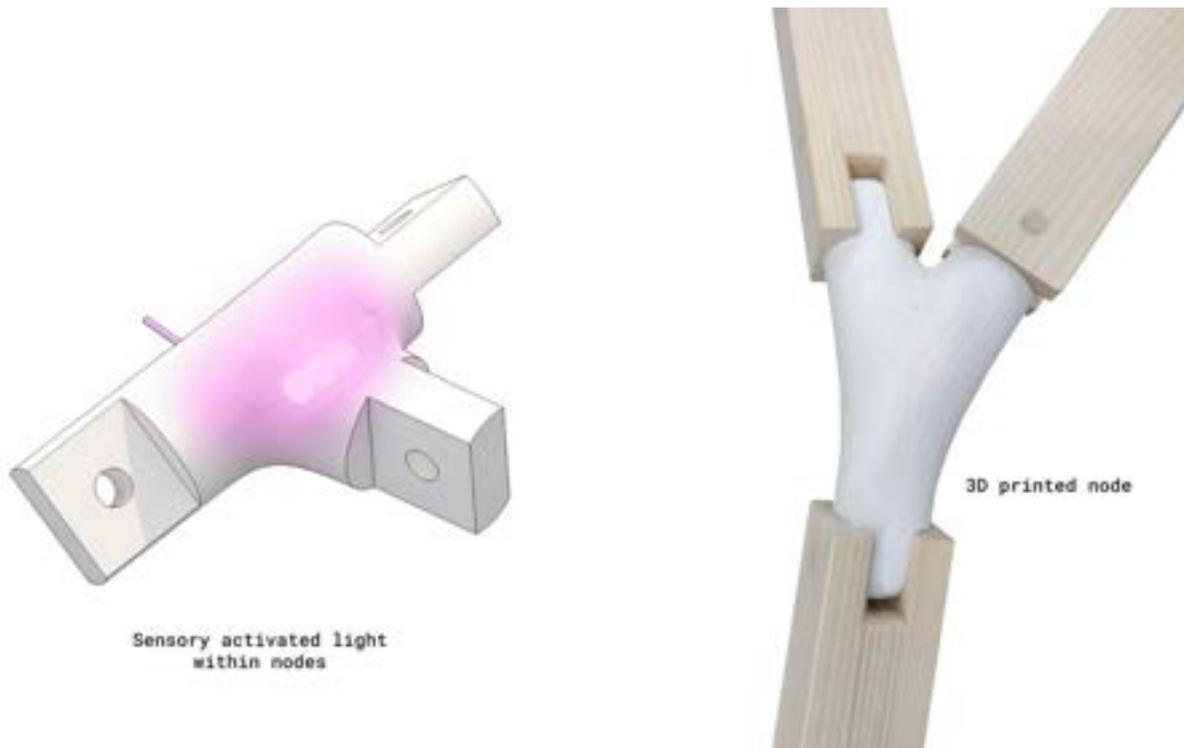


Figure 10

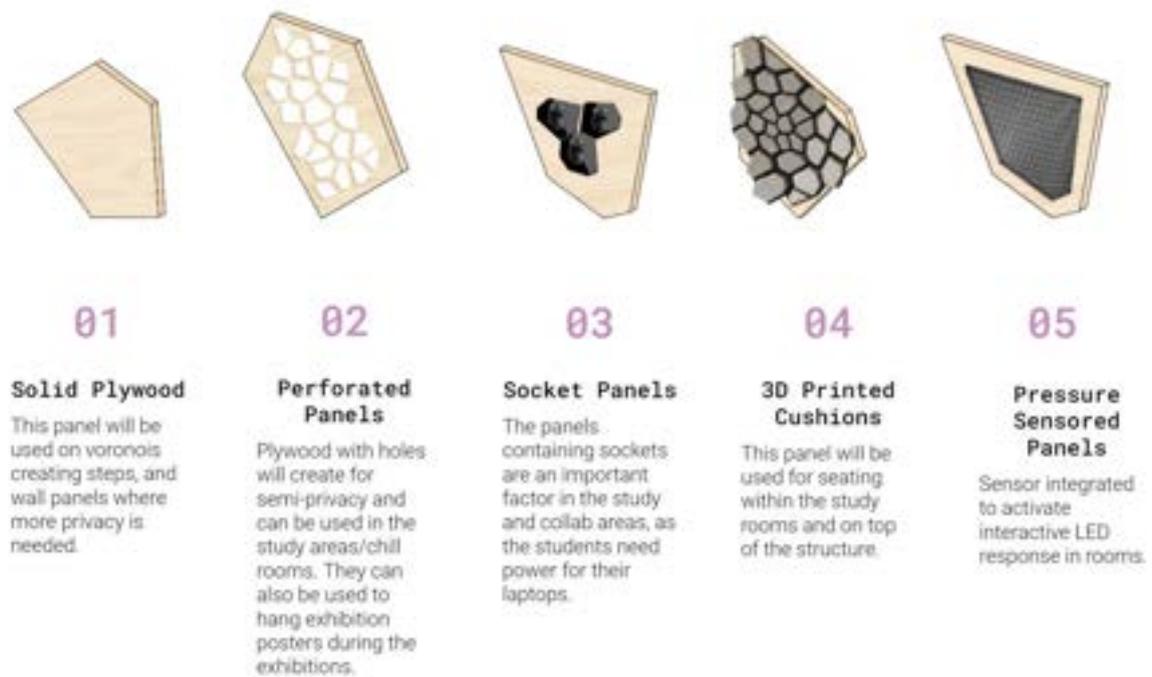


Figure 11

## Design at 'MESO'scale

The Meso scale consists of the individual rooms. Furthermore, these rooms are specifically designed for three different uses in mind: study, collaboration, and chill. The voronoi shaped rooms are multifunctional whereas the same shaped voronoi rooms can hold different uses in accordance with the current demand. There are four different varieties of study rooms, these range from single study, and small, medium and large study (Figure 12). The single study holds only one person whilst small study holds two people, medium study holds six people and the large study holds up to ten people. Here the seating furniture is mostly flexible.

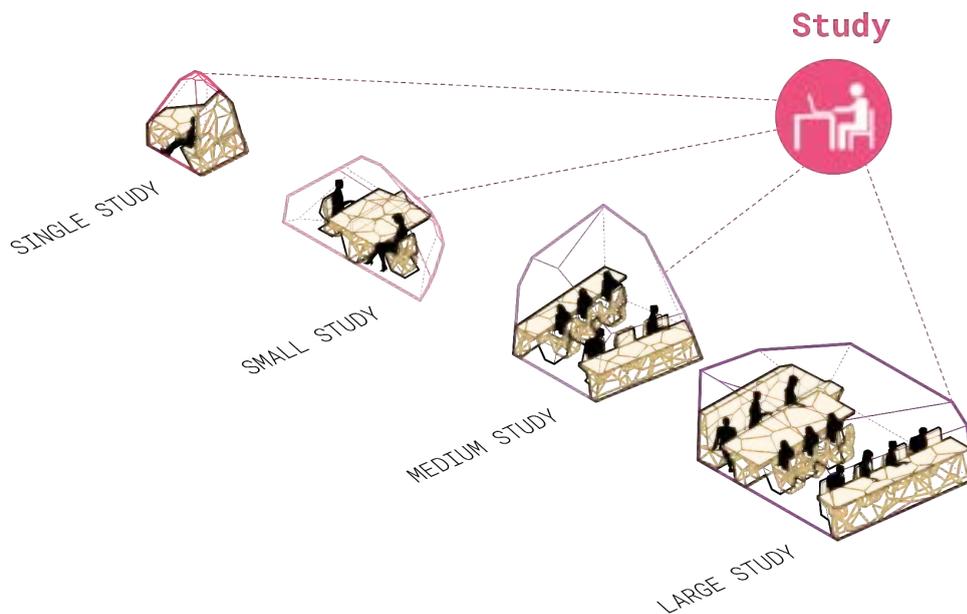


Figure 12

The collaboration rooms are also divided into small, medium and large rooms, whereas the small room holds up to four people, the medium room holds six people and the large collab room holds up to eight people (Figure 13). Here the largest room has fully flexible furniture which can adapt to the collaboration situation and presentations. There is a high demand for collaboration spaces in the library with long waiting lists. Therefore, we wanted to create more collaboration spaces due to this demand. An important factor for us was also to make them easily accessible with no reservation option, to firstly increase the noise level in the library, but also to add spaces for quick and spontaneous group meetings.

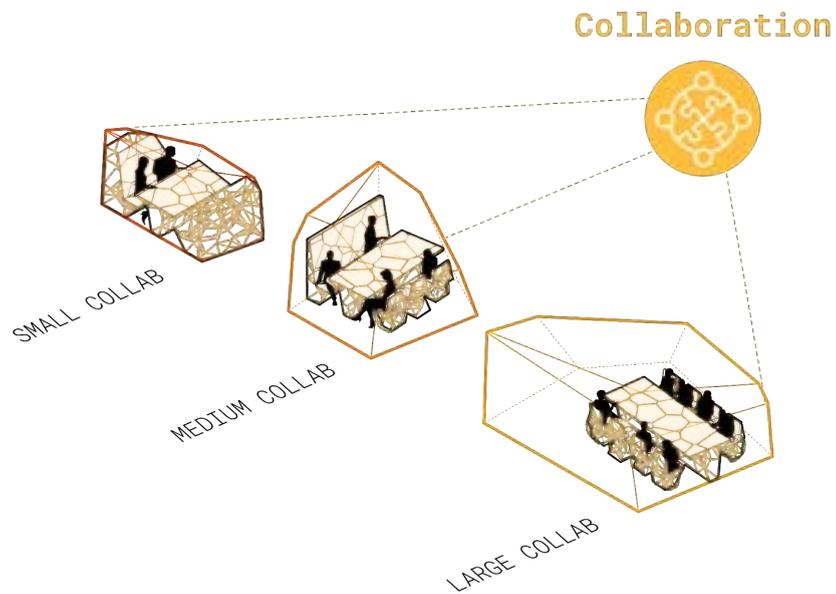


Figure 13

The last room typology is the chill rooms for lounging. Here there are only two scales, which are the small chill room and the large chill room (Figure 14). In both of these rooms the furniture is non-flexible as the furniture is moulded and constructed along the shape of the voronoi room and fills the whole room with couches. The small room fits 1-2 people whilst the large room can fit up to 8-10 people. This room is designed due to the lack of informal and successful well-being spaces and is a place where the student or public can catch a coffee break or a phone call.

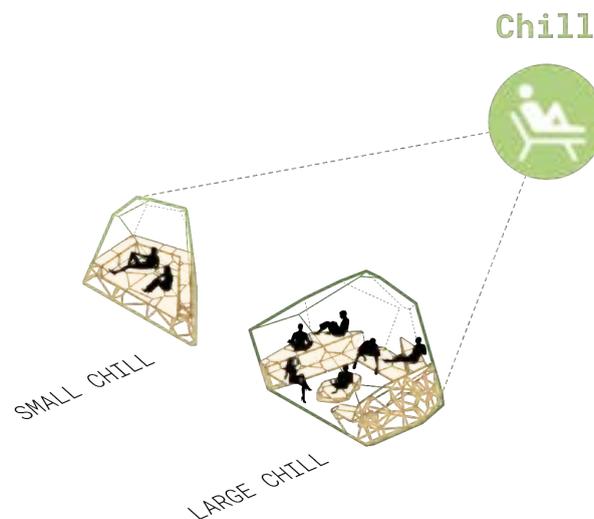


Figure 14

## Design at 'MACRO' scale

The shape of the Macro scale is determined by the arrangement of the voronoi rooms. The Macro scale is the overall shape of the structure that consists of the wooden beams and 3D printed nodes connecting the rooms and creating a top surface that starts from ground level and stretches over the roof surfaces of the rooms. This structure is walkable and multifunctional. The rooms can be scattered around the library where there is a demand for it (Figure 15). Furthermore, our proposal is creating structures with mixed uses within, yet with the focus on more collaborative spaces as the main driver. We also chose to focus our structures on the right side of the library where there are more opportunities for increasing the sound level.

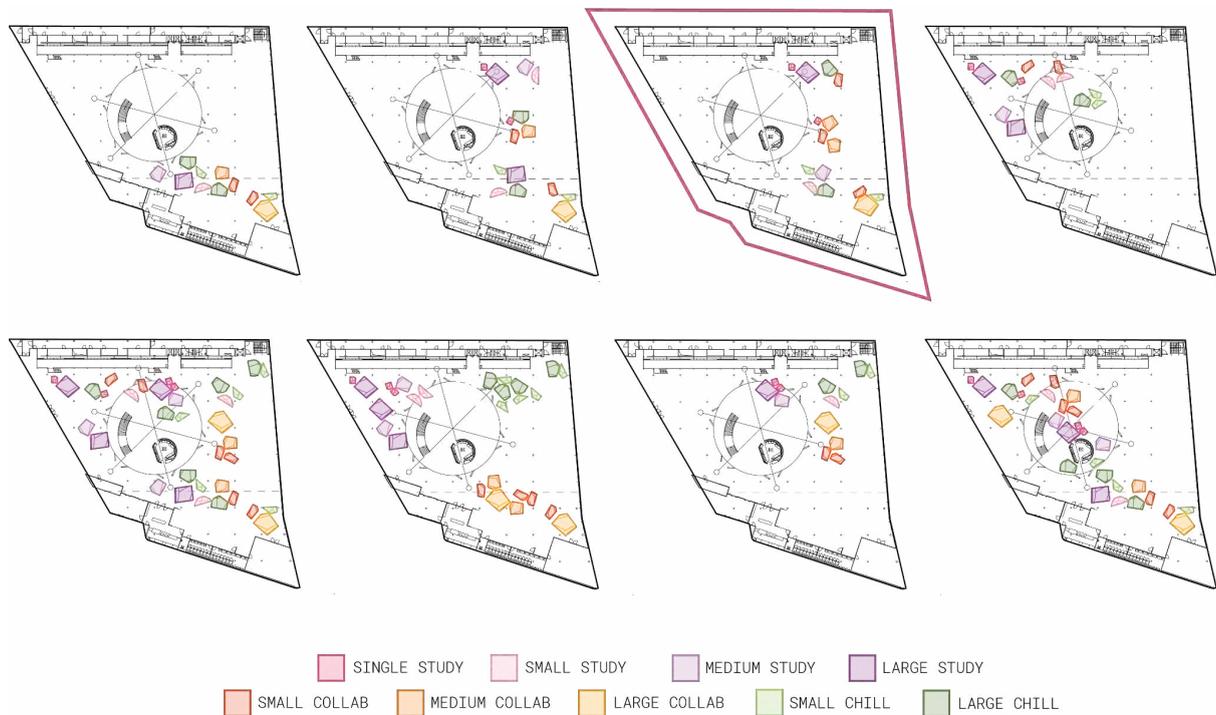


Figure 15

From the chosen room composition there are several variations of the Macro roof structure design. The structure can either be divided into several small structures, medium structures, large structures, mixed structures or an extra large structure combining all rooms (Figure 16). We chose to use a mix of sizes, creating one small, one medium and one large structure. However, the large structure touches the ground in the middle to create passage for the route that leads to the toilets (Figure 17).

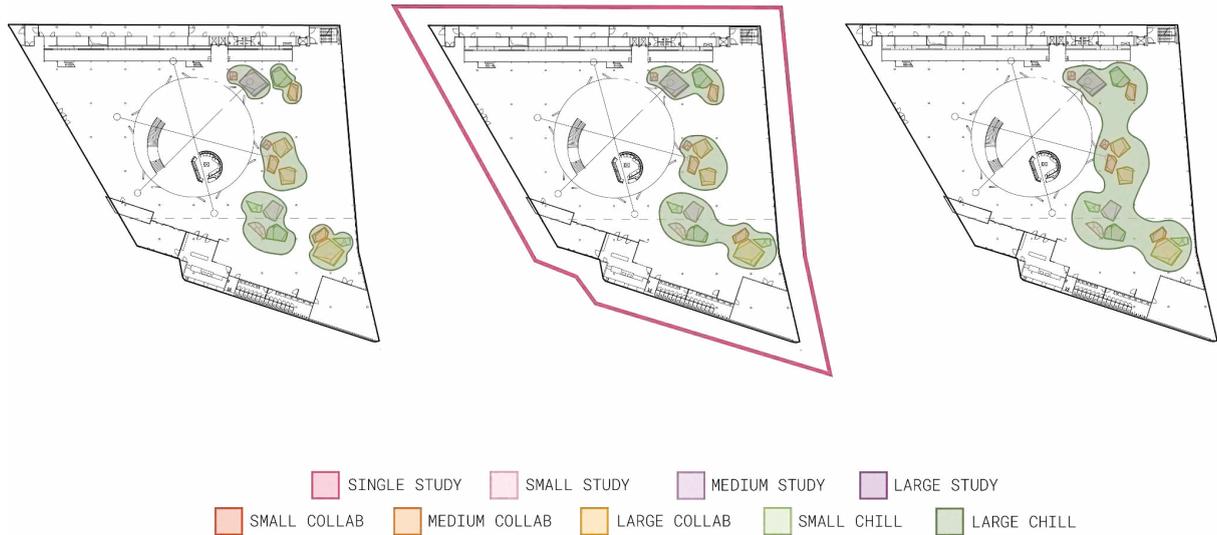


Figure 16

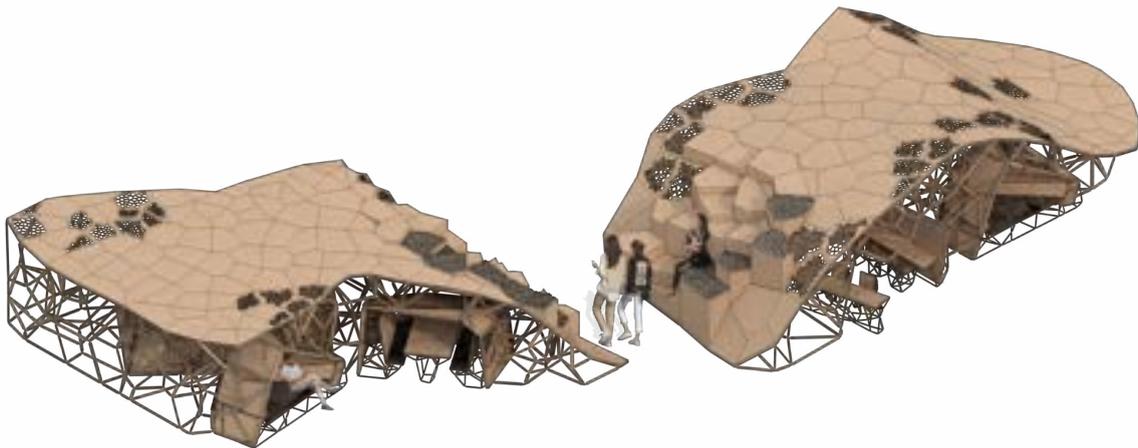


Figure 17

An important factor for the structures is that they are never fully enclosed and easy to see through, yet still feel some privacy when sitting within it. They are never supposed to block orientation, but create spaces that are easily orientable from both within and without. The stairs extruded from the top surfaces allow for users to climb the structure and use the stairs as informal seating for short breaks (Figure 18). These stairs can also be used as seating in presentation and event settings within the library. As the top surface also is generated from voronoi panels, the panels can easily be switched out and created for more comfortable cushion seatings and/or add more light within the rooms through the use of the perforated panels (Figure 17).



Figure 18

## Sensor Integration

*Branch* incorporates the use of sensor actuators to further encourage user interaction. Our project proposes the use of pressure sensors which activate an LED response (Figure 19). The integration of this closed-loop system will provide visual indicators for occupied rooms (Figure 20).

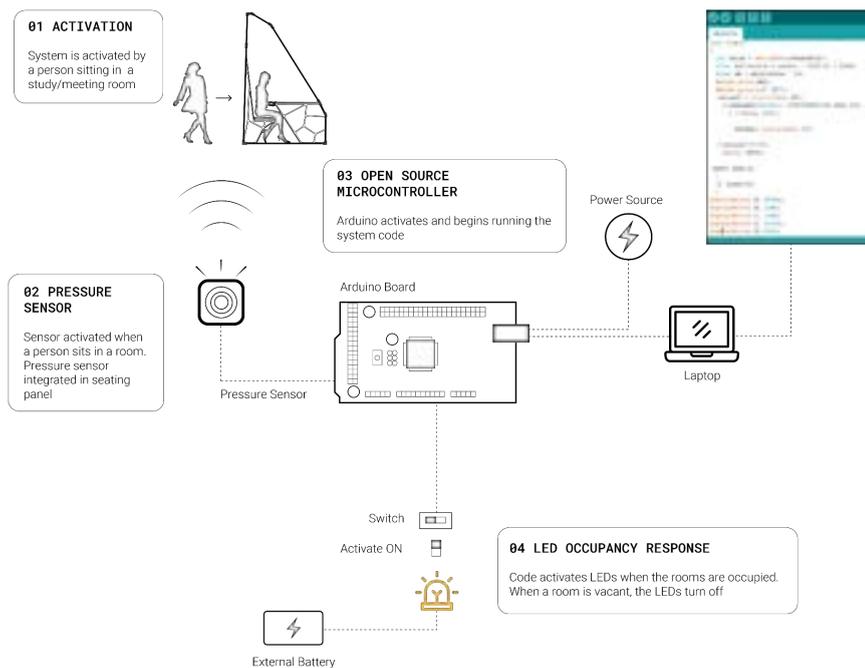


Figure 19

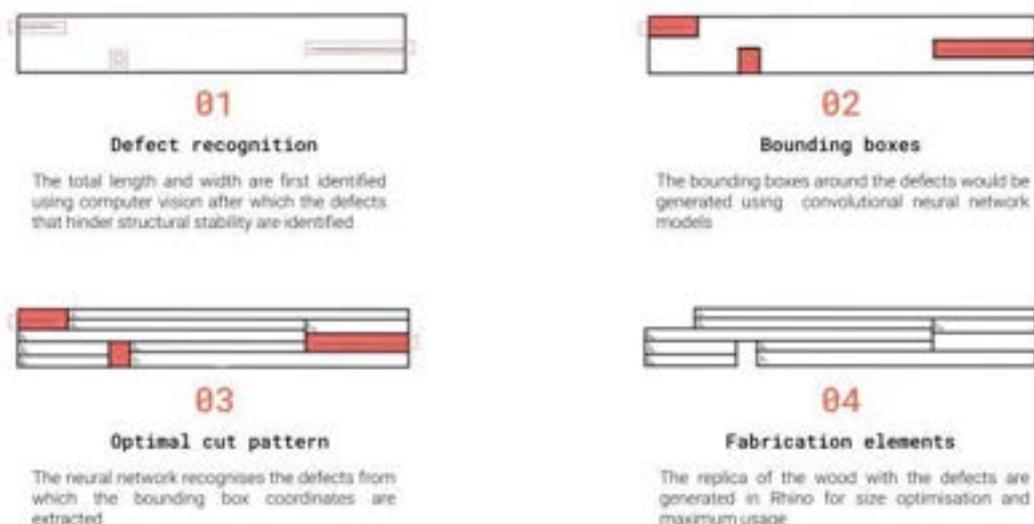


Figure 20

Our design intentionally requires human interaction in order to bring the structure to life. Without humans the rooms remain dark. However, once a person decides to sit within one of the rooms, the pressure sensors within the seats will activate LEDs embedded within the structural nodes around that room to turn on. The more people occupying the rooms, the more vibrant the *Branch* becomes. It directly responds to the humans that occupy it, creating a playful relationship with the visitors of the TU Delft library. The nodes surrounding these spaces would be designed to support LEDs embedded within their structure, and the LEDs would remain on until the occupants stand up and the pressure sensor is no longer activated. The implementation of sensor actuators within *Branch* is practical in terms of visual wayfinding throughout the landscape, and interactive as it calls upon the users of the library to engage with the spaces it provides.

## Computer Vision

The idea of using computer vision was to integrate it in the core of the project and where no other solution could replicate it as accurately as a computer could, using machine learning and CV. The idea was to integrate computer vision in procurement of circular wood where the computer would help identify defects in the wood and demarcate out the unusable parts that would hinder the structural integrity of the usable wood to create beams. The project would be split into two primary tasks of defect identification and coordinate generation of the usable wood.



A very linear pipeline of object identification, defect detection and boundary extraction would be followed to make use of the output data to further use them in the design process. The inputs would have to be images of circular wooden boards on a conveyor belt scanned using a line camera and synchronised using a pulse encoder. Once the CV is able to extract the size of the board, a trained model would then identify the defects by demarcating them with boundary boxes. These would then be converted to text/coordinate data that would then be used within Grasshopper in Rhino, to generate a convenient pattern for cutting the usable wood.

**IMAGE CAPTURING SETUP**

Each board is scanned with its dimensions marked out and points of defects recognised. The program re-estimates the number of pieces that can be cut with a certain threshold amount for the widths and lengths which will then be used in the design.

**Line scanner + Diffused light**

The line scan camera can be used to capture sharp images of moving objects in high resolution which is evenly lit using an angled light in the exact spot being captured.

**Wooden panels**

The claimed wooden panels are run through the conveyor before being scanned for creating a dataset for training and scanning.

**Pulse encoder**

The pulse encoder or an incremental encoder helps synchronize the speed of the conveyor belt with the speed of image capturing, making sure of no overlaps.

**Conveyor Belt**

The conveyor belt is made with a see-through membrane so a simultaneous scan can be made for both the surfaces of the wood that passes on the belt. This will also be used for data collection to train the dataset.

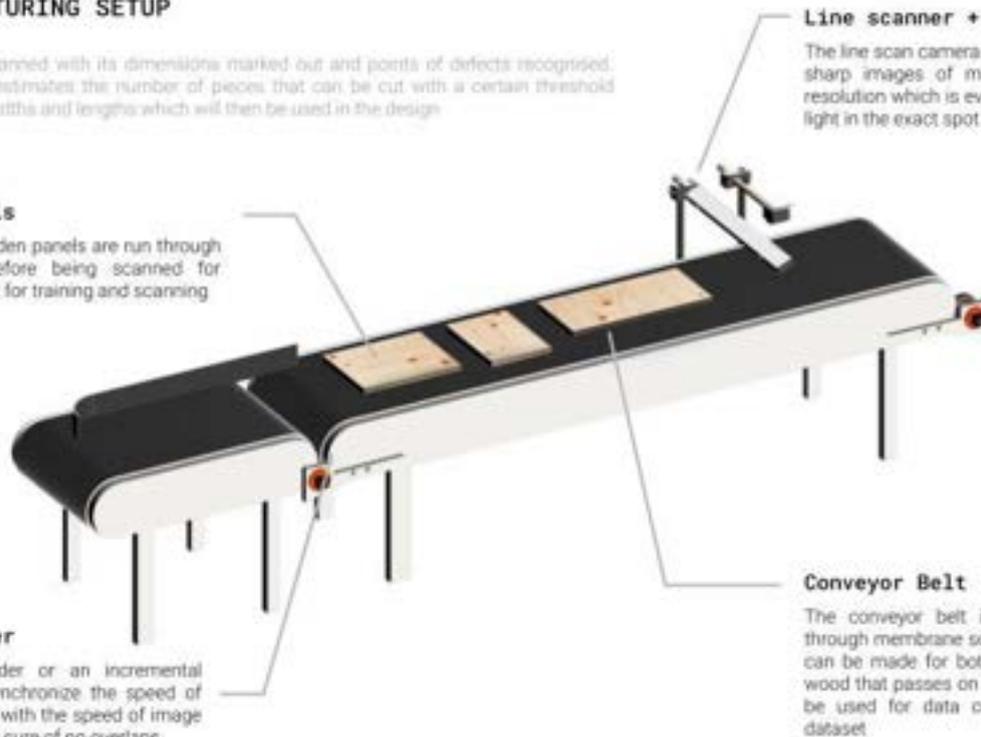


Figure 21

While the angled light and line scanner camera helps capture the image, the main contributor to separating and finding out the height of the boards are the ultrasonic sensors that are placed such that the start and end of the boards are when it starts taking the picture. The difference in the height causes a variance in the emitted and receiving waves which also help determine the thickness of the wood panels and also in cropping the panel's image.

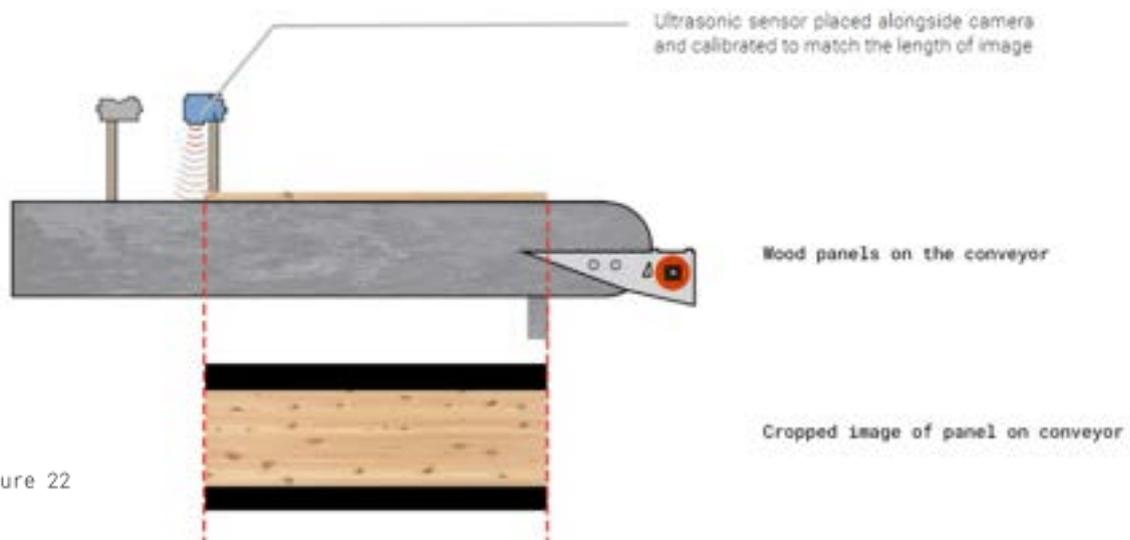


Figure 22

We obtained a large scale dataset of 4000 wood images with 8 visible defects already pre labelled as part of another dataset through Kaggle, each image was around 1MB with a resolution of 2800x1024. Upon training the Yolov5 model with 200 epochs, these were the results.

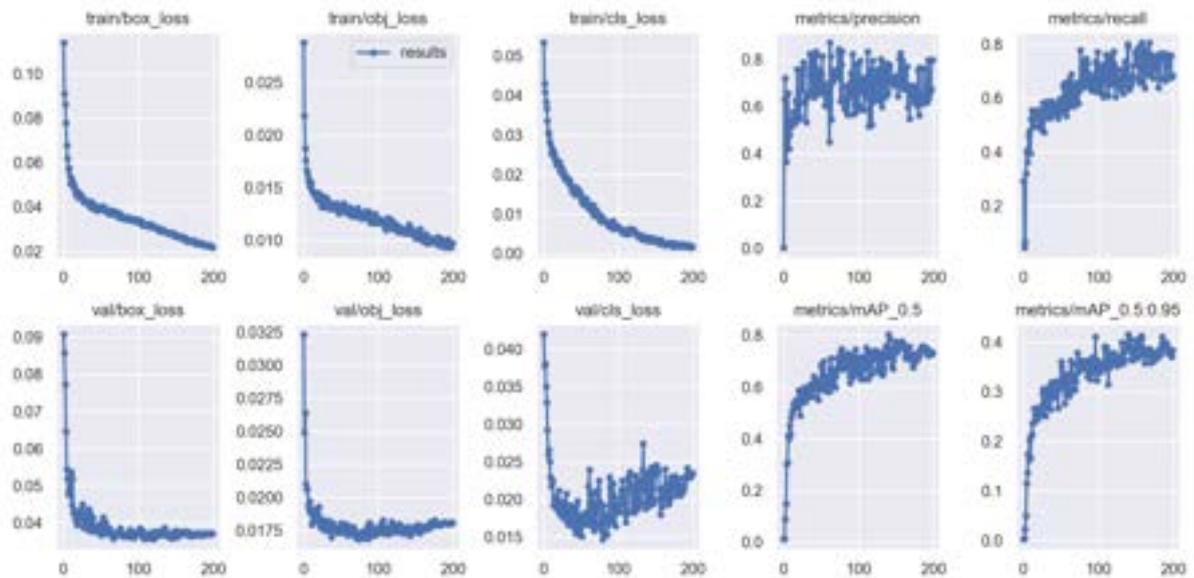


Figure 23

The bounding boxes, object and class loss in validation data kept improving until the 200 epochs the dataset was trained on, while the class loss seems to be going up beyond 80 epochs. The precision metrics improved upto 120. The validation batches and predicted batches for the training are shown below.

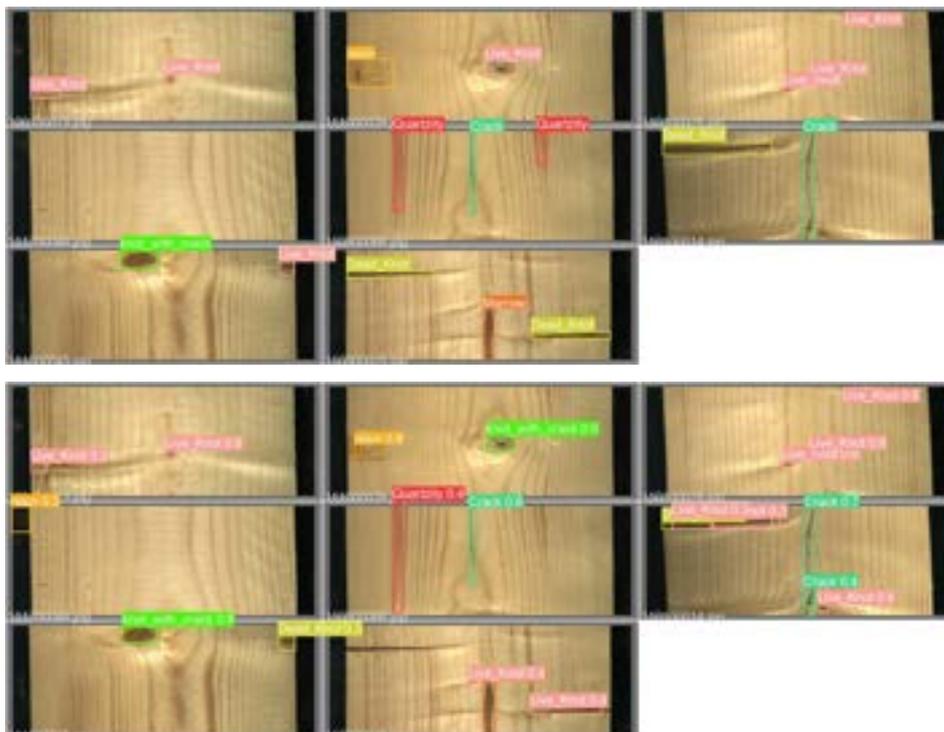


Figure 24

The trend on the correlogram shows how the defects in general tends to be closer to the central portions of the wooden pieces along the y-axis, resulting in complex cuts in post-processing of the design, as shown below from the results

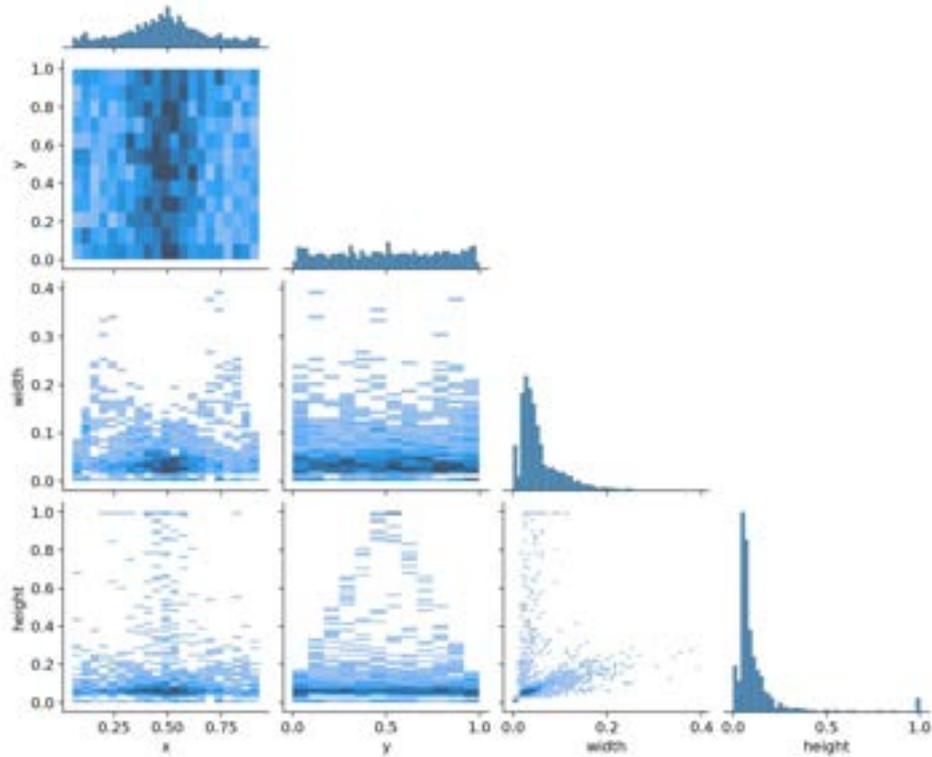


Figure 25

The final step was to test this out on sample images of the wood and in exporting these bounding box data out as CSV files that were then opened in grasshopper to get the vectorised coordinate data of the wooden piece and its defects which then allows us for optimising the wood for being cut during the fabrication .



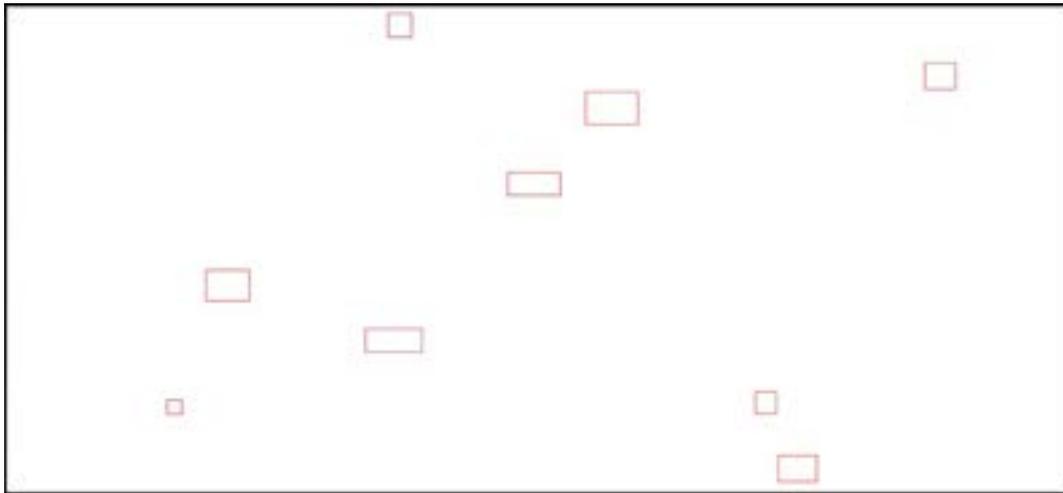


Figure 26

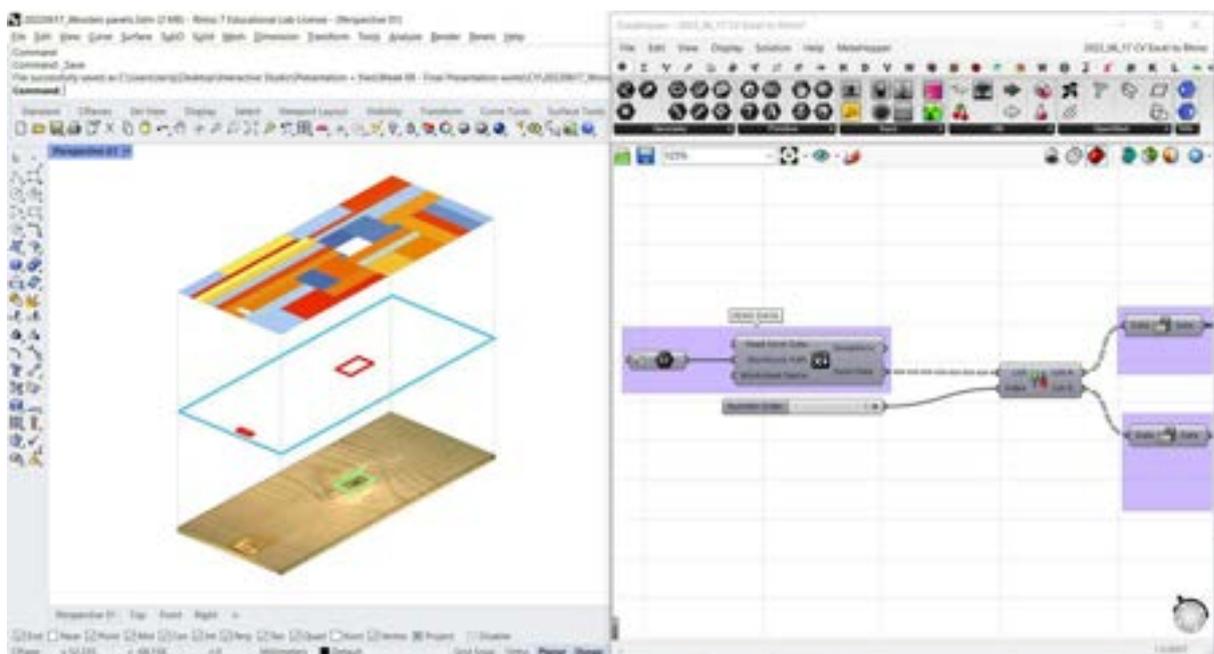


Figure 27

## Fabrication Process

In its simplest form, Branch can be reduced to three primary component types: nodes, members, and panels. These elements form a dynamic kit of parts consisting purely of elements that are treated as being unique from a fabrication and assembly perspective.

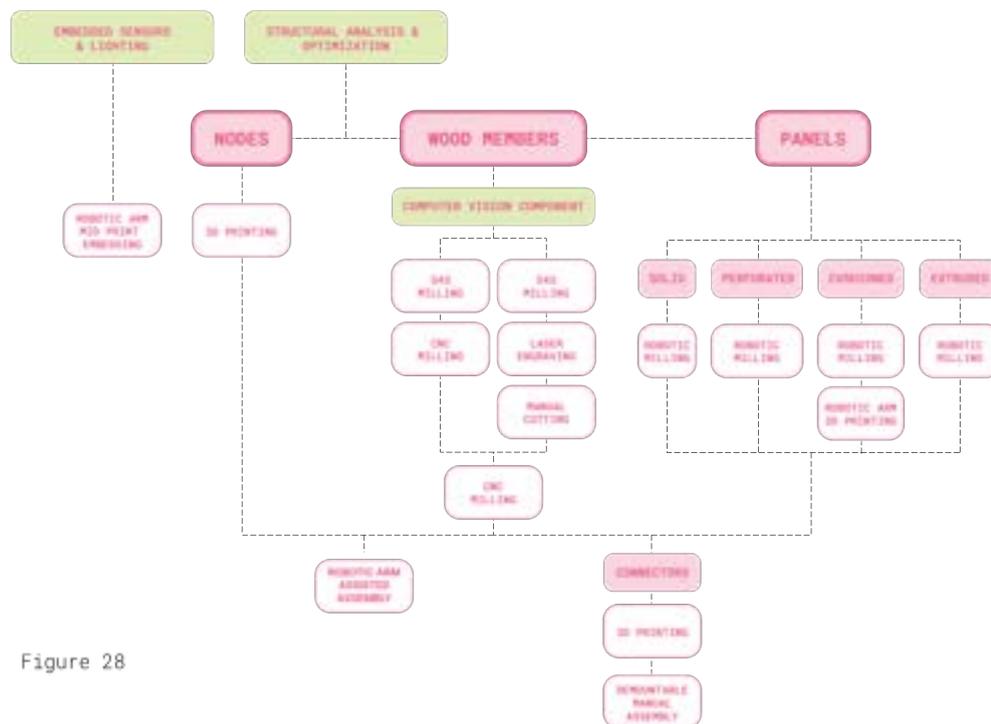


Figure 28

## Reclaimed Wood Members

*Branch* is predicated on the affordance of utilising reclaimed wooden elements in its design. Wood is inherently a difficult material to work with due to its non homogenous nature, and reclaimed wood more difficult due to the prevalence of foreign materials embedded in the boards as well as defects such as warping, bending, and twisting. Through use of computer vision and neural networks, individual boards (both reclaimed and otherwise) can be scanned for defects, their properties catalogued, and filed away for cross reference as the design develops. While not explored as part of this studio, this workflow has the potential to be expanded to include affordances for wooden elements which are warped, bowed, or have an otherwise difficult to work with form that has little impact on the structural performance of the wood.

Two primary methods of cutting the boards to the final dimension were explored. The first is reliant more heavily on an automated pipeline, with boards being milled using a three axis CNC machine or milling head on a robotic arm. This approach poses challenges with regards to clamping, removal of components from the cutting bed, and component sorting for future steps. The second method would be to utilise laser engraving to mark cut patterns and dimensions on individual boards for operators to mill through more traditional methods such as a table saw and chop saw combination for rip cuts and cross cuts respectively. Both methods are also open to the possibility of laminate timber elements which carry numerous benefits but were deemed beyond the scope of the studio.

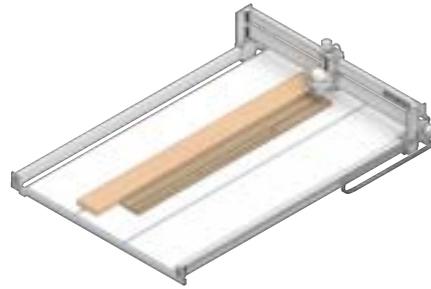
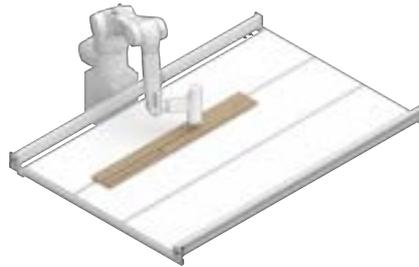
**CNC Wood Milling****Robotic Arm Wood Milling**

Figure 29

## Structural Nodes

One constraint imposed by the design of *Branch* is the need to keep the nodes from intersecting with the panels which are attached flush to the outer face of the reclaimed wood members. The ability to offset panels, thereby removing this restriction, was deemed too problematic to be pursued.

The proposal for *Branch* makes a number of assumptions regarding the construction and viability of the nodes due to a lack of opportunity to run structural tests on prototype units. While the proposal indicates that the nodes could be 3D printed using plastics such as ABS and PLA, there is the possibility that a different approach may be required after more testing. The possibility of printing using a composite material including sawdust, a waste material from earlier stages, was also discussed and shelved for the purposes of the studio.

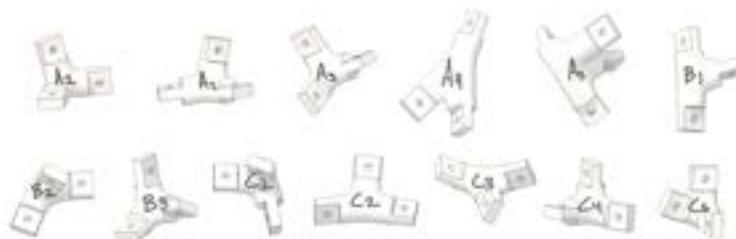
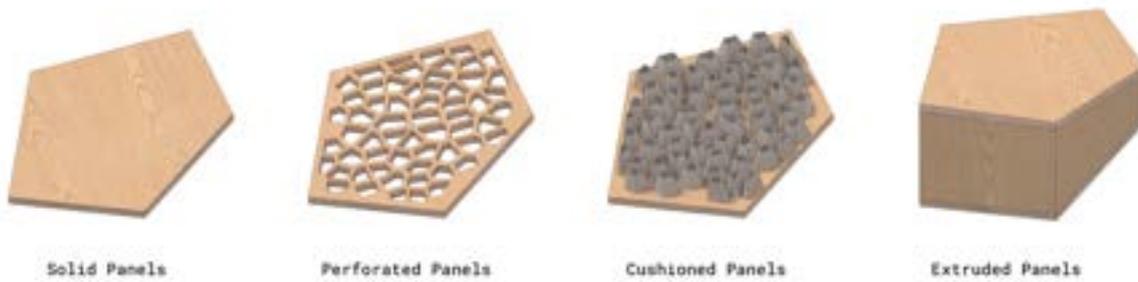
**Collection of Nodes**

Figure 30

## Panels

The proposed set of panels represent a subset of possibilities for different panel types suited to a variety of functions. For the scope of fabrication four primary types will be explored.



### **Solid Panels**

Solid panels would be fabricated using a six axis robotic milling arm. A three axis CNC mill would also be suitable for applications where neighbouring panels share the same planarity, though a six axis robotic milling arm would be required for mitered connections between non planar panels.

### **Perforated Panels**

The initial steps are the same as the solid panels, with perforations being milled into the panels perpendicular to the face, allowing for either three axis CNC or six axis robotic milling arm to do the work.

### **Cushioned Panels**

Same initial steps as the perforated panels, but with the alteration that the milled voronoi do not reach full depth. This leaves a flat surface upon which a robotic arm with an additive manufacturing attachment can print the cushions. Initial tests have been done with TPU, though current geometris suggest nozzle widths greater than 0.4mm will result in a higher than desirable stiffness.

### **Extruded Panels**

The base place of the extruded panels follows the same logic as the steps used for the solid panel, with the added complexity of the chosen method of joinery. Dry connections are preferred, with a modified version of a dowelled dovetail intended for CNC proposed.

### **Connection Details**

The connection detail between the panels and the reclaimed wood members is something that could very likely be rethought, but the current iteration fulfils the desired role of being entirely demountable. The demountability allows for the swapping of different panel types.

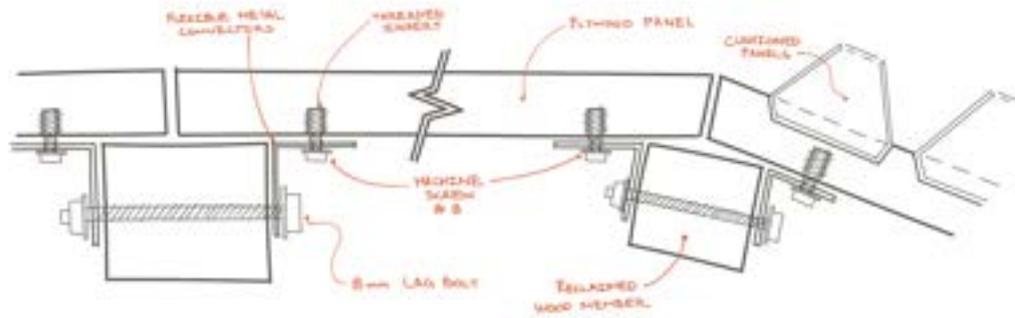


Figure 31 **Connection Detail - Member to Panel**

The detail between the node and the reclaimed wood member is a bit more involved. Given the desire to construct a functioning prototype, the connection had to be something that could be produced reliably through traditional fabrication methods as well as plausibly fabricated using the more advanced methods explored in the course.

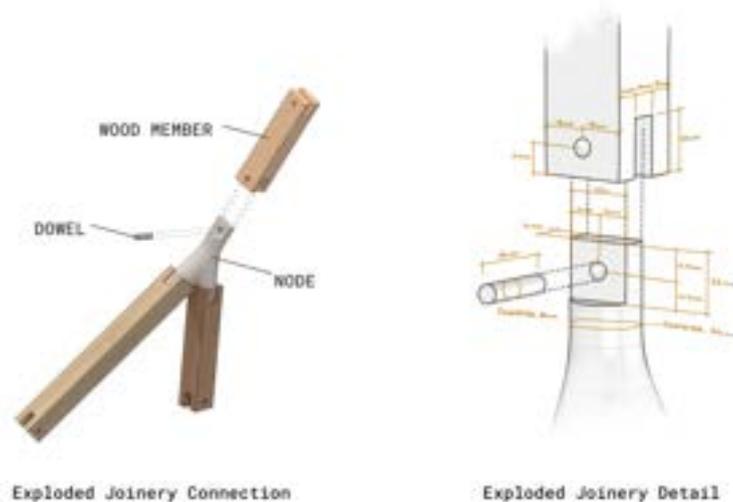


Figure 32

The resulting connection represents a hybrid between a tongue and groove connection and a dado, and can be fabricated (with minor modifications, namely rounding inner corners) using a CNC machine as well as more traditional methods. The through dowel offers a demountable connection that holds together as a friction fit.

As a result of the testing undergone during the fabrication of the prototype stool, the design of this connection has been revised to better address certain fabrication issues as well as provide more support against bending moments.

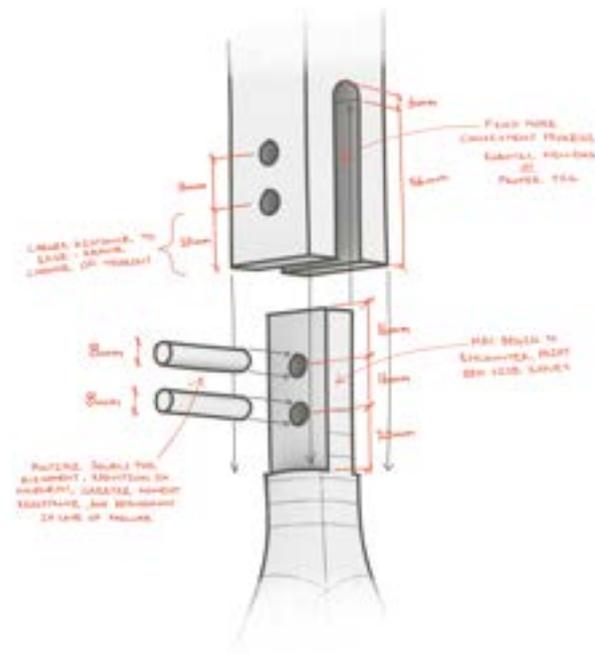


Figure 33

### Revised Connection Detail

## 1:1 Prototyping

Two 1:1 prototyping explorations were undertaken as part of the studio. This first exploration was the development of a cushioning system following on the work done by the Robotics Lab previously. This involved the design of a series of open topped voronoi chapped cushions which were printed using 0.8mm layer heights out of TPU.

The initial tests were unfinished as a result of the prints failure due to foreign material in the extruder head, but were promising in their flexibility. The second test was a mass of several voronoi cushions being fabricated as a single print. The 3mm width of each of the walls along with the infill pattern proved to make the cushions incredibly stiff. The final prototype was printed using a single layer of print width on a 0.8mm nozzle. While promising, there is still a greater than desired amount of stiffness at the corners. A further exploration would be to round the corners over and test the flexibility of this iteration.

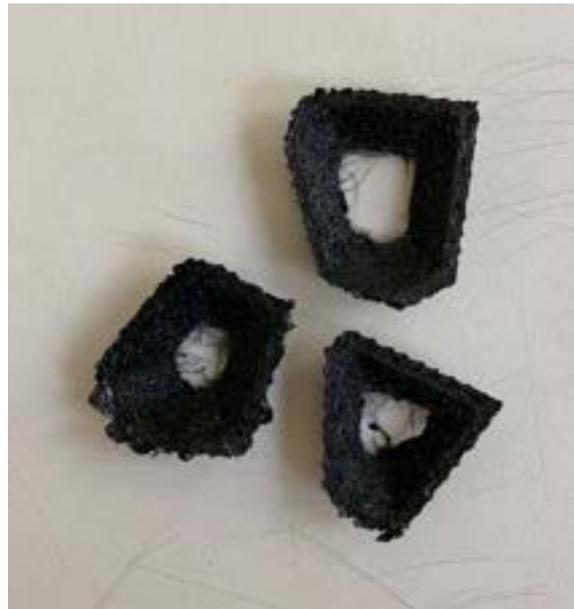


Figure 34

**Results of Test 01**

A void to fit the cushions was then milled out of a 200mm side length cube of EPS foam using a KUKA robotic milling arm. The toolpaths were generated by modifying an existing grasshopper script provided as part of the course. The first pass of the milling resulted in a depth that was roughly 4mm too shallow to accommodate the cushion, so the block was flipped over and raised by that amount in order to mill to the correct depth.

**EPS Milling**

Figure 35

The second exploration conducted as part of the studio is the creation of a prototype stool. To limit the complexity of the milling process for the workshop assistants, a fixed cross section of 36mm x 36mm was selected for the stool. The nodes and members were designed using a variation of the grasshopper script used for furniture generation. The parts list, consisting of fifteen nodes and twenty members, was produced and fabrication began.



Figure 36

The nodes were 3D printed in the TU Delft robotics lab using white PLA filament. There were some challenges in this process as print settings were adjusted, with many of the nodes having broken surfaces due to insufficient outer print layer depth. The wooden members were milled to cross sectional dimensions at the TU Model Hall using a table saw and thickness planer, and then the joinery cut by hand using primarily a japanese pull saw, chisels, callipers, and a rough file.



Figure 37

Laying out components for top-frame assembly

Due to inconsistencies in the dimensions of the printed nodes compared to the digital model, many of the members had to be adjusted for the holes to line up. This process was rather inexact and further reduced the tolerances. Future tests would almost certainly involve the creation of proper joinery jigs to reduce tolerance issues.



Figure 38 &amp; 39

The completed stool represents a strong first attempt at using the system for the generation of furniture and later larger structures. Next steps would include developing a stronger structural model for optimization operations and the reduction of material along with testing of robotic milling operations with the wooden members.

## Conclusion, Reflection & Feedback

The course has allowed for us to look at design on varying levels where the idea of scalability is at its core concept. The initial weeks allowed us to look not only at previous innovations from eras gone by, but also enriched us through the precedents and ongoing research within the field of interactive architecture and furniture design.

Early explorations were primarily based in structures that could hold pneumatic systems, to more balloon like mediums for fabrication, which then moved towards having systems that become kit of parts for varying furniture but looking at the options generated midway through the course, we come to take notice that the voronoi system not only facilitates this approach of growth at every scale, but also accommodates for varying applications of computer vision/machine learning and human-robot interaction along multiple steps of the process.

While we proceeded with a kit of parts of our panelling system for the voronoi based curvilinear structure with rooms within them, we reflected on the comment that panel attachment on a growing system is still a modernist approach. Structural analysis and member reductions being the other reflection where the large number of members between the room's structure and the walkable roof-top could use a reduction in members between them which we suppose would eventually be possible with larger members in comparison to the existing design or through optimisation.

The seamless integration of computer vision in the process of creating these members by reducing waste through data transfer into Grasshopper, before fabrication was deemed to work well within the pipeline of the system and while the cushioning material could use more flexibility, which would have achieved greater success having used 50-60 shore hardness over 98A for the TPU, the learning of the robotic toolpath for milling was well worth it in the process.

We concluded the project by trying out our design system through a small stool which was taken directly from one of the furniture systems within the design, and was prototyped at a 1:1 scale. The stool used wooden beam members and laplacian smoothing of the nodes which were 3D printed using PLA and sat on for stress testing by every member of the group and to ensure stability and structural integrity.

While the studio felt fast paced and competitive, every step of the process has bestowed us with an improved approach to design by sharpening our systematic thinking and future (if not ongoing) process of D2RA&O processes within architecture.