

M Y C O B U I L T

COMPUTATIONAL FORM-FINDING METHODS FOR  
MYCELIUM COMPOSITE STRUCTURES

Ilan Keymeulen



# Mycobuilt: computational form-finding methods for Mycelium composite structures

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## A B S T R A C T

The rapid development of CAD/CAM programs has made the designing of freeform surfaces more accessible but often lacks a production method to develop these complex geometries in real life. This thesis is an attempt to create a design system and material that is fully renewable, biodegradable and that is also functional for computer aided design. This new material is mycelium in combination with jute and rattan weaving to create a new composite material. First the different components of the composite are researched after which a physical experiment is conducted to find out the material specifications and production process as well as the best composite composition. Through computer aided design a parametric design method is created to optimise the use of the mycelium composite as a building material. Mainly form-finding is used to optimise the structure while digital design tools are used to model the composite material.

To conclude, a 1:1 scale model of an arch is produced to test the feasibility of this composite and the proposed design language. The design language developed here can be extrapolated towards larger structures allowing fully biodegradable pavilions to be built.

Image: One of the test pieces for the composite material consisting of mycelium, jute and woven rattan. This test piece was used in the uniaxial compression test



# EXTENDED ABSTRACT ENGLISH

In our education, sustainability and durability are becoming more of a priority each day. This has greatly affected the way we look at architecture as a whole. On a global scale the focus on finding a more sustainable way of living is also getting more and more attention. One of the biggest impacts is not only industry but also the building sector, being responsible for a third of the total waste the European Union produces. Because of this, a lot of research is being done on how this waste stream can be reduced. (European commission, 2018) In search of finding a solution, this thesis ventures into digital tools that could help aid this reduction of waste.

Form finding, computer aided design and manufacturing is evolving at a very rapid rate. These new technologies have the potential to truly revolutionize the way buildings are constructed. However, in order to match the pace of these high tech technologies, materials are also getting thinner, lighter and stronger. These materials are often created using very intensive production processes while often having no proper way to dispose of these materials at the end of their life cycle.

A multitude of solutions are being looked at today to reduce the amount of waste the building industry produces. For this thesis the main methods that will be used are impacting the design and the material used

to construct said design. Firstly, designs can be optimised using software to reduce the amount of material needed while also optimising the form to reduce the stress the structure is under. The technique used here will be form-finding, a technique where the final design is based on the forces applied to the structure.

Secondly, the advancement of designing software also allows new materials that were previously impossible to be built with to turn into valid options for construction. One of these materials that can now be considered is mycelium, a substrate infused with the root system of mushrooms. This material has a rather low strength but provides other advantages such as being fully biodegradable and renewable. With these two methods, modern technology can harness a living material, combining low tech and high tech techniques.

Mycelium itself is already a great example where high tech production processes are used on a very low tech natural material. The mycelium that grows in plain nature is cultivated in laboratories to optimise the growth process and make sure no other fungi or bacteria grow in the substrate. This combination of high tech and low tech is in my opinion one of the best ways to go forward. Low tech methods and materials are often seen as outdated and ancient. Instead, they should be seen as a way to live

together with nature, a topic that is getting more and more relevant each day.

The focus of this thesis lies in the optimisation of mycelium by using computer aided design. Computer aided design can be used to develop a composite that not only offsets the weaknesses of mycelium but further enhances its positive aspects. This composite is then combined with structural optimisation such as form-finding and a physics engine to create an optimised structure. This structural optimisation allows materials such as mycelium that have a limited strength to be used in the building sector.

The creation of this composite was the first step of researching this new material. To do this, mycelium itself was first looked at in depth to understand the weaknesses of the material. The main problems the composite will set out to solve are the non-reusable molds in which mycelium structures have to be grown as well as the low strength. This solution took the form of weaving, an ancient technique that has been around for ages. By weaving the molds out of natural fibres, in this case rattan, these could become part of the final composite which also greatly increases the strength of the material. In addition, jute was added as an outer skin to allow the mycelium to grow properly without a plastic mold. This was the first test of the thesis, a comparative

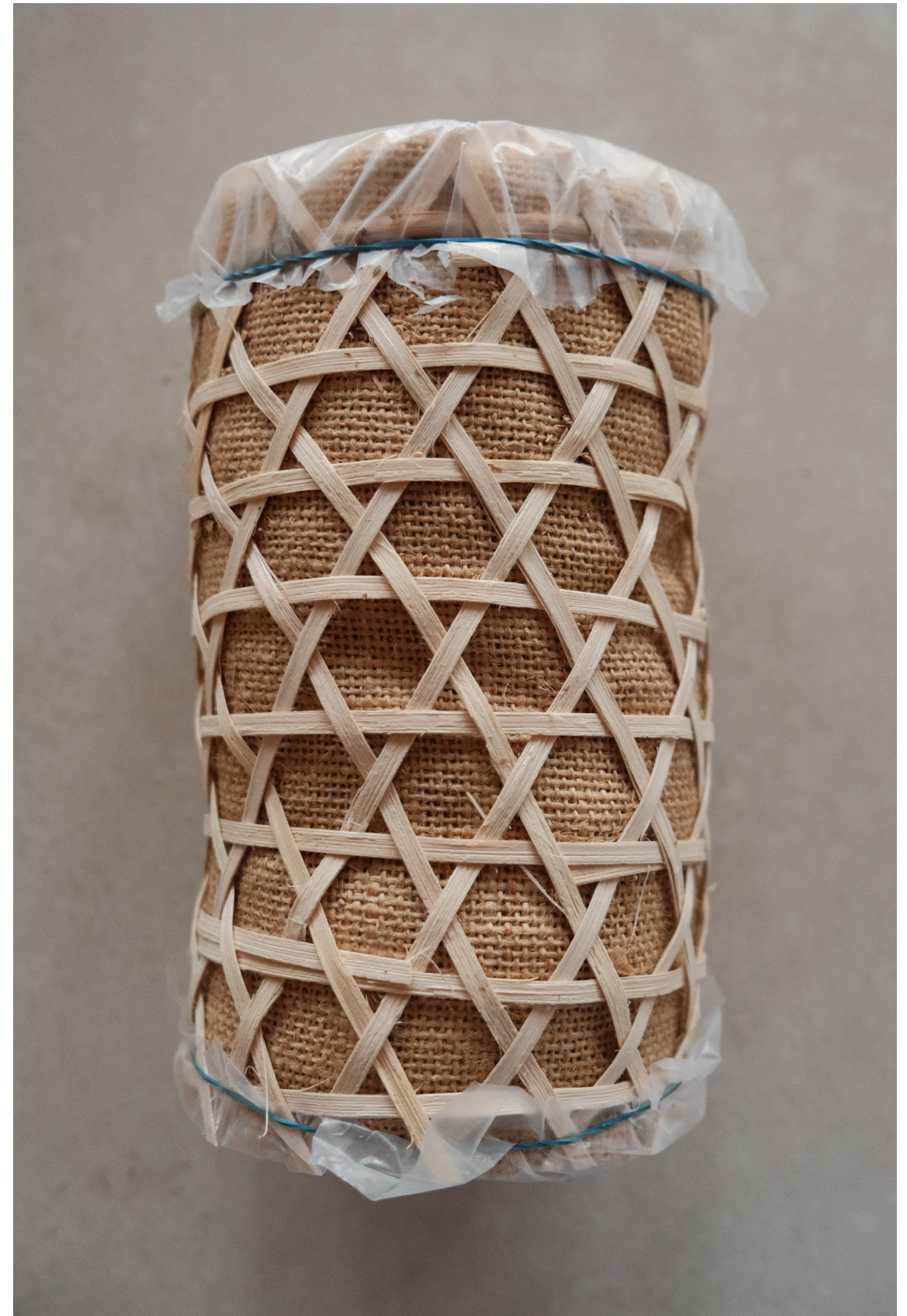
study to find the best composite. A number of different combinations of rattan and jute with different densities were created. In order to compare these combinations, a three-point bending test as well as a uniaxial compression test were executed.

Based on these results, the most optimal combination of jute, mycelium and rattan weaving was chosen. In order to make this composite applicable to structures, a design system had to be created for this new composite. The program used to create this design was Rhino 8 and Grasshopper, a parametric modelling tool that is part of Rhino. The first step in the digital production process was to create a Grasshopper definition capable of weaving complex geometries. This was achieved through the use of a plugin called Weaverbird. (Piacentino, 2023) Next, the jute skin needed to be modelled, this was done by sewing different sheets of jute together, allowing complex forms to be woven. These sheets were based on patterns derived from unrolling the complex geometries in Rhino.

Next, a structural design language that is optimised for this composite had to be modelled. This was achieved through form-finding using the Kangaroo3D plugin (Piker, 2017) for Grasshopper. The proposed structures consisted of the mesh edges of curved surfaces. This allows a large freedom of form making it possible to construct virtually any curved surface out of a mycelium composite. The last step in the digital process is the linking of the composite design tool to the structural model developer. A number of different solutions were tested to try and link these two parts together until a working Grasshopper definition was made. The different steps of linking these two parts together was also documented in this thesis.

Finally, a life size model was built to test the feasibility of the structure. A simple arch was modelled using the various Grasshopper definitions created in the foregoing steps. The Grasshopper definitions were also the basis for the weaving patterns of the various knots needed to construct the arch. The jute geometries were created in a similar fashion. After each individual piece had been finished the arch could be assembled. After the final setup of the structure a final review was done of the results and possible further steps that could be made were discussed.

Image: One of the test pieces for the composite material consisting of mycelium, jute and woven rattan before the growing phase





# EXTENDING ABSTRACT

In onze opleiding is duurzaamheid meer en meer een prioriteit aan het worden. Dit heeft een grote impact op de manier waarop we architectuur in zijn geheel bekijken. Op wereldschaal krijgt de focus op het vinden van een meer duurzame manier van leven ook meer en meer aandacht. Eén van de meest vervuilende sectoren is niet alleen de industrie maar ook de bouwsector. Deze is verantwoordelijk voor een derde van het totale afval dat de Europese Unie produceert. Er wordt dus veel onderzoek gedaan naar manieren om deze afvalstroom te verminderen (European Commission, 2018). Op zoek naar een oplossing waagt deze thesis zich aan digitale tools die bij deze afvalreductie zouden kunnen helpen.

Form-finding, computer-aided-design als ook productie evolueren zeer snel. Deze nieuwe technologieën kunnen voor een revolutie zorgen in de manier waarop gebouwen worden ontworpen. Om zich aan te passen aan deze innovatieve technologieën worden materialen dunner, lichter en sterker. De productie van deze materialen verloopt vaak volgens zeer intensieve processen waarbij er meestal ook geen goede manier is om zich van deze materialen te ontdoen op het einde van hun levenscyclus.

Vandaag wordt een veelheid aan oplossingen bekeken om het afval dat door de bouwindustrie geproduceerd wordt te verminderen. Voor deze thesis zullen de belangrijkste gebruikte methodes de impact op het ontwerp zijn en het materiaal dat gebruikt wordt bij de constructie van dit ontwerp. Ten eerste kunnen ontwerpen geoptimaliseerd worden door het gebruik van software om de hoeveelheid van het benodigde materiaal te verminderen en terwijl ook de vorm te optimaliseren om de belasting die de structuur ondervindt te verminderen. De techniek die hier gebruikt wordt is form-finding, een techniek waarbij het uiteindelijke ontwerp gebaseerd is op de krachten die op de structuur toegepast worden.

Ten tweede maakt de vooruitgang in de ontwerp software het ook mogelijk om nieuwe materialen waarmee vroeger niet kon gebouwd worden te veranderen in waardevolle opties voor constructies. Eén van deze materialen, dat nu kan overwogen worden is mycelium, een substraat verrijkt met het wortelstelsel van paddenstoelen. Dit materiaal heeft een lage sterkte maar biedt andere voordelen zoals het feit dat het volledig biologisch afbreekbaar en hernieuwbaar is. Met deze twee methodes kan moderne technologie een levend materiaal benutten door low tech en high tech technieken te combineren.

Mycelium zelf is al een goed voorbeeld waar high tech productieprocessen gebruikt worden voor een zeer low tech materiaal. De mycelium die groeit in de wilde natuur wordt gecultiveerd in laboratoria om het groeiproces te optimaliseren en ervoor te zorgen dat er geen andere fungi of bacteriën in het substraat groeien. Deze combinatie van high tech en low tech lijkt mij een van de beste oplossingen naar de toekomst toe. Low tech methodes en materialen worden vaak beschouwd als verouderd en antiek. In plaats daarvan zouden deze moeten kunnen gezien worden als een manier om samen te leven met de natuur, een topic dat elke dag meer en meer relevant wordt.

De focus van deze thesis ligt bij de optimalisatie van mycelium door het gebruik van computer aided design. Computer aided design kan gebruikt worden om een composiet te ontwikkelen dat niet alleen de zwaktes van mycelium compenseert, maar zijn positieve aspecten verder versterkt. Deze structurele optimalisatie maakt het mogelijk om materialen met een beperkte kracht, zoals mycelium, te gebruiken in de bouwsector.

De creatie van het composiet was de eerste stap in het onderzoek naar dit nieuwe materiaal. Om dit te doen werd eerst mycelium zelf grondig bekeken om de zwaktes van het materiaal te begrijpen. De belangrijkste problemen dat het

composiet zal moeten oplossen zijn de niet herbruikbare mallen waarin de mycelium structuren moeten groeien en ook de beperkte sterkte. De oplossing kwam onder de vorm van weven. Door de mallen te weven uit natuurlijke vezels, in dit geval rotan, worden deze een deel van het finale composiet, wat ook de sterkte van het materiaal enorm verhoogt. Daarbij werd jute toegevoegd als een buitenste huid om het mycelium goed te laten groeien zonder het gebruik van een plastic mal. Dit was de eerste test van de thesis, een vergelijkende studie om het beste composiet te vinden. Een aantal verschillende combinaties van rotan en jute met verschillende densiteiten werden gecreëerd. Om deze combinaties met elkaar te vergelijken werd een drie-punts buigtest en een uniaxiale druktest uitgevoerd.

Gebaseerd op deze resultaten werd de optimale combinatie van jute, mycelium en rotan vlechtwerk gekozen. Om deze composiet toepasbaar te maken op structuren, moest een ontwerpsysteem gecreëerd worden voor dit nieuwe composiet. Het gebruikte programma om dit ontwerp te creëren was Rhino 8 en Grasshopper, een parametrische modeleertool die deel uitmaakt van Rhino. De eerste stap in het digitale productie proces was om een Grasshopper definitie te creëren die complexe geometrieën kon

weven. Dit werd bereikt door het gebruik van een plugin genaamd Weaverbird. (Piacentino, 2023) Dan moest de jute huid gemodelleerd worden, dit werd gedaan door verschillende stroken jute aan elkaar te naaien en zo het weven van complexe vormen mogelijk te maken. Deze stroken waren gebaseerd op patronen die afgeleid zijn van het uitrollen van deze complexe geometrieën in Rhino.

Dan moest een structurele ontwerptaal gemodelleerd worden voor dit composiet. Dit werd bereikt door form-finding, gebruik makend van de Kangaroo 3D plugin (Piker, 2017) voor Grasshopper. De voorgestelde structuren bestonden uit de mesh randen van gebogen oppervlakken. Dit geeft een grote vorm vrijheid en maakt het mogelijk om virtueel eender welk gebogen oppervlak uit een mycelium composiet te ontwerpen. De laatste stap in het digitale proces is het linken van de ontwerptool voor de composiet met het structureel model. De verschillende stappen van het linken van deze twee delen werd ook gedocumenteerd in deze thesis.

Tenslotte werd een levensgroot model gebouwd om de haalbaarheid van de structuur te testen. Een eenvoudige boog werd gemodelleerd, gebruik makend van de Grasshopper definities die gecreëerd werden in de vorige stappen. De Grasshopper definities waren ook de basis van de

weefpatronen van de verschillende knopen die nodig waren om de boog te bouwen. De jute geometrieën werden op dezelfde manier gemaakt. Nadat elk individueel stuk gemaakt was kon de boog samengesteld worden. Na de finale opbouw van de structuur werd een eindevaluatie gedaan en werden mogelijke volgende te nemen stappen besproken.

Image: One of the test pieces for the composite material consisting of mycelium, jute and woven rattan





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# O R I G I N S

The main inspiration to use a biobased material such as mycelium is a book by Julia Watson called “Lo-TEK: Design by Radical Indigenism”. (Watson, 2019) This book studies ancient traditions of building that have been used for centuries. Instead of considering these methods as primitive, it shows the way humans can sustainably live with their environment and how some communities have been doing just that for centuries. In this book, these more resilient ways of living that focus on tradition and simplicity are seen as the way forward. This is done by taking a step back from the further and further development of materials and going back to these techniques. Instead of fully renouncing the high tech methods that are developing at a rapid rate my personal belief is that learning from these methods that have been around for centuries and applying them to modern design systems and materials is the way forward.

The reason these methods of building became obsolete is because of clear disadvantages that can possibly be solved by modern techniques and programs. Based on this belief the search for a biobased material started.

This biobased material was eventually found at the Architecture Biennale of 2023 in Venice where the Belgian pavilion had sustainability as its main theme. (Biennale Architettura, 2023) After entering the original pavilion of 1985 a second pavilion had been constructed in its main exposition room. The goal of the pavilion was to create something that was locally and responsibly sourced. It consisted of a wooden structure that provided support for the mycelium panels hung up on it. This wooden structure also functioned as the boundary in which a loam floor was created. The three smaller exposition rooms around the central pavilion were used to delve deeper into the





3 materials used to create the pavilion. Sonian Wood Coop is a wood producer that responsibly harvests wood from the Sonian forest in Brussels. BC Materials provided the loam floor, the main goal of BC Materials is to reuse building materials that are seen as waste and to start using traditional techniques like loam plasters again. Finally, PermaFungi grew the mycelium panels used for the pavilion. PermaFungi is a mycelium producer based in Brussels. They created an urban mushroom farm in the basement of the Tour & Taxis site in the centre of Brussels. The humid environment proved to be an excellent place to cultivate mushrooms and mycelium. Visiting this pavilion made me realise that this was not some futuristic material but something that can work in real life already without complicated production processes.

Mycelium is a material that has recently become more popular as an alternative for many of the more traditional building materials. Its low own weight in combination with very good thermal and acoustic performances makes it a really interesting material for the building sector. The fact that it is fully renewable and biodegradable are also the reason it is looked at in this thesis as a base material to study. The production process is also almost fully waste free while the energy needed is fairly low. The only

waste stream is the formwork that can only be used five to ten times. There has been a lot of experimenting with this new material for furniture as well as insulating panels and acoustic panels. The low strength however has made the structural applications for bigger loads difficult.

A composite material could be the solution for the low strength while also removing the need for the plastic formwork that is used today. One of the goals would be to have a fully biodegradable end product but also a zero waste production process. The composite material could function as a strengthener while doubling as a framework that becomes part of the end product. Because of this the composite material was chosen as the starting point of the research on this subject.

Previous page: Doorway of the Belgian Pavilion at the 2023 Biennale in Venice. Structure out of wood with mycelium panels, floor made out of loam

Right: Detail of the connection between mycelium paneling and wooden structure

Bottom: Inner space seen from the doorway







## P R O B L E M & A P P R O A C H

The main question this thesis revolves around is how CAD/CAM methods can be applied to a biobased material such as mycelium to optimise its production process as well as the properties of the material. The two main components to achieve this are the creation of a composite material and the development of a design language based on form finding. Firstly research should be done on materials that can be used as additives to this composite material as well as on the mycelium itself. This was done through finding reference projects and material studies.

Then a proper understanding of form finding has to be achieved. After performing literature studies the step towards physical models will be set. These physical models will not only determine the properties of the composites but will also provide valuable experience on the production process. Based on these results a digital design method will be developed for both the composite material and the structural form. Finally a life size construction will be made out of the composite material based on the determined form finding method. This way an example is created that showcases the feasibility of the proposed system.

Left: Cylinder for uniaxial compression test, consisting of a mycelium core with a jute cover



# M Y C E L I U M

The main material this thesis revolves around is the mycelium itself. Mycelium is the root structure of mushrooms. Some references were looked at to gain a better understanding of the material while also providing inspiration towards the ways the material can be used. Through an interview with Jan Van Nuffel, the Research Manager of Mycelia, the production process of mycelium has been documented. Finally research papers that are included in the bibliography were used to determine the properties of the material.

## B L A S T   S T U D I O R E F E R E N C E S

Blast studio is a London based organisation that uses used coffee cups and mycelium for 3D printing. (Hahn, 2022) The coffee cups are gathered from the different coffee shops in London and then shredded. This shredded material is then mixed with water until a paste like texture is achieved. Mycelium is then added to this mix to create a printable bio material. This project focuses on creating optimised designs for the mycelium to grow on. The 3D printing software makes columns that are a folded surface. These creases allow pockets in the column that are protected from wind and light which makes them the perfect environment for mycelium to grow. The humid and dark spaces quickly get taken over. These pieces are left to grow in a dark and humid place. The only limitation here is the fact that all pieces have to be 3D printed. This means that all designs need to take into account the stacking logic of the printer and the fact that overhangs are not possible. Finally the size of objects is limited to the range of the 3D printer, making bigger pieces consists of creating multiple blocks that can be stacked on top of each other. Mycelium has the big advantage that it can grow as long as a food base is present. This means that the 3D printed can be stacked on top of each other and then placed in a dark and humid environment again to grow them together. This shows the potential of mycelium as a material once it is combined with modern day technology.

Right: Freestanding column made out of 3D printed mycelium mixed with old coffee cups (Hahn, 2022)



# F U N G A L ARCHITECTURES R E F E R E N C E S

A reference project called Adaptive Fungal Architectures by the Royal Danish Academy served as the main inspiration for using rattan as a framework to keep the mycelium in place. The project focusses on trying to remove the need for a plastic mold and creating mycelium pieces that incorporate the formwork in the final product. An array of different methods were looked at to optimise the composite. From changing the composition of the mycelium substrate mix to using synthetic fibres. This research was done for an exposition called “70% less” which happened in 2022. (Adamatzky et al., 2022) Sadly this exposition has ended but a 3D camera was used to virtually record the exposition making it possible to still visit the exposition online. (Udstillingen Det Kongelige Akademi, 2022-present)

The research done here focussed more on the optimisation of the material then creating a design language for the material. Although most of their research is about the properties of the composites an interesting reference can be found in the way they try to

combine rattan weaving with the mycelium. A number of layers of rattan woven surfaces are stacked on top of each other with mycelium in between to combine everything into a single material. A combination is made of very open weaves consisting of synthetic material for strength while rattan weaves are placed to keep the mycelium in place. The mycelium is still a big part of making the composite work but the main structure is the woven material.

Weaving these complex shapes can be very time consuming so an effort was done to see whether this could be done by robotics. Since the weaving is already based on a virtual model this could be optimised to allow a robotic arm to create these weaving patterns, greatly reducing the time and effort needed to create the rattan weaves. Another big part of their research consisted of trying different materials to create the substrate base the mycelium will grow on. Also using different families of mycelium can greatly affect the final strength of the material.

Right: Close-up of the texture of a mycelium curved surface, using geometric patterns in the mold to create texture (Adamatzky et al., 2022)  
Bottom: Kagome woven rattan structure used instead of a plastic mold, allowing the mycelium to grow inside of the rattan (Adamatzky et al., 2022)





# M Y C O T R E E

## R E F E R E N C E S

The MycoTree was a project in which a lot of different actors took part. It was part of the architecture and urbanism Biennale of Seoul. For this thesis the most notable were the circular construction lab and Block research group. A structural tree created out of mycelium was designed to hold up a wooden structure on top. A structural design lies at the base of this structure, creating a structure that is fully in compression without any bending or tensile stress. (Heisel et al., 2017) This is then further developed until an actual form is created from the string model as seen on the picture. The mycelium itself was a waste product from a large scale oyster mushroom farm. The farm consists of thousands of bags filled with substrate and mushroom roots out of which oyster mushrooms grow. Once a bag has been depleted it is thrown away creating a waste product. This seemed to be an opportunity to prolong the use of this waste material by using it as a material for the MycoTree. Although the idea to make use of this waste stream is very viable and creates a more efficient mushroom farm, the execution turned out to be less sustainable. The oyster mushroom farm in question was an Indonesian farm while the research was conducted in Zurich. This meant shipping the mycelium pieces across the globe. Because of this wooden plates with dowels were added to the sides of the pieces to connect them once they arrived in Zurich. The entire design logic still makes sense, if a local mushroom farm is used, the environmental impact is also greatly reduced. The molds used for these pieces were also plastic ones that are so specific for each test piece that they can only be used once.

Top: Close-up of a connection, consisting of a mycelium core with a wooden end. Wooden pins are used to connect the different pieces together

(Heisel et al., 2017)

Bottom: Entire structure seen at the Architecture and urbanism Biennale of Seoul in 2017

(Heisel et al., 2017)



# G R O W I N G P R O C E S S

For this thesis, the mycelium will be premixed to allow focus on the construction of the composite construction itself. The production process however provides insight in the limitations of the product. The production process looked at here is for the mycelium insulation panels made at Mycelia. Mycelia is a company based in Deinze, Belgium. They produce a variety of different fungi cultures that can be bought at different growth stages. This will also be the company where the mycelium is bought that is used for all physical tests and structures used in this thesis. (Deverick L, 2023)

First of all the mycelium strand that will be used needs to be selected. Different species of mushrooms have different strengths and weaknesses. Here the *Ganoderma Lucidum* will be used since this strand provides one of the strongest mycelium networks while also having a rather fast growth rate. Another noteworthy point is the fact that *Ganoderma Lucidum* is a native species in Belgium.

This means that the possible introduction of an exotic species into the Belgian ecosystem is avoided. It mostly grows on the base of dead trees and can be harvested this way. The possibility exists to find a culture oneself and start a cultivation from this sample. After talking with Jan Van Nuffel, the Research Manager of Mycelia however, it became clear that getting an isolated culture this way would be fairly difficult and time consuming, especially for someone who does not have experience with the cultivation of fungi. Furthermore, this would lead us too far away from the main topic of this thesis. The following process is therefore executed by Mycelia. The multiplication of the mycelium itself is done in a sterile and controlled environment since the start of a culture is very delicate. After the culture has grown to a certain size it becomes more resilient to infections of molds and other strands making it possible to mix it with the substrate. The substrate mix will further determine the mechanical and insulating properties of the end product.

The mix provided consists of equal parts chopped hemp, chopped flax and chopped straw. This provides a more balanced thickness of particles to create strong bonds as well as sufficient structural strength. Particles should stay between .5 and 3 cm in length to ensure a good bond as well as sufficient airflow to allow proper growth throughout the mycelium. Next, water is added to the mix until 70% of the mix consists out of water. This mix is then placed in a sealed bag to inoculate. This has to be done in front of a laminar flow. Now a first incubation can be started.

Once the bags are fully colonised they can be used to fill the molds. This is the final step done by Mycelia before sending the mycelium substrate to their clients. In order to make sure the mycelium substrate does not grow during transport it is kept at 2°C. This way it is too cold for the mycelium to multiply, temporarily halting the growth.

After bringing it back to room temperature and adding flour as a starter the multiplication process of the mycelium can start once again. Now a second incubation takes place, this should take around 2 weeks. Important for this step is the cleaning of the mold and all tools with 70% ethanol to remove the chance of infection of the mix. After this step the shapes can be taken out of the molds and left for another 2 to 3 days so the mycelium can grow a protective outer layer, this is the third and final incubation. Once this layer has fully formed, the mycelium has to be killed to stop the growth process. This is done by drying, for panels and smaller pieces this is done in a drying oven. A temperature of 80°C has to be sustained for 3 hours in order to fully stop the growth process. For bigger pieces that won't fit in a drying oven a bag can be used that is hooked up to a heater element that blows in consistent air of 80°C. This is now considered the final product and ready to be used.



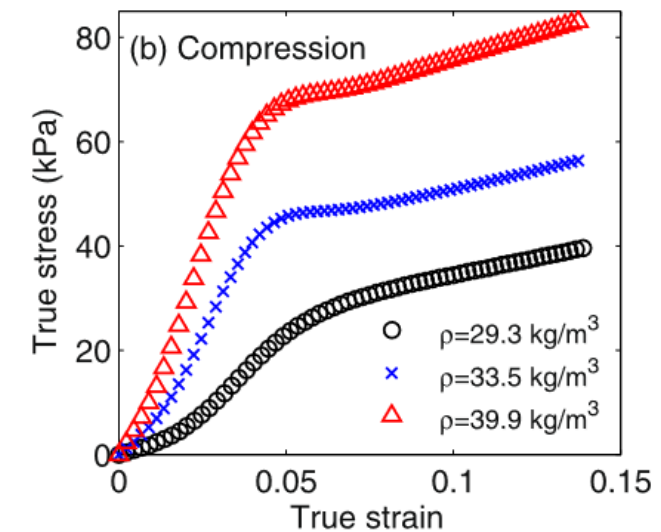
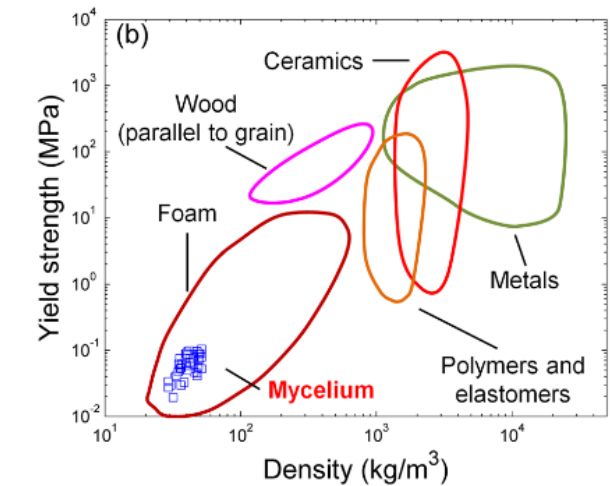
# M E C H A N I C A L P R O P E R T I E S

As already mentioned, mycelium is a rather weak material that can't take on too big loads. In general mycelium is better suited to take loads in compression in comparison to tension. This is due to the much lower amount of strain hardening in compression. The behaviour of mycelium is not the same in compression and tension. In tension a linear elastic response is seen at lower strains, followed by yielding of the material in the form of strain hardening followed by rupture. In uniaxial compression different behaviour is observed. Here a linear-elastic behaviour foregoes a plateau regime of the stress – strain curve. (Lelivelt et al., 2015)

Because the compressive properties are more optimal for construction a design made entirely or mostly in compression is favourable. The yield stress of mycelium is 40 to 80 kPa, based on the density of the mycelium fibres in the substrate. This yield strength is based on the change of the angle of the true stress – true strain curve. This happens at around 8% of the total strain.

(Islam et al., 2017)

Top: Comparison of mycelium with different other materials used in the building industry (Islam et al., 2017)  
Bottom: Effect of sample density on the stress-strain response in compression (Islam et al., 2017)  
Next page: Rattan fibres used for weaving, the strands are rolled up and delivered as a spool



# H I S T O R Y & T E C H N I Q U E S

## R A T T A N W E A V I N G

The idea to use rattan weaving is based on the Fungal Architectures paper that was discussed on page 9, where rattan is used as a composite in combination with mycelium already to create shell-like structures. The rattan can create a formwork for the mycelium that is fully renewable and biodegradable while also improving the properties of the mycelium by becoming part of the final product. First, the history and different weaving techniques were studied after which some reference projects were looked at. Finally an attempt was made to create a woven cylinder.



Rattan is a type of fibre made from the rattan palm. This plant grows mostly in Asia, because of the large availability it is a low cost material that has been widely used throughout history. Not only was it used a lot for furniture but also for construction of houses and other structures. (Hélène J., 2024) This created a specific design language consisting of weaving patterns. These traditional weaving patterns could be digitalised through Grasshopper and then fed to a robotic arm to create the skeleton of the product. Because the use and programming of a robotic arm is very time consuming this will not be used in this thesis. Instead, the skeleton will be woven by hand under the assumption that what can be done by a human will also be possible by the use of a robotic arm. If the process proves to be quick and rather simple it could be used without a robotic arm and keep the production process rather low tech and not over complicate things.

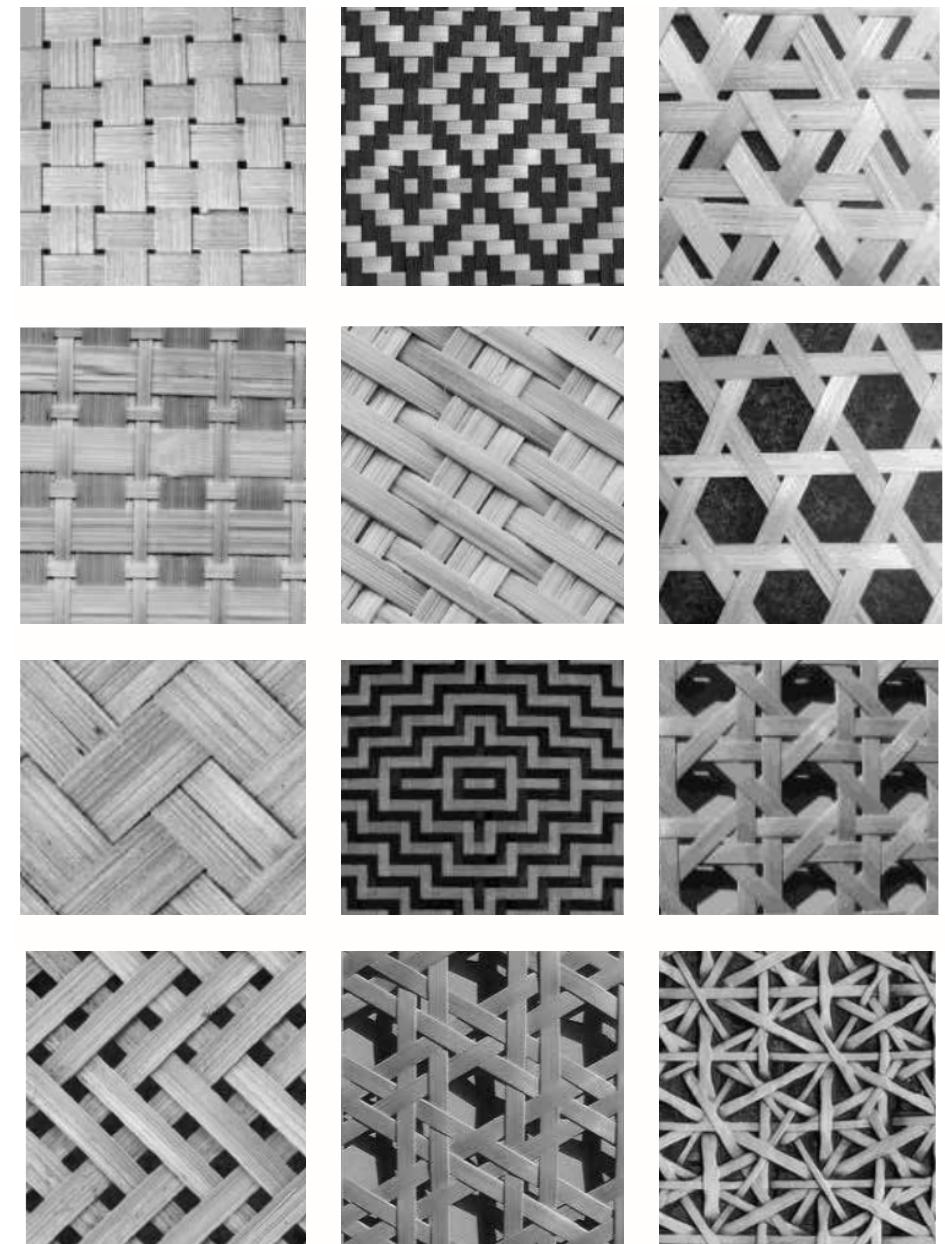


For the weaving techniques an extensive number of patterns can be looked at. The weaving of cane, bamboo and rattan has been a centuries old tradition in the East especially. Rattan and bamboo furniture were the main inspiration to use rattan as a skeleton for the mycelium. A variety of different techniques has been developed by different civilisations throughout history. American native people have used woven baskets, remains of baskets dating from 3000 B.C. have been found in Egypt and even in northern Europe remains of woven baskets were found in peat bogs. Out of these civilisations most produced the same types of patterns, a variety of weaves are still used up to this day. (Hélène J., 2024) A lot of different sources exist on the weaving techniques but the most extensive one that was found for this thesis is the Training Manual for Bamboo Craft by the CEMCA. CEMCA, the Commonwealth Educational Media Centre for Asia, is an organisation focusing on open source education. They provide a variety of different courses and one of those courses is based on weaving. (CEMCA, n.d.) The document focuses on bamboo as the base material for weaving. The main difference with the rattan that is used in this thesis is the harvesting method and the way fibres are produced.

Since the rattan is bought as a finished product already this is of no importance. The basic methods explained are: the vertical weaving method, multi angle weaving method, round weaving method, cross weaving method and other. Most of the more intricate patterns are based on one of these basic patterns. Artisans started to experiment more with these patterns and created their own unique patterns by changing the density or weaving order of the existing methods.

The most relevant pattern for complex geometry seems to be the hexagonal plait. The hexagonal plait, also known as the Mutsume Ami or Kagome weave, has been mostly used in Japan. It is a type of weave based on the multi angle weave. The main advantage of this weave is a very robust weave while being simple and quick to weave. Another interesting pattern is the octagonal weave, mostly known from the typical Thonet seats. This weave is also an adaptation of the multi angle weave. Here the seating surface is woven in an octagonal pattern. The main advantage over the hexagonal weave is the extra strength since the pattern is denser. But because of the extra density the flexibility of the pattern is not as flexible for making complex shapes.

Image: A variety of different weaving patterns, not only the 5 basic patterns are shown here but variations are included as well (CEMCA, n.d.)



# B E Y O N D T H E B A S K E T C A S E R E F E R E N C E S

This paper by Phil Ayres, Alison Grace Martin and Mateusz Zwierzycki looks into the relationship between traditional basket making techniques and computer generated geometries. There are two parts to this paper. The search for a mesh topology that is optimised for creating Kagome weaving patterns and the best weaving pattern for complex geometries. (Ayres et al., 2018) This way they hope to upscale the weaving techniques to the building scale. The use of minimum surfaces and mesh relaxation lies at the base of the mesh creation. Before this step the mesh is triangulated and organised in a way that all triangles are in the same grid regardless of curvature. Now any geometry can be modelled. Next the Kagome weave is looked at, in particular the addition or subtraction of extra fibres and the impact of curvature. By removing fibres from a specific cell the shape turns more and more conic while adding extra fibres to a cell curves the surface in the opposite direction. This lies at the base of their approach for creating more complex geometries. These geometries have also been greatly upscaled so instead of using rattan or bamboo, strips of maple wood are used. These structures show great potential in terms of free form design and create an expectation to create complex geometries on a building scale using their design method.

The advantage here is the base strips being straight, while allowing curved, double curved and freeform surfaces to be modelled. This ties in to the need for a simple and low cost method of mass production for these types of geometries. This method allows for the existing infrastructure to create the base material needed for the Kagome woven structures.

An attempt to create such a structure on a larger scale was made using geo-synthetic cementitious composite mats that were cut into strips. (Ayres & Danish Academy, 2020)



Top: Large scale model made from maple wood strips, all strips are straight making production efficient while still allowing complex shapes (Ayres et al., 2018)

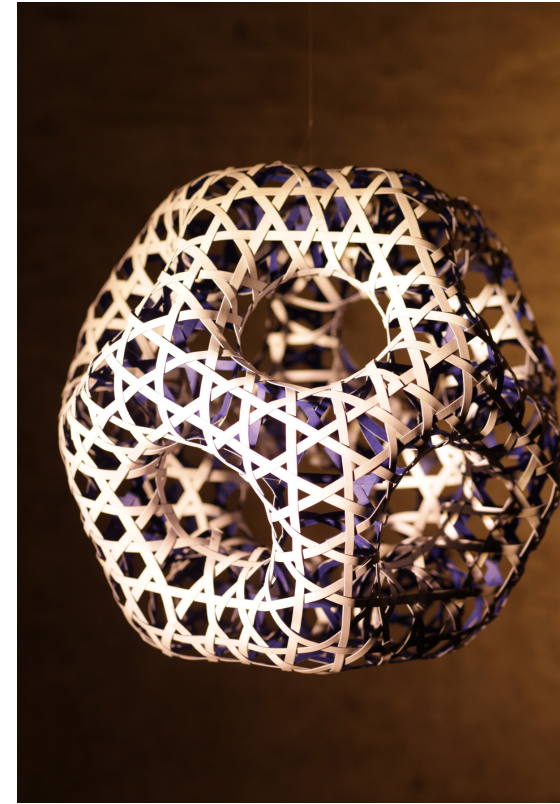
Bottom: Architectural scale application of the researched patterns, using a composite material (Ayres & Danish Academy, 2020)



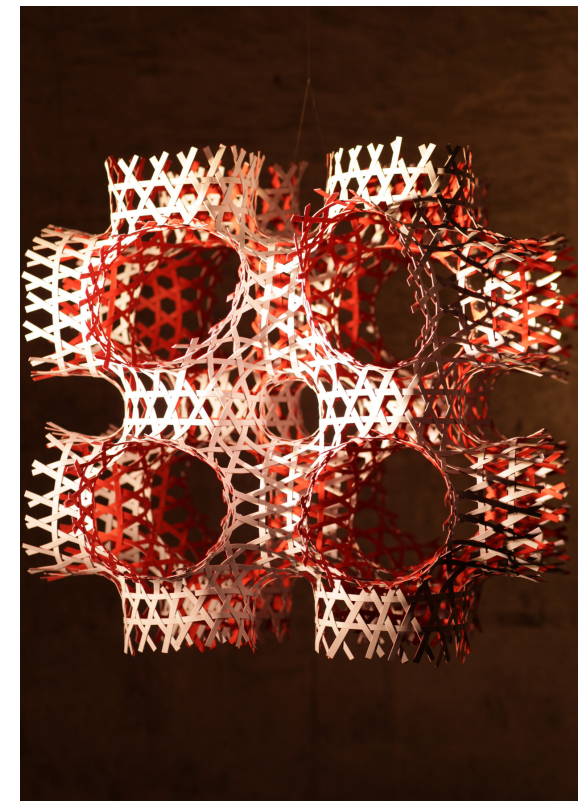


# B R I D G E S C O N F E R E N C E R E F E R E N C E S

The Bridges Conference is an annual conference on connections between art and mathematics. During the 2013 Bridges conference exposition, Alison Grace Martin worked on creating woven curved surfaces. (Grace Martin, 2013) The exposition consists of three different surfaces that are normally difficult to create a physical model of. These have been woven using paper strips of which one side has been coloured. This makes the difference between inside and outside more pronounced. These shapes are heavily inspired by nature, in nature a constant striving for efficiency is present. Because of this minimal surfaces are often approximated in natural systems. The first surface is based on the hypothetical shape of fullerene and graphitic structures. Fullerene is a molecule completely consisting of carbon atoms. The second shape is a high genus fullerene structure which is also observed in some seeds, pollen, grains and types of fungus. The development of these shapes using weaving techniques originated from the want to create these surfaces without complex measuring, folding or production techniques. The curvature of the surfaces is achieved solely by the use of weaving patterns, making the production process intuitive and simple. The chosen shapes were heavily influenced by nature, Alison Grace Martin believes that nature and minimal surfaces are closely related to one another.



Top: Woven structure made out of bi-coloured paper strips, based on the structure of fullerene (Grace Martin, 2013)  
Bottom: Woven structure made out of bi-coloured paper strips, based on a high genus fullerene structure (Grace Martin, 2013)





# WEAVING METHOD

In order to get a feeling for the material and to find the limits of the weaving technique a simple cylinder was woven. First of all, the rattan fibre used here was a 3mm thick round fibre. Before rattan can be woven it needs to be soaked in water to make the fibres flexible. (Studio Russi, 2022) If the rattan is used dry the fibres will simply snap at very low bending angles. First, circles were made by intertwining the ends of a fibre until the diameter of the cylinder was achieved. After this the vertical cross pattern was achieved by weaving over and under these cylinders while using clamps to keep them in place. After creating this base the cylinder can be further extended as long as needed. Once the fibres are at their end a new fibre can be woven along the old fibre to in essence extend the fibre further. This can be infinitely repeated.

Image: First attempt at creating a woven cylinder. A glass bottle is used as a base to create the weaving pattern around. The weaving pattern created here is prone to unraveling easily





# H I S T O R Y

## F O R M F I N D I N G

Form-finding has greatly evolved in the last 20 years due to the rapid advancements of computer software and hardware. This is the form finding that is associated with the term today, the actual discipline itself however goes way further back in history from long before the computer existed. To get a better understanding of form finding this history is delved into. After this two projects are looked at that represent the issues and advantages of form-finding before the computer was used.

After researching the materials themselves a design language has to be developed for this new composite material. The compressive strength is way bigger then the tensile strength and a certain freedom of form is achievable.

Because of this form-finding came to mind as a way to optimise this new composite material. Form-finding has been applied long before the development of the computer and programs like Grasshopper and finite element analysis. One of the biggest influencers of form-finding was the discovery of the catenary line in the 17th century. (Kaplan, 2008) Long before this, shapes like the arch where already used to optimise the structural performance of buildings. The roman aqueducts are a great example of this. The catenary however allowed for a more accurate shape in comparison to the arch. After this other shapes like double curved surfaces were discovered. Today programming even allows for much more complicated shapes to be designed based on their structural properties. One of the best ways to design in compression is through the use of the catenary line. Here an arch is created which is solely under compression. The best way to demonstrate how this works is by letting a chain hang solely affected by gravity while holding only the ends and then welding the links so that the shape is now fixed. This chain that is fully in tension

can now be flipped into an arch and will only have compressive stresses applied to it. One of the best examples where this was used is The Church of Colònia Güell in Santa Coloma de Cervelló by Antoni Gaudi. Here a scale model was constructed out of strings but hanging instead of standing. In this way only tensile stresses could be applied to the scale model and if it would be mirrored the whole would be in compression. This is how the stability of the church was verified. (Fang, 2016) To be able to alter the shapes, weights were used to adjust the form of the arcs and allow for more artistic freedom. This is also one of the first basic versions of a parametric model; by altering the weight on one string the entire shape of the whole shifts to accommodate for the change. This catenary line is the base on which form-finding has been build. Some other great examples of form-finding are the double curves surfaces. These were used during the modernist era to create very thin concrete shells. In order to better understand how form finding can optimise a structure but also the limits once these structures have to be build 2 cases will be looked at more in depth: The Palmira chapel by Felix Candela and The ponte Musmeci by Sergio Musmeci. Both cases exhibit a great understanding of form-finding in an age where computational strength didn't exist the way it does today.

# P A L M I R A C H A P E L R E F E R E N C E S

Within the works of Felix Candela a lot of designs make use of form-finding. The use of curved and double curved surfaces is a staple within his oeuvre. This was mostly used for aesthetic reasons to create very slender looking buildings. But it brought a lot of extra benefits such as the reduction of material needed making it also cheaper, the double curved surfaces are also very earthquake resistant as seen throughout history. While most structures are devastated after a larger earthquake, the domes of churches are most of the time left standing. The Palmira chapel in Mexico was chosen out of the many projects Candela did using form finding since this geometry is rather simple and kept pure. The chapel was built in the post war period in 1958. It consists of a single massive hyperbolic paraboloid. (Tomas et al., 2010) This is a type of double curved surface that greatly increases the strength of a building. Using this design language allows for very thin shells since most of the structural strength comes from the geometry and not the building material itself. Because of this a thickness of 1,6 cm could be achieved at the zones under the lowest stress. The use of a hyperbolic paraboloid also meant that great spans could be achieved without the use of beams or columns. Further creating this feeling of the thinness and low weight of the shell.

In general these shapes seem to be very interesting for building but not used as much as one would expect. This is because of the feasibility once these structures turn from plans into real life buildings. The most logical material to use for these constructions was concrete since this can be moulded in virtually any shape. The downside however is the need for a formwork to let the concrete harden. To create these shells the formworks had to be very intricate and most of the time they had to be so specific that they could only be used once. Especially today the amount of labour needed to create the Palmira chapel would simply cost too much already in terms of labour alone. Another issue is the fact that the formwork consists of wooden beams which are straight. However the hyperbolic paraboloid has the advantage that it can be created through the use of straight beams reducing the complexity by a substantial amount. Through this project one of the main issues with form-finding gets illustrated; the difficulty to build these optimal shapes in real life and the large cost the current construction techniques bring with them. Modern day form-finding has also greatly evolved in comparison to the time the Palmira chapel was built. Much more complex and specific shapes can be calculated and modelled but are often difficult to translate into real life buildings and structures.



Top: Inside of the shell of the Palmira chapel, showcasing the 24m high hyperbolic paraboloid  
Bottom: Construction of the paraboloid, a large amount of wood is needed to create the formwork.

Images by gallery 400

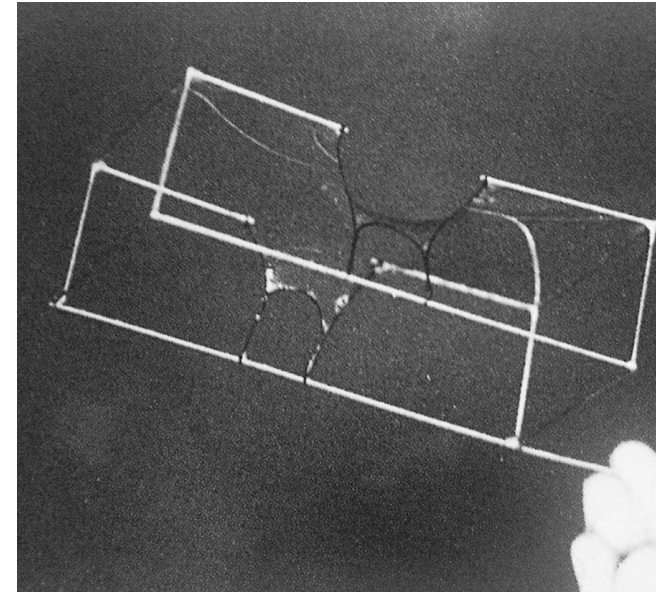




# P O N T E M U S M E C I R E F E R E N C E S

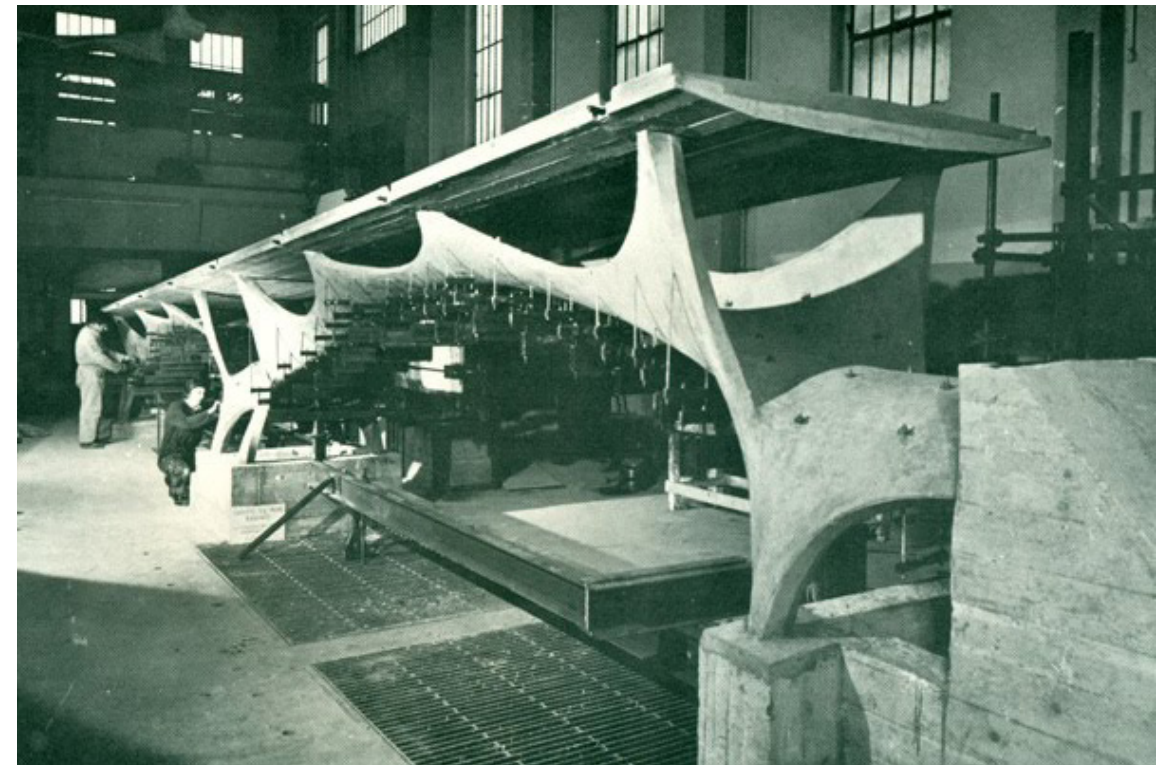
The Ponte Musmeci has construction wise the same advantages and disadvantages as the previously discussed Palmira chapel but the design process of the Ponte Musmeci is very interesting to look at. The Ponte Musmeci was built in 1971 by Sergio Musmeci in Potenza, Italy. (Docomomo, 2011) Form-finding programs like Grasshopper with the Kangaroo plugin or finite elements didn't exist yet so another design method had to be used. Here a combination of analytical calculations in combination with scale models was used to design the bridge. These calculations and also the scale models have been replaced by a digital version today but it is interesting to look at the way these methods were originally used. The analytical calculations are too specific and complicated to look at in this thesis but the scale models applied can be interesting to have a better understanding of how kangaroo operates. First of all a soap film model was used. This is a way to create and design minimal surfaces before computers could calculate these surfaces. By creating the edges of a surface and then dipping it in soap water a soap film is formed connecting these edges which is also the smallest possible surface needed to connect these edges.

Next a rubber model was used, shaped after the soap film model. This way the model was less fragile and tension could be applied at the points where the bridge would actually be subjected to compressive forces to see how the shape reacts to the loads. Next a Perspex model was used. This model is used to see the deformations the bridge would undergo. This material is transparent which makes it possible to spot cracks inside of the model to see where the deformations originate. The problem with this method is the fact that these models are very difficult to create and are also very expensive. Lastly, to clear any doubts since Musmeci himself wasn't even sure if the bridge would actually hold and the Italian Ministry of Public Works requested it, a 14m concrete model was built. This model allowed for more accurate testing since actual concrete was used and even the reinforcements were scaled and laid out exactly the way it was designed for the actual bridge. Thankfully today form-finding has become more accessible and accurate thanks to programs like Grasshopper and Kangaroo.



Top: Soap film model to create a minimal surface. All edges are made out of string, dipping the structure in a soap solution will form a film connecting the edges (Docomomo, 2011)

Bottom: 14m scale model of the bridge made out of concrete to check the stability of the bridge (Tedeschi, 2011)



# E X E C U T I O N

After researching the different materials and finding references the next chapters will be about the executed experiments and developed programs. First of all a first test is conducted to find the material properties of the composite as well as to get some hands on experience with mycelium. After this first experiment the different parameters are calculated and compared to find the best composite. Based on these findings, a design is developed taking into account the results of this first test. The design process consists of developing a number of Grasshopper definitions alternated by experiments. Once a final working program has been achieved, a 1:1 structure is constructed using the created definition.



# EXPERIMENTAL DETERMINATION OF THE PROPERTIES OF MYCELIUM

## INTRODUCTION

To test the hypothesis that a composite material will increase the strength of the mycelium an experiment was set up. The experiment consisted of making a variety of cylinders to execute a comparative compression test on, in combination with a three-point bending test for tensile- and bending forces. First of all the different combinations had to be thought out. These consisted of different combinations of the mycelium, the woven rattan and jute.

|               |                             |
|---------------|-----------------------------|
| pure mycelium | double jute                 |
| rattan        | dense rattan                |
| jute          | dense rattan & dense jute   |
| rattan & jute | double rattan & double jute |
| double rattan |                             |

# PREPARATIONS

By using these combinations, a densification of the rattan weave can be compared to its regular counterpart. At the same time the effect of extra layers can be seen on the strength of the material. For the compressive strength a hollow cylinder is created. To be comparable, PVC cylinders had to be used instead of weaving the framework. The accuracy needed for producing ten nearly identical cylinders was not feasible. An outer PVC tube with a diameter of 125mm and a height of 200mm is used while the inner tube has a diameter of 50mm. the inner cylinder is needed to make sure all mycelium has sufficient air circulation for growth. To further promote air circulation, holes were drilled in both inner and outer cylinder. For the three-point bending test, holes were drilled in the bottom of the containers and also in the lid to make sure proper air flow is sustained throughout the experiment.

Top: Drilling of holes for ventilation in the PVC tube  
Bottom: Cutting PVC tubing to size, the entire tube was divided into 9 pieces of equal height





An important part of this step is using a chisel and sanding paper to remove all extrusions of the holes created by the drilling. This is a necessary step to make sure the mycelium doesn't form a rigid connection with the mold.

Bottom left: All outer cylinders, partially finished inner cylinders placed per cylinder  
Top right: Removing leftover plastic from the drilled holes using a chisel  
Bottom right: Sanding of rough edges to make sure the mycelium does not attach to the cylinder

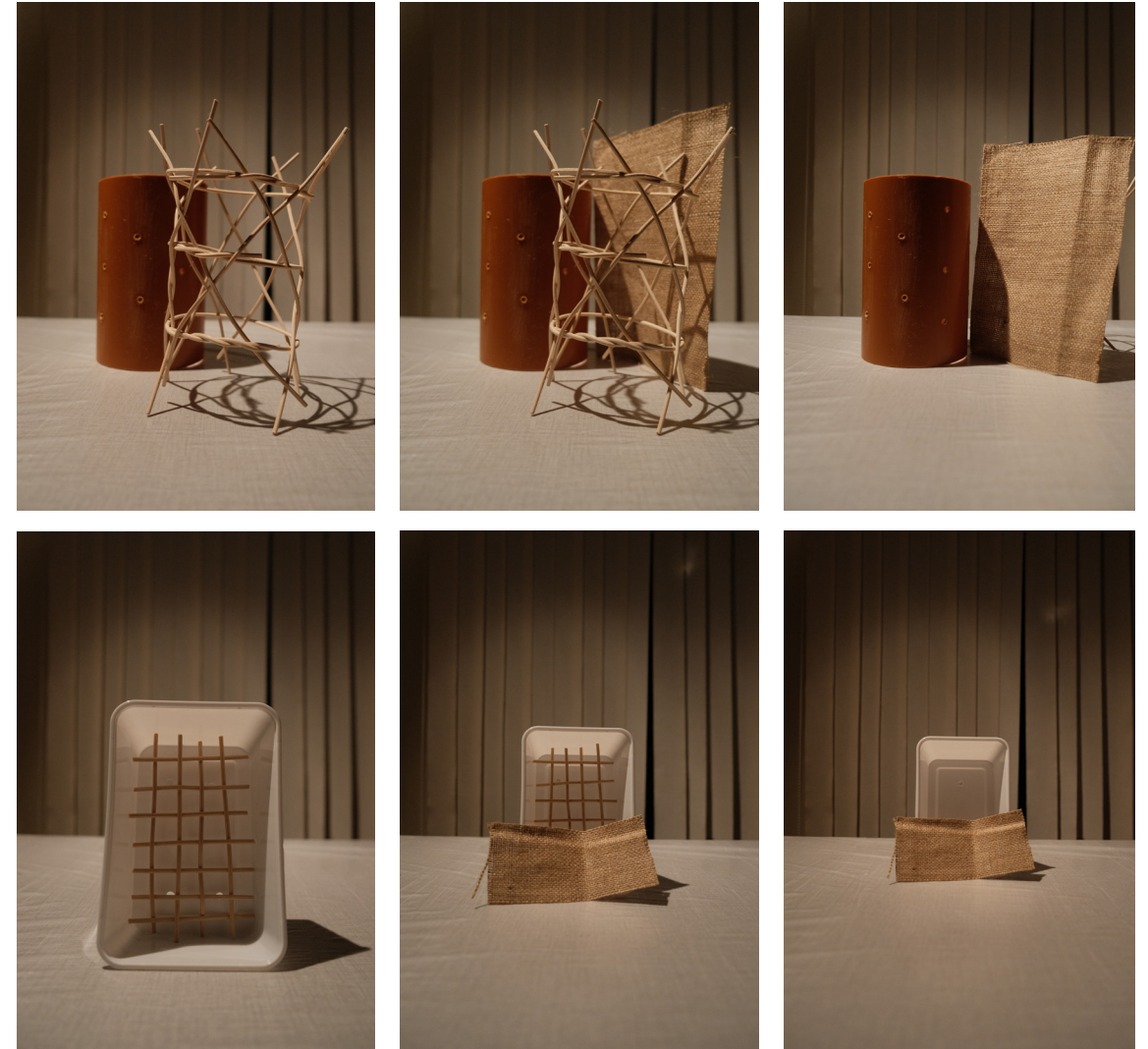




The next step consists of preparing all rattan and jute parts. The jute is simply cut to the necessary size. For the rattan, an interwoven rectangle was made to fit the containers both regular and dense. For the cylinders a more complex approach was needed. First circles were formed and left to dry. Afterwards these were used in a hexagonal weave to create the cylinders.

Next the work station has to be prepared to fill all molds. The preparation of the work station is one of the most important steps since proper care for sterilisation will be one of the deciding factors whether a mycelium culture can grow. Here a sanitiser was used made specifically for mycomaterials, killing all bacteria and viruses but not interfering with the mycelium. A plastic film is wrapped over the table and putting on plastic gloves in combination with a face mask should provide a sterile environment to work in. Sterilisation of the table and gloves is the first step. After this every time new material is used it is first sanitised and then placed on the table. Whenever something leaves the table it is again sterilised. This work ethic will prevent infection of the mycelium. The rattan weaves, jute and molds were all sterilised piece by piece and kept on the table after they were filled.

Right: Collection of images showcasing the different combinations used in the test. The first row consists of cylinders for the uniaxial compression test. The second row are molds for the three-point bending test





# F I L L I N G

Now the mycelium has to be activated. After the mycelium has been produced it needs to be stored by Mycelia, the company where the mycelium used in this thesis is bought. This is done by reducing the temperature of the mycelium to 2°C. This way a batch of mycelium can be kept for up to 4 months. After shipping the mycelium needs to be reactivated after the prolonged exposure to the cold. This is done by adding flour to the mycelium and thoroughly mixing. After waiting 5 minutes the mycelium is ready to be processed.

The next step is filling the molds one by one. For the cylinders a plastic film is placed on the table on which both inner and outer cylinder are placed. These can now be filled with mycelium after placing the jute and woven rattan in place when needed. After filling up to a height of around 50mm the mycelium has to be lightly compressed before further filling the mold, this is similar to the production of rammed earth constructions. This is then repeated until the mycelium reaches the top of the mold. Here a sanitised plastic film is once again placed on top of the cylinder. This way no mycelium is directly touching the outdoor air. For the containers a similar process is used but instead of using plastic film the lid is placed on the container, leaving around 10mm of air space.



Top: Bag filled with mycelium substrate, this is the way the mycelium is shipped. By adding flour to the substrate the mycelium is activated and can be used once again

Bottom: cylinder being filled. Jute and rattan is added to the outer cylinder in this specific test piece







Left: Filling of a test piece with mycelium  
 Top right: Trimming the top edges of the jute sheet, the jute was over dimensioned to make the filling easier  
 Bottom right: A fully filled cylinder with mycelium. A multitude of layers have been compacted to ensure a correct density





In addition a number of extra test pieces were added. A cylinder not using an inner cylinder to test the maximum thickness of pieces. Here there was also no sanitiser used at all, rattan was left on the ground together with the jute to check how sensitive the mycelium is to infection. An intricate geometrical pattern was also used as a mold to check how well the mycelium can copy said pattern. The addition of mycelium without a plastic cover was also added to see how the growth progresses if it isn't restricted by a mold. Lastly, a proof of concept was added. Here a hexagonal rattan weave was interwoven with jute to create the outer mold without the use of any PVC or plastic film. This way the proposed technique to interweave the mold with the mycelium can be tested. The test subjects are now ready for the growing phase.



Left: After filling a thin plastic film is added on top to fully enclose the mycelium

Top right: Test piece where mycelium is left in contact with air during the growing stage, no plastic film or jute are added to cover the mycelium

Bottom right: A test piece with no outer PVC cylinder. The mycelium is kept in place solely by the rattan and jute





# G R O W I N G

For the growing phase a constant humidity and temperature of 20 to 25°C has to be maintained throughout the entire growing process. To create these conditions, an MDF plate is placed on top of an empty bathtub in the bathroom. On this a plastic film is placed, big enough to cover the MDF but with still enough extra room to wrap around the test pieces placed on top of the MDF. By wrapping the plastic film around the test pieces a small space is created which moisture is entrapped in. This way the moisture that is already present in the mycelium should be sufficient to allow proper growth of the mycelium.



Left: Test pieces covered by plastic film sheet, this way a high enough relative humidity can be achieved

Right: Growth of the mycelium after 10 days, some fruiting bodies can be observed already





After 12 days of growing the first growth stage is finished. The mycelium has now fully inhabited the substrate and bonded with the jute and rattan. It has now reached its final strength and can be removed from the mold. During the removing of the mold the outer cylinder was easily removed while the inner cylinder was very difficult to remove. This was because of the shrinkage of the mycelium. During the growth process the volume of the mycelium goes down because the mycelium consumes the food sources in the substrate. This causes a reduction in volume which in turn creates friction on the inner mold, making it difficult to remove. After it has been removed from the mold it is put back under the plastic film together with some water reservoirs. Because the surface of the mycelium shapes is now in contact with the air under the plastic film it could potentially dry out. This would inhibit the growth of the mycelium which is why the water reservoirs are added, to increase the humidity of the air preventing drying out. This step is done to create an outer layer of pure mycelium on the substrate. The main advantages of this are the creation of a velvet like layer on the test pieces. This protects the parts from future infections while also having an even finish on the created test pieces.

Top: Mycelium three-point bending test pieces removed from the containers, these are left for two more days to grow a finishing layer  
Bottom: Mycelium cylinder removed from PVC tubing, also left for two more days to grow a finishing layer







Left: All test pieces removed from PVC cylinders and containers  
 Right top: Proof of concept, uneven growth on the outer layer of jute  
 Right bottom: Placing the plastic sheet over the test pieces to start final growth period of two days





# B A K I N G

The next step is baking the mycelium. By exposing the mycelium to heat for a prolonged period of time all organisms present in the test piece get killed. This way the growth of the mycelium is halted without influencing its strength. There is no exact method for doing this. Different producers of mycelium products each have developed their own method. The method used here is the one described in a standard operating procedure for insulation panels. (Deverick, 2023) Here a temperature of 90°C is maintained for 3 to 4 hours. One issue that presented itself was finding an oven big enough to bake all the test pieces at the same time to avoid running a regular oven for multiple days. This was solved by using a sauna, putting the temperature on 90°C while keeping the relative humidity under 10% created the conditions necessary for the baking of the mycelium. After the baking they are left to dry out and let any leftover moisture evaporate.

Image: Baking of test pieces, here the three-point bending test pieces are shown after two hours of baking





# T E S T S E T U P

Now that the test pieces have been created the actual tests can be run to check the strength of the different combinations of materials. First the three-point bending test is done. This test consists of two trestles placed next to each other with a 100mm gap in between. On this gap a rectangular testing piece is placed. A metal tube is placed on top of it, rope is used to hang a weight from this tube. In between the tube and the weight a dynamometer is added to see the weight increase. The weight in question consists of a bucket which is slowly loaded with pebbles until failure occurs. Two main stages are important to document; the weight at which the first cracks start to show and failure of the material. Out of these tests the tensile and bending strength of the material can be calculated. For the compression test the cylinders are loaded with the bucket and slowly filled with pebbles again. Afterwards the bucket is weighed to get the total load. The mycelium was stronger than predicted however and the 20 kg weight of the pebbles was not enough to induce failure. This was solved by using a piece of a glulam beam with a weight of 22kg and placing the empty bucket on top. This way the bucket can be filled again to gradually increase the total load till failure. For some test pieces this still didn't suffice but the same method was used until a weight of 100kg was used.

Left: Uniaxial compression test of a mycelium test piece  
Right: Three-point bending test of a mycelium test piece  
Following page: Comparison between four different test pieces in terms of flexural strength. Different phases of the bending of each test piece are shown





# THREE - POINT BENDING TEST

For materials like concrete a tensile stress test is difficult to execute. Since mycelium is very comparable to concrete in terms of behaviour a similar approach will be used to look at the tensile strength. This difficulty is because of the brittle nature of materials like concrete and mycelium, no reliable values for the tensile stress could be derived from a standard tensile stress test. A solution for this problem was the development of the three-point bending test. By placing a test piece over a span while applying a downward force on it in the middle, the flexural stress can be determined. This force induces bending in the test piece. In bending the outer fibre at the bottom of the test piece is completely loaded in tension while the top fibre is fully in compression. This means the tensile stress of the material can be derived by using the following formula.

$$\sigma_{flexural} = \frac{Mc}{I}$$

With  $\sigma_{flexural}$  the flexural strength  
 $M$  the maximum moment  
 $c$  the distance between the neutral axis and the outer fibre of the beam  
 $I$  the second moment of inertia

Since the moment is applied at the centre of the beam, the maximum moment is

$$M = P * r = \frac{F}{2} * \frac{L}{2} = \frac{FL}{4}$$

With  $M$  the maximum moment  
 $F$  the force applied to the beam  
 $L$  the length of the span

For  $c$ , the following formula is used

$$c = \frac{d}{2}$$

With  $c$  the distance between the neutral axis and the outer fibre of the beam  
 $d$  the thickness of the beam

The second moment of inertia of a simple beam is

$$I = \frac{bd^3}{12}$$

With  $I$  the second moment of inertia  
 $b$  the width of the beam  
 $d$  the thickness of the beam

If the formulas are now combined into the first one, the following formula can be derived after some simplifications

$$\sigma_{flexural} = \frac{3FL}{2bd^2}$$

For the test, the values  $L$ ,  $b$  and  $d$  are constant throughout the different test pieces. The only variable is  $F$ , the force applied. The table on the page after the experiment pictures shows the different combinations used with their respective flexural strength results.

(De Belie, 2019)



pure mycelium



double rattan



rattan & jute



double rattan & double jute





| test 1                      | first crack<br>(kg) | failure<br>(kg) | $\sigma_{crack}$<br>(N/mm <sup>2</sup> ) | $\sigma_{failure}$<br>(N/mm <sup>2</sup> ) |
|-----------------------------|---------------------|-----------------|------------------------------------------|--------------------------------------------|
| Pure mycelium               | 6,5                 | 7,2             | 0,038                                    | 0,042                                      |
| Jute                        | 5,2                 | 16              | 0,031                                    | 0,094                                      |
| Double Jute                 | 6,22                | 23,2            | 0,037                                    | 0,137                                      |
| Rattan                      | 4,56                | 11,36           | 0,027                                    | 0,067                                      |
| Dense Rattan                | 5,46                | 13,02           | 0,032                                    | 0,077                                      |
| Double rattan               | 5,02                | 7               | 0,030                                    | 0,041                                      |
| Rattan + Jute               | 6,3                 | 11,4            | 0,037                                    | 0,067                                      |
| Dense Rattan + Jute         | 7,3                 | 17              | 0,043                                    | 0,100                                      |
| Double rattan + Double jute | 7                   | 25              | 0,041                                    | 0,147                                      |

| test 2                      | first crack<br>(kg) | failure<br>(kg) | $\sigma_{crack}$<br>(N/mm <sup>2</sup> ) | $\sigma_{failure}$<br>(N/mm <sup>2</sup> ) |
|-----------------------------|---------------------|-----------------|------------------------------------------|--------------------------------------------|
| Pure mycelium               | 5,12                | 5,12            | 0,030                                    | 0,030                                      |
| Jute                        | 4,84                | 19,46           | 0,028                                    | 0,115                                      |
| Double Jute                 | 6,48                | 22,5            | 0,038                                    | 0,132                                      |
| Rattan                      | 7,8                 | 12,9            | 0,046                                    | 0,076                                      |
| Dense Rattan                | 8,96                | 13,08           | 0,053                                    | 0,077                                      |
| Double rattan               | 6,6                 | 13,18           | 0,039                                    | 0,078                                      |
| Rattan + Jute               | 6,96                | 21,58           | 0,041                                    | 0,127                                      |
| Dense Rattan + Jute         | <u>4,9</u>          | <u>8,1</u>      | 0,029                                    | 0,048                                      |
| Double rattan + Double jute | 4,56                | 20,6            | 0,027                                    | 0,121                                      |

| test averages               | $\sigma_{crack,average}$<br>(N/mm <sup>2</sup> ) | $\sigma_{failure,average}$<br>(N/mm <sup>2</sup> ) |
|-----------------------------|--------------------------------------------------|----------------------------------------------------|
| Pure mycelium               | 0,034                                            | 0,036                                              |
| Jute                        | 0,030                                            | 0,104                                              |
| Double Jute                 | 0,037                                            | 0,134                                              |
| Rattan                      | 0,036                                            | 0,071                                              |
| Dense Rattan                | 0,042                                            | 0,077                                              |
| Double rattan               | 0,034                                            | 0,059                                              |
| Rattan + Jute               | 0,039                                            | 0,097                                              |
| Dense Rattan + Jute         | 0,036                                            | 0,074                                              |
| Double rattan + Double jute | 0,034                                            | 0,134                                              |

For the dense rattan in combination with jute, a small error was made. During the filling of the mold the rattan and jute weren't placed low enough in the beam. They were placed in the centre of the beam, around the neutral fibre. This means that little to no effect was seen in adding the materials. This explains why the underlined values are closer to the values of pure mycelium than in the other test.

In general, there aren't any relevant differences between the tensile stresses at which the first cracks are produced. The total stress induced at failure however, differs greatly between tests. This is a logical observation, the way mycelium interacts with the rattan and jute is similar to how composites consisting of fibres and a matrix material work. The mycelium takes the role of a matrix material. Having a lower tensile strength, the tensile forces are being transferred to the fibres (here the rattan and jute). Whenever the tensile stresses are higher in the matrix material than the tensile resistance of the material, cracks begin to form. This will not induce failure since the fibre structure of the composite can still carry the tensile load.

The issue here is the fact that the outer fibre of the mycelium composite is mycelium and not rattan or jute. This means that the place where the most tension is created is beyond the placement of the rattan or jute. The cracks will form since there is no reinforcement here until the crack reaches the jute or rattan. Here the tensile load can be carried and, until the capacity of the rattan or jute is exceeded, no further cracks will develop. Once the fibres can no longer carry the tensile load or the connection between the mycelium and the fibres is too weak total failure is observed. This shows that using the jute and rattan as an outer shell will make the most optimal use of their advantages in strength.

Image: Test piece after executing the three-point bending test





# COMPRESSION TEST

For the compression tests a simpler calculation can be made. Here it simply suffices to calculate the pressure per square millimetre to be able to compare the different test results. For this the following formula is used.

$$\sigma_{compression} = \frac{F}{A}$$

With  $\sigma_{compression}$  the compressive strength  
F the force applied  
A the surface area

All cylinders used for testing have the same surface area, meaning they can be compared to each other based on the applied weight already. The surface can be calculated by reducing the outer diameter with the inner diameter, this gives us a total surface of 17.671 mm<sup>2</sup>. However one testing piece consisted of a fully filled in core and also had a load applied to it. Here the surface area is 49.087 mm<sup>2</sup>. This was done since the recommended thickness of a mycelium object is a maximum of around 75mm. This thickness is used as a maximum in almost all reference projects. This way a check could be done if ignoring this rule had a noticeable effect on the strength of the material. The following table compares the results of the conducted test. (De Belie, 2019)

| material                    | load of first deformation (kg) | load at failure (kg) |  |
|-----------------------------|--------------------------------|----------------------|--|
| Double Jute                 | 30                             | 100                  |  |
| Rattan                      | 30                             | 100                  |  |
| fully filled rattan         | 35                             | 100                  |  |
| Double rattan               | 20                             | 55                   |  |
| Rattan + Jute               | 10                             | 20                   |  |
| Double rattan + Double jute |                                |                      |  |

| material            | $\sigma_{deformation}$ (N/mm <sup>2</sup> ) | $\sigma_{failure}$ (N/mm <sup>2</sup> ) | total deformation (mm) |
|---------------------|---------------------------------------------|-----------------------------------------|------------------------|
| Double Jute         | 0,017                                       | 0,055                                   | total failure          |
| Rattan              | 0,017                                       | 0,055                                   | total failure          |
| fully filled rattan | 0,007                                       | 0,020                                   | 10                     |
| Double rattan       | 0,011                                       | 0,031                                   | 40                     |
| Rattan + Jute       | 0,005                                       | 0,011                                   | total failure          |

Image: Execution of the uniaxial compression test on the mycelium cylinder without an inner cavity and a jute skin



Important to note is that more test pieces were prepared but weren't used. This has multiple reasons. One of the first reasons is the fact that some test pieces weren't properly filled. The double rattan with double jute made it difficult to properly fill up the mold with mycelium. Especially at the bottom, a way thinner layer of mycelium is observed. This is due to the size of the mycelium, in terms of filling it is comparable to rammed earth. This makes it difficult to fill up gaps and pockets created by the jute. When just moving said test pieces around it could already be observed that these didn't have much strength. Since the results of the experiment wouldn't have been representative anyway, keeping them as material samples seems more valuable. This is also the reason the double rattan has a low strength and after this the decision was made to not use the other failed ones. Another issue arose from a storage problem. Some of the test pieces weren't instantly used since it seemed interesting to have some materials to show during a guidance session. However these needed to be kept for 2 weeks. The test pieces were kept in a cardboard box in a room which had a high relative humidity. Because of this mold started to form and unfortunately some had to be thrown out. The mold problem is specified further.



Top: Execution of the uniaxial compression test on not fully grown mycelium cylinder. This did not yield correctly results but detaching of the rattan could be observed

Bottom: Further compression of the test piece caused total failure and large deformations





## F U R T H E R T E S T I N G

Finally some extra tests were added to test some of the properties of mycelium. The first one consisted of examining how mycelium grows if no outer layer that can act like a skin is added. This means not using a mold, plastic film or jute layer to cover the mycelium. A second test consisted of exploring how well the mycelium takes over more complex shapes of molds. A final test was a proof of concept to see if the use of jute and rattan as formwork could be achieved.

# N O O U T E R L A Y E R

This test was executed to see if a structure made out of rattan that is covered with jute can be used as a base where mycelium grows on without covering it. To simulate this situation, a piece of jute is interwoven with rattan and then covered with mycelium. This is then placed under the plastic cover used to grow the mycelium in but without touching it. After two weeks no noticeable mycelium growth is seen. The outer parts of mycelium dried out and made it possible for a limited amount of mycelium to grow inside of the substrate. The dried out outer part functions as a shell around the inner part, protecting it from further drying out. This shows that a mold needs to be used to fully grow a structure.

Top: Upon zooming in some white specs of mycelium can be observed under the outer skin created by the dried out substrate

Bottom: View of the entire test piece after going through both grow phases





# C O M P L E X S H A P E S

For this test the inner mold is replaced by a bowl with a complex geometry. First the outer bowl was filled with mycelium and then the inner bowl with the pattern was pushed in. The outer bowl has holes in the bottom which creates the necessary airflow for the mycelium to grow. After 2 weeks the molds can be taken of and the mycelium is an exact copy of the geometric pattern. This shows the potential of the material for more design oriented projects. The biggest factor is the size of the substrate. If the size of the substrate grains decreases, the accuracy of the pattern increases but the strength of the mycelium decreases and vice versa. This principle is used for mycelium as a material for 3D printing. (Hahn, 2022) For this thesis however this method was not looked at since the particles have to be small enough to fit through the nozzle. This means the strength of the material is too low to use it for a structural application on a bigger scale.

Top: Inside surface of the bowl clearly following the geometric shape of the original mold used. The edge of the bowl was not restricted hence the randomness of the growth

Bottom: Side view showing the smooth finish of the outside





# P R O O F      O F C O N C E P T

The final test consists of checking if mycelium will grow in a mold made from jute and rattan. For this a rather open framework made out of rattan was interwoven with a jute cylinder to form the outer mold. Here some very important observations were made. First of all, a denser rattan weave is needed to ensure the shape is kept. When filling the mold the rattan and jute couldn't handle the horizontal force created by compressing the mycelium. This made the cylinder bulge out. Secondly the jute can in fact be used as a skin for the mycelium, the mycelium has almost fully overgrown the outer surface of the jute. At some places the jute has not been grown on while other parts have pure mycelium bulging out. This might be because the mycelium couldn't be fully compacted. Applying too much force while compacting the mycelium caused the jute and rattan to disconnect since the weave pattern wasn't fine enough. Because of this some parts weren't fully filled and some gaps between jute and mycelium came to be. Where gaps exist the mycelium behaves the same way as in the test where no outer layer was used. This issue can be resolved in the future by creating a denser and firmer rattan weave. Compaction won't be a problem since this denser weave will be able to take the horizontal forces induced by compressing the mycelium.

Image: Side view of the proof of concept, clearly showing patches of jute where no mycelium has grown. Upon further inspection an air gap was between the jute and the mycelium inside of the jute. If better compaction is possible, this issue will be resolved





# I N S I G H T S

After this first test a lot of insight was gained about both the production process as well as the strengths and weaknesses of the composite material. The limitations of doing these kinds of tests at home also became apparent. The bending test yielded good and accurate results because of the gradual increase of stress in combination with the scale giving live results. A distinction could also be made between the different composites proving the theory that adding jute or rattan can strengthen the material. The compressive tests proved to be less scientifically valuable. By not using a proper scientific testing machine the load was not applied perfectly vertical. The fact that the mycelium cylinders were not perfectly grown in combination with the faces that should be horizontal having slight to large differences in angles induced horizontal forces in the uniaxial compression test. This is also visible in the results, some of the cylinders have deformed horizontally under the pressure. Even more noticeable was buckling of some test pieces under these horizontal forces. Even with these issues, the fully filled in test cylinder with a jute cover showed great potential. The jute absorbed the horizontal normal forces created by the uniaxial vertical pressure, allowing for larger loads to be applied. Since the greatest tensile stresses were observed at the outer fibre the reinforcements should also be placed as much to the outside as possible. This way cracking should be limited while also providing reinforcements at the most optimal location. This means that using the

formwork as reinforcement would also be placed ideally. Another important observation was the forming of mould on the test pieces that were kept to show during a guidance session. After the baking of the test pieces all living organisms, the mycelium itself but also possible contamination that is present in the test pieces, are killed off which stops the growth of the mycelium. That's why not a lot of thought was given to storage since normally all processes that needed to be done in a controlled environment were finished. The issue however is the nature of the mycelium. In order to let mycelium grow optimally, the substrate is a nutrition mix optimised for growth. By baking the test pieces, all living organisms already present are killed but future contaminations aren't taken into account since the mycelium is still rich in nutrients. Normally this is solved by lowering the level of humidity by letting test pieces fully dry out before use. These pieces were still rich in moisture even after baking. By testing the proof of concept the realisation came that the weave used for the first experiment was not dense enough. When filling the freestanding rattan cylinder lined with jute the pressure applied to the mycelium to densify caused the cylinder to deform. This is partly because the rattan isn't interconnected, the idea was that the mycelium will hold the rattan in place. This worked once the mycelium had grown but during the filling this caused too much deformations. Densifying the weaving pattern should solve this problem.



Top: Test piece after uniaxial compression, the rattan is detached once again from the mycelium. Deformations due to shear forces can also be observed

Bottom: Comparison between an unloaded cylinder and the solid cylinder that withstood 100kg to showcase the small permanent deformation after unloading the cylinder



# C R E A T I O N O F A D E S I G N

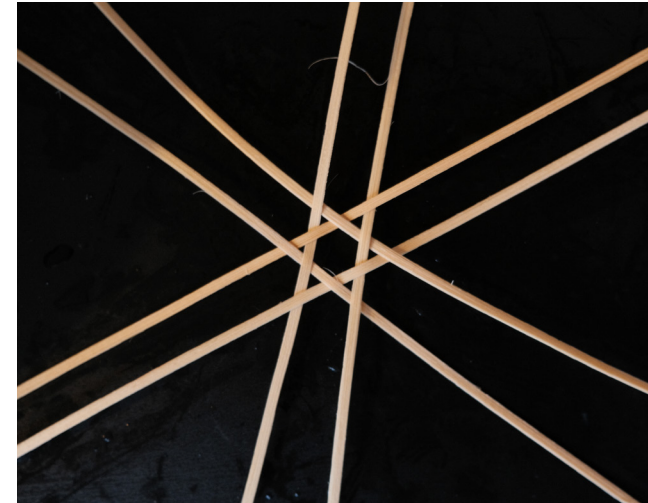
Based on the references and the conducted experiments a design can now be made. Before physically constructing another mycelium composite some digital work has to be done to create a design language as well as a way to create the composite material. The findings of the first experiment should also be incorporated into this design.



# IMPLEMENTATION OF EXPERIMENTAL FINDINGS

First of all, the rattan used in the first test was very difficult to use in a denser weave. After doing some research the cross section of the rattan fibre is of importance depending on the size of the weaving pattern. The rattan used in the first experiment had a circular cross section. This was under the assumption that having an isotropic material would be beneficial since the mycelium has a tendency to sometimes grow in an unexpected way. This was thought of as a way to accommodate for this randomness that is inherent to the material. The issue however was that this also meant bending was equally difficult during the weaving because of the higher strength in all directions. After further researching traditional rattan weaving techniques it became apparent that a wide strip as a strand was preferable. This way the material became anisotropic and had a lot of material in the direction the forces are applied while being very thin and bendable in the other direction which allowed for easier assembly of a weaving pattern.

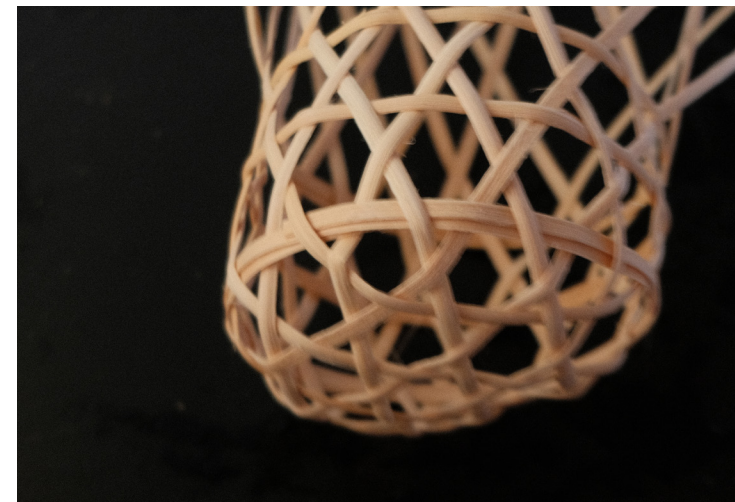
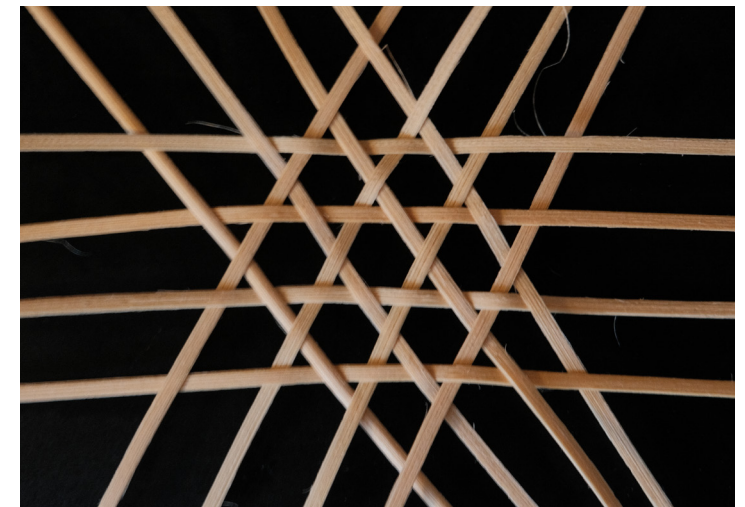
Secondly, the rattan weaving pattern did not properly support the mycelium while also not providing a solid boundary during the filling. This first attempt was not based on actual techniques and just an intuitive attempt at trying to weave a rattan cylinder. To optimise this process research was done in the fabrication process of rattan basket making. (CEMCA, n.d.) The most used method found in any tutorial was firstly creating a base hexagon. This is done by overlapping each rattan strand over the previous one in a hexagonal shape. A base is now created that can be further developed. This is done by adding an extra strand at each edge of the original hexagon. Now the bottom of the cylinder has been created. The next step is creating the mantle of the cylinder. The easiest way is to not create a perfect circle as a base but a larger hexagon. At each corner of the hexagon a pentagon is used to create the angle between base plate and mantle. Now extra circles can be created increasing the height of the cylinder. In order to make the circles keep their shape they are doubled and made to overlap. This technique of using pentagons can create a change in angle in the weave.



Top: Single hexagon cell and start of weaving pattern

Middle: Adding one strand of rattan perpendicular to the first six strands to increase the amount of cells

Bottom: Introducing pentagon cells at the corner causing inward curvature. Afterwards further development by adding rattan rings and using only hexagon cells







Top left: Rattan with a round section used for the first weaving test  
 Bottom left: Flat rattan used in second test, the flat rattan allowed easier weaving because of the bending capability in one direction  
 Right: Woven cylinder base, the cylinder can be further extended by adding more rattan circles





Finally, it became apparent that the mycelium shapes should have a limited thickness. Since leftover moisture in the baked mycelium can cause unwanted fungi or mould to grow, proper drying of the pieces should be ensured. The mould that grew on these test pieces consisted of Dactylium, also known as cobweb mould, and Trichoderma. Trichoderma has a green colour, spreads rapidly and can infect an entire culture at a rapid rate. However, it is not harmful for humans. (Martian Mushrooms, 2024) The second species known as cobweb mould looks like a spiders web as the name suggests. It is carried by dust and therefore very hard to avoid. The only way to avoid it is drying the test pieces enough so it does not get the chance to grow. This is once again not harmful for humans. (Grogan et al., 2008) Creating hollow structures will optimise the drying out the most. Firstly the thickness of the mycelium will already be greatly reduced for the same outer volume and the fact that it is hollow creates extra surface area. This extra surface area is in contact with air thus creating a second surface it can dry out from.

Images: Development of mould on the test pieces, the pieces were stored in an environment with a too high relative humidity. This can be avoided by leaving more time to dry





# CHOOSE DESIGN LANGUAGE

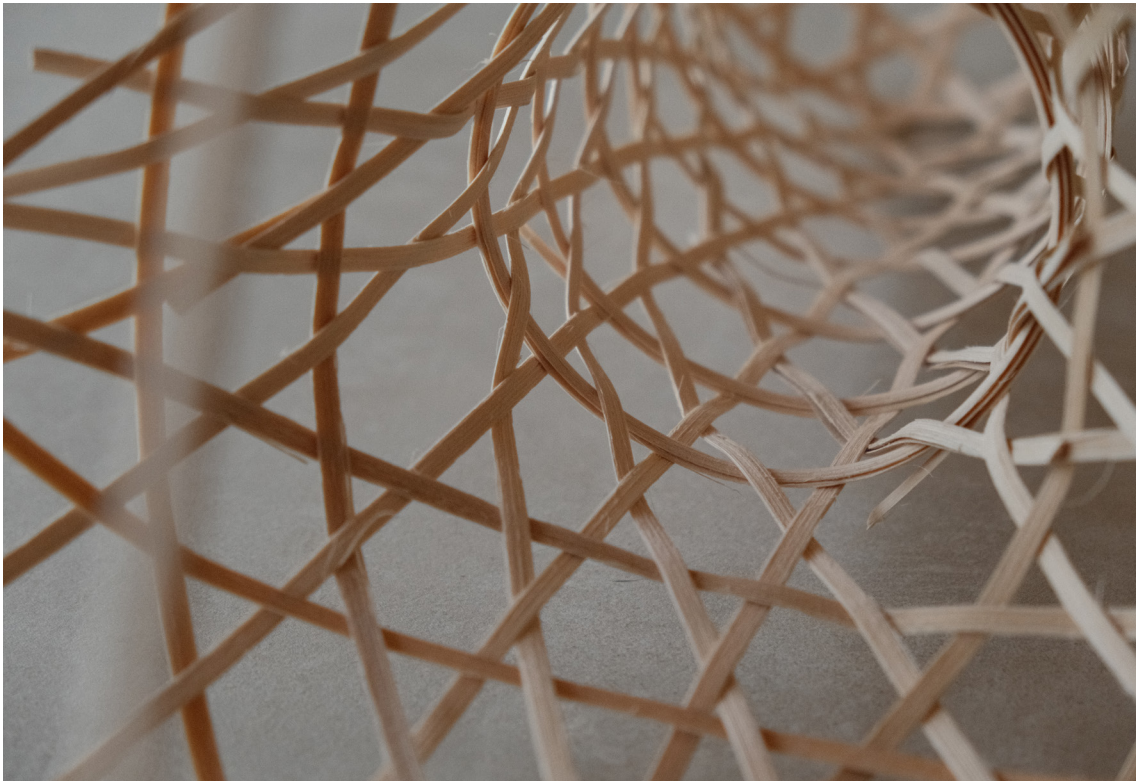
After researching form finding and conducting the compressive and bending experiments two main design languages came to mind. The first idea was to create a bamboo skeleton on which a rattan weave could be placed. On top of this a layer of jute would be placed to support the mycelium. Then a final jute layer is placed on top of the mycelium to let it grow. The main issue here seemed to be the baking process. This would mean the pavilion would need to be grown as a whole and also baked as a whole. Furthermore the mycelium would not even work as a structural element anymore. The only structural function would be to transfer the stresses to the bamboo skeleton. This way the potential of the material wouldn't really show. The second option originates from the cylindrical shape used for the compression test. A system of rods could be used to create structures, creating knots at the intersection points of the different rods. This would really show the potential of the mycelium since the earlier discussed composite would be the only material used.

Because of the above mentioned reasons the second system was chosen and will be further developed. The weaving of the cylinders is simple enough with the new system for weaving based on basketry. The issue arises at the intersections of said cylinders. A shape has to be woven that interconnects the different cylinders at their intersection. First of all the feasibility of such a knot has to be researched.

Image: Hollow cylinder  
made out of mycelium  
the outer skin consists of  
a layer of jute







## DIGITALISATION OF WEAVING P A T T E R N S

The next chapter will describe the different steps that have been taken to create weaving patterns. First the main plugin for Grasshopper that is used here, Weaverbird will be looked into. Afterwards a way to create meshes that can be applied for weaving patterns will be developed and finally a way to convert such a mesh into a weaving pattern is discussed.

Image: Woven rattan geometry, because of the pattern curvature is introduced in the weaving

# WEAVERBIRD

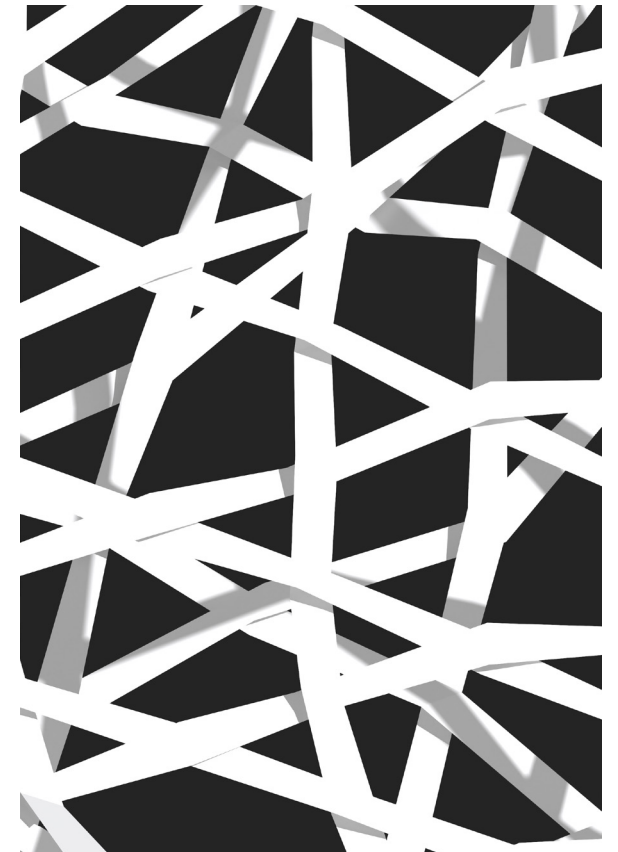
The first idea to create a digital weaving pattern was to find real life references of more intricate knots woven out of rattan or bamboo but after numerous searches none could be found. All references of complex patterns were digitally fabricated ones. Some research has already been done into digitalising the Kagome weave with a limited amount of real life structures created based on a digital twin. This is probably due to the complexity of the weaving pattern needed to create complex shapes. This meant that the first step would be to create a way to digitally represent shapes in a Kagome weave pattern.

Upon researching further a plugin for Grasshopper seemed to be highly efficient for this problem, Weaverbird. (Piacentino, 2023) The name is inspired by a south African bird, known for creating very large nests that can house up to hundreds of birds. These nests would get so big that the tree could no longer support the nest and the branches would break. In a similar way, the Weaverbird plugin allows mesh manipulation to allow parametric weaving patterns. Since Kagome weaves have already been successfully produced by this plugin the method of how these were created was firstly studied.



Top: A nest of weaverbirds in Namibia, the nest keeps expanding until the weight of the nest makes the branch collapse

Bottom: A zoom in of a weaving pattern created using the Weaverbird plugin





The most important part was the need for a mesh created solely out of triangles. That is where the Weaverbird plugin comes into play. It has a number of different remeshing tools that allow complex geometries to be simplified. The main use for it here is the Loop subdivision tool based on the method developed by Charles Loop in 1987. (Pharr, 2021) The development of this new technique came forth out of the issues the previous modelling techniques had when it came to complex geometries. The most used techniques were polygon meshes and spline-based representations of surfaces. Polygon meshes didn't allow smooth mesh generation, after zooming in the mesh would become faceted no matter how smooth it is modelled. Spline-based representations of surfaces allowed smoothness but are very hard to locally increase the amount of detail in a mesh. The first solution for this was found by Edwin Catmull and Jim Clark in 1978. The algorithm developed by them allowed quad based meshes to be subdivided into smaller quads creating smooth and detailed meshes.

This method is now called the Catmull-Clark subdivision method and is still widely used in the 3D-modelling industry. It allows for complex mesh based geometry without straining the modelling software too much. This inspired Charles Loop to create a similar system but for triangle based meshes. The way it works is by subdividing each triangle into four new triangles, this is easily achieved by creating a line connecting each midpoint with each other. The curvature however is more complex. This is based on the edges and normal of the original triangle. The way it checks for adjacent triangles is by the orientation of the mesh edges. Two edges running in opposite direction that have the same coordinates are considered as an edge of the new mesh. This is also the reason that the original mesh has to be a manifold mesh. Having more than two edges at the same coordinates will not allow the subdivision to weld the triangles into a single mesh at this edge. A basic understanding of the Loop subdivision tool is needed before starting on a base geometry to make sure the method of creating the mesh is compatible with the subdivision.

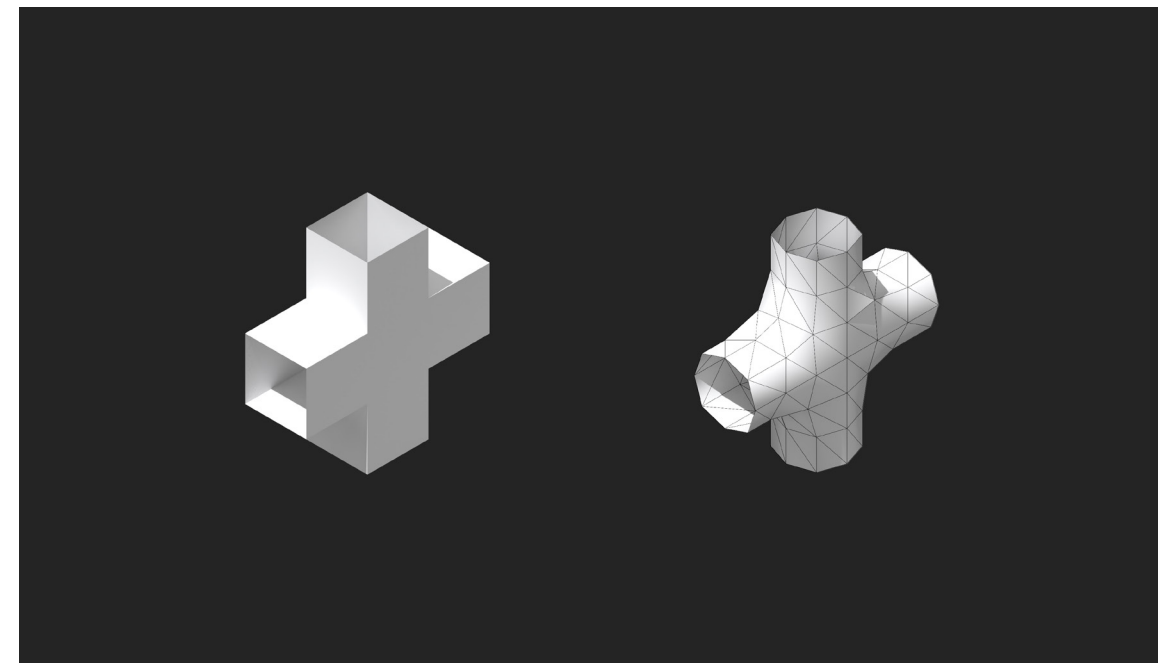


Image: Comparison between the original input and the final output of a geometry on which the Charles Loop division method has been applied

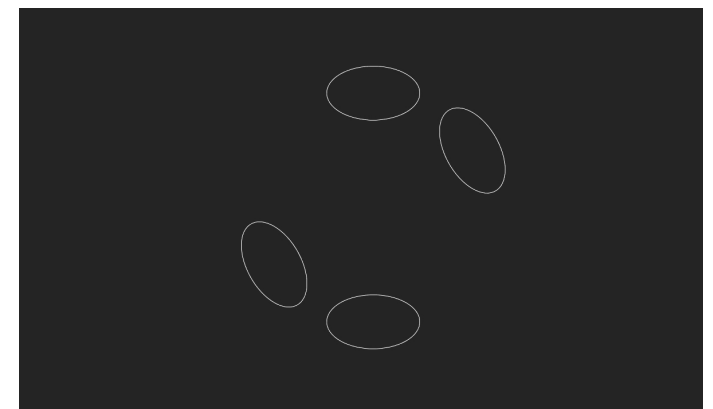
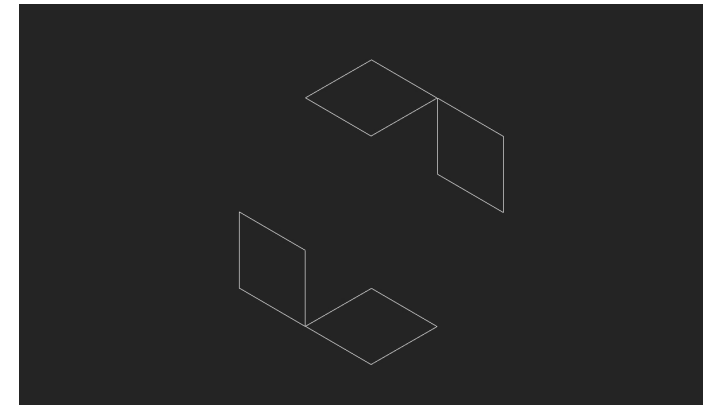
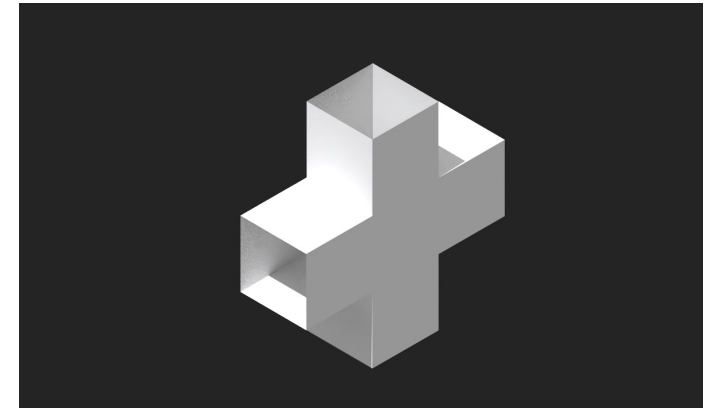
# BASE GEOMETRY/ MESH RELAXATION

The next step is the creation of a base geometry to do the Loop subdivision on. Here a lot of problem solving was needed and a multitude of approaches have been tested before a working model was found. The first and most obvious approach was the use of minimal surfaces. Minimal surfaces are created by calculating the minimal surface area needed to connect different curves together. In Grasshopper this can be achieved through mesh relaxation. To test the method of mesh relaxation a simple base mesh was created. It consists of four rectangular pipes joining together orthogonally and all in the same plane. More complex knots can be looked at once the base system is working. The start of the mesh relaxation was the definition of the naked edges. These boundaries had to be determined and made sure to not transform during the mesh relaxation. They should remain in place so they can properly attach to the cylinders in a later stage of the project. They will also serve as the boundary conditions for the mesh relaxation itself. First of all they have to be converted to vertices and any duplicates have to be removed. The next step is converting the square boundaries to circles to make them fit the cylinders connecting the knots. This is done by fitting a plane through the points achieved by the vertices of each boundary to get the orientation of the circle. Next the average of all points of a boundary is taken to define the middle point of the circle. Now these points on the square boundary can be projected onto the circle that was just defined. This way a location to anchor has been defined for each point. This is where the Kangaroo plugin comes into play. (Piker, 2017)

Top: Original input of the base mesh used

Middle: Isolation of the naked edges of the geometry, these will be used as a boundary condition

Bottom: Based on the naked edges a circle is placed at the midpoint of each different boundary plane, the different points of the original boundary are then projected onto the newly created circle

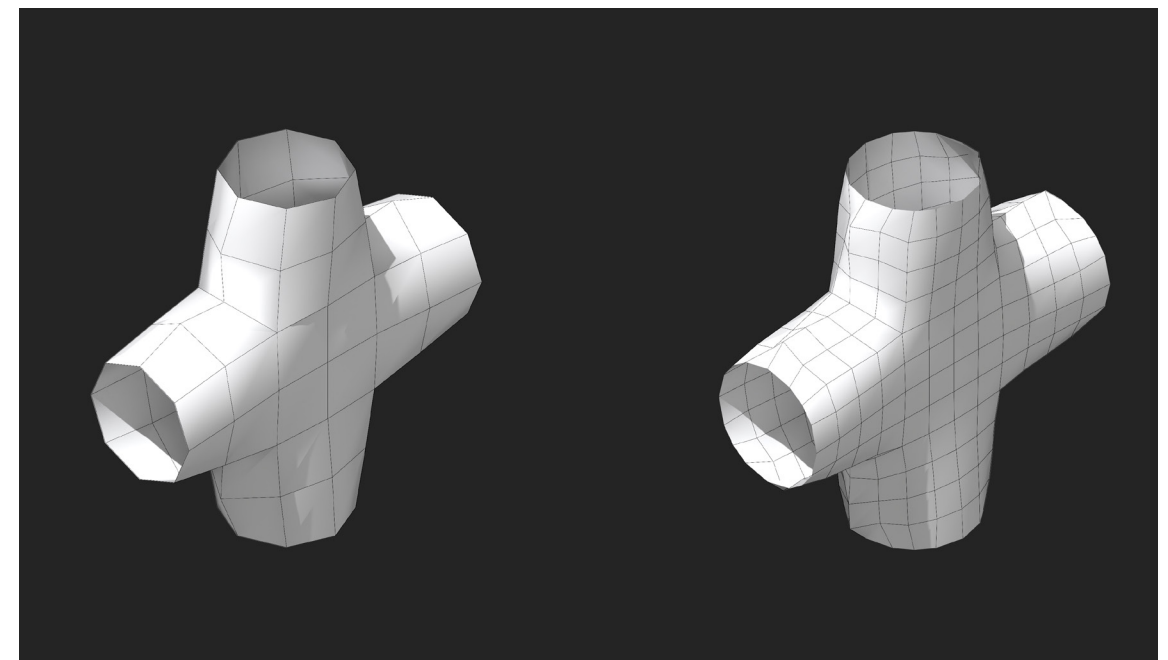
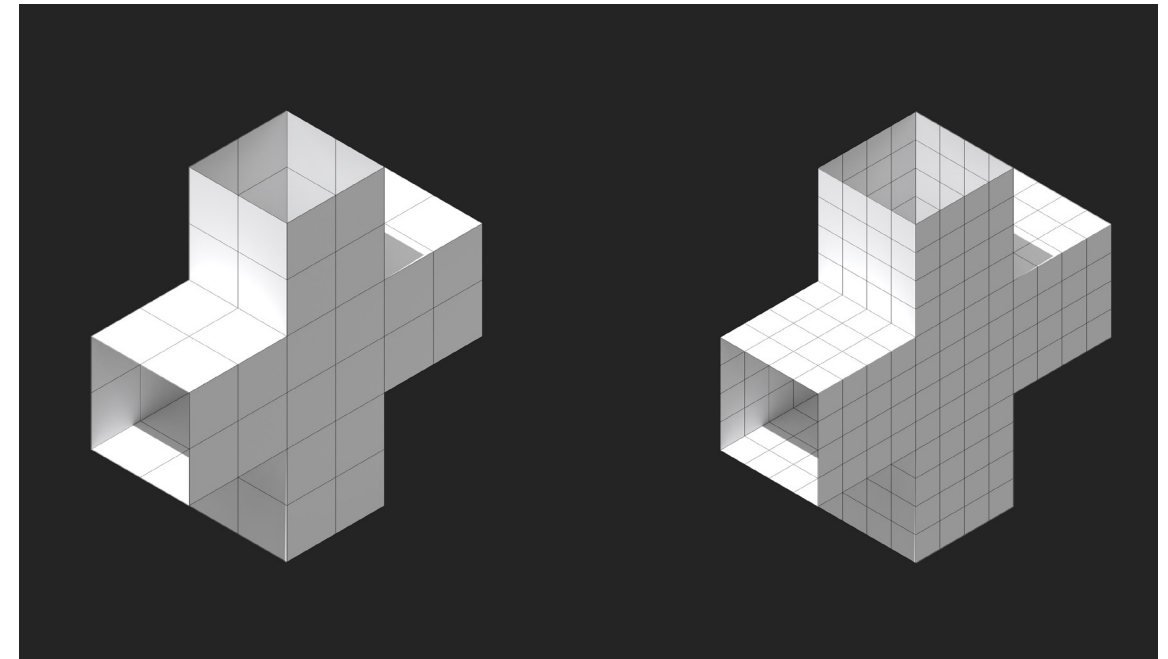




Kangaroo is a physics based engine that can solve a physical problem from its boundary conditions. The first condition defined for this problem is the anchor points. By defining an original location and a point to anchor to, the first boundary condition has been set. The other boundary condition is the tension that is placed upon the original mesh. This is done by defining the new edge length the solver should strive towards. If this is set to for example 0.5, the solver will try to halve the distance between adjacent vertices of the input mesh. If it is set to 2 it will try to double the length.

This way tension and compression can be simulated by the kangaroo solver. By using the refine tool on the original mesh before giving the inputs to the kangaroo plugin a finer or rougher mesh can be created. This is very similar to how the Catmull-Clark subdivision works. By refining the mesh each square gets split up into four new square faces which increases the smoothing. The issue with this method is the fact that the output mesh consists of square mesh faces. This is easily solved by applying Charles Loop's subdivision to the end mesh to split every square face into two triangular faces.

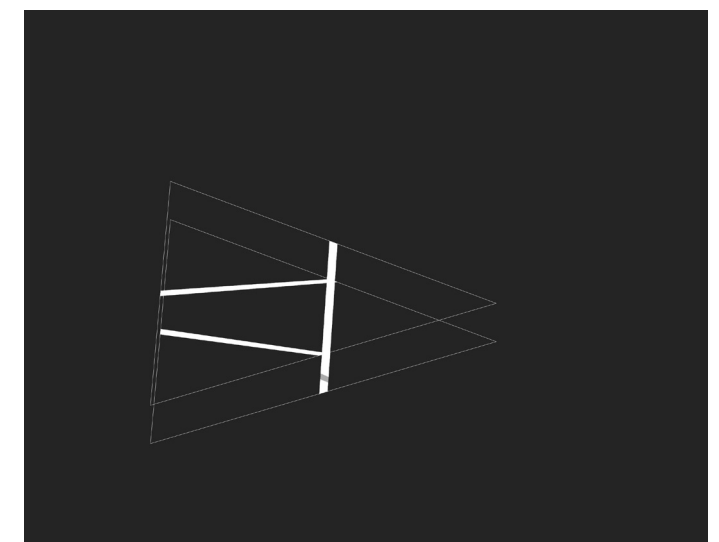
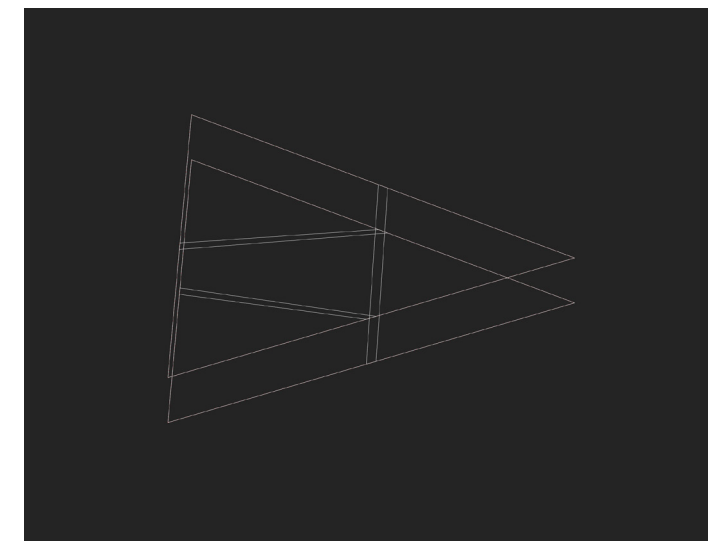
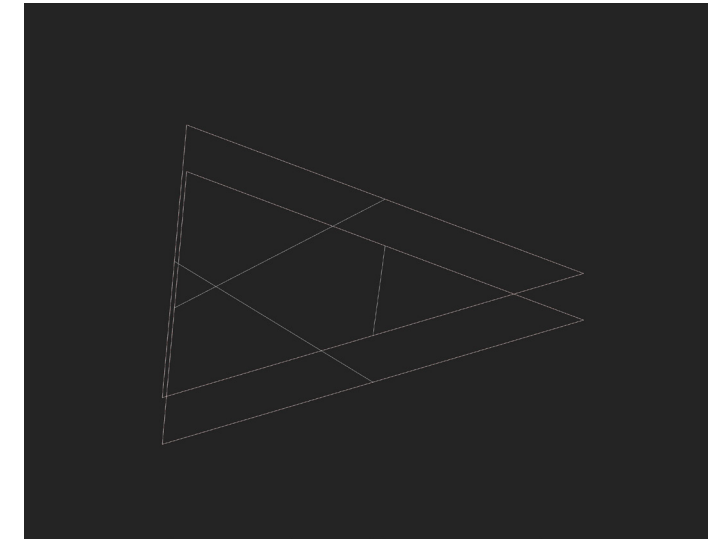
Top: Comparison between two different input geometries. the geometry is the same but the mesh has been refined to have double the amount of mesh faces  
Bottom: Comparison between the output of the mesh relaxation, the geometries have the geometries above as their initial input



# W E A V I N G P A T T E R N

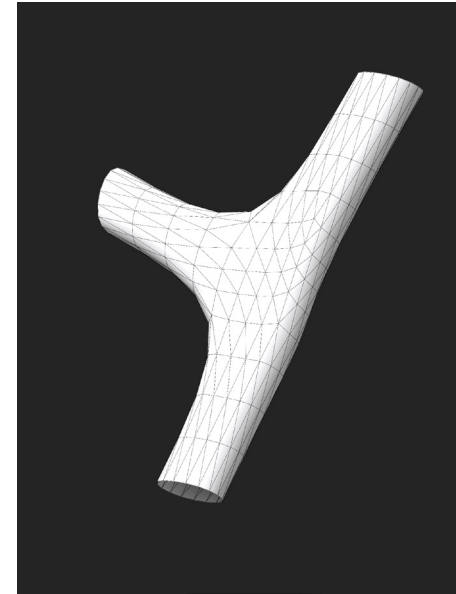
With this mesh a proper base has been created to try and create a Kagome weaving pattern with. Before looking at a complex mesh the method will be explained based on a single triangle. The main idea is to offset a triangle and then connect the midpoint of the bottom edge with the midpoint of the adjacent edge of the top triangle. If this is repeated for each edge, three lines should be drawn overlapping each other. If this is repeated for the adjacent triangles, it will always match up since the midpoints of the edges will always line up of two adjacent triangles. This means that the method for a single triangle is applicable for any mesh that solely consists out of triangles and is a manifold surface. To create the offset of the mesh another Weaverbird function is used. This is needed because every triangular face of the mesh has to be offset along its normal to make sure the weave is performed correctly for each individual face. This is done by the weaverbird's offset mesh component. This measures the distance between the new and original mesh based on the diagonals of the mesh faces. Thus correctly offsetting each face. Now a line system has been created that is already woven. The next step is to convert the line into a geometry that approximates the shape of the rattan fibres. This is easily done by creating an offset of the middle point along the edge in both directions to create the corners of each quad mesh.

Top: Connection between the midpoints of two triangles. The bottom midpoint is connected to the midpoint clockwise next to it of the top triangle, this is repeated for all three midpoints  
Middle: An offset of the lines connecting the midpoints is made along the edges of the triangle in both directions  
Bottom: A surface is constructed based on the lines specified before

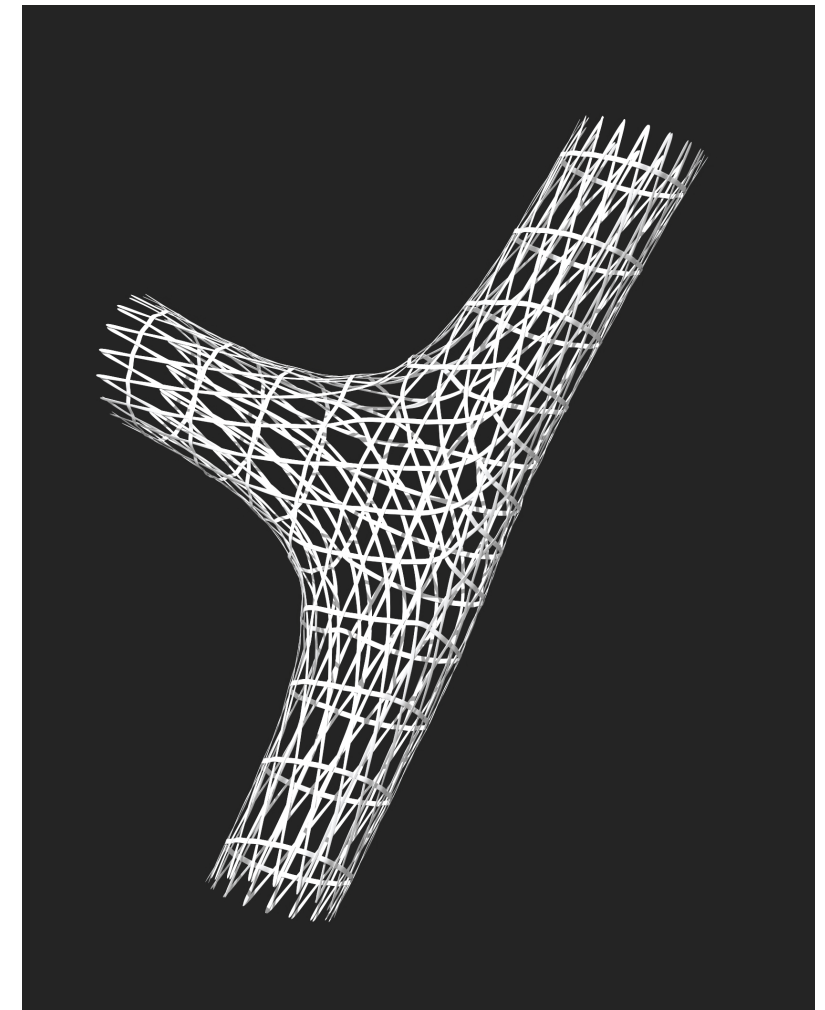




Next the weave tool is used to create a list per four corners. Important to remember here is the order in which the vertices are entered into the weave component. Since a mesh has to be constructed out of this set, the points should be entered clockwise or counterclockwise, if they are put in randomly the mesh will not be created properly. Important to do is edit the way the input data is received. The input parameter should be grafted, this way there won't be any relationships list-wise between points of different triangles to avoid unwanted connections being made. Now a mesh can be created and joined using the weaverbird join component. This way each mesh of a single triangle gets connected with the corresponding mesh of each adjacent triangle and thus creating the fibres. Finally a thicken component from weaverbird is used to give a thickness to the mesh after which the Charles Loop subdivision is used again to smoothen each strand, making it an accurate digital representation of a rattan weave.



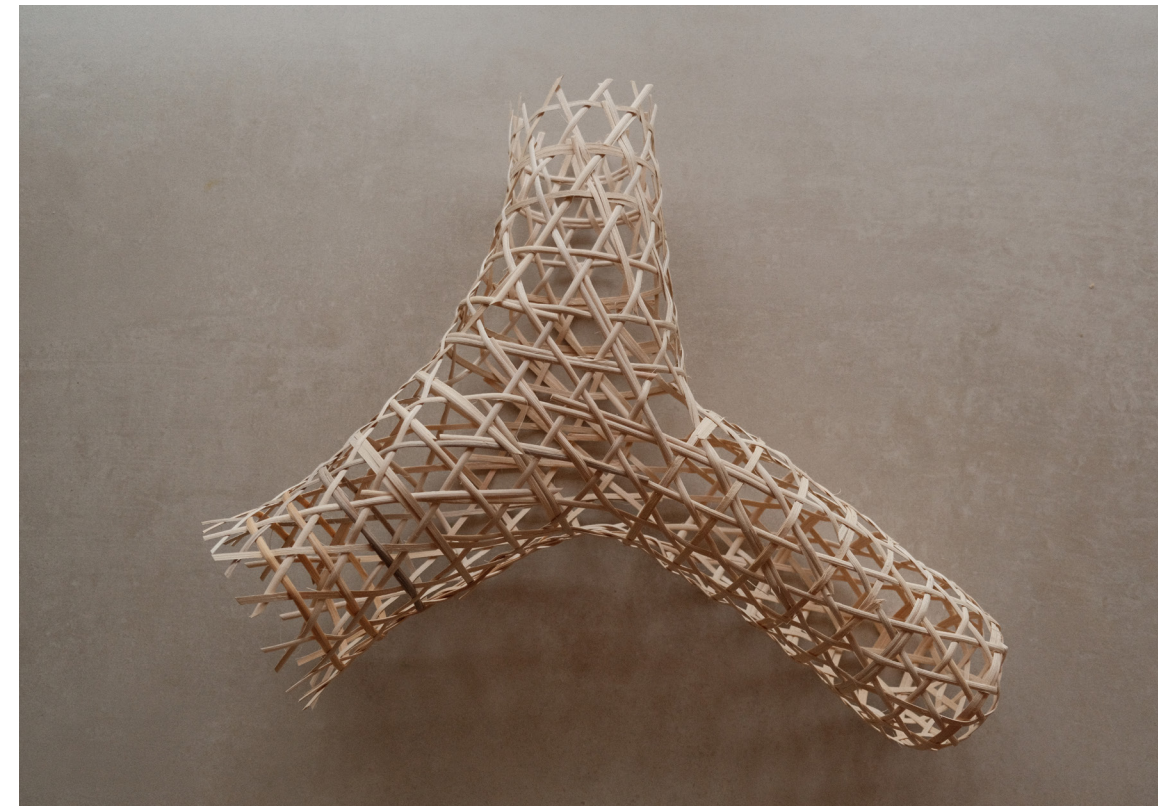
Top: A more complex geometry subdivided using the Charles Loop method  
Bottom: Weaving pattern created by using the mesh developed by the Charles Loop method



# C R E A T I N G A R E A L - L I F E T W I N

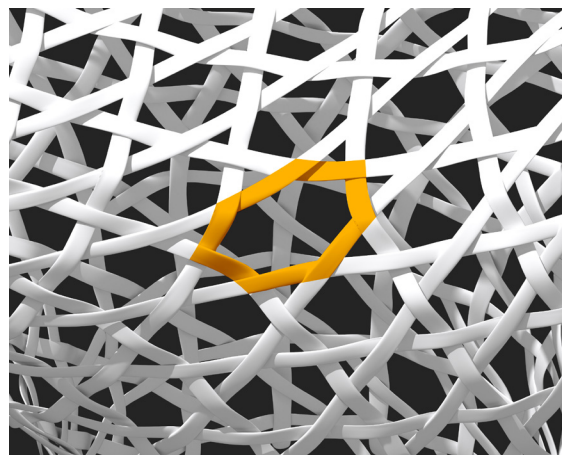
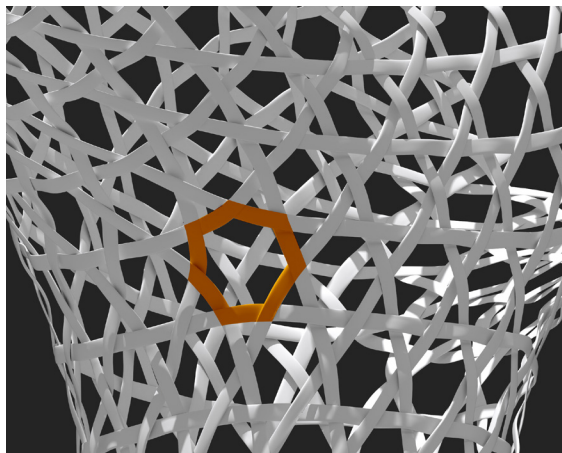
At this point a way to represent more complex geometry as a weave pattern is accomplished. The next step is to try and create said complex geometry physically. The first way to do this was the creation of the most simple knot possible, a T-joint. After modelling a simple mesh consisting of four cubes and feeding it into the weaving definition a weaving pattern emerges. The start is by creating a simple cylinder based on the basketry technique discussed in the implementation of experimental findings on page 79. After a certain height is achieved the cylinder has to branch into two different cylinders. This is achieved by changing up four hexagons into heptagons. This way extra fibres get introduced that make up the extra strands needed. These two extra strands added can now be used to create the base from which the two branching cylinders will start from. After further developing the joint, two new heptagons are created to introduce the final two strands needed to create the last missing pieces of the pattern. This also compensates for the change in angle introduced by the branching.

Top: Curving the woven rattan cylinder by introducing heptagon cells. This way, a more complex geometry can be created  
Bottom: Fully woven T-joint out of rattan.

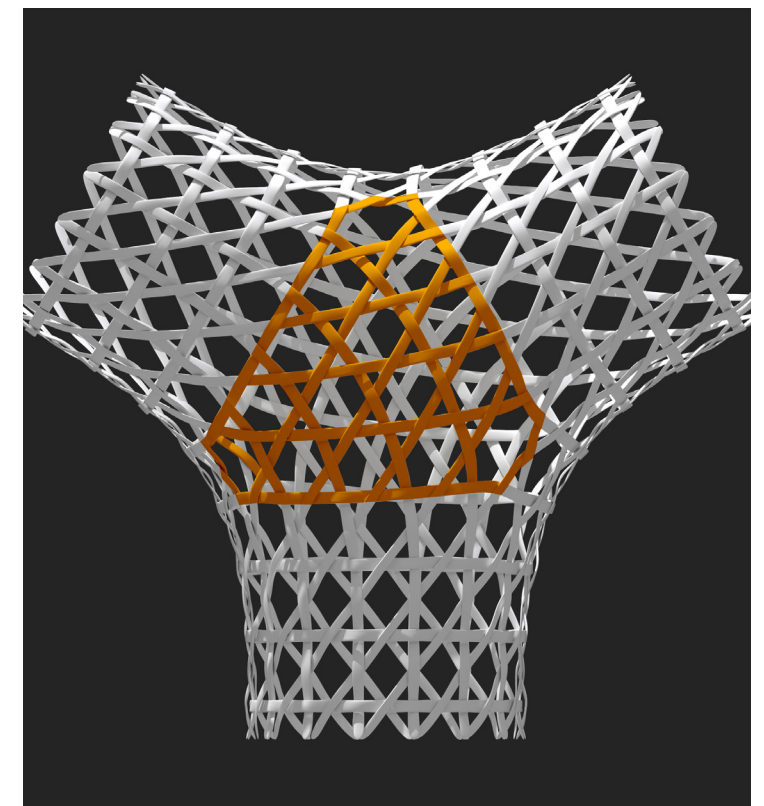
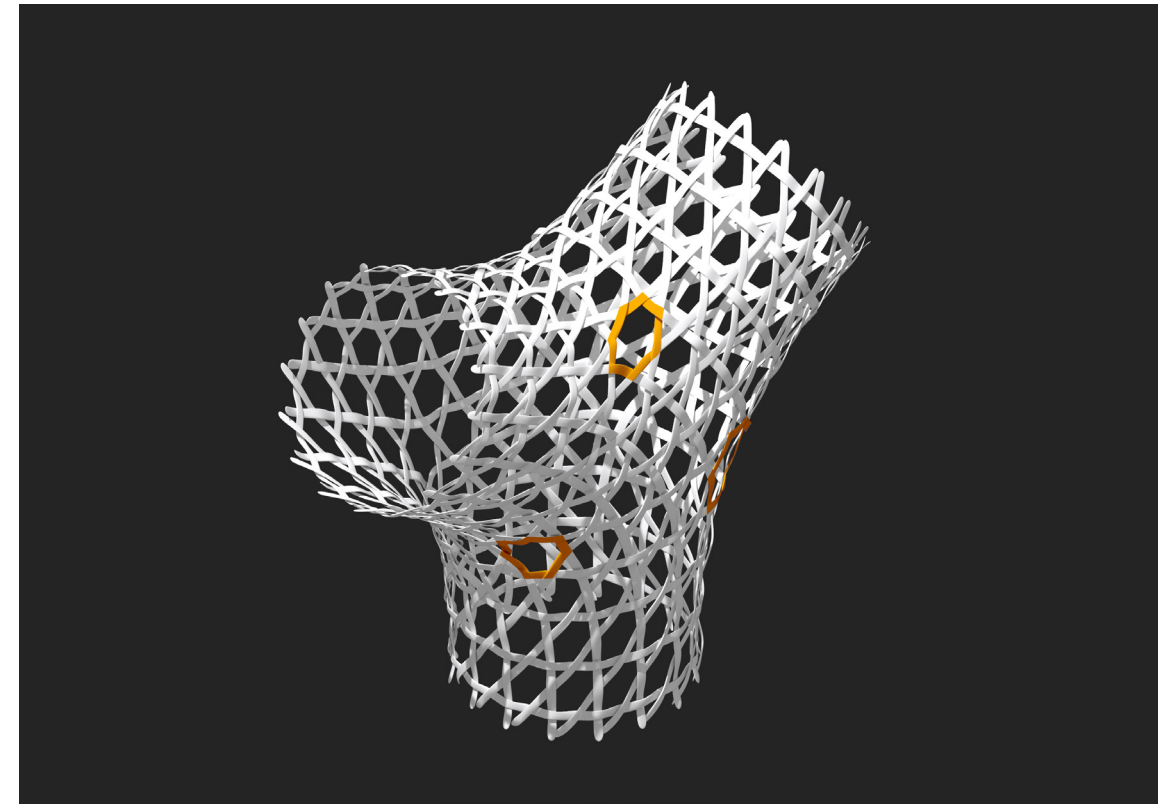




By looking deeper into the way the pattern changes some insights can be gained on how the branching system works. If the amount of cells is counted between each heptagon it is always 3 cells. If we highlight these a bigger triangle is seen, here every corner consists of a heptagon and all other cells are standard hexagons. Also interesting to see is the fact that these heptagons are always located at the corners where different geometries meet, regardless of the density of the pattern.



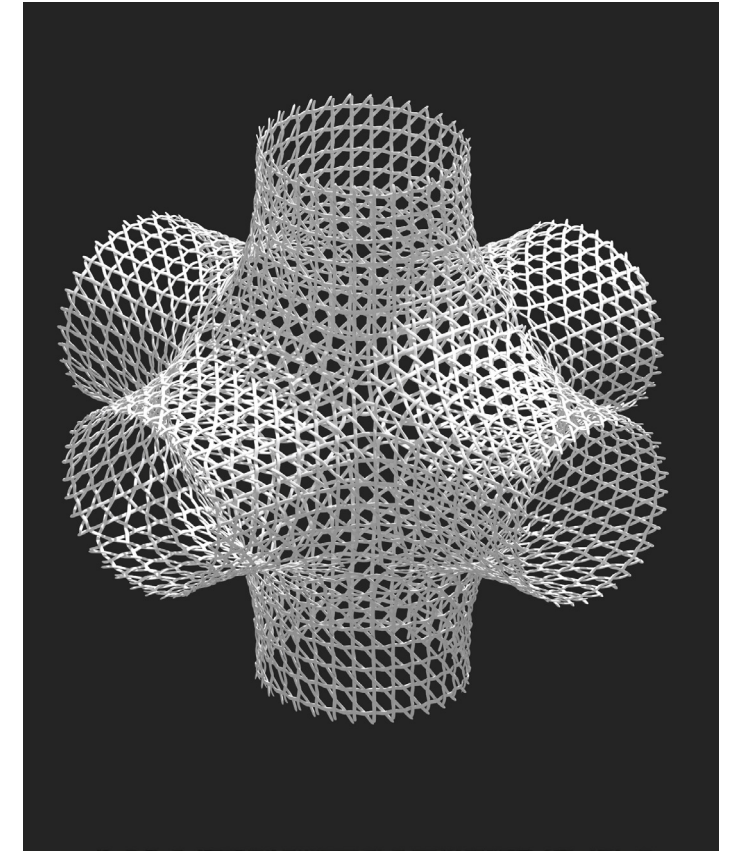
Left: Zoom ins of different heptagon cells to induce curvature  
Top right: Overview of the different heptagon cells  
Bottom right: Larger triangle which is mentioned in the text



# I N C R E A S I N G C O M P L E X I T Y

Next a digital model was created of a knot consisting of four different cylinders, all in the same plane and orthogonally oriented. Upon inspecting the digital model it was clear that the method was exactly the same as the T-joint but instead of using only one heptagon cell at the top two are used to create the extra cylinder. The only difference here was the need for two extra fibres to create the extra upper arm. These were added by substituting two heptagons by octagons. After weaving the real- life counterpart this hypothesis seemed correct. Finally a model was made joining six cylinders into a single knot. A multitude of attempts was done to try and create a real-life knot out of this digital pattern but the complexity of a decathlon was too difficult to achieve by hand. It might be possible to create these decathons by hand after a lot of practise or finding someone with more experience. Robotics could also solve this issue since it should be physically possible based on the model. No fibres split into multiple pieces and no extreme angles are present. For this thesis however it was decided that this type of knot was simply too difficult since the main focus was the new composite material.

Top: Complex 6 cylinder knot, to make the geometry clear a higher density was used for the weaving pattern  
Bottom: 4 way knot woven out of rattan fibres

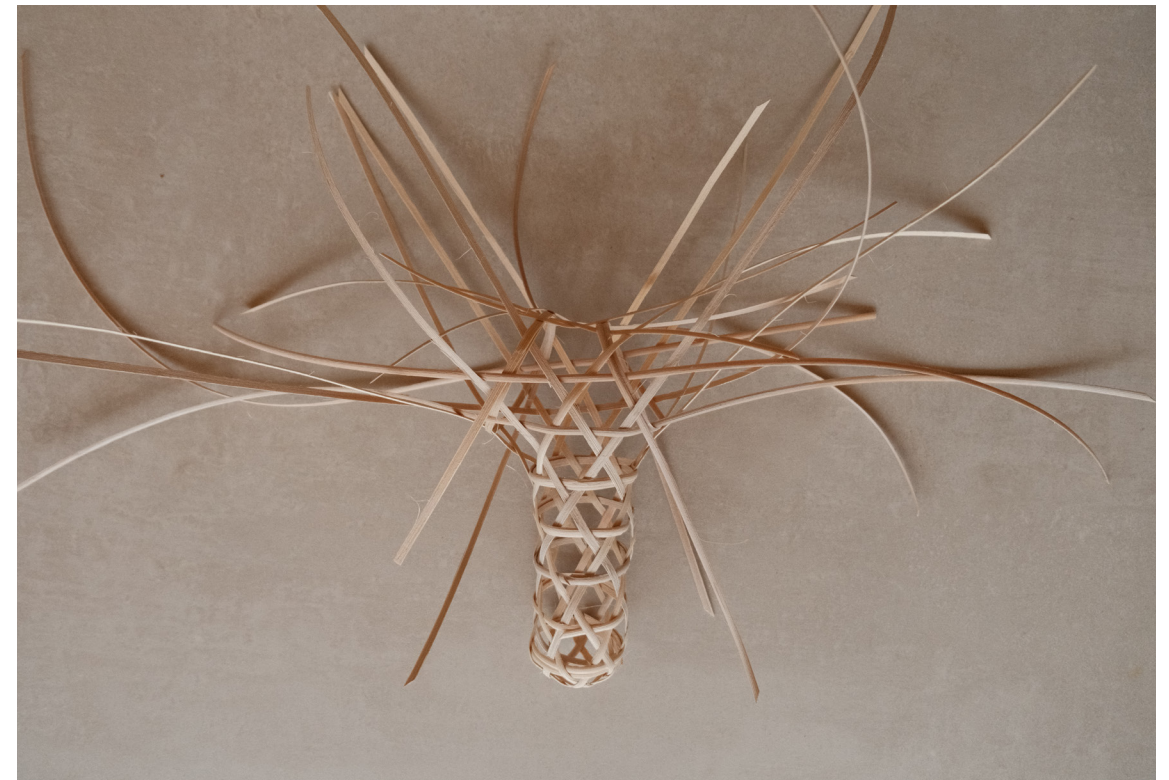




# CREATING HOLLOW JOINTS

After this was accomplished the need for an inner structure was needed. This way hollow cylinders and knots can be created making sure the pieces dry out properly as discussed earlier. So for this test the amount of rows in the base plate was reduced by one. This created a smaller cylinder and once the heptagons needed to be created it became obvious that exactly the same pattern is used but instead of three cells in between each heptagon it is now only one. This means that any size can be achieved by simply increasing the amount of rows in the base plate and increasing the space between heptagons with the same amount. One issue arose however. The knot with a smaller diameter can't be placed inside the bigger one. This means that the larger knot has to be woven around the smaller one, creating a more complex assembly system then necessary. Another thing to take into account is time management. In the time a single knot is created, multiple cylinders of the same diameter can be woven. Because of these two disadvantages, the choice was made to substitute the inner knot with regular cylinders since they also achieve the goal of letting moisture leave the test pieces.

Top: Start of a woven cylinder with a smaller diameter, the base plate of the cylinder consists of a single hexagon  
Bottom: Splitting the single cylinder in to two by introducing heptagon cells



# IMPLEMENTATION O F F O R M - F I N D I N G

At this point the knots proposed for the structure can be modelled and woven. The next step is implementing form-finding into the design. This form-finding method will have a structural model as its final output. Afterwards the weaving definition can be linked to this structural model to create a final digital structure that can be created in real-life.



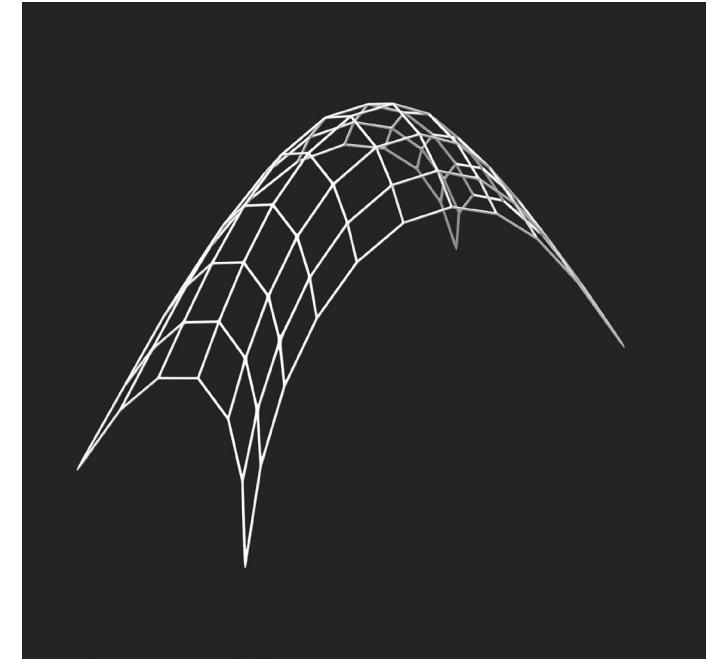
# CREATING THE STRUCTURAL MODEL

Based on the foregoing tests the maximum allowed joint is a four way knot. This boundary condition can now be used as a base to develop a system that allows pavilions to be constructed. Since the main force applied to the mycelium should still be in compression as stated before in mechanical properties on page 15. To allow such a design Kangaroo 3D (Piker, 2017) is a very efficient design system. It has already been used in this thesis for the minimal surface but it can also be used to design structures solely in compression. In comparison to the minimal surface definition quite a few extra factors come into play to develop a proper structure that is fully in compression.

The way Kangaroo works is by first defining a base plane that will be the floorplan of the final structure. This base plane should be a mesh, this way the amount of subdivisions in both X and Y direction can be edited separately through the mesh plane component. By extracting the mesh edges the length component already has its base length defined. If we use multiplication we can easily change the goal length as a second input. A strength slider is also possible for this component. In the previous use of Kangaroo this was of no importance since the changing length of the mesh edges was the only variable. For the design of the structure however other forces will be applied to the structure. These forces will be discussed later but it is worth mentioning that the strength slider will determine how big of an influence these forces will have on the calculation.

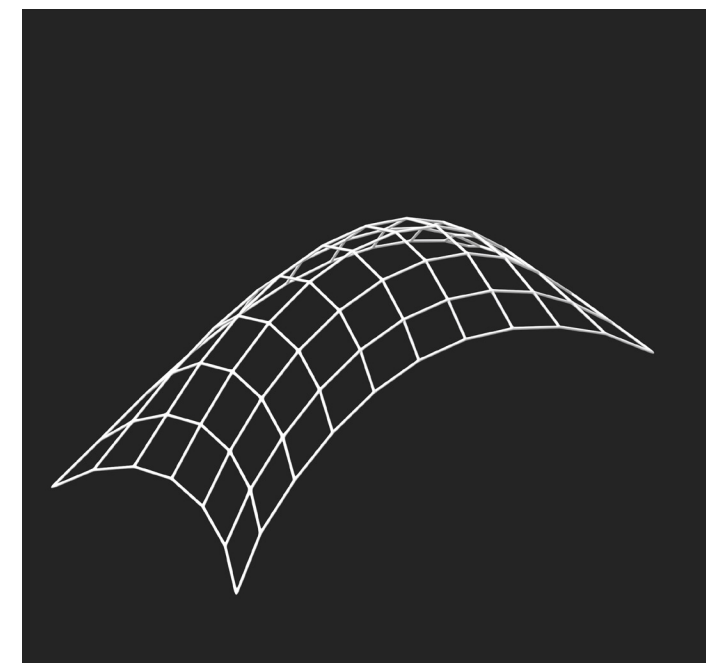
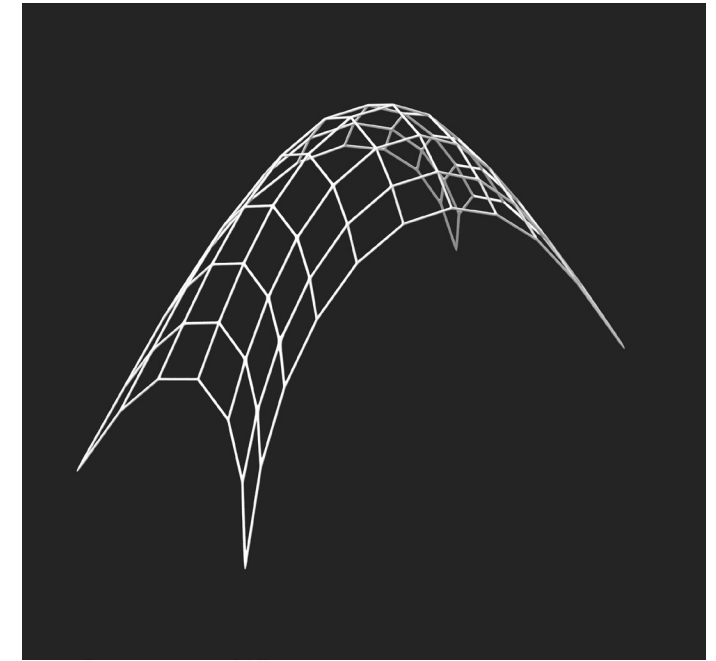
Top: Structural model with a high subdivision of the original surface

Bottom: The same settings as the top image but with a lower subdivision count



After this step the anchor points have to be defined. As a first test the corners were simply chosen as anchor points. Since the first basic plane chosen is a simple rectangle this means the creation of 4 anchor points. The strength of the anchor points can also be changed, here the anchor points are seen as immovable coordinates so the strength of the anchor points is many times greater than the strength of the different forces applied to the simulation. Next the own weight of the structure has to be taken into account. This way a compressive model can be created. This is done by the load component. By deconstructing the mesh the vertices can be extracted from the model and a load can be placed at each vertice. This simulates the earlier discussed catenary lines, the dispersion of the weights is a chain with every weight placed at the chain link. By flipping the vector of the weight added to the vertices a compressive model can be created.

Images: comparison between the same structure with a different own weight applied to it, by increasing the weight the height of the geometry increases to accomodate the larger load



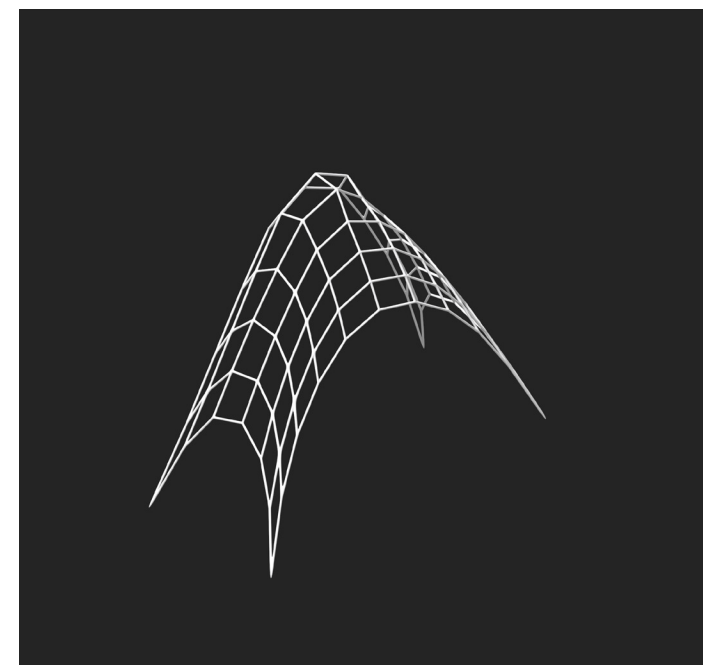
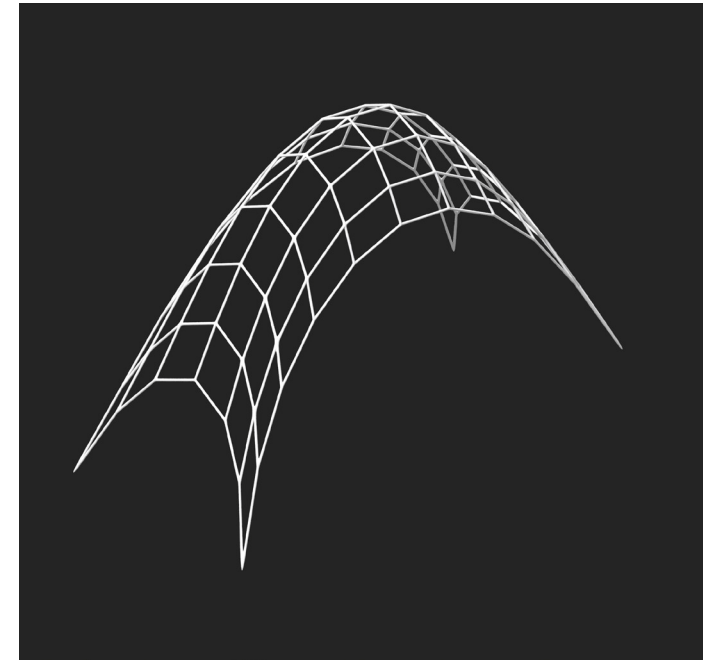


Lastly, it seemed beneficial to create a system that allows localised forces to be applied to the model. This would make it possible to not only model structures that support their own weight but also make stackable designs a possibility. This was done by creating a boundary on the base plane and evaluating which vertices are inside the boundary. These vertices are then fed into a second load component. One of the issues Kangaroo has is that no exact loads can be added. If for example an arch has to support a load of 50 kg on top of its own weight, these values can't be directly placed into Kangaroo. The way this is normally solved is by creating a range of real life and digital twins, seeing how they react in real life and then changing the load in Kangaroo until the digital twins closely approximate the real life situation. Since the process of creating mycelium is rather time intensive this method wasn't an option to use for this thesis. It would mean one test can be conducted every two weeks and including time to adjust the model and shipping times one test a month would be a very optimistic number.

Since this did not seem like a qualitative end result a different approach was used. No exact forces will be applied to Kangaroo, instead the most optimal form will be used that can be designed in Kangaroo. Instead of using exact loads the forces applied will be relative to each other. This way the weight distribution should be the same in real life as in the digital space regardless of the exact weights used. Now all these boundary conditions can be fed into the Kangaroo Bouncy Solver. This will let all the forces and boundary conditions run until an equilibrium is achieved. This is called the converged model.

Top: Structure where the only weight applied to it is the own weight of the structure

Bottom: introduction of a second weight to the solver, the structure heightens at the localised force to accomodate the change in weight

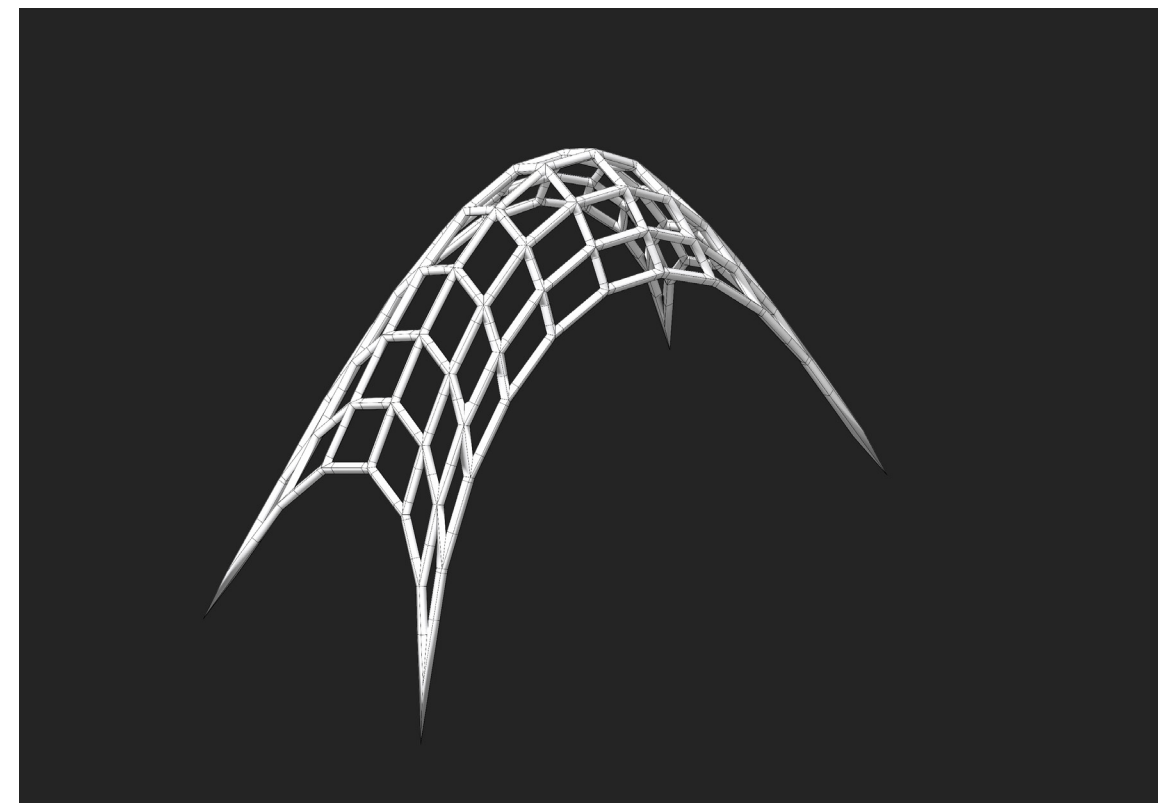
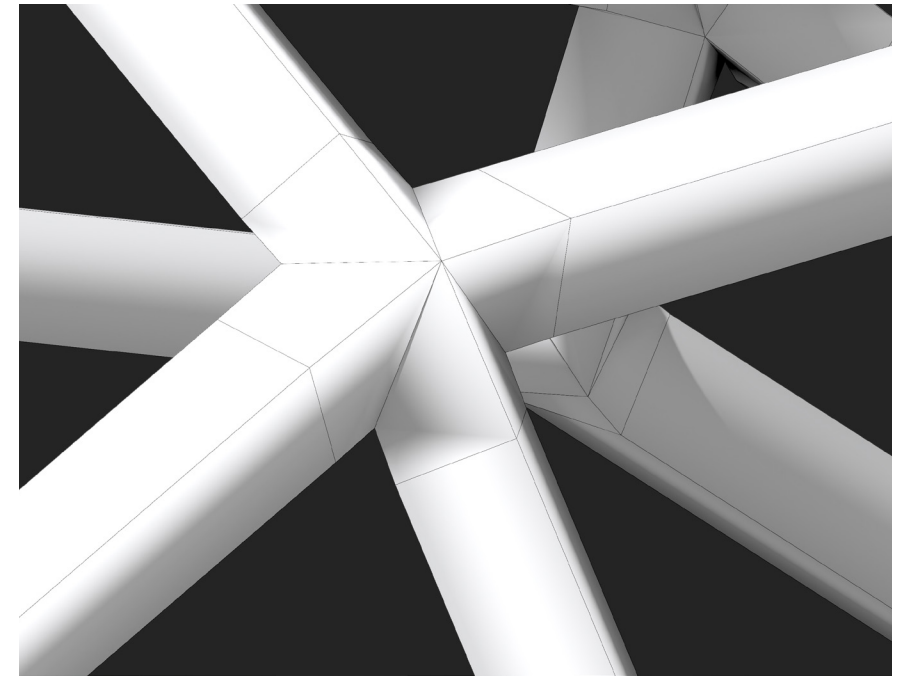


# WEAVING THE STRUCTURAL MODEL

Finally a mesh has to be created from the structural line model that can be fed into the minimal surface solver. The easiest way to do this would be the use of the multipipe tool. The multipipe tool is a component that has been implemented since Rhino 7. This update introduced some subdivision tools in the base version of Grasshopper. It allows a pipe system to be created around a group of connected lines. This creates a smooth curved surface as output which is not optimal for the mesh relaxation method that starts from an orthogonal mesh with minimal faces. Luckily the multipipe tool also gives a boundary box mesh as output which is constructed in exactly this way.

All parts needed to create the structure and generate a weave pattern for it have now been individually developed. Next, a way to integrate all these different parts into a single working model has to be determined. The first idea was to just multipipe the entire line system created by Kangaroo and then weave this mesh. However Rhino is not optimised to run a difficult design system that works in multiple steps as quickly became apparent. The multipipe tool didn't have any issues creating a mesh but the moment mesh relaxation was attempted to create a minimal surface Rhino instantly crashed. The amount of computational power needed is simply too much for a simple laptop and Rhino to handle.

Top: Zoom in of a knot of the arch. A mesh is created using the multipipe tool  
Bottom: The derived mesh when the multipipe tool is used on the entire structural line model

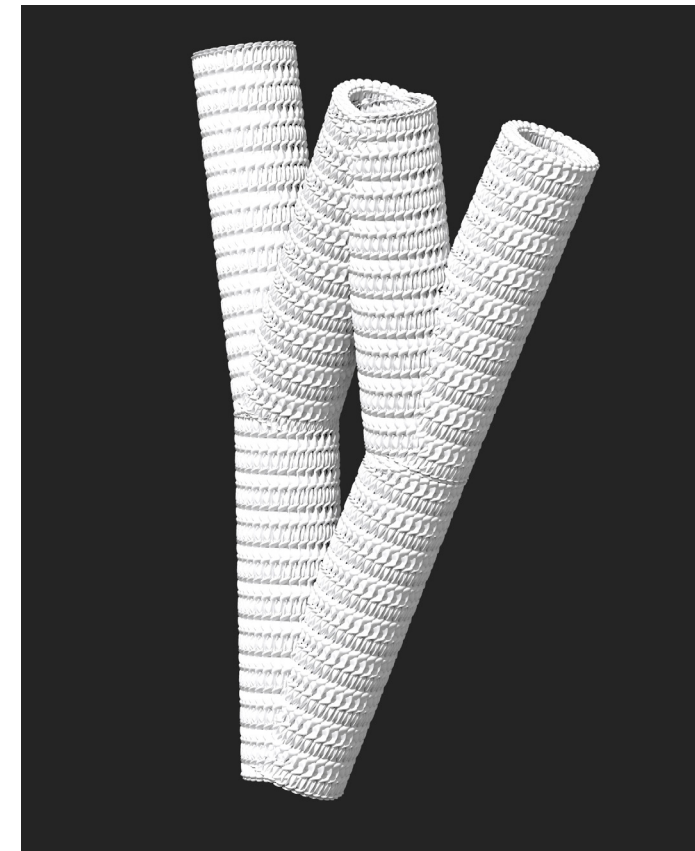




Because of this a change in approach was taken. Instead of seeing the entire structure as one problem to solve it is divided into a set of knots and rods. This way each knot can be calculated separately greatly reducing the strain Rhino has to handle. For now this was simply done by manually selecting the lines of a single knot. This ended up working and allowed Rhino to calculate an end result.

This still managed to crash a multitude of times during testing however. The first mistake was leaving the weaving definition connected to the minimal surface component. Since the minimal surface takes a while to converge, the weaving component would try to create a working pattern for every single iteration. Simply disconnecting the two parts from each other before changing any parameters of the Kangaroo solver quickly solved this issue. The second issue was the subdivision becoming too small which made it very intensive to create a weaving pattern out of it. This is solved by controlling the amount of subdivisions the Charles Loop method creates since the minimal surface already consists of quite some quads.

Image: Very dense weaving pattern used on a non optimised mesh, the production of this geometry caused a Rhino crash



# COMPARING CHARLES LOOP AND MINIMAL SURFACES

One of the issues with this method was the fact that the minimal surface consisted of a rather dense quad mesh making it hard to create simple weaves, the size of the weave would always be smaller than desired scale wise. The shape of the minimal surface did not change much after utilising the Charles Loop subdivision which also raised the question; how useful is applying both methods in sequence? A simple base geometry was chosen to test this. First, a minimal surface was created based on a mesh that was then subdivided using the Charles Loop method. Secondly, the Charles Loop method was used directly on the initial mesh. This way both methods can be compared to each other. It became apparent that the Charles Loop subdivision already approximates the minimal surface. This meant the creation of a minimal surface made the process needlessly complex and could be removed. Removing the Kangaroo solver from the definition already greatly sped up the generation speed of the knots. The density of the weave also became more controllable. Lighter weaves with a lot of space in between became possible to model.

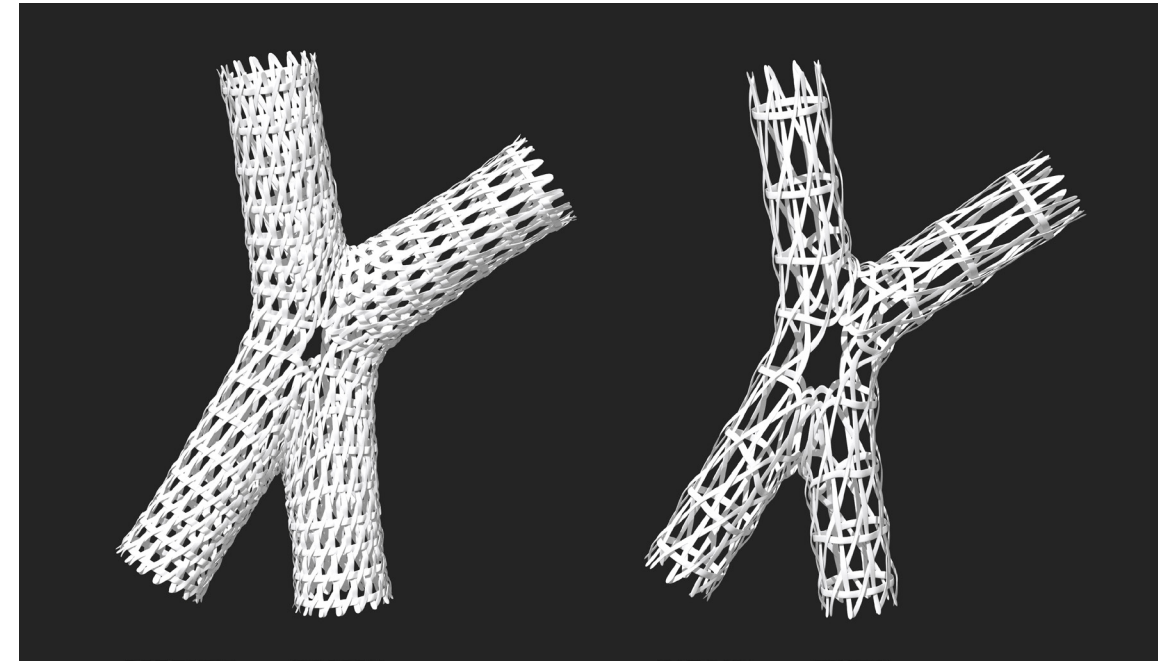


Image: Comparison between the weaving pattern derived from using the minimal surface method (left) and directly applying the Charles Loop method to the base mesh (right)

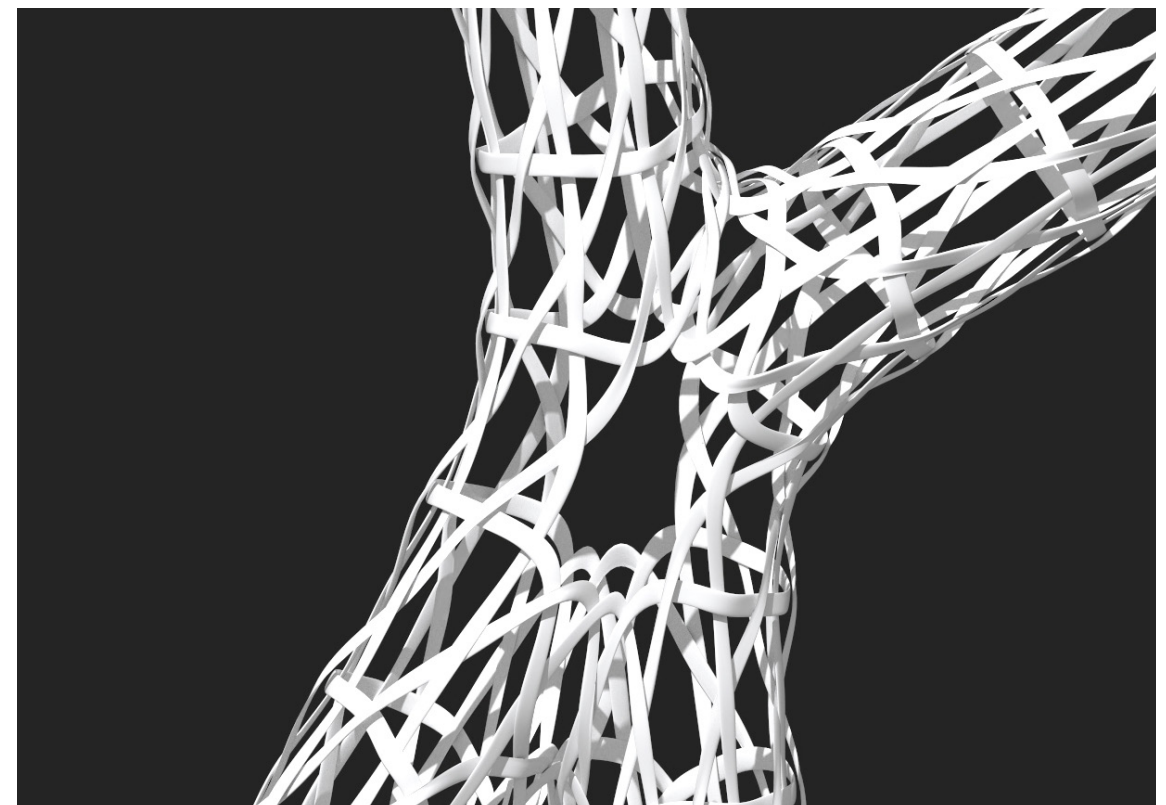
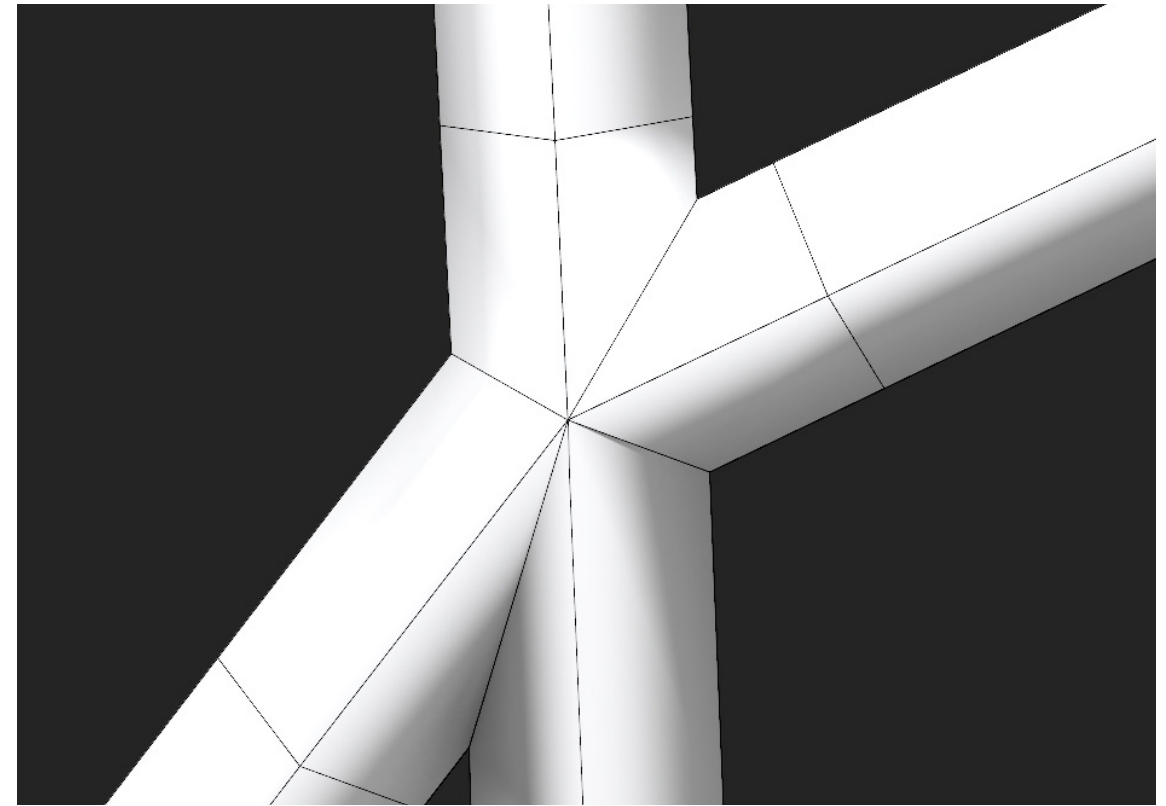


# P R O B L E M S O L V I N G

The biggest issue however came from the multipipe tool. Because of the way the weaving system constructs a mesh, it always creates a complex polygon at each corner where different geometries coincide. The multipipe converges all pipes to a single point, this means that all pipes come together in a single point, creating a very complex polygon. As stated earlier, this is very difficult to develop in real life. Now even a simple t-joint suddenly became too complex to weave in real life. The solution seemed to be a small adjustment at first glance.

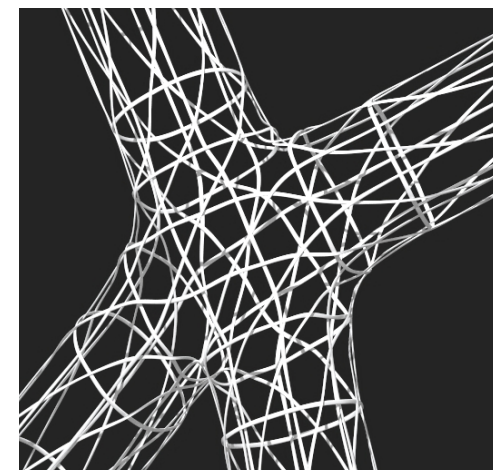
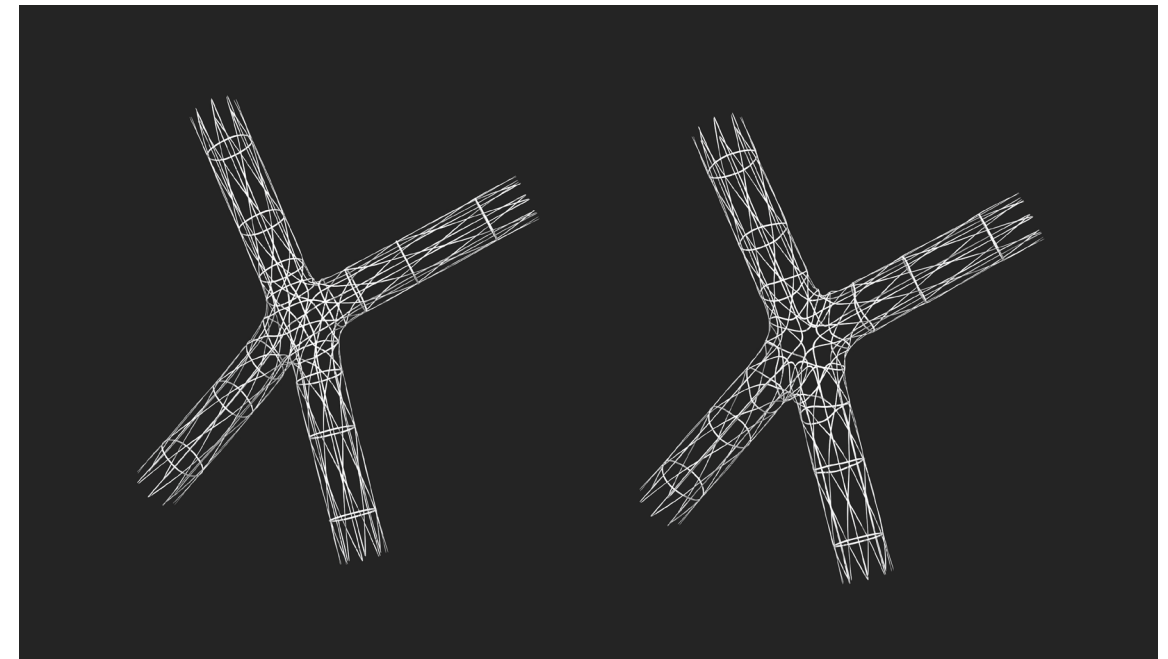
Top: Base mesh derived from the multipipe tool with a complex central vertice

Bottom: Weaving pattern created using the top mesh as an input. The complex central vertice causes a complex polygon in the weaving pattern



The multipipe tool had a boundary condition called CubeFit. If this is set to true the component will try to fit a cube at each node and have the corners of the node coincide with the boundary box around the cylinders. This is also the way the first tests were conducted. This seemed to work for some knots but at others the multipipe would not be able to fit a cube at the centre. After doing some research the problem became clear, the multipipe tool would only create a box at the centre if all lines part of the pipe system would be more or less in the same plane. Since the structure here assumes the form of a curved surface this posed a rather big issue. Trying to change the way the structure is developed seemed like the wrong approach since the catenary line is an integral part of the design logic and this would mean that not a single knot would have all its lines in the same surface. The logical solution was to find a different way to construct the base mesh instead of the multipipe tool. The fact that if a cube was in the middle the weave would be modelled correctly was the base of the new system that needed to be created. This meant that if the mesh edges no longer meet in a central vertice the mesh should produce a proper weaving pattern.

Top: Comparison between a knot where the original mesh is in a single plane (left) and a knot that is not in a single plane (right)  
 Bottom left: Zoom in of the correctly modelled weaving pattern  
 Bottom right: Zoom in of the complex polygon

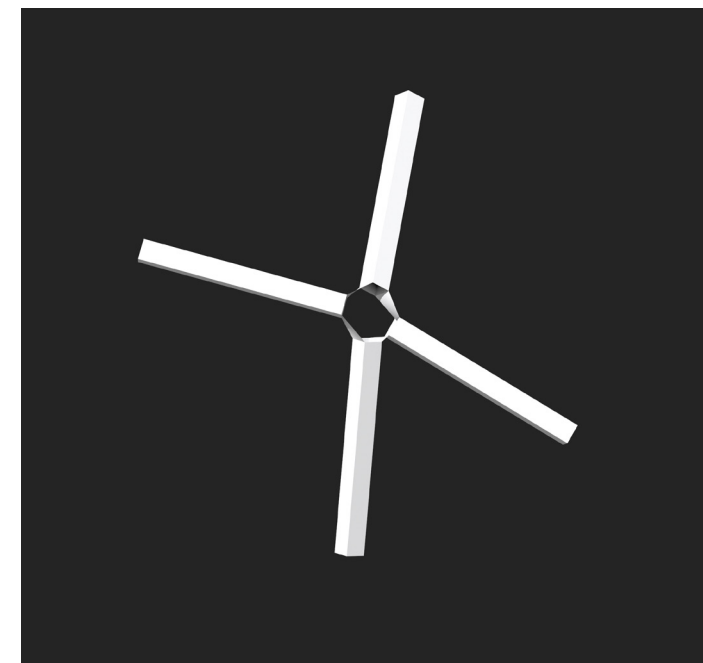
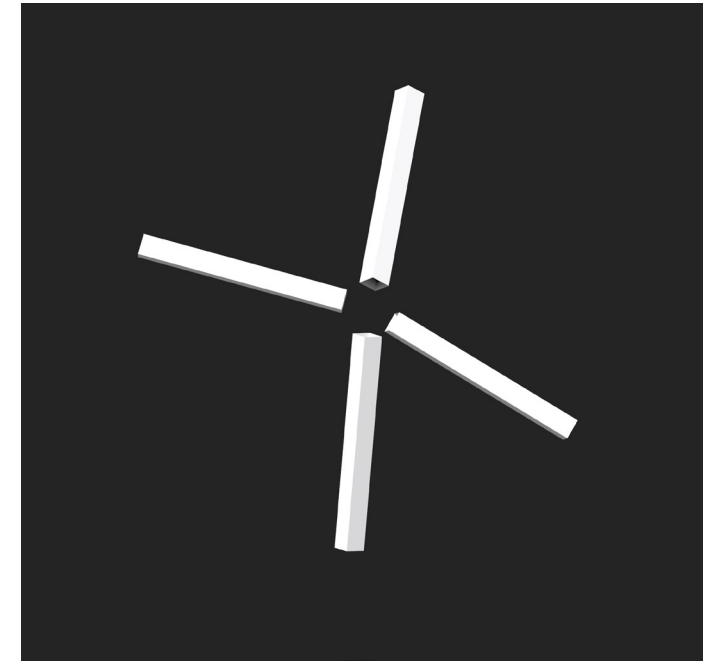




# PROBLEM SOLVING FIRST ATTEMPT

The first attempt to solve this was to create a square mesh lofted along each line. At the point where they all come together create faces connecting each edge with the edge of the adjacent square and then use the cap tool to close the top and bottom. Creating a manifold mesh where not a single point has a high amount of edges coming together. The first step was using the polygon tool and setting it to 4 edges. This was chosen over the rectangle tool since here it is easy to work from a base plane. This base plane is derived from the vectors of each line, using this vector as the normal of the surface instantly defines the direction as well as the location of each square. Next new mesh faces have to be created connecting the adjacent edges of the squares to each other. This was done by extracting the corners from the squares and then creating lines connecting the top and bottom corners of adjacent squares. These lines could then be used to loft a surface from the bottom to the top lines created.

Top: Creation of the extruded base rectangles  
Bottom: Connection of the adjacent edges of each extrusion

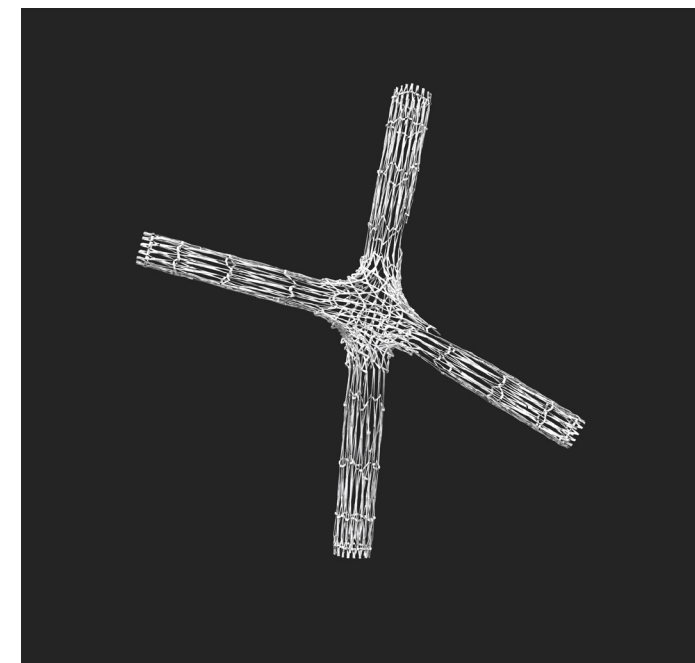


The next step was selecting all the top lines and creating a polyline from them, then using the cap tool. Using a surface did not work since the polyline is not planar. If the original created squares are now extruded, all surfaces have been created needed for the base mesh. A very important step is to unify the mesh before trying to use the Charles Loop method. This is because of the earlier discussed way adjacent triangles are recognised. If the normal aren't all facing either inwards or outwards the method will not work since it doesn't recognise the different mesh faces as one mesh. Instead it will divide the mesh faces separately instead of as one mesh.

The first attempt at creating a weave pattern from this mesh resulted in a failure. The complexity of the knot was too high resulting in wrongly woven patterns. The first attempt at solving this problem was changing the way the caps are created. By connecting the corners of one set of squares that face each other, the geometry can be simplified into three vertices per side. This still did not result in a proper weave. After trying a different knot to check whether or not it was a specific problem or a global one, the realisation came that the order of each corner completely changed per knot. This meant that the constructed faces would all need to be respecified for each individual knot or a different system has to be used to create the faces. Upon trying a knot with steep angles it quickly became apparent that the mesh became very distorted and would not put out a usable mesh even after optimisation and fixing the current problems. Because of these reasons a different approach was taken.

Top: Cap placed on top of the open central mesh to create a non manifold mesh

Bottom: Wrongly woven mesh using the upper mesh as a base for the weaving pattern



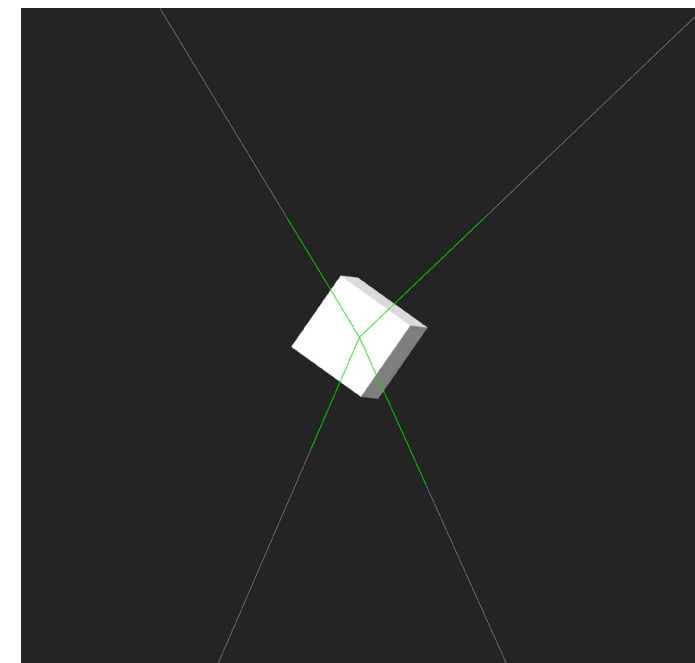
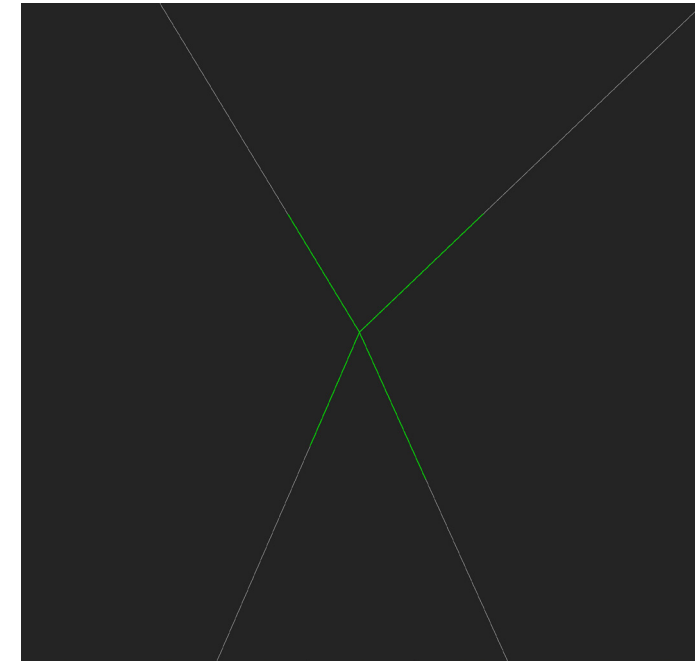


# PROBLEM SOLVING S E C O N D A T T E M P T

The cubefit function of the multipipe tool was the inspiration to try another approach very similar to how the multipipe tool works. The basic idea is very simple. Have a cube at the centre of the knot and then extrude the surfaces in the direction of the different lines provided by the kangaroo model. This new approach would mean redesigning the multipipe tool from scratch. Since no actual cylindrical surface was needed but having a cube at the centre this became the start of redesigning the multipipe component. Simply placing a cube and extruding the surfaces along the lines of the original knot was the basic idea. This turned out to be a more complex endeavour than initially thought.

To give the cube the right orientation after it has been placed at the centre of the knot a vector is needed. This vector is calculated by taking the average of all vectors starting from the centre point. Important to note here is that the structural geometry created by Kangaroo is generated by starting from one side of the vaulted surface to the other side, the end point of one line of the vault structure is the starting point of the next line. This means that not all starting points are at the centre so they have to be redrawn before using them for the following steps.

Top: Selecting all vectors  
used to find the average  
vector  
Bottom: Placement of a  
cube in the central point  
of the knot



Now that a cube has been placed and oriented, the extrusion has to be done. This is done by matching the surface with the correct vector using the list item component. Since the cube faces will have a random order regardless of their orientation the faces have to be matched to the vector and not the other way around. Matching these was possible by creating a point at the intersection point of the line that is supposed to be used for the extrude and the list of surfaces. By then using the closest point on the midpoint of the surface and the point just created, the mesh surface can be matched up with its respective vector.

Now the surfaces can be extruded along their respective vectors. This will create a box having 6 faces so the 2 smallest faces still have to be removed from the selection. This is easily done by taking the average area of the 6 faces together and then removing all surfaces with a lower area then the average. The only downside of this method is that once the extrusion distance becomes smaller than the length/height of the extruded surface the selection will stop working and not create a usable mesh. For the function here this is not an issue since the extrusions will always be rectangular shaped.

Top: Extruding the edges of the cube along the previously defined vectors

Bottom: Selecting the mesh faces that are needed to create the knot and joining them together in a single mesh



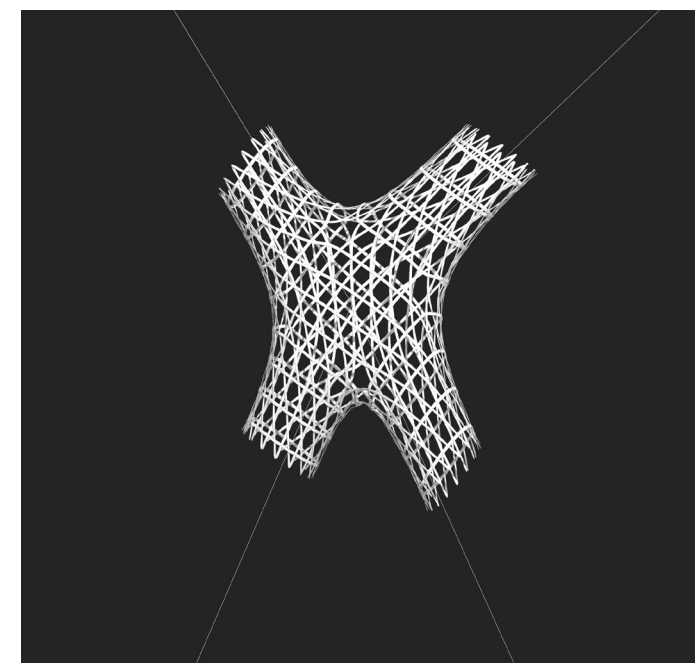
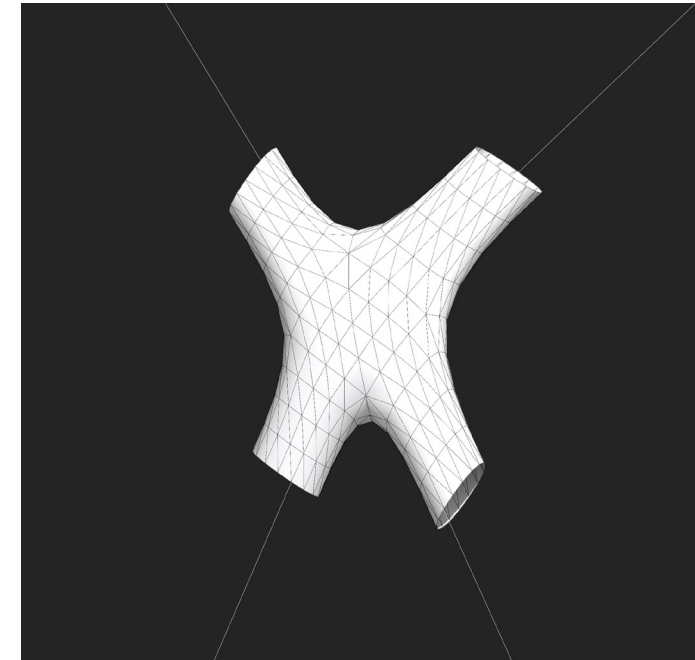


Now the only missing faces are the top and bottom mesh of the original cube. For now the cube still has six faces so the inner four faces have to be removed, leaving only the top and bottom face. The same way the faces for the extrusion get selected can be used to select these two faces. Instead of using the lines created by Kangaroo the average of the vectors used to define the normal of the cube is used. This will always be the top face of the cube and taking the reverse of it will always be the bottom face. An important final step before joining the mesh is using the custom mesh settings component. This is needed to make sure every mesh face consists of a single face. This is very important since having multiple faces will influence the way the Charles Loop method processes the mesh. After testing multiple knots this way this turned out to be a very successful way of creating the weave patterns. The lengths of the arms can be adjusted and the density of the weaving pattern as well.

Top: Applying the Charles Loop method to the previously defined base mesh

Bottom: Creating a weaving pattern based on the mesh created by the Charles Loop method

Next page: Wrongly oriented cube on the top image compared to a correctly oriented cube on the bottom image, only a very small reorientation is needed to correctly create the base mesh

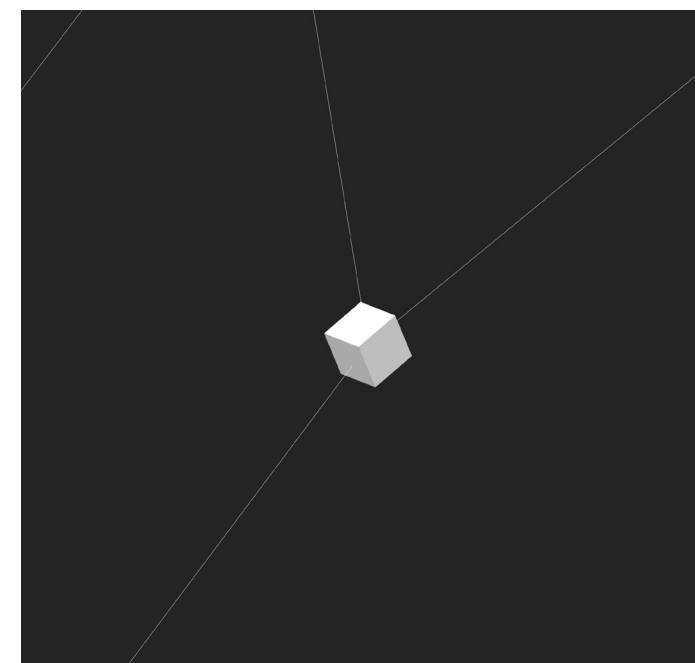
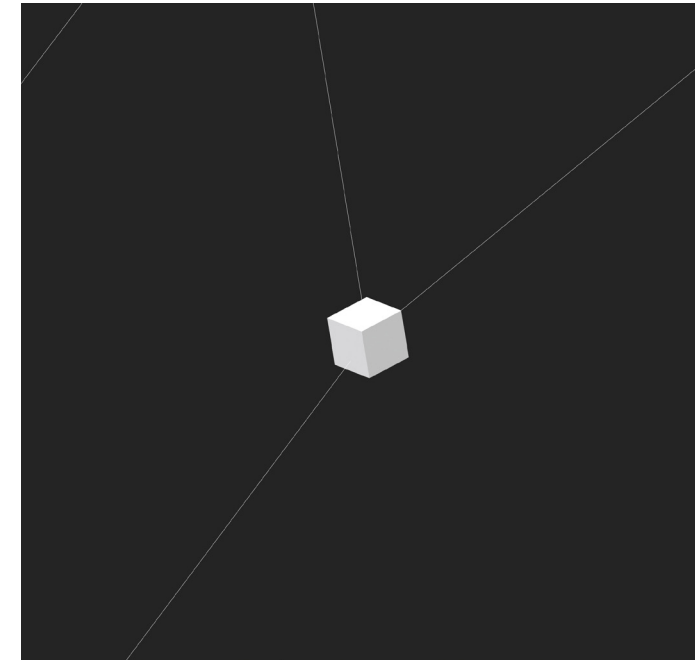


# CREATING THREE WAY KNOTS

A successful method to create weaving patterns for four way knots has been achieved. It is however also needed to create three way knots, the structural line model will always consist of three way joints at the edges of the model. These three way joints work in a very similar way as the four way joints but need a number of small changes to make the system run smoothly.

First off all not all four sides need to be extruded. The three sides that intersect with the structural line model still get extruded but the fourth side needs to be extracted. This is done in the same way the surfaces meant for extrusion were isolated. Instead of using an existing vector defined by the line model, the average of all three lines is taken and then flipped. This way it will intersect with the surface that is needed to cap the mesh. The next issue arises from the way the cube is defined. It is now based on an origin point, the centre of the knot, and a normal, this vector is derived from the cross product of the different vectors created by the line model in the same way as the four way knot. This means the X-axis and Y-axis are not defined. Since every face of the box can only intersect with one vector from the structural line model this poses a problem in the knots with steeper angles.

The solution to this consisted of finding the smallest angle between two adjacent lines from the structural model since this was where two lines intersected with a single face of the cube, making a non-manifold mesh. If the corner of the cube would align with the bisector of the angle it would become impossible to have two lines intersect with the same face of the cube. Upon creating a system that can compare the three angles of each knot it became apparent that the smallest angle would always be between the first two lines of the list consisting of the angles in between the different lines. This meant that it was not needed to check which angle was the smallest, making the Grasshopper definition simpler. By using the mean of these two vectors and then aligning the surface with this vector the base plane of the cube gets rotated into the correct position. A second rotation is needed to change the relation between base plane and cube. The axis of the plane will always be perpendicular with the cube, rotating the plane until the corner of the cube aligns with the axis makes it possible to have the correct orientation of the cube on any joint of the structural model.





# JUTE PATTERN CREATION

The next step is the creation of a system to create a jute skin for the mycelium to grow in. The jute will help absorb the normal forces together with the rattan while also allowing the mycelium to properly grow.

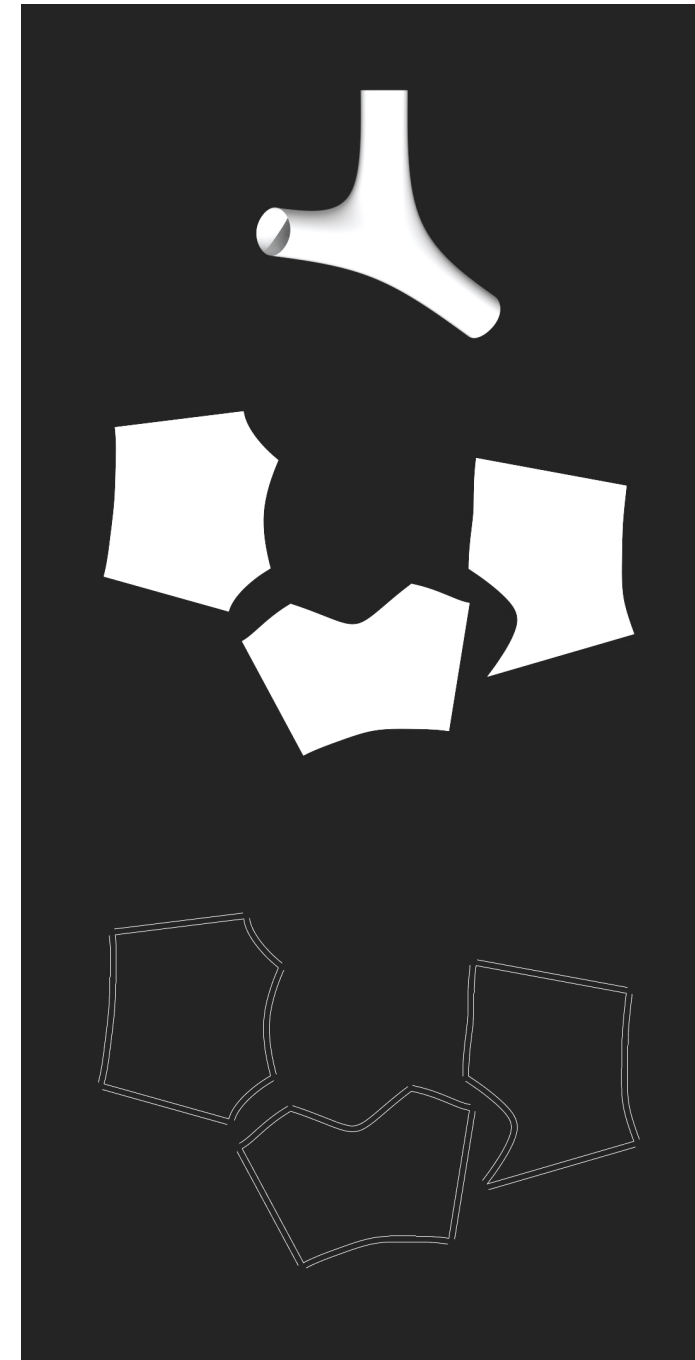
# D I G I T A L P A T T E R N S

Firstly a digital template has to be created for the jute. To optimise absorption of the normal forces the jute should be placed at edge of the test pieces, right above or under the rattan. In order to make the filling of the molds as easy as possible the rattan should be the outer layer. This way the mycelium can be fully compacted against the jute ensuring a good mechanical connection. Creating the shape in Grasshopper and then sewing the shape in real life seems to be the simplest way to execute the idea. Using the knowledge acquired from the creation of the rattan knot Grasshopper definition this became fairly easy to execute.

The issue that the multipipe posed by creating a single vertice where all faces of the surfaces connect in a single point is not an issue for the sewing. The surface created by the multipipe tool can just be unrolled. Since the surface has more than one direction of curvature, it can not be unrolled in Grasshopper. The solution is the smash command in Rhino that allows the unrolling of surfaces with multiple curve directions. This will not be one hundred percent accurate but the difference is only a maximum of 2 percent. Since this falls within the tolerance margin for the simple task of sewing the jute pieces together this method will be used.

Before continuing the surface has to be baked and the smash command has to be manually applied to the geometry. The human plugin allows baking straight out of Grasshopper simplifying this process. After using the smash command the unrolled surfaces can be brought back into Grasshopper. Here an offset is created of the sides that overlap. This way a seam can be created to sew the different parts of the pattern together creating the desired geometry. These templates can just be printed and traced onto the jute pieces.

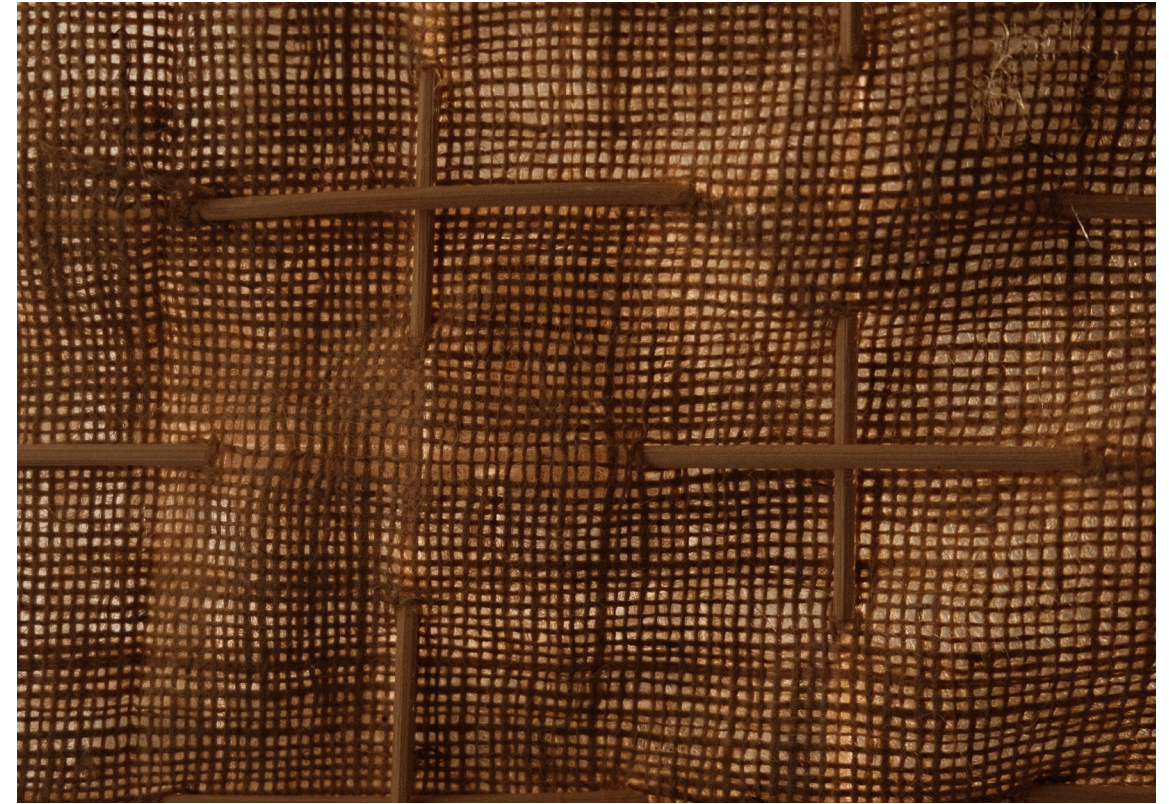
Image: A base mesh created by the multipipe followed by the unrolled surfaces that the geometry consists of. Finally an offset of the surfaces is created to allow the sewing together of the different surfaces





# JUTE & STITCHES

Now that a system is in place to create the different jute patterns needed to develop the composite material, some physical tests have to be done to determine which jute will be used. Two different types of jute sheets were tested. The first one being the heavy duty jute used for gardening and mostly known as potato bags while the other type was composed of thinner jute fibres. The heavy duty material had a rather open weave in comparison. Both were tested on their strength but it quickly became apparent that the strength of jute greatly surpasses the strength class used for this thesis. Since this is no longer a parameter for choosing between the two textiles the main factor will be how well sewing the different jute sheets works. The heavy duty jute sheets would unravel easily once cut while sewing them together would also easily unravel the sewn edges. These issues did not arise with the lighter but denser jute hence this textile was used for the composite material.



Top: Heavy duty jute  
with a more open weave  
Bottom: Thinner jute  
textile with a denser  
weave





The final step consisted of the sewing itself. First of all, a wire had to be chosen that would be used to sew the different jute pieces together. A jute wire was chosen since it is a strong organic material that is already used for sewing jute sheets in a variety of different fields. Three different sewing patterns were tested to find out which one would be best to use for its specific function here. The running stitch was the first one since this is a very efficient way to sew different sheets together. Next an overcast stitch was used and finally an overlock stitch was tested. All stitches had about the same strength meaning that speed and ease of sewing became the main factors to decide which would be used. In the end the overcast stitch was chosen since this stops the unravelling of the jute sheets and is comparable in speed to the running stitch. The overlock stitch took longer to do and also put extra tension on the jute which could be avoided by using the overcast stitch.

Top: Jute textile sewn using the running stitch  
Middle: jute textile sewn using the overcast stitch  
Bottom: Jute textile sewn using the overlock stitch





# M O D E L

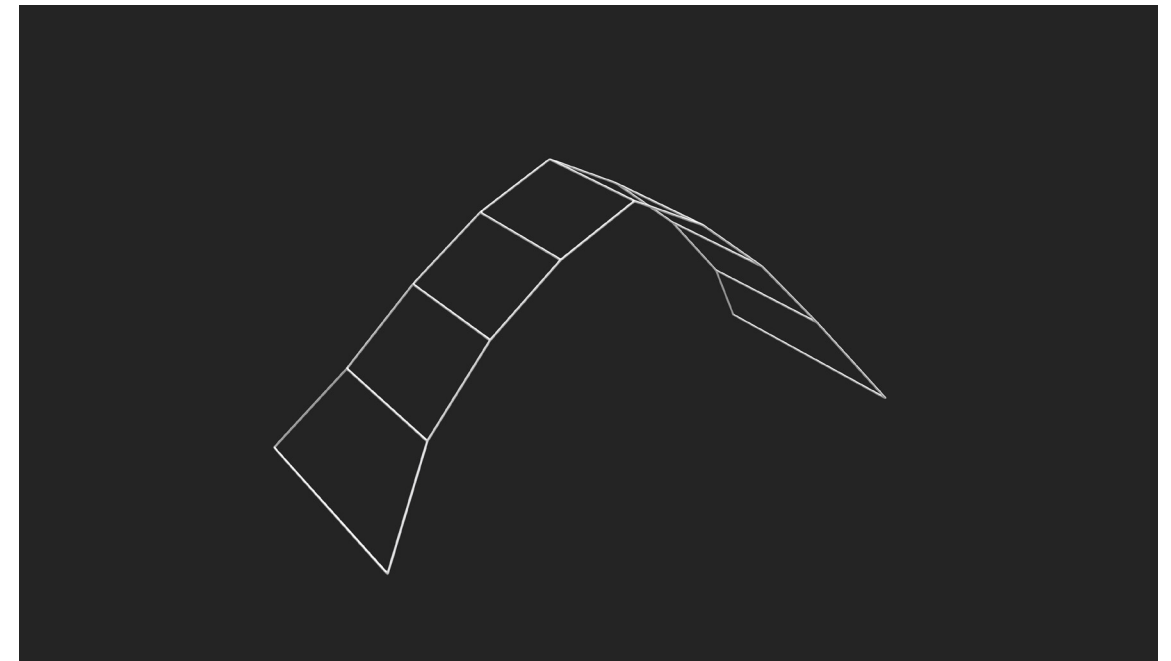
The final step of this thesis is the actual creation of a structure using the developed method. This structure is created as a full scale model to test the proposed design method. The chosen structure is an arch which is then divided into a set of knots that are all created separately. After finishing each knot the arch can be assembled and loaded.

# D I G I T A L C O U N T E R P A R T

Since all weaving will be done by hand a simple structure will be chosen. To have a proof of concept, a simple arch consisting of 14 knots will be produced. The arch will be divided into separate knots and these will all be created separately from one another. This arch with a width of 1,7 m and a height of 0,8 m will then be loaded to test the strength of the geometry as well as the composite. The modelling method is the one developed in the implementation of form-finding chapter on page 110.

This full scale model is meant to showcase the strength of the structure but also a first test to see if larger structures can be created in this way. If successful, this could be produced on a bigger scale creating an actual pavilion big enough to let people walk underneath the curved surface. By creating a one on one scale model a lot of practical knowledge is also gained about the feasibility and creation method of the mycelium while also finding more potential weaknesses and allowing for further optimisation.

Image: Digital shape of the arch



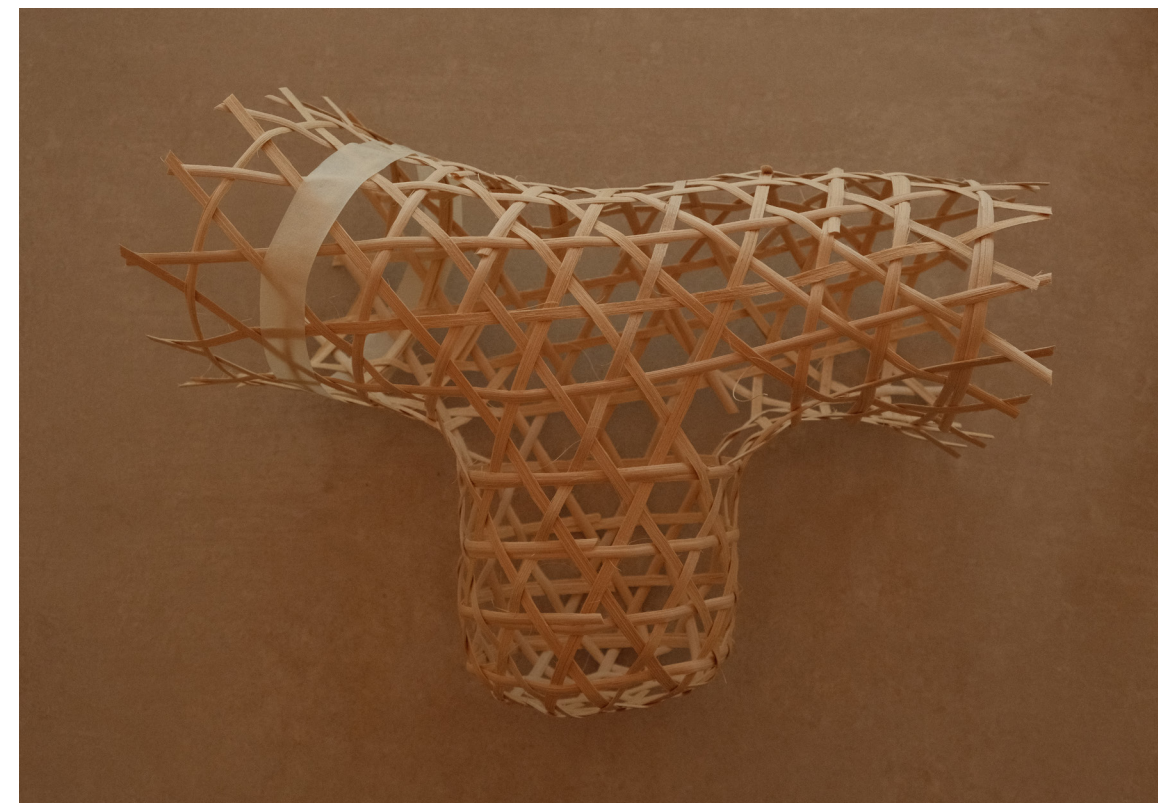
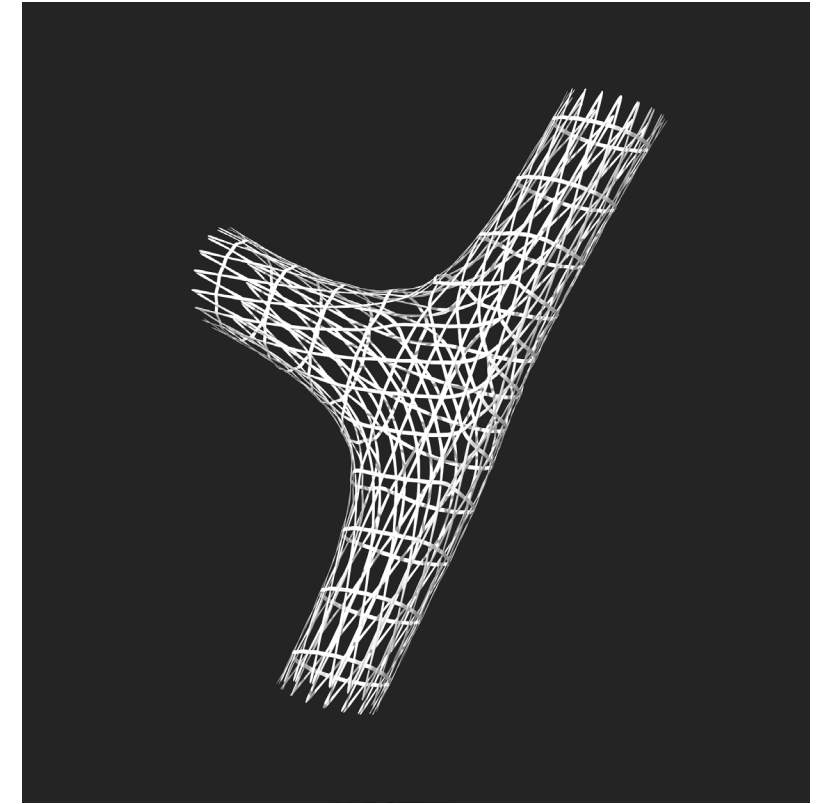


|   |   |   |   |   |
|---|---|---|---|---|
| K | N | O | T | S |
| O | U | T | E | R |
| W | E | A | V | E |

The first step was the weaving of the different knots. Each knot was first modelled through the Grasshopper file and then woven by hand out of rattan. The weaving pattern was generated by the earlier created weaving definition in Grasshopper. A general scheme was drawn up and all knots were labelled to make sure all pieces end up in their correct location for the final assembly. This is needed because each knot is unique and specifically designed to optimally link the rods together.

Upon creating these knots more insight was gained about the production method. An assumption was made that all three way joints would be constructed in a similar matter. Using the heptagons at the corners of the mesh faces as it was done with the previously woven three way joint. However, this is only true for a base mesh where the central box is instead an extruded triangle. Once a box is used two octagons need to be introduced at the mesh intersections. To keep the design method as similar as possible between the three- and four way knot this octagon method was kept with a box in the middle of the base mesh. This also allowed for more flexibility once the deformations of the base mesh became more complex to accommodate for sharper angles in some knots. Labelling the different knots and cross referencing them with a scheme of the final arch is also done to make sure the final assembly is done correctly.

Top: Woven pattern for a three-way knot made using grasshopper  
 Bottom: Real-life counterpart made using rattan weaving, the length of the sides has been shortened slightly in comparison to the 3D-model



# R O D S

## O U T E R

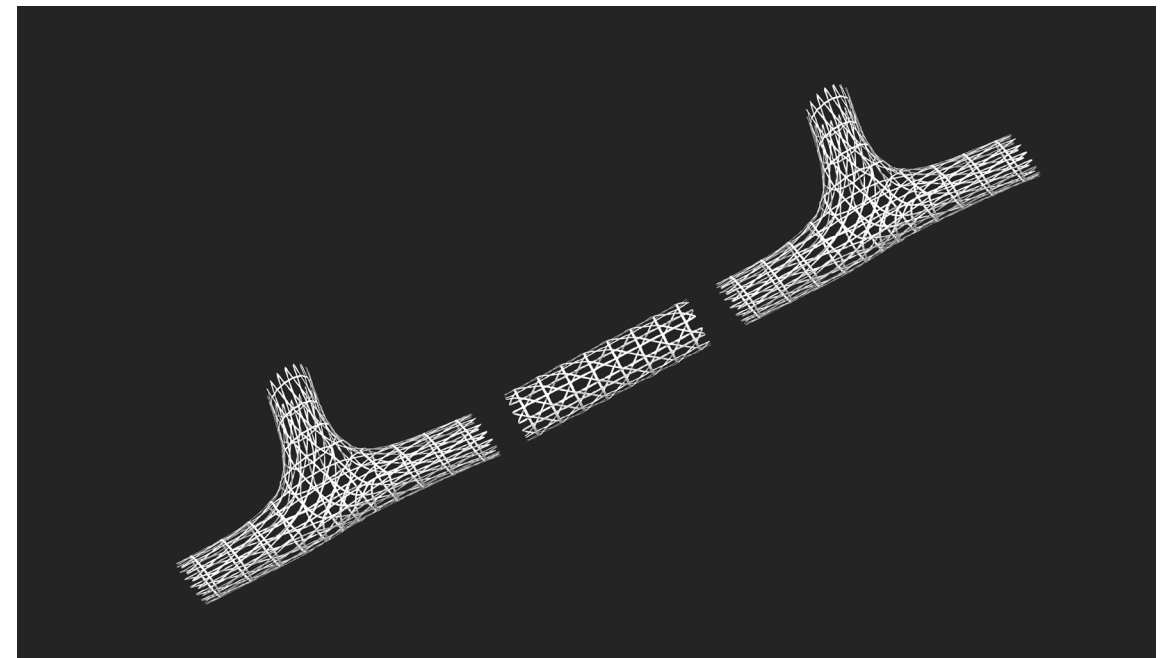
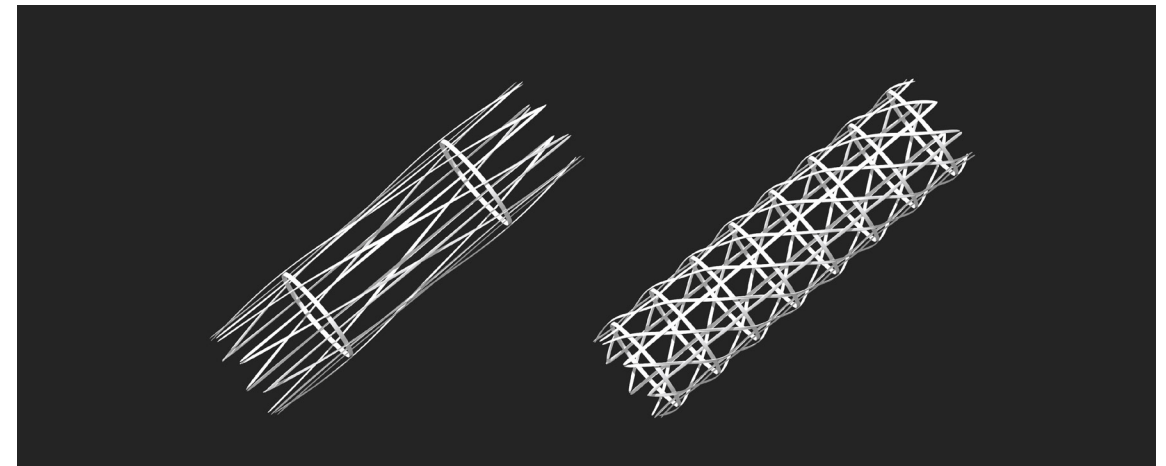
### W E A V E

For this particular case, the rods have limited lengths so the length was divided in two and achieved by lengthening the arms of the knots. This lowers the complexity of the test setup without influencing the structural working. Whether rods are needed or not is entirely dependent on the size of the oven and the personal preference of the designer. In some cases smaller pieces will be preferable making it necessary to divide the pieces. Since the rods of the arch have limited length this was not needed but for cases where it would be needed the work method is still explained.

After the knots have been created the rods can be woven. The knots have to be developed first since the knots extend along the structural line system modelled using Kangaroo. By subtracting the length of arm of the knot from the total length the desired length for the rod can be determined. This is not done in Rhino since the weave is not complex at all for a cylinder. The basket weaving technique that has been used before is applied here once again. If this needs to be done digitally however, the following method is used.

First a box of the correct length is created and the sides are subdivided into squares. If the base length is used instead of subdividing them into equal squares the Charles Loop method will always use the same amount of subdivisions regardless of the total length of the box. This means that the subdivision of a square box is used and then stretched until the desired length is achieved. This greatly distorts the weave up to a point that it becomes unstable once built and thus loses its structural function.

Top: comparison between a wrongly modelled and correctly modelled woven cylinder, the sides of the left cylinder were not subdivided into equal squares  
Bottom: mock up of how the different parts are oriented relative to each other





# KNOTS

To make sure the mycelium can properly dry out the knots are modelled as hollow knots. To create these openings, a woven cylinder is used. This makes sure that the cavity stays open during the filling and does not deform. These cavities will have the diameter of a rattan cylinder consisting of a single hexagon as its base plane. This way an inner cavity of five centimetres is created. If these are then slid into the inner jute shape the filling of the shapes with mycelium will be greatly simplified. These cylinders all have the same diameter with only a varying length making production very fast and simple. The length is measured based on the length of the inner cavity from each connection piece. The minimum diameter of these rattan cylinders is around four centimetres for the rattan used in this thesis. This is caused by the width of the rattan strands in combination with the weaving pattern.

Since this width is still too large for the structure modelled here a different approach is taken. Instead of using rattan as the inner cylinder wooden pegs are used with a diameter of two centimetres. These are removed after the filling of the knots to create the inner cavity.

Afterwards a jute cylinder is sewn out of a rectangular piece of jute fabric. This way the mycelium can be compacted against the inner woven cylinder or wooden peg. After removal of the peg the jute becomes part of the composite to keep the mycelium in place.

Top: Cylinder woven out of rattan used to fill the interior, the length can be decided based on the needed length  
Middle: Wooden pegs used for the inner cavity in this arch  
Bottom: The wooden pegs placed inside the jute cylinder

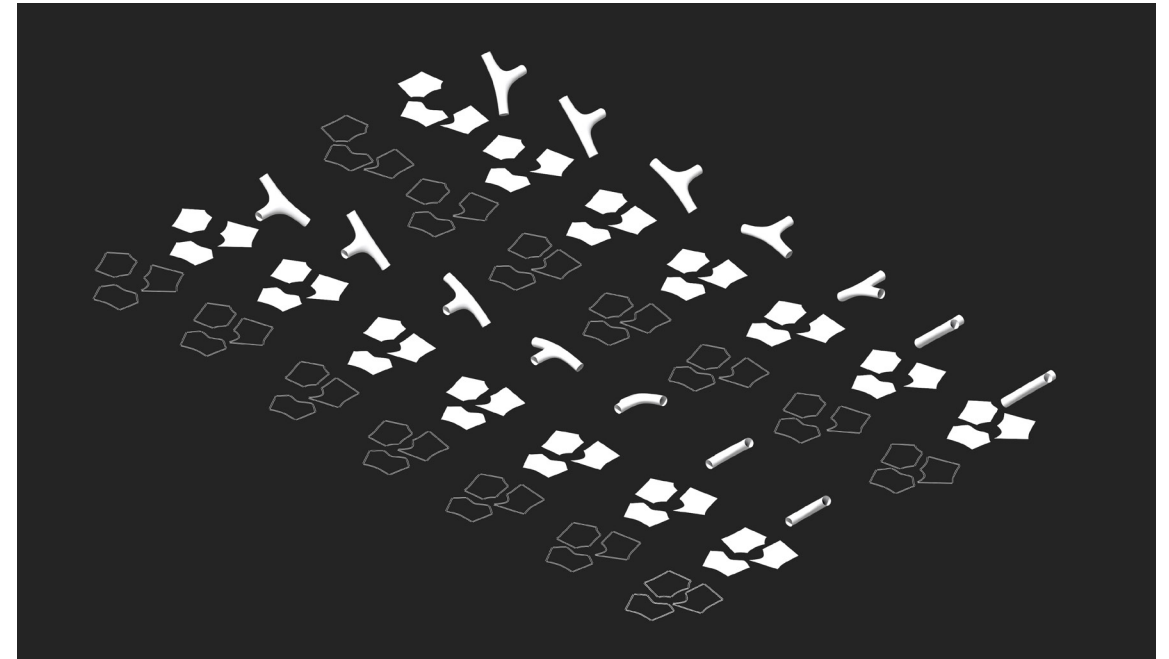


# J U T E S E W I N G

As already looked at during the development of a design method the jute shapes needed for each knot can be extracted and unrolled from the digital model and translated into real life patterns. This is done for each of the different knots. These are subdivided in 3 different surfaces that each have an offset to sew them together into a single shape. After printing out these templates they are traced onto jute sheets and cut out.

These shapes can now be fitted inside the rattan weaves of each knot. Before placing the jute inside the rattan, the jute shape should be turned inside out, making sure the seam is at the inside allowing the jute to be flush with the rattan. This will ensure a good connection during the growing process between all components. The same method is used for the inner jute shape since the knots and rods are hollow to allow proper drying out of the pieces. Here the seam should be at the inside so the shape is not turned inside out.

Image: All knots used for this arch with subdivision into jute templates including edges for sewing







Left: Cutting of the jute patterns, the template is printed and attached to the jute sheet. The template is then cut out of the jute textile

Top right: Jute pattern of a single cylinder that has been stitched

Bottom right: the fully cut out pattern with the template still attached







Left: The three different cylinders of a knot placed into position, all cylinders have already been sewn

Top right: Two cylinders are first placed together after which they are sewn together along the corresponding edge, the third piece is sewn on after

Bottom right: After all three cylinders are sewn together the entire shape is flipped inside out to make the stitches face inwards



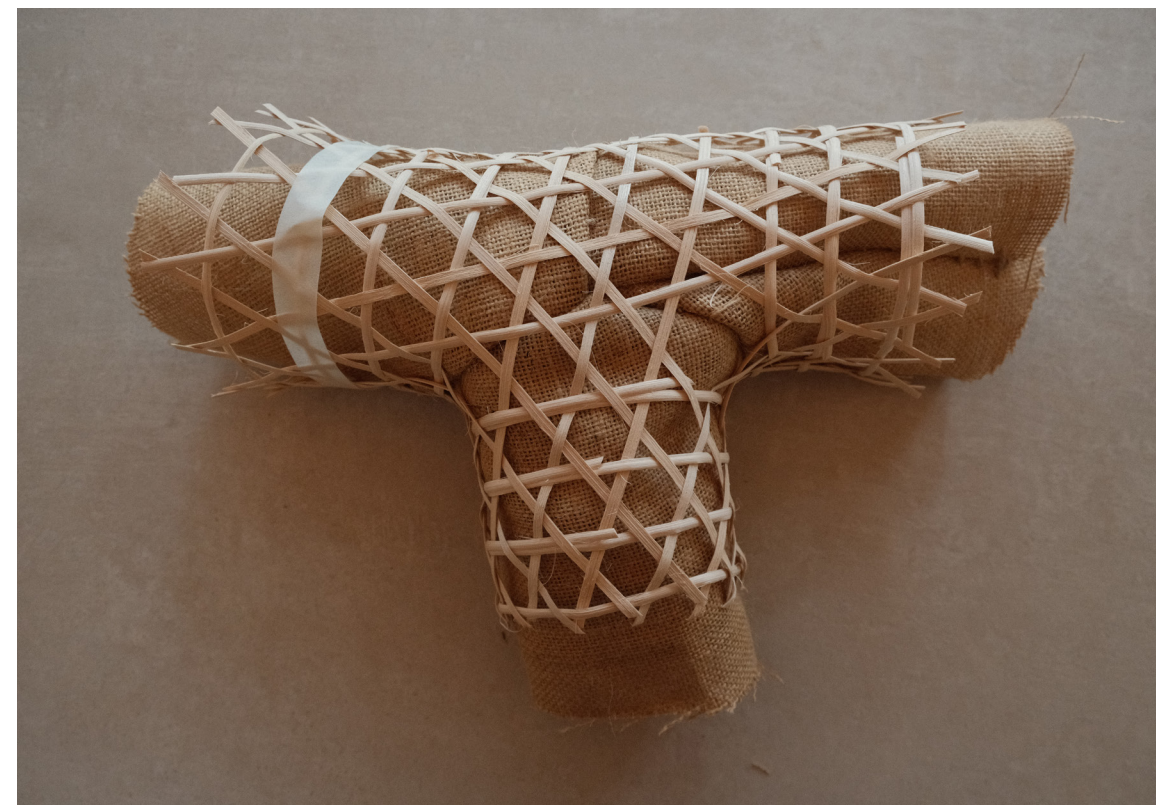
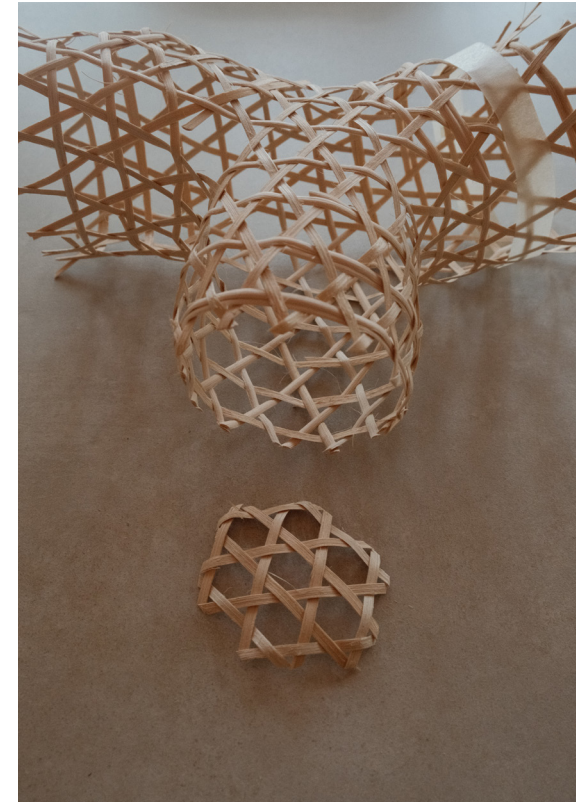


# K N O T S A S S E M B L Y

All different parts have now been created and they can come together in a final assembly. First of all, the bottom of the outer rattan shell is cut off. This makes it possible to fill the rattan shell with the jute shape. The outer skin has now been prepared. For the inner cavity the wooden pegs are placed inside the jute cylinders. These will be put into place during filling. The edges of the rattan shells were prone to unravelling during the placement of the jute, in order to avoid further unravelling during the filling stage the edges of the knots were taped. A label was also placed on the label to differentiate between the different knots.



Left: Woven rattan knot on top of the corresponding jute knot  
Top right: Cutting the bottom plate off the knot, this was needed to create the weaving but can now be removed for the filling  
Bottom right: jute knot placed inside the woven rattan knot, the knot is now prepared for filling





# K N O T S F I L L I N G

All parts are now prepared and the final knot can be created. The same method is used as in the first experiment when it comes to sterilisation of the work place and tools. The jute and rattan were not sterilised this time since the test cylinder were these parts were not sterilised yielded perfect results. By not sterilising these parts the mycelium can grow more easily making it worth the risk.

The filling itself was done by first filling the outer shell with a base amount of mycelium. Once enough mycelium was added the inner jute cylinders with the wooden pegs were pushed in and put into place. After this step mycelium was added and in regular intervals compacted to make sure the knots were fully filled. The jute edges were also over dimensioned to make the filling easier. Once the knot is fully filled the wooden peg is removed and the jute edges are cut to size. Finally these edges are covered using a thin film to ensure proper growing.



Top: Part of the extending jute that has been cut to make filling easier

Bottom: Placing of the wooden peg with jute cylinder, the mycelium can now be further compacted







Left: Fully filled knot  
with jute cut to size and  
removed wooden peg  
Right: fully filled knot  
with addition of plastic  
film at the edges to  
ensure proper growth





# G R O W I N G

Now that all knots have been filled they need time to properly grow. All parts are once again placed in a warm environment with a high relative humidity just like in the first test. The main difference with the first test is the duration of the growing stage. The recommended duration of ten days growing with an extra two days of growing outside of the molds seemed to long. The proof of concept test piece of the first test had grown too much in comparison to the other test pieces. Since all pieces follow this structural approach the growing stage was reduced. This time a growing stage of nine days without the extra two das was used. This duration was chosen by monitoring the growth process each day. On day nine fruiting bodies started to form which means the mycelium has fully matured.

Top: Finished pieces under thin plastic film to grow the mycelium, a temperature of 22 degrees is kept with a high relative humidity  
Bottom: Growth process of the mycelium after two days of growing







Left: Fruiting body that is starting to develop after nine days of growing  
Top right: Side view of a knot after removing the plastic film  
Bottom right: bottom side of the knot, the pressure created by the weight caused the surface to have a different finish





# B A K I N G

To stop the growing phase the mycelium has to be baked. In the first experiment the baking duration was four hours and at a temperature of 90°C with a relative humidity of 10%. Because of the larger size of the test pieces the duration was increased to five hours. The knots were also flipped every hour to make sure each side dries out evenly. This was done because in the last experiment the bottom side of certain test pieces had a higher moisture content than the top side.

Top right: Baking of mycelium pieces, the knots have been flipped after two hours of baking  
Bottom: Baking of the different knots, here the pieces have just been placed in the oven and are still wet

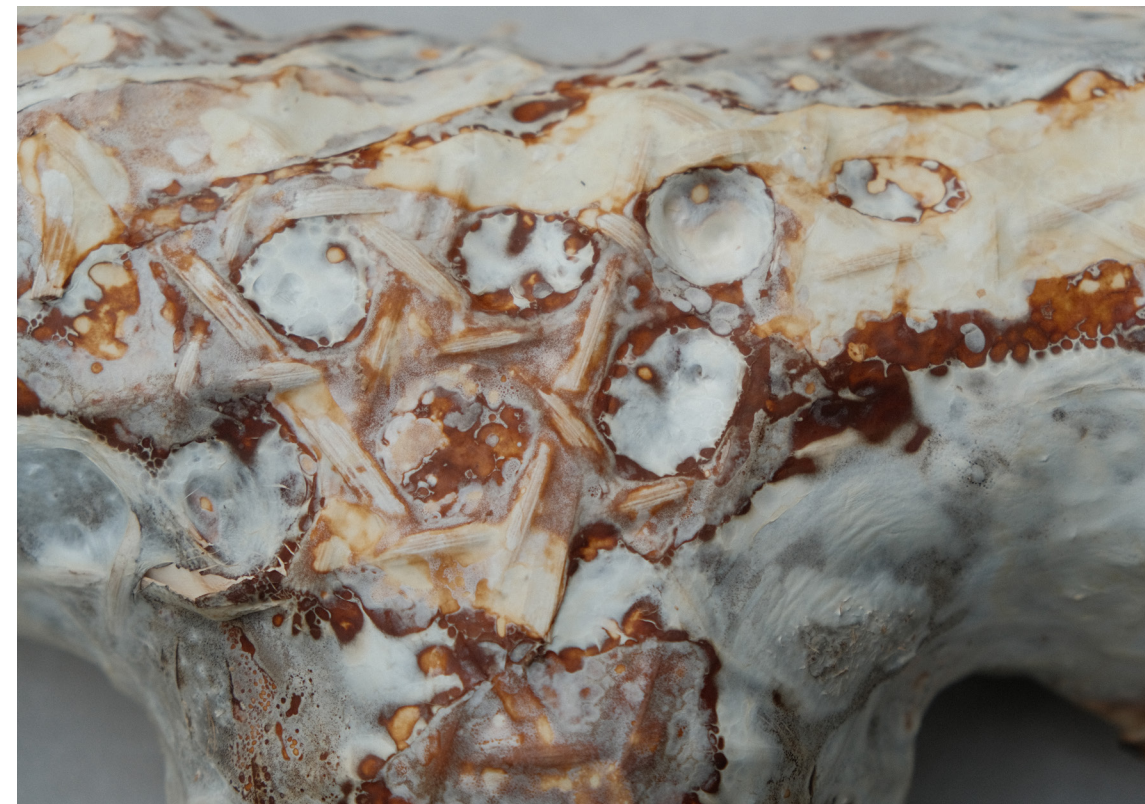




# K N O T S F I N I S H E D

By baking, the growth process of the mycelium has been fully halted. Some close up images are added of the different knots to showcase the different finishings.

The side on which the mycelium was growing is very noticable. The surface is flatter and the mycelium has permeated less deep through the jute. This is because of the weight of the mycelium pushing the knot against the mdf plate during the growing phase.



Images: A variety of different knots which each have a unique pattern, the mycelium has fully overgrown the jute and rattan creating these complex patterns. The next page has more pictures of different knots









# A R C H A S S E M B L Y

The actual assembly of the arch is based around running ratchet straps through the cavities of the knots in the direction of the arch. By tightening these straps the knots will get pulled against each other while making sure all knots are in compression against each other. Using ratchet straps also makes sure all forces are applied to the mycelium since the arch is modelled fully in compression and the cables can only absorb tension. To assemble the different knots into the final arch a base plate has to be prepared. Four holes are made in the base plate at the supports of the arch. This makes sure the horizontal component of the forces can be absorbed. Now each knot can be slid over the ratchet straps. To connect the knots facing each other a small wooden peg is used and a rope pressures the knots against each other. The wooden peg was kept short to make sure the effect of this peg on the strength of the arch is minimal. After all knots are placed in their correct position tension can be applied to the ratchet straps to get the arch in its correct position.

Top: Creation of the holes through the base plate. A drill and chisel were used to create these holes  
Bottom: The ratchet straps are fitted through the holes







Top left: The ratchet cable is pulled through the hollow knot using a thinner rope that has been passed through the knot using a steel wire

Bottom left: The wooden peg that is used to connect facing knots next to the knots

Top right: After installing the wooden peg a rope is tied around the knots to pressure the knots against each other

Bottom right: The knots are shoved onto the ratchet straps one by one  
Next page left: All knots are placed in position

Next page right: The ratchet cables are tightened causing the arch to take its final form  
Page 186: the arch in its final shape













# I N S I G H T S

After finalising the arch, a few notes can be added about the structure. The first point being the connection between the different knots. The initial assumption was that the edges of the test pieces would consist of a thick layer of pure mycelium. This happened in the first test and this pure mycelium has a rubber like texture. The idea was that the tension on the ratchet cables would apply enough pressure to deform these rubber like ends to a perfect fit. However, the mycelium itself was way stronger than anticipated and this was not as effective as initially assumed. At two points this method did not work because the difference between the knots was too great. The other connections were more aligned with each other making this method work perfectly. Because of these two weak points the arch ended up collapsing after about half an hour. The knots themselves however would not bend in the slightest, these were very solid and would not bend in the slightest during any point of the assembly. The conclusion can be made that the system works but a different technique has to be applied to the connections between the knots. If the edges of each knot can be kept straight and a type of wedge is placed in between the two pieces to accommodate the curvature this would pose no problem.

Image: the collapse of the arch caused by two points acting as hinges, these points were not fully grown into the correct form and could not handle the final load







Top left: Example of a knot that is not correctly grown, leaving too much space between the two knots and creating a hinge in the arch

Bottom left: Example of a correctly grown knot, the edges of both knots fit perfectly creating a strong connection

Top right: Inside view of a knot acting as a hinge

Bottom right: Mock up of a wedge in between two straight knots





## S E C O N D A R C H

Since most pieces of the arch were properly connected to one another the idea came to mind to just remove the pieces that caused the collapse and instead use the working pieces to create a smaller arch. This smaller arch would not have a fully correct form since the pieces were optimised for a different arch but it can still be used to create a stable arch for the sake of having a working final product. The hatchet cables were used once again but the tightening was executed differently. Once the cables were under pressure a wooden plate was used to push the arch into its shape. This proved to be a simpler method. Once the arch was in its correct shape the wooden plate was kept in place using clamps. This second arch kept its shape but no additional weight could be added. The fact that the knots were shaped for a different arch made the overall shape of the second arch not properly redirect the forces applied to the arch. Supporting its own weight proved to be no problem though.

Image: Tightening of the straps by pushing the wooden plate along the straps







Left: The second arch, made from five correctly grown pieces of the initial arch  
 Top right: Inside view of the top of the arch, all connections fit perfectly  
 Bottom right: Small deformation of the arch due to the shape of the knots, the knots were modelled for a different arch causing this deformation  
 Next page: Detail of a knot





# CONCLUSION

The main focus of this thesis was the creation of a fully renewable and biodegradable composite that was optimised for parametric design and freeform surfaces by using computer aided design. This was achieved by creating a composite using mycelium, jute and rattan weaving. A freeform surface was developed based on catenary principles to optimise the structure for the composite. This structural model can also incorporate loads added to the nodes of the structure, making stackable designs and load bearing structures possible to model.

The way this was done was by first studying and experimenting with the different materials. References were found and research papers were looked at after which physical tests were executed. After testing these materials by themselves a first test was set up to determine which combination would work best for the composite. By doing this a lot of insight was gained on how the different materials interact with each other as well as the production process of mycelium.

After gathering enough knowledge and doing physical tests the step could be made towards developing a Grasshopper definition capable of creating the weaving patterns, creating the templates for the jute as well as the structural model. These were developed simultaneously, allowing each

different part to influence the other definitions at an early stage, making sure problems in compatibility were noticed early on.

After developing the different Grasshopper definitions a scale model of a 1:1 scale was made. This served to test the feasibility of the design as well as the strength of the composite. While the thesis already explores a lot of different aspects of creating a composite that can be applied to any freeform surface, further development is still possible. This thesis is by no means a finished product. Further optimisation of the Grasshopper file is still possible. The knots have to be selected by hand to extract the weaving pattern as well as the jute template. The different knots could be woven one by one automatically and placed in a grid.

Further optimisation of the weaving production is also possible. For now all weaving is done by hand, one knot approximately takes one and a half hours up to three hours based on experience. This could also be further optimised by using robotics to speed up this process. Since the weaving by hand is already fully based on a three dimensional model the step towards automated weaving using robotics could be made without changing much about the current Grasshopper definitions. The idea

to try this for the thesis was shortly touched upon but the understanding needed to properly program a robotic production of the weaving patterns was simply too time consuming to include in this thesis. Finally, the connection between the different knots of the design have to be further researched. A different type of connection has to be made or a connector piece has to be thought of. This could be a type of simple wooden wedge or spacer but could also be incorporated into the composite to make it grow correctly.

The research that was conducted shows the advantages of combining simple biobased materials and advanced techniques to create complex geometries based on parametric modelling and form finding. It also highlights the further research that is needed on this topic to make it possible to truly apply this method to the construction of larger scale structures. Hopefully this thesis can serve as a base for further development of this type of symbiosis between nature and CAD/CAM software.



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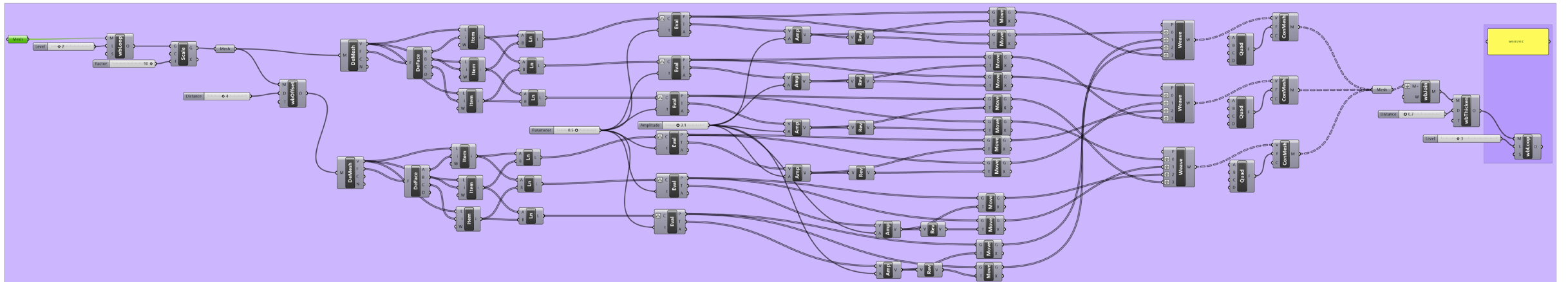
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## G R A S S H O P P E R D E F I N I T I O N S

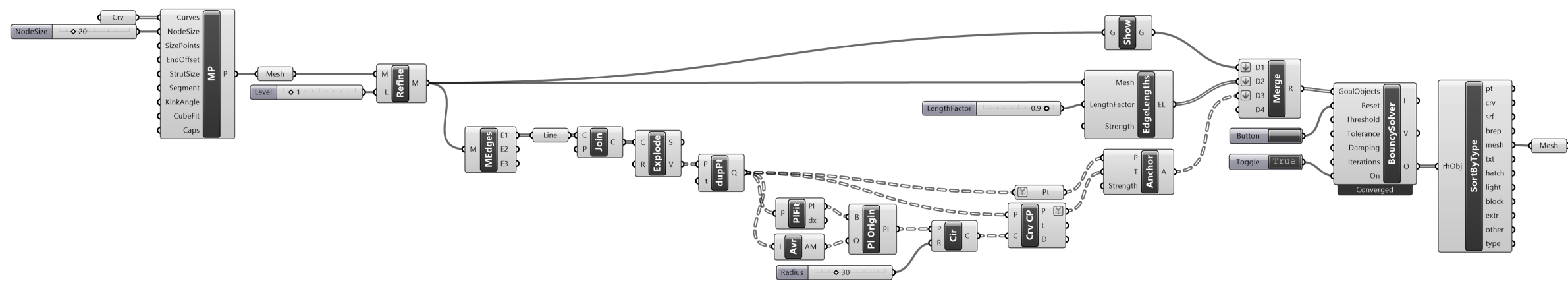
Finally all Grasshopper definitions are added as a final part of the annex. All definitions are split into their respective parts to increase the readability of the definitions.

## Weaving





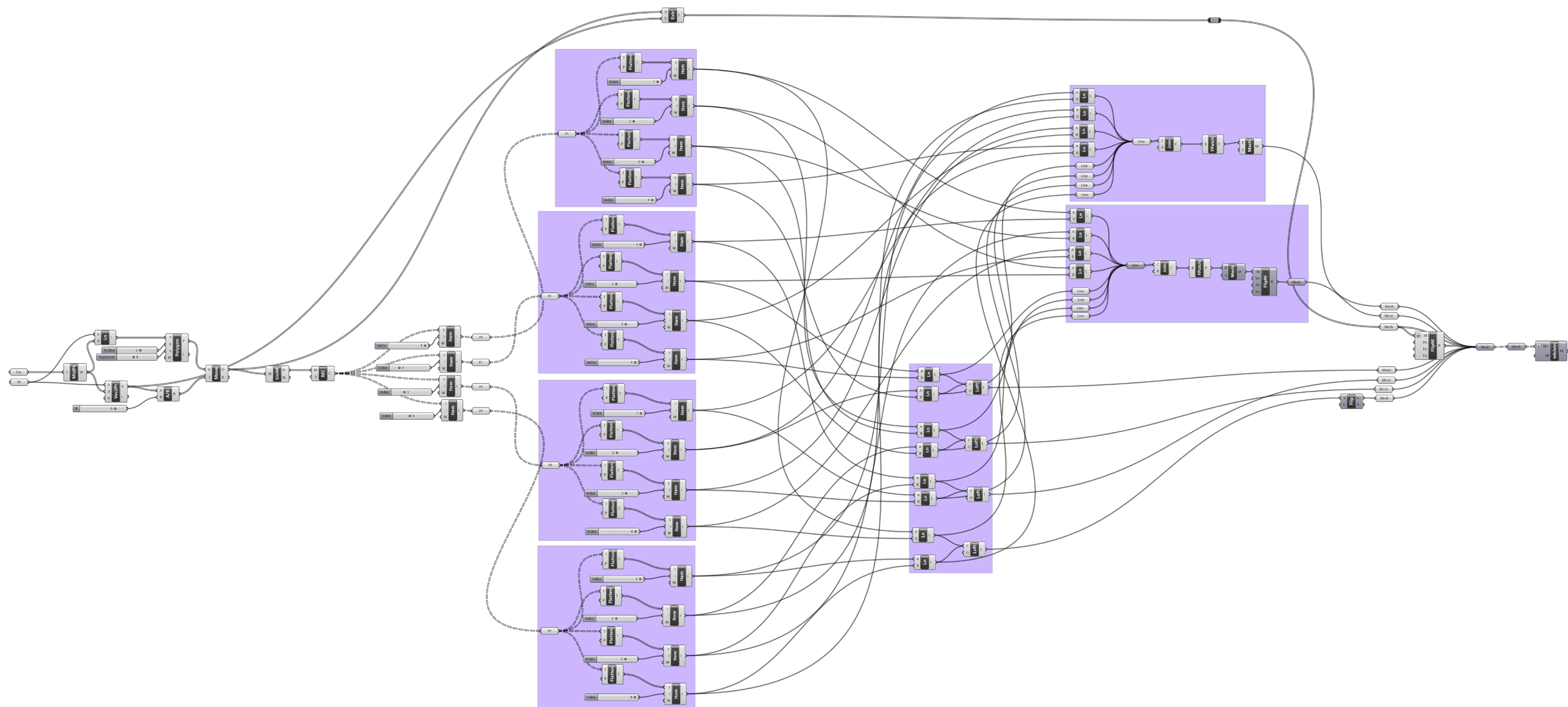
Mesh relaxation



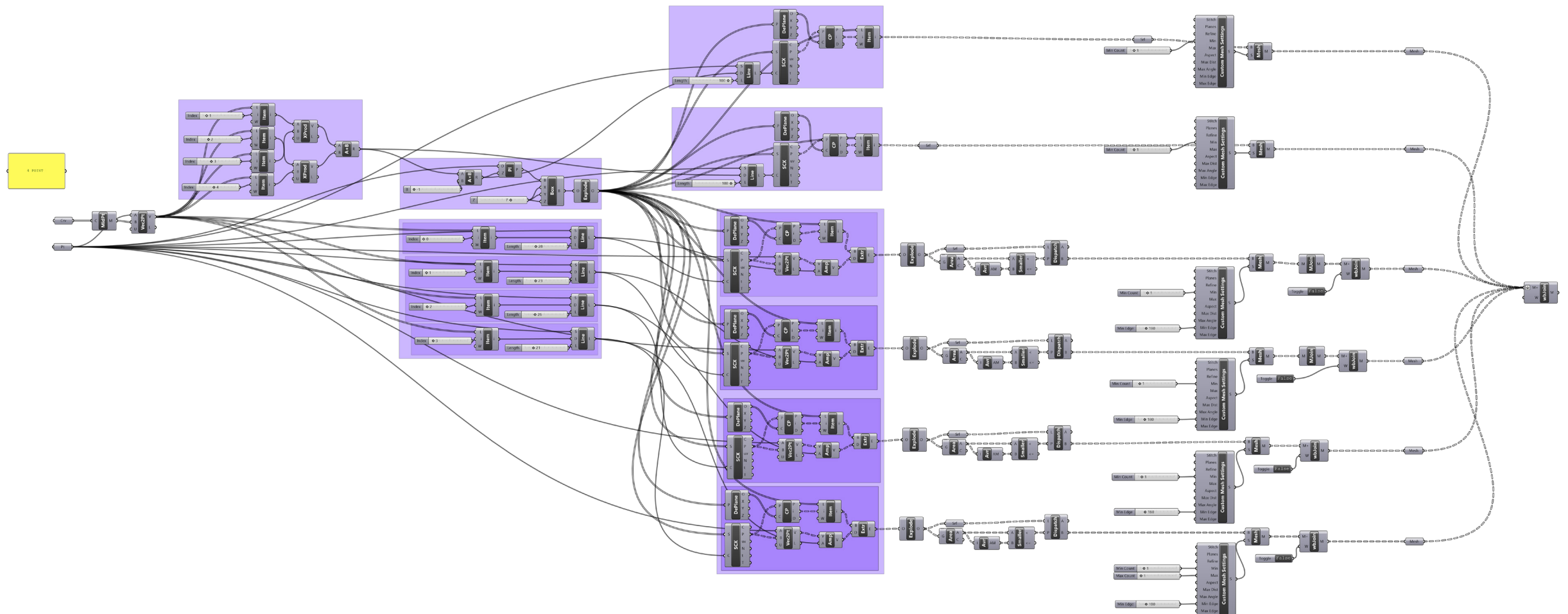




Problem solving first attempt

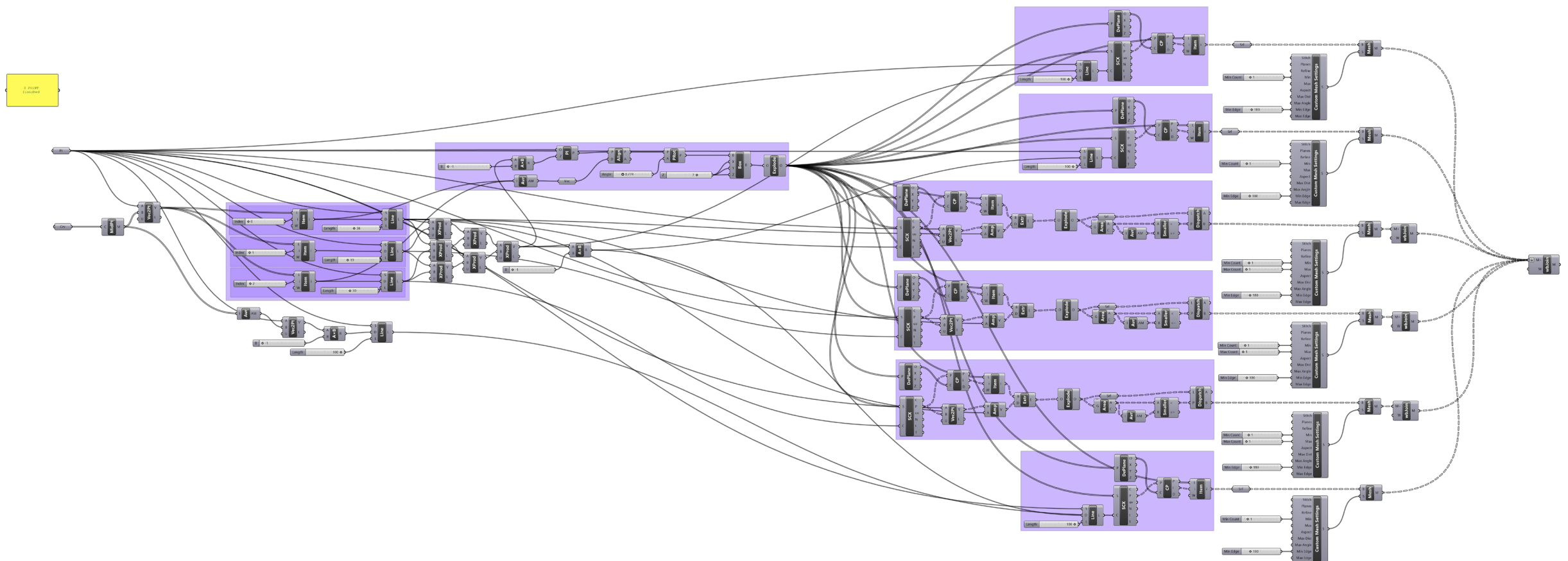


### Problem solving second attempt





## Three-way knots



# Digital patterns

