INHERENT FORM

PARJAREE MANUCH

Architectural Experimentation
MATTER & MEDIA

Examiner/Supervisor
JONAS LUNDBERG

Chalmers School of Architecture
Department of Architecture and Civil Engineering

Master's Thesis
Spring 2024

CHALMERS
UNIVERSITY OF TECHNOLOGY

INHERENT FORM

PARJAREE MANUCH

Examiner/Supervisor:
JONAS LUNDBERG

Architectural Experimentation
MATTER & MEDIA

Master's Thesis Spring 2024

Master's program in Architecture and Urban Design
Chalmers School of Architecture
Department of Architecture and Civil Engineering

Fig. 1. *Inherent Form*. Structure Prototype.

ABSTRACT

Rather than viewing digital tools as incongruous with craftsmanship, 'Inherent Form' suggests that they reinforce certain principles characteristic of craftsmanship that help elevate fabrication with benefits for architecture.

The thesis aims to reveal the potential of architecture shaped by the interplay between natural materials, craftsmanship, and the capabilities of digital tools. It explores the design of medium span structures entirely composed of non-standard timber components derived from the inherent forms of local wood and demonstrates the potential of a raw timber structure for an architectural application for public use.

The development of 'Inherent Form' involves a combination of design-driven research and material experiments. The thesis methodology offers a holistic approach to the design and construction process, rooted in material exploration, data acquisition, and structural solutions. It focuses on hands-on making as a means to explore and develop ideas, encompassing three key stages: Prototype, Timber Detail Design, and Architectural Application. These stages overlap during the development of the thesis, formalizing knowledge of design tools and techniques. *Prototype* involves utilizing digital tools for structure design, as well as point-cloud processing and photogrammetry to compile data from physical raw wood. *Timber Detail Design* is the process of crafting wood joinery for irregular tree bits, serving as a pathway to deeply understand and appreciate the material qualities of raw wood in structural way. *Architectural Application* presents a raw timber structure for a greenhouse situated within the Gothenburg Botanical Garden.

The thesis makes a contribution to the field of sustainable architecture by demonstrating an alternative to conventional timber construction that relies on the use of standardized materials produced through an industrialized process. Using non-standard found material to create architecture provides complexity and constraint to the design and fabrication process, but at the same time, it enables more sustainable material practices. By incorporating raw wood components into design, it is possible to not only diversify the design and construction methods according to locality but also create a new form of architectural expression.

Keywords: Tree; Raw timber; Wood connection; Natural material

INTRODUCTION

PURPOSE

‘Inherent Form’ refers to the external geometric form of trees. The thesis endeavors to propose a method rooted in natural material exploration for approaching the design and fabrication processes. It aims to explore building systems for a medium span structure, utilizing non-standard timber components derived from the natural forms of local wood. The development of ‘Inherent Form’ involves a combination of design-driven research and material experiments. The thesis’ main emphasis is on exploring the application of digital workflows combined with non-digital fabrication processes to materialize architecture, showcasing the potential of a blend of natural materials, traditional craftsmanship, and new technology in shaping sustainable architectural design.

METHOD

The thesis methodology focuses on hands-on making as a means to explore and develop ideas, encompassing three key stages: Prototype, Timber Detail Design, and Architectural Application. These stages overlap in the development of the thesis, formalizing knowledge of design tools and techniques. The purpose of these three stages is not to depict the process in a direct chronological order, as the developments occurred simultaneously.

Prototype involves using digital tools for structure design and also the use of point-cloud processing and photogrammetry to compile data from collected physical raw wood. Throughout the stage, a series of four prototypes were developed, each varying in complexity from simple to intricate designs.

Timber Detail Design is the process of crafting wood connections for irregular tree bits, serving as a pathway to deeply understand and appreciate the material qualities of raw wood. The study of collected physical raw timber pieces was integral to the investigation of wood-to-wood connections, aimed at learning joinery techniques.

Architectural Application demonstrates the potential of raw wood as a durable and functional material for architecture. The design proposal centers on a raw timber greenhouse structure within the Gothenburg Botanical Garden.

THESIS QUESTIONS

“How can digital design and fabrication tools be used to develop structures from non-standard raw wood components?”

“What advantages do raw wood components offer in designing structures?”

“How can raw wood be leveraged through innovative architectural design and construction methods to promote sustainability?”

Fig. 2. Collected raw wood, which could be divided into 4 types by topological differences in shape: bifurcated, curved, straight, and bent (crooked).

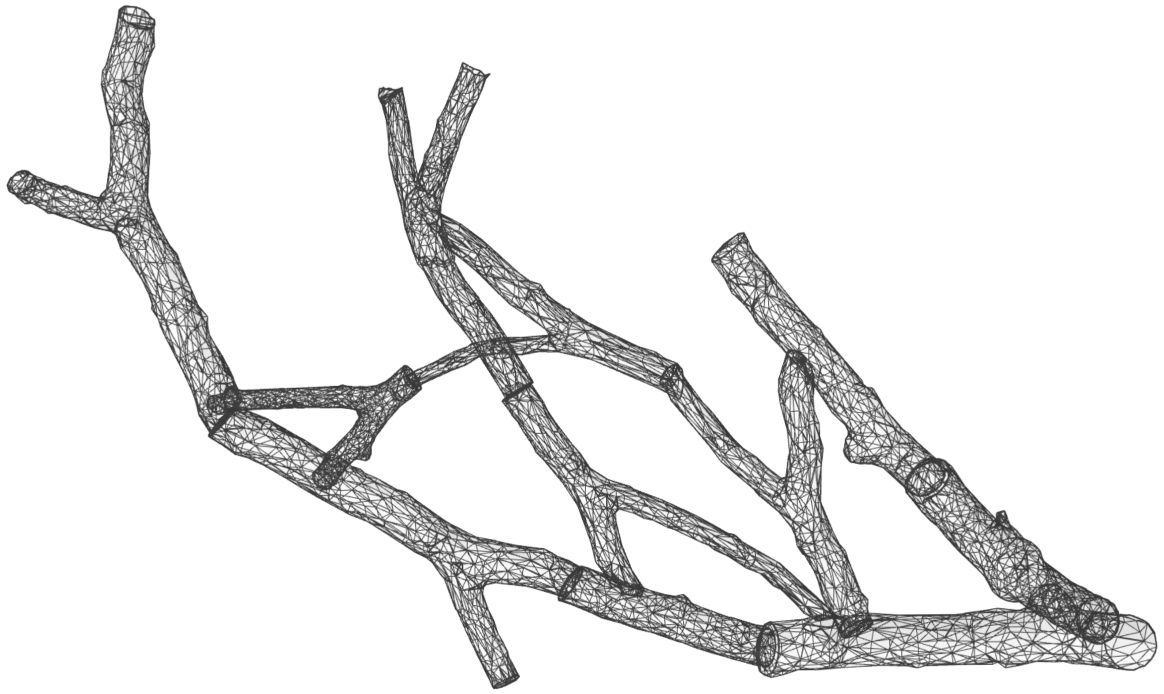

Fig. 3. Prototype 4. Structural members.

BACKGROUND

Wood has stood as a fundamental construction material, valued for its versatility and strength throughout history. In ancient times, when human energy was the primary shaping force, builders devised intricate jointing systems that skillfully utilized the inherent diversity of wood. However, the industrial age brought about a transformation in the production of building materials. With the development of machinery, industrialization allowed for the application of increased physical energy to shape building materials. Variation, once valued, became an obstacle to overcome, with machinery enabling repetition and standardization over customization [8].

A reliance on standardized building components or blocks of material persists in many contemporary timber construction projects. The current industry tries to reduce irregularly grown wood into standardized straight timber. During such processes, internal fibres of the wood are repeatedly cut, which leads to the sacrifice of structural strength [1; 3]. Currently, only around 35% of harvested timber is used in construction worldwide [7], when considering only straight tree trunks. Small-radii, curved, or forked wood is discarded. A significant percentage of premium wood is still thrown away as pulp or firewood, despite the timber industry's use of extremely advanced geometrical analysis technology to minimize waste.

Architects became aware that high performance comes from the ability to adapt to local conditions [6]. Research on raw wood for architectural applications has been a well-studied field in the last decade. The research seeks to provide alternative approaches to the use of raw wood in construction. Digital design and fabrication tools offer architects and designers unprecedented capabilities for developing structures from non-standard raw wood components. Another way to use computation in rationalizing design is to incorporate non-uniform natural materials into the design. Several technologies, such as laser scanning and increased computation power, have developed sufficiently to allow this to be feasible [9].

Using non-standard timber components to create architecture provides complexity and constraint to the design and fabrication process, but at the same time, it enables more sustainable material practices. The complexity, irregularity and coincidence can be coped with by employing digital tools for means of control and a flexible design methodology. This challenge is understood as an advantage and potential for experimentation and novelty [4]. There are a variety of projects that focus on new adaptable design-to-fabrication workflows, which demonstrate that there are possibilities for making better use of the capacities found in natural wood by employing technologies to gain control over complexity. The processes include creating a digital material inventory, finding the best match between the initial design and the material inventory, creating a balance in structural performance, generating machine code for fabrication, and assembling the required raw wood elements to build the structure.

Some architectural research institutes, such as the Architectural Association postgraduate program Design + Make, Cornell Robotic Construction Lab, and Taubman College of Architecture and Urban Planning, have investigated different prospects of wood natural forms as structural elements. They integrate emerging tools, such as 3D scanning, generative modeling, and robotic fabrication, enabling feedback between the designer and the material properties of raw timber.

Through the rethinking of architectural design methods for using non-standard materials, the thesis tries to identify approaches that can contribute to the reduction of waste production in the current industry. The process, at the same time, discovers the unique architectural expression and aesthetic and structural qualities of this natural material. With this investigative approach, material capacities and fabrication methods are explored towards new workflows and architectural applications, where material, craftsmanship, digital tools, and design are closely interlinked.

Fig. 4. *Limb*. Diagramming CNC-milling potential on historical prints.

STRUCTURAL DESIGN METHODS USING RAW TIMBER

Applications of raw wood can be classified into three main types based on their topology. First, straight wood is utilized in forms such as slabs, frames, trusses, grid-shells, and nexorades. Second, bifurcated wood, which includes tree forks, necessitates new digital surveying, design, fabrication tools, and reinterpretation of traditional carpentry methods. The grain direction and natural form of forked branches in wood can be used to create innovative timber structures by serving as optimized structural nodes. Third, crooked curved wood is employed in experiments aiming to fit curved beams to larger surfaces, used in grid-shell systems.

There are at least a dozen recent examples of research in the field of raw wood [5]. One of the first prominent examples of truss structures was built in Hooke Park, UK.

Other examples investigate wood joinery and assemblies of tree forks, branches, or just the crotch part, as well as reciprocal linkage of sawn timber and round logs. The research projects that follow make use of crooked trees and tree bifurcations to harness the strength of raw timber's continuous grain that is optimally aligned to transmit force.

Tree forks are inherent structural connections in trees that function as cantilevers, allowing for effective force transfer due to their internal fiber structure. While a tree fork has a structural advantage over beams connected with external fasteners, it imposes a structural topology limited by an angle between two branches. Consequently, tree forks' applications have a specific structural and architectural vocabulary based on the available stock of tree crotches [11].

Fig. 5. *The Tree Fork Truss.*

The tree fork truss, designed by the AA, London's Design & Make program, exemplifies contemporary tree fork utilization. The design approach incorporates four core strategies: a precise referencing system for consistent component placement, photographic and photogrammetry techniques for creating a database of tree geometries, evolutionary optimization for component placement, and automated tool-path generation for connection fabrication.

This innovative process minimally alters the natural tree form, focusing fabrication at the connection nodes, ensuring dimensional precision and structural integrity while embracing the inherent uniqueness of each tree component. The design method of Tree Fork Truss is demonstrated by fitting the inherent forms within a system which has been designed with them in mind - developing a set of variable control modeling tools which would allow the rationalization of complex forms into a rather simple geometric organization [8].

Photogrammetry was used to 3D scan 25 forks from the forest on campus based on the structure's parameters. Together with Design & Make students and engineers, a Rhino/Grasshopper organization script generated a final fork component arrangement. This digital model was then translated into fabrication information with which the 6-axis robotic arm transformed each fork into a finished component. These huge components were pre-assembled in the workshop using a precision assembly jig before being moved to site for final installation.

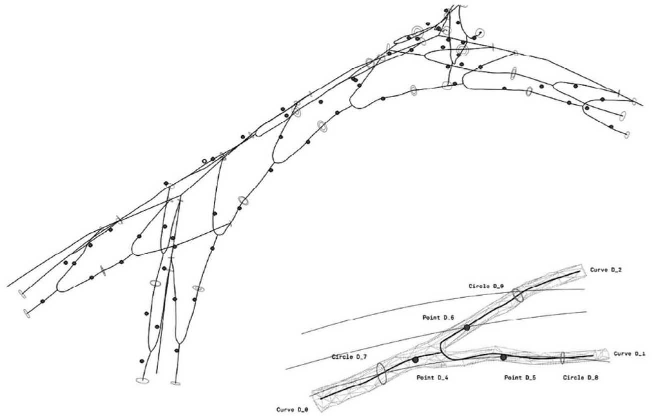

Fig. 6. *The Tree Fork Truss.* Final truss geometry exported from organization script.

Fig. 7. *The Tree Fork Truss.*

Fig. 8. *Limb*. Full-scale installation of one leg of a three-legged reticulated shell structure.

The LIMB project was realized to explore the potential use of natural tree bifurcations as a new joinery method in a heavy timber construction. The placement of forks was based on the angular dimensions and dynamic inventory-constrained form-finding. The process selects the available crotch geometries intothe design geometry through optimization to minimize the geometric discrepancies of the intended design [11].

Design explorations of tree forks can be seen in cellular formations [Fig. 9 & 10]. Another approach to studying tree bifurcations is with regard to structures derived from a tetrahedral-based recursive aggregation algorithm and the performative potential of a particular set of unique elements and the relative emergent formations, rather than relying on a predetermined design for which elements have to be manipulated.

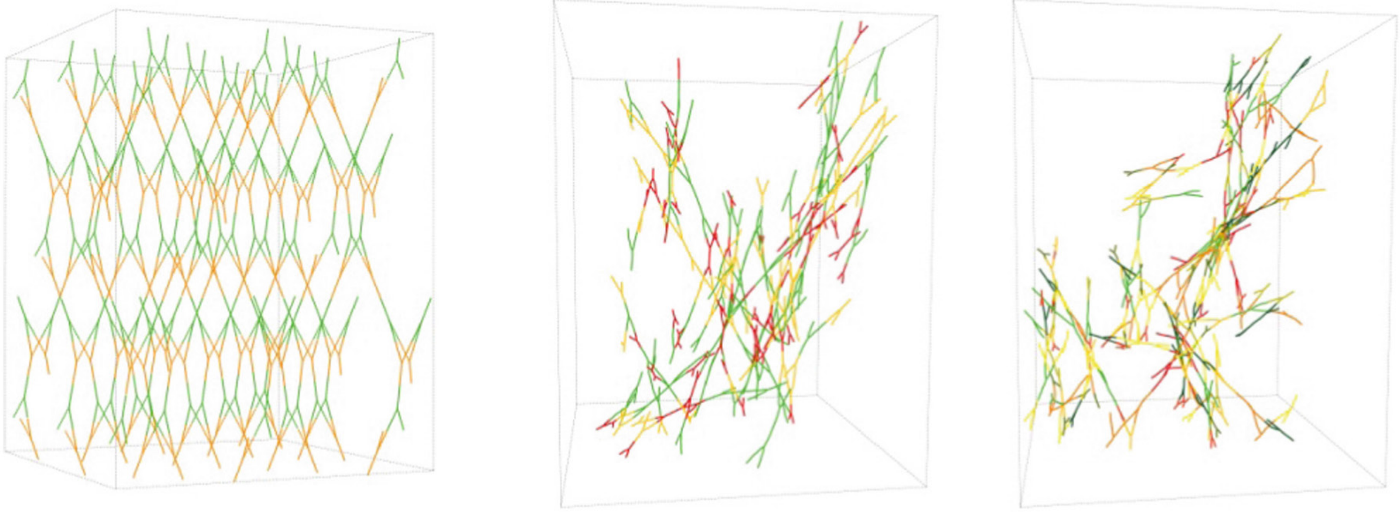

Fig. 9. Wasp aggregations of tree forks with same count of elements but varying number of proto-parts.

With the aim of creating unique, non-standard spatial structures at an architectural scale, the proposed workflow assumes a collection of physical branch parts and their distinct properties as the starting point and design driver. The branching parts are joined by following the direction of the wood grain. This is done to activate the structural potential that is built into the material logic of bifurcating strands of fibers. The design and manufacturing process involves several key steps. First, digitization of branches using 3D scanning and automated feature extraction. Next, categorization clusters scan geometries and generate "proto-parts" in the form of averages. Discrete element aggregation then creates design structures by recursively aggregating proto-branches. Population replaces "proto-branches" with real branch geometries based on design and performance parameters, such as length and cross-section. Relaxation compensates for gaps using force-based relaxation of the model. Finally, detailing for fabrication involves placing original meshes and post-processing for fabrication.

Experiments with crooked wood often aim at a curved beam fitting to a larger curve or surface. Log knot [Fig. 11] is a robotically fabricated architectural installation that creates variable compound timber curvature utilizing both regular and irregular roundwood geometries [12]. The project also provides minimal-formwork assembly, bending, and moment force optimization of bespoke mortise and tenon joints. The project builds an infinite loop of roundwood that curves three-dimensionally using figure-8 knot logic.

The new digital design and fabrication tools help develop design methods with irregular elements, whereas industrial applications only focus on the use of straight timber sections. These projects manifest the idea of exploring timber of minimal value with a particular architectural language coming from the appearance of elements. The overall workflow needed to be developed for the tree forks, such as scanning and robotic cuttings, demonstrates the diverse use of non-standard materials (not necessary timber) that do not need to be unified into equal shapes to have value in construction.

Fig. 10. Structural exploration based on tetrahedral cell aggregation in a 3D grid

Fig. 11. *Log Knot*. Robotically Fabricated Roundwood Timber Structure.

DIGITAL FABRICATION METHODS OF RAW TIMBER

Raw-timber fabrication is feasible due to software and hardware developments that facilitate transforming timber into pre-determined design models. The first challenge is to generate a digital representation of the wood, which can be used to align it with a specific component design, position it during manufacturing, and create machining toolpaths. The machining setup is a prevalent concern in raw wood fabrication workflows due to the unique shapes of each raw wood piece. Moreover, unlike conventional rectangular oak beams, the round surfaces lack any reference points.

Scanning and machining are the two primary methods employed to cut irregular raw timber. Numerically-controlled machines (CNC and Robots) are capable of milling every conceivable angle from a wooden element to a certain extent.

3D scanning procedures have been used by the forestry industry to maximize tree growth and sawing procedures for straight wood. The use of cutting-edge technologies, including CT scanning, 3D analysis, LIDAR and RADAR scanning, and customized sawing, is highly developed in this industry. Nevertheless, these methods are limited to sawmill or forest growth statistics. Since 2010, an increasing number of studies in the field of raw wood research have used scanning techniques to shape structural forms using raw timber. The techniques rely on the topology of a tree log, including tiny and large radii, straight bending, and bifurcated trees, as well as economic reasoning, SDK availability, and scalability [11].

Fig. 12. *Mother Maple.* 3D scanning of a well known tree at Asitu’lisk.

Scanning

Various scanning methods provide valuable insights for industrial fabrication and guide design decisions. These methods include manual measurement, using markers and tracking devices, photogrammetry, camera sensors, laser scanning, virtual reality applications, and volumetric scanning.

The 3D scanning technique is deployed to identify tree forms, thereby building a comprehensive database of available geometries. This process is necessary for three main reasons: a) Each tree trunk is different; b) the design space has to consider these differences; and c) the timber fabrication requires to know the most accurate tree trunk position within the machining space.

Therefore, it is necessary to collect the data about the real-world object (the tree) and possibly its appearance (the color).

The collected data could reconstruct a 3D model or the low-level 3D representations, such as the central axis and radial parameters [11]. Specialized software for point clouds can facilitate the creation of mesh geometry from the point cloud data. Nonetheless, the objective was to obtain a NURBS geometry representation, aiming for a lightweight data format and consistent construction of sawlog geometries. [See Fig. 13].

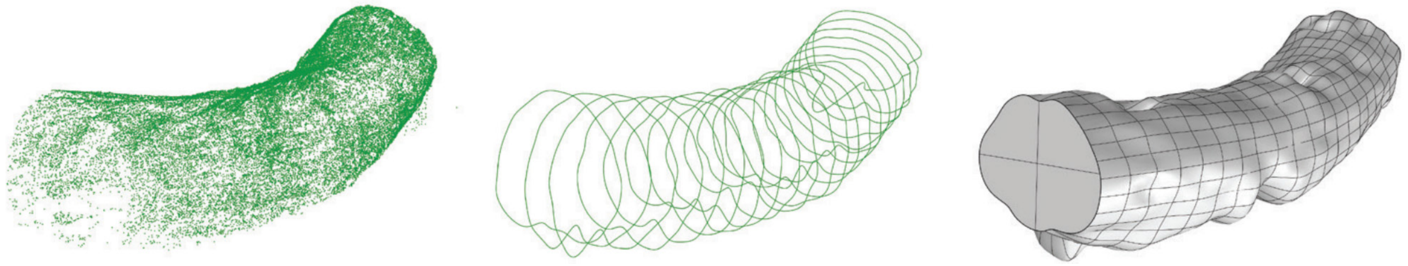

Fig. 13. Point-cloud processing of a log laser scan. Scanned data are transformed into NURBS geometry, which functions as a lightweight representation of the digital stockpile. The overall shape of the log is precisely described using simply geometry.

Fig. 14. A 3D model of a log with isocurves (Left). Physical log with milled isocurves (Right).

Fabrication Tool-path Generation

Tool-path generation is necessary for robotic fabrication because it guides the precise movements required for cutting and drilling physical raw wood. The process provides essential information about cut orientation, corner shapes, tool inclination, and the volume of material to be subtracted, ensuring that machines can efficiently handle the overall dimensional precision of raw-wood connections.

According to scanning methodologies, scanned raw wood can be represented minimally in 3D using two parameters: a central axis and radial parameters along this axis. Connection geometries are then positioned based on these parameters and subtracted using polygonal primitives. This approach allows for faster digital representation and tool-path generation for wood-wood connections.

The most efficient approach for generating a toolpath that defines the precise location of the tool is through Cartesian Coordinate Programming using an offline method [2]. This method establishes the end-effector's position and orientation within a previously established Cartesian coordinate system. This can be either point-to-point (PTP) commands, in which the end-effector goes from one place to the next with the fewest axis rotations, or linear (LIN) commands, in which the end-effector moves in a straight line.

Each cut in digital fabrication is governed by tool-head dimensions and machine reachability, as well as the size of components and joints, while a digital fabrication tool, e.g. CNC or robot, allows each saw to approach the work-piece in ways a human operator may not manage [11].

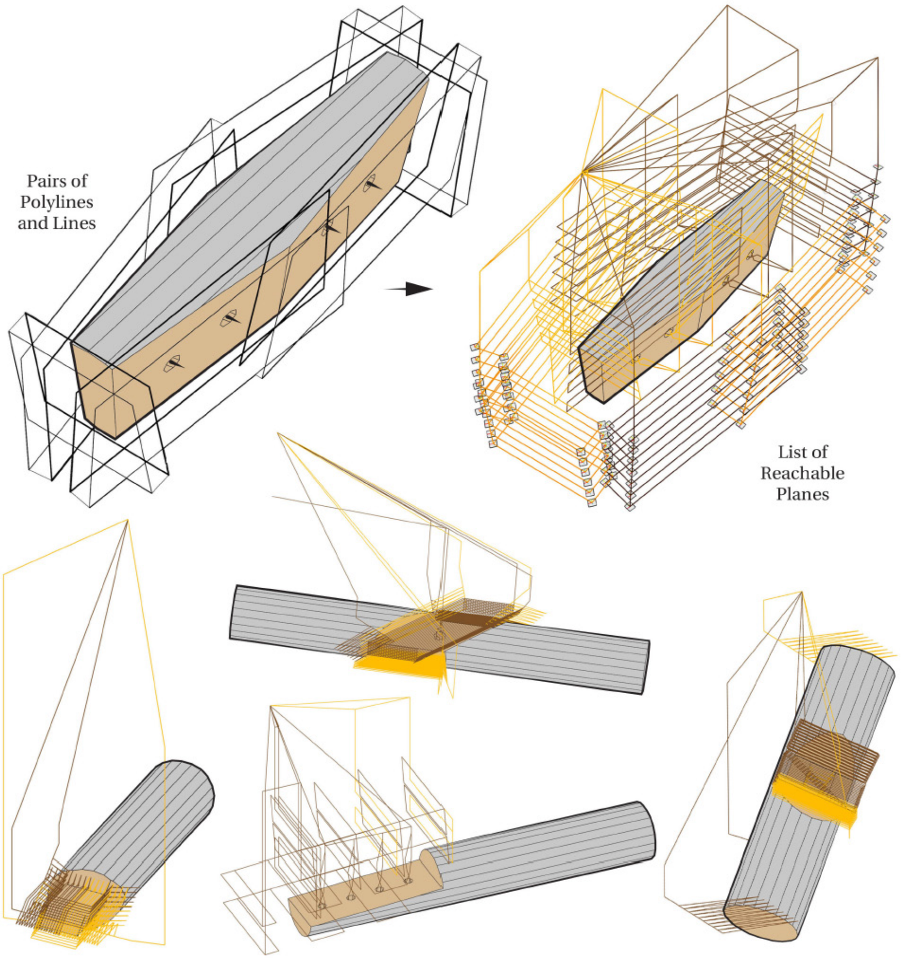

Fig. 15. Multiple tool-paths for a timber joint fabrication. The connections are defined as pair of polylines for cutting and lines for drilling.

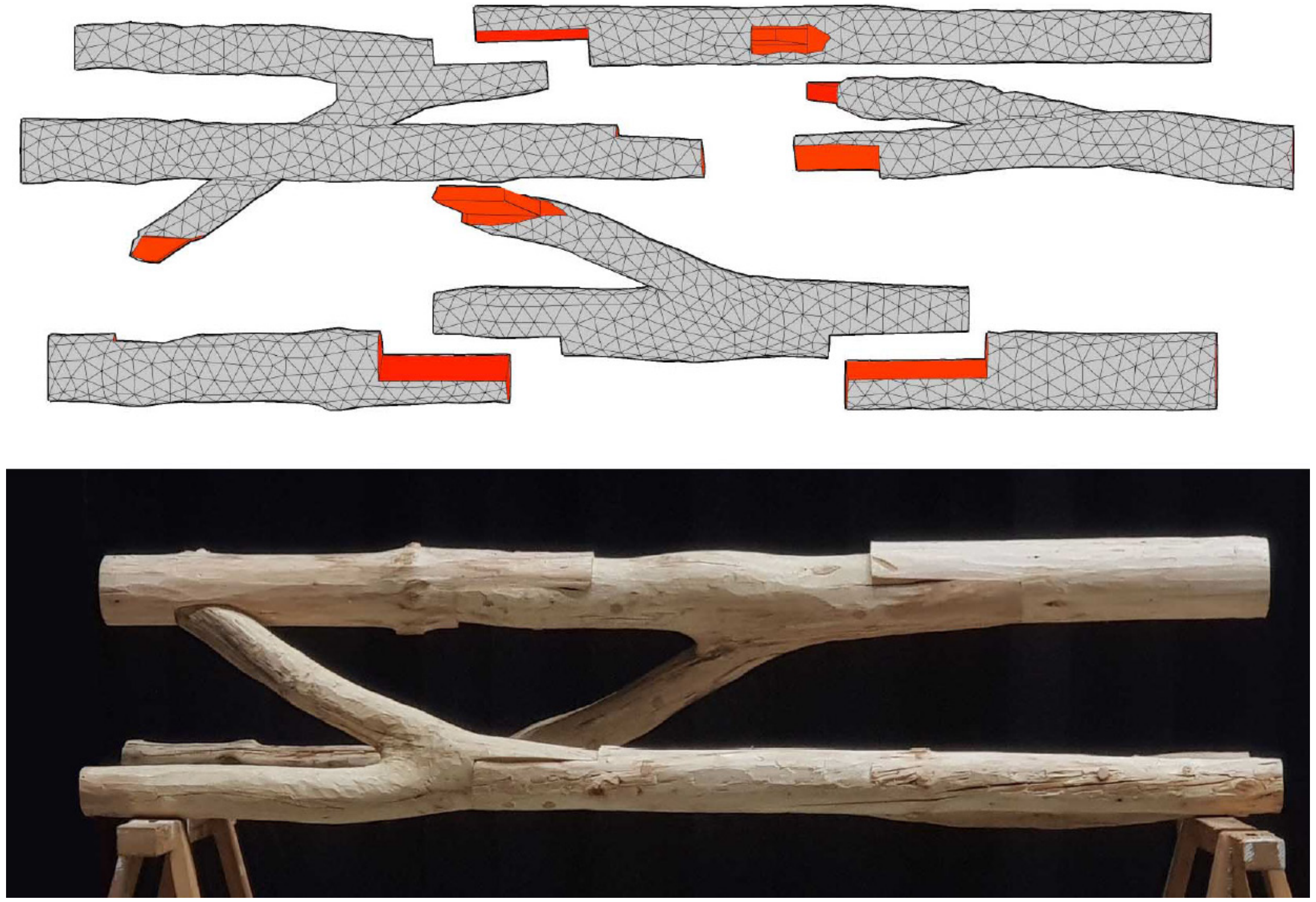

Fig. 16. Mesh Boolean operations on tree meshes, where a collection of outlines are constructed around the connection nodes (Top). Assembled prototype (Bottom).

Fig. 17. Tenon-mortise joint from raw wood.

Industrial Robot Arm

Industrial robot arms have become the common tools for fabricating raw wood, enabling customized workflows that integrate various cutting and vision tools. While mechanical fasteners have become standard practice for jointing timber assemblies due to their ease and predictable performance, Robotic Fabrications explores the development of complex timber to timber connections [10].

Raw wood cutting may require a set of customized tools atypical of traditional CNC machining, for example, bandsaws and chainsaws. Equipping a robotic arm with an analogy tool means implementing the potential offered by traditional techniques. It helps to materialize the complexity of digital space derived from the lack of homogeneity of the material and its tolerances [11].

Ashen Cabin [Fig. 19 & 20] is an experimental prototype for 3D printing and robotic architecture.

Using a KUKA KR200/2 with a custom 5hp band saw end effector, the designers can saw irregular tree logs into naturally curved boards of various and varying thicknesses (down to 2 mm thin). To integrate the non-standardized material, the sliced boards are arrayed into interlocking SIP facade panels. By adjusting the thickness of the bandsaw cut, the robotically carved timber boards can be assembled as complex single curvature surfaces or double-curvature surfaces. The SIPs are insulated using a two component closed-cell foam for which a fully biodegradable option is available [13].

Fig. 18. Chainsaw robotic arm machining a surface on to a tree's stem.

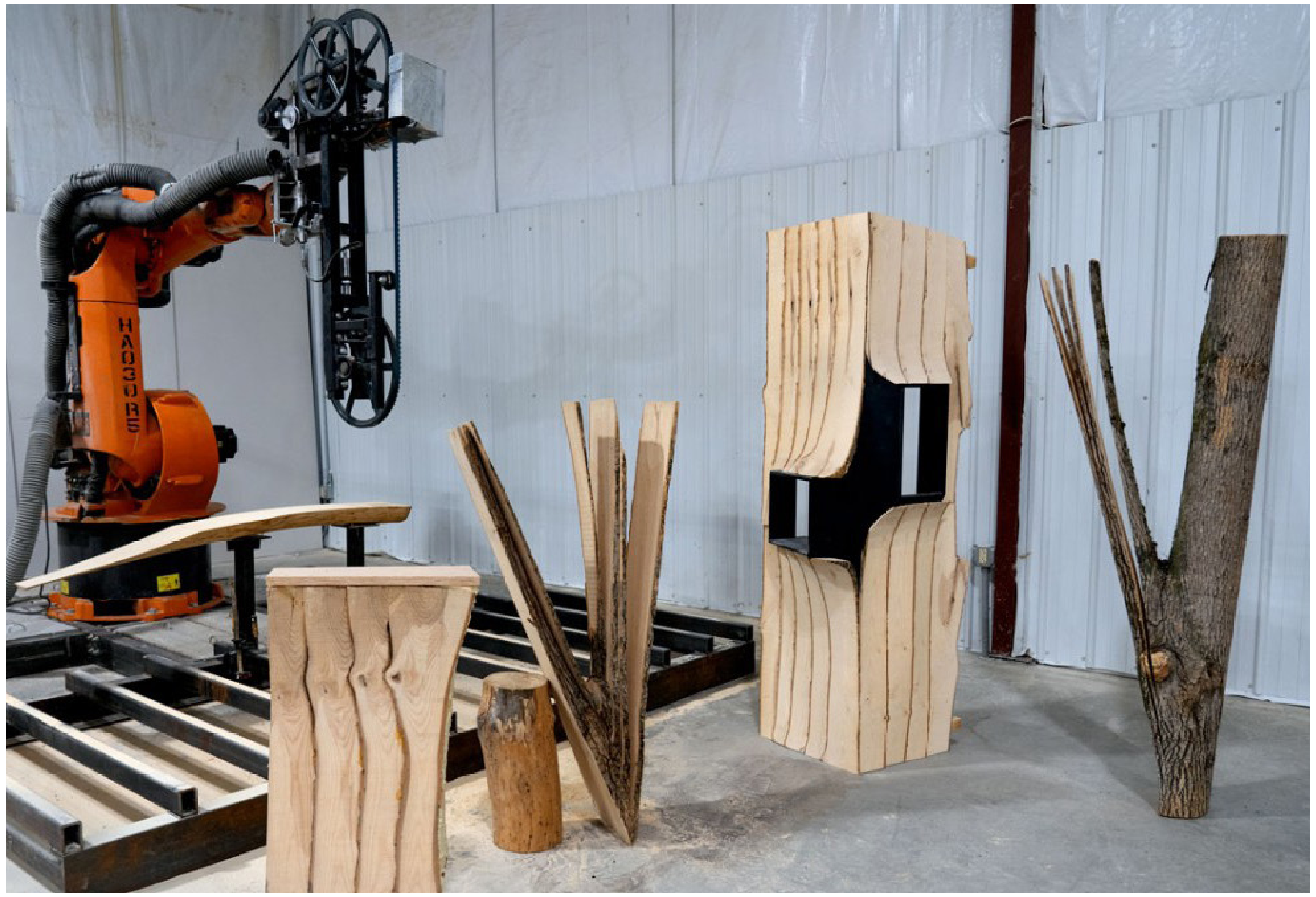

Fig. 19. A robotic arm with a custom band saw end effector is used for sawing irregular tree logs into naturally curved boards of varying thicknesses.

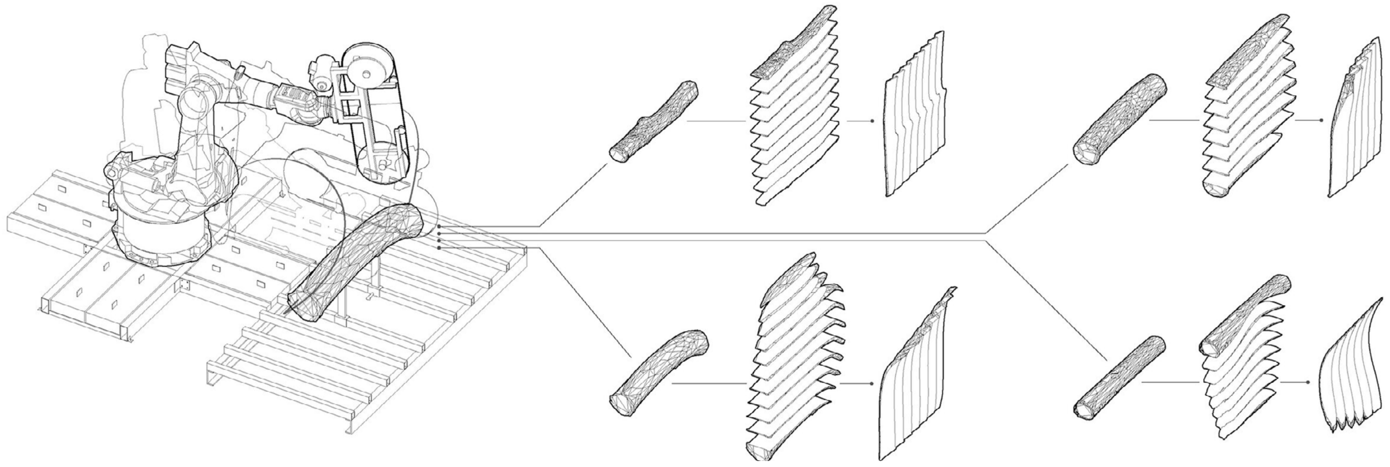

Fig. 20. Log geometries and resulting wall surfaces.

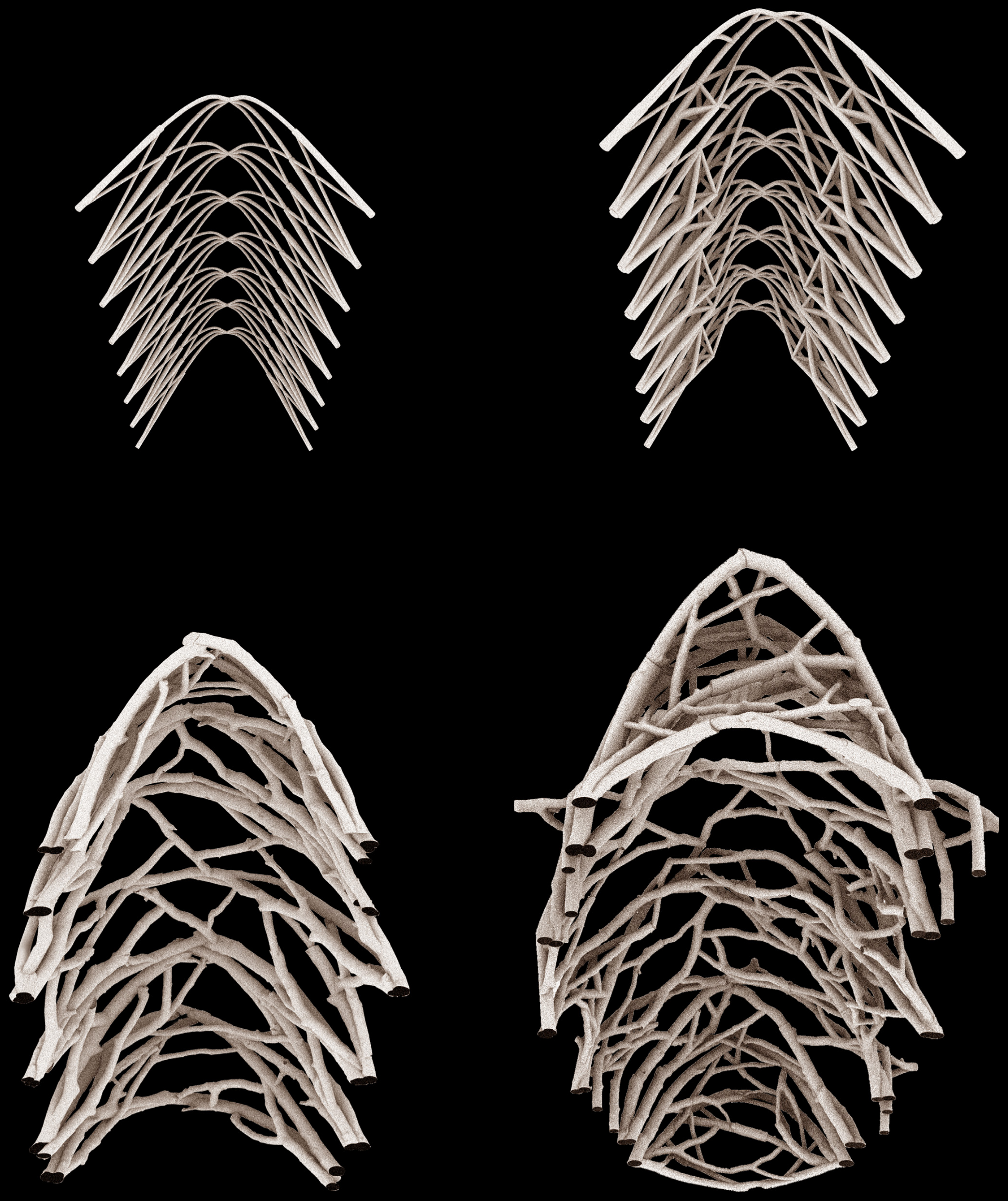

Fig. 21. Structure Development.

PROTOTYPE

The Prototype stage focuses on designing and developing structures. This involved conceptualizing the structure's overall geometry as well as arranging and controlling each individual component. Digital exploration informed by raw materials plays a crucial role in refining these prototypes, allowing for the precise arrangement and control of each structural part. Throughout the stage, we developed a series of four prototypes, each ranging in complexity from simple to intricate designs. The first prototype served as a foundational model, informing the design and construction of the second prototype. Insights and improvements gained from the second prototype are applied to the formalization of the third prototype, which in turn guides the development of the fourth. This iterative method ensures a progressive enhancement in the design and versatility of each subsequent structure prototype. These prototypes served as tangible representations of the exploration of structural possibilities.

The stage investigates the solution for both a feasible structural arrangement and a structural design method. We started the process by digitally exploring the design of structures to understand their global geometry and potential spatial properties. Following this phase of digital exploration, the project moved on to the collection and preparation of physical materials. Tree bits, selected for their manageable dimensions suitable for woodworking hand tools, were carefully cut and collected from discarded piles and fallen trees around the campus. These locally sourced raw wood materials were intended for various types and stages of experimentation, ensuring they were manageable in both analog and digital contexts. The found materials are cataloged, and digital representations of each are created by photogrammetry operations, one of the most cost-effective solutions to obtain 3D models from 2D imagery.

During the prototype stage, both analog and digital fabrication techniques materialized a collection of physical models. The primary method of producing the physical models involves the use of 3D printers, which enables rapid idea testing. These physical 3D-printed models play a crucial role in transitioning to the timber detail design phase, where the raw material informs the design's specifics. These models were created to improve comprehension of structural assembly sequences.

The outcome of the Structure Prototyping is the creation of a final structure assembled from 140 distinct tree bits. Each component, characterized by its unique typological shape, is connected directly to one another, resulting in a cohesive whole that showcased the culmination of the prototyping process.

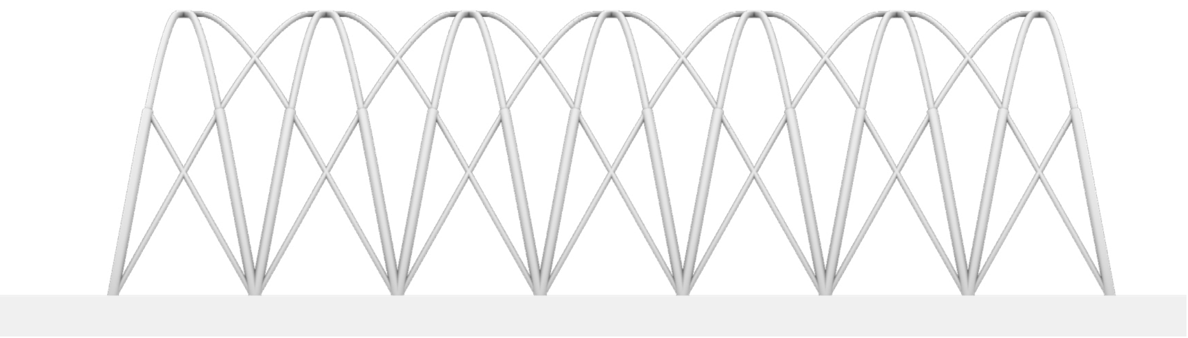

Fig. 22. Prototype 1. Side view.

Fig. 23. Prototype 2. Side view.

Fig. 24. Prototype 3. Side view.

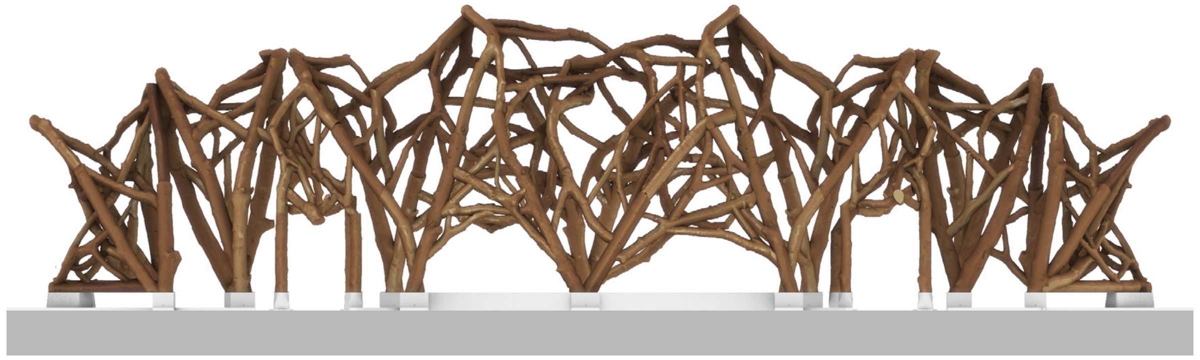

Fig. 25. Prototype 4. Side view.

PROTOTYPE 1

The early stages of structural design focus on how natural tree forms could loosely inform the structure's global geometry. The objective is to create a design that not only reflects the organic shapes found in nature but also functions effectively within an architectural context. Prototype 1 is primarily concerned with realizing geometric and spatial properties with regard to scale and structural design optimized for an open-plan layout. The concept revolved around utilizing natural tree shapes for structural components, ensuring that the design could be practically applied in a local context.

To achieve this, iterations of the structure were explored during the development of Prototype 1. These iterations aimed to investigate different geometric configurations of the structure, all comprising relatively similar framing members. Each iteration targeted a uniform structure size of 15 x 30 x 8 meters.

Through this iterative exploration, the arch frame structure emerged as the most promising design for further development into Prototype 2. This particular structure was selected due to its ability to emulate the natural parts of a tree, with members that closely resemble branches and trunks. The arch truss frame not only provided a robust and stable configuration but also maintained the aesthetic integrity of natural forms, which was a crucial aspect of the design ideology.

The insights gained from Prototype 1 were instrumental in refining the design and ensuring that the structural and architectural goals were met. The selection of the arch frame structure aligned with the intention of local application, demonstrating how the design could be effectively utilized within the specific context of the Gothenburg Botanical Garden. This decision was based on the structure's ability to integrate with the natural environment, providing an ideal solution for a botanical greenhouse that requires both functionality and aesthetic harmony with its surroundings.

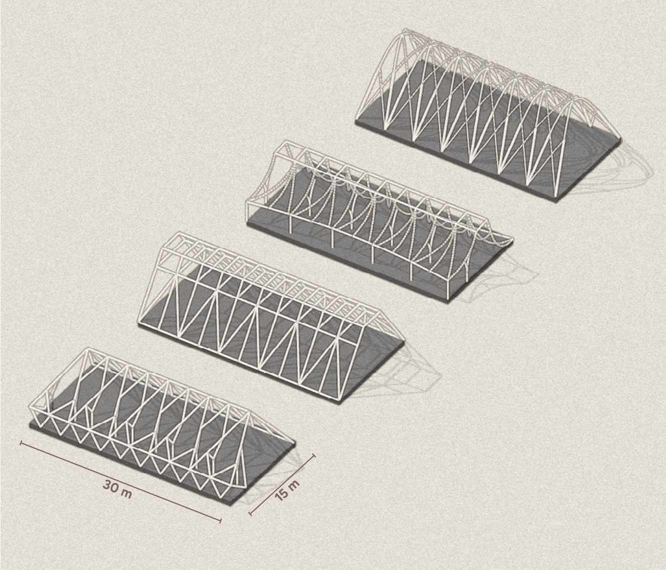

Fig. 26. Early structure design exploration.

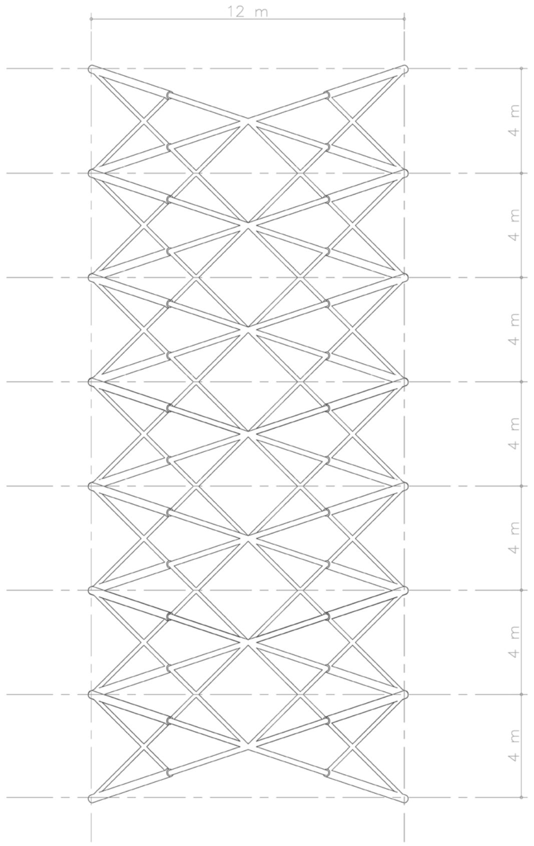

Fig. 27. Prototype 1. Structure Plan.

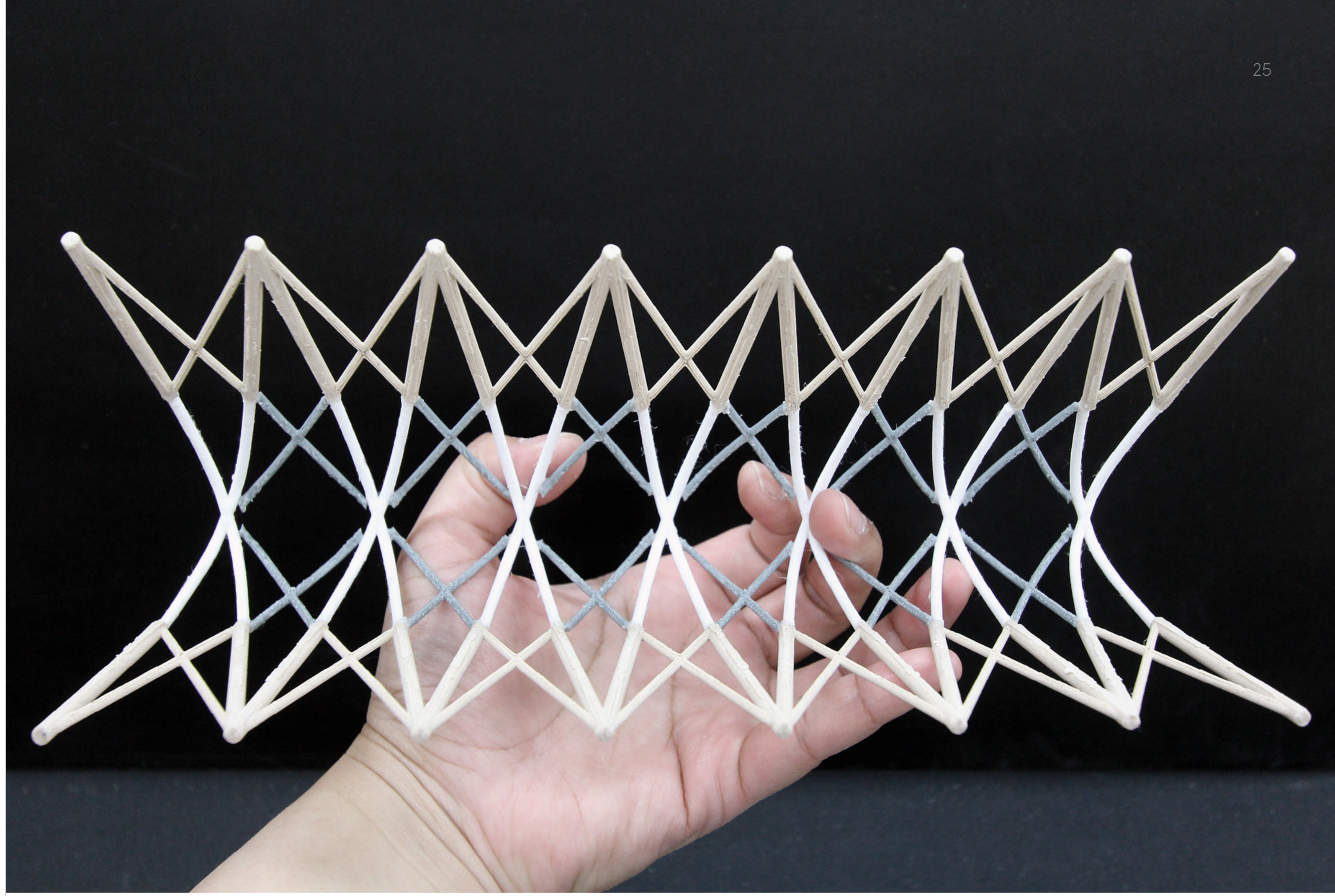

Fig. 28. Prototype 1. 3D printed model in 1:100 scale.

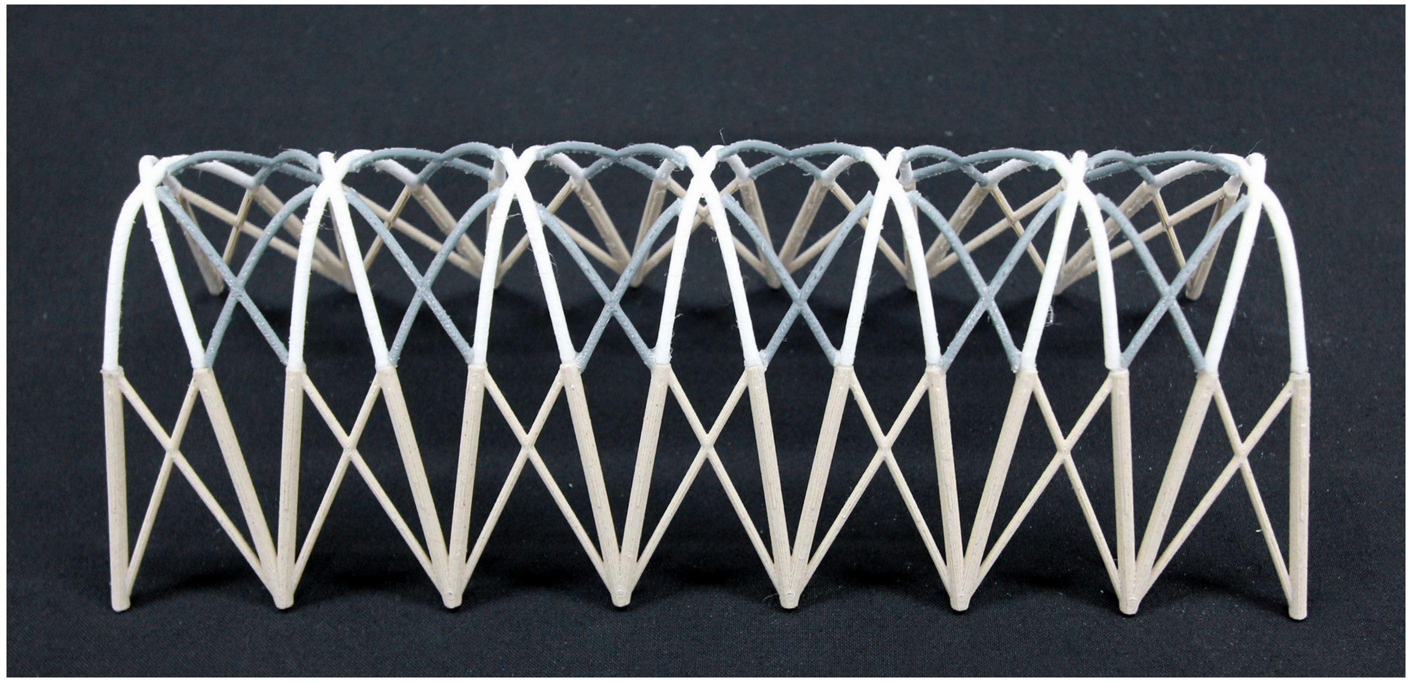

Fig. 29. Prototype 1. 3D printed model in 1:100 scale.

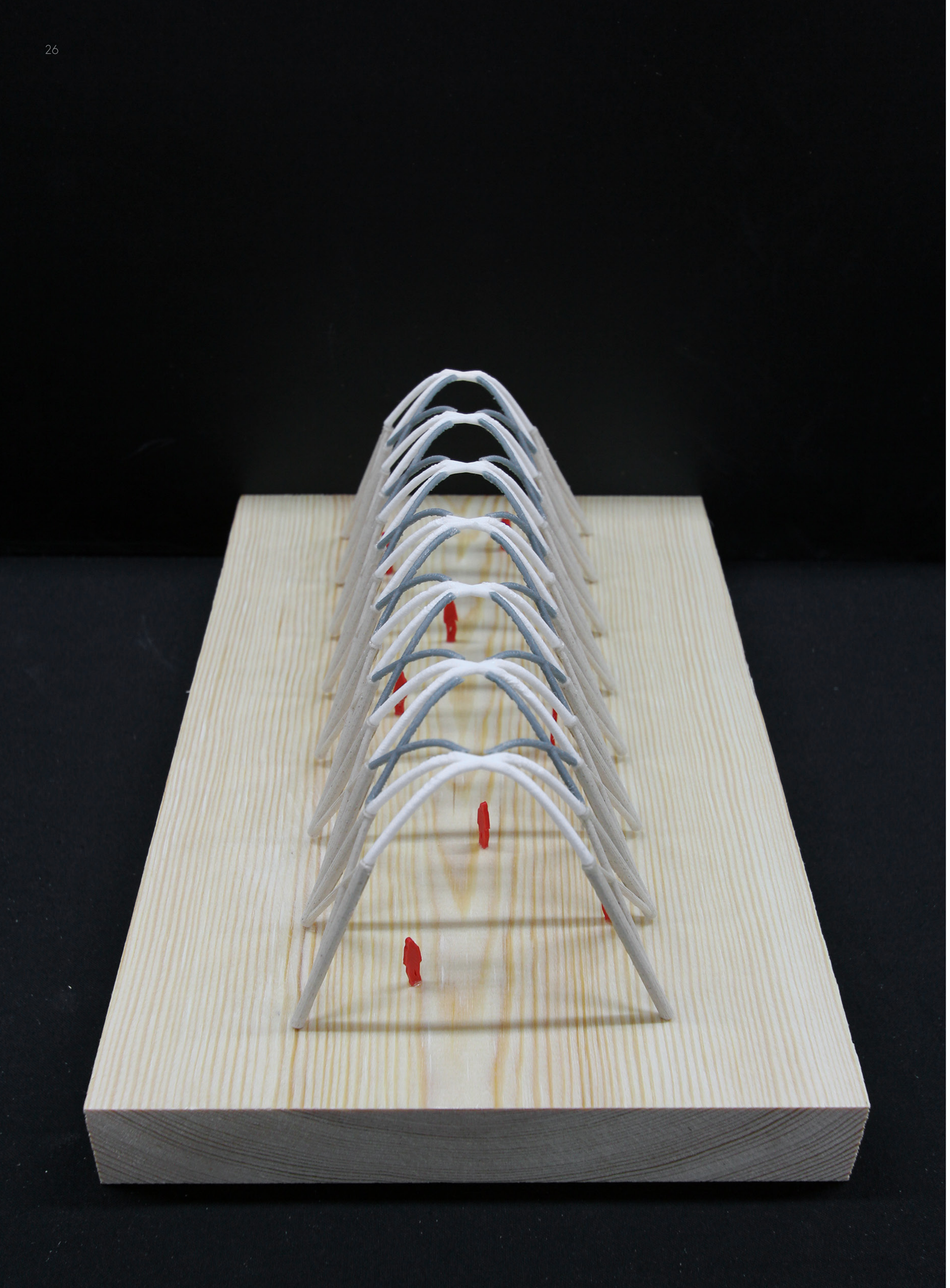

Fig. 30. Prototype 1. 3D printed model in 1:100 scale.

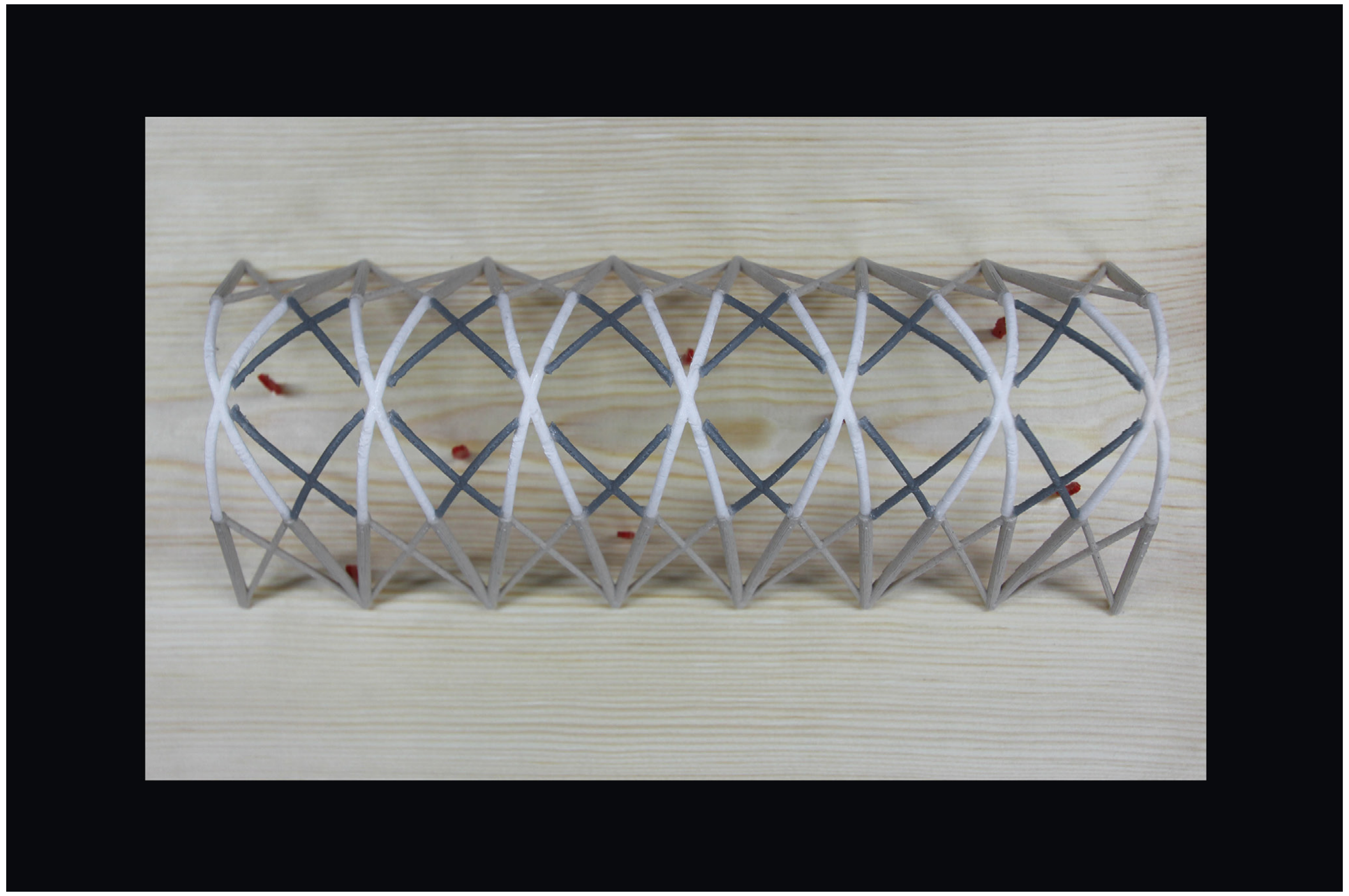

Fig. 31. Prototype 1. 3D printed model in 1:100 scale.

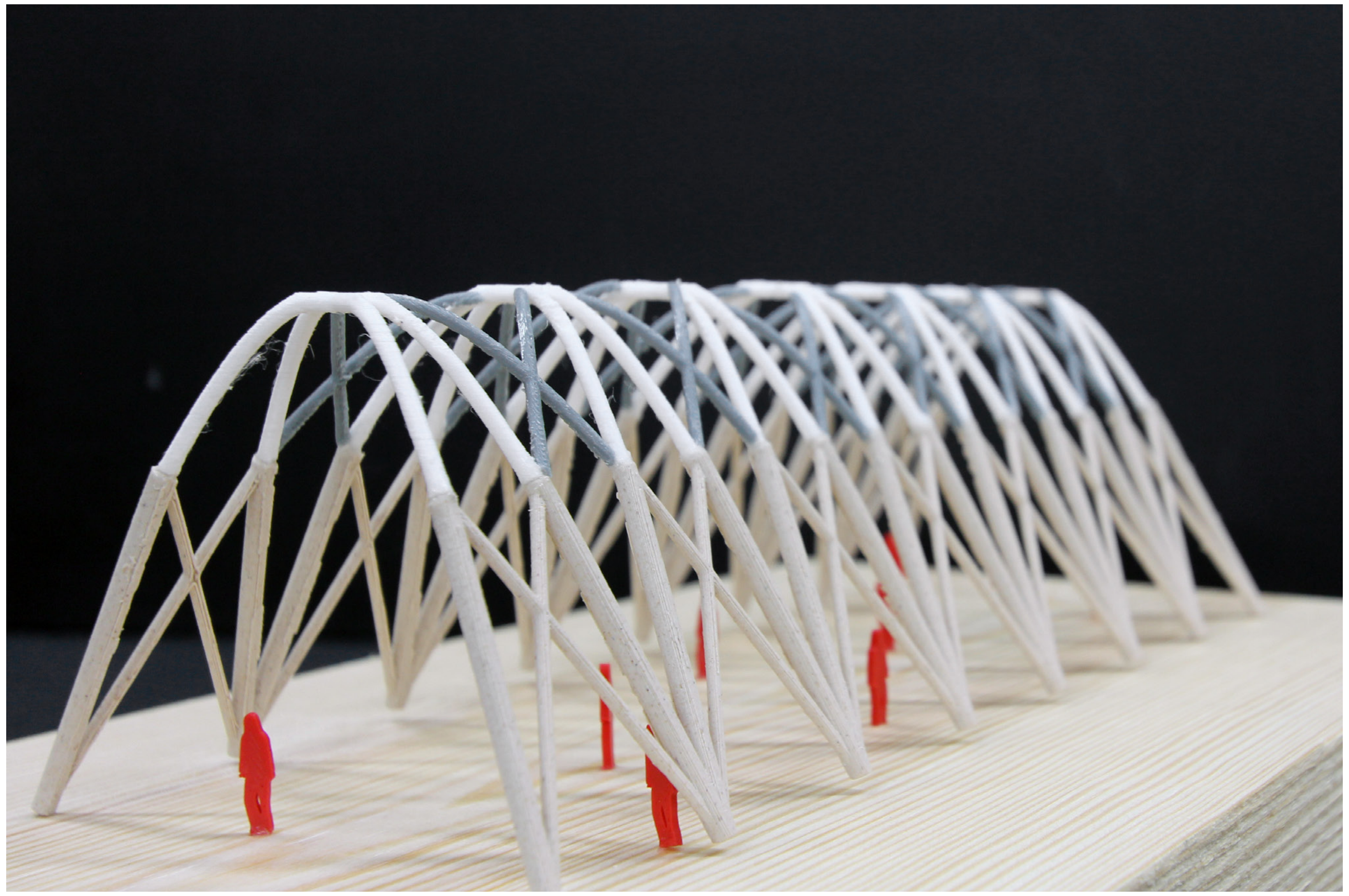

Fig. 32. Prototype 1. 3D printed model in 1:100 scale.

PROTOTYPE 2

The development of Prototype 2 aims to improve its design and structural integrity. Initially, considerations are made for the augmentation of framing members and the detailed 3D modeling to closely replicate the shape and size of the tree's trunk and branches.

Prototype 2 retains the global geometry and structural repetitive patterns established in Prototype 1. However, a deeper level of systems thinking was applied to the structural components. This involves the division of components into units, each strategically designed with the sequences of assembly in mind.

The structural units are composed of a variety of parts in an effort to optimize structural performance. In Prototype 1, the framing members exhibit uniformity in size. The transition from Prototype 1 to Prototype 2 is characterized by a shift from uniformity to variability in both shape and size of the framing members. They're diverse in shape and size based on position and the way they carry the loads.

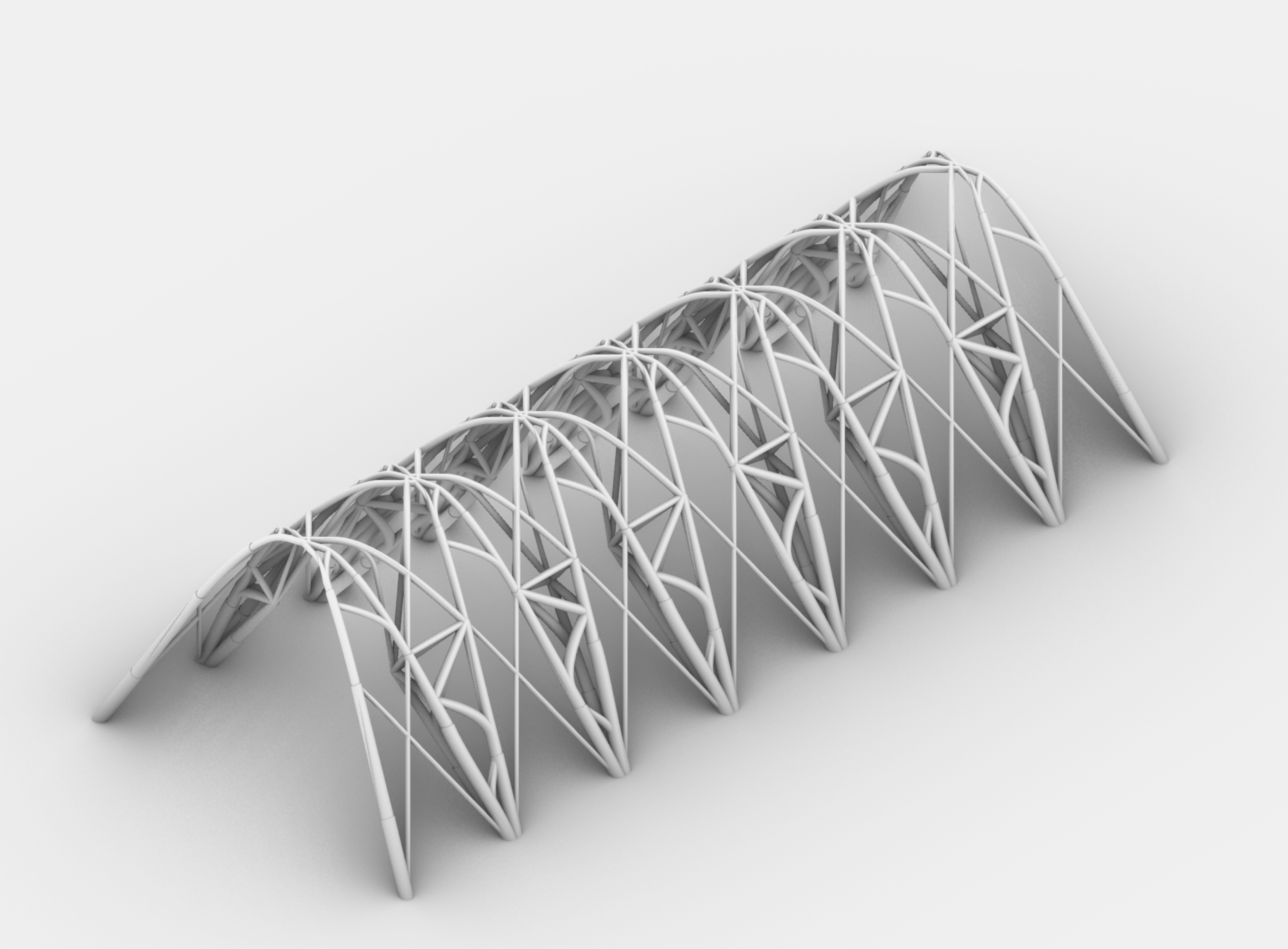

Fig. 33. Prototype 2. Digital model.

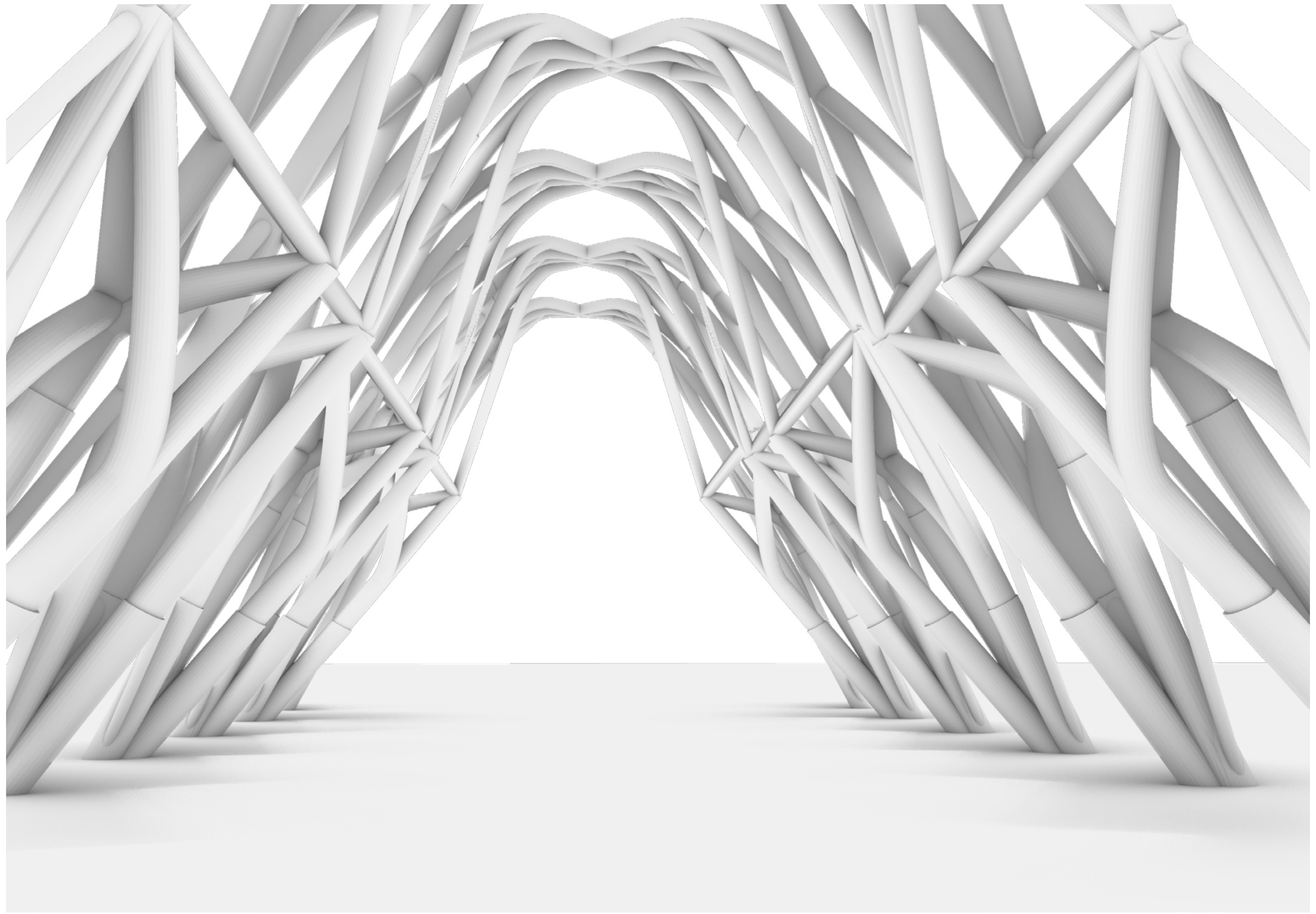

Fig. 34. Prototype 2. Digital model.

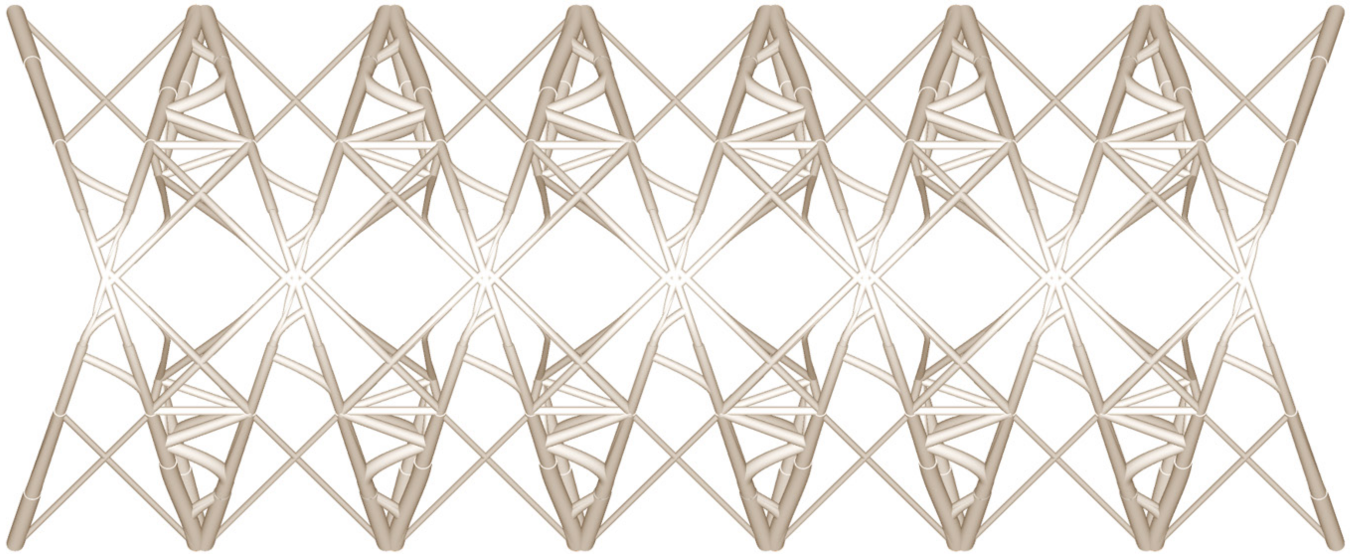

Fig. 35. Prototype 2. Plan view.

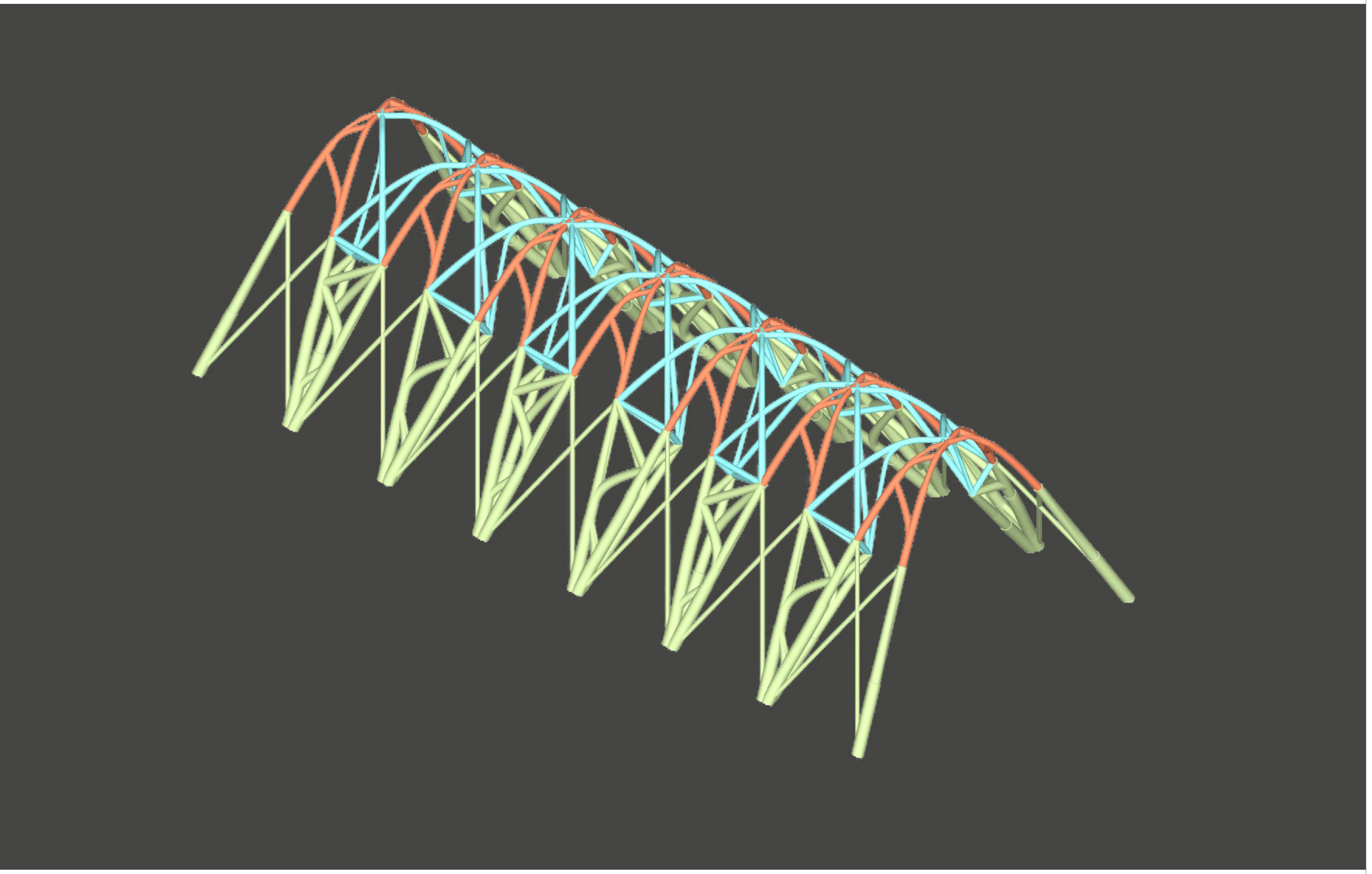

Fig. 36. Prototype 2. Three groups of structural members.

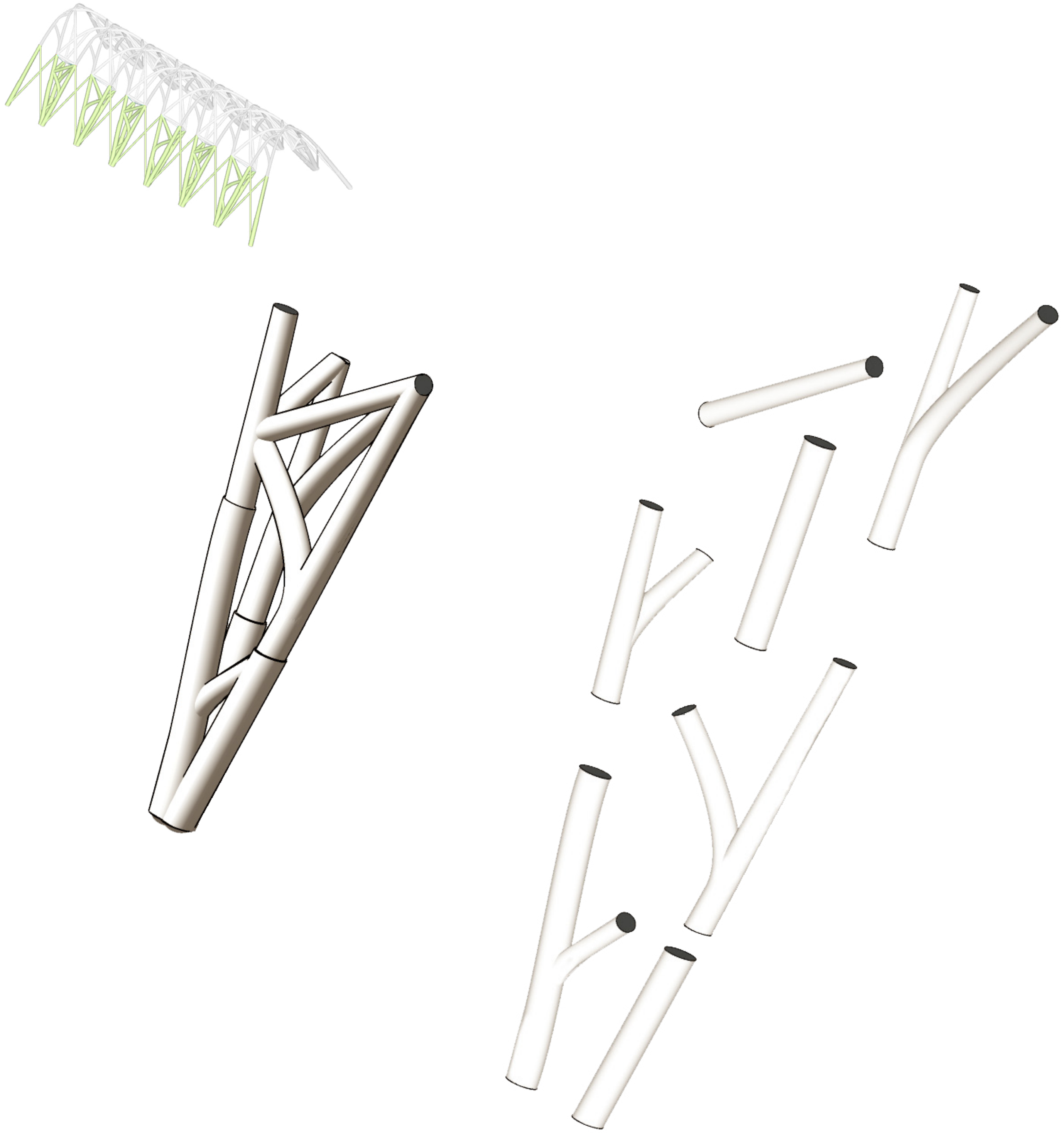

Fig. 37. Prototype 2. Structural members within one unit group.

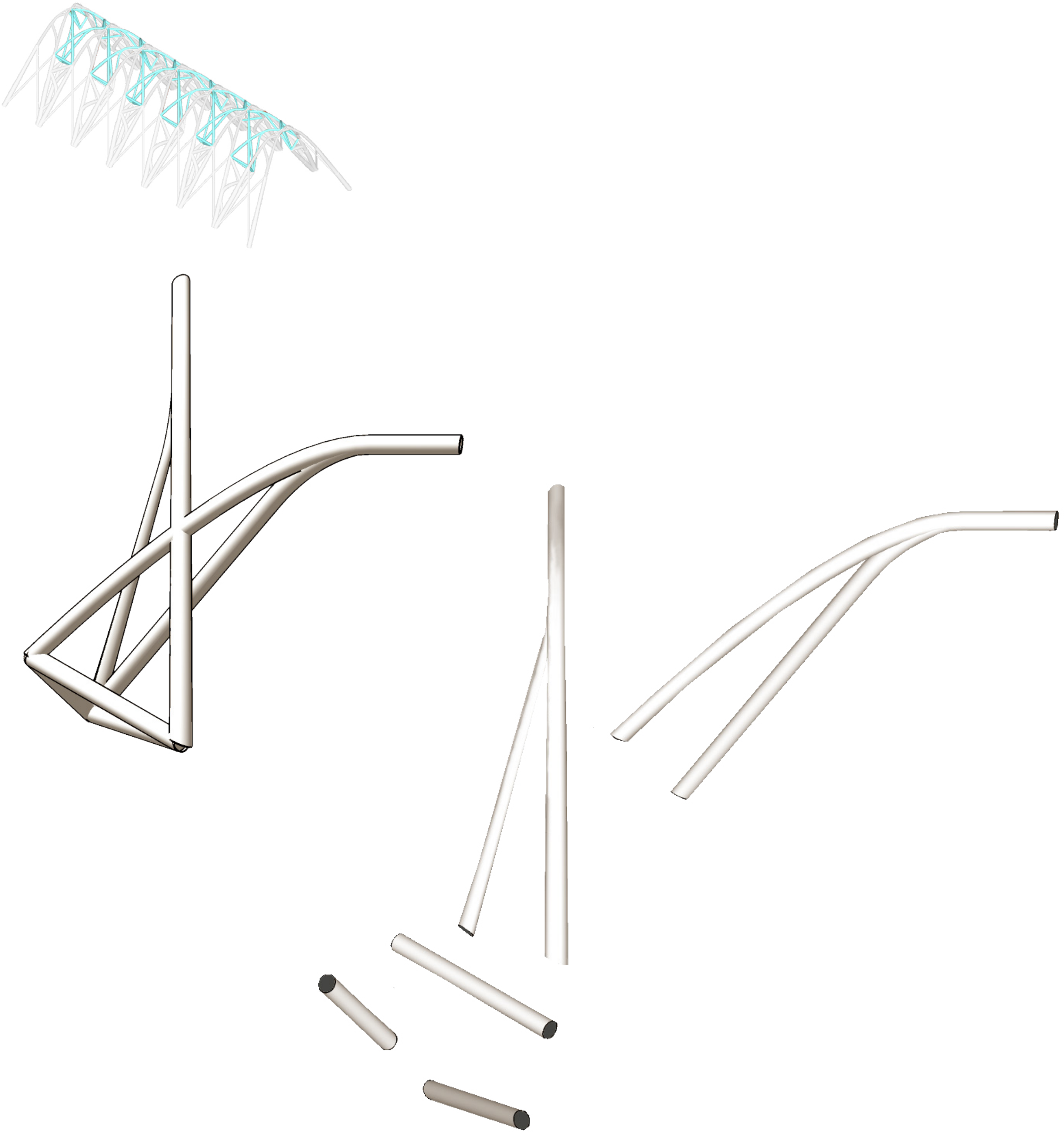

Fig. 38. Prototype 2. Structural members within one unit group.

Fig. 39. Prototype 2. Structural members within one unit group.

PROTOTYPE 3

With the goal of applying inherent forms of tree parts to create a non-standard structure at an architectural scale, the workflow of the subsequent prototypes (Prototype 3 and 4) assumes a collection of physical local raw wood as the departure point and structural design agents. This aims at exploring the unique design potential of a specific set of elements, testing both their ability to adapt a predetermined structural geometry realized in the previous stages of prototyping and their potential to freely self-organize to directly inform the refinement of a structure.

In the beginning of the development of Prototype 3, a dataset of found forms was generated. A detailed dataset was made by 3D scanning 23 distinct raw wood pieces via photogrammetry operations. Raw wood was intentionally collected for digital and analog experiments. They could be divided into a few types by topological differences in shape: straight, bent, curved, and bifurcated bits. This operation leads to an opportunity to build a relationship between the physical raw materials and digital exploration that would be crucial for the rest of the design process.

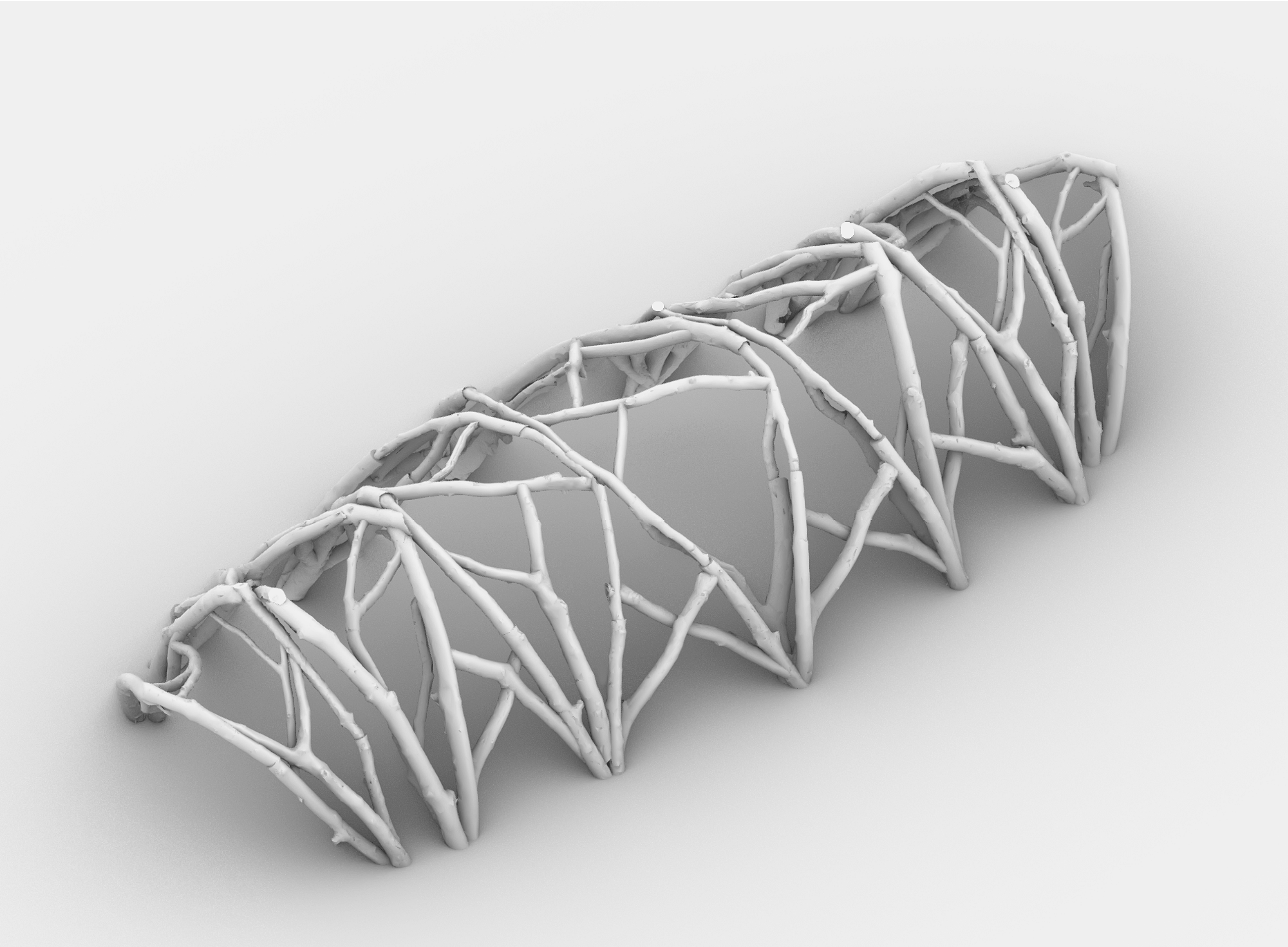

Fig. 40. Prototype 3. Digital model.

Fig. 41. Prototype 3. 3D printed structure model in 1:50 scale.

Fig. 42. Found form inventory.

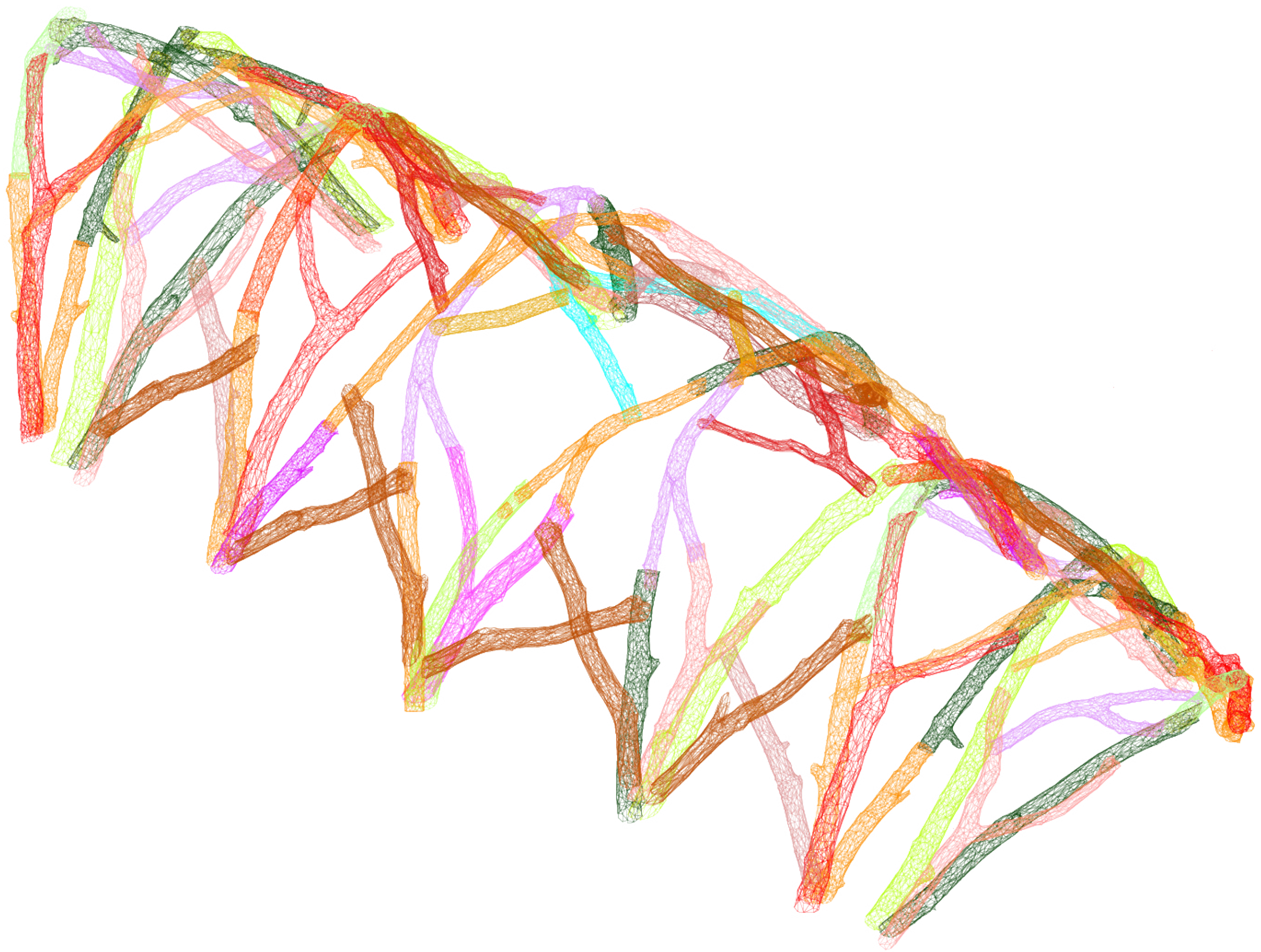

Fig. 43. Prototype 3. A digital model showing a polygon mesh of structural components.

In prototype 3, the process is time-invested in digitizing physical branches to create a set of manageable polygonal mesh models as their digital twins. The scanned branches are categorized according to their geometric attributes, including length and diameter, arranged from largest to smallest. 3D-modeling software scales up the scanned 3D meshes of branches, multiplies, and manipulates some of them to ensure adequate structural components, enabling their arrangement within a larger geometrical constellation of the predetermined structure, ready for adaptation to specific designs. In these arrangements, the straight and curved tree bits play a significant structural role, acting as an axial member, while the forked bits spread throughout this structural system.

Fig. 44. Prototype 3. A digital model showing a polygon mesh of structural components.

Fig. 45. Prototype 3. Bottom view.

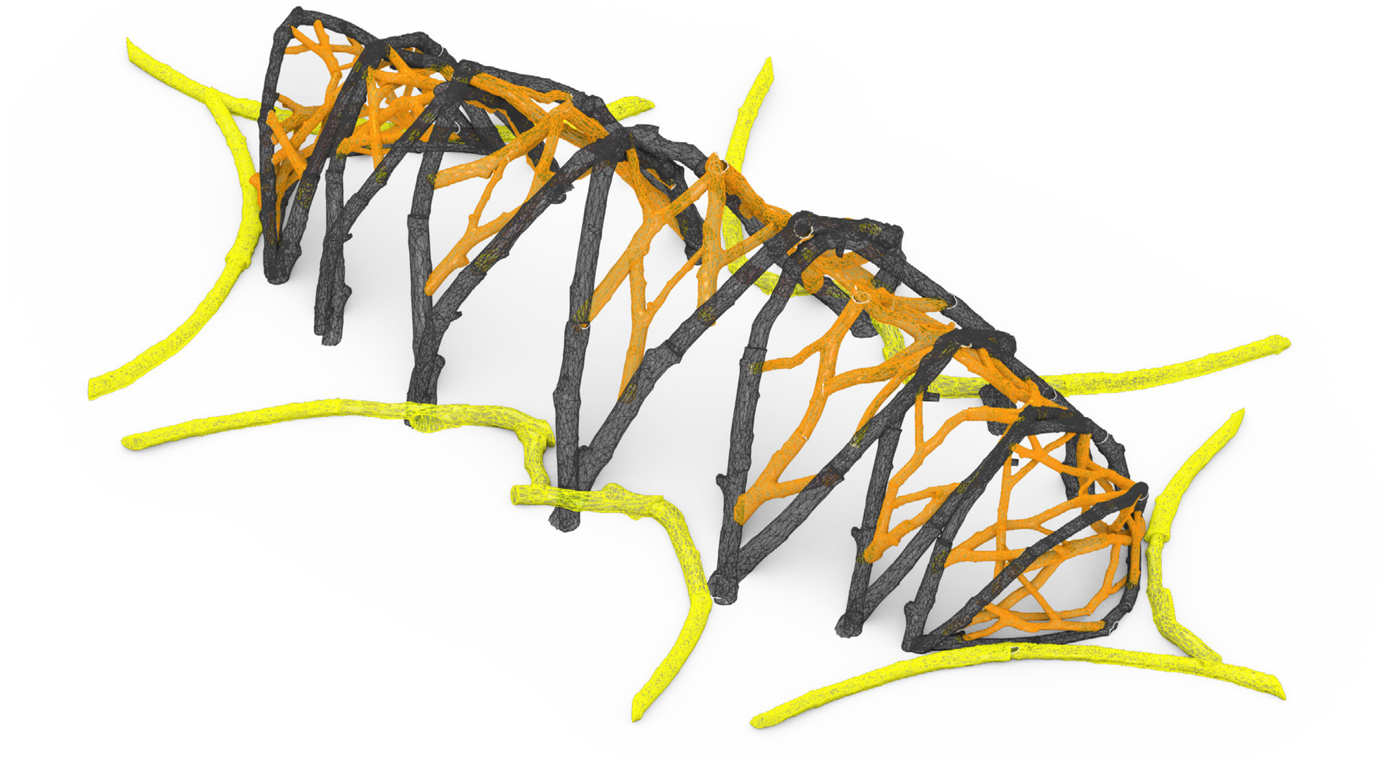

Fig. 46. Prototype 3. Structural members are categorized by raw wood topology.

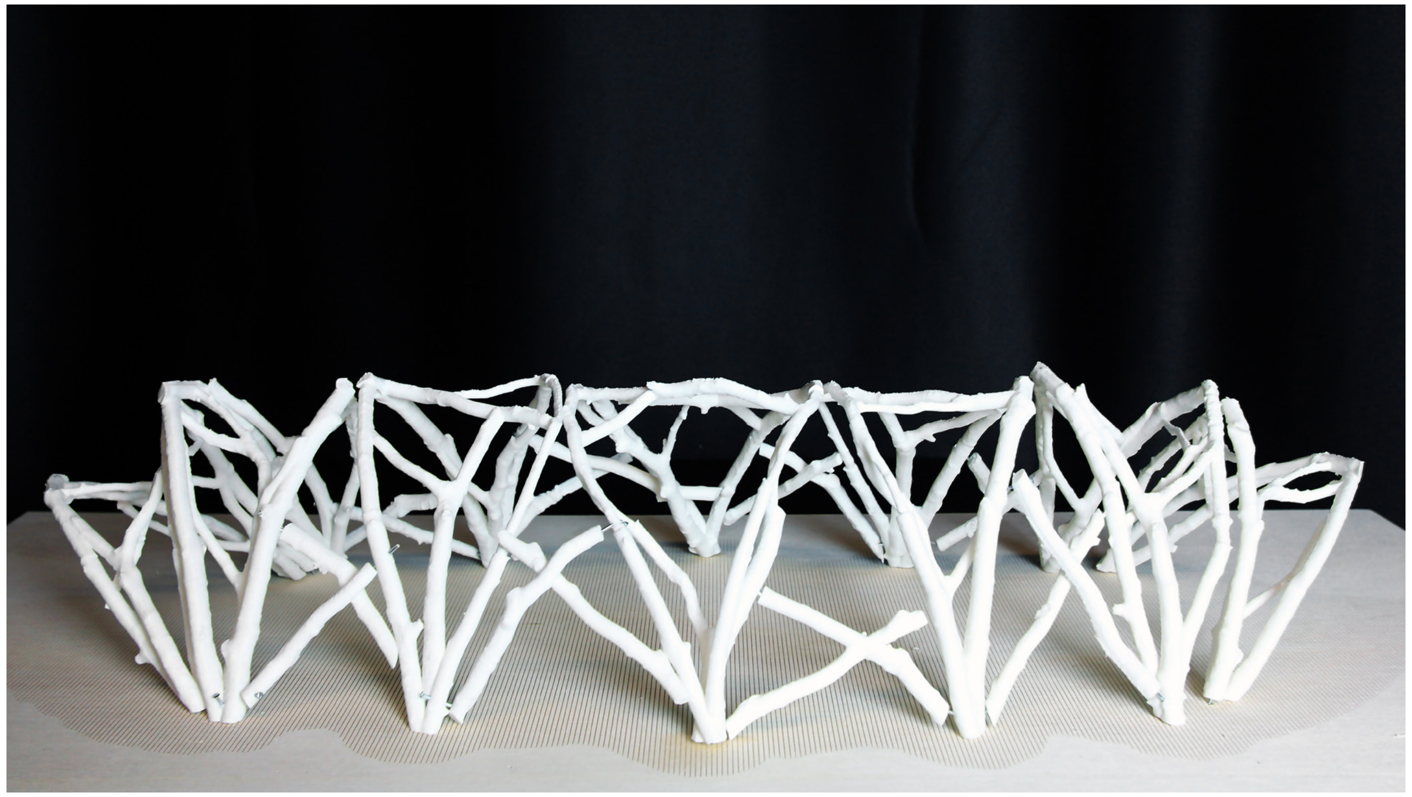

Fig. 47. Prototype 3. 3D printed model in 1:50 scale.

PROTOTYPE 4

The Prototype stage results in the final development of a structure built from 140 distinct raw wood components connecting directly to each other by way of milled connections. The final structure is made up of seven arched frame units that land at fourteen points. To exploit the structural capacity of the fork junction, Prototype 4 uses more forked bits to compose the structure supporting the main inclined arched frames that are composed of bent bits. The structure is an interplay of many curvatures, consisting of forked pieces weaving together. The strategic use of forked bits allows for innovative structural solutions, reducing the need for additional support elements.

The development of Prototype 4 represents a significant evolution from Prototype 3, characterized by a notable shift in the approach to structural member placements. In Prototype 3, the structural units maintained a high degree of uniformity, reflecting a preliminary exploration of form and function. However, Prototype 4 diverges from this uniformity, embracing a varied and distinct approach to highlight the wild and organic forms inherent in the raw wood components.

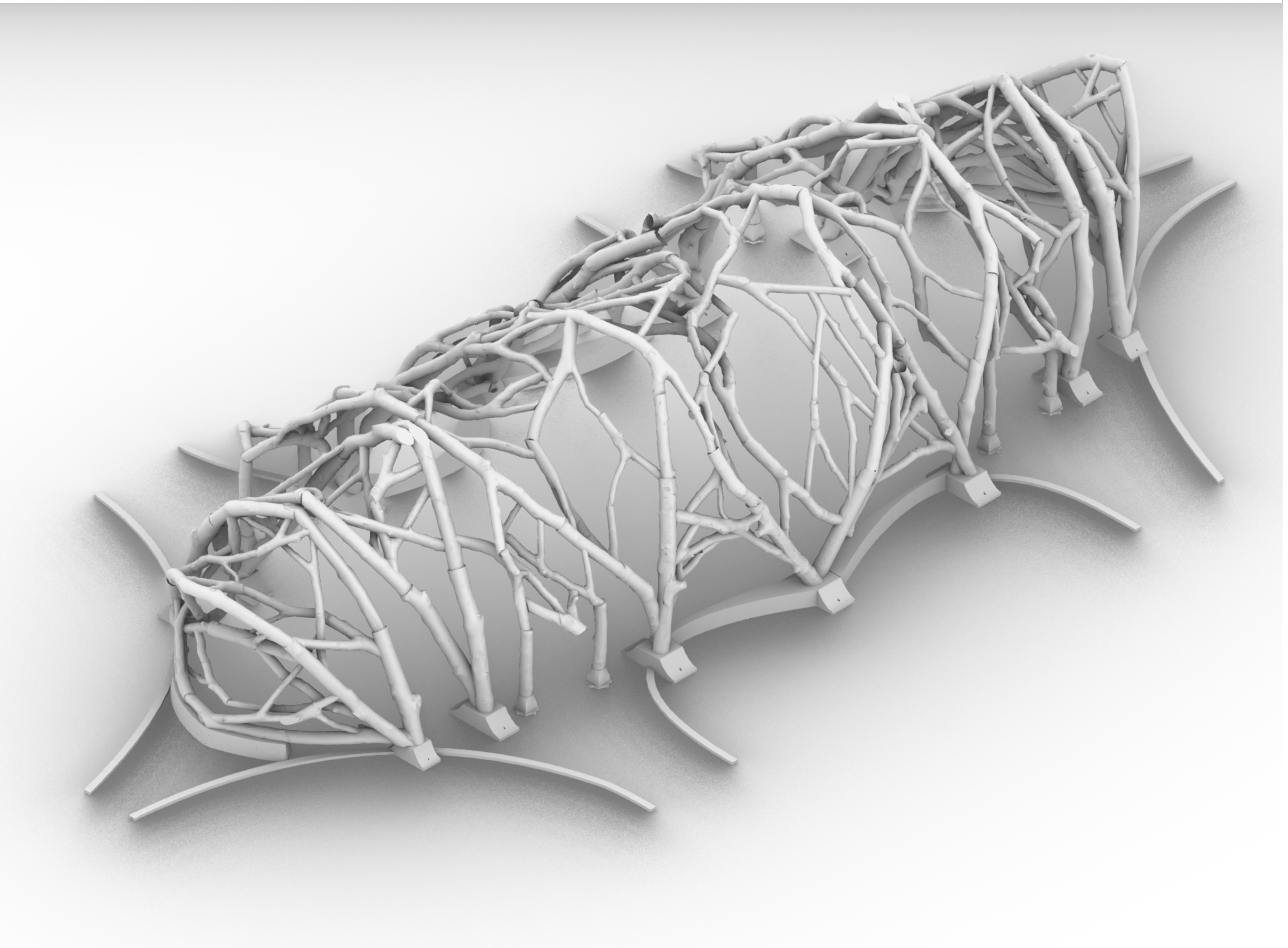

Fig. 48. Prototype 4. A digital model showing raw timber structure on concrete bases.

This variation in Prototype 4 is intentional, designed to emphasize the unique geometrical and morphological characteristics of each piece of raw timber. The structural units in Prototype 4 are carefully differentiated, leveraging the natural diversity of the wood to create a more dynamic and visually compelling structure.

Prototype 4 demonstrates a higher level of readiness and consideration for practical architectural applications. One significant aspect of this readiness is the thoughtful increase in the number of components to accommodate an additional membrane, enabling the structure to function effectively as a greenhouse. This adaptation reflects a deeper integration of environmental considerations and functional requirements into the design process.

Additionally, the development of Prototype 4 incorporates a more refined approach to structural integration with its base. The design includes detailed provisions for attaching the timber structure to a concrete foundation, recognizing the necessity of such support in real-world construction scenarios. This consideration ensures that the raw timber structure can be securely anchored, providing the necessary stability and durability for practical use.

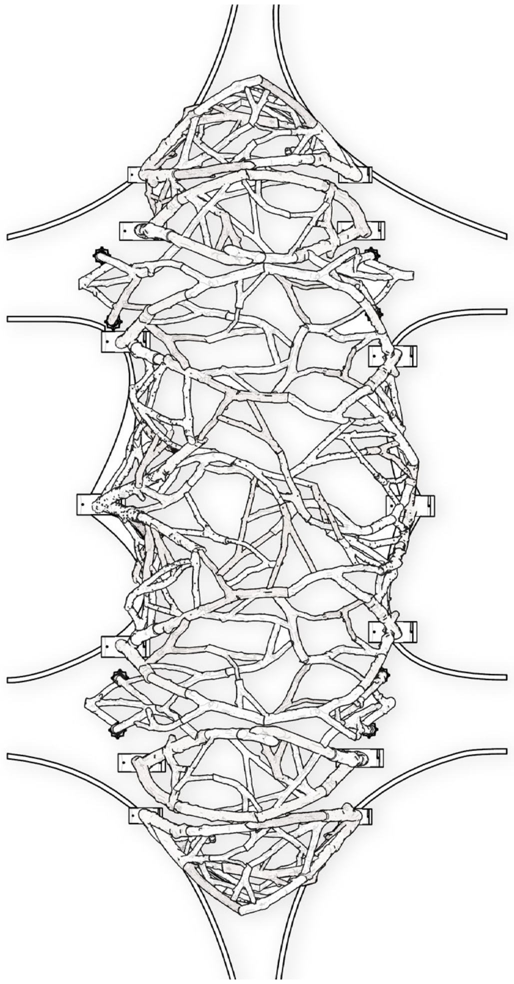

Fig. 49. Prototype 4. Structure plan.

Fig. 50. Prototype 4. 3D printed model with organic support unremoved in 1:200 scale.

Fig. 51. Prototype 4. Structure Model. Physical raw wood pieces were 3D scanned, and the resulting structure was 3D printed in 1:25 scale.

Fig. 52. Prototype 4. Structure model in 1:25 scale.

Fig. 53. Prototype 4. Bottom view.

Fig. 54. Prototype 4. Structure model in 1:25 scale.

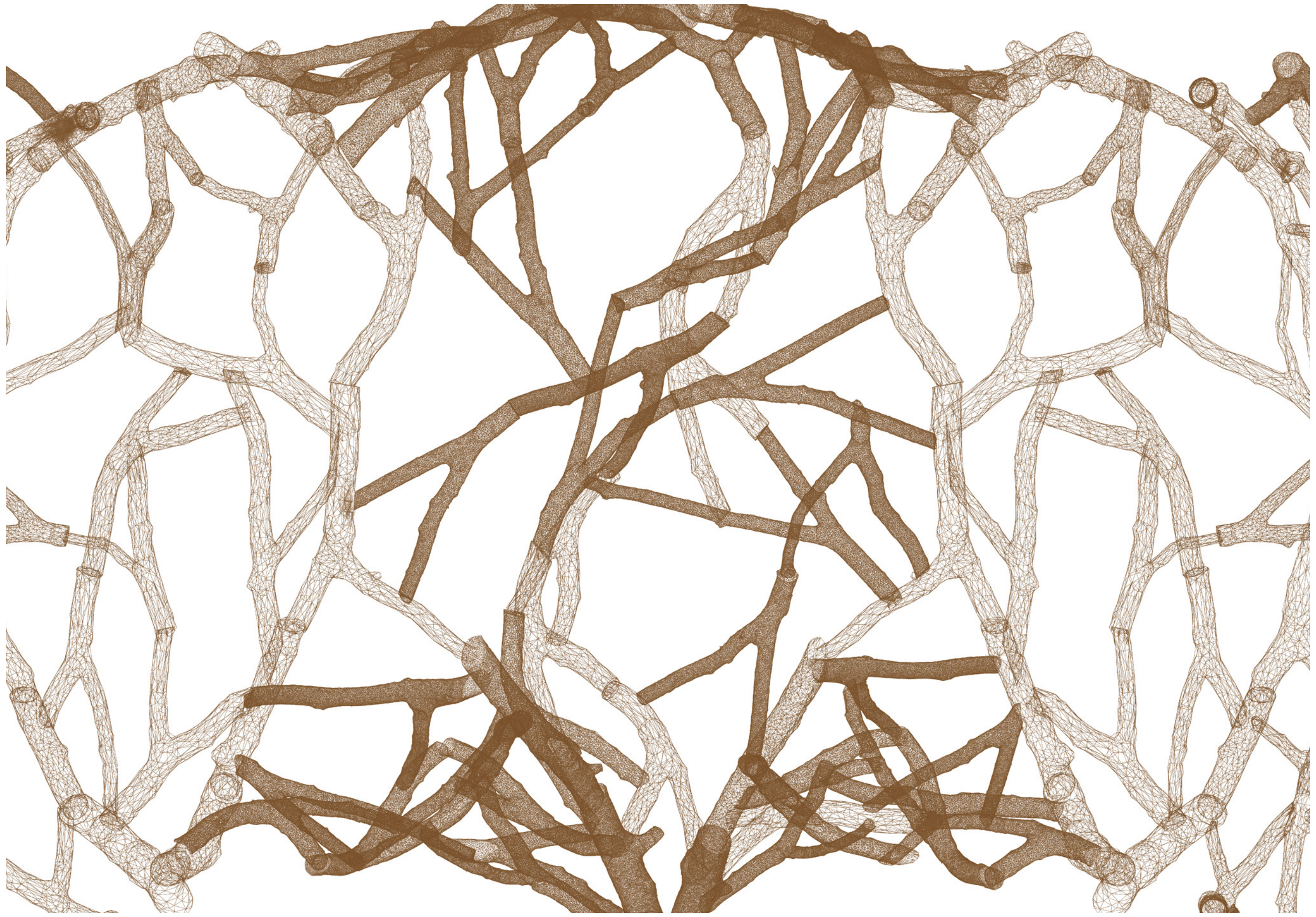

Fig. 55. Prototype 4. Structure plan showing original and simplified component meshes.

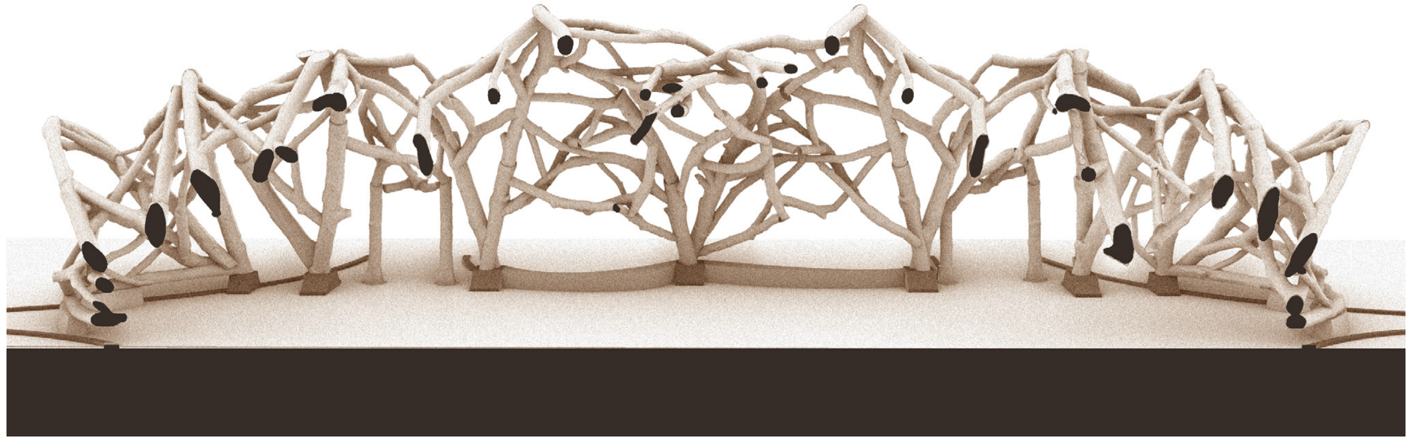

Fig. 56. Prototype 4. Section.

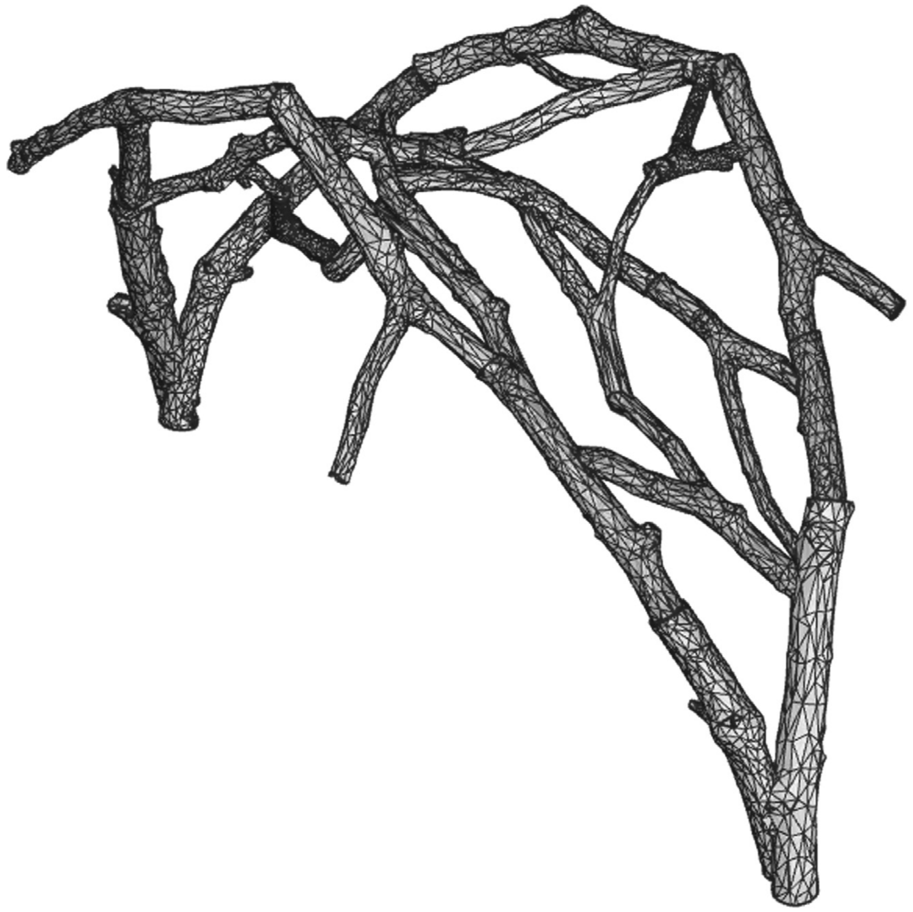

Fig. 57. Prototype 4. Structure Unit.

Fig. 58. Prototype 4. Structure model in 1:25 scale.

Fig. 59. Prototype 4. Pre-assembly of structure model.

The evolution of the structure from Prototype 1 to Prototype 4 demonstrates a progression in design strategies. Prototype 1 focuses on how the natural forms of trees could loosely inform the overall geometry and architectural scale, leading to the selection of an arched frame structure. Prototype 2 refines this design with a deeper level of systems thinking, introducing variability in the size and shape of the framing members to optimize structural integrity. Prototype 3 introduces digitization, which creates manageable mesh models of real branches for digital explorations, significantly increasing structural complexity. Finally, Prototype 4 incorporates more structural components, enhancing both structural integrity and visual complexity, while also accommodating an additional membrane for practical application as a greenhouse. This prototype also includes provisions for attaching the timber structure to a concrete foundation, ensuring stability and readiness for architectural application.

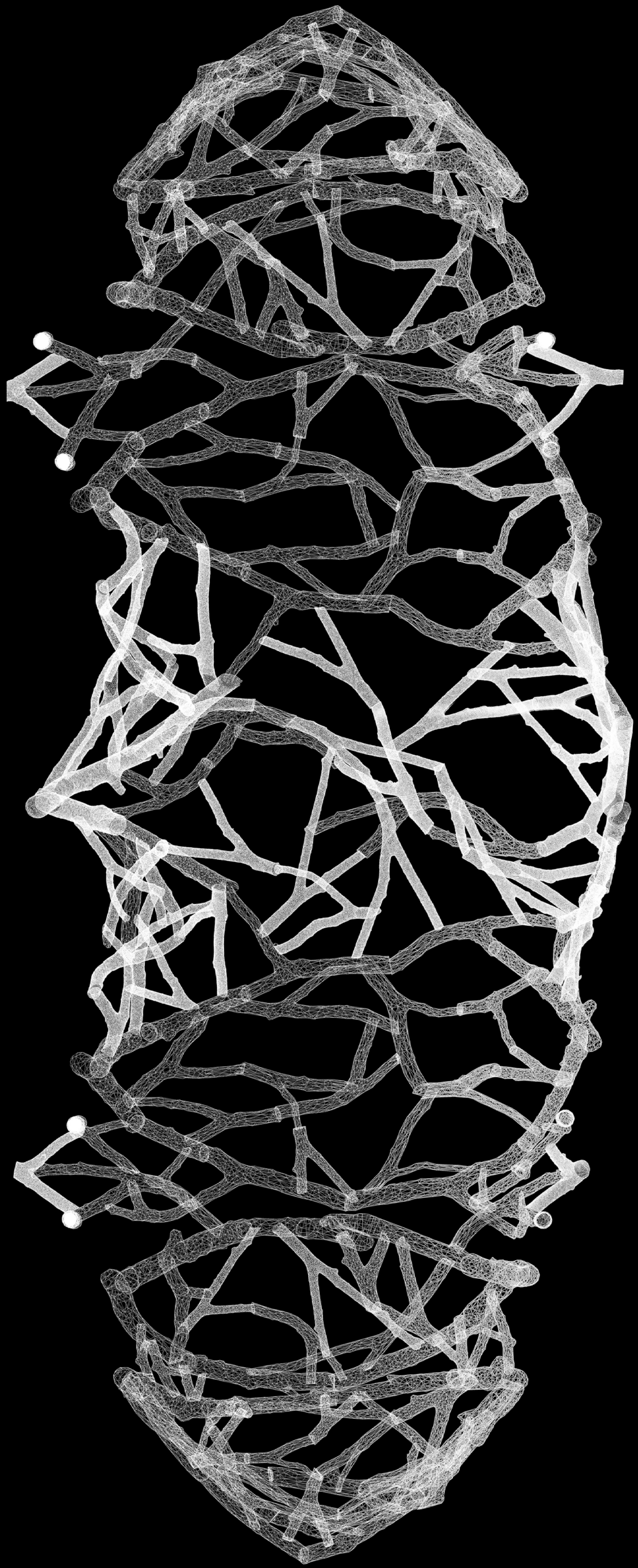

Fig. 60. Prototype 4. Structure plan.

Fig. 61. Prototype 4. Structure model in 1:25 scale.

Fig. 62. Prototype 4. Structure model in 1:25 scale.

Fig. 63. Prototype 4. Drawing of seven structure units.

Fig. 64. Prototype 4. Structure physical model in 1:25 scale.

TIMBER DETAIL DESIGN

The connection topology of raw wood connections can be categorized as follows: a) side-to-side, b) top-to-side, c) top-to-top, and d) cross-halving. Additionally, they frequently implement additional fasteners. While mechanical fasteners have become a standard practice for jointing timber assemblies due to their predictable performance and simplicity of use, research in robotic fabrication could investigate the development of intricate timber-to-timber connections that are inspired by traditional wood joinery.

Timber Detail Design is an experimental stage that involves a detailed examination of how raw wood components could be effectively joined, considering the natural irregularities inherent in the material. Through a series of experiments, a range of joinery methods were developed, each requiring both planar and non-planar cuts to accommodate the unique geometries of the raw wood.

A common technique for defining joinery for irregular timbers is to create solid connection geometries — a pair of corresponding'subtraction volumes' defined by each of the pair elements meeting at a given connection zone. In short, a joint is composed of a female and a male element that must be crafted from raw wood. These subtraction volumes consist of geometric rimitives, such as cuboids, cylinders, and truncated cones, and represent the wood material's volume needed to be removed to obtain the connection surface [8].

The joinery studies are conducted using roundwood with a diameter of two to six centimeters. These experiments resulted in the creation of milled connections using woodworking hand tools, precisely shaping each timber element to fit together seamlessly.


Fig. 65. Top-to-Side connection of a forked piece and a bent piece.

In the full-scale realization of the structure, these joinery studies will inform the robotic fabrication process, utilizing cutting and milling techniques with the precision afforded by industrial robotic arms. This precision ensures that the joining of parts can be achieved without the need for additional extension elements.

The joint studies conducted can be digitized using scanned branches, facilitating the production of robotic simulations and full-scale prototyping. For the final development of the structural prototype, multiple types of joints will be required. The spatial complexity introduced by the geometry of the parts, along with their specific locations, necessitates the use of an organization script and joinery solver for the assembly process.


Fig. 66. Close-up of milled connection.


Fig. 67. Milled piece of tree fork attached to base.

Fig. 68. Series of milled connections.

Fig. 69. Final joinery.

Fig. 70. Top-side joint.

Fig. 71. Top-side joint.

ARCHITECTURAL APPLICATION

The knowledge gained from the prototype and timber detail design stages is integrated into the development of an architectural application. The objective of this stage is to demonstrate the potential of raw wood as a durable and functional material for architecture. The design proposal centers on a novel greenhouse structure within the Gothenburg Botanical Garden.

The proposed raw-timber greenhouse will be situated adjacent to the newly built greenhouse facilities at the Gothenburg Botanical Garden. This design aims to showcase the feasibility of constructing sustainable structures using locally sourced materials. The design proposal illustrates how local resources can be effectively utilized for sustainable architectural applications, with a particular architectural language coming from the appearance of found elements.

This final design proposal incorporates the use of two layer inflated ETFE membrane cushion, highlighting the raw timber structure's capability to support such membranes. The integration of these panels presents a significant challenge, as it involves designing the membrane to complement the structure aesthetically and functionally. The ETFE outer layer is a significant benefit of the membrane design because it protects the raw timber structure from the weather.

The approach to membrane design begins with the strategic placement of anchor points for individual cushions to be fixed, which are distributed across the structure in accordance with the arrangement of the raw wood pieces. Following this, the outlines for the membrane panels are designed to ensure a cohesive and visually appealing integration with the underlying timber structure.

Fig. 72. Exterior view of the raw-timber greenhouse.

1 The Raw-Timber Greenhouse
2 Herb Garden
3 Alpine House
4 Horticultural Gardens
5 Växthusen

Fig. 73. Gothenburg Botanical Garden site plan.

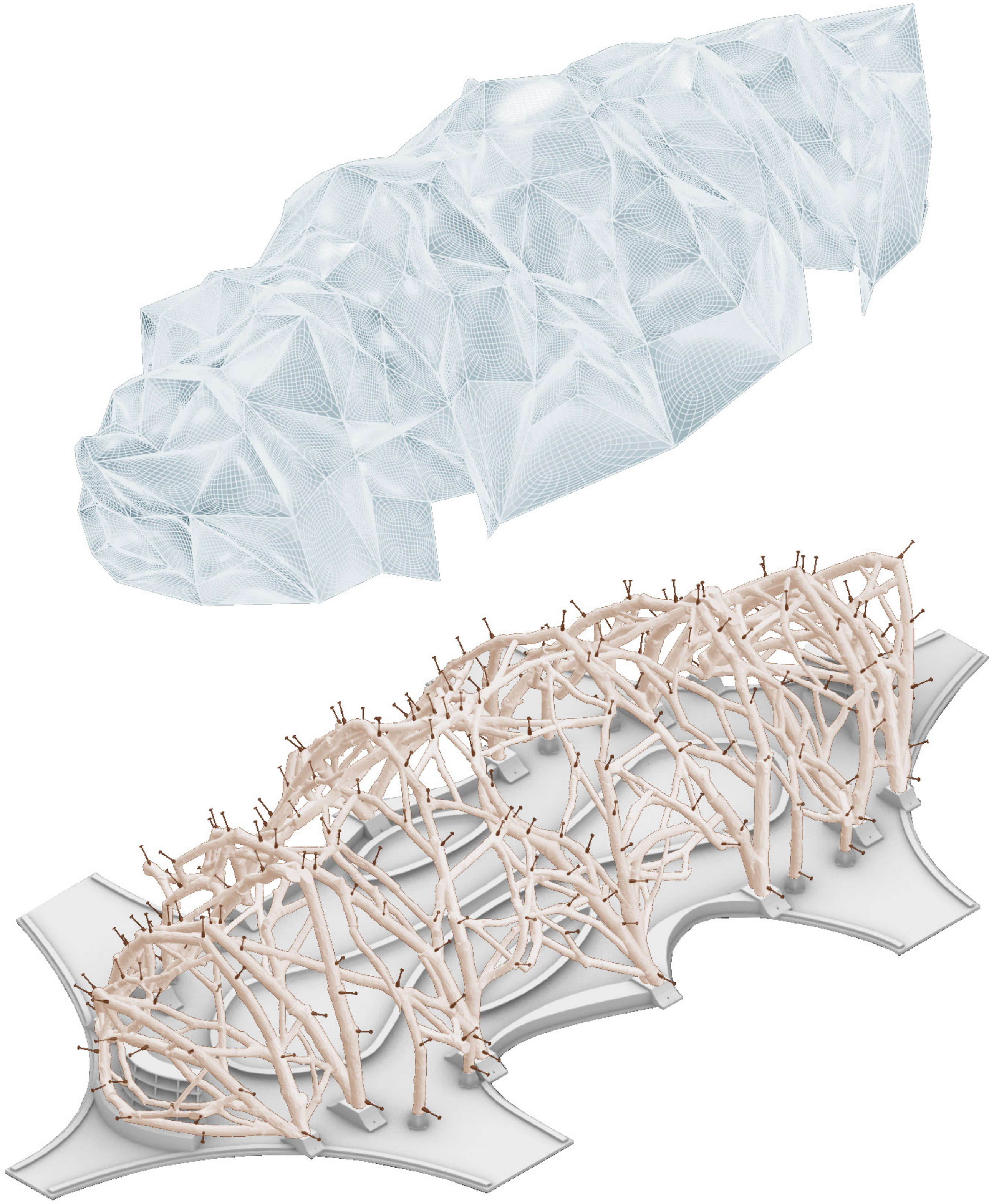

Fig. 74. Greenhouse's components. Main structure with anchor points and ETFE panels as outer membrane.

Fig. 75. Exterior view of the raw-timber greenhouse.

Fig. 76. Aerial view of the raw-timber greenhouse.

Fig. 77. Section.

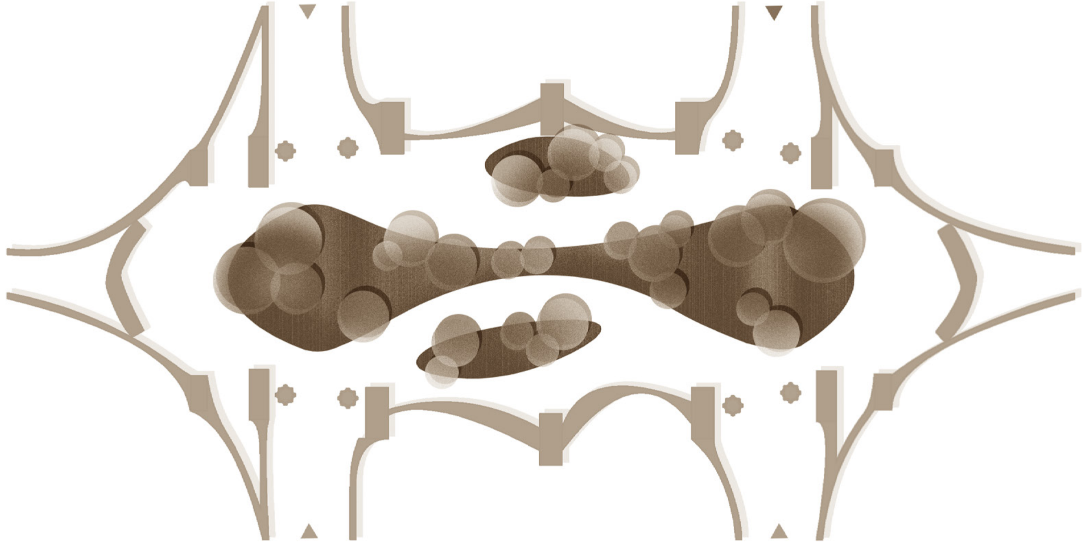

Fig. 78. Floor plan.

Fig. 79. Section.

Fig. 80. Interior view of the raw-timber greenhouse.

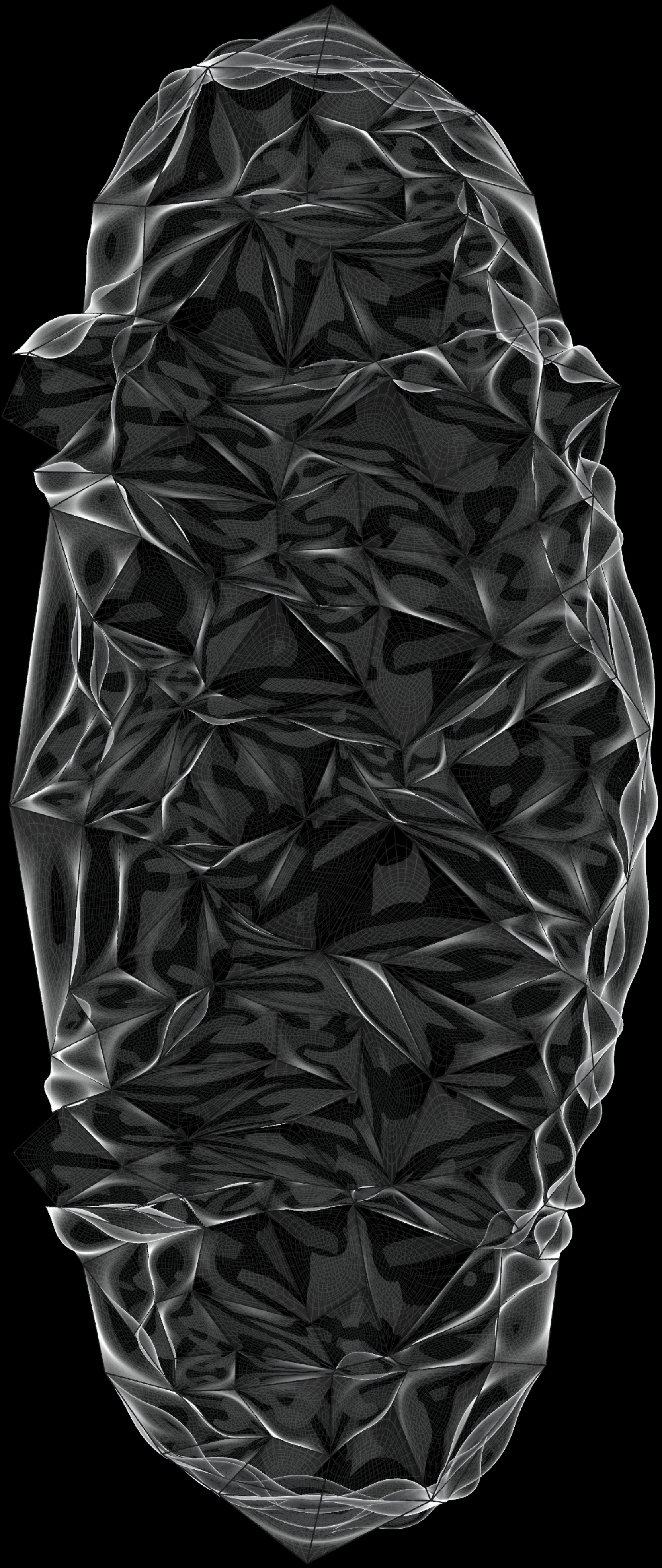

Fig. 81. Top view of greenhouse's outer skin.

CONCLUSION

Inherent Form unfolds the architectural design method for non-standard wood components. The design method is directly inspired by a growing research field addressing new ways of processing raw wood as well as initiatives at the Architectural Association's Hooke Park facilities, such as *The tree fork truss*, which utilizes Y-shaped tree trunks for construction.

There are three key explorations within this design research: the development of a structure; timber joinery studies; and architectural design, where the general concept is to collect physical branch parts for joinery testing, digitize each found branch, and establish a database of a found form that can function as the basis for specific design solutions. The design research relies on a predetermined structure design approach, aiming at adapting and fitting the found elements within a system that has been planned with them in mind rather than exploring the emergent formations based on their ability to self-organize. The structure is designed to a specific scale at first and intended to suggest potential architectural expression through its geometric properties.

To advance this design research and improve the design method, future investigations will primarily focus on refining the component placement strategies to ultimately achieve optimal structure when the original material exhibits complex irregularities. This can be achieved through the further incorporation of the following key points:

- **Development in the procedure of the inherent form organization:** It is beneficial to utilize a set of variable control modeling tools that can simplify complex forms into more straightforward geometric organizations. This rationalization will enhance the method for structural member placement, which could inform the joinery strategies.
- **Comprehensive Branch and Structure Analysis:** Capturing a branch's form involves more than merely recording its visual appearances. with tools such as photogrammetric software. It also necessitates non-destructive techniques to formalize the branch's specific physical, mechanical, and inherent behaviors. This holistic approach ensures a thorough understanding of the material properties, which is crucial for structural simulation.
- **Joinery Solver:** To integrate the use of an algorithm aiming at geometry generation for pair-wise wood-wood connections, it will help facilitate the connection method, which in the context of this study depends on the complex element orientation.

Fig. 82. Details of a final structure model.

VISUAL REFERENCES

Fig. 4.	Kasey Vliet, Peter von Bülow, & Steven Mankouche. “Limb”. 2018.
Fig. 5.	Zachary Mollica. “Tree Fork Truss”. 2015.
Fig. 6.	Zachary Mollica. “Tree Fork Truss”. 2015.
Fig. 7.	Zachary Mollica. “Tree Fork Truss”. 2015.
Fig. 8.	Steven Mankouche. “Limb”. 2018.
Fig. 9.	Lukas Allner, Daniela Kroehnert, & Andrea Rossi. 2020.
Fig. 10.	Lukas Allner, Daniela Kroehnert, & Andrea Rossi. 2020.
Fig. 11.	Jeremy Bilotti. “Log Knot”. 2018.
Fig. 12.	Zachary Mollica. “Mother Maple”. 2021.
Fig. 13.	Anders Aagaard, & Niels Martin Larsen. 2020.
Fig. 14.	Anders Aagaard, & Niels Martin Larsen. 2020.
Fig. 15.	Petras Vestartas. 2021.
Fig. 16.	Petras Vestartas. 2021.
Fig. 17.	Petras Vestartas. 2021.
Fig. 18.	Emmanuel Vercruysse, Zachary Mollica, & Pradeep Devadass. 2019.
Fig. 19.	John Munson. 2019.
Fig. 20.	Leslie Lok, & Sasa Zivkovic. 2019.

All other drawings and images by the author.

BIBLIOGRAPHY

[1] Bianconi, F., Filippucci, M. (2019). Digital wood design: innovative techniques of representation in architectural design.

[2] Braumann, J., & Brell-Çokcan, S. (2011). Parametric Robot Control: Integrated CAD/CAM for Architectural Design. ACADIA proceedings.

[3] Hoadley, R.B. (2000). Understanding Wood: A Craftsman’s Guide to Wood Technology. 1st edition. ed. The Taunton Press.

[4] Allner, L., Kroehnert D., & Rossi, A. (2020). Mediating Irregularity: Towards a Design Method for Spatial Structures Utilizing Naturally Grown Forked Branches. in Impact: Design With All Senses, C. Gengnagel, O. Baverel, J. Burry, M. Ramsgaard Thomsen, and S. Weinzierl, Eds., Cham: Springer International Publishing.

[5] Kerezov, A.D., Koshihara, M., Tachi, T. (2023). From Natural Tree Forks to Grid Shells: Towards a Self-forming Geometry. In: Cheng, LY. (eds) ICGG 2022 - Proceedings of the 20th International Conference on Geometry and Graphics. ICGG 2022. Lecture Notes on Data Engineering and Communications Technologies, vol 146. Springer, Cham.

[6] Kolarevic, B. (2005). Performative Architecture - Beyond Instrumentality. Spoon Press.

[7] Ramage, M.H., Burridge, H., Busse-Wicher, M., Fereday, G., Reynolds, T., Shah, D.U., Wu, G., Yu, L., Fleming, P., Densley-Tingley, D., Allwood, J., Dupree, P., Linden, P.F., Scherman, O. (2017). The wood from the trees: The use of timber in construction. Renewable and Sustainable Energy Reviews.

[8] Mollica, Z. (2016). Tree Fork Truss: An Architecture of Inherent Forms. Design and Make. URL:http://zacharymolli.ca/assets/download/Mollica-DMThesis-Tree-Fork-Truss-an-Architecture-of-Inherent-Forms.pdf.

[9] Stanton, C. (2010). Digitally Mediated Use of Localized Material in Architecture.

[10] Vercruysse, E., Mollica, Z., & Pradeep, D. (2018). Altered Behaviour: The Performative Nature of Manufacture Chainsaw Choreographies + Bandsaw Manoeuvres. In Robotic Fabrication in Architecture, Art and Design.

[11] Vestartas, P. (2021). Design-to-Fabrication Workflow for Raw-Sawn-Timber using Joinery Solver [Doctoral dissertation, Swiss Federal Institute of Technology Lausanne]. EPFL scientific publications

[12] Živković, S., Havener, B., & Battaglia, C.A. (2020). LOG KNOT: Robotically Fabricated Roundwood Timber Structure. Open.

[13] Živković, S., & Lok, L. (2019). Ashen Cabin. Open.

Parjaree Manuch holds a Bachelor of Science degree in Architectural Design from the International Program in Design and Architecture at Chulalongkorn University. With a background in practicing architecture in Thailand, she has gained hands-on experience in hospitality and residential projects, where her focus extends beyond design to encompass construction aspects as well. Parjaree also worked in interior design, further enhancing her understanding of the intimate scale of architectural work. She is interested in craftsmanship and the utilization of digital tools in architectural design, which she has investigated in her Master Thesis at Chalmers University of Technology in Sweden.

I want to thank the following people who have been important to this work:

My family in Thailand for always rooting for me.
Jonas Lundberg for instructive guidance.
Bongkodpast Tantipisanu for making impossible tasks possible.
Erica Hörteborn for sharing valuable ideas.
Tabita Nilsson for showing me the right techniques.
Chalmers Fuse for model-making tools and materials.
Eylül, Jiaming, Xiaofei, and August for help.
My friends in Thailand for constant encouragement.

I dedicate this thesis to my father, who was my tree.

Parjaree Manuch
parjaree.manuch@gmail.com