A Process of Innovation: Technological Development in Wood Construction

by

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DALHOUSIE UNIVERSITY

SCHOOL OF ARCHITECTURE

The undersigned hereby certify that they have read and recommend to the Faculty of Graduate Studies for acceptance a thesis entitled “A Process of Innovation: Technological Development in Wood Construction” by Samuel E. Lock in partial fulfilment of the requirements for the degree of Master of Architecture.

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ABSTRACT

This thesis explores the use of small diameter, round timber in the construction of lightweight gridshell structures. The project intention is to develop a simple and accessible construction method, based on locally available material that embraces a diverse range of technology. The design is developed using a material based approach, which first explores the behavior and limits of the material through testing at full scale. This information is used in a rapid prototyping process of scale modeling which focuses on material and construction sequence to develop a structural system. Using available materials as a design parameter, the work is an exploration of how the gridshell system can be adapted to the specific context of rural Nova Scotia. This design method is explored through the design of a craft school at the Ross Creek Centre for the Arts in Ross Creek, Nova Scotia, Canada.

ACKNOWLEDGEMENTS

Thanks Nic, for your support. We did it!

CHAPTER 1: INTRODUCTION

> The form of a structure arises in a specific model-medium on the basis of objective principles. The degree of freedom exercised in forming the structure lies not so much in the molding itself as in the choice and definition of the basic conditions under which the form determination takes place.[1]

Topic

This thesis explores lightweight compression structures, as pioneered by Frei Otto and the Institute of Lightweight Structures. It takes the ideals of structural efficiency that these systems represent, and applies them to the specific context of the site and program. Using available materials as a design parameter, the work is an exploration of how the system could adapt to the specific context of rural Nova Scotia.

The main design challenge when working with shell structures is form finding. Using the established research in form finding as a baseline I explore how material, landscape and program can influence this process.

Wood harvested directly from the site makes up the material palette. The surrounding early successional forest offers several types of small diameter timber or pole timber, which is currently marginalized by standards in forestry and the building industry. My intention is to create a new use for this material. The work explores ways in which small diameter timber can be used in the design of a grid shell.

The design method involves testing of the wood available on site, to evaluate its capabilities in bending at full scale.

1 Frei Otto, *IL 10. Gridshells* (Stuttgart: University of Stuttgart, 1974), 7.

The information gathered in this process is used in a process of physical modeling, which establishes a structural form. In this way the material itself informs the shape of the architecture.

Rather than observing nature on a microscopic level to mimic the internal structures, the proposed method of material based form finding lets the macro-level properties of the material guide the explorations.

Thesis

This thesis explores ways in which material understanding can spark innovation in design and construction processes. The term innovation in the context of this thesis refers to a form of incremental innovation as defined by engineer Joseph F. Engelberger. According to Eingelberger innovation requires a recognized need and the application of relevant technology.[2] In this case the recognized need is the underutilized small diameter timber of the forests of Nova Scotia, to which relevant low tech methods of local construction practice are applied to develop the design.

The design process focuses on the sequence of construction and on establishing material parameters. By isolating material driven methods of design I find innovative solutions that arise from the specific behavior of the round timber. The success of this method is evaluated by large scale tests of the structural system in a 1:2 model. The work contributes to a continuum of research in grid shell structures by developing an additional materials based approach, to link the global idea of the shell to the local context. By cre-

2 *J. F. Eingelberger, "*Robotics in Practice: Future Capabilities*" Electronic Servicing and Technology magazine* (August, 1982), 18-26.

ating a link to the forest in the processes of design, material becomes my main focus.

My intention is to develop a simple construction method, suitable for local trades. It requires a diverse range of technology and the use of locally sourced materials.

The concentration on local material and trades might contribute to the preservation of regionally specific crafts and thus might contribute to rural economic growth.

Ethically, the project is based on an economy of means, using minimum amounts of material to reduce environmental impact. Working with small diameter timber might create a new local use for this under utilized material. Using small diameter timbers in building should increase the efficiency with which local forests are managed by creating a new market for wood.

Forestry In Nova Scotia

The design intention of this thesis is to develop a building practice that is well suited to the current forests in the province and that will align with sustainable management strategies for the future.

Forestry has been an important component of Nova Scotia's economy since the time of early European settlement. Demands on the forest have changed and intensified over time. Forests not only provide wood to support the forest industry, but are also recognized for their contribution in providing wildlife habitat, recreational areas and providing cultural and spiritual heritage.

In the early years of harvesting in the province, much of the old growth forest in the province was cut, and the largest and most valuable lumber removed.[3] The resultant forest is new growth stands that are not well developed and as the demand continues to increase, the cutting continues.

Early successional forest at Ross Creek, Nova Scotia. This forest, which has been recently clear cut, now thrives with shade intolerant trees. Poplar, birch and red maple spring up, and grow until they are thinned out by natural selection or as a method of silviculture. These small diameter timbers represent an under-utilized forest product.

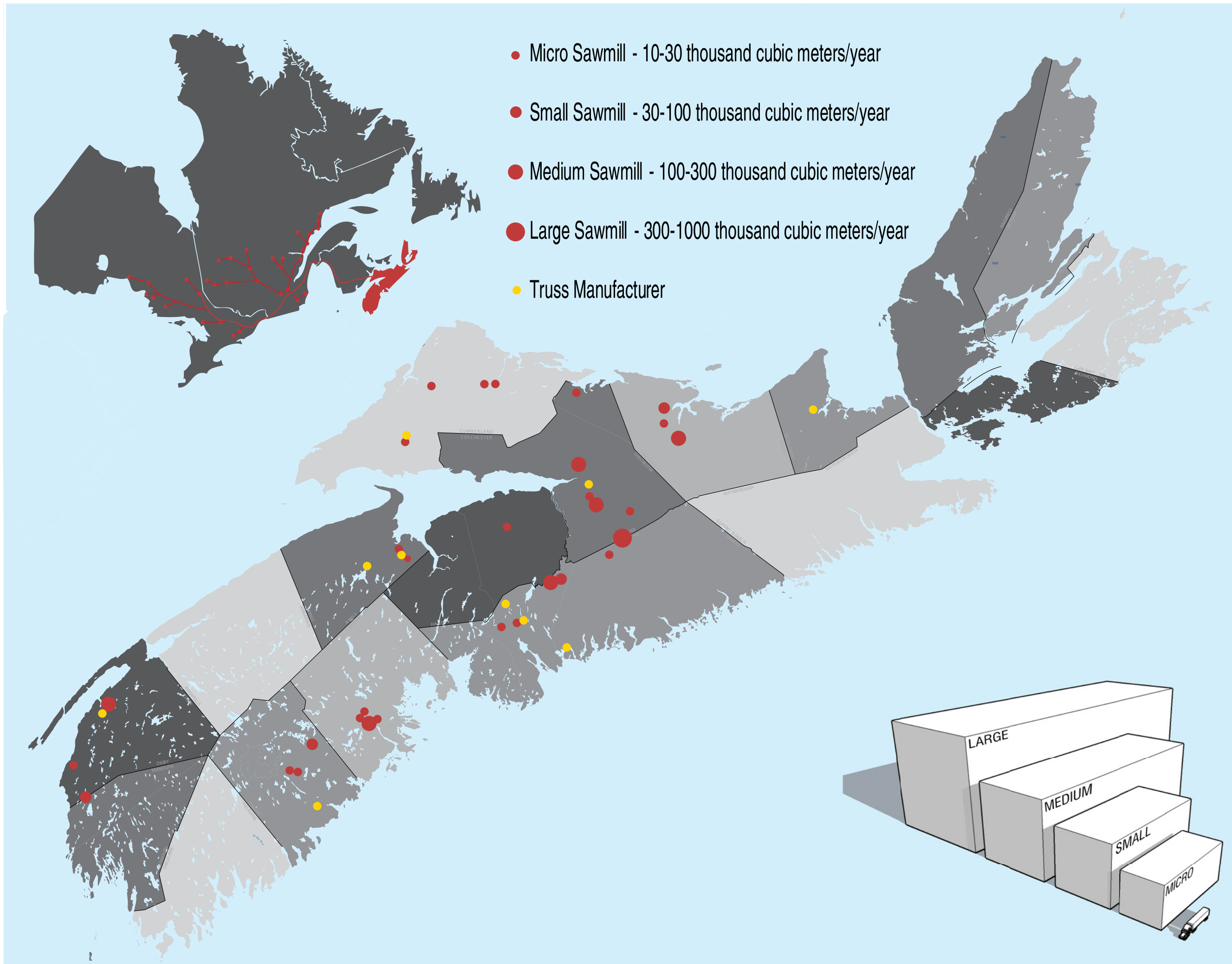
3 Ralph S. Johnson, *Forests of Nova Scotia: A History* (Halifax: Four East Publications, 1986), 63.

Most of Nova Scotia's timber products today come from out of province. Larger operations in Ontario and Quebec are able to produce a more standard product for cheaper, simply because of the scale of the operations. Forests in Nova Scotia are now primarily used for pulp and paper, which dictates the type of forest management that is practiced.[4] Pulp wood is harvested when it is immature, and most often clear cut so that the bulk of the forests are never given a chance to properly mature and develop into the types of landscapes capable of providing ecosystems, recreation areas and the other 'non forestry' uses.[5] Pulp and paper harvesting also means that there is less need for milling in the provinces forestry sector. Mills have been closing down steadily over the past 100 years.

Clifford Long & Sons Sawmill: closed in 2009, leaving two remaining sawmills in Kings County.

4 Greg Levy (owner and operator of S.G. Levy & Sons Sawmill).

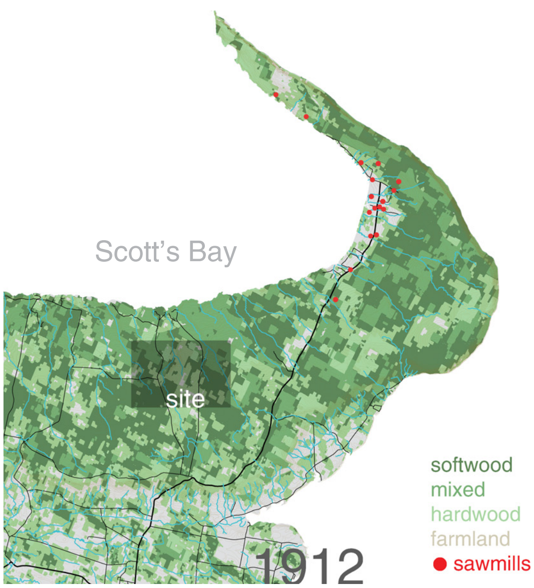
5 Canada/Nova Scotia Cooperation Agreement for Forestry Development, *Nova Scotia's Forest Management Strategy* (Ottawa: Canada/Nova Scotia Cooperation Agreement for Forestry Development, 1994), 7.



Map of sawmills and truss manufacturers in Nova Scotia. Base map from Nova Scotia Government. Statistics from Natural Resources Canada.

Forestry in King's County

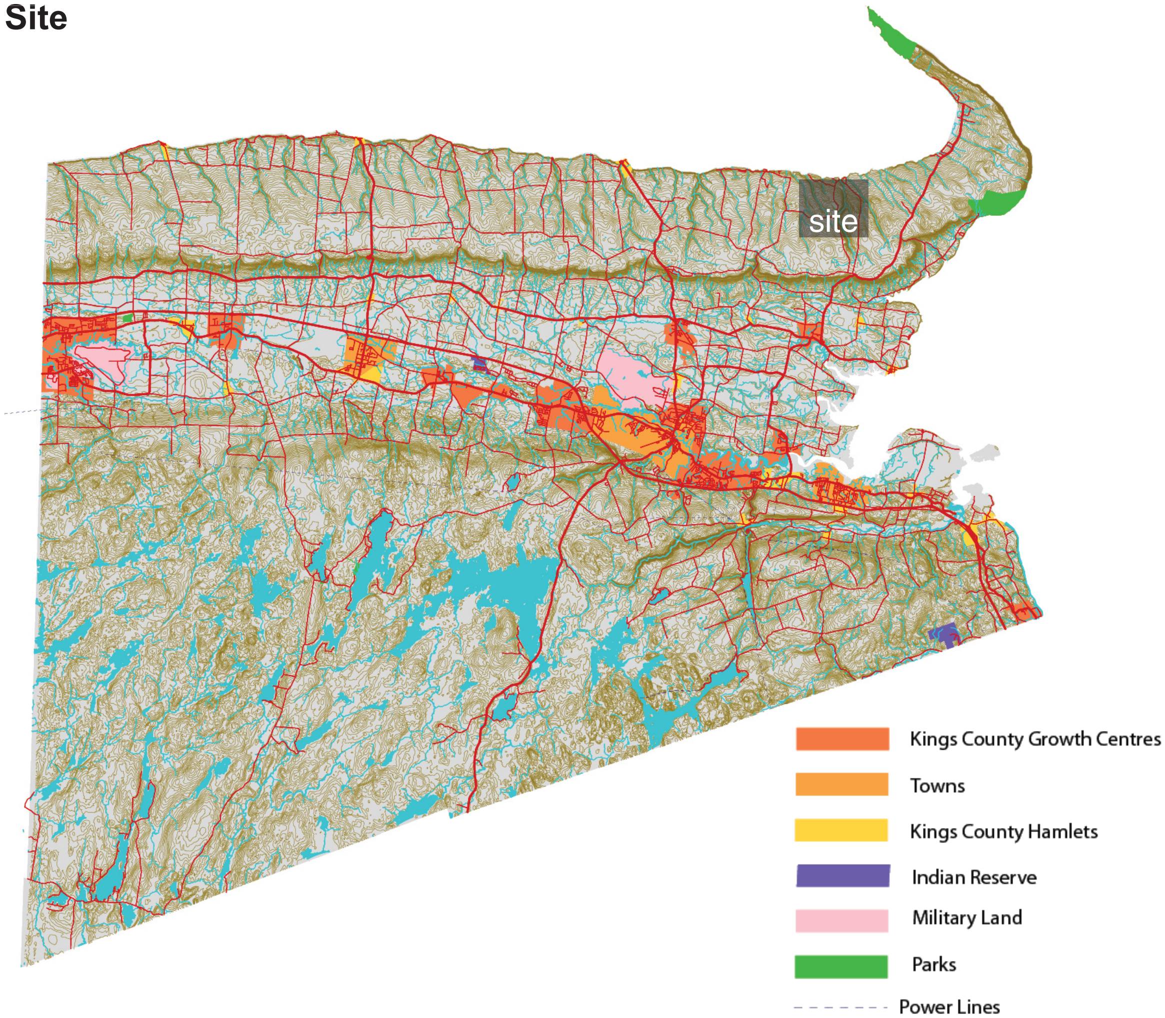
Forestry is a historically significant practice on the North Mountain. Logging, milling, and shipbuilding were the first industries in the Scots Bay area of Kings County, Nova Scotia. At the end of the 19th century, as many as 18 sawmills operated along the Scots Bay Road. The mills were supplied by loggers from the surrounding forest. Every creek running off the mountain into Scots Bay had a sawmill, that supplied shipyards in the bay, and also delivered timber by barge to Parrsboro, and as far as New England.[6] Today two small scale mills operate in the area. The scale of production can't compete with large scale operations. The forest patterns have also changed over the years. Areas that used to be primarily hardwood forests, now are predominantly softwoods. The forests are cut regularly for fuel wood and pulp and paper.



Two maps comparing forest types and number of mills on the North Mountain 1912 and 2011. Content from Archaeological Survey of Scots Bay Mills and Shipyards. Base map from Nova Scotia Government.

6 Ralph S. Johnson, *Forests of Nova Scotia: A History* (Halifax: Four East Publications, 1986), 96.

Site

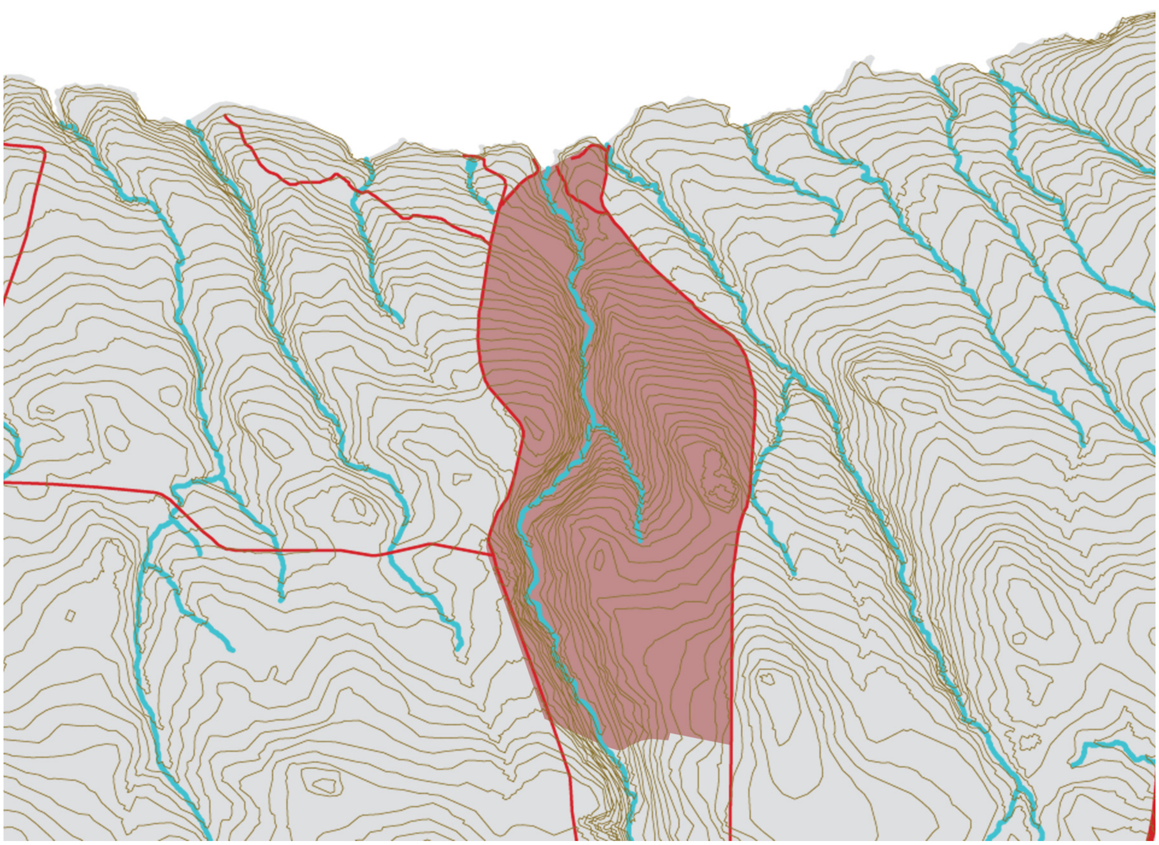


Map showing the location of the site in its context. Base map from Nova Scotia Government.

The proposed site for this study is the Ross Creek Centre for the Arts. The rural arts centre runs camps for children, as well as hosting resident artists. The centre is built around a renovated cattle barn, and opens on to 186 acres of land on the North Mountain of Nova Scotia's Annapolis Valley. Grand views to the Bay of Fundy and the valley below serve as inspiration to the artists as they create work in this rural environment. The centre's property, consisting of cleared agricultural land and forest, serves both as an inspiration and space for recreation for the facility. The centre is a cultural hub in the rural community, supporting fine art, performance art, and music as well as film and technology. It contributes to a healthy tourism economy in the Annapolis Valley, hosting performances, open houses and activities in all seasons geared towards a wide range of age groups.

The neighboring property is a woodlot, owned by the Minas Basin Pulp and Paper Company. The property stretches between the Ross Creek Arts Centre to the south and the shore of the Bay of Fundy to the north. For the purposes of this thesis, this property will be included as part of the site.

The total site including the arts centre property consists of 720 acres. This working forest will serve as the study area and connect the design process to the processes of woodland management and harvesting.



Map highlighting the total 720 acre site within the context of the north side of the North Mountain. Base map from Nova Scotia Government.

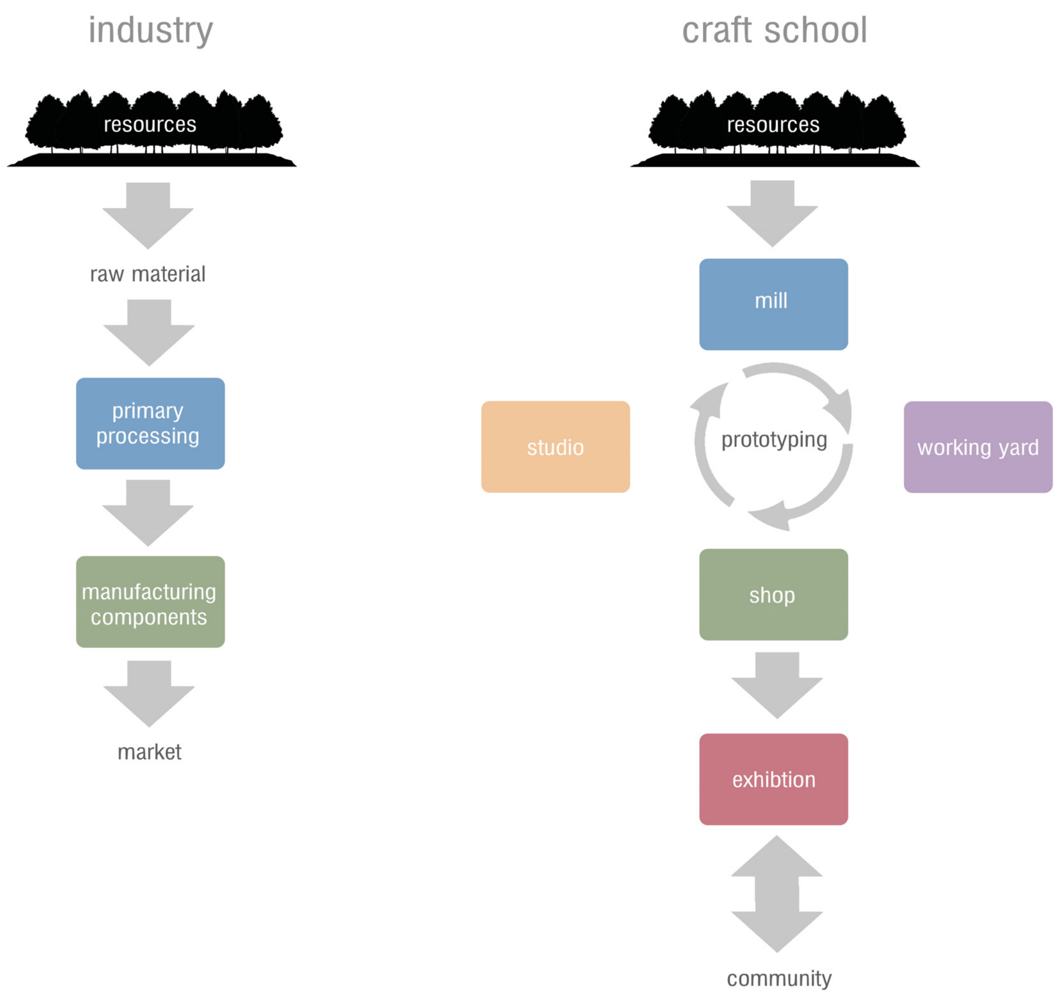
Program

The program for the thesis is a craft school. The school is intended to promote innovation in wood construction, with a focus on the whole life cycle of wood as a material. The site offers 720 acres of forest, which would be utilized as a teaching tool and provide all the wood for the program. The school would offer certificate courses in wood for students in engineering, architecture and trade schools, as a part of their traditional education. It is envisioned as a series of intensive programs lasting several weeks each immersing the students in the forest where they learn about wood as a material form the forest to finished building. Longer term residence programs would also be part of the school, giving students a chance a chance to fully develop their ideas, adding to local technical knowledge and to locally available skills.

The school would work with students who practice conventional wood frame construction and educate them about the possibilities of whole wood construction. It would explore new types of construction through study of the material in all phases of processing. Students would accompany wood through forest management, harvest, transport, processing, design and building. Students would gain an appreciation of the energy embodied in the building material and observe information contained in the wood itself. The organization of the program is intended to reflect the processes of the forest and construction industry, so that the process can be followed in a clear way.

The facilities would include a mill, large workshop, studios, classroom spaces, a lecture hall and an exhibition space.

In this proposal the main aspect of the educational process are prototyping and testing new ideas and designs. Full scale mock-ups are constructed in the large working space and on the landscape. By working with the wood at full scale, without the stringent control of standards and codes, students would gain an understanding of the possibilities offered by the material. The students, as the provinces next generations of builders and designers, would emerge with skills to make innovative design possible in the construction industry.



This diagram illustrates the typical linear process that timber goes through in the building industry (on the left) and the process as it would happen in the school (on right).

Forest Feedback Loop

The School is intended to create a feedback loop with the forest. Information gained in the management and harvesting of trees informs the processes of design and in return, the design and prototyping work informs the way that the forest is managed and harvested to serve innovation. The parts of the process, separated in traditional models, are more integrated, developing together and informing each other. The design is intended to be didactic, in that it tells the story of its own making through traces that remain in the finished structure.

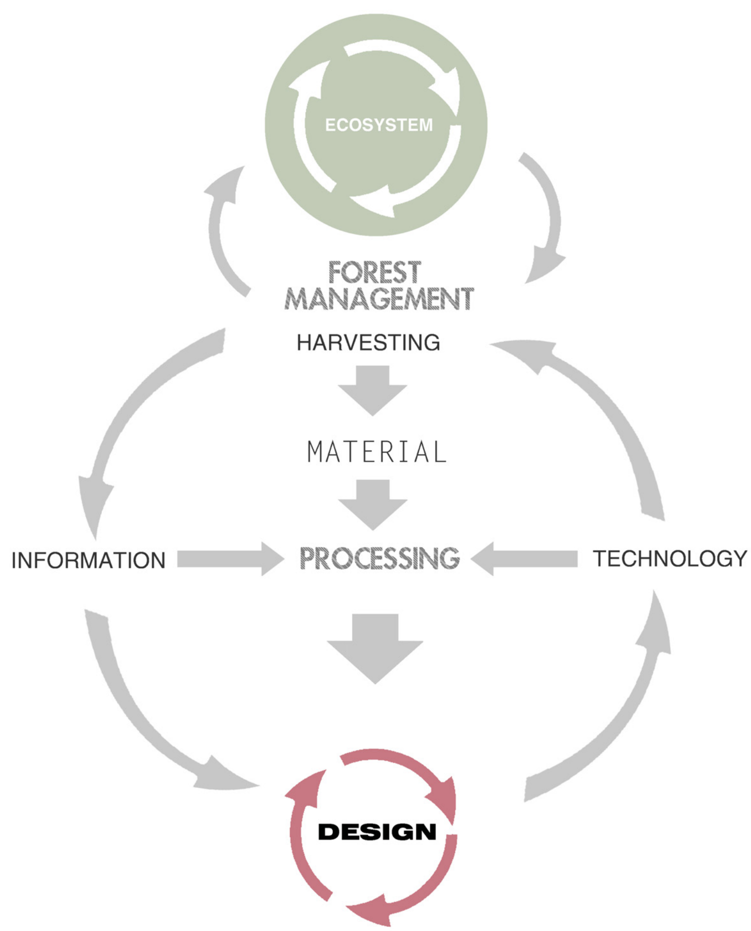
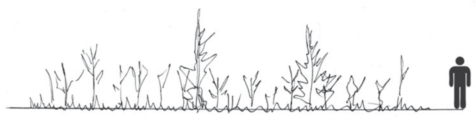


Diagram illustrating the proposed relationship between the forest and the design process, allowing each one to influence the other.

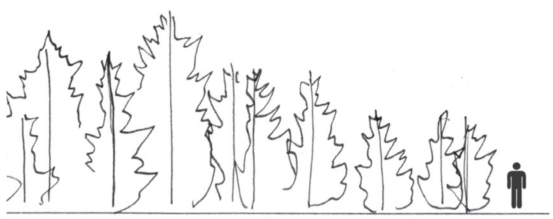
Satellite image: Summer. Google Maps.

Satellite image: Winter. Google Maps.

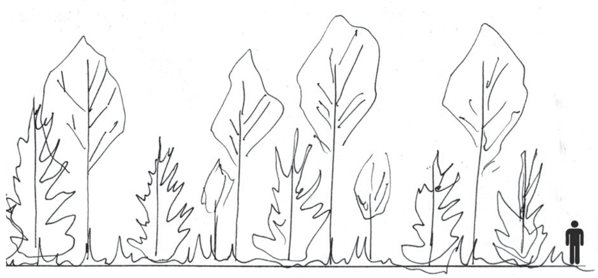
Secondary Succession Forest
Area recently clear cut, dominated by shrubs and small saplings. Species: poplar, red maple (shade intolerant species)



Young Softwood
Dominated by spruce trees, dense growth.



Young Mixed
Hardwood & softwood - white birch, poplar, red maple, spruce & pine.



Young Hardwood Stands
White birch dominant over poplar and spruce saplings

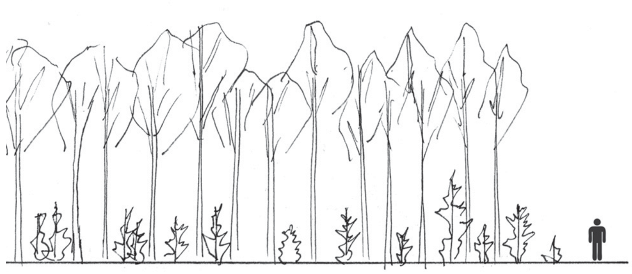
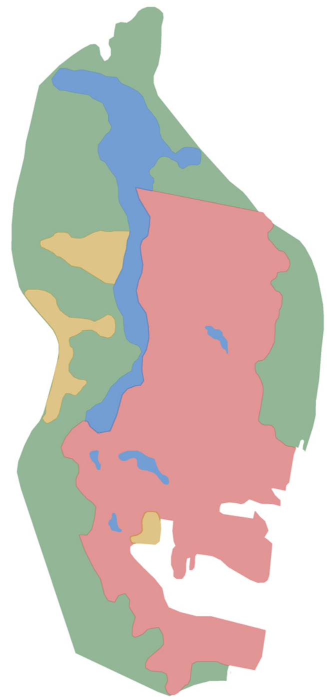


Illustration of forest types. For detailed map of forest types in their context see Appendix A.



Distribution of forest types in study area.

Thinning
Removal of trees so that others in the stand will grow faster. These thinnings are an under utilized forest product and will be tested as this stand grows. Thinnings are divided into to categories; pre commercial thinning of saplings and commercial thinning of pole timber.

Shelter wood
A uniformly thin overstory is maintained to produce light conditions suited for desired species. The remaining overstory must be harvested when suitable regeneration in the understory.

Selective Group Cutting
A process of harvesting patches of trees to open the forest canopy and encourage the reproduction of uneven aged stands.

Special Management Zone
Forest stands along a stream are delicate. They are highly susceptible to soil erosion and extreme windfall if improperly managed. This zone also has some of the most mature trees on the property.

Description of forest management zones

Distribution of forest management zones in study area

Coppicing

Coppicing is a method of harvesting dimensionally diverse pole timber from a previously cut stool. The practice makes use of, and nurtures, well-established root systems and it uses selective cutting methods in order to sustain a robust and resilient forest ecosystem. Because of the well established root system the poles grow very quickly and can be continually harvested on a cyclical basis.

Coppice stool sketch

Small Diameter Timber

Because the forests areas are largely in early succession stages, the initial focus of the program will be small diameter timber. Small diameter timber is a forest product group which is under utilized and growing in value due to the reduced amount of available saw timber. The trees are measured and grouped by their diameter at breast height (dbh), a standard measurement of a tree’s diameter, usually taken at 4 1/2 feet above the ground. The classifications are:

Sapling - 1” - 4” dbh

Pole Timber - 4” - 10” dbh

Saw timber - 11” - 18” dbh

Large Saw timber - 18” + dbh

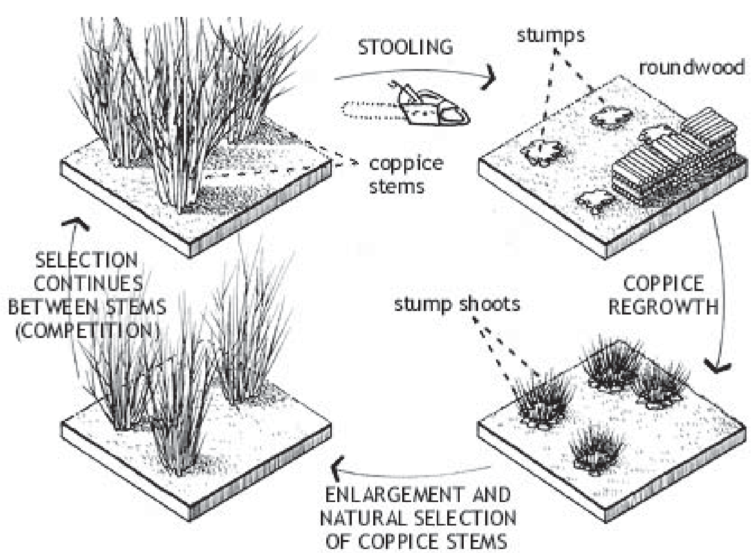


Diagram showing the cycle of a coppice. From Arbourtec Tree Care.

User Groups

The proposed school is designed to accommodate between 25 and 40 students at one time. Also, 4 or 5 teachers and up to 100 guests at any time view an exhibition or observe the processes of the school.

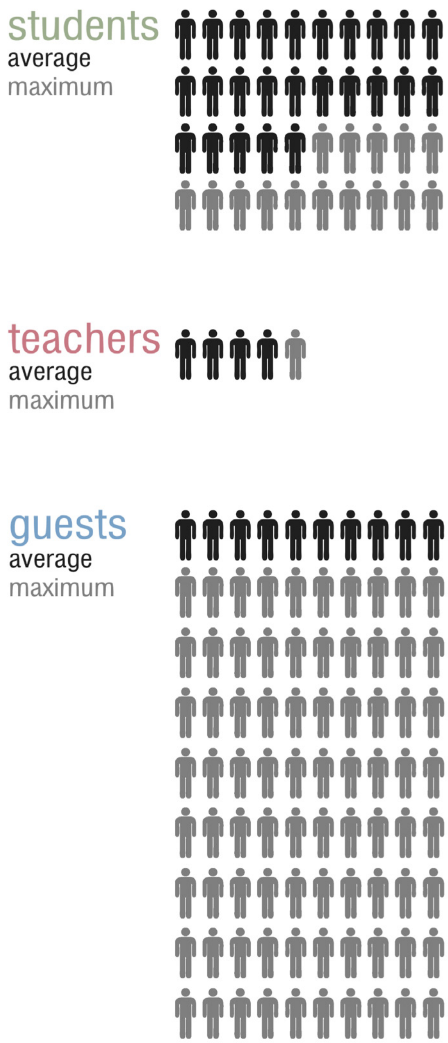


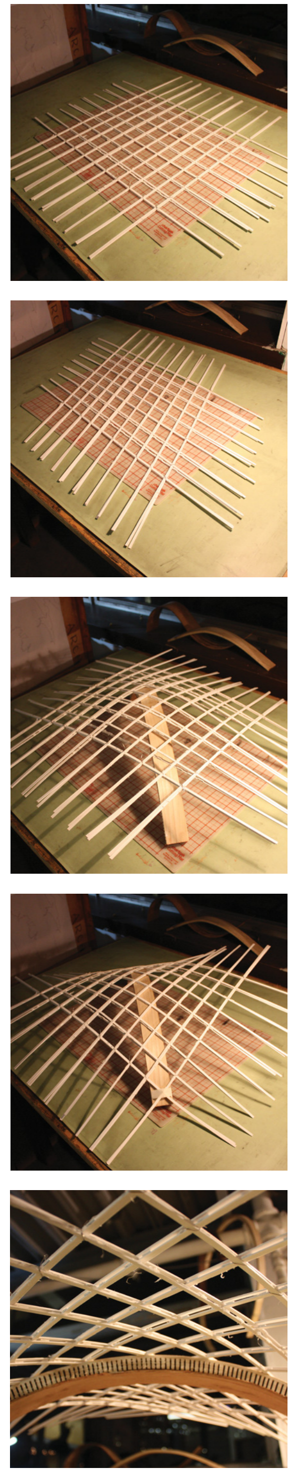
Diagram illustrating the average and maximum numbers of different user groups.

Method

The design method for this thesis is based on a notion described by philosophical writer Richard Sennet, in his book *The Craftsman*, that "making is thinking". He argues that "when the head and the hand are separated, it is the head that suffers; both in understanding and expression." [7] My working method tests his theory by isolating the act of making as a tool for design. I challenged myself to work by hand using physical models, working with a real material in an attempt to learn through experience like a craftsman.

Frei Otto pioneered the form finding of gridshells with his physical models, which are well documented in the publications of the Institute of Lightweight Structures. Although the use of physical models to determine structural optimization has been made obsolete by the available computer analysis and 3D modeling, I worked by hand to gain a better understanding of the dynamics of the gridshell system. I believe, that by working in this way I can better understand the subtle stresses in the structure, through a physical interaction.

My first explorations were funicular models using hanging chains, finding optimum thrust lines, and thrust surfaces. Although this type of modeling has been extensively documented, in almost infinite variations, by Frei Otto, my exploration in this medium was to gain an intimate understanding of the shapes of catenary curves, through creating them by hand.



Model exploration of dynamic gridshell formation process

7 Richard Sennett, The Craftsman (New Haven: Yale University Press, 2008), 7.

My hypothesis is that the information collected through my hands in making these forms, is internalized and translated forward into other types of models, almost as an unconscious knowledge, allowing me to find efficient and expressive forms, that I would not have otherwise found working in a digital model. From these initial models I moved into gridshell system models in wood or card, applying the principles, to the real material.

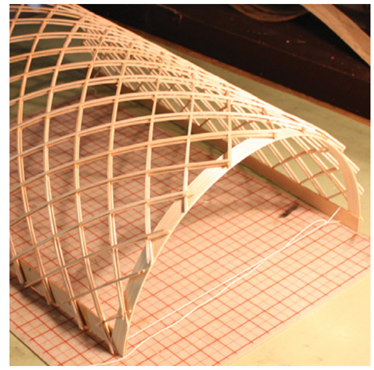
My design process involved circling back, through certain processes as information was gathered, following the model of rapid prototyping, where ideas are tested quickly, to evaluate their merit. As the forms are to be based on the types of wood available on site, the explorations focused on modeling using analog materials, that perform in a similar manner to the real material.

In the deign process I attempted to be conscious of the tools of design, and what implications they have on the design itself. This was achieved by embracing different mediums of modeling.

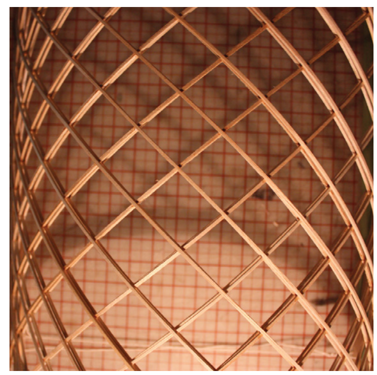
The material as the primary design parameter dictated the expression of the form, in an attempt to best facilitate the programmatic requirements. In the proposed project, the landscape determines the ‘support conditions’ of the model, which affects the form of the gridshell. In this way the form arises out of material, site and program.

Gridshell

Grid shells are curved structures made up of crisscrossing laths, which are assembled as a flat matt, and then raised or lowed into position and secured to 'find' their final shape. Gridshells have the properties of shell structures, they gain strength and stiffness through curvature. Shells with double curvatures are the most efficient in terms of minimum use of material.



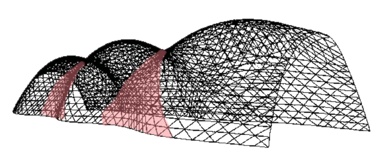
Frei Otto was a pioneer of many types of lightweight construction including gridshells. From 1946 - 1949 Otto extensively modeled suspended fabric to find forms suitable for vaulted roofs. From 1950-51 he explored thrust line and thrust planes through hanging chain and hanging nets. An inverted thrust plane represents the ideal form of a lightweight compression structure.



Otto explains their motivation in *IL 10*, "to span the widest space possible without inner support and to build adaptable structures with a minimum expense".[8] Prefaced with a survey of the most important examples of compressive stressed vaulting found in the past, the publication lays out a long continuum of research, that I am working within and building upon.

Gridshell structure study models.

A common gridshell shape is the undulating tunnel vault, that can be seen in Shigeru Ban's Japanese Pavilion and Ted Cullinan's Downland Gridshell. The undulating shape provides a three-dimensional curve to deal with the lateral strain along the long side of the structure. Highlighted on the right, the valleys provide lateral strength.

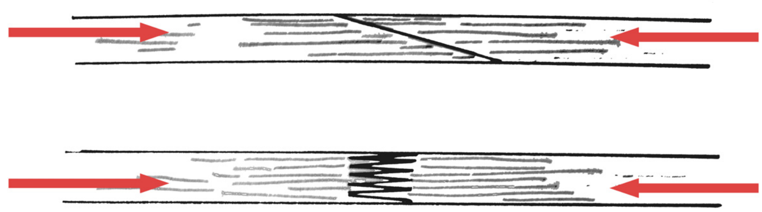


Valleys provide lateral stability

8 Frei Otto, *IL 10. Gridshells (*Stuttgart: Universtiy of Stuttgart, 1974), 10.

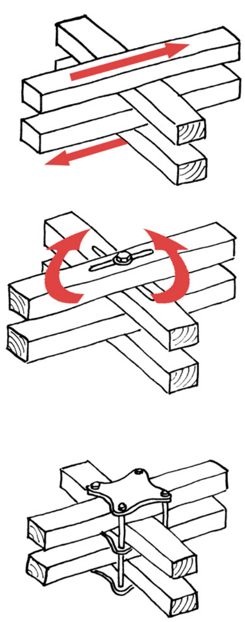
Critical Connections

The gridshell lattice is made up of long continuous lathes, created from shorter members. The end to end connection needs to withstand shear forces as they are loaded in compression. Typical connections shown below are the scarf joint and the finger joint.



End to end connections. First: scarf joint, Second: finger joint.

Nodal connections, shown below, must allow for rotation about the centre point and for outer layers to slide parallel to inner layers. They can be dealt with by pin connection with a slot or binding connection.



Nodal connections

Design Precedents

Mannheim Multihalle - Frei Otto

Built in 1975 for the Rural City Exhibition. It was meant only to be temporary, so it didn't have to pass rigorous standards, however the building was such a success that it remains in place today. The building is the result of an extensive form finding process, which is well documented in IL 13.

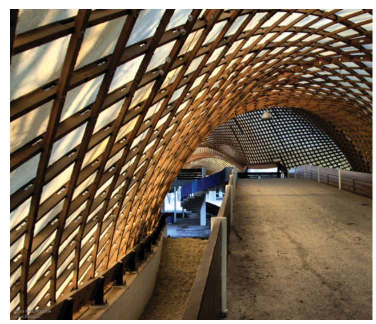
Connection detail of the Multihalle by Frei Otto. Image from Foto.SC

Dimension: 72m long, 35m wide, 15.5m high, area- 3600m^2

Material: 50mm x 50mm hemlock pine

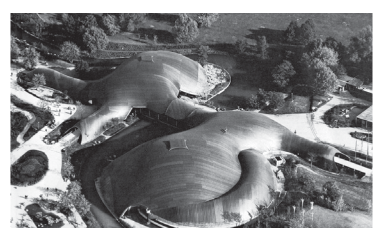
Connection: Bolt connection with milled slot

Process: The lattice was assembled flat on the ground and then raised into place using scaffolding, tripods and fork-lifts.



Interior view of the Multihalle. Image from Foto.SC

Influence: The Multihalle exemplifies the extreme possibilities of a timber shell in covering large flexible interior spaces. The study provides a lesson in the shapes that can be produced by gridshells as the form finding process involved hundreds of scale models and developed a catalogue of forms and shapes that the gridshells can generate when hanged. Problems encountered in the construction involved a dangerous process of lifting the lattice from a flat matt on the ground, intensive requirement for scaffolding and the pin connection used at the nodal connections. The connections weakened the laths at those points and lead to over 11,000 laths breaking during the construction process.



Aerial view of the Multihalle by Frei Otto. From Otto, *IL 13*

Downland Gridshell - Edward Cullinan

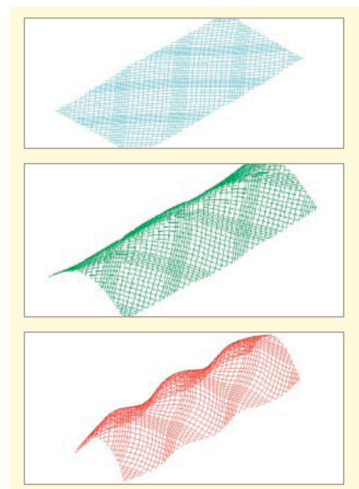
This building was the first double layered gridshell to be built in the UK. It serves as a shop for restoring and storing artifacts at the Weald and Downs open air Timber Construction Museum. The museum sought a design that would reflect craft construction, not just mirroring the past but serve as an exemplar structure of a modern rural building.

Finished structural from Harris, *Downland Gridshell: An Innovation in Timber Design*

Dimension: length - 48m long, 16m wide, 10m high

Material: Oak - 50mm x 35mm

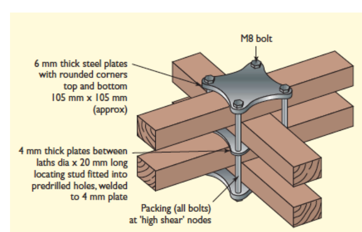
Process: flat mat of laths assembled on scaffolding and lowered into place



Formation process from Harris, *Downland Gridshell: An Innovation in Timber Design*

Connection: patented steel plate binding joint

Influence: This project developed an innovative binding connection as a preferable alternative to pin connections. The connections allow the necessary movement, without a hole or slot in the laths. The ingenious process of dynamic relaxation, used gravity to lower the structure into place. The process still demanded a massive network of scaffolding. The development of a doubly curved gridshell from a flat, square or rectangular grid is made possible by the low torsional stiffness of timber. During formation the timber lattice must allow rotation at the nodes and bending and twisting of its constituent laths. Shell action is accomplished by diagonal bracing, providing in-plane shear strength and stiffness. The double layered shell allows a tighter curve to be achieved. Timber shear blocks installed upon formation allow the transfer of shear force between the layers giving the lattice the properties of a deeper section.



Binding connection detail from Harris, *Downland Gridshell: An Innovation in Timber Design*

Saville Building - Glen Howells Architects

Built in 2006 and is the largest timber gridshell in the UK. Made up of four layers of larch laths.

Dimension: 98m long, 24m wide, 10m high

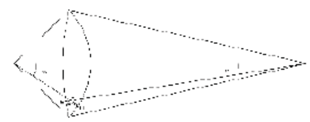
Material: European larch 80mm x 50mm (four layer)

Process: flat mat of laths assembled on scaffolding and lowered into place

Connection: bolt and slot pin connection.

Influence: The Saville gridshell provides lessons on formative geometry. The perimeter is set out using arcs of two intersecting circles. The curved centre line on plan is the midline between the circles. The centre line of the roof, in section, is generated by a sine curve, of varying amplitude, with its peaks and troughs at the tops of the domes and the bottoms of the valleys. The cross-section is then set out across the sinusoidal centre line as a series of parabolic curves of varying shape. Onto this surface a grid of equal length elements is generated. A damped cosine wave in the x direction and upside down parabolas in the y direction. By having a clear geometric basis to the surface shape, the architects and engineers could work together to adjust and agree on a shape that met the aesthetic aspirations and practical constraints. Onto this surface a grid of equal length elements is generated. The fitting of the equal mesh net on the surface is done using the fact that it is known where two opposite diagonal nodes of a little rhombus lie on the surface; the other two can be calculated. This problem is known as constructing a Chebyshev net.

Interior of structure. Image from Harris, The Saville Garden Gridshell Design and Construction



Plan geometry sketch. Image from Harris, *The Saville Garden Gridshell Design and Construction*

Japanese Pavilion - Shigeru Ban & Frei Otto

Built for Expo 2000 in Hanover and Intended as a structure that would exemplify reduced waste in a construction process. The goal was to recycle or reuse all the material that went into the building.

Tube detail from Shigeru Ban Architects

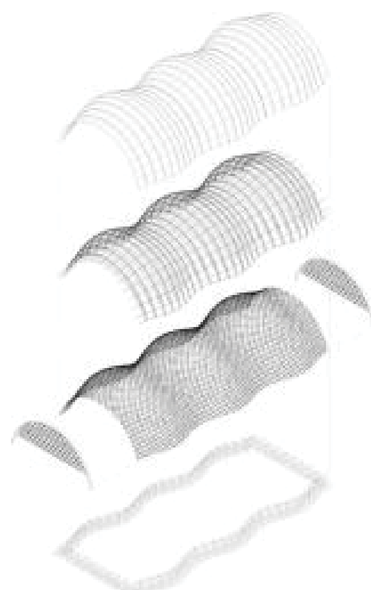
Dimension: 73.8m long, 25m wide, and 15.9m high

Material: Recycled paper tubes

Process: flat mat of tubes raised from the ground on scaffolding

Connection: Joints of fabric & metal tape were tied on the flat matt and were pulled tight as the intersections began to scissor, as the structure took shape

Influence: This Pavilion incorporates an Innovative use of materials. Recycled paper tubes make up the main compression element of the structure. The shape is a response to the structural challenges .The most critical factor was lateral strain along the long side, so instead of a simple arch the shell has three-dimensional curved lines with indentations in the height and width directions, which are stronger when it comes to lateral strain.



Japan Pavilion exploded axo from Shigeru Ban Architects

The connection is a simple fabric or metal tape. As the intersection between two paper tubes was pushed up to form the three-dimensional grid, an angle would open and a suitable amount of tension would be applied. Since the paper tubes themselves would rotate to draw a gentle S curve, the joint would allow for three-dimensional movement. Tape was an appropriate solution.

Vernacular Precedents

Yurt

Yurt walls are built with several sections or khana, each of which consists of 33 wooden shearing slats. In old yurts the hinges are made by simply lashing them together, but the current factory produced ones work with screws or rivets. The khana unfold, and typically 6 or 8 are combined, wrapped in a circle, each side of a wooden door. Woven tension bands are wrapped around the whole structure to create rings, giving the structure rigidity.

Yurt frame from For Love of Yurts

Native American Long House

Longhouse frame from Native American Shelters

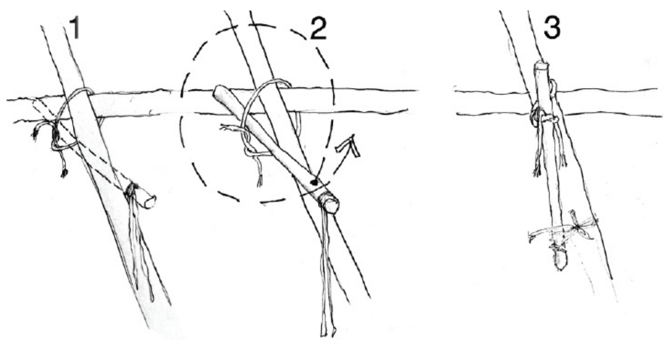
Longhouses were built by native peoples in various parts of North America, sometimes reaching over 100m and generally 5 to 7m wide. The walls were built of sharpened and fire hardened poles driven into the ground. The poles were woven with bark as a building envelope. Fire hardening was a process of removing moisture by slowly lighting and charring it over a fire. This made the points more durable to bury in the ground. The structures were lashed together using wooden splints or rope made from elm or basswood. From the main poles the roof was constructed by bending young saplings to span between the walls.

Exterior of longhouse reconstruction from Canadian Enyclopedia

Thai Scaffolding Tie

Builders in Thailand use this simple connector for building bamboo scaffolding. This 'zero capitol' construction technique is an elegant and efficient solution for connecting round members. The stick is lashed together with the poles and twisted to tighten, then tied off to one of the poles so that the connection can not come loose.

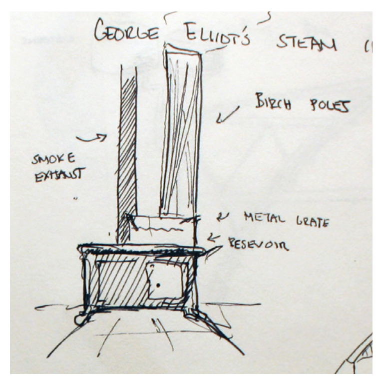
Scaffolding tie in context from C.A.S.T.



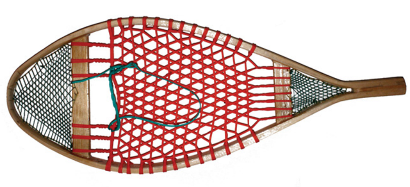
Thai Tie sequence Sketch from C.A.S.T.

Snowshoe

George Elliot of Maine Brook NL makes these shoes in the shop behind his house, from switches of birch, that he chooses by hand for their bending ability. The switches are air dried for 6 months, split, steamed and bent to jigs, that have been used for generations. This contemporary craftsman incorporates traditional methods with the materials that are readily available. The birch frames hold woven mats made up of fishing net and nylon rope. Each shoe is hand made and unique.



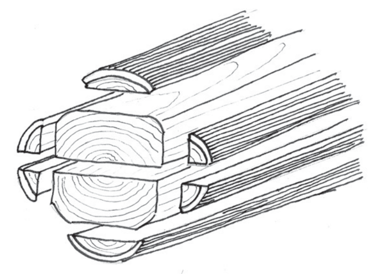
Sketch of Georg Elliot's Steam Chimney for steaming the birch.



George Eliot's Snow Shoe

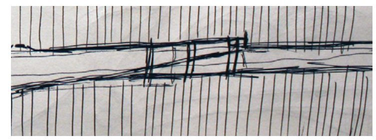
CHAPTER 2: DESIGN

The main design challenge of this thesis is to create a structural system based on the material properties of the available small diameter timber. Milling the small diameter timber is not an efficient solution as the sawing begins with a centre cut to establish a flat edge. This means that the available dimension is halved (plus waste). Saplings and pole timber are usually not milled because the yield is too low to make it worthwhile.

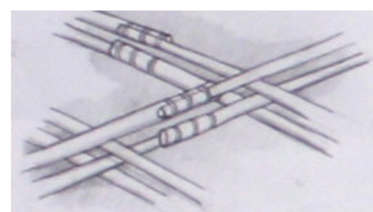


Sketch showing the minimum cut for milling small diameter timber.

The round timber brings its own set of unique challenges to bear upon the design and construction of gridshells. The differential diameter of the poles means that end to end connections are made more difficult as the dimensions vary from end to end. This change in diameter also means that the pole bends differentially, rather than in a uniform radius. The implication of differential bending is that a uniform curve cannot be achieved by the usual method of scarf jointing the timber end to end.

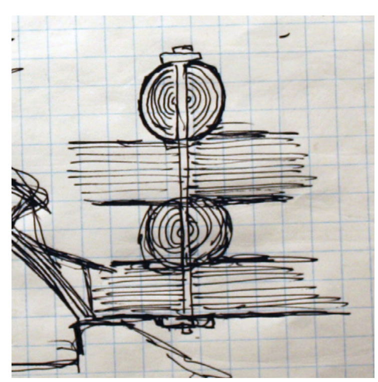


Sketch of a round timber scarf joint.



Sketch of lashed round timber laths.

The material is also unpredictable. Using the material in its natural round form means that you can't count on a standardized size or structural property throughout. One valuable lesson taken from the standard gridshell construction is the advantage of binding connections over bolt connections. Bolt or pin connections reduce the cross sectional area of the members and correspond with cracks that form as the green wood dries.



Undesirable pin connection.

The unique challenges presented by the round timber necessitate a new strategy for creating the structural network.

Full Scale Testing

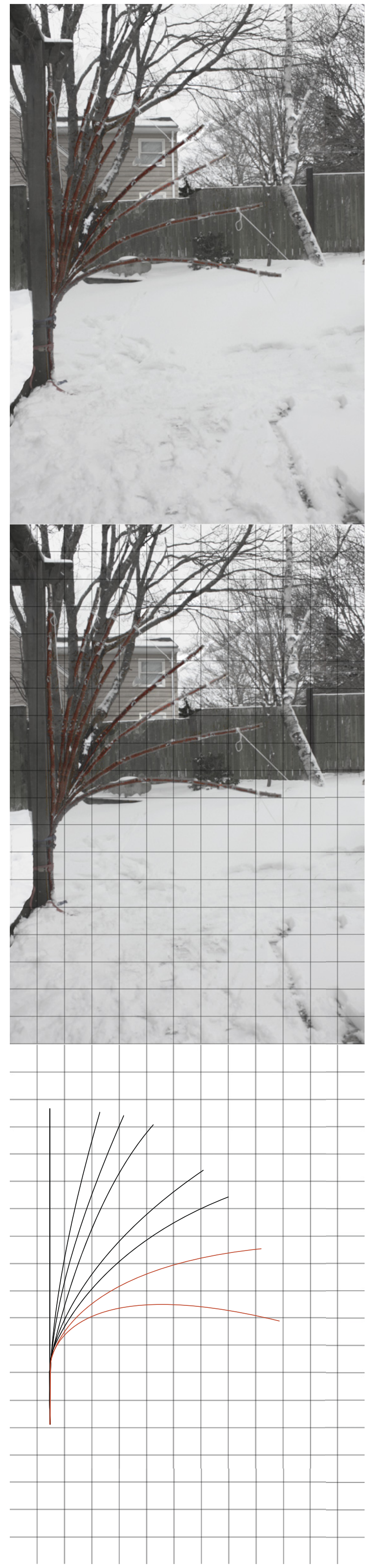
The first step of the material-based design process was an exploration at full scale. The material testing involved bending pole timber harvested from the site in order to establish its behavior and limitations. The poles were fastened at one end and bent with a rope tied near the tip. The low tech approach to material analysis is consistent with the intentions of using simple technology. It facilitates an understanding of the material through a hands on approach consistent with my design process.

The behavior of the material in bending was recorded by photograph. This method allowed analysis of the dynamic process without the interference or additional challenge of measuring equipment.

The series of images on the right shows how the photographs were compiled and laid over a grid so that the curve could be described. The black lines represent the group of curves that the material could conform to comfortably. Beyond these curves the material began to be compromised and ultimately failed. These curves are represented by red lines. It was determined that the pole timber was comfortable in curves up 30 degrees over the length of the pole, or a bending radius of approximately twenty feet.

These tests highlighted the differential bending which is an important characteristic of this material. By understanding the material behavior, the design process was able to replicate the material's behavior in scale model.

These tests also allowed me to understand the way that the material would fail. The poles were tested green and



Sequence of material bending process and curve analysis steamed. Steaming the poles proved to be unnecessary. Having been recently harvested and green the poles were flexible enough to achieve a desirable curve without steaming. In addition to adding an extra step the steaming seemed to reduce the quality of the wood, which although failed in a much deeper bend, seemed to be compromised much earlier, the wood became more mushy than flexible.

The Nature of Failure

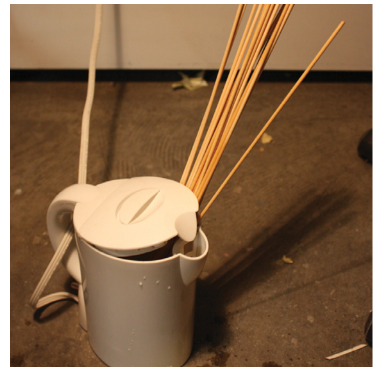
Steamed Birch

Green Poplar

Green Birch

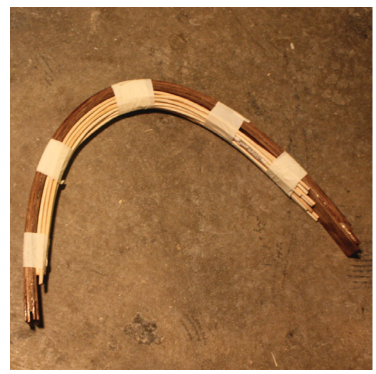
Analogous Material Modeling

In order to accurately represent the pole timber while working at a small scale, the design process involved the use of analog materials. Analog materials behave and often look like the materials that they represent. Using these materials in physical models allow the design to consider how the processes and tools might extend to the full-scale design.



Steaming dowels to be bent for model building

Mark West of the C.A.S.T. workshop at the University of Manitoba explains that this method relies on the intelligence of the materials themselves for clues to the architectural potential they may hold. This is a fertile and practical method of invention and discovery, particularly well suited to architectural research aimed at real constructions.[9]



This parabolic jig allowed the formation of many different parabolic curves.

> New forms generated exclusively through computer modeling programs will tend to arrive without any hint of how they might actually be constructed. The problem of how to construct these virtual forms becomes a difficult puzzle that must be solved separately by engineers or builders. The sense of freedom and power offered by computer-generated form is often only a beautiful illusion that, in reality, merely serves to alienate the designer from the world of construction. By generating new forms directly through play with physical matter, the solutions to full-scale construction are contained in the forms and methods themselves. In this way the designer is placed in the very centre of construction knowledge. This method of empowers a designer to bring new architectural ideas into constructed reality.[10]

Hardwood dowels were found to be a suitable analog of the pole timber. By steaming the dowels became flexible

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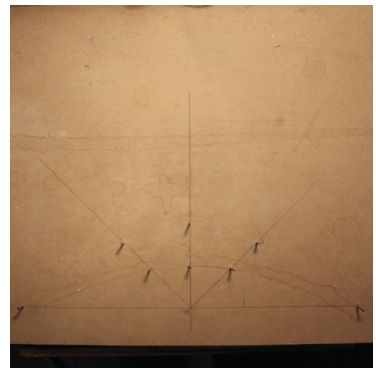
9 C.A.S.T. http://www.umanitoba.ca/cast_building/research/index.html (accessed February 3, 2012).

10 Ibid.

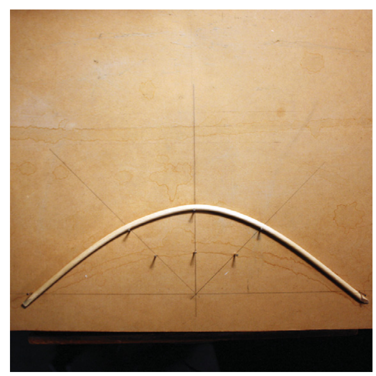
enough that they could achieve the same bending behavior found in full scale testing. In order to simulate the differential or parabolic bending of the pole timber, the dowels could be turned to be thinner at one end. This was done by mounting one end in a drill and spinning it over sand paper to narrow the opposite end.

Differential bending of a wooden dowel for modeling. The dowels are turned smaller at one end to mimic the differential diameter of the real round timber.

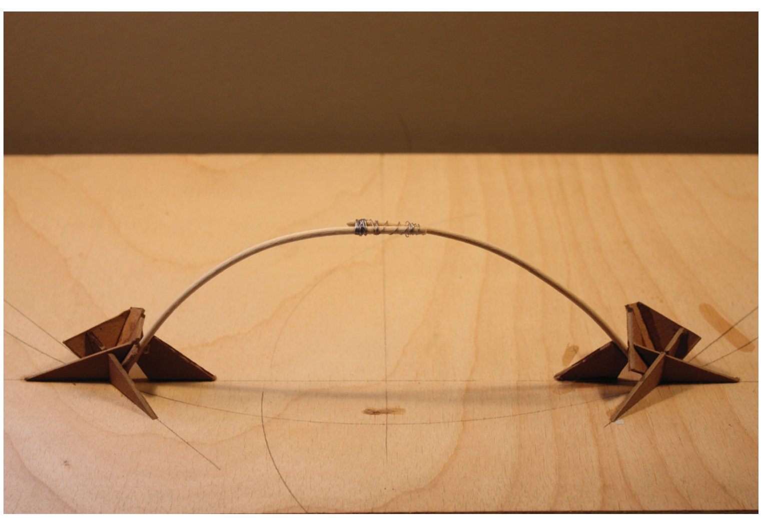


Model bending jig

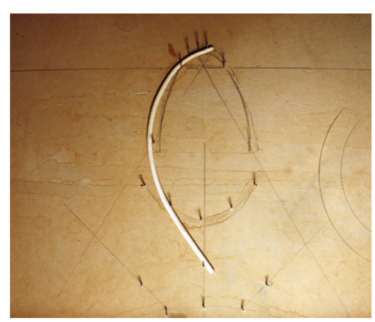
This design method allowed the process of rapid prototyping to happen at a scale that was manageable and affordable. I could work on my desk top using the exact performance of the material as a guide. The model materials guided the design with specific attention to the material properties.



Dowel in model bending jig



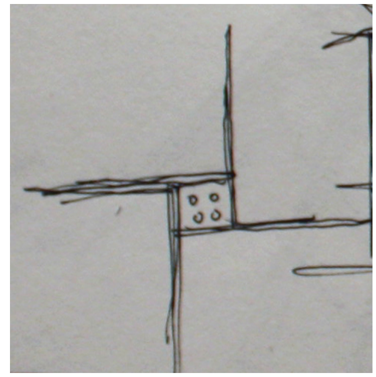
Bent wood, three pointed arch concept developed with processes of physical modeling



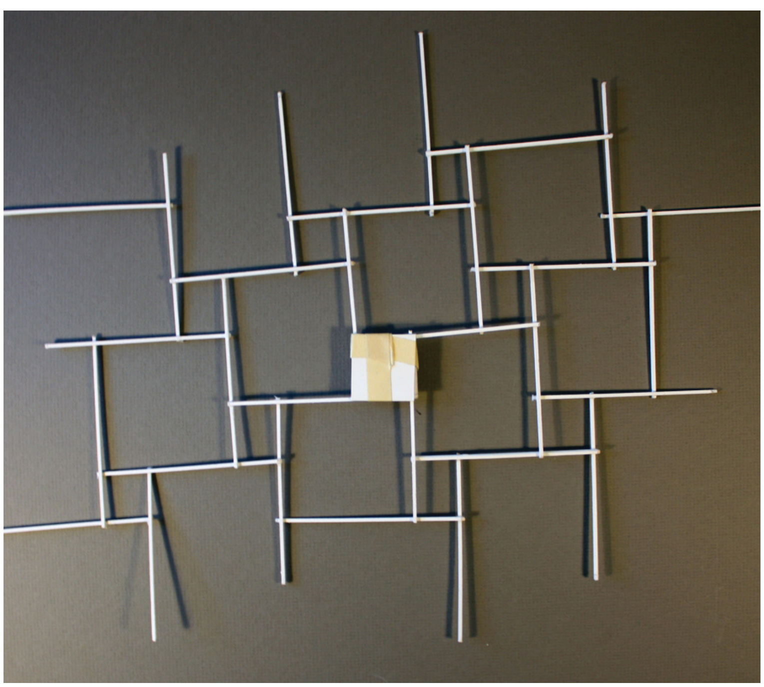
Extreme limit of the differential bending

Connection Detail

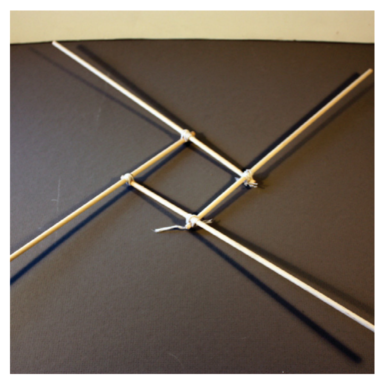
The round timber required the development of grid detail that was that better suited to its material characteristics and its behavior. Using conventional gridshell connections was not suitable to the new material. Differential diameters causing differential bending was the major concern. The solution was to put the wide ends of the timber together, so that the nodal connections now either deal with four large ends or four thin ends. This strategy reduces the range of differentiation and therefore unpredictability in each connection. By joining the members in this way the structure becomes a lamella system, characterized by shorter separate pieces connecting together at the nodes to make up the grid, rather than the long continuous laths of the gridshell system.



Original concept sketch of the lamella system

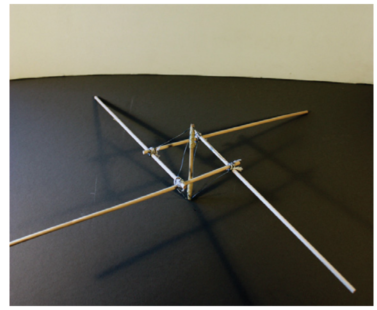


Lamella network model



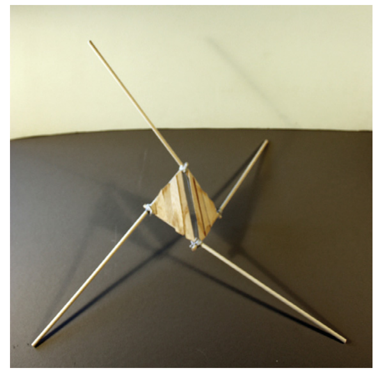
First model of the lamella connection

The lamella network takes a shape by rotating at its connection points rather than by bending of the members. By developing a joint with some depth I was able to reintroduce bending of the members into the system as a sort of pre-tensioning of the system. Creating a three dimensional joint gives rigidity to the system and allows the members to be pulled into bending.

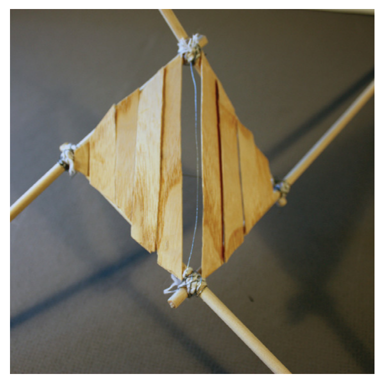


First prototype of a 3D joint

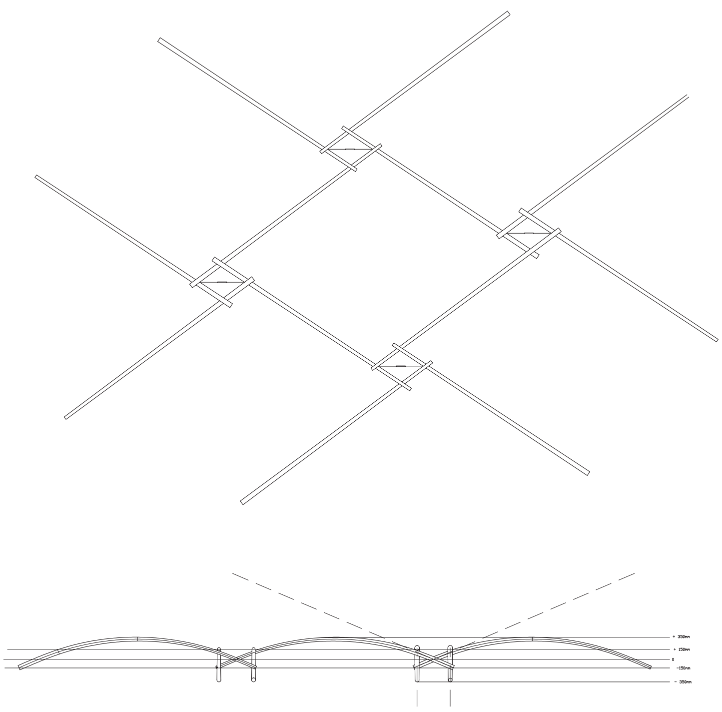
The final joint divides the forces of tension and compression at the nodal connection. A tension member pulls two corners of the connection cell together, they become the low points of the cell. The other two corners become the high point. By cladding the cell to take up the compression forces the joint becomes rigid and can be tightened to add tension to the structure.



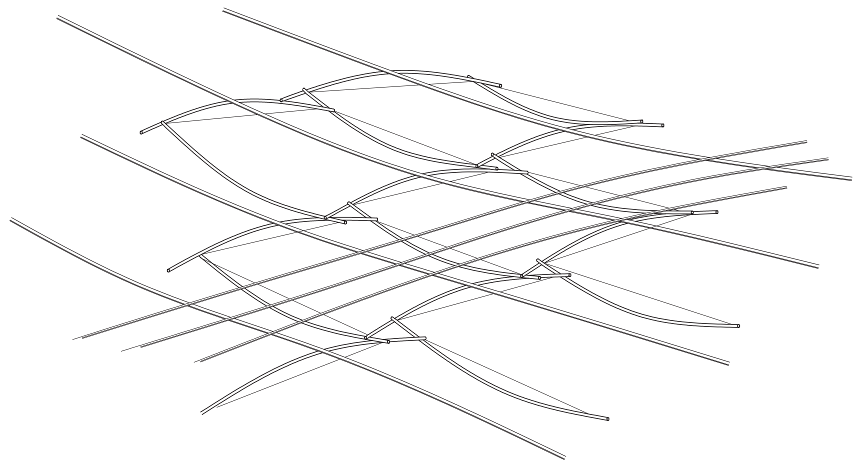
Second prototype



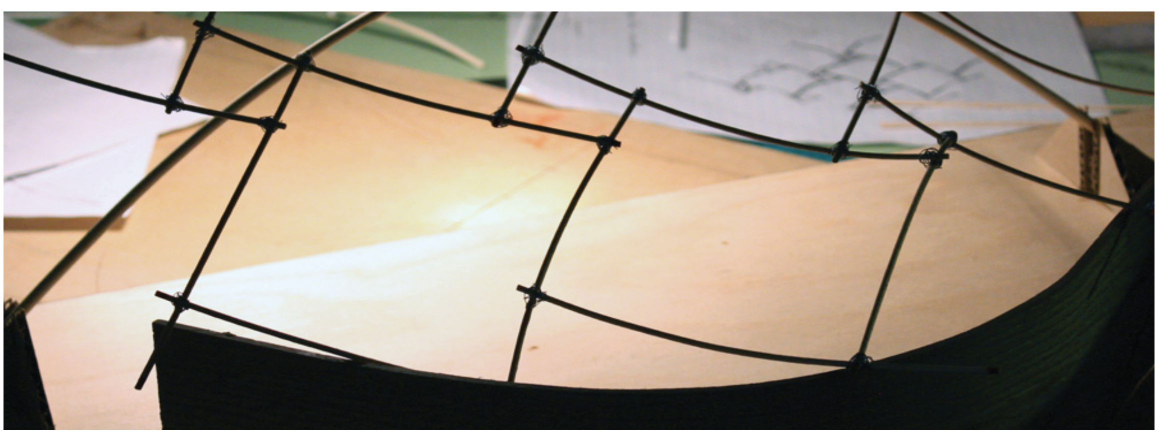
Model connection detail.



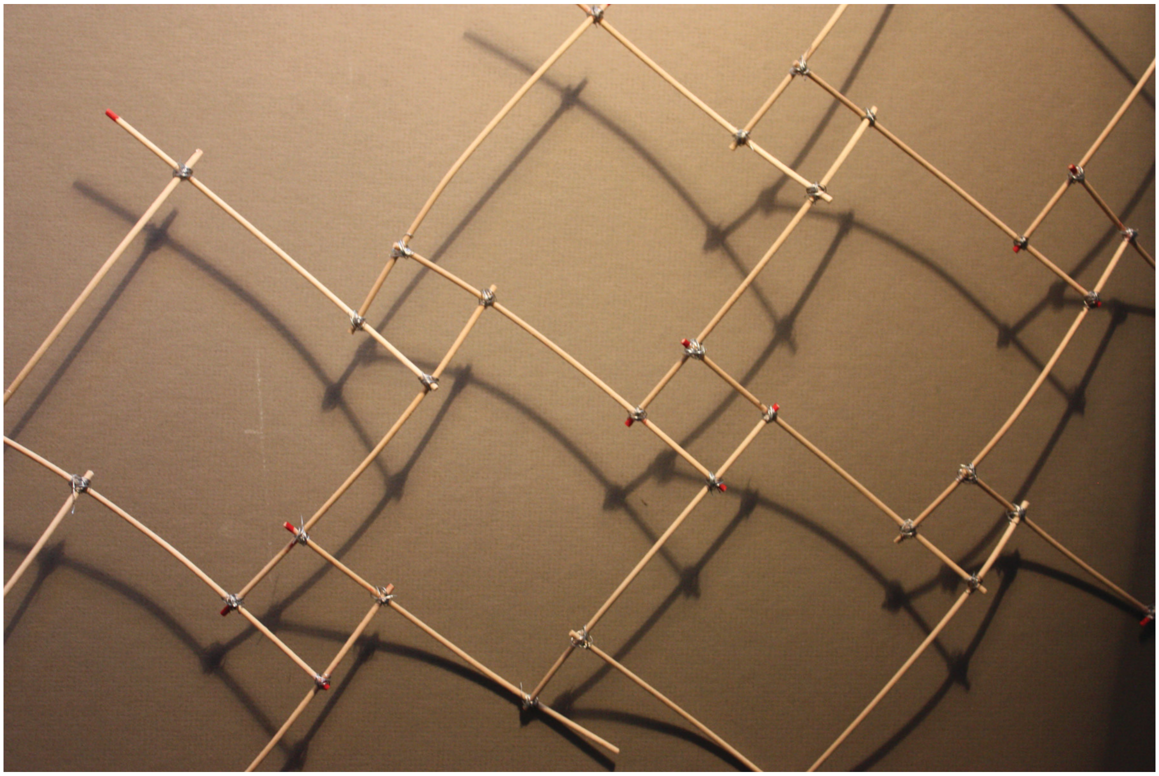
Plan and section of a portion of the network showing the depth introduced to the connection point and the resultant bend in the members.



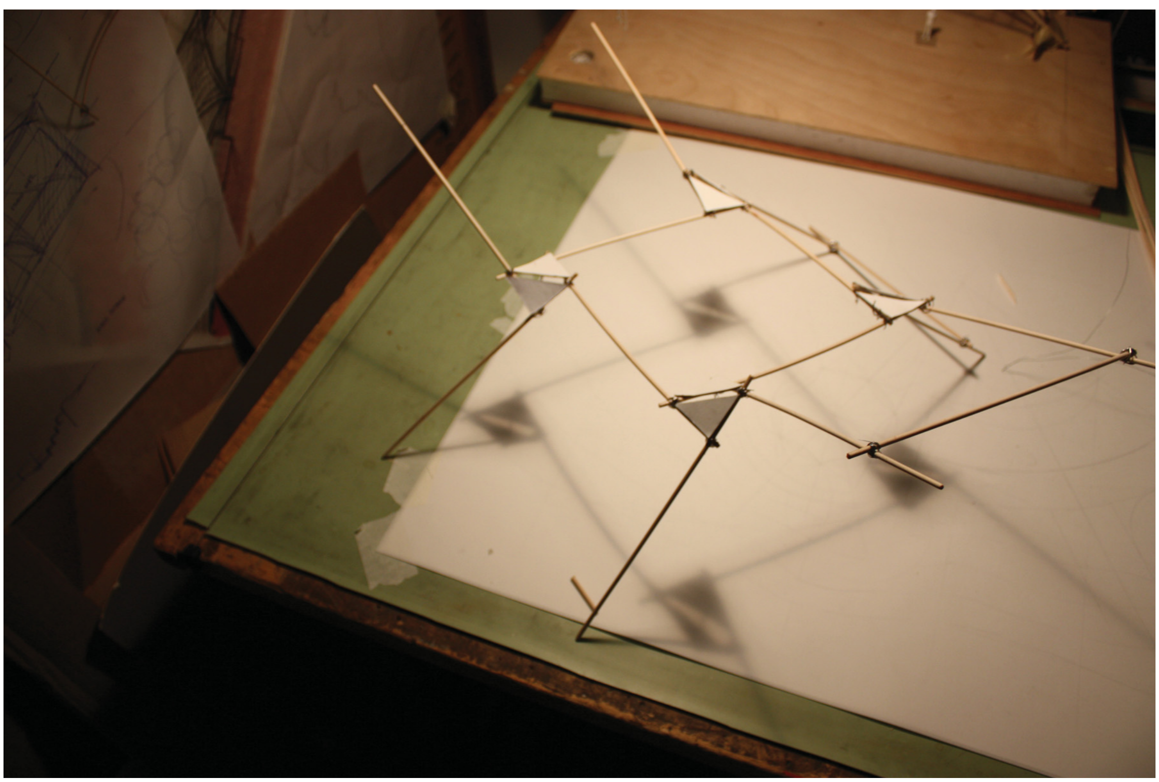
Perspective drawing of the system with purlins running in two directions: The primary purlins span from the high points of the bent members. Secondary purlins run in the other direction giving the system enough density to attach cladding.



Structural system sketch model



1:20 model of the system, using bent members.

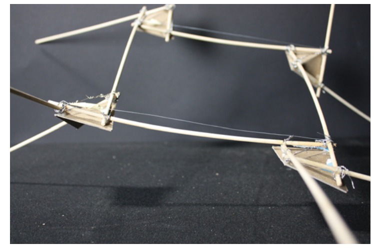


1:10 model of the system. This model relied on the tension members, represented by wire to pull the dowels into bending. This model represents the limits of the small scale prototyping.

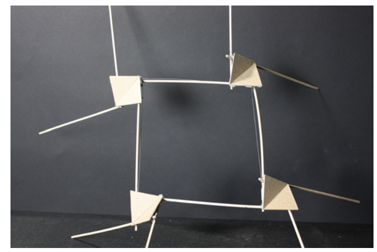
1:2 Model

The small scale prototyping was found to be limited in its ability to accurately represent the connections. Following the forces of tension and compression was inaccurate as the analogous materials used in the connections did not accurately represent or act like the real connection. The explorations in small scale modeling, scales 1:10 - 1:50 were useful in establishing the network but the scale and the representative quality of the analogous materials were limited in terms of the connections. To evaluate the connection detail it was necessary to build at a larger scale. This process of the large scale mock up was also an opportunity to highlight opportunities and challenges in the construction process.

The 1:2 model material were birch poles at half scale. The poles were 8 feet long with a diameter of 1” to 2” end to end. In this model the network was assembled on the ground and raised into place in the manner of traditional gridshell construction.



1:10 system model showing tension members represented by wire



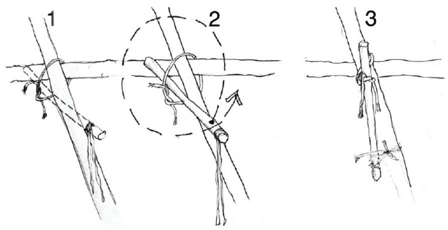
1:10 system model showing compression plates represented by card.

Freshly cut saplings used for the 1:2 model.

Network laid out flat on the ground.

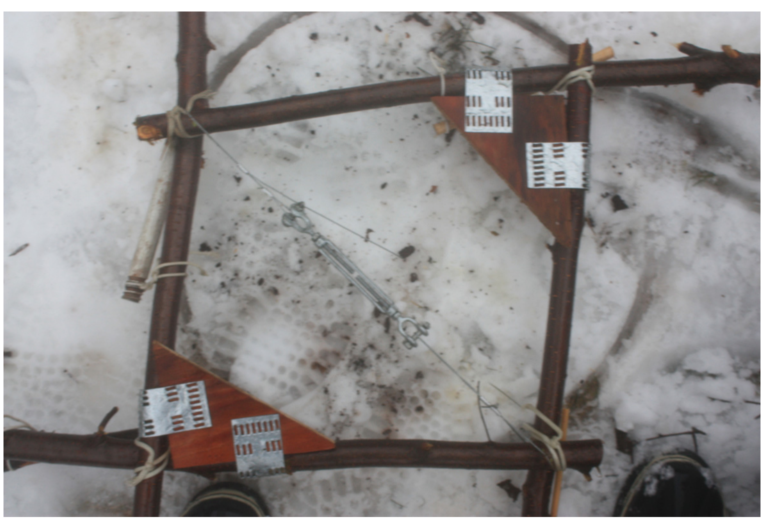
Laying out the model required a temporary connection. The Thai scaffolding tie was implemented as a quick connection for joining round material. The connectors were quick, made of scraps and offcuts and would simply be left in place after the permanent connections were made, to tell a story of the building's construction.

The temporary connectors.



Thai tie sequence Sketch from C.A.S.T.

Steel cable with a turnbuckle used to tighten the connection



First iteration of the compression plates: Proved to be too small

Second iteration of the compression plates.

Underside of the connection shows the tension member pulling the system into tension

Final connection detail

View of the system at 1:2

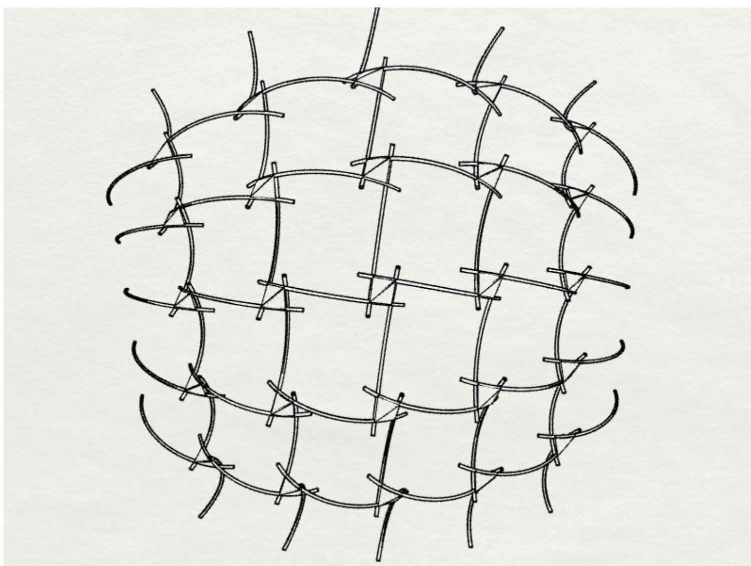
The final model consisted of 9 connection points and was a large enough portion of the network to test the success of the connection detail. The larger compression plate was able to hold the shape of the node while the steel cable was tightened, pulling the birch members into bending. The model highlighted the main challenge of the connection, which is the connection of the plywood compression plate to the birch poles. The first attempt used plastic zip ties, representing the proposed steel straps in the real construction. The zip ties were the weakest point and couldn't hold the plates in place well enough for the system to be pretensioned. The force applied to the turnbuckles caused the ties to break.

A second version was built using gang nail plates, which were strong enough for the system to be pulled into tension. The system was loaded by hanging car tires from the network, and again the compression plate was the failure point. I remain optimistic about the use of plywood for this plate as it is quite strong when isolated in the cross plane dimension, but the connections to the poles is an area for further study. The large scale model was a success in understanding the forces acting on the nodal connection.

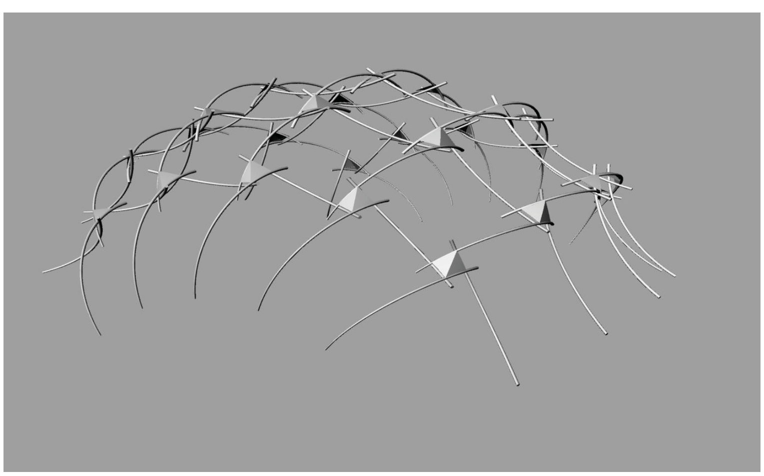
View of the network from below.

Computer Model

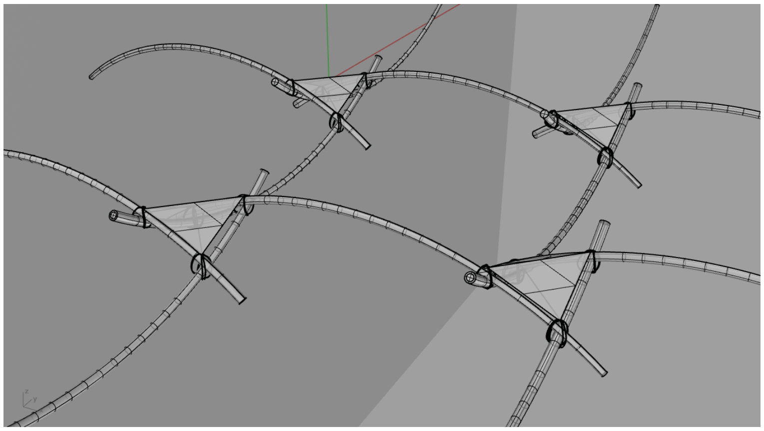
A 3D computer model is used in parallel with the physical modeling to help more accurately define the geometry. The model allows the rapid determination of possible geometry and helped determine the relationship between the angles of the intersection and the curvature of the shell. The model also allows the design of a large segment of the shell which is difficult in scale models.



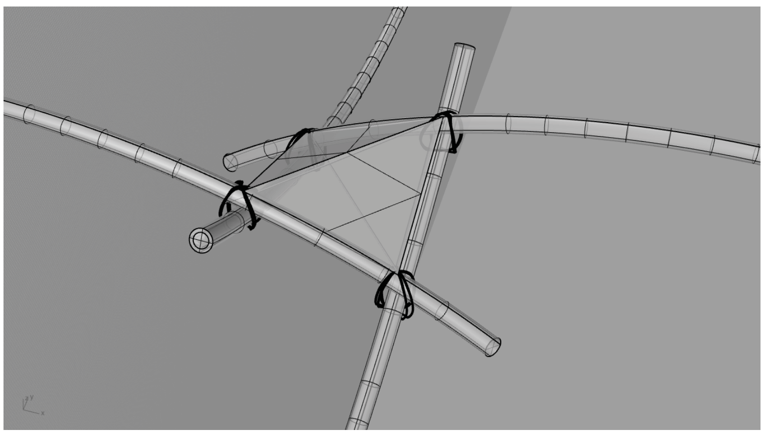
Plan view of the system



Perspective view showing how the system can take on a curved shape

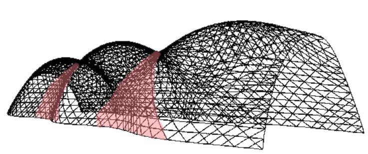


View of the network and the connection details



Single connection detail.

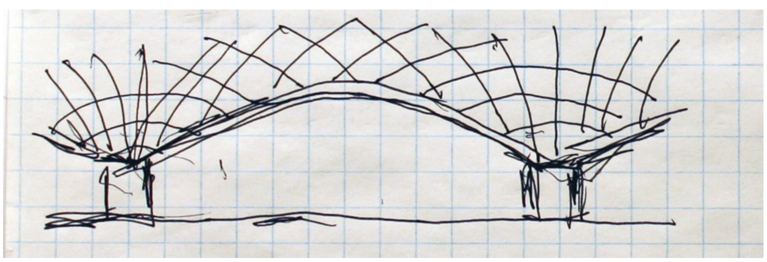
In addition to the analysis of geometry and forces at the individual connections the computer model allowed the creation of forms based on the specific parameters carried through from the real material.



The valleys in an undulating system experience tension forces which are resolved by the convex of the bulge.

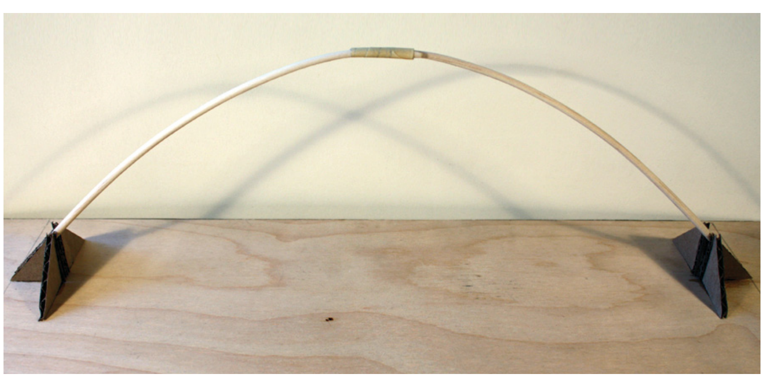
Primary Structure

The way that the grid is resolved is one of the main challenges of the gridshell system. The structural forces need to be transferred to the ground evenly. To help express the lightness of the system and to express the ideal form of the shell, the system ‘springs’ from a series of compression stressed rigid arches, each with its own foundation point. Using the method explored in the full scale testing the members will be anchored at the base and bent together, exploiting the differential bending of the round timber. The bent wood arch creates a primary structure that the network will build up from, rather than being draped over scaffolding and lowered into place.



Base condition sketch

Concept sketch



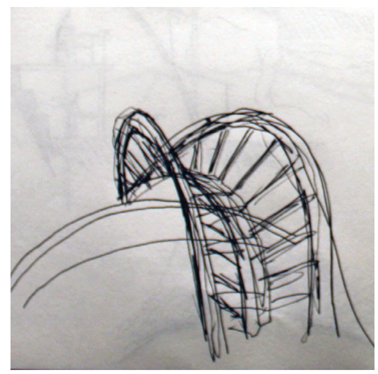
Bent wood three hinged arch

Sketch model

Evolution of the Primary Structure

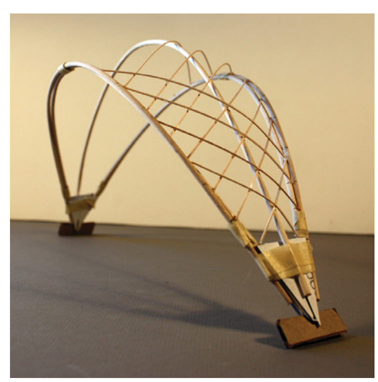
The development of the primary structure was a process lead by the material properties of the timber in the same way that the network was developed.

Sketch model of a laminated roundwood truss



Sketch of the truss.

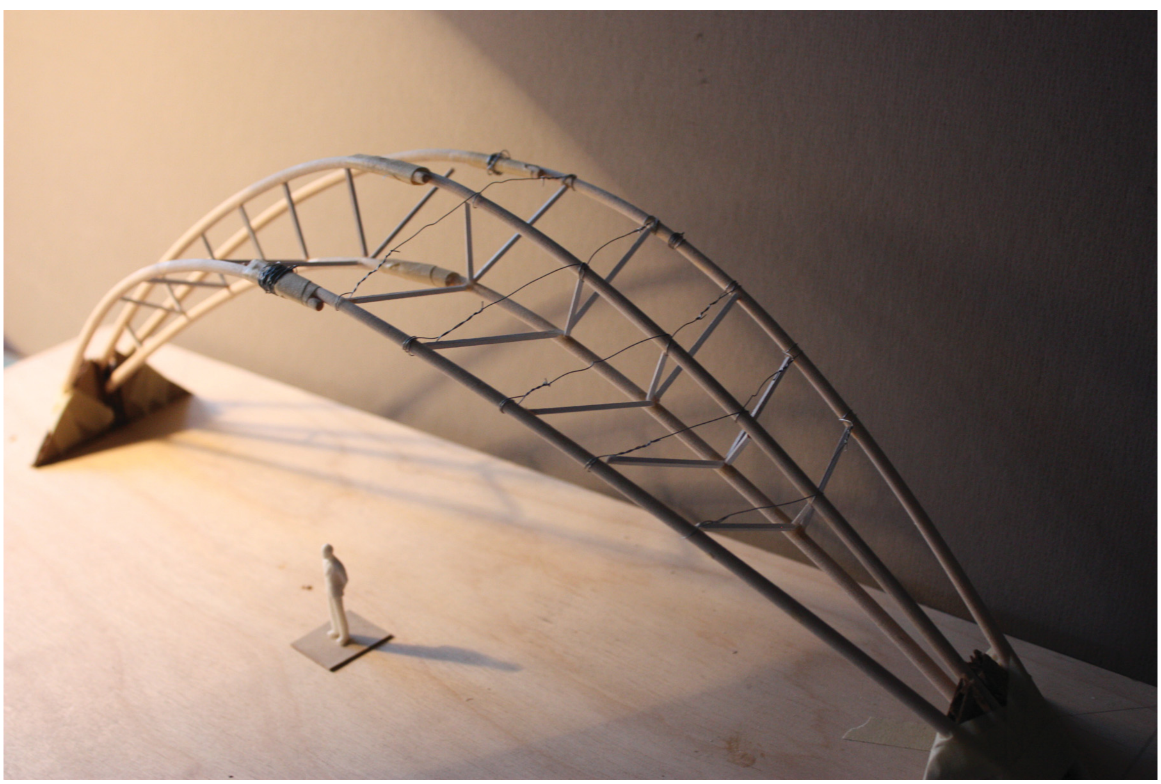
Sketch model



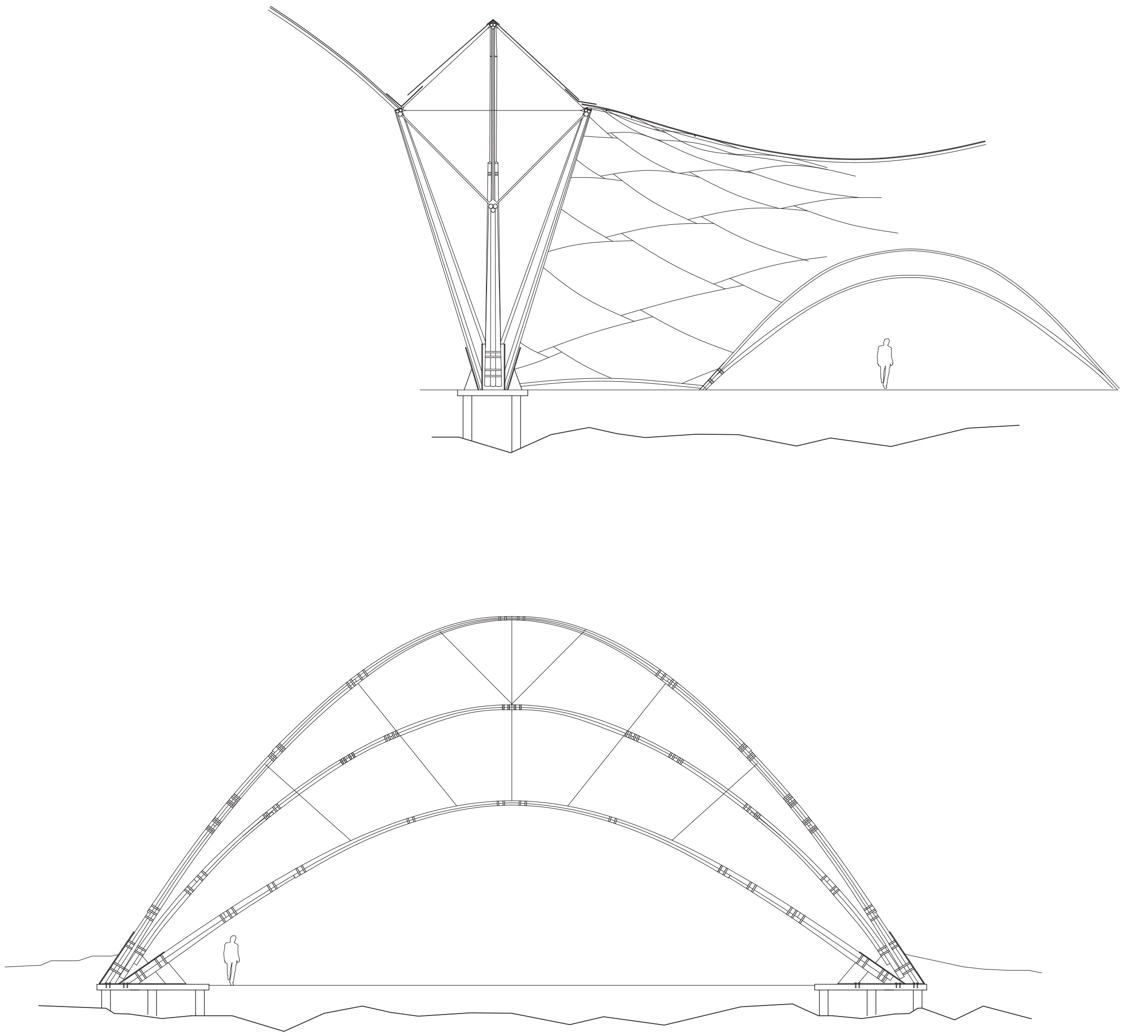
Sketch model of the truss

Truss

Detail view of the bent wood truss.



Bent wood truss.



Truss sections

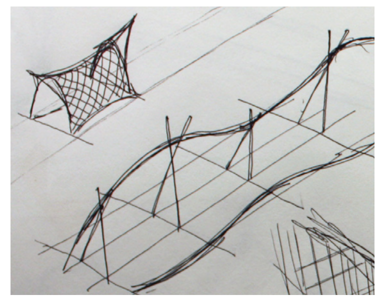
These sections show the design concept for large trusses that could be the base constraints for large shells. Each cord of the truss is made up of round timber poles laminated together with steel straps. The Truss is designed to negotiate between shells allowing shells to be used together and be built in sequence.

Construction Process

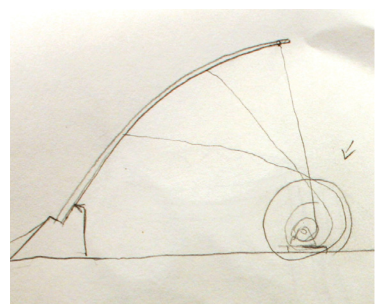
tech-nol-o-gy

the sum of ways in which social groups provide themselves with the material objects of their civilization.[11]

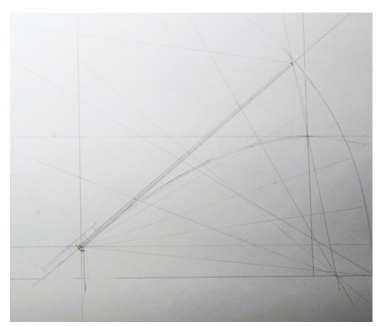
Throughout the thesis my design work has intended to be conscious of the construction sequence. By being conscious of this process and modeling it, the leap from design to construction can be diminished.



In the same way that the forest can be managed, based on the stages of growth and cycles, so too can the construction process.



The standard gridshell construction process is a dynamic one, where the structure is lifted or lowered into it's position. The matt of laths has to be laid out completely on top of the scaffolding and slowly lowered into place. This poses two problems. One is that the amount of scaffolding that must be brought to site, erected, and taken away does not align with the intention of the project to create minimal environmental impact. The second is that the laths dry out, losing valuable moisture content when laid out while the whole matt is assembled, especially if they have been debarked. The solution is to design a sequence where the grid can be erected piece by piece without a huge amount of temporary support structure.



Series of sketches developing the processes of construction

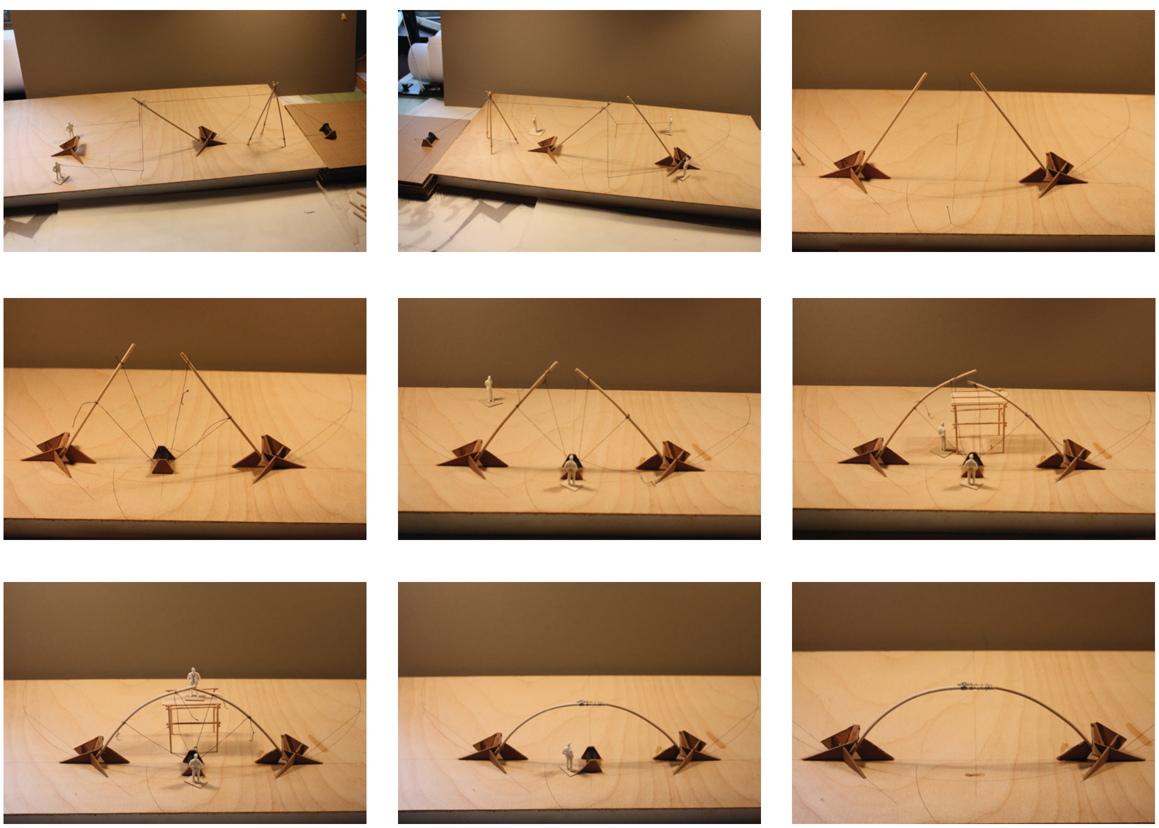
11 Dictionary.com. http://dictionary.reference.com/browse/technology (accessed September 19, 2011).

Photos of a model showing how the gridshell system will spring from the primary structure. Tension connections inspired by the tension connections in the network are used to hold up the system during construction, rather than letting it rest on scaffolding.

Animation as a Tool for Design

One of the methods of design is to create animations of the construction process. This process demands that each frame, therefore each step of the construction is carefully considered and flows into the next.

Not only does the animation process help to clarify the construction process but it can be used to develop details that can tell a story or help the user reconstruct the process in their mind after the building is completed.



Some frames from an animation of the construction of the compression trusses that make up the primary structure. Shown here is the erection and pre-tensioning of the first cord of the truss.

Landscape

The landscape makes up the second parameter of the formation of the shell, the first being the properties of the material itself. These form finding models were used to explore how the shell can negotiate between different levels. The support conditions of the form finding models are determined by the landscape. By hanging the fabric model from supports that are different heights the structure can take its shape directly from the conditions of the site.

Design model - fabric and plaster. This model explores how the shell can negotiate the changing landscape by changing the support conditions of the suspended model.

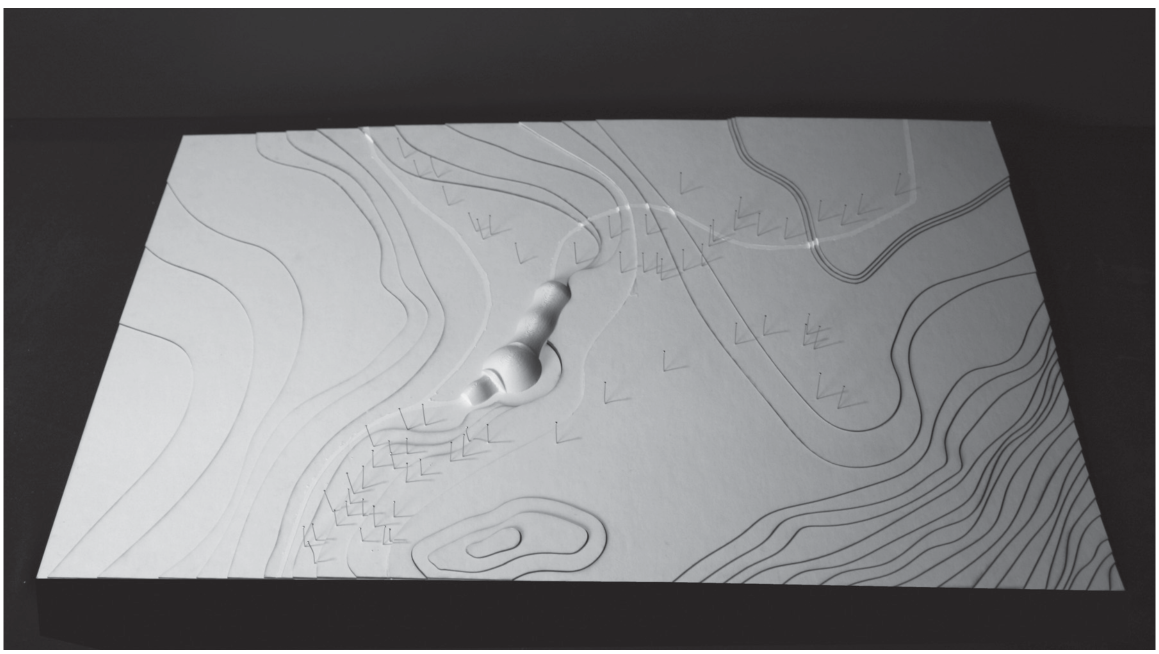
Site Strategy

The site strategy is to create a gateway between the working forest and the area of the arts centre. The craft school will negotiate between the two. The siting is intended to foster a connection to the arts camp so that they can develop a relationship of shared learning. Installations from the craft school are envisioned to spill out onto the land as a large open exhibition area. The proposed site is an area with a stand of young birch trees that will be taken down and used in the structure. More mature stands are preserved to provide shelter from the wind. Environmental considerations, such as solar exposure, are also taken into account. Environmental Information: See Appendix B.

Site strategy sketch: This sketch shows the property and buildings of the art centre, and a concept sketch of the proposed building as a gateway between the centre and the working forest. Darker areas representing more dense forest are preserved to shelter the building.

Photo showing one of the more mature stands on the site. These areas are preserved in the design and used to shelter the building.

Site model showing the proposed site in relation to the existing facilities and the creek valley.



Site model showing the building's relation to the landscape.

Program Organization

HARVESTING SHEDS - 400 ft^2 - Storage and maintenance of harvesting equipment including tools, vehicles, livestock, and any gear required in the forest.

MILL - 800 ft^2 - Provides for all primary processing of logs from the forest, including debarking, sawing, planing and marking information for further processing.

SOLAR KILN - 300 ft^2 - Drying of round and sawn stock.

STEAM SHED - 300 ft^2 - Provides heat and moisture to plasticize wood for bending.

SHOP - 800 ft^2 - Home of all stationary tools, benches for precision working, and tool storage.

WORKYARD - 10000 ft^2 - Large open, sheltered area for building. Most of the mock ups, prototypes and full scale projects are built in this space.

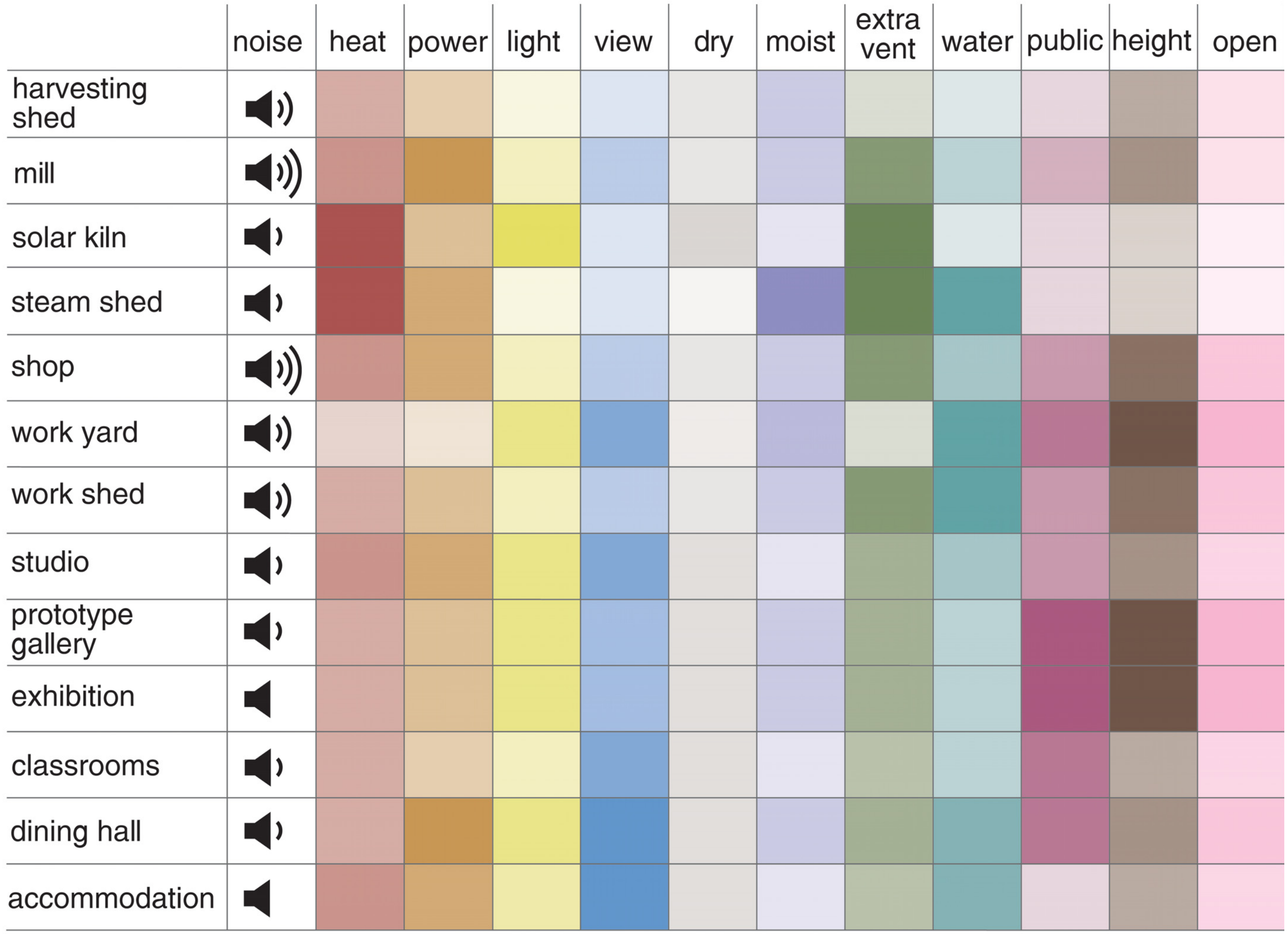
WORKSHED - 1000 ft^2 - More enclosed space for large scale construction.

STUDIO - 3000 ft^2 - Space for modeling, drafting and research. Each student will have their own space with drafting table and computer station, with large shared model and work tables.

PROTOTYPE GALLERY - 3000 ft^2 - Space for showing and storing finished prototypes for record and future reference.

EXHIBITION - 3000 ft^2 - More formal exhibit space

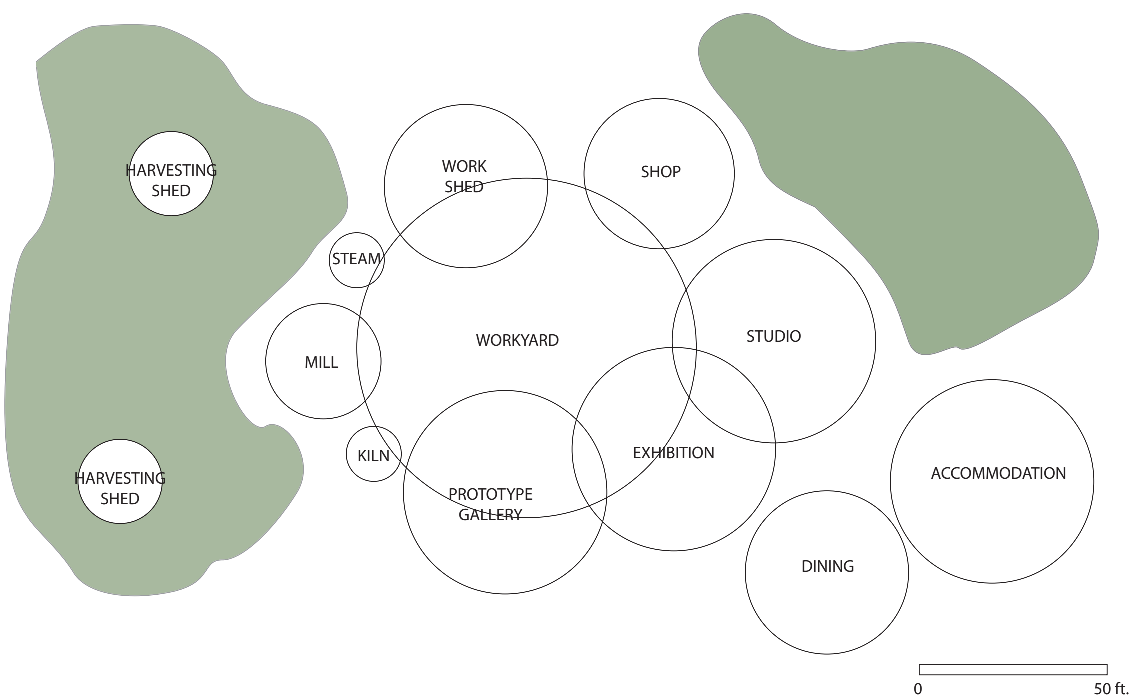
CLASSROOMS - 2000 ft^2 - 4 rooms for teaching and group work



This table looks at the different program spaces in terms of things that they require. It is intended to help align the different spaces, based on common need. There is a colour associated with each column, or program requirement and 4 levels of saturation to describe the level of need for each program space.

The workyard and the workshed make up a large portion of the schools area. These spaces are thought of as seminal to the design process, where the important discovery and experimentation will take place. Supported by the secondary spaces of studio, shop and mill, the workyard and workshed is where all of the learning comes together in the built works. Parts, jigs, materials, students and instructors come together in this space to create the prototypes and large scale versions of their design ideas. These spaces are central to the organization of the program.

The gridshell will be used as a linking element to physically join the steps in the process of production to tell the story of woods journey as a material. It will connect indoor and outdoor spaces to contribute to the narrative of the process.

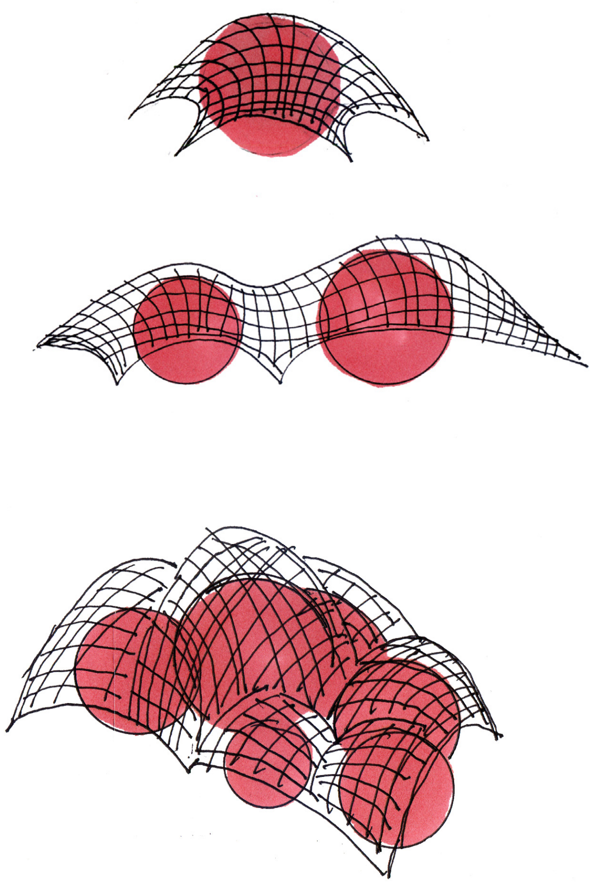


Program space areas diagram

Form Finding

To facilitate the program, the structure will be formed using the requirements of the specific areas of program. Volume, heights, views climatic conditions etc. will be determined for each programmatic zone and applied to the method of form finding. The process involves several different modeling techniques on several scales, thrust line and thrust surface modeling (inverted tensile models), Analog material model (bent wood models) and large scale mock ups and tests.

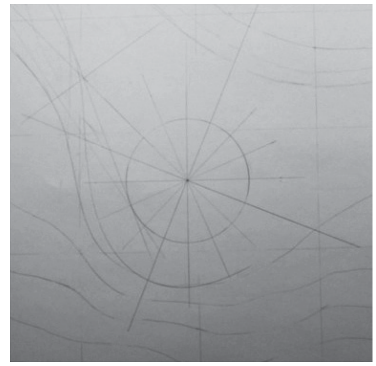
Hanging chain model that shows the ideal form of the shell

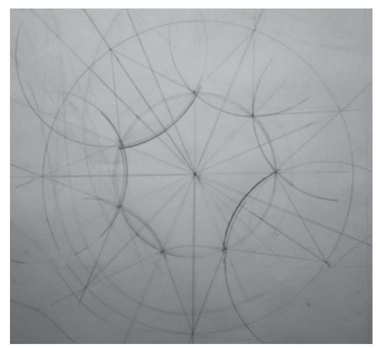


Diagrams depicting forms generated by programmatic requirements.

Series of sketch models showing a variety of methods for form finding.

Growth of Form





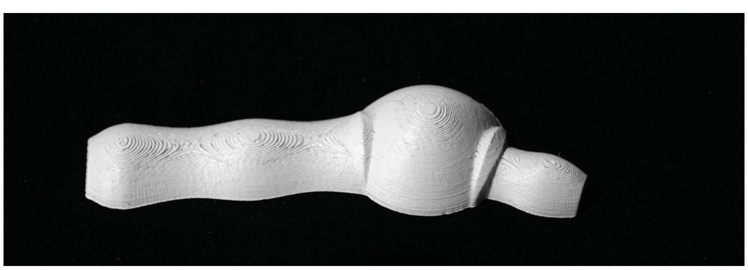
A series of photos showing the evolution of the form of the building in plan from the construction lines of the workyard enclosure.

The introduction of the architecture is viewed as a series of steps, rather than an instantaneous manifestation. The buildings will, in a sense create themselves based on the advantages provided by the steps that preceded it. For example, the workyard as the initial form provides a sheltered area to work and a predictable jig surface which can be utilized in the evolution of the structure.

.Construction is seen as a process, emerging based on the necessity of the forester. Spaces are generated in the order that someone would require them from the point of entering the forest. The first space provided is the sheltered work yard. The rest of the form grows out from this primary element.

> Every Object is characterized by the process through which it was created. This process of creation can usually be ascertained from the form. The generation of the form is not a single act rather a continuous process of variation.[12]

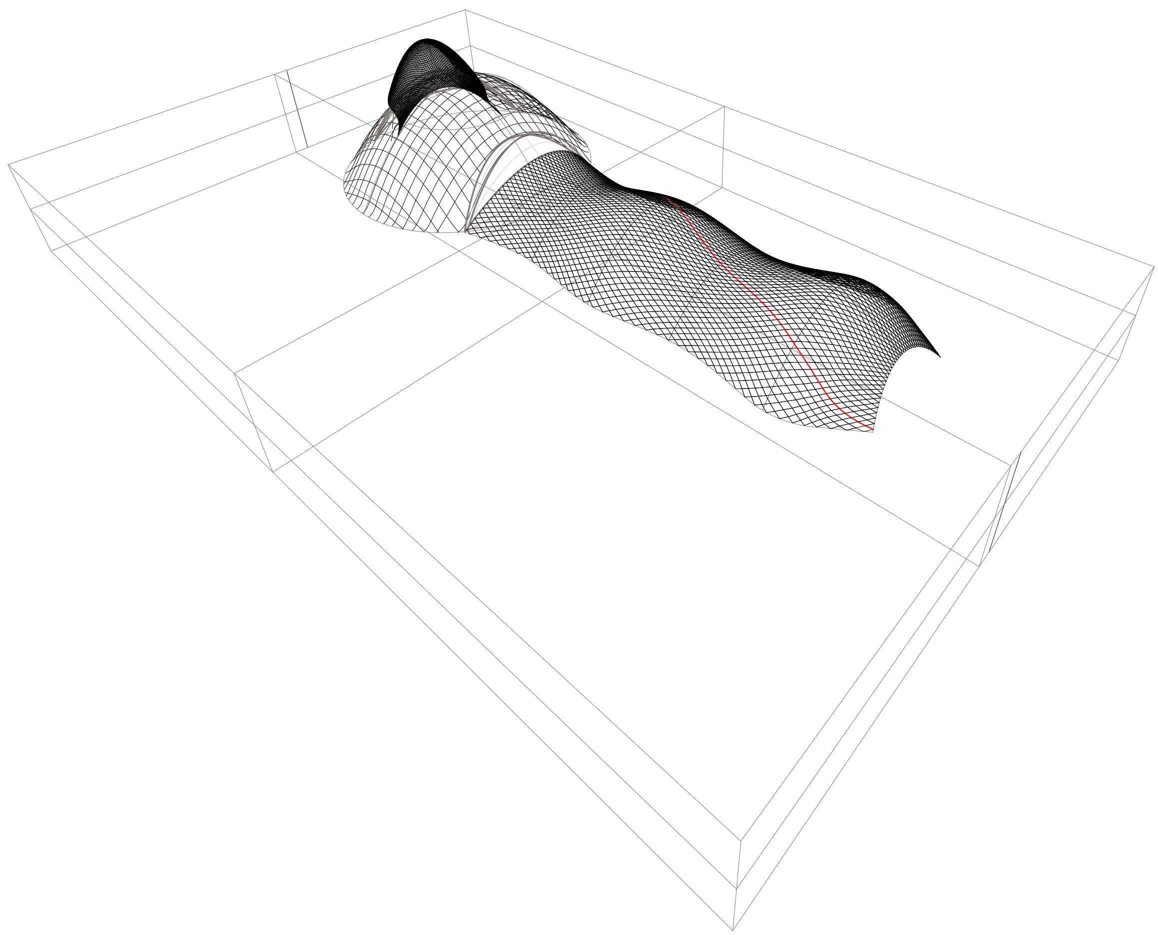
The workyard is seen as a seminal aspect of the program. It is given a central location and reads as the largest volume from which the other spaces extend. If the workyard can be though of as the head, the studio and mill portions would make up the arms.



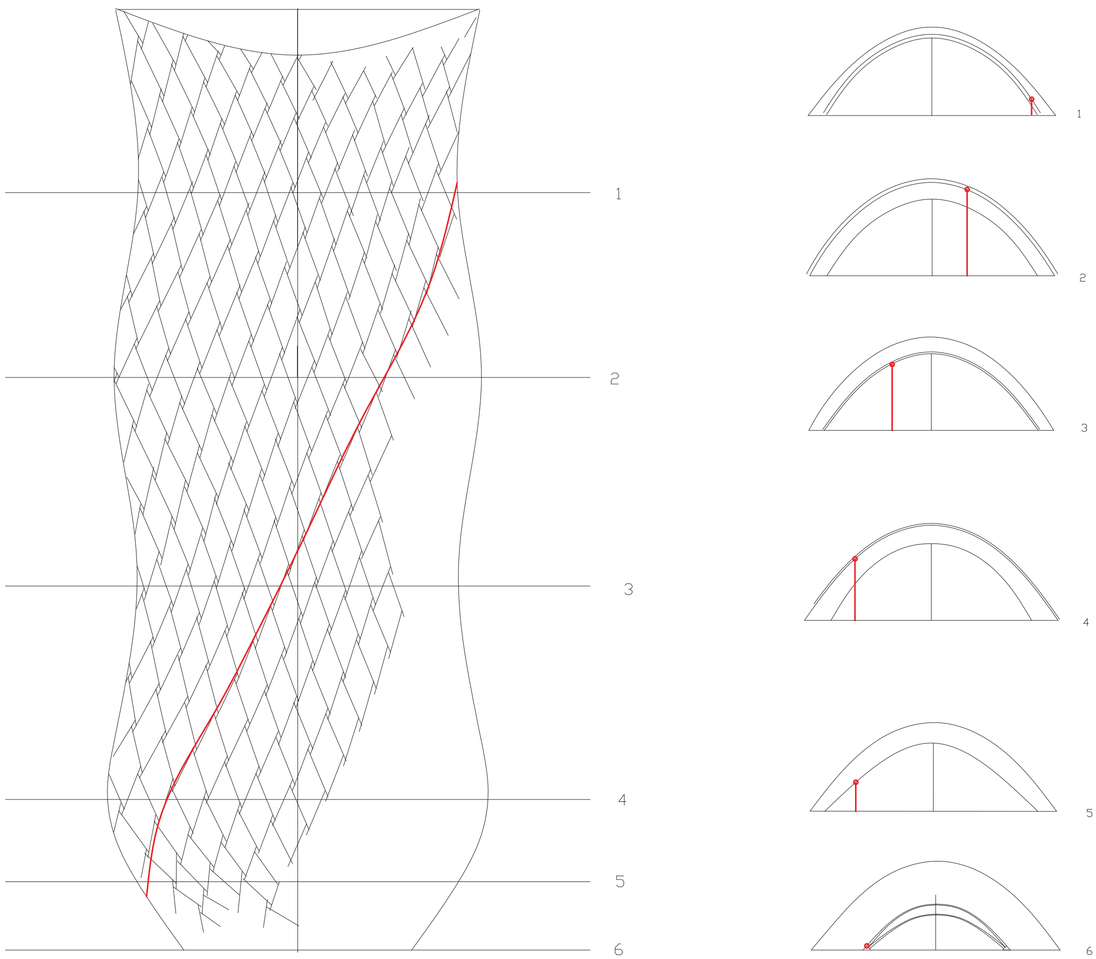
Model of the form of the building.

12 Frei Otto, *IL 10. Gridshells (*Stuttgart: University of Stuttgart, 1974), 14.

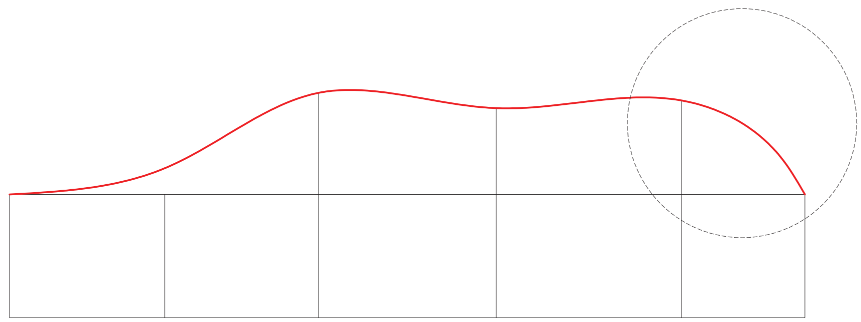
Analysis of the Digital Model



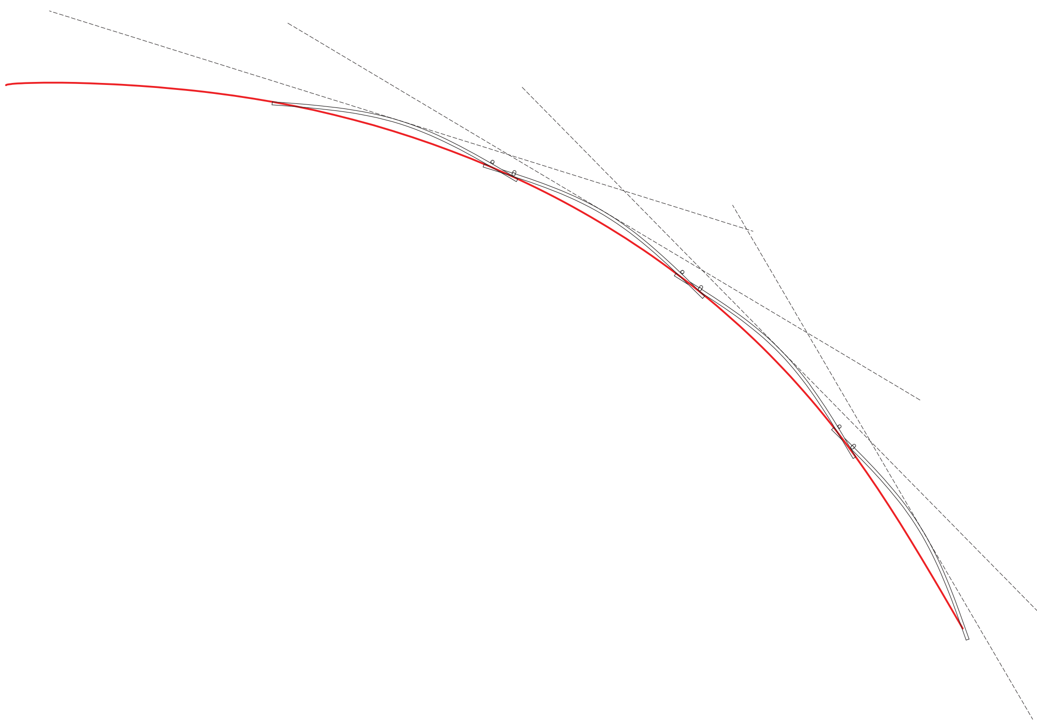
Rhino model highlighting a single line of the network to analyze the geometry of the system throughout the shell.



Roof plan and cross sections of the studio highlighting the position of a single line through the network.

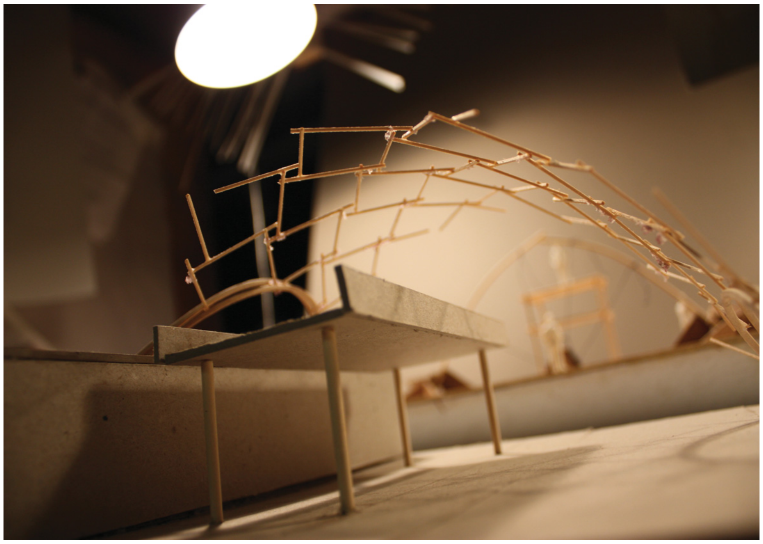


Longitudinal section of the single line through the network.

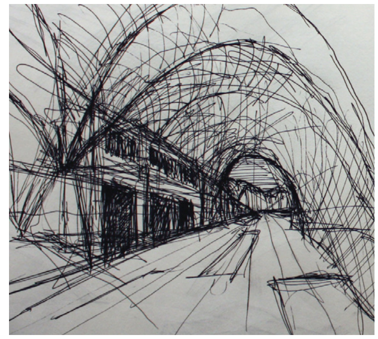


Detail of three segments of the longitudinal section showing the curvature of the members.

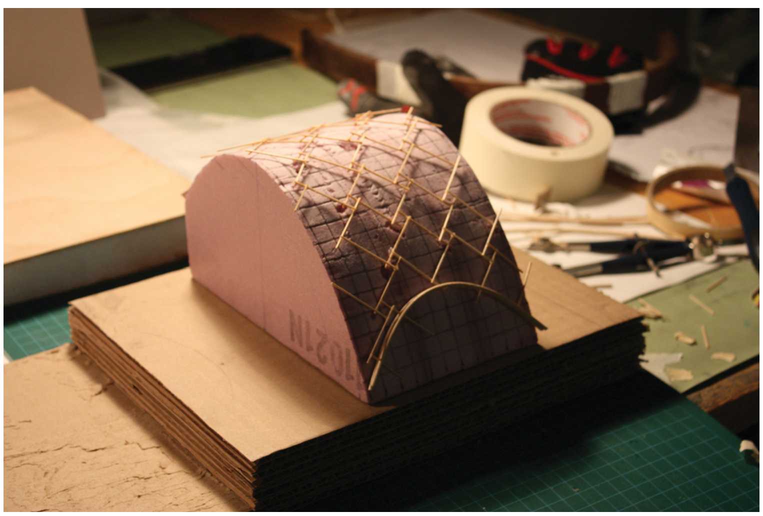
Spatial Experience



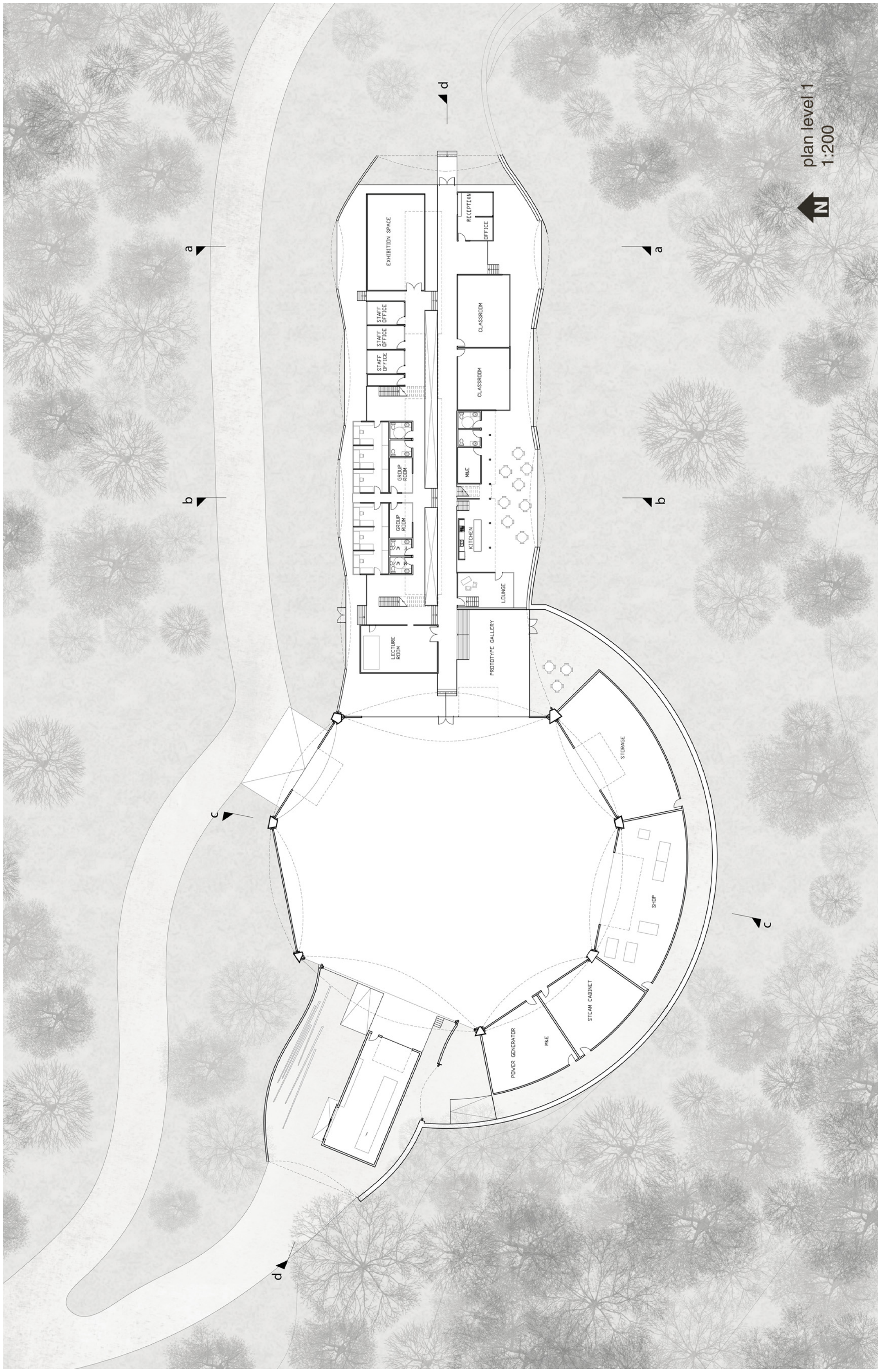
This section model through the studio portion of the building is intended to show the spatial experience beneath the grid. It is a working model to help organize the program within the shell.



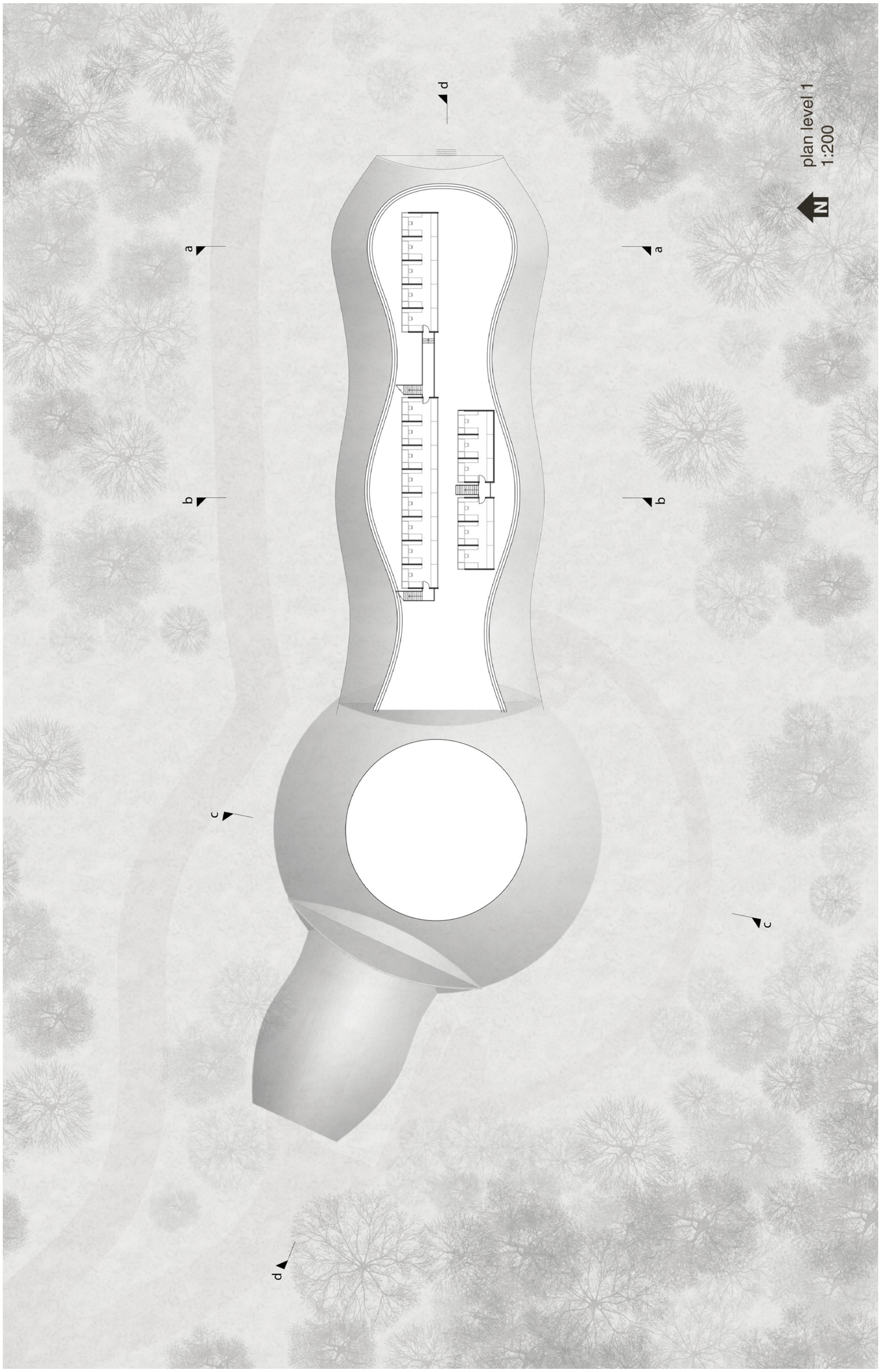
Concept sketch



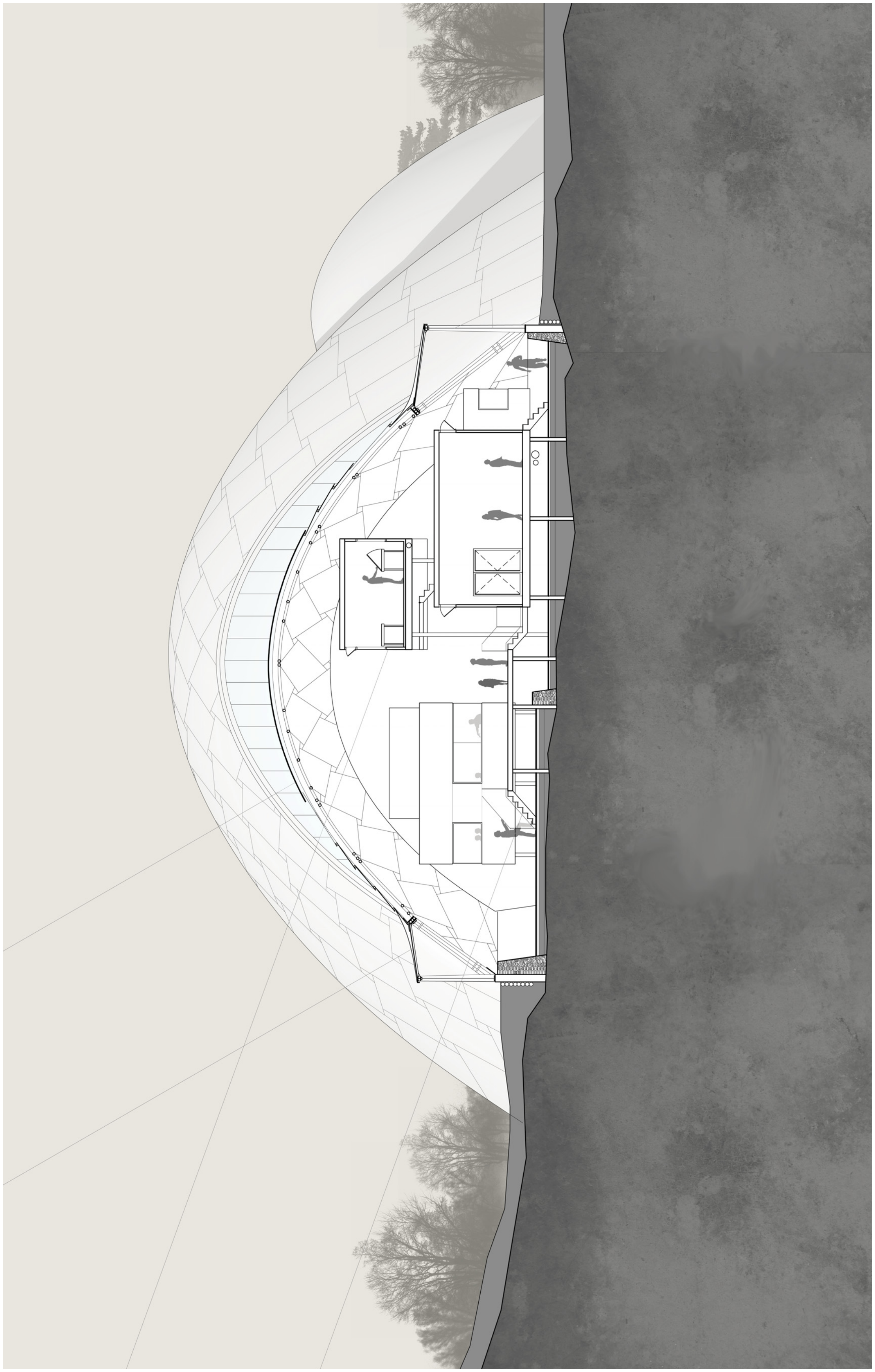
Process of building the shell model.



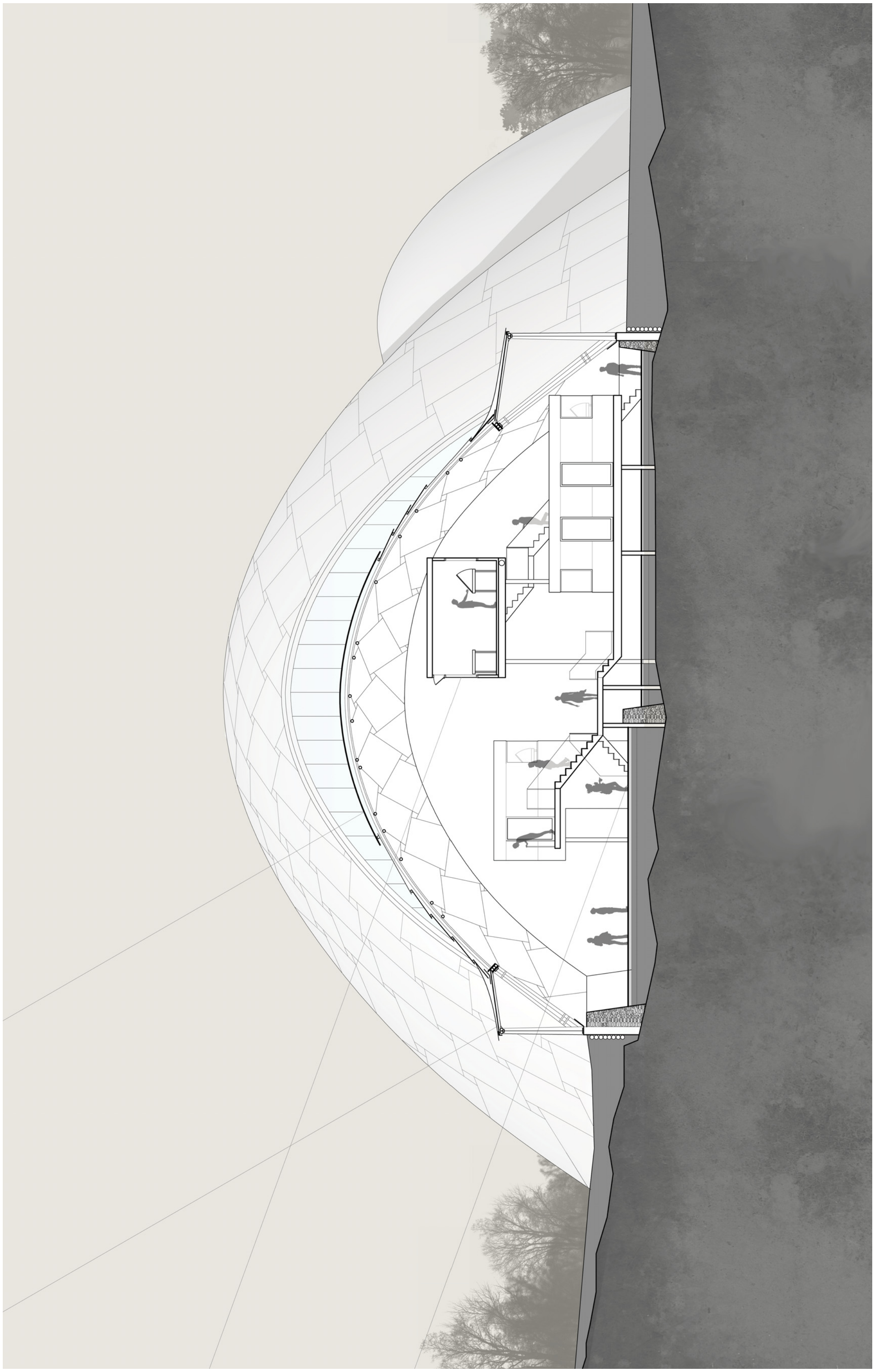
Plan level one



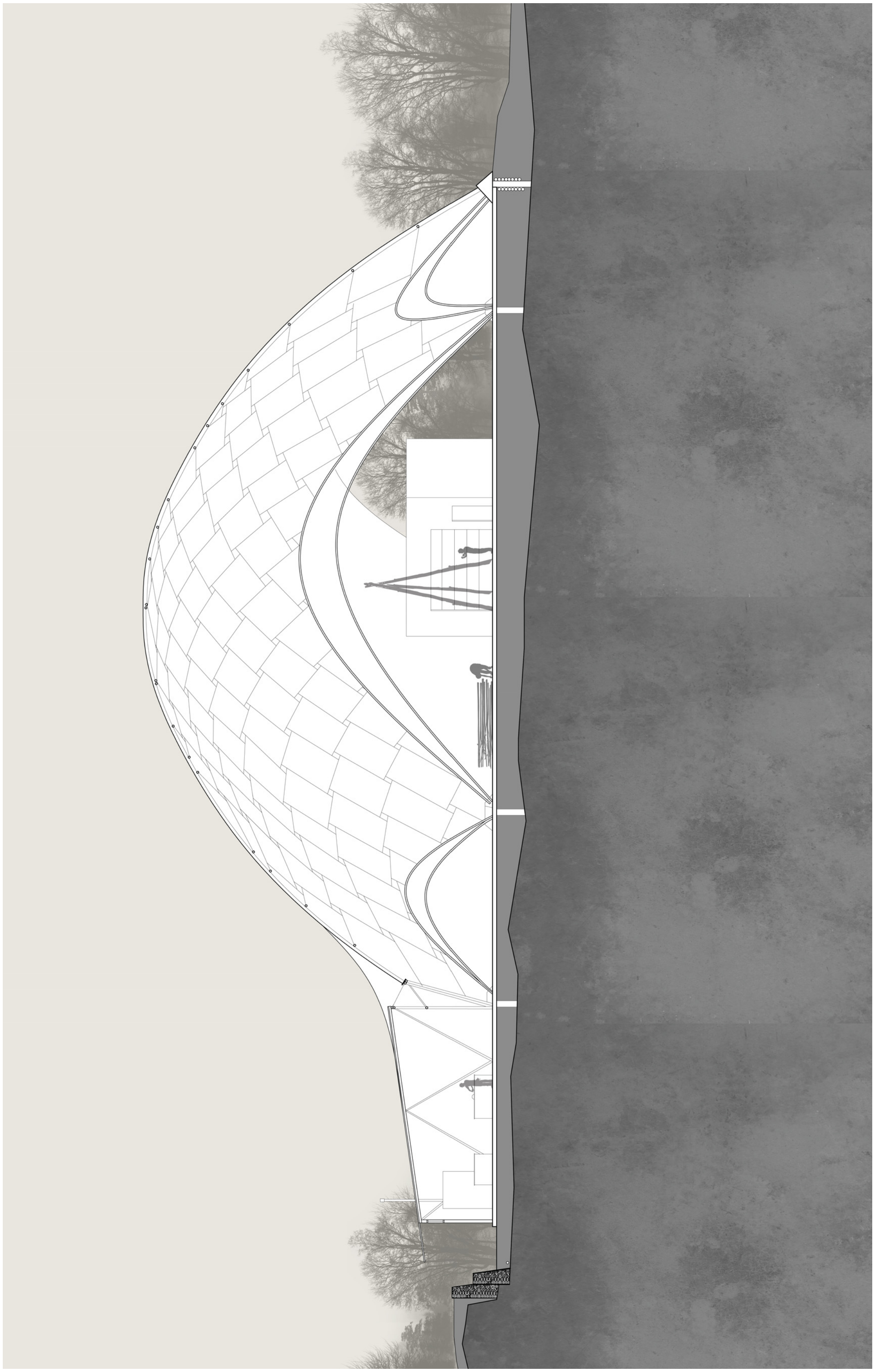
Plan level two



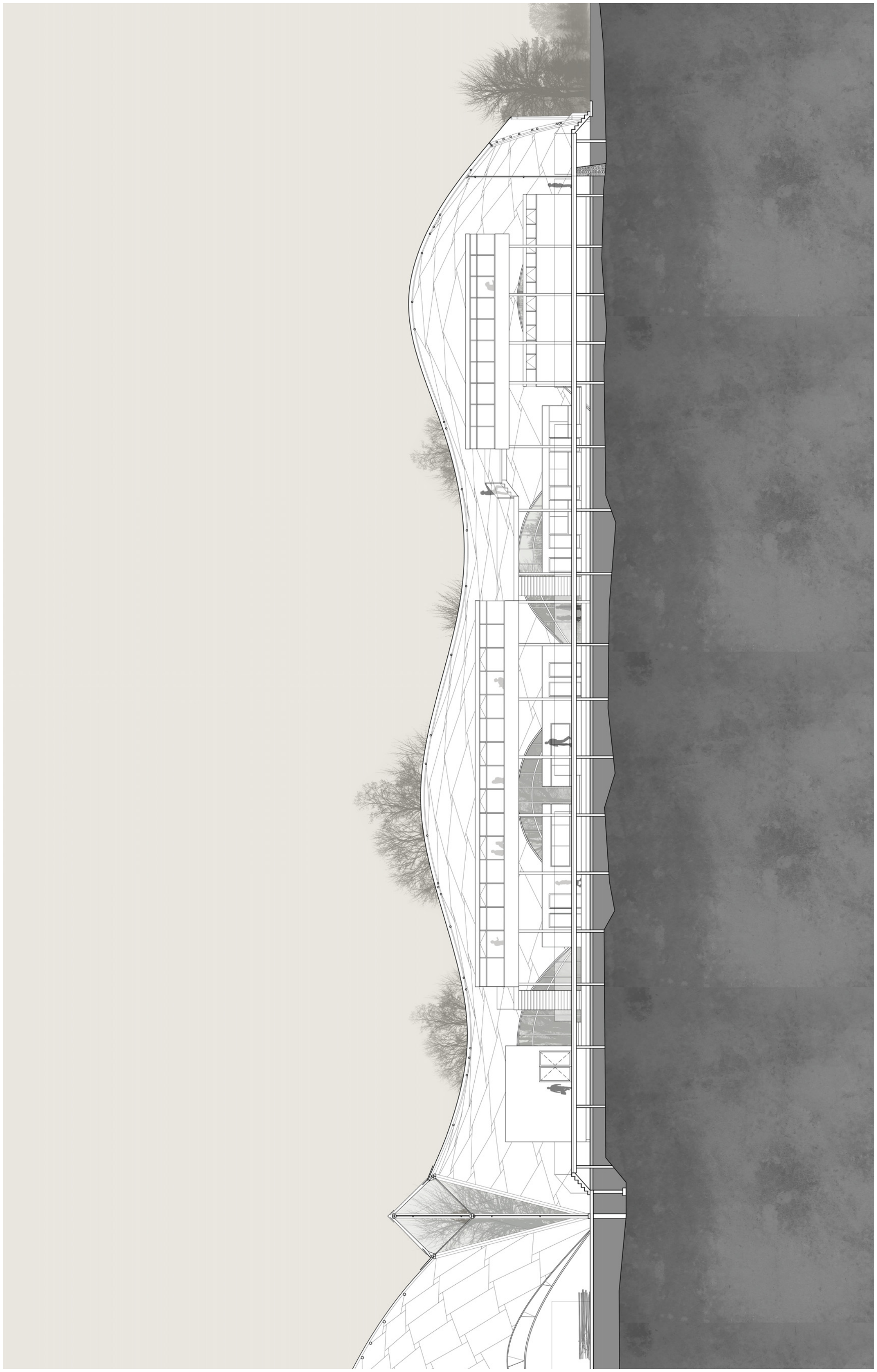
Section A



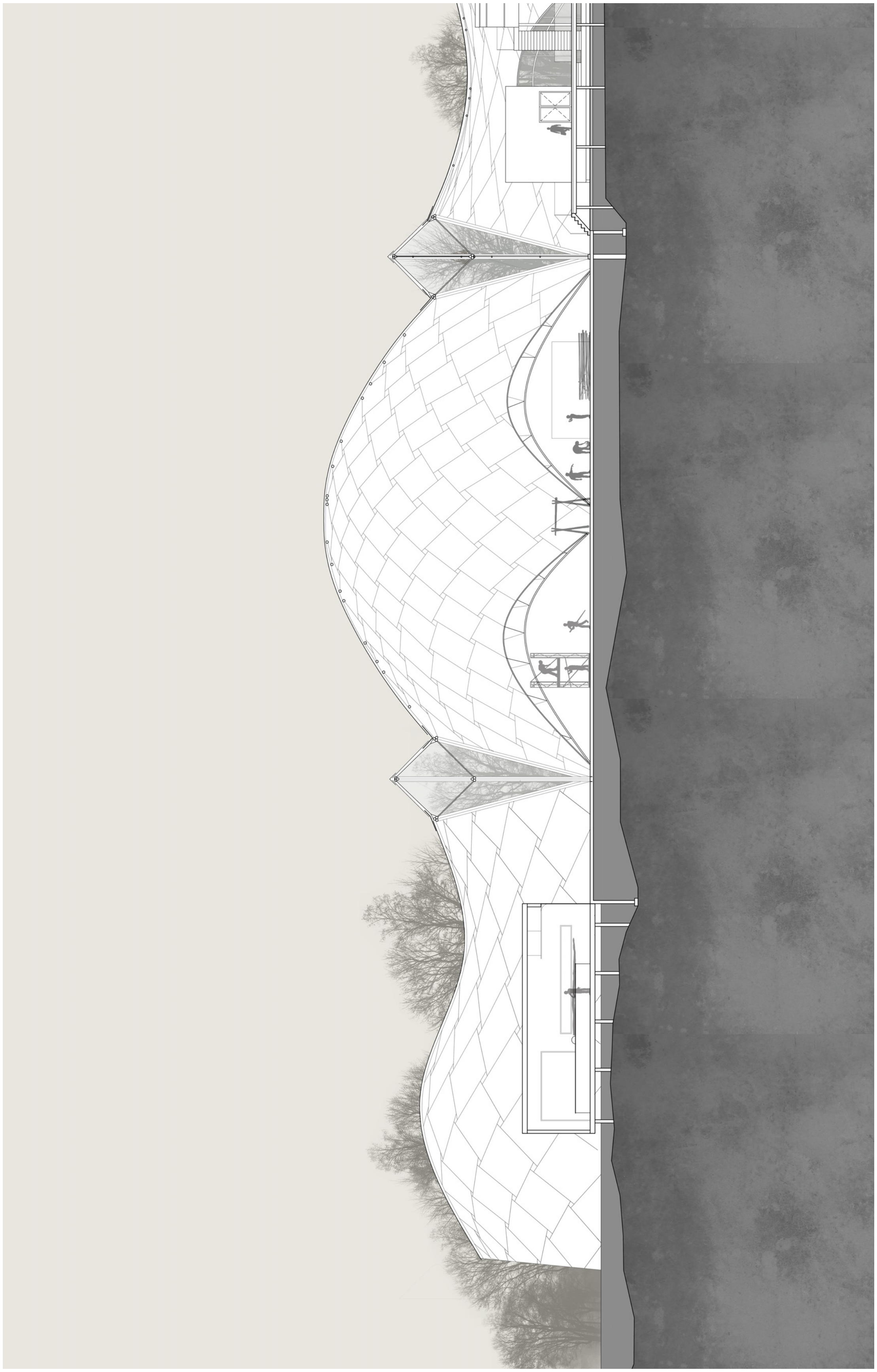
Section B



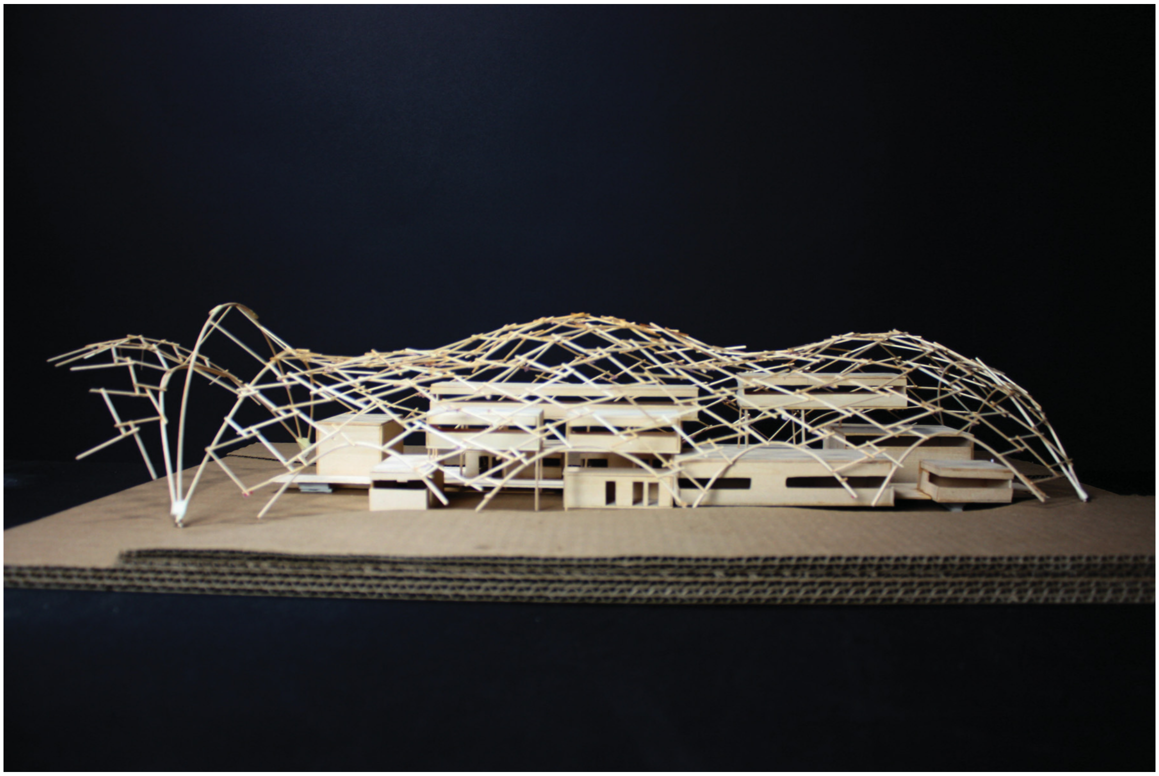
Section C



Section D, Part 1

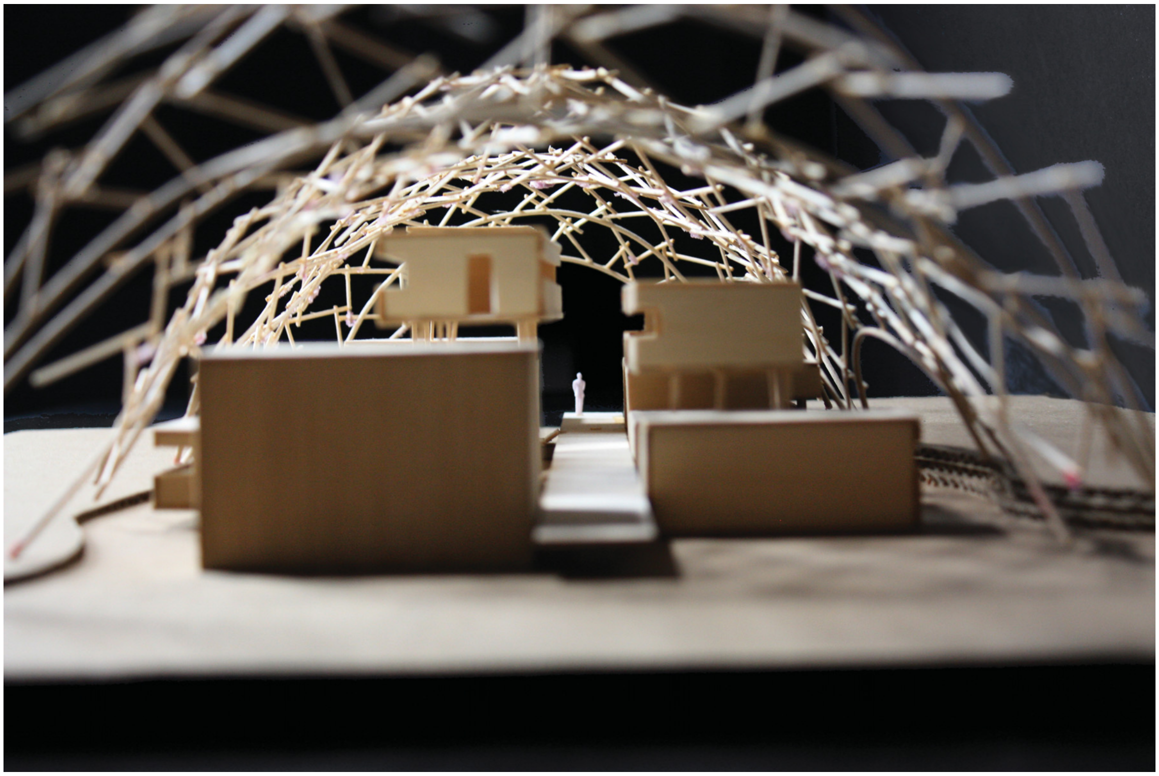


Section D, Part 2

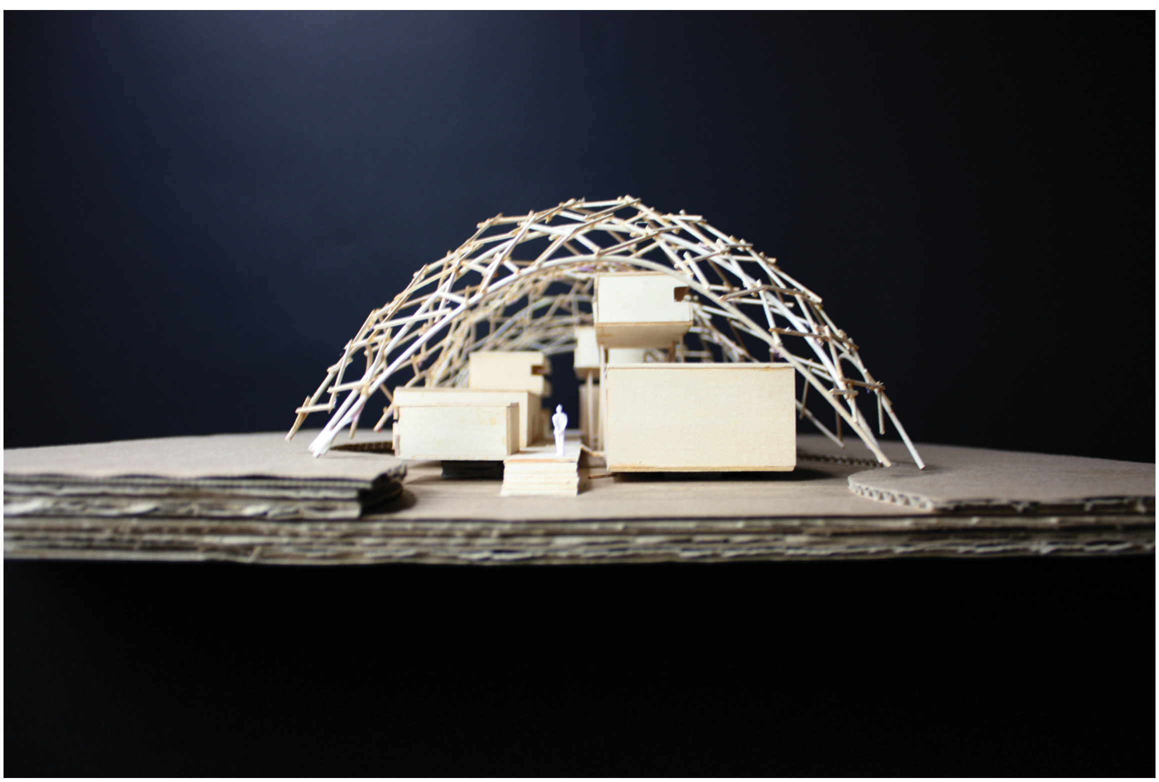


Elevational view of the studio model

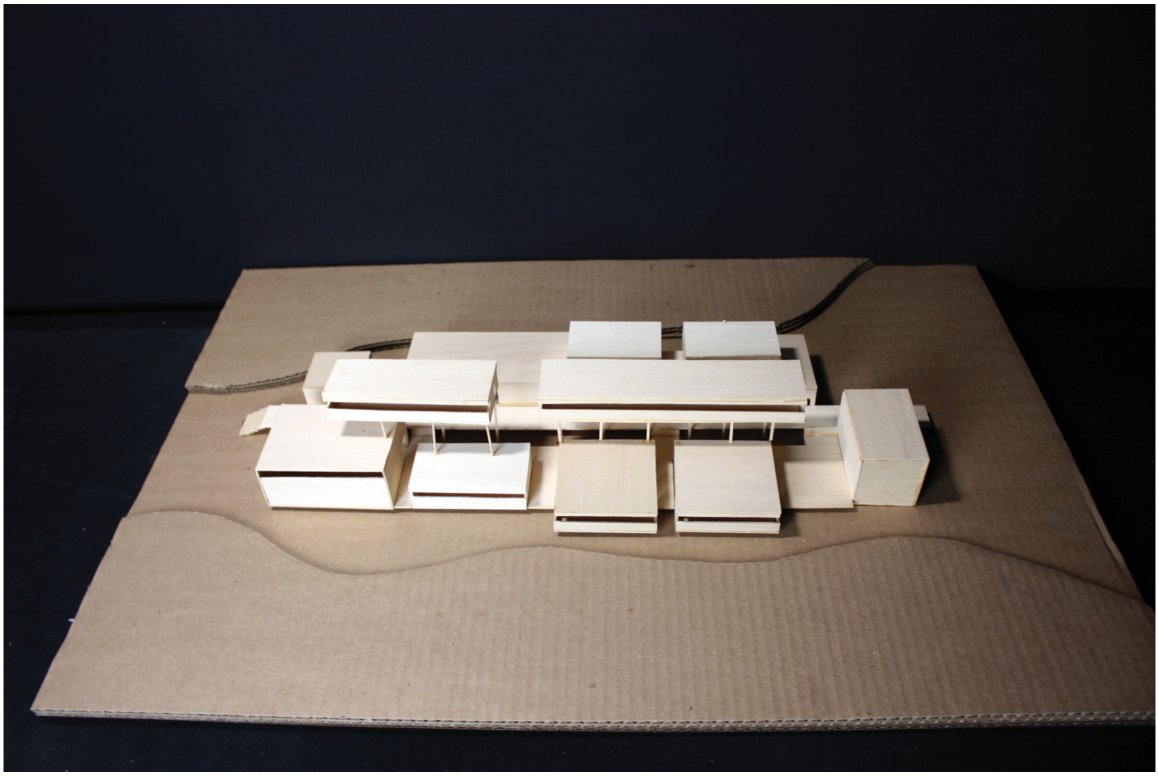
Elevational view of the studio interior volumes



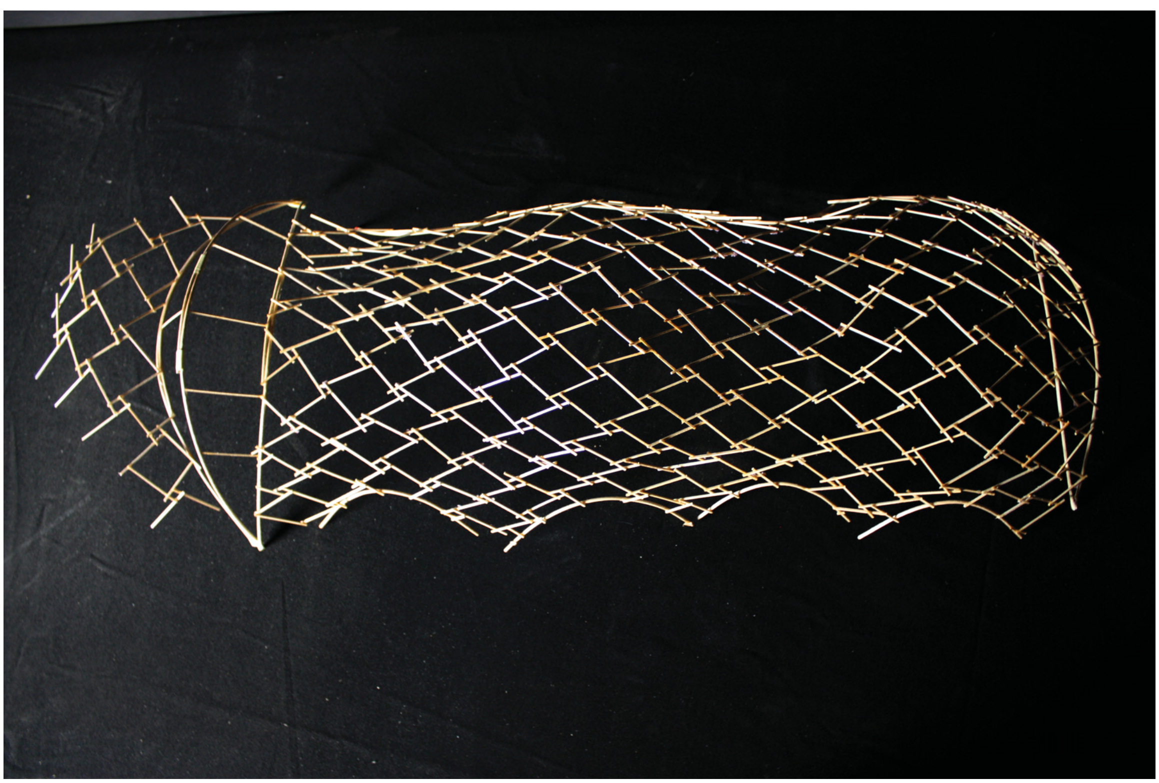
View from the workyard to the studio



View of the studio from the front entrance.



Bird’s eye view of the studio interior volumes.



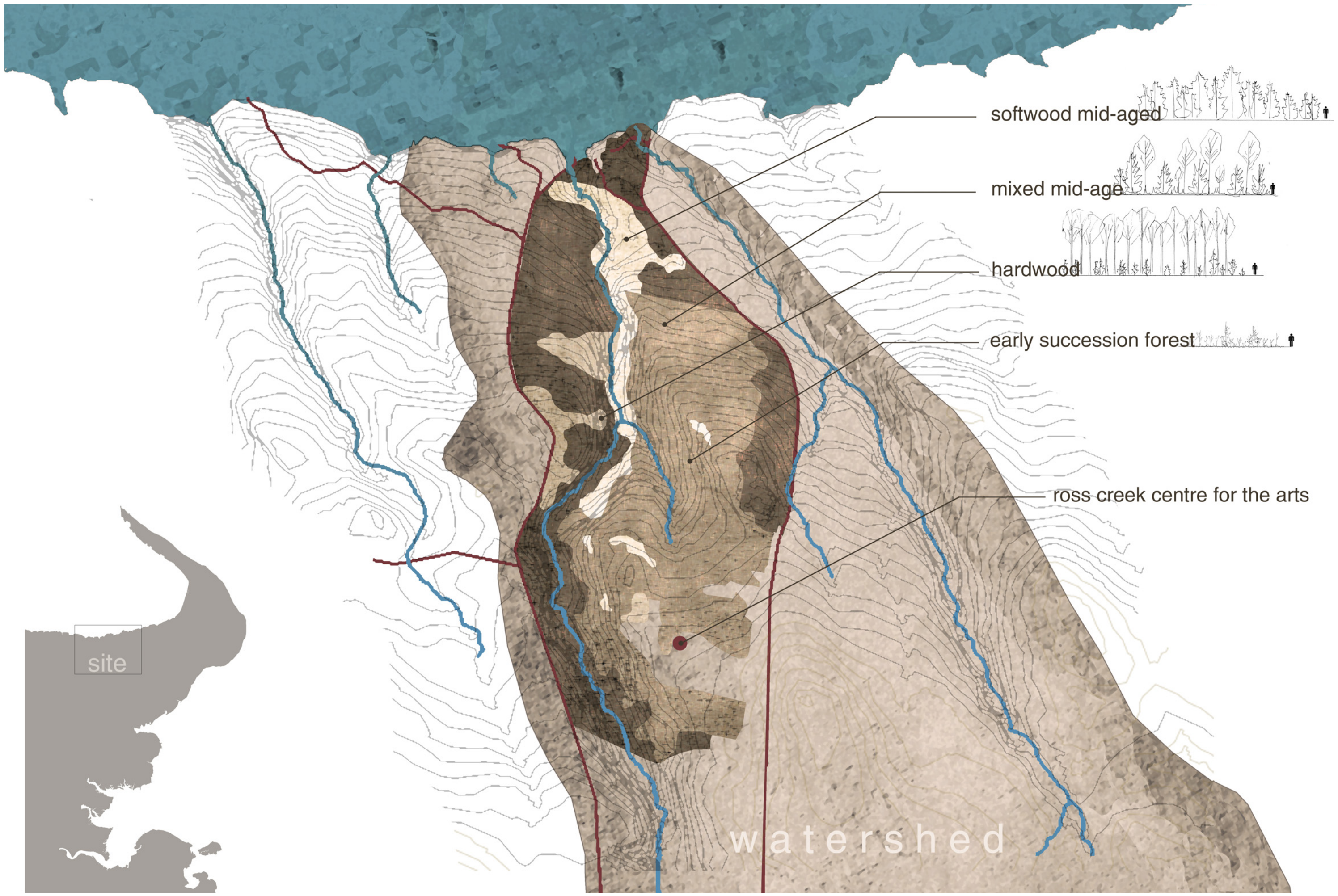
Bird’s eye view of the studio shell structure.

CHAPTER 3: CONCLUSION

The information embodied in wood has yet to be fully explored as a generator for design. I believe there is a great potential in material based methods of design. This thesis represents the beginning of ongoing research in lightweight wood structures, and has helped develop a working method which will be carried forward into future development.

I believe that the utilization of small diameter timber holds a powerful role in the future of construction and that a new method of design and building can have an impact on the stewardship for our forests.

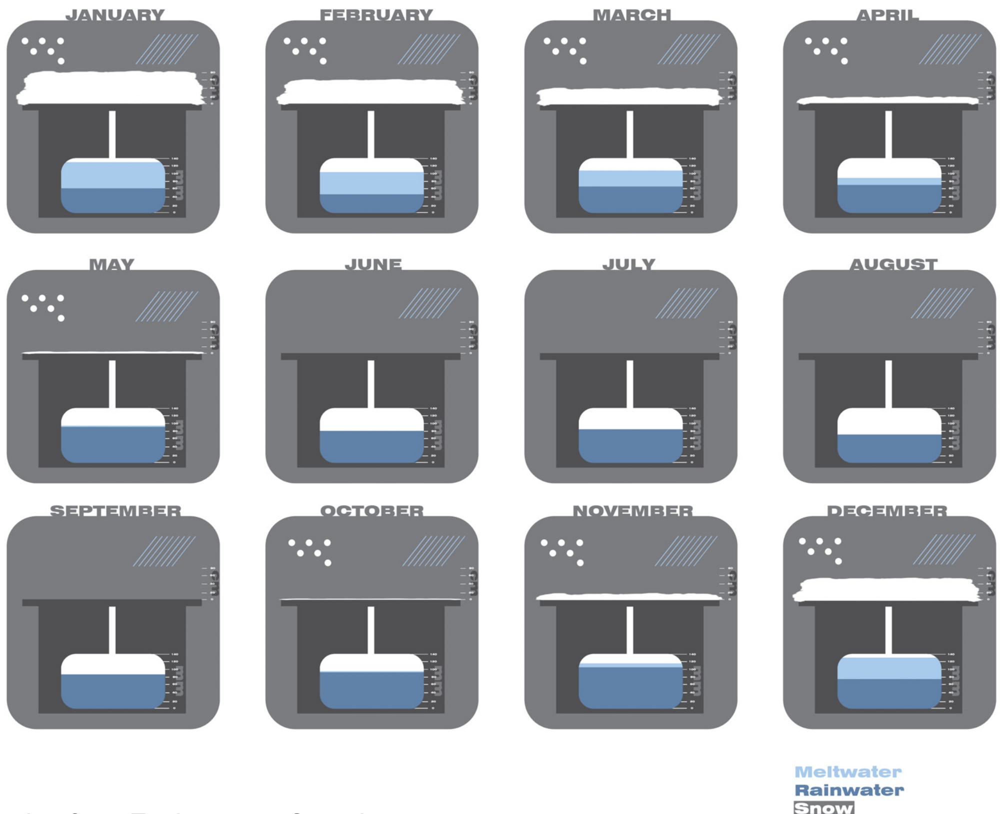
APPENDIX A: FOREST TYPE MAP



Map showing the study area and its different forest types. The larger light grey zone indicates the extent of the watersheds that the site spans. The two creeks are Ross Creek to the west (top of page) and Bennet Creek to the east (bottom of page)

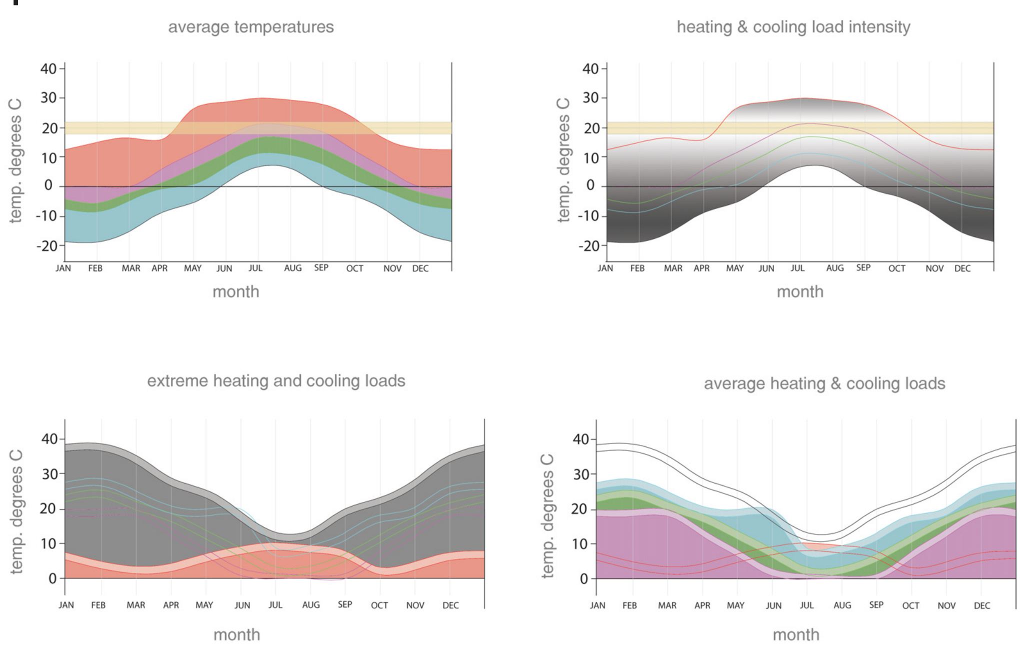
APPENDIX B: ENVIRONMENTAL INFORMATION

Precipitation



Information from Environment Canada

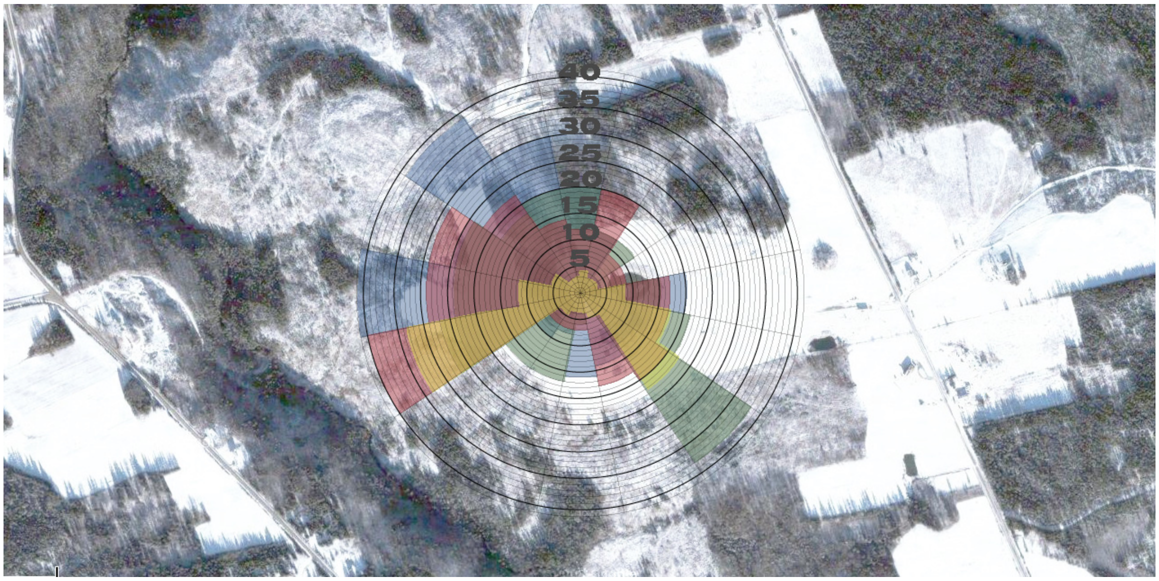
Temperature



Information from Environment Canada

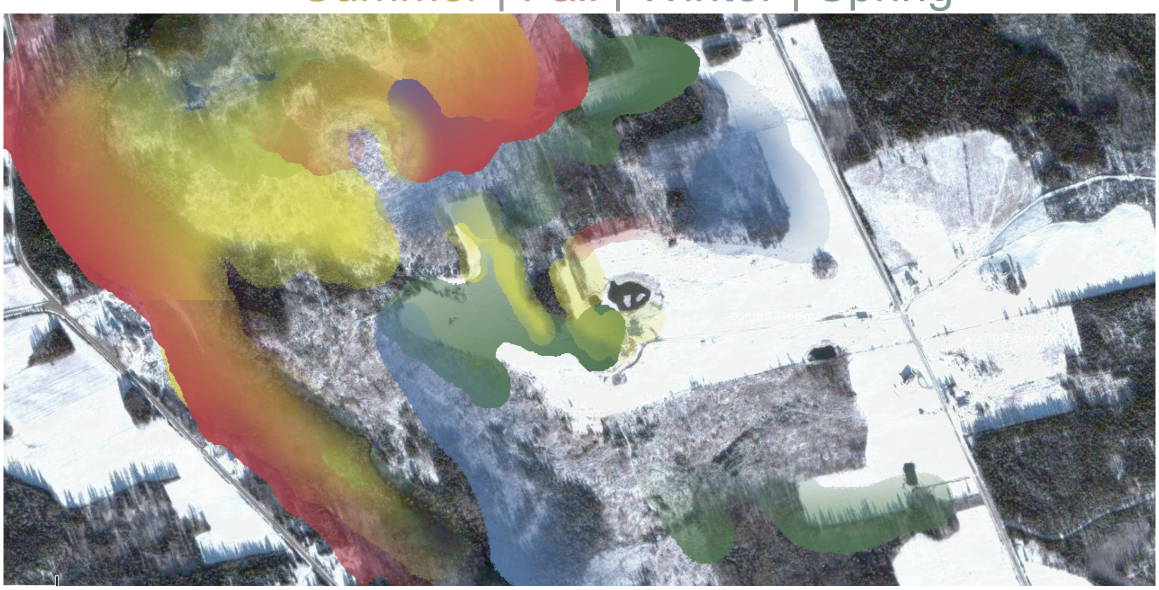
Wind Information

Summer | Fall | Winter | Spring



Wind rose on site.

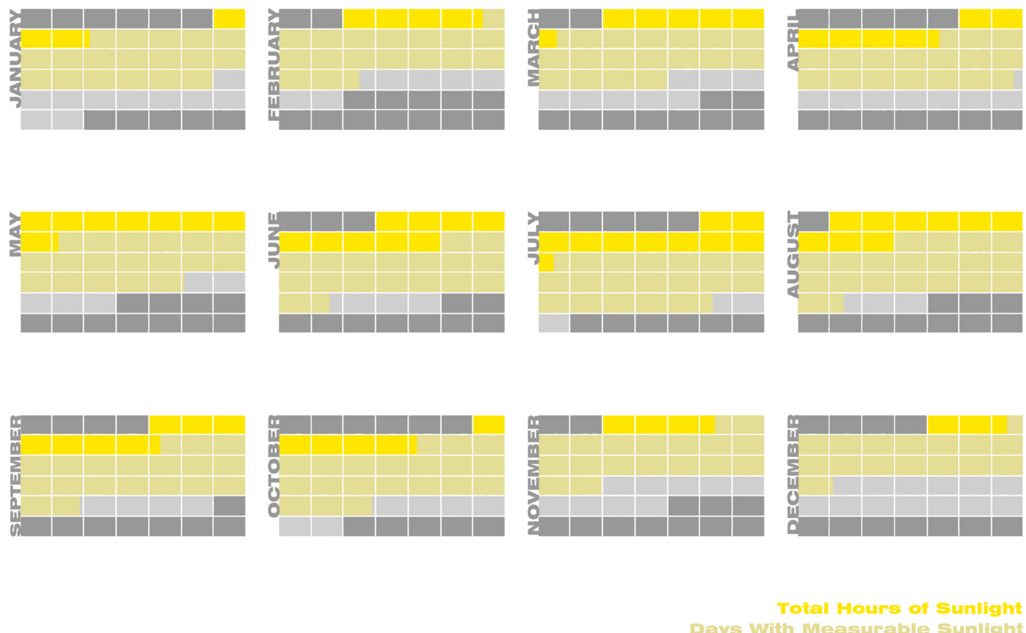
Summer | Fall | Winter | Spring



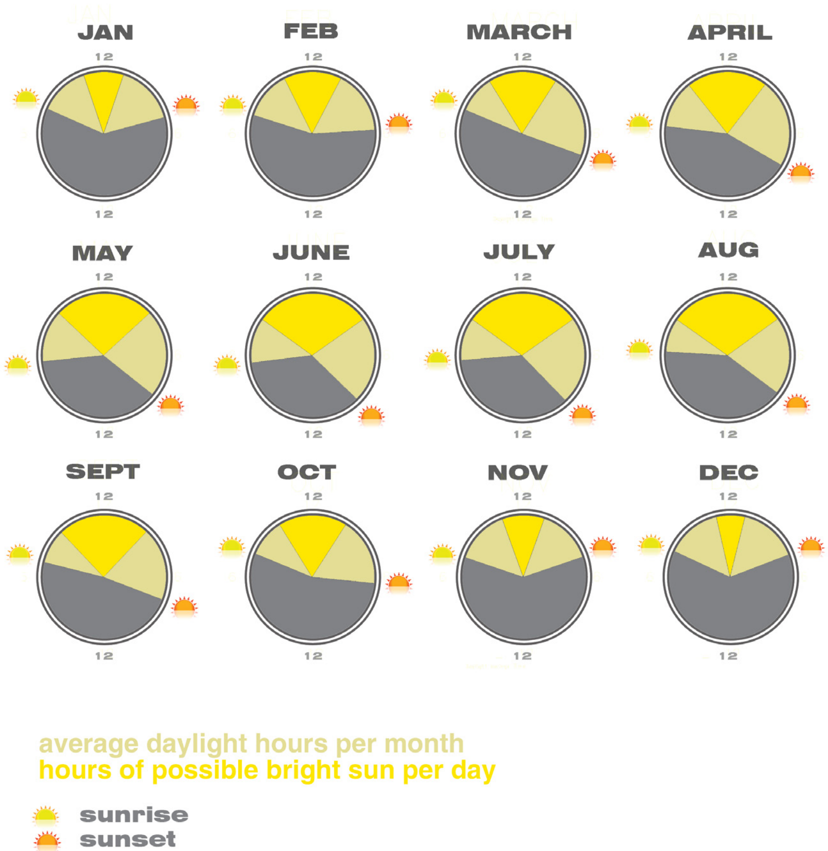
Sheltered Areas.

Information from Environment Canada

Solar Information

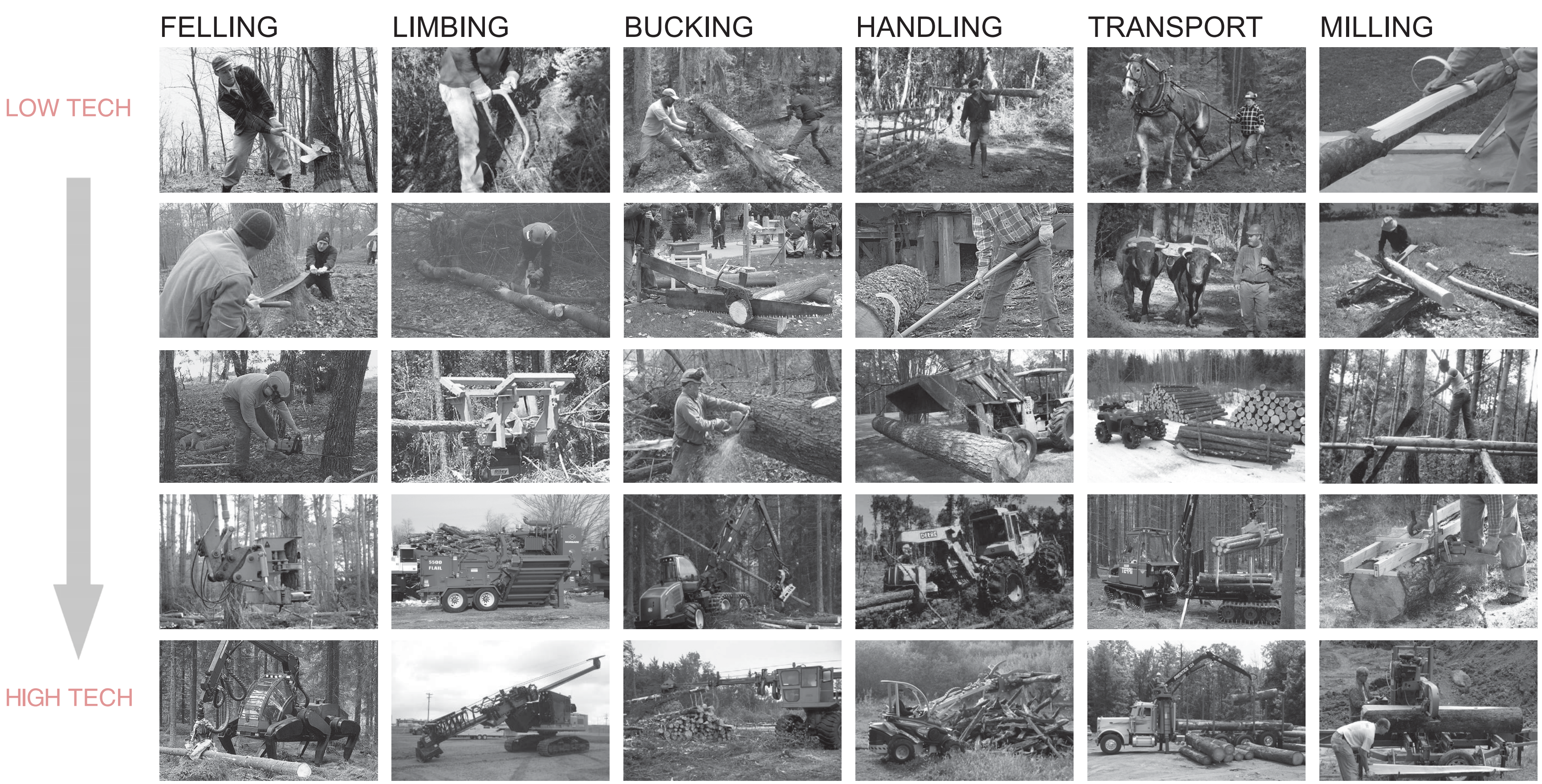


Information from Environment Canada



Information from Environment Canada

APPENDIX C: METHODS OF HARVEST



The program will focus on utilizing diverse technologies. Low tech methods will be embraced in teaching and research situations to learn about the material during harvest but high tech methods will also be embraced to make the best use of the small diameter lumber.

APPENDIX D: PROGRAM CASE STUDIES

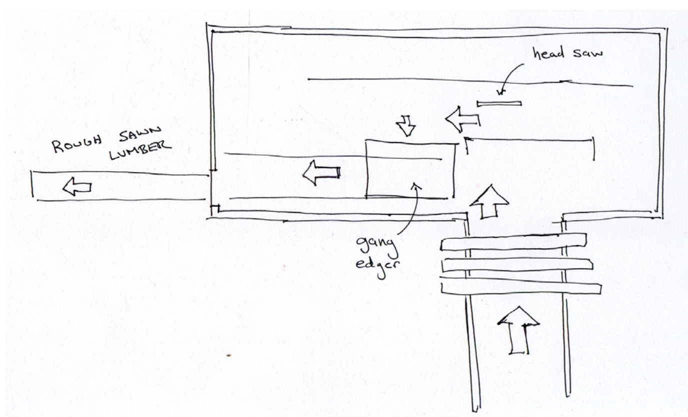
S.G. Levy & Sons Sawmill

Kings County, N.S.

Photograph of mill

This family operated mill has been running in Kings County for several generations. Owner Glenn Levy explains that they used to provide lumber for house building, but over the last decade lumber from out of province has filled that market. The mill continues to operate supplying a few local carpenters for small projects like barn and deck building and filling niche markets, providing some hardwoods and wood for making apple barrels.

Byproducts



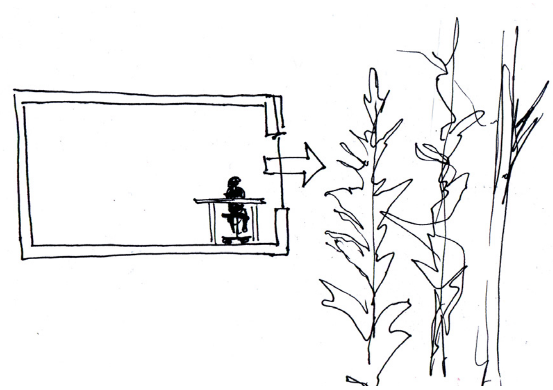
Process

Haystack Mountain School of Craft

Haystack Mountain School of Crafts is an international craft school located on the Atlantic Ocean in Deer Isle, Maine. The school offers intensive studio-based workshops in a variety of craft media including clay, glass, metals, paper, blacksmithing, weaving, woodworking and more. Programs range from short workshops to two-week sessions and anyone may participate, from beginners to advanced professionals.

The programs involve intensive and focused studio time, the exploration of other art forms including music, poetry and dance, a diverse student body, and an award-winning campus. Students live, eat, and work at the school, and studios remain open 24 hours a day, seven days a week.

The students work while immersed in the landscape, allowing them to draw inspiration from their environment, and develop a deeper understanding of the materials that they work with, and the implications of their design decisions. Students of design work closely alongside students of craft and art, allowing them to learn form the way others take inspiration from their surroundings.



Hooke Park

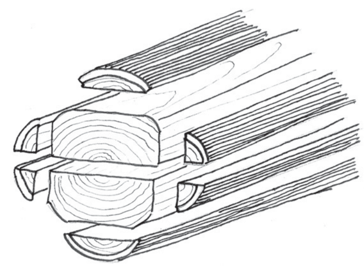
Hooke Park is a 350-acre working forest in Dorset, south west England, that is owned and operated by the Architectural Association. The woodland contains a small educational facility centred on a woodworking workshop, that was built in the 1980s and 1990s as a furniture and forestry college. AA aims to develop Hooke Park as a site for exploring rural architectures, the crafts of construction, and sustainable timber technologies. From spring 2010 a group of students have been resident full-time at Hooke and the new Design & Make graduate design course began in autumn 2010. The existing buildings at Hooke Park, designed by collaborations between ABK, Frei Otto, Buro Happold and Edward Cullinan, are remarkable demonstrations of an intelligent approach to maximizing the resource provided by the forest.

Genesis Centre - Memorial University - Business Incubator

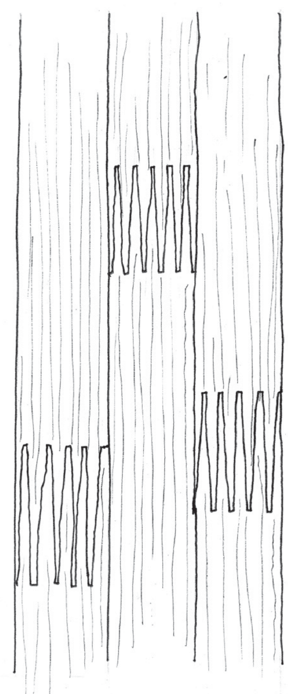
A business incubator is an organization that provides space, equipment, services, advice and support to assist fledgling businesses to become established and profitable. Many Universities have incubators to assist with the commercialization of new technologies developed by students and faculty. The craft school will utilized this sort of program to support successful prototypes and ideas through development, until they are ready to stand up to the rigorous standards of the construction industry

APPENDIX E: MILLING

Minimum Cut



Sawing small round timber begins with a centre cut to establish a flat edge. From there a square piece of lumber can produced. Saplings and pole timber are usually not milled because the yield is too low to make it worthwhile. However new technology is making the wood in small diameter timber more reliable



One of the main commercial uses of small diameter timber is in engineered composite wood products, or 'value added wood products'. These involve using the individual strands or small sections of the wood, and gluing them together to create structural members. These products include

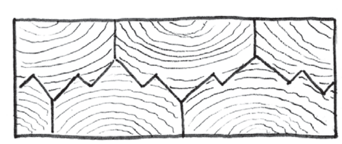
OSB (oriented strand board)

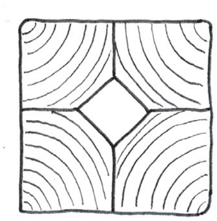
LVL (laminated veneer lumber)

Finger joined wood

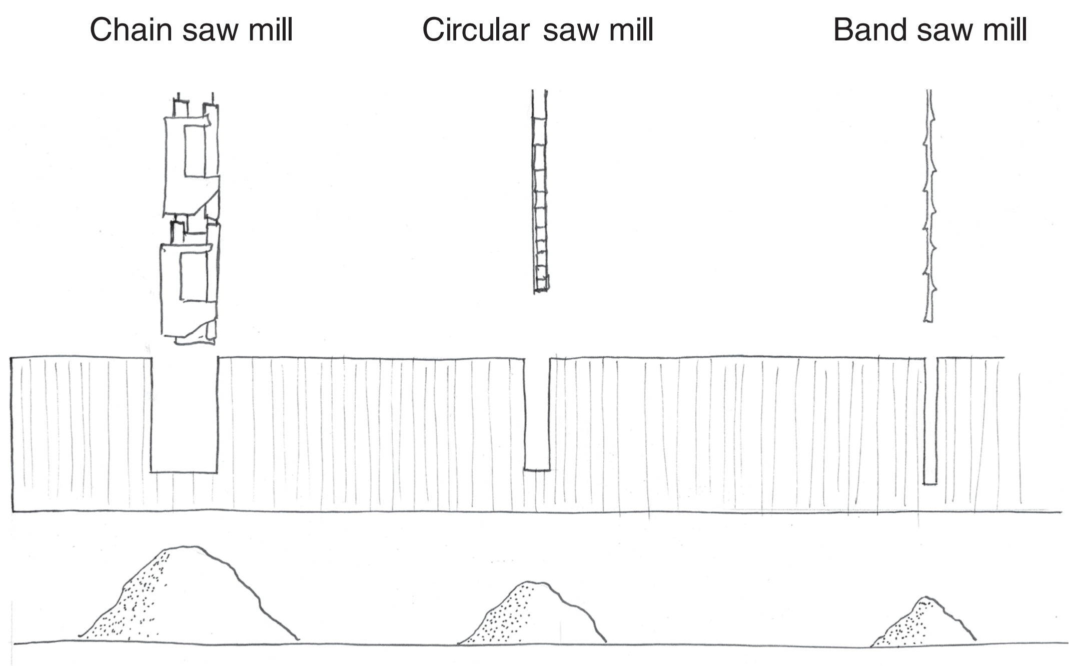
Gluelaminated

Crosslaminated





Types of Mill



Largest kerf	Medium kerf	Smallest kerf
most waste	medium waste	least waste
portable	not portable	somewhat portable
operable by one person	operable by one person	operable by two
ideal for large lumber	ideal for mid size lumber	ideal for small lumber

High Tech Milling

Resaw - A large band saw optimized for cutting timber along the grain to reduce larger sections into smaller sections or veneers.

Curve Saw - A type of computer controlled power saw that can cut to the contour of a curved log, creating less waste in the milling process

Gang Saw - A type of power saw that makes several cuts simultaneously, pulling logs across its blades to cut an entire section into planks with one pass. The most common modern gang saw is the band saw. Gang sawing occurs in the middle of the steps in processing a tree into lumber. Before the tree reaches the saw, it goes through a series of single blade saws that remove the bark and outer variations in the tree. After these steps, the wood is shaped like a large rectangular box. This box is sent to the gang saw, where it is made into planks.

Sapling - 1” - 4” dbh

Pole Timber - 4” - 10” dbh

Saw timber - 11” - 18” dbh

Large Saw timber - 18” + dbh

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