REED ROBOTICS

Discrete Digital Assembly of Biodegradable Reed Structures

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ABSTRACT

Common Reed (*Phragmites Australis*) is an abundantly available, sustainable construction material that can be found throughout the world. Reed is most commonly used for thatch roofing in Europe, providing insulation and a weather-tight surface. Elsewhere, traditional techniques of weaving and bundling reeds have long been used to create entire buildings. This research develops a new alternative to these techniques with the aim of showcasing the ability of reed to perform as structure, insulation, and cladding all at once. In the Netherlands, the availability of inexpensive imported reed has led to a decline in demand for Dutch reed for thatching. This is problematic as the management of reed beds is essential for nature conservation. The research aims to promote the use of Dutch reed for construction through utilising a digital production chain in order to reduce labour costs. Through an iterative process of designing from the micro to the macro scale and by experimenting with robotic assembly, the result is a reed-based system in the form of discrete components that can be configured to create a variety of structures. The project questions permanence in architecture, through the proposal of a series of nature observation structures for the National Park Duinen van Texel. The structures are intended to last ten to twenty years and utilise completely biodegradable materials which can be disassembled whenever necessary. This semi-permanence allows for future flexibility and ensures preservation of the natural environment. Physical prototyping and testing of the proposed robotic assembly process validates the approach.

CONTENTS

Figure 1:
Stand of Reeds located on Texel Island in the Netherlands (By Author, 2019)

1 - INTRODUCTION

1-1 Context

The future of sustainable architecture lies in solutions which merge natural or waste materials with new technological processes to solve environmental problems and reduce negative impact. The design and construction of sustainable buildings is of key importance for the clean energy transition as building construction and operations continue to account for a substantial portion of energy related carbon dioxide emissions; 39% in 2017 (I.E.A., 2018). In the simplest terms, a building results from material that has been formed to provide defined space. Therefore, it can be argued that material choices and production and assembly methods ultimately determine the sustainability of a building in terms of the amount of energy required for construction, the longevity and quality of the building, and the ecological impact.

Cement, steel, plastics and aluminium account for 1.6 billion tonnes of materials used per year in the European Union (I.E.A., 2018). Finding alternative renewables in substitute for these emission producing materials is an important challenge for architects. In considering sustainable materials for use in the European climate, plant based resources, such as timber and bamboo, have been heavily investigated as quality materials that offer good performance characteristics. Other plant materials have been less widely studied. Common Reed (*Phragmites Australis*) is capable of performing as structure, insulation, and cladding, and is abundantly available throughout Europe (Figure 1). Reed has traditionally been used for thatch roofing, providing insulation and a weather-tight exterior cladding. In other countries, such as Peru and Iraq, traditional techniques of weaving and bundling reeds have long been used to create entire structures. In the Netherlands, the availability of inexpensive reed from other countries such as Turkey and China has led to a decline in demand for Dutch reed. This is problematic as the management of reed beds is essential for nature conservation; so important, that in some parts of the country Dutch reed cutters receive subsidies for their role in nature management (Bink, 2017). The research aims to promote the use of Dutch reed for construction through the utilisation of a digital production chain in order to reduce labour costs.

"Without a broadly based process that penetrates deeply into the very heart of how things are made, any success will be fleeting and unsustainable"
- KieranTimberlake Architects

In considering production methods, the use of digital design, fabrication, and assembly is becoming an increasingly popular model. However, the aim should not be towards automating every step of the process as there are certain tasks which will always be better performed by humans. Additionally, the more automated a process is, the more energy it requires in manufacturing. Using materials in their raw forms limits the amount of processing required, thereby improving life cycle cost. On the other hand, the use of digital tools can expand architectural possibilities by introducing a level of complexity and precision that would not be achievable through alternative means. A newly emerging model in digital design is the use of voxelization or discretization, in which architecture is composed of discrete digital materials or components with embedded data that dictates the spatial arrangement and assembly process. The philosophical term *mereology* describes the study of relations between parts and wholes. Through an iterative process of designing from the micro to the macro scale and by experimenting with robotic assembly, this research proposes an innovative and sustainable approach to using reed for architectural applications. The project also questions permanence in architecture, through the proposal of a series of nature observation structures for the National Park Duinen van Texel. The structures are intended to last ten to twenty years and utilise completely biodegradable materials. This semi-permanence allows for future flexibility and ensures preservation of the natural enivronment.

This first chapter describes the relevance of using natural plant fibers and the importance of incorporating fabrication and assembly methods into the design process. Chapter 2 documents the characteristics of reed including the growth and harvesting process and historic uses in architecture. In chapter 3, digital design processes are discussed. In chapter 4, a case study is introduced and the proposed system of robotically assembled reed blocks is described. In the final chapter, the results are discussed.

1-2 Problem Statement

Despite the abundance of plant fibers and their potential as sustainable, low cost construction materials, their use has historically implied a lack of modernity, which has led to a decline in use in the contemporary context. Plant fibers offer many benefits; they are locally available and abundant in most parts of the world, they sequester carbon, are biodegradable, non-toxic, non-irritant, have high thermal storage capacity, and their thermo-hydric properties allow for breathable wall constructions (Piesik, 2017). Bamboo is widely used and continuing to grow in popularity, whereas other nonwood plant fibers, such as reed, hemp, flax, or straw, are rarely employed other than in composites or as insulation material.

The challenges in using plant fibers are the need for frequent repairs or replacement of the plant fiber, and the difficulty of fireproofing and waterproofing. These disadvantages have been overcome in the past by tightly packing plant fibers. Thatch roofing is one example, which when properly constructed and maintained can last up to 50 years, and in some cases up to 100 years (Lautkankare, 2007). Common Reed is particularly well suited for providing weather protection and insulation. Reeds are a good construction material to work with, as they are easily cut and bent. Reeds have a long history of use in architecture; the Mudhif, a traditional guest house constructed entirely of the reeds is thousands of years old, and is still constructed by the Marsh Arabs in Iraq today (Figure 2). However, there exists a negative perception of plant fibers, for example, in Rwanda, thatch roofs were banned as they are viewed as a symbol of poverty (Survival International, 2011).

Common Reed (*Phragmites Australis*) offers a sustainable, low cost material for construction and is abundantly available in the Netherlands, as well as many other countries. However, the use of reed as a construction material in contemporary architecture has diminished, as the material is often perceived as weak and primitive. There are few studies which look to find new architectural applications for reed through the use of innovative fabrication methods. Rather than declining in use, reed should be considered a viable contemporary construction material for sustainable architecture.

Figure 2:
Traditional Mudhif guest house, constructed with woven reeds by Marsh Arabs in Iraq. Photo Credit: Ikhlas Abbis (Abbis, 2009).

1-3 Research Questions

How can a digital design process reframe the use of reed in contemporary architecture?

How can this provide a solution for non-intrusive observation buildings in the natural landscapes of Texel Island in the Netherlands?

1-4 Relevance: Innovation, Significance, and Sustainability

Contemporary architecture must meet many requirements to be successful. Buildings must be sustainable, employ advanced technology and use smart materials, while balancing the performative, experiential and aesthetic qualities of the space. The proposed research combines a sustainable material, traditional craft techniques of weaving and thatching and design explorations informed by an advanced robotic fabrication process. The research is of significance, as it experiments with the possibilities of the aforementioned techniques to provide an impetus for increasing the use of reed in contemporary architecture.

When properly managed and harvested, reedbeds can contribute to healthy wetland ecosystems, providing a habitat for a variety of birds and animals. The proposed case study of nature observation buildings for the National Park Duinen van Texel on the Island of Texel in the Netherlands will demonstrate how architecture can integrate with natural habitats, allowing for human interaction and observation while minimising the impact to the environment. The project also questions the longevity of architecture, by proposing semi-permanent structures for programs which are likely to have changing needs in the near-term future. The life cycle of the project is consider in detail, resulting in a circular production chain.

Figure 3: Thatched Reed Roof on Texel Island, Netherlands (By Author, 2019)

2 - MATERIAL RESEARCH

2-1 Common Reed (Phragmites Australis)

Common Reed (*Phragmites Australis*) is a grass from the Poaceae family. The native plant grows on every continent except Antarctica, and can grow in a wide variety of habitats although it is best suited to wetland habitats in fresh or brackish water (Huhta, 2007). The reed plant has a creeping rhizome system, a modified subterranean stem that produces roots and shoots from its nodes. The shoots grow into long upright basal stems which reach 1-3 meters in height, sometimes up to 7 meters, with temperature, environment, and nutrient levels impacting productivity (Packer, 2017). The stems are grouped in stands and are covered with long leaves and topped with 'feathers' scientifically known as the panicle; the flowering part which produces seeds (Figure 5). Reed is resilient, and sometimes considered invasive as it spreads mainly through its extensive rhizome and from seeds while preventing competition from other plants through the density of the reed stand and root system (Roosaluste, 2007). In some cases, reed shoots may appear up to 10 meters away from the rhizome (Huhta, 2007).

Figure 4:
A Bearded Reedling (Panurus biarmicus) rests on a reed stem. Photo Credit: Steve Knell (White, 2014)

Depending on the location and circumstance, reed can either be beneficial to the health of an ecosystem, or an invasive species which reduces biodiversity, although this is uncommon in Europe. Reed bed habitats are home to many bird species such as the Sedge Warbler (*Acrocephalus schoenobaenus*), a migratory songbird that feeds on reed insects, and the Bittern (*Botaurus stellaris*), which relies on large reed beds for nesting and may spend its entire life in the same reed bed (Ekstam, 2007). Reed bays support the migration of water birds as they stop to rest and obtain nourishment (Below, 2007). The ideal condition for a diverse bird population includes a variety of waterways of different depths with coastal meadows connected to the reed beds, as the majority of birds prefer to inhabit the border between reed bed and open water (Below, 2007). The responsible harvesting of reed requires a management plan to conserve natural habitats and increase structural diversity of the reed bed.

2-2 Material Characteristics

Reed beds are not consistent in their composition, some are made up of dense reed stems, whereas others have a mix of other vegetation interspersed with the reed. Due to the wide variety of possible growing conditions, harvested reed stems vary considerably in characteristics, and not all reed beds are of high enough quality to produce stems suitable for construction material. For use in thatching, high quality stems are those which are straight, firm, approximately 2000 mm long and 5-6 mm thick, and bright yellow in color with a red tone at the stem base (Räikkönen, 2007).

The chemical composition of reed is approximately 52% crude cellulose, 27% hemicellulose, 12% lignin, 3% crude ash, and the remainder made up of supplementary mineral substances, such as silicium and nitrogen (Wöhler-Geske et. al., 2016). The decomposition rate of dead reed stems is very slow due to the high cellulose content and lack of nitrogenous proteins, resulting in a poor quality food for herbivores and detritivores (Ekstam, 2007). In Nordic climates, decomposition of reed stems was found to range between 1-3 years (Ekstam, 2007). The subjection of reed to moisture increases the speed at which it deteriorates.

The exact structural properties of reed stems are not easily ascertained, as the variation in diameter and density of bundles of reed differ considerably, even when limiting the study to Common Reed sourced solely from Dutch and German suppliers (Wöhler-Geske et. al., 2016). The thermal conductivity is relatively consistent, around 0.05 W/mK, and is not affected by geometry (Asdrubali et. al., 2016). Acoustic behaviour is highly dependent on stalk configuration, with a longitudinal stalk layout particularly effective in sound absorption (Asdrubali et. al., 2016).

Figure 5:
"Typical morphology of Phragmites australis showing (a) panicle, (b) leaf sheath containing fringed ligule, (c) leaf blade, (d) spikelet, (e) stoma and (f) horizontal and vertical rhizomes with roots. Above-ground reed parts were collected by Bohdan Krısa in the field in the Czech Republic. Below ground material was collected from the common garden of The Czech Academy of Sciences. Drawings by Anna Skoumalova." (Packer, 2017).

2-3 Harvesting and Processing

In Holland, 6-7 million bundles of reed are collected annually for construction (Lautkankare, 2017). The average density of a reed bed is between 40 to 100 shoots per square meter, but can be up to 300 shoots at its densest (Jalas, 1958). Approximately 1,000 bundles of reed can be produced from a hectare of reed bed. For one square meter of 35 - 40 cm thick thatch roof, approximately ten bundles of reed are required.

Traditionally, reed was harvested by hand in the summer and autumn with the cutter wading in water or using a small boat to cut the reed with reed scythes and sickles (Häkkinen, 2007). Today, harvesting of reed is rarely done by hand as it is much more efficiently achieved with purpose-made machinery (Figure 6).

Figure 6:
The Seiga Harvester is capable of cutting and tying around 1500 bundles of reed daily. Photo Credit: Andy Hay (White, 2014).

Figure 7:
Storage of reed bundles, with one 60 cm bundle of reed sourced from Turkey displayed (By Author, 2019)

In Northern Europe, reeds flower at the end of summer, after which the stems become woody and shed their leaves. The best reed for roofing is harvested in winter when the stems are hard (Ikonen, 2017). Collecting reed is easier when the water of the reed marsh is frozen, allowing equipment access. The reed bed is best maintained by cutting the stems during the winter, as summer cutting leaks nutrients, resulting in exhaustion of nutrient storage in the root system (Huhta, 2007). Additionally, winter cutting increases the number of shoots produced in the following year as removal of the dead stems improves the amount of daylight reaching the shoots (Huhta, 2007). The maximum moisture content for thatching reed should be 18 percent; naturally dried winter harvested reed is suitable (Köbbing, 2013).

Figure 8:
Reeds vary considerably in length, culm diameter and material properties. These images show Dutch reed (left) and Turkish reed (right). (By Author, 2019)

In the European market, bundles of reed of 60 cm diameter are typically sold in lengths ranging from 1m to 2.3m. The cost of a bundle of reeds in the Netherlands is in the range of 2-3 Euros. Riethandel E. Prosman b.v. is a Dutch company located in Gouda, which sources reed from several countries, supplying to thatchers for projects worldwide. On January 15, 2019 a visit to the office and storage facility was undertaken to survey the types of reed commonly available in the Netherlands. Arjan Prosman provided a tour of the facility. The visit was at the beginning of the harvesting season, therefore the reeds available were from the previous year's harvest. This included reed from China, Turkey, Hungary, and the Netherlands with a range of available lengths and diameters. The Hungarian reed was particularly straight, Chinese reed was available in a wide variety of lengths, Turkish reed was longer and of larger diameter, and the Dutch reed had smaller diameters. Prosman explained that the smaller diameter was aesthetically preferred for thatch roofing. The quality varies and is not related to the country of origin, but rather the growing conditions, care of the reed bed and harvesting process. Higher quality reed lasts longer, but determining the quality of the stems can be challenging. Excessive infection with insects or fungi is undesirable and should be avoided in selecting reed for construction (Wöhler-Geske et. al.)

The embodied energy in shipping the reed is a consideration, as reed sourced from further away requires more energy for shipping than reed sourced locally. Despite the reduced shipping costs, Dutch reed is more expensive because the labor costs in the Netherlands are higher. Increasing the use of local reed requires the development of less labor intensive processes. The stems come in a variety of colors, however once exposed to the elements the reeds fade to gray within a year.

2-4 Traditional and Contemporary Use in Architecture

The use of reeds in architecture can be found in several forms, particularly in traditional buildings. The use of reed for contemporary buildings is particularly relevant today as it offers a renewable and ecologically sound material that can perform in a multitude of ways. Reed has excellent acoustic and thermal properties and is very lightweight. A reed roof, including battens weighs only 40 kg/m2 (Madalik, 2007). Reed can be easily worked with and has a low material cost.

Building Structure

The Mudhif, a traditional guest house built by the Marsh Arabs in Iraq, is constructed entirely from reeds (Figure 9). Bundled reeds form arches to support the structure and woven reeds of varying porosity create the enclosure. These buildings continue to be constructed today, functioning as an assembly space and place for guests to stay.

In Japan, the possibility of reed as a structural material was shown through the design and construction of a temporary pavilion (Figures 10 & 11). The utilization of reed is seen as an important issue in regions of Japan, to preserve the culture and environment (Nagai, 2017). The resulting structure is extremely lightweight and required stabilisation from wind loads with sandbags. However, it shows the potential for reed not only as a structural material, but also its ability to produce a unique spatial quality, with undefined edges and diffused daylighting.

FIgure 9:
Interior of a traditional Mudhif guest house in Iraq. Photo Credit: Ikhlas Abbis (Abbis, 2009).

Figure 10:
The reed structure is formed from arches consisting of straight, tied pieces of reed. Design and Construction of Temporary Pavilion Using Reed as Structural Material, Japan (Shirai, 2016).

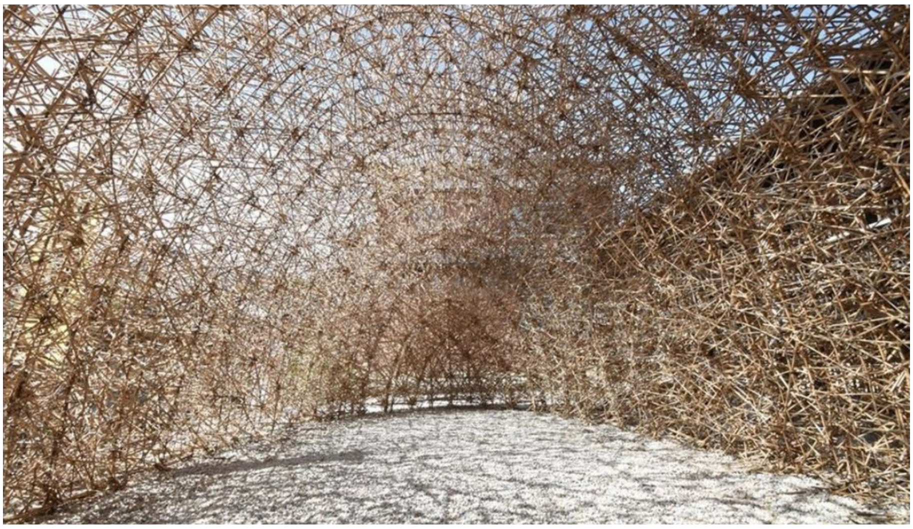


Figure 11:
The interior space has undefined edges and diffused daylight. Design and Construction of Temporary Pavilion Using Reed as Structural Material, Japan (Shirai, 2016).

Thatch Roofing & Siding

Reed has been used as a material for thatching for at least one thousand years (Wöhler-Geske et. al., 2016). History has proven reed to be an ideal roofing material capable of performing in a multitude of climatic conditions. In Europe thatched roofs are often constructed from reed, although also made from rye or wheat straw. The availability of rye straw for thatching diminished after the mechanisation of rye harvesting, resulting in an increased use of reed, which was found to withstand wind better than straw and lasted many years longer (Häkkinen, 2007). In the Netherlands today, the number of houses thatched with reed is rising (Lautkankare, 2007). In addition to thatching the roof, thatching the exterior walls of buildings has become common in contemporary architecture, such as the recently built Wadden Sea Centre by Dorte Mandrup Architects. The amusement park De Efterling in the Netherlands features the world's largest thatch roof. When properly constructed and maintained, a thatch roof can last from 50 - 100 years (Lautkankare, 2007).

Figure 12:
Making of a reed roof
Photo Credit: Martti Nakari (Stenman, 2008).

For the Yusuhara Machino-eki building in Japan, Kengo Kuma used thatch as a facade panel. Unlike traditional thatch roofing, which leaves the ends of the reeds exposed to rain, the reeds are bundled and placed so that the cut end will not be exposed to rain, thereby making the panels last longer (Figure 13). Additionally, “pivots are set on the steel mullion at the both ends of each thatch unit, so that it can rotate and take in fresh air from outside, which will [make] the maintenance of the thatch easier” (Yusuhara Marche, 2012).

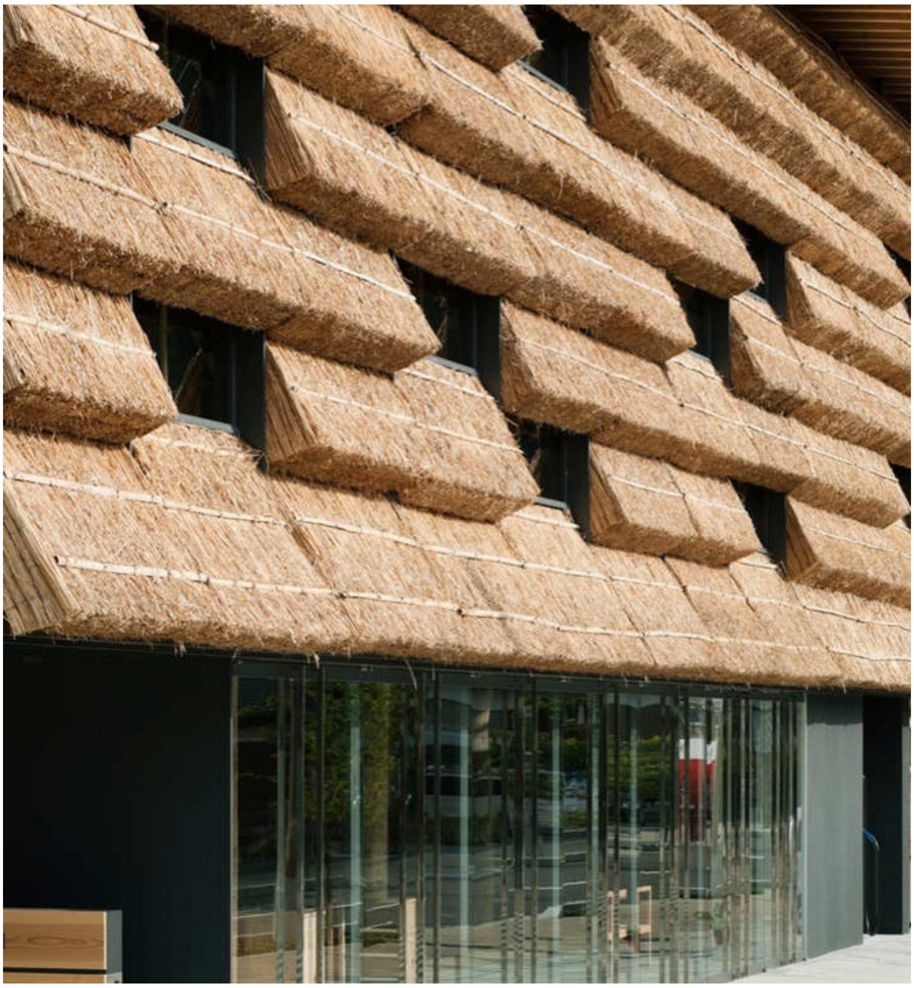


Figure 13:
The Yusuhara Machino-eki building in Japan, Kengo Kuma (Yusuhara Marche, 2012)

Insulation Panels

In Finland, Oy E. Sarlin Ab manufactured ‘Berger’ reed panels from 1938-1944 (Figure 14). The panels are made from reed stems squeezed tightly together and sewn with wire to form thick panels. The panels are fire resistant, lightweight, and had excellent insulating properties for both heat and sound (Häkkinen, 2017). Reed panels are 30 - 50 mm in thickness and Specific Heat Capacity of approximately 300 (c)(J/kg.K) (Piesik, 2017). Reed panels of 3 - 5 cm thickness have a thermal resistance reading (λ) of 0.056 - 0.065 (W/m.K) (Madalik, 2007).

Figure 14:
Manufacturing of 'Berger' panels in Saaremaa, Estonia, in 2006. Photo: Eija Hagelberg (Ikonen, 2017).

Reed Mats

Reed mats may be used as an external wall cladding to protect from sun and rain, or for providing shade in the form of screens. In Peru, the Uru people live on floating islands formed from reed. They construct houses and boats from reed mats and bundled reeds. Reeds are commonly used for sun shading by weaving wires over and under individual reeds to produce a flat surface capable of diffusing sunlight. A recent project which exhibits the fine spatial quality achievable through this method is the installation *Roof Sentiment* (Figure 15). Reed mats can also be used as a base material for plastering.

Figure 15:
An installation made from reeds provides sunshading at Korea's National Museum of Modern and Contemporary Art in Seoul by Society of Architecture (Roof Sentiment Installation, 2016)

2-5 Maintenance and Fire Safety

The main concerns in using reed as a building material are the maintenance and fire safety. The need for maintenance and longevity of the reed material can be improved through the detailing. It is important to prevent water from collecting and standing on the reed; typically a pitch of 45 degrees or more is required to allow water to shed. Exposure to sun and wind allows the reed to dry out, thereby prolonging its life. It is important that a reed construction is not located in a heavily shaded area. North-facing surfaces are susceptible to algae growth due to the lack of sun exposure. Algae can form a permanently damp layer, precipitating deterioration of the reed underneath as fungi begin to grow on the damp surface and feed on the cellulose in the reed. An algaecide can be applied to kill existing algae and moss and prevent their regrowth. Ideally, a thatch roof would be cleaned yearly by removing any dead leaves and scraping off moss growing on the surface to ensure the roof is able to dry out periodically.

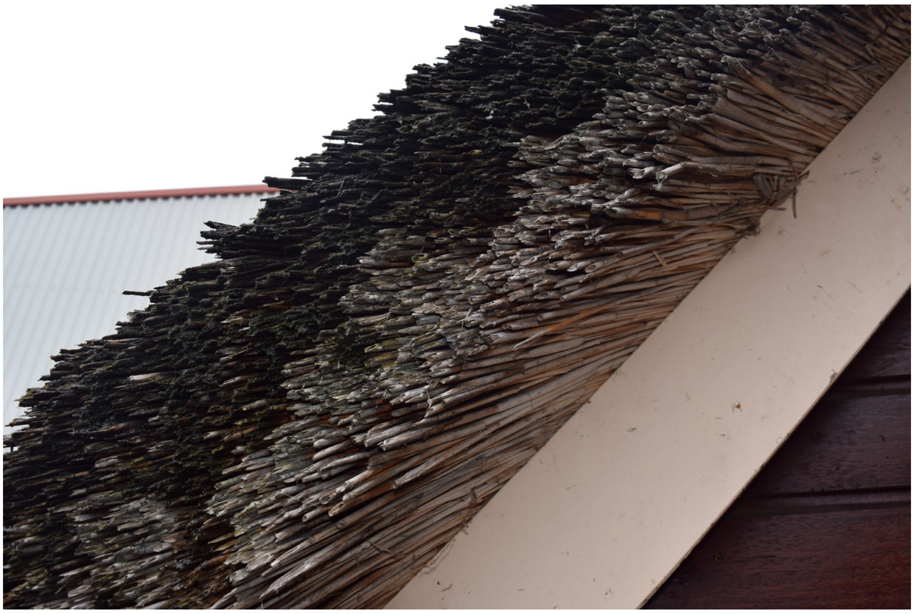


Figure 16:
A wet thatch roof in Gouda. It can be seen that the upper layers of reed retain moisture after a period of rain, while the protected lower layers remain dry. (By Author, 2019)

Fire safety is a concern for reed roofs, as fire can spread quickly across the roof and sparks can be carried some distance from the source of the fire. In particular, the combination of a reed roof with a fireplace chimney requires careful detailing, with the chimney constructed of thick brick or stone and never metal. However, reed roofs are not as flammable as often assumed. This is due to the material retaining a certain amount of moisture in the outer layers which only dries out during extensive dry periods (Madalik, 2007). It is the underside of the roof, where the material is dry that is most vulnerable to the spread of fire.

Various fire prevention methods exist but the suitability of the method depends on how the reed is being used. A common method is spray application of a fireproofing liquid; several have been developed that are safe for health and the environment, however they must be reapplied every 3-5 years as the protection wears away (Madalik, 2007). Fire safety of thatched roofs can also be improved by modifying the roof assembly through the addition of layers of OSB or Rockwool. When used underneath plastering, reed does not need additional fire treatment. When densely packed, as in the case of insulation panels, reed can withstand fire well.

Figure 17:
"Hartwig Reuter is 'trying' to burn part of a Berger plate, which is an insulation plate made of reed. This thick plate is not easy to burn." (Ikonen, 2007)

3 - DIGITAL DESIGN AND PRODUCTION

3-1 Material-Based Design

Architecture is the result of material manipulation; the choice of materials and how they are formed and joined is paramount in determining the quality of the architecture in every aspect, including functionality, aesthetics, durability, and cost. Considering this, it can be understood that choosing materials after designing a form is a backwards process. Material selection and fabrication processes should be considered from the outset of design, thereby directly influencing the form-making and effectuating a fast and efficient design-to-fabrication workflow (Garcia, 2019). Especially with the pressing need for sustainable architecture, materials should be selected based on local availability and performance in the given climate, rather than solely on aesthetic value or the ability to achieve a desired form.

Digital design is clearly not a requirement for architecture, as can be seen from a long history of successful buildings produced solely with analog tools. It is important to carefully consider when and where to implement a digital process in order to enable complex (rather than complicated) construction that makes the best use of material. “Something complex can assume the appearance of simplicity, while the complicated always excludes everything simple from itself” (Bellut, 2008). This research results in a material-based design, an increasingly dominant design model that experiments with the synthesis of new digital techniques and material design and fabrication technologies in an experimental design model (Oxman, 2015). The exploration and integration of digital materialization is an emerging issue in architectural design.

3-2 Discrete Design Model

"Discrete design methods aim to turn the continuous paradigm upside down, shifting formal complexity from the design of the whole to the assembly logic of the parts."
- Manuel Jimenez Garcia

In most cases, architecture must be fragmented in order to construct the whole from a multitude of parts. It is worth considering how a building is segmented as this has a substantial impact on the resulting form. Mario Carpo argues the newly emerging alternative model for digital design is voxelization or discretization; architecture made up of fragments aggregated and informed by big data (Carpo, 2014). These discrete methods use Cartesian geometries that create surfaces through the combination of orthogonal blocks, or voxels, capable of forming curvilinear space through adjusting their size and arrangement (Garcia, 2019). In many cases, this method results in an unusual architectural resolution, where buildings do not become more refined as you approach, but rather exhibit the pixelated, fragmented components they are composed of. As Carpo states; "today's data-driven design environment is messily postmodern: disconnected, broken, fragmentary, rickety, patchy, and aggregatory" (Carpo, 2014). In experimenting with digital strategies for the assembly of reed, this project utilises a strategy of discrete interlocking elements, thereby situating the work within the current paradigm of discretized architecture. This is discussed in detail in *Section 4-3 Components and Connections.*

Figure 18:
Diamond Strata, by Gilles Retsin Architecture (Retsin, 2016)

Gilles Retsin contends that robotic assembly in architecture is only possible “in the context of digital materials and discrete computation, which has a limited set of connectivity problems” (Retsin, 2016). Retsin goes on to argue for the use of discrete building blocks with automated assembly to increase speed and complexity (Retsin, 2016). With the technology available today, it is fatuous to attempt to automate every part of the construction process. Each stage, from material harvesting through to final assembly, should be evaluated to determine if it is best achieved through a digital or analog process, or something in between. Mass-customization is explored at two levels in this research, first in the fabrication of reed-based components, and second in their assembly. The proposed methodology and construction process is discussed in detail in *Section 4-4 Design and Assembly Sequence.*

3-3 Relevant Research Projects

Several recent research projects were reviewed as a background to this research in order to learn from the latest developments in digital design technology. This section provides a brief overview of these relevant projects.

The most relevant project in terms of material is *Experiments in Robotic Thatching*, a design studio at Aarhus School of Architecture, taught by Jan Buthke (Buthke, 2016). The team came up with two study processes; massy, which used bundled reeds, and messy, which used single reeds placed one-by-one. At the start of the study, natural reeds were considered, but after seeing the wide variation of natural reed stems, it was determined that working with a synthetic plastic reed of consistent lengths would be more suitable for robotic fabrication. Custom joints were designed and 3D printed to attach each reed to the next. The final result was a 1:1 installation, fabricated with ABB robots and programmed using HAL (Figure 19).

University of Stuttgart’s 2018 ICD Aggregate Pavilion is an example of aleatory architecture, which uses components of a standard shape arranged in a semi-random configuration (Figure 20). The negative, inhabitable space of the structure is defined first by using inflated balloons over which spiky components are dropped. The balloons are then deflated and the resulting structure is held together through

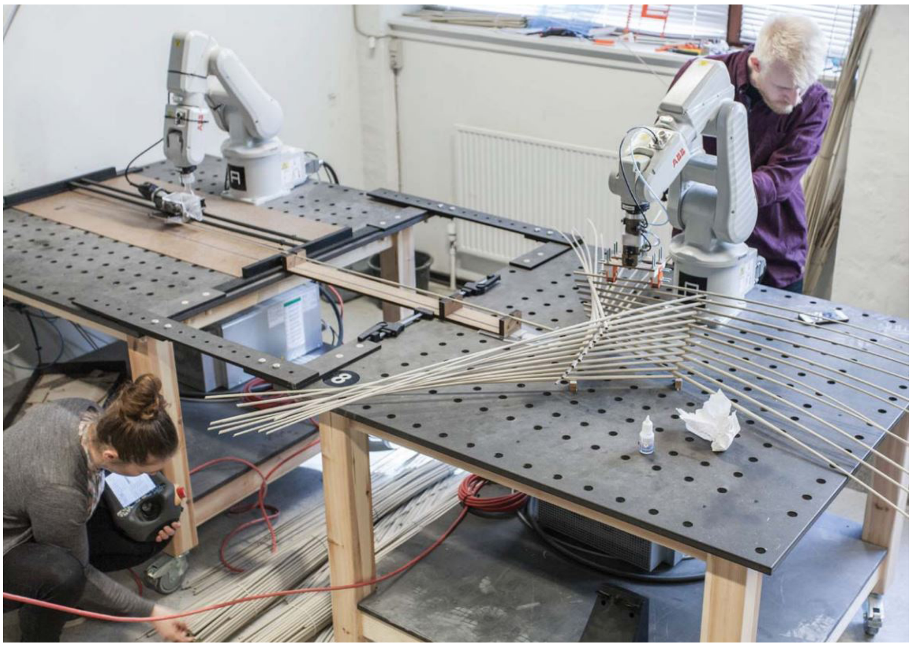


Figure 19:
Robotic placement of reeds. Experiments in Robotic Thatching (Buthke, 2016)

Figure 20:
University of Stuttgart's 2018 ICD Aggregate Pavilion is one example of aleatory architecture in which components are randomly placed.

the friction between components. The benefit of this strategy is that it simplifies the robotic assembly process, there is no need for complicated algorithms for the connection and sequencing of elements. However, determining the structural stability of a random, friction based structure is a challenge.

Researchers from ETH Zurich have been exploring robotic fabrication of timber elements, discussed in the paper *Robotic timber construction — Expanding additive fabrication to new dimensions*. The research is tied to ongoing projects including "The Sequential Wall" and "The Sequential Structure" (Figure 21). The paper discusses "The Sequential Roof" project in which a roof structure was built utilising automated gripping and cutting, and spatial positioning of wood elements. The central goal for Robotic Timber Construction is to "foster design methodologies, which must be 1) informed by material, construction and fabrication criteria, and 2) be able to adapt to multiple functional requirements" (Willman, 2016). The integration of computational design and structural analysis tools was vital for the implementation of the project. The term "sequential" is important, as it greatly simplifies the computation required for robotic assembly; by assembling elements in a sequential manner, problems of collision avoidance and complex computation are avoided.

Another related project from ETH Zurich is *Robotic Fabrication of Bespoke Timber Frame Modules*, which explores the prefabrication of timber frame construction utilising robotic assembly processes with the aim of reducing the need for scaffolding and allowing for construction of non-planar geometries (Thoma, 2018). The research considers assembly sequencing and construction tolerances as important aspects of precise robotic fabrication of multiple parts. An elaborate test setup allowed for 1:1 fabrication of timber modules used for the DFAB HOUSE, a testing ground test for new digital construction technologies.

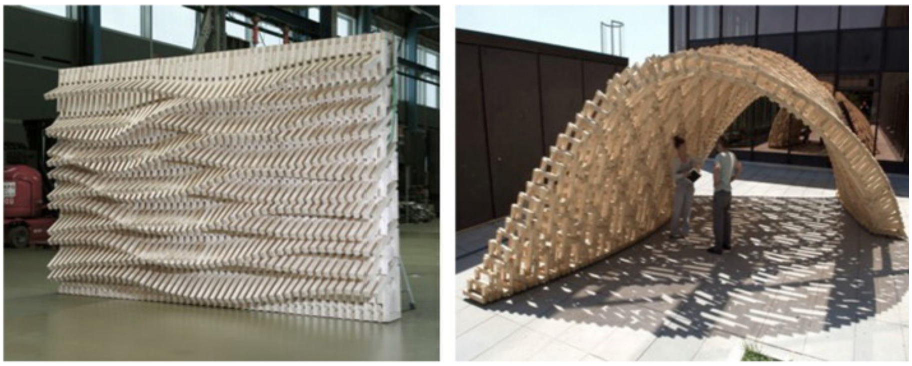
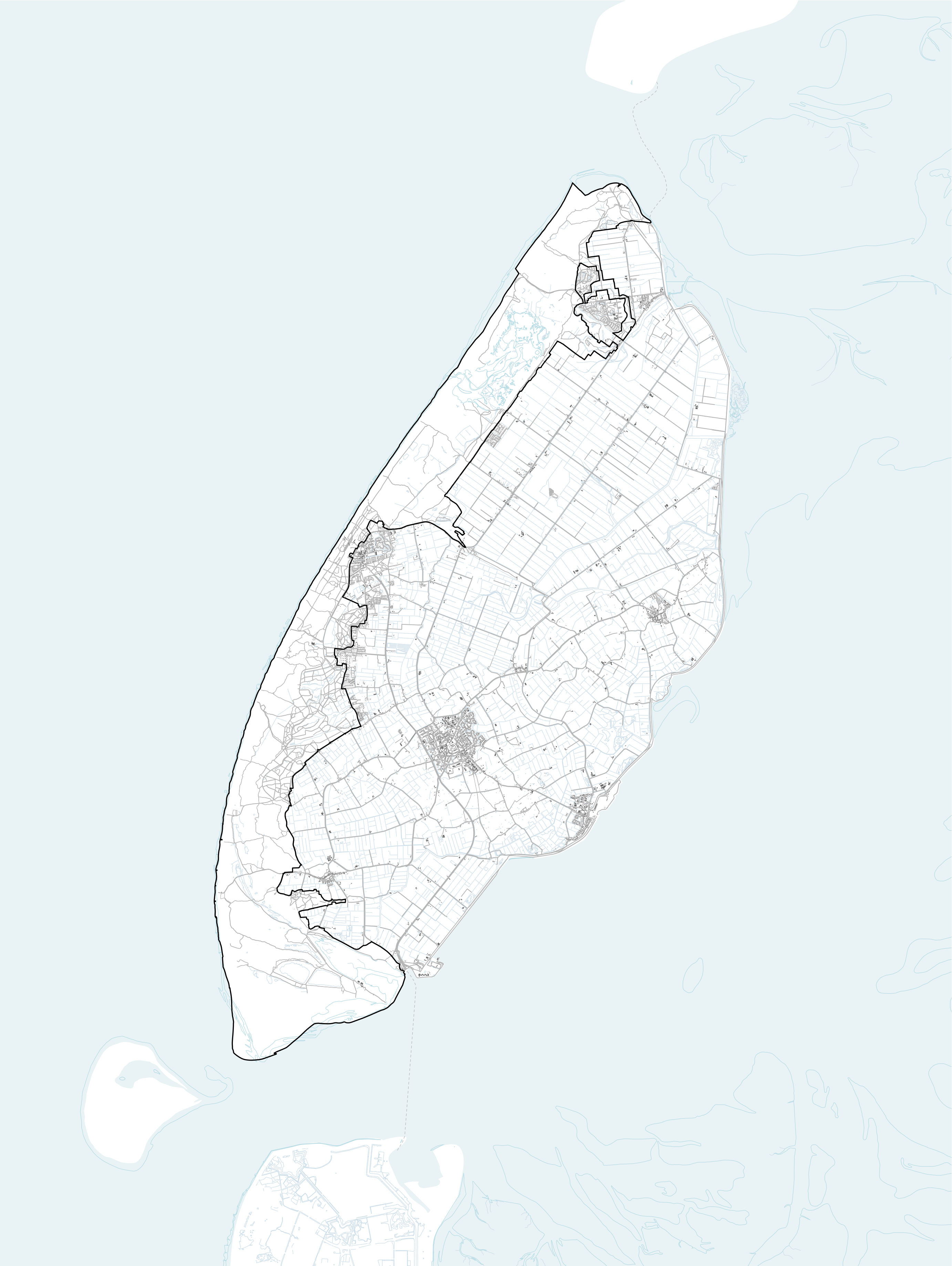


Figure 21:
"The Sequential Wall" and "The Sequential Structure", Gramazio Kohler Research, ETH Zurich, 2008 - 2010 (Willman, 2016)

The *Ripple Wall* was an installation created for the Digital Arts Center at the University of North Carolina at Charlotte. The project consists of CNC-cut plywood strips which are joined without mechanical fasteners or adhesive connections resulting in a rippling wall surface with varying depths (Beorkrem, 2017). By adjusting the length of the pieces the pattern of the surface is defined. Friction-fit connections are designed to fit together like 3D puzzle pieces.

In the research *Biomimetic Robotic Construction Process* beaver dams inspired the concept of using an all-terrain construction robot equipped with a 3D scanner to recognise sticks on the terrain for constructing gravity-driven wood structures (Cheng, 2016). The research consists of two parts, the arrangement of materials placed by a robotic arm and the use of machine learning to scan the terrain for appropriate building materials. The research aims to enable the use of irregular natural materials in construction.

There are many more related projects which are relevant to various parts of the proposed design and fabrication process. As previously discussed, the work is situated within the emerging design models of discretization and digital materialisation. Academic researchers at various institutions continue to open up new possibilities within these fields. A common research method is direct 1:1 prototyping of robotic fabrication processes. Research into digital design and fabrication requires the validation of results through physical testing. This research is no exception, resulting in the production of several physical prototypes at multiple scales.



4 - RESEARCH BY DESIGN

4-1 Context

Returning to the main research question, the primary objective is to use a digital design process to produce an innovative and sustainable use of Dutch reed. As the project is highly focused on sustainable design, an ideal application is for projects which need to be inserted lightly in natural environments. In nature, there is not a sharp boundary from one ecosystem to the next; a region exists between them with characteristics of both. This transition area is called an ecotone. In land-water ecotones in Europe, Common Reed is a dominant species (van der Putten, 1997). The proposed design aims to treat architecture as a kind of ecotone by diffusing surfaces to create a blurred architecture. As a case study, the design of a series of nature observation buildings is considered for the National Park on the island of Texel, in the Netherlands.

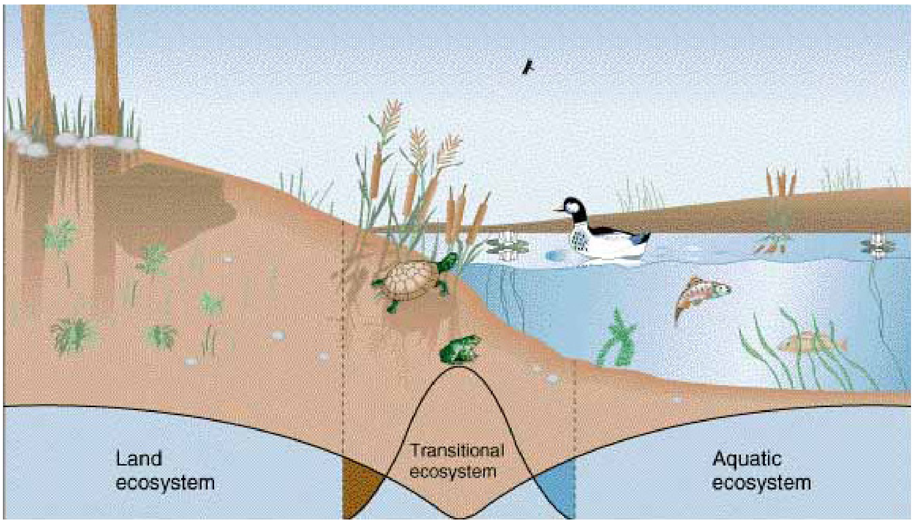


Figure 22:
Diagram of an ecotone; a transitional ecosystem (Layosa, 2014)

Texel is a municipality in the North Holland province and is the largest of the West Frisian Islands in the Wadden Sea. The island can be accessed via ferry from Den Helder or by air through Texel International Airport. Texel became an island In 1170 when it separated from the mainland due to the All Saints Flood. Unlike the other Wadden Sea islands, the landscape of Texel is widely varied. Covering 43 square kilometers of area along the west coast of the island is National Park Duinen van Texel, a unique habitat for wildlife that is well known for bird watching and

Figure 23:
Map of Texel, the National Park Duinen van Texel occupies the entire west coast of the island. (By Author, 2019)

Figure 24:
Varying landscapes across the National Park. Images (Nationaal Park Duinen van Texel, n.d.)

the wide variety of natural landscapes including dunes, heathland, deciduous and coniferous forests, tidal marshes, and beaches. The network of trails allows visitors to observe the many rare plant species and protected birds, with varying levels of access depending on the vulnerability of the area. The National Park is the focus for this project, requiring a delicate approach that allows visitors to engage with the natural landscape while simultaneously preserving it.

The site is ideal as a case study because reed already grows on the island, there is a long tradition of thatch roofing, the National Park is an ecologically sensitive area, and the different landscapes require different types of nature observation structures depending on the context, thereby enabling testing of the different capabilities of the proposed system. The following site analysis documents the characteristics of the varying landscapes of the National Park in order to determine ideal locations for nature observation buildings and the best suited programmes.

These programmes accommodate activities commonly performed on the island, including bird watching, star gazing, and warming huts for winter hikers.

The National Park is comprised of several defined areas. In the south are dunes and heathland, including De Mokbaai, Horspolders, Kreeftepolder, De Hors, De Geul, De Bollekamer, and Westerduinen. In the center a range of dunes, heathland, meadows, marsh and forests includes De Mient, Bleekersvallei, De Dennen, Het Alloo, Seetingsnollen, De Muy, and De Nederlanden. The center of the park is also the location for Ecomare, a nature museum and aquarium. The north side has a unique salt marsh called De Slufter, the Krimbos forest, and the Eierlandse duinen which features an iconic lighthouse.

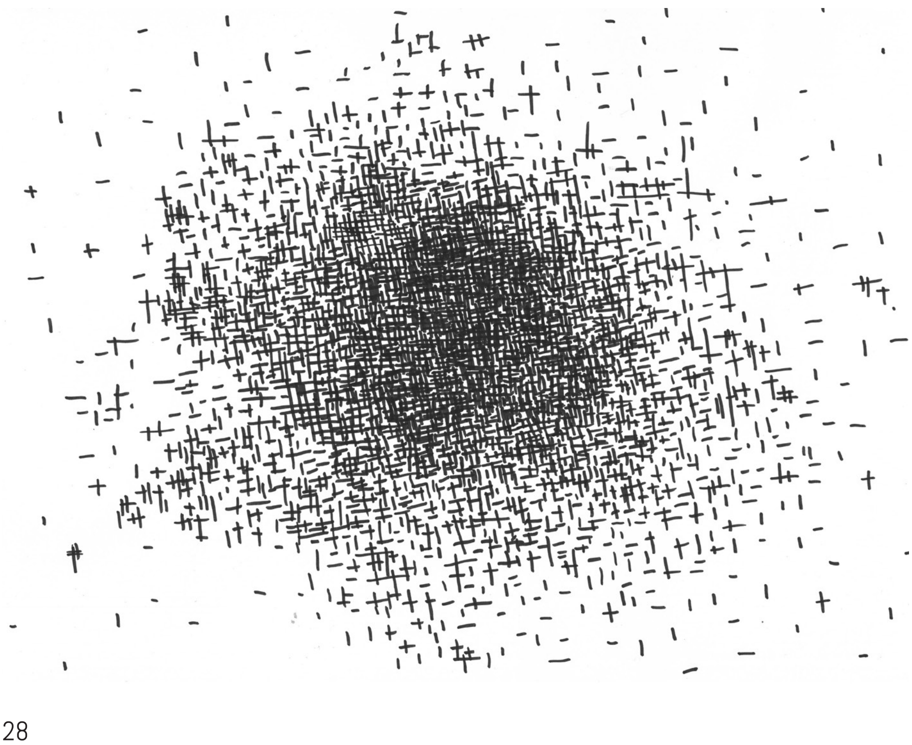
The case study focuses on the central and southern areas of the National Park. There already exist a few nature observation structures within the park. Several small bird blinds allow for concealed viewing of birds. Particularly striking is the Fonteinsnol lookout tower located in De Dennen. The timber structure provides a staircase up to a platform that looks out over the forest and dunes. In general, it was observed that many visitors run, hike or cycle along the paths in the park. Several benches are placed along the paths, however there is a clear separation between the nature areas and the defined paths for visitors. This is of course important to preserve the natural environment. The aim for the observation structures is to pull visitors from the main paths and invite them to sit and observe for a longer period of time by shifting the focus directly towards nesting areas, wildlife habitats, plant life, and unique views.

Figure 25:
The observation tower allows visitors to view the island from above the treetops (By Author, 2019)

4-2 Conceptual Design

The project questions the need for permanence in architecture by proposing structures which can be left alone in the natural environment and will slowly deteriorate without disturbing the ecology. On face value, it seems undesirable to construct a building that will degrade at a rapid rate. However, there are many circumstances when it makes sense to build in a more transient manner. The needs of people are rapidly changing due to advancements in technology and changes in lifestyle. Flexible designs are preferred, but designing in a flexible way reduces the capacity for customization. It is not sustainable to expend effort on the construction of material and then abandon a building when it no longer functions. While ways are found to renovate or expand buildings to adapt to needs, this can also be overly costly to achieve when needs have fundamentally shifted. A building that is completely customized to a specific use and set of conditions will be better suited to materials which can be disassembled, reused, or biodegraded. On the other hand, there are many situations where buildings should be constructed of long lasting, durable materials with a maximum lifespan. In the case of this project, the nature observation structures are planned to exist for a period of ten years or more after which they can be disassembled or left in the landscape to deteriorate. This method allows for adaptability as wildlife shifts to different locations, the landscapes change, and the number of visitors to particular areas fluctuates.

"Architectural ideas are not usually born as clear and final forms; they arise as diffuse images, often as formless bodily feelings, and are eventually developed and concretized in successive sketches and models, refined and specified in working drawings, turned into material existence through numerous hands and machines, and finally experienced as purposefully functioning utilitarian structures in the context of life."
- Juhani Pallasmaa



Concept sketch: diffusion and collection of elements create ambiguous form

In developing a blurred architecture that merges with natural landscapes, the works of several architects were consulted. Kengo Kuma is particularly well known for his affinity towards buildings that dissolve into their surroundings. His design for Sunny Hills is a good example of this; the building is concealed within an inhabitable wood structure that serves as a transition space from the exterior (Figure 26). Another notable project is *Unschärfe* (Blur) by Matthias Loebermann & IAS, a pavilion composed of alternating stacked steel mesh mats and lattice girders. (Figure 27). Loebermann argues that fuzziness in architecture is often explored in art and photography, but rarely in architecture - “The forest fascinates me as a geometrically undefined place” (Loebermann, 2014).

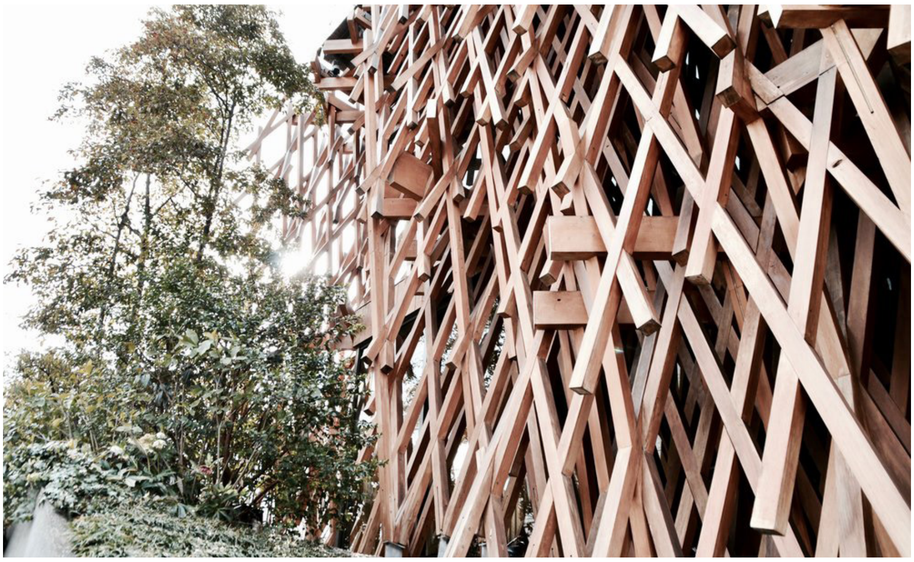


FIgure 26:
Sunny Hills, Kengo Kuma (Sunny Hills, n.d.)

Figure 27:
Unschärfe, Matthias Loebermann & IAS
(Unschärfe, 2014)

The concept of blurriness is reminiscent of Impressionist painting in which the subject matter is represented ambiguously and meaning is conveyed through light and a sense of passing time and movement where “everything is reflected in everything else” (Ruskin, 1964). Achieving a blurred architecture is similarly reliant on lighting and the space between matter. Rather than using surfaces to define space, the proposed design is generated through the definition of negative space.

Several parameters are used to generate the building form for each unique location of observation structure. First, the programmatic use of the building influences which performance characteristics the reed must take on.

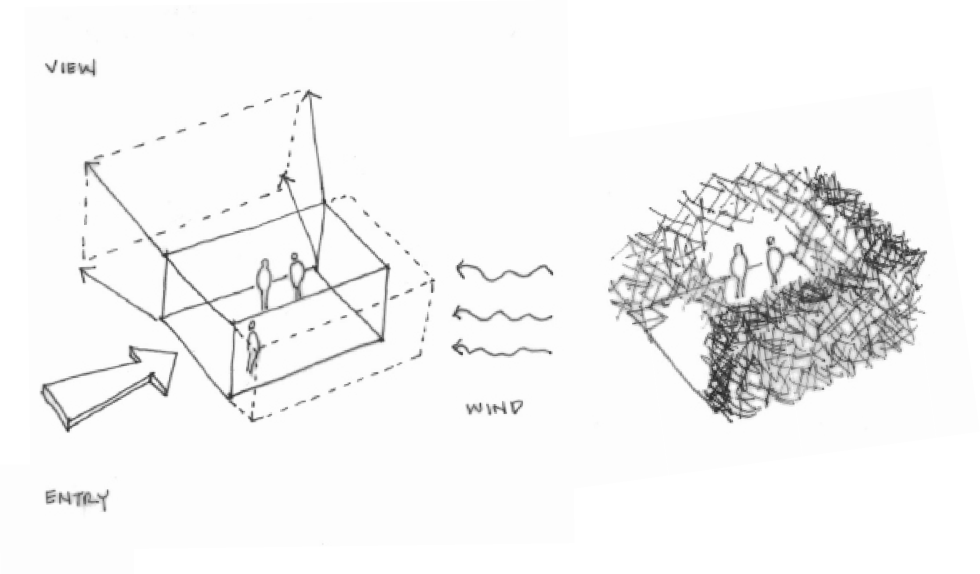
Types of observation structures:

Bird watching (400 species)
- View
- Concealment

Warming Hut
- Thermal Insulation
- Weather protection

Star Gazing
- View to sky
- Thermal Insulation

For tour groups
- Acoustics
- Focused Views
- Weather protection

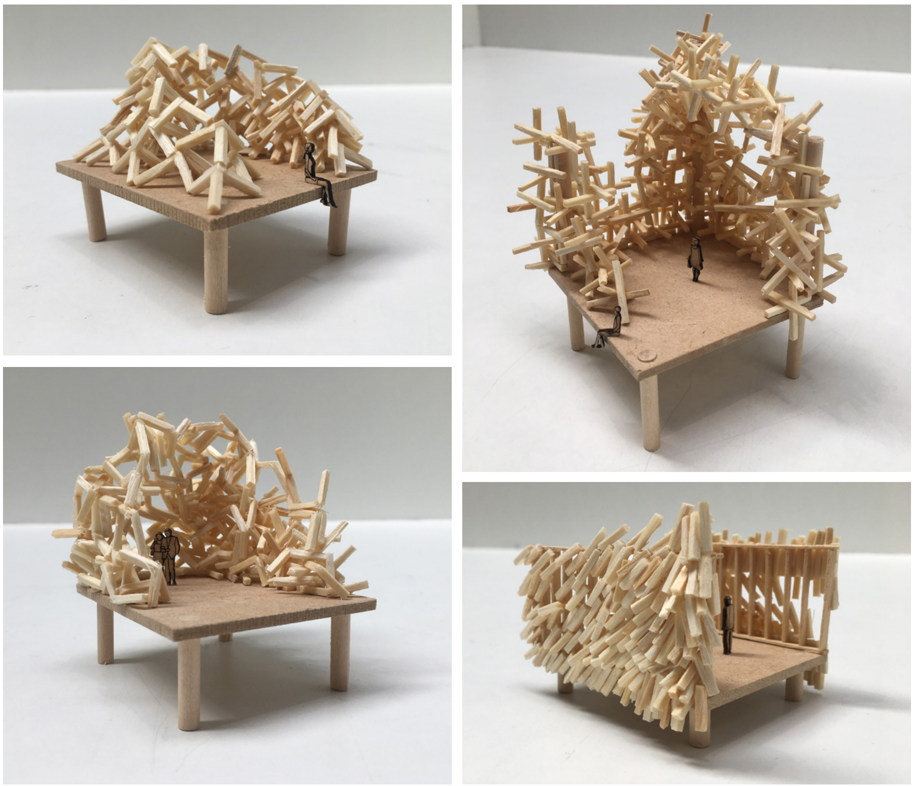


Form is defined by level of openness or density, rather than surfaces

“The dissolution of the surface repositions us as viewers - we are immersed in the work, but without a firm foothold - creating an aesthetics of uncertain and pure effect.”
- Vittoria Di Palma

Each of these programs can be sized to accommodate a varying number of people. The unique characteristics of each specific site are important to capture as this allows the architecture to be blended into the landscape. Existing path access, topography, plant life locations, and direction of views are documented through drone scanning and photography. The ideal parametric model would be the creation of a three-dimensional gradient spatial volume that defines density or openness based on the program and site characteristics. This model could then be adjusted by the designer. The result then informs the placement of material, resulting in a direct correlation between local characteristics and the resultant form. While developing this model would be ideal, the focus for this thesis is on robotic assembly, rather than digital design. Currently the design for the buildings is done manually, with the idea of future implementation of a parametric model.

Reed bundled with wire and string form interlocking star-shape components

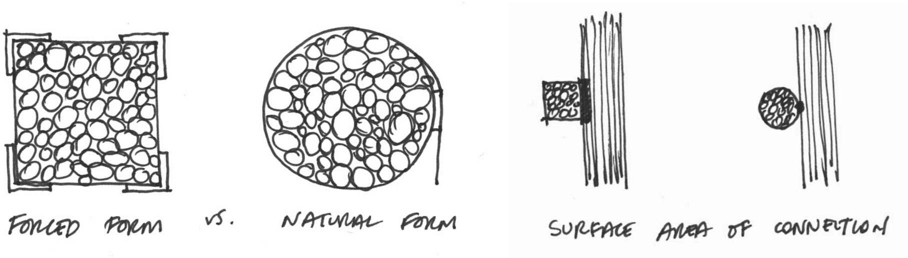


Initial studies for the nature observation structures - the resulting forms are influenced by the shape of component used

4-3 Components and Connections

Reed is an inconsistent material; each stem varies in diameter across its length making it challenging to work with in digital fabrication. Reed performs best when bundled together to form a block or surface; combining many individually weak pieces to create a strong component. A thatch roof is weather-tight due to its thickness. Only the top few centimeters absorb water, with this sacrificial layer preserving the integrity of the reed below. Over time, the reed must be maintained by removing the worn top layer and replacing with fresh reeds. To reduce the need for maintenance, the reed can be arranged in a way that allows for shedding of water and the thickness of reed components increased to preserve the underlying material for a prolonged period of time. Tightly compacting the reed is necessary to create weather-tight cladding and insulation. The cut end of the reed is best placed in a way that it will not be exposed to rain.

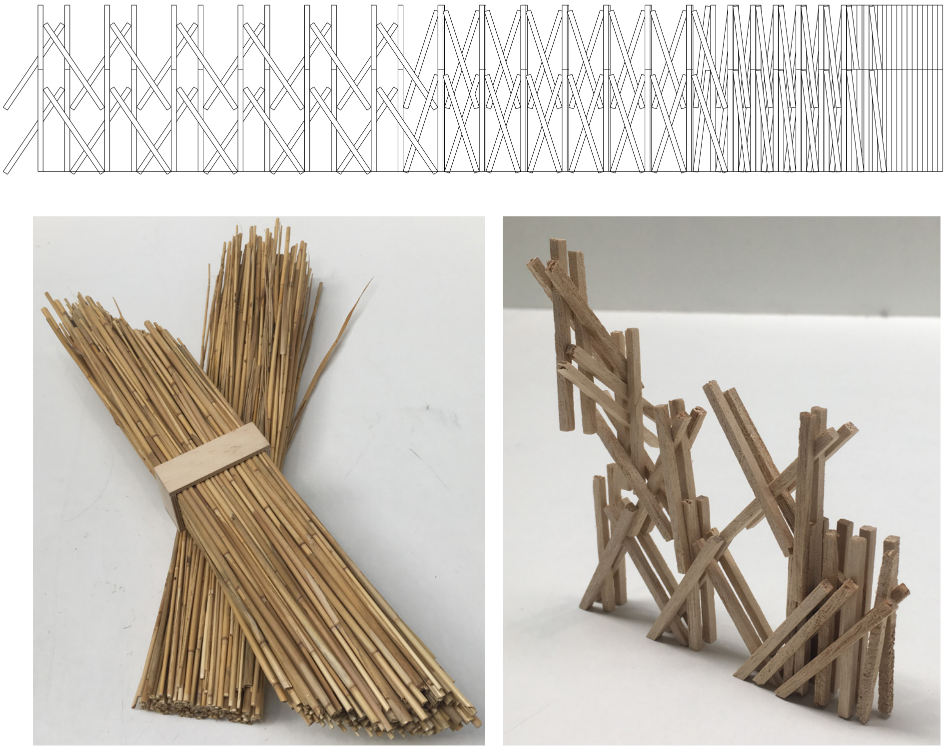
Initially, several shapes of reed bundles were considered. The shape of the reed components is largely determined by how they are bundled together. If tied with rope or wire the reed tends to form round bundles. Round bundles were dismissed as their aggregation would result in gaps, reducing the insulative and weather-proofing capabilities. Conversely, square or rectangular shapes can be aggregated to create continuous, solid surfaces (Figure). Several options for bundling reed, and connecting and aggregating the bundles were tested through physical models (Figures). Two 60 cm bundles of reed were provided by Prosman for initial testing; Chinese reed with a thin culm diameter and shorter stem, and Turkish reed with wider culm diameter and longer stem. Reeds can be stitched together with string or wire or bonded with materials such as clay or epoxy resin. Although some of these methods seem promising, it is important for the site context to use fully biodegradable materials. A model emerged which utilized a wood sleeve to standardize the reed bundles into square sections and provide a point of attachment between adjacent bundles (Figure).

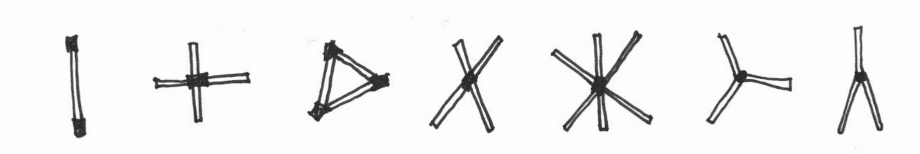


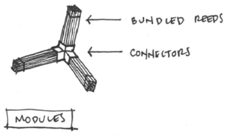
Comparison between square and round sections; square sections allow for tighter packing of successive components.

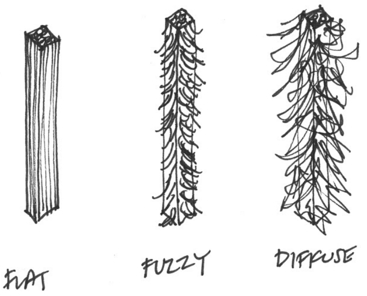
Physical prototyping of reed components; a variety of joining methods were tested

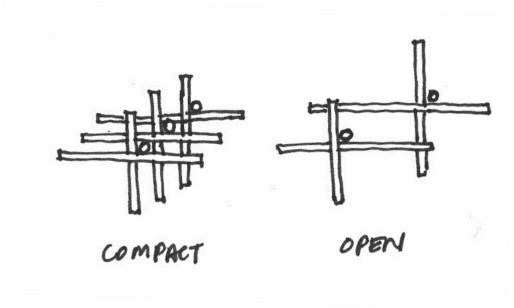
Development of a square-section component that can be aggregated to form solid or open wall assemblies.

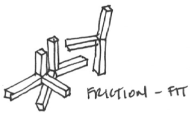


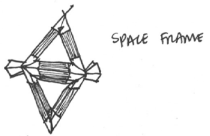


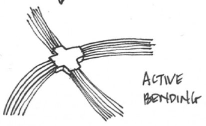

BUNDLED REEDS
CONNECTORS
MODULES

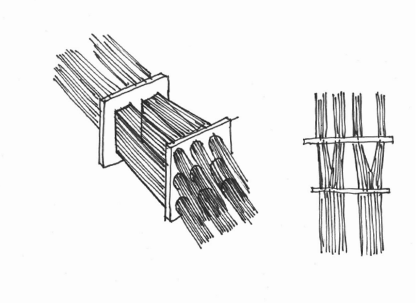

FLAT
FUZZY
DIFFUSE

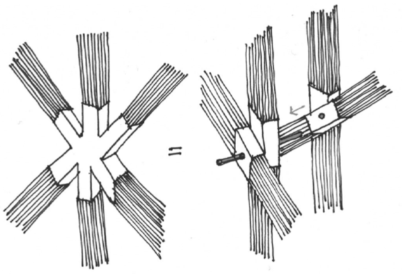

COMPACT
OPEN

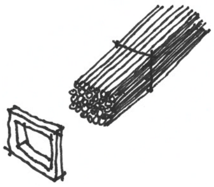

FRICTION - FIT

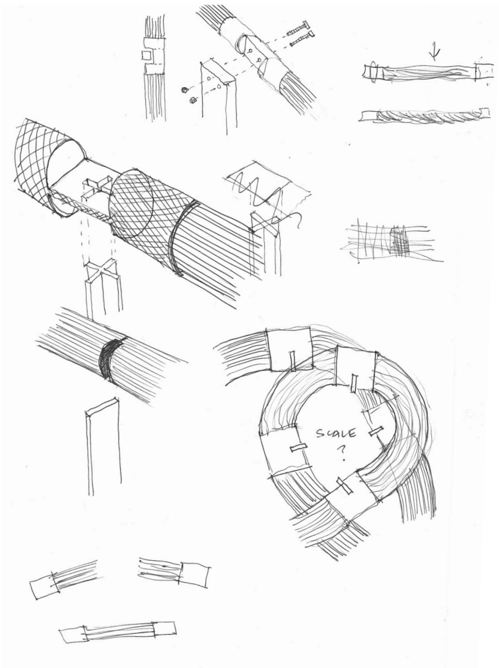

SPACE FRAME

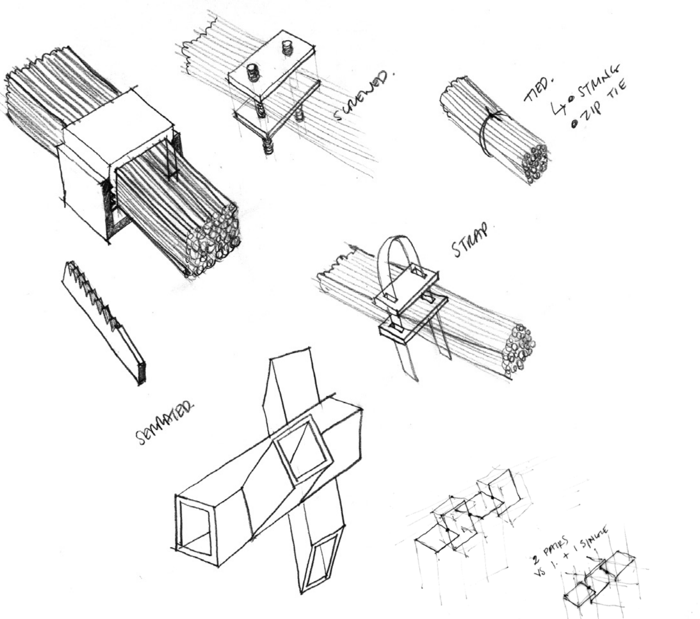

ACTIVE
BENDING

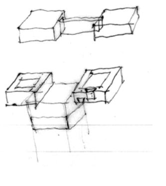


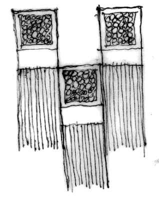


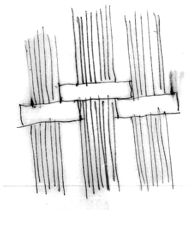


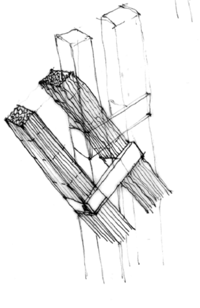

SCALE
?

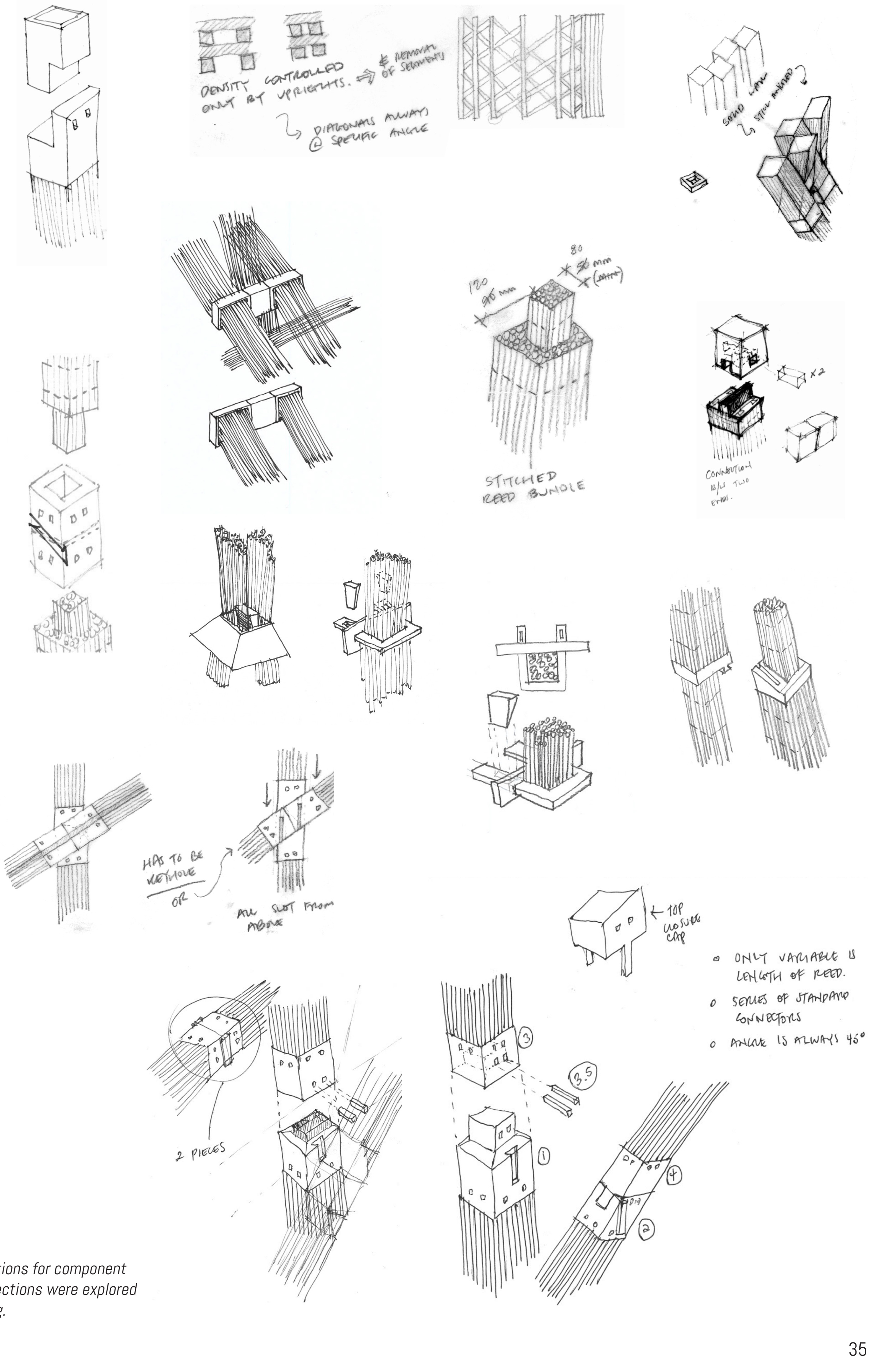

SCREWED.
TIED.
↳ STRING
ZIP TIE
STRAP
SERRATED.
2 PAIRS
VS 1. + 1 SINGLE
CENTER ACTS
AS CONNECTOR





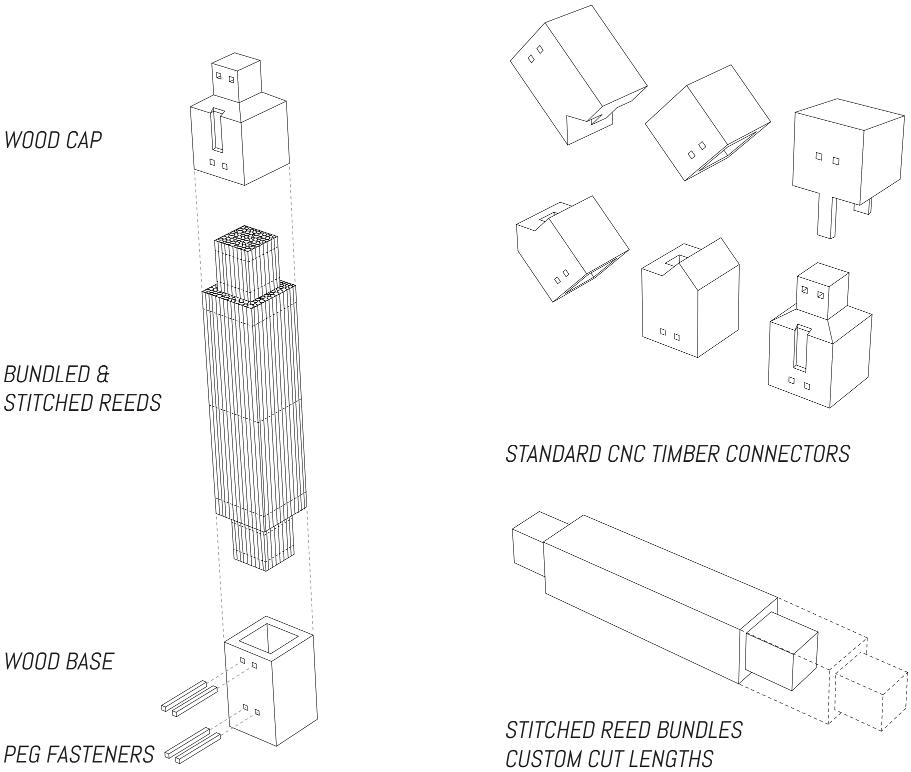




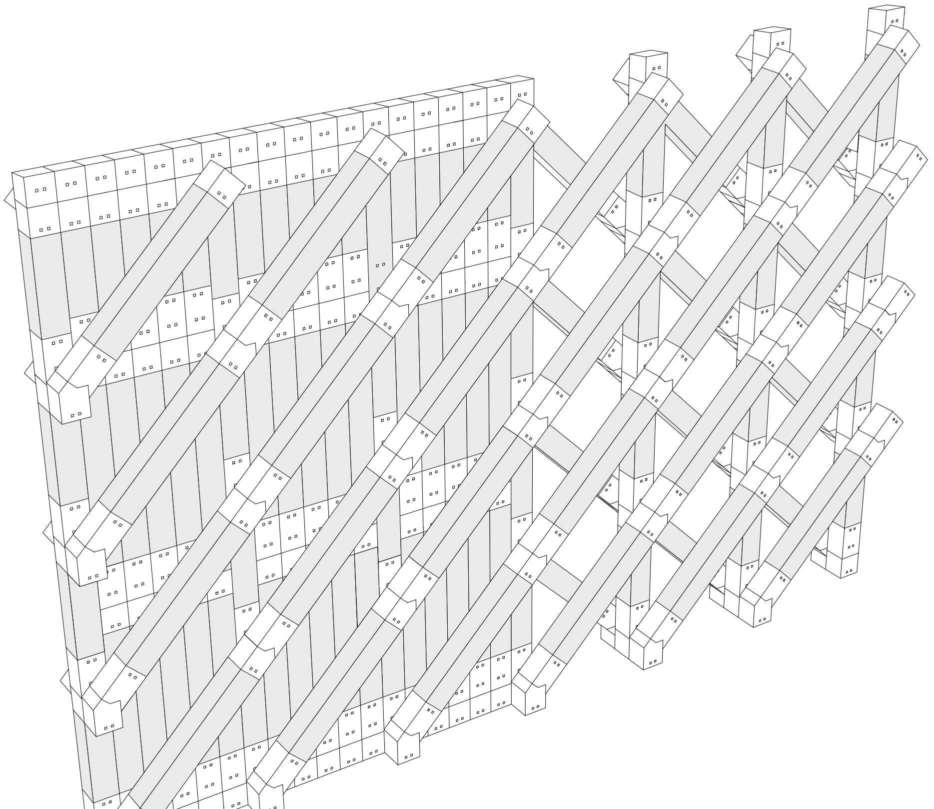


- ONLY VARIABLE IS LENGTH OF REED.
- SERIES OF STANDARD CONNECTORS
- ANGLE IS ALWAYS 45°

A multitude of options for component shapes and connections were explored through sketching.



An iteration of the joint system; while functional, the many unique timber connectors are not simple to fabricate.



Wall assembly with open and closed configurations

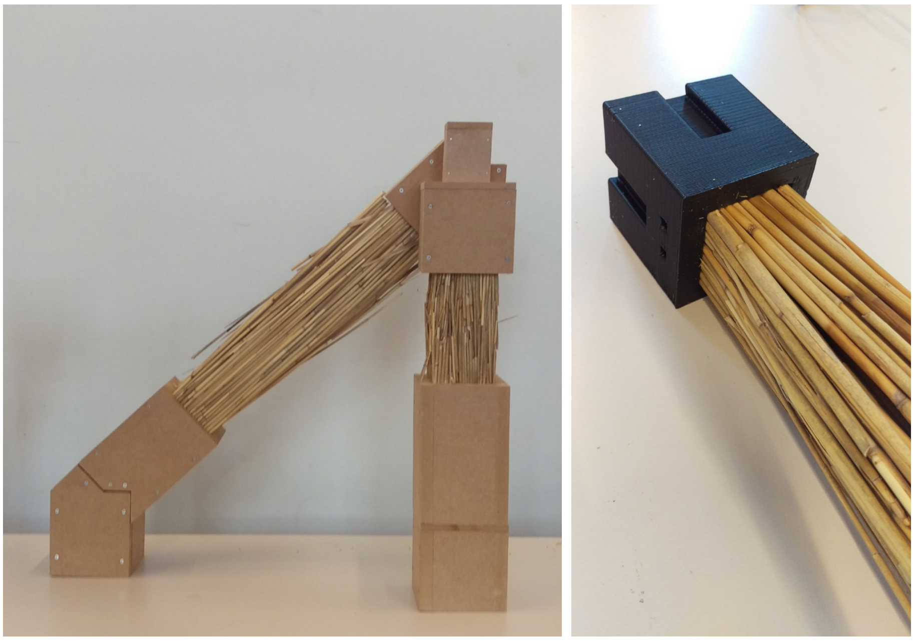
"In an intricate network, there are no details per se. Detail is everywhere, ubiquitously distributed and continuously variegated in collaboration with formal and spatial effects."
- Greg Lynn

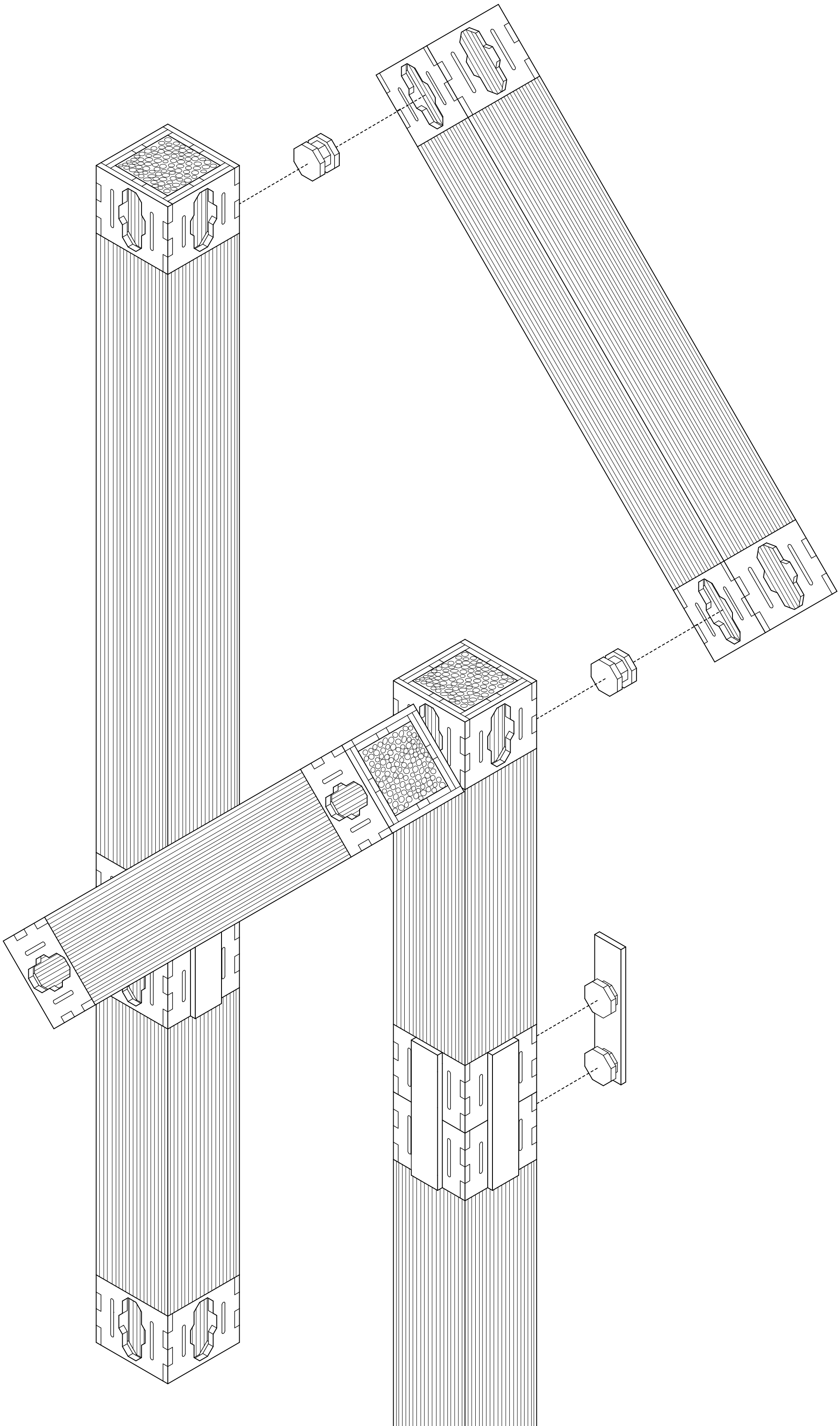
The proposed system of discrete linear reed components is intentionally simple; most anyone could figure out how the components slot together. The simplicity of the construction system allows for a complexity in configuration. The reeds can form solid and open areas and there is an underlying pattern in their organization.

The proposed design follows a Cartesian logic, with grids at 90, 45, and 135 degrees used to order the components. By constraining the components to these angles, a clarity is brought to the design which may otherwise appear chaotic. The limited number of positions and connection possibilities is indicative of a discrete, digital system (Ward, 2010). In this system, variation is provided solely through changing the length of the reed bundles and their positioning within the whole.

After studying and prototyping many variations, the final result is an octagonal joint which allows for attachment of successive components at the desired angles of 45, 90 and 135 degrees. Each component within the system is simultaneously identical and unique as the only change to the form is in the elongation or shortening of the reed block. The joint is CNC milled from Siberian Larch, a hardy soft wood that is easily milled, while having excellent weather resisting properties.

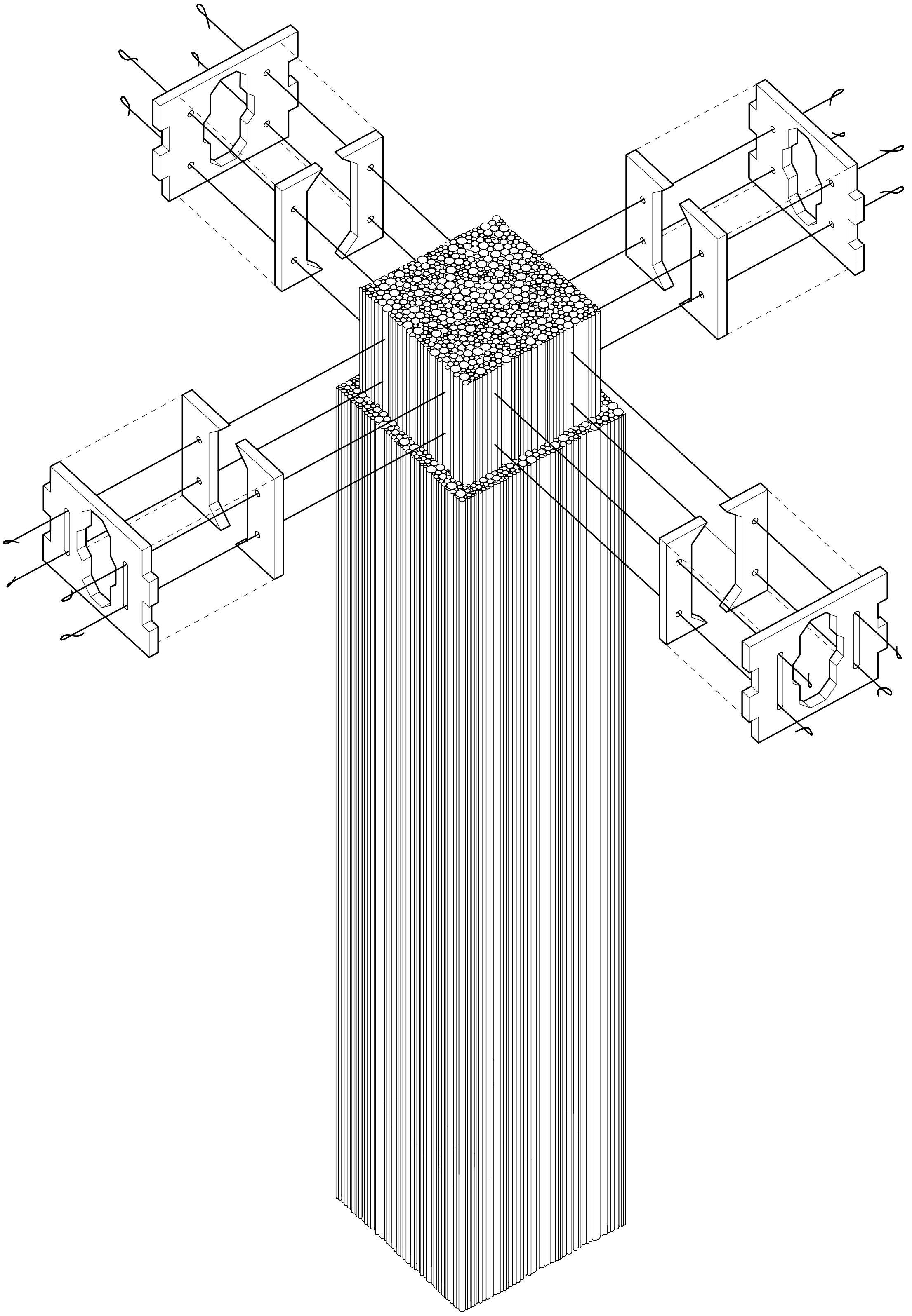
Prototyping of connection systems with MDF and 3D printed joints



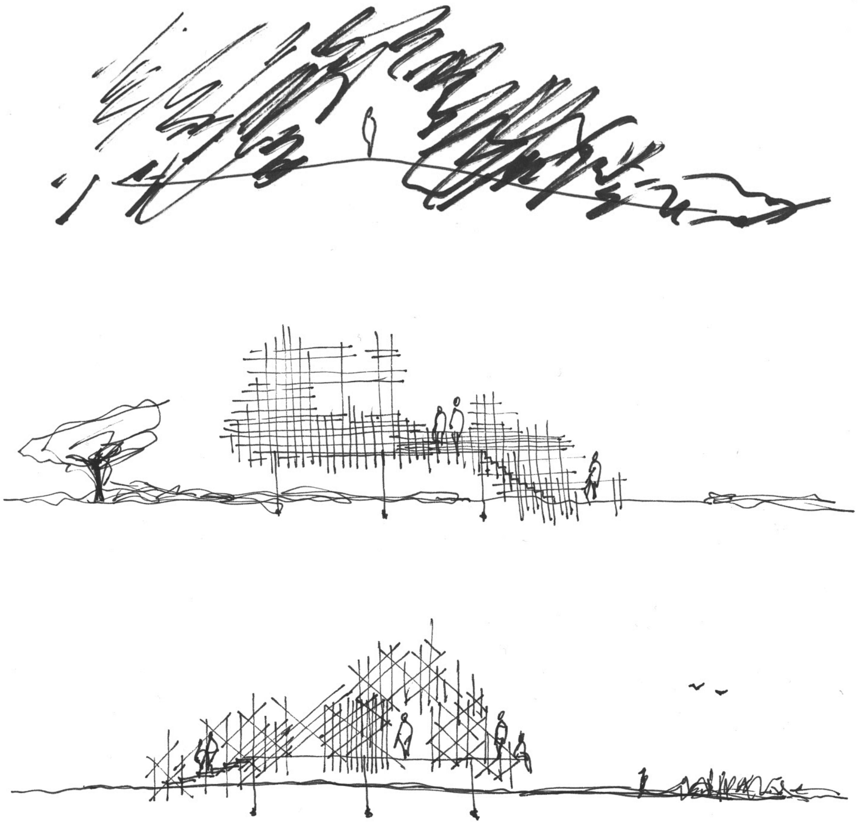


Proposed system assembly
Octagonal keyhole joints allow for standard end connectors that can be attached at 45, 90, or 135 degrees.

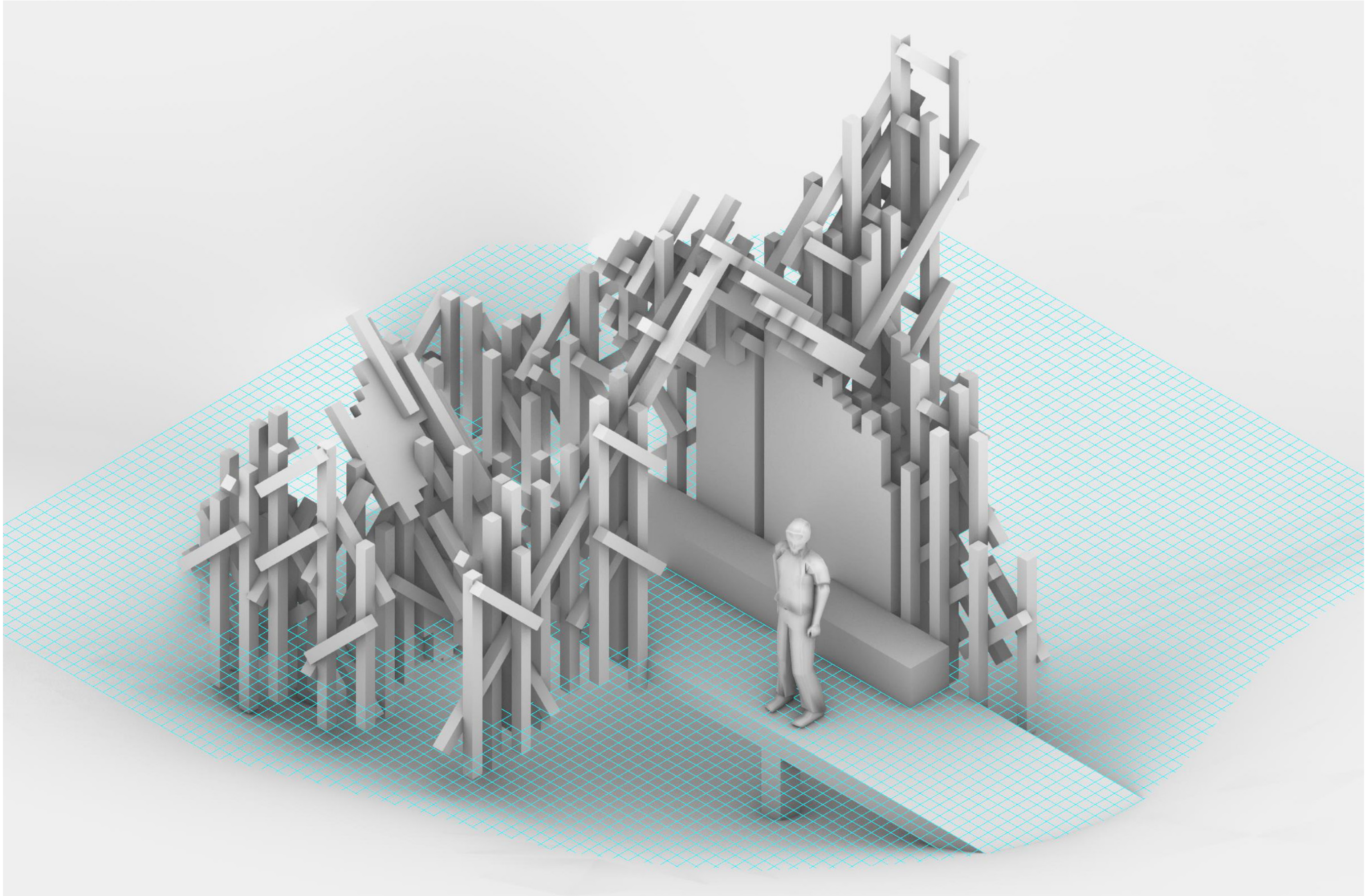
Connection of wood elements to stitched reed bundles with natural rope fiber and bio-glue

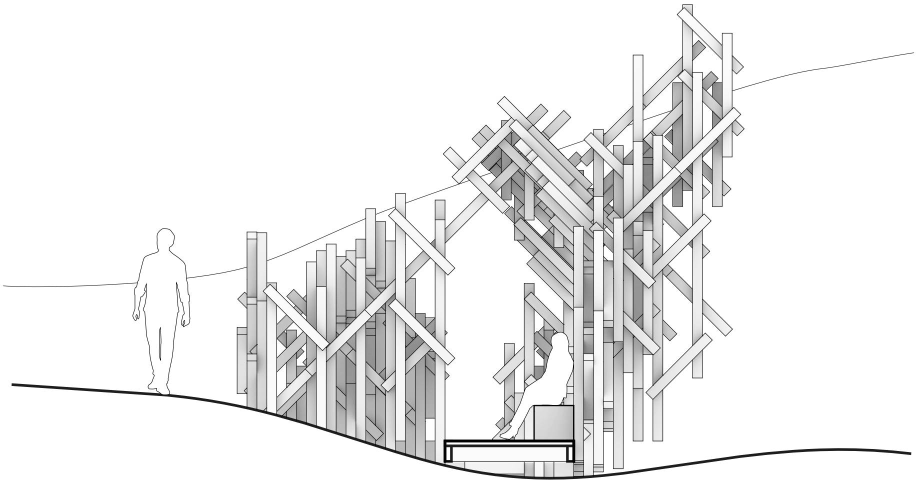


Concept sketches

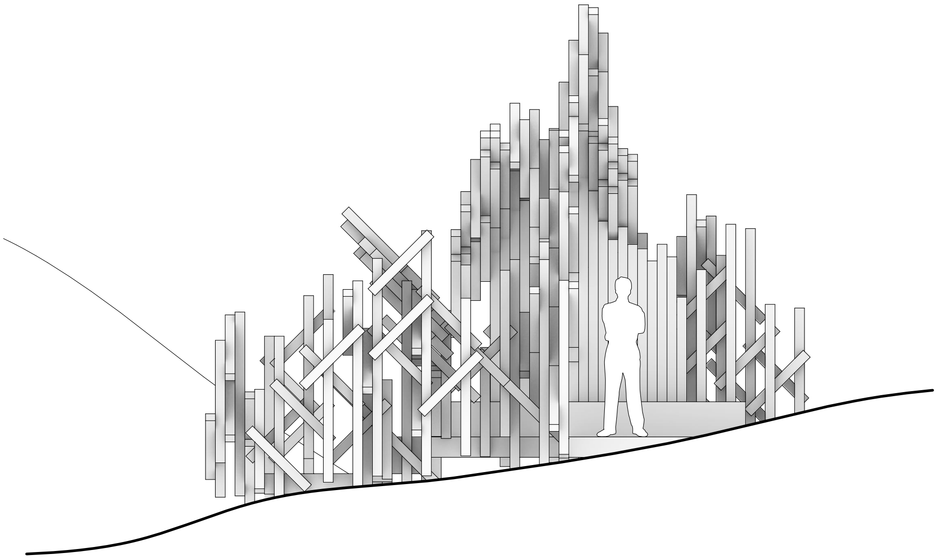


The proposed design utilises a linear component which can be positioned at varying spacing and angles to produce open or solid space and wall and roof surfaces.

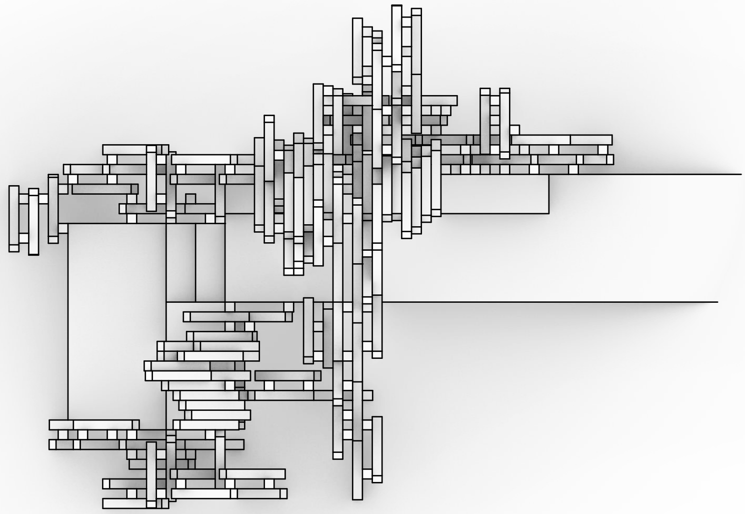




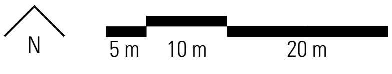
EAST ELEVATION

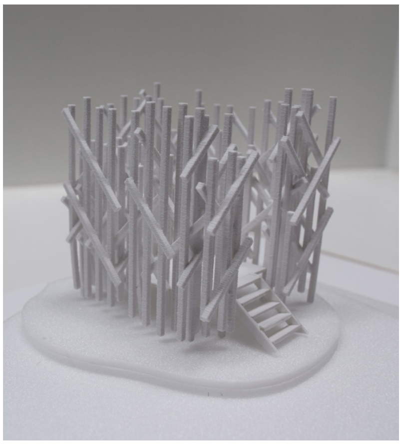


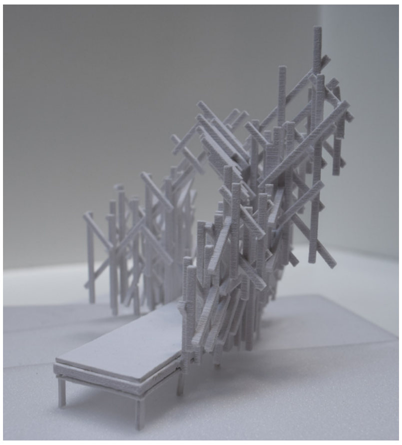
SOUTH ELEVATION

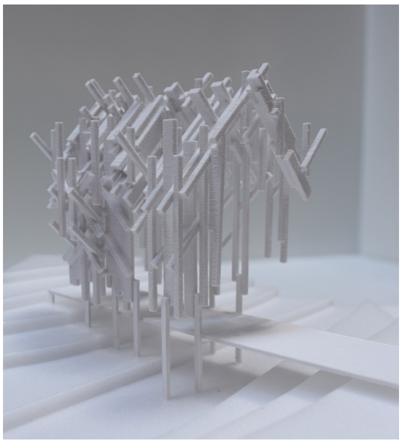


ROOF PLAN

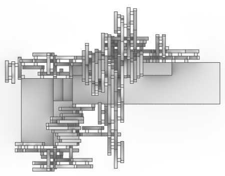


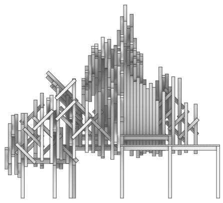


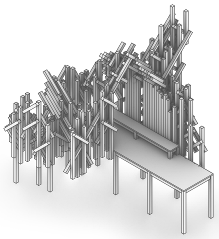


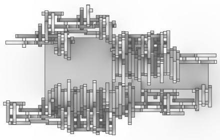


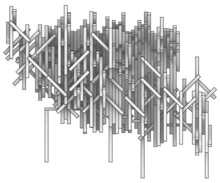
Physical models at a variety of scales show the details of the proposed reed structures.

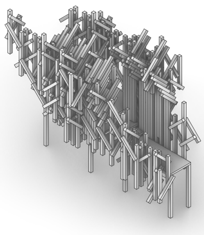


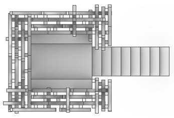


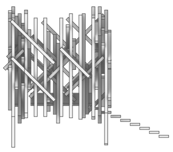


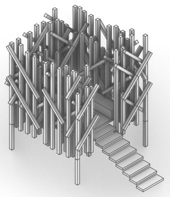


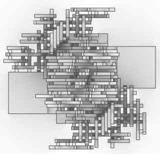


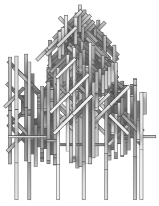


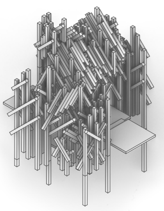


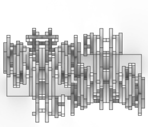


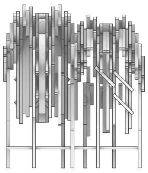


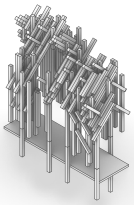


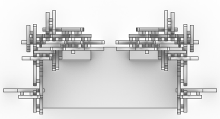


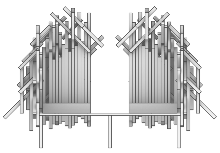


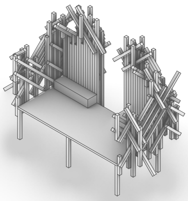


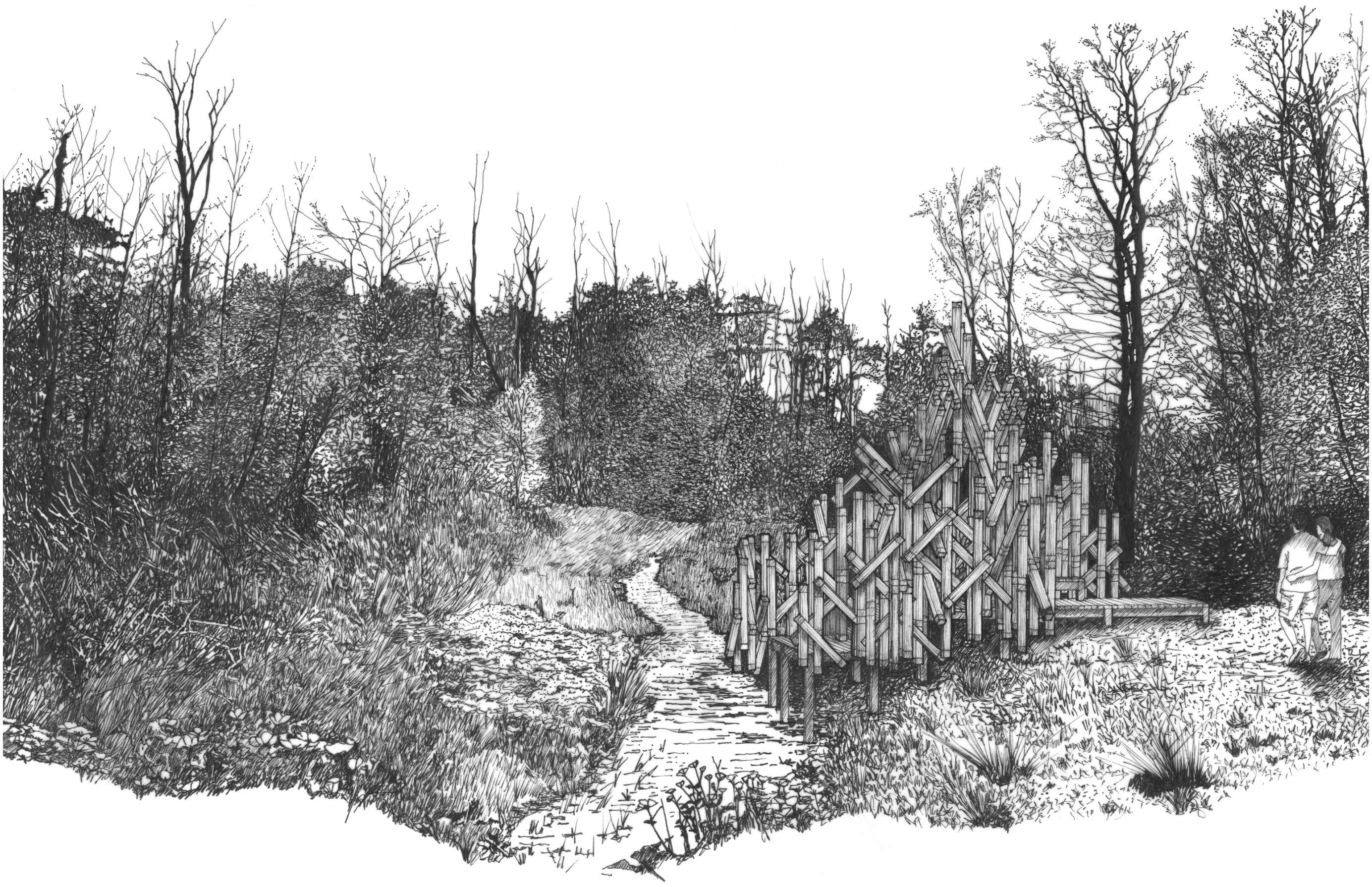












The system allows for a wide variety of design variations that can adapt to suit the landscape they are sited in.

4-4 Design and Assembly Sequence

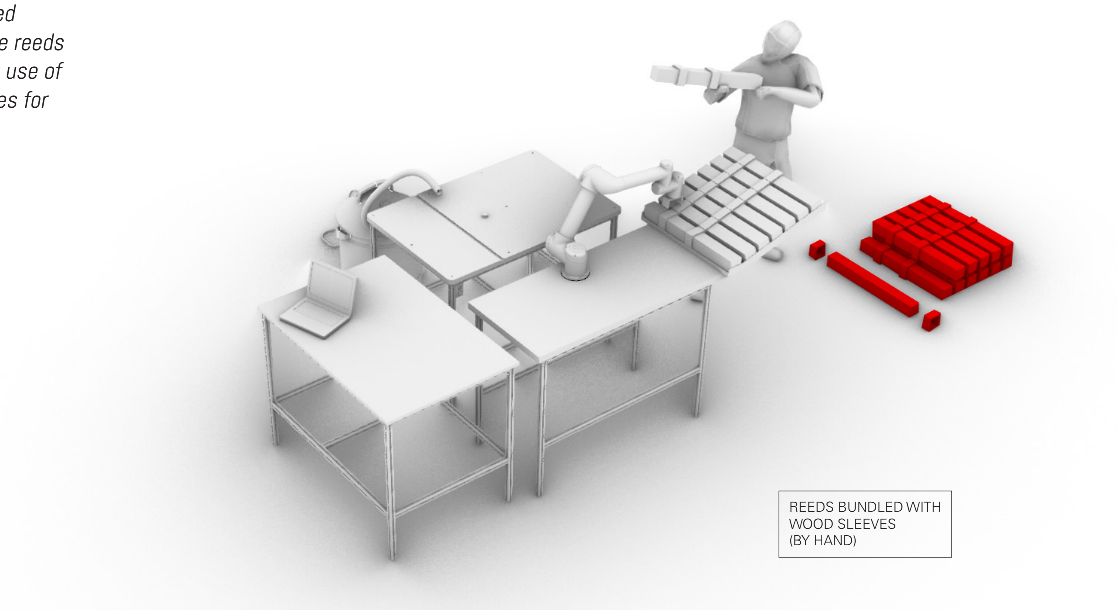
The first phase in the design and assembly sequence is the development of a digital model representing the proposed building. The second phase is the fabrication and assembly process, including the fabrication of reed bundles and the wood connectors. The final phase considers construction and the end of life of the buildings. The sequence is circular, as material is harvested and processed on the island and returns to the ground once the lifespan of the structures is reached.

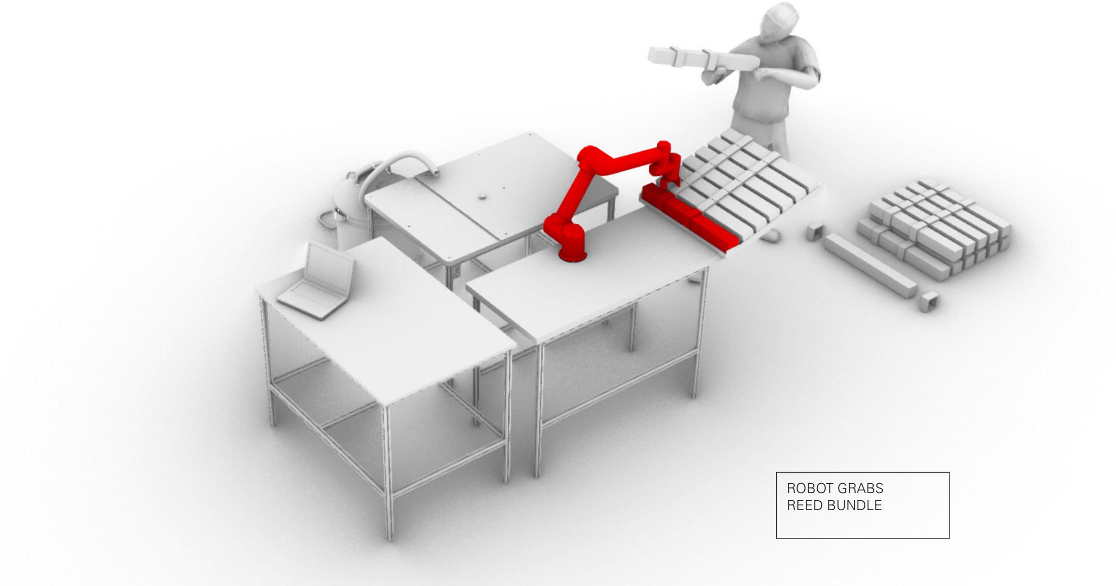
The generation of a digital model is necessary to produce the component data, including the length of the reed bundles and the specific location of the component within the structure for robotic assembly. The integration of this information with the assembly process allows for the generation of a highly complex arrangement of essentially simple components. Once the digital model is complete, the data can be extracted for use in production and assembly. From the outset, the amount of material required and estimated production time will be predictable.

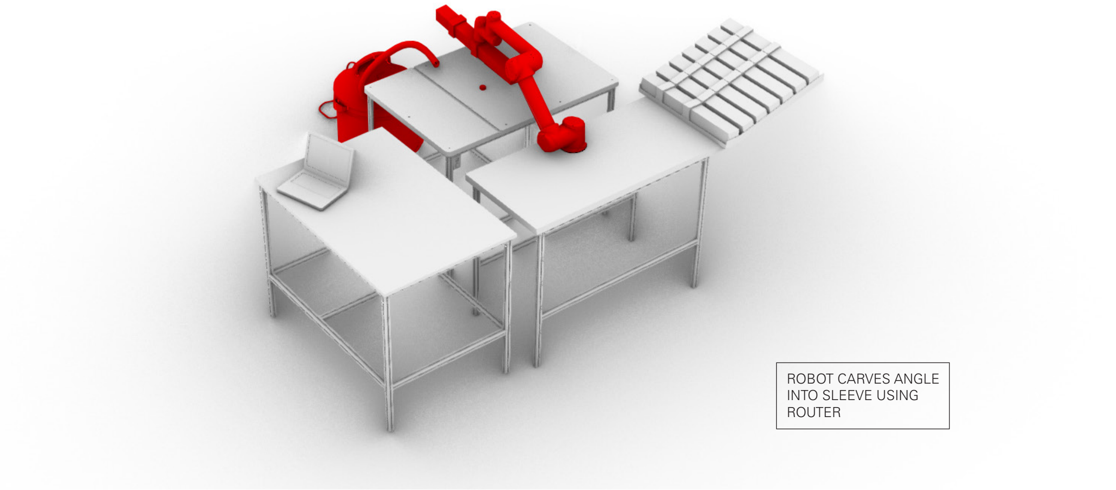
The fabrication and assembly sequence has been considered throughout the design process. Changes to the component design or building design required reconsideration of the fabrication techniques. The diagrams on the following page show an initial concept for robotic fabrication, in which reed bundles of standard size have pre-attached wood connectors, which are then routed to produce joints of very specific angles. This was abandoned in favor of consistent angles for the components, with the variation instead provided by changing the length of the reed bundles. Reeds are currently sold in round bundles 60 cm in diameter, which are optimally sized for a roof thatcher to carry and work with. Harvesting and bundling reeds for alternate architectural uses has not been considered. The proposed process starts from the harvesting process and considers the whole life cycle of the buildings. It is difficult to predict the longevity of the structures as such a system has not been tested before. The reeds will likely deteriorate before the wood connectors. In this case, the reed blocks can be maintained by removing the outer surface and reapplying a fresh layer of reed to protect the inner layers.

The diagram on the next spread elaborates on the specific steps of the proposed design and assembly sequence.

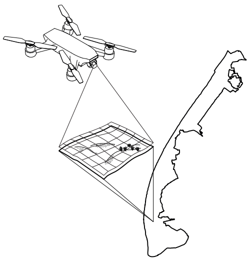
The first fabrication concept involved attaching blank wood sleeves to the reeds and then controlled milling with the use of a robotic arm to create unique angles for each component.





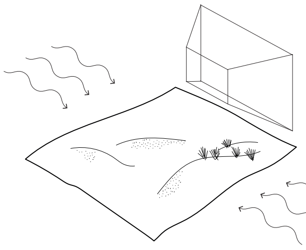


Design and Assembly Sequence



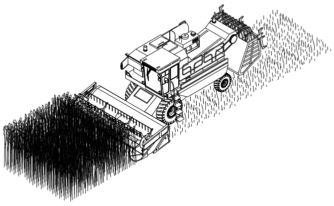
A1. TERRAIN DATA

The terrain surrounding the proposed nature observation building is scanned to produce a digital model.



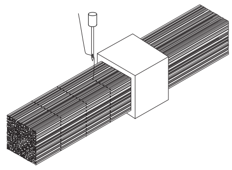
A2. DIGITAL MODEL

The digital model has layers of information to inform the design model, including climate aspects, views and important site features.



B1. REED HARVESTING

Reed is harvested in the winter when the stems are hard and dry, and the least impact is made to the reed bed ecosystem.

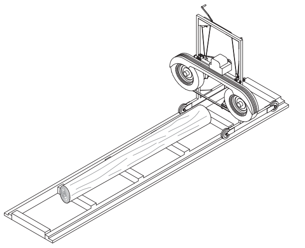


B2. STITCHING REEDS

As the machine harvests the reed, 120 mm square bundles are produced through compressing and stitching the reeds together.

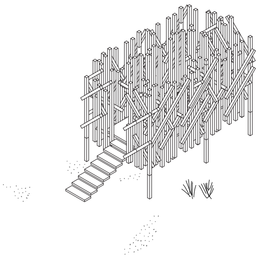
C1. FOREST MANAGEMENT

As part of the forest management within the National Park Duinen van Texel, selective harvesting of trees occurs.



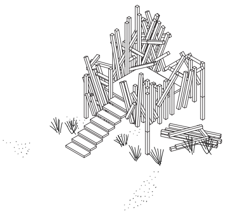
B2. MILLING LOGS

Logs are milled into straight planks using a sawmill.



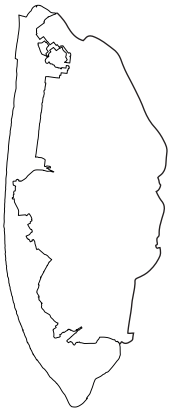
4. FUTURE EXPANSION (OPTIONAL)

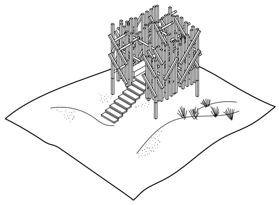
If required, the building can be expanded by adding more components. The buildings can also be maintained by replacing components as they deteriorate.



5. DISINTEGRATION: RETURN TO NATURE

As the buildings are no longer maintained or used, they slowly fall apart. The reeds and wood connectors disintegrate over time, returning to the land they came from.





A3. BUILDING DESIGN

The building design is produced through an algorithm that considers the site features and programmatic requirements. The designer can select from options and adjust the design as required.

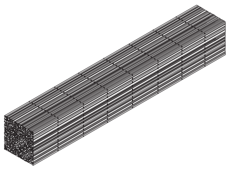
PART #	REED LENGTH	LOCATION	ANGLE
1	870	(683, 632, 967)	45
2	978	(308, 699, 904)	45
3	432	(277, 315, 343)	45
4	678	(665, 571, 14)	90
5	745	(903, 371, 809)	90
6	467	(368, 871, 521)	90
7	863	(275, 805, 835)	90
8	978	(463, 616, 583)	90
9	496	(782, 374, 688)	90
10	870	(919, 697, 556)	90
11	978	(436, 908, 115)	45
12	432	(749, 196, 588)	45
13	678	(386, 809, 895)	45
14	745	(177, 627, 626)	45
15	467	(594, 463, 382)	135
16	863	(209, 305, 903)	90
17	978	(825, 539, 833)	135
18	496	(172, 635, 260)	90
19	870	(587, 126, 962)	45
20	978	(751, 497, 397)	45
21	432	(571, 27, 573)	135
22	678	(580, 36, 258)	90
23	745	(752, 483, 821)	90
24	467	(31, 655, 659)	135
25	863	(357, 395, 614)	90
26	978	(817, 940, 488)	45
27	496	(417, 384, 361)	45
28	432	(974, 646, 737)	90
29	678	(713, 770, 855)	90

A4. CONSTRUCTION DATA

Construction data is exported from the digital design model.

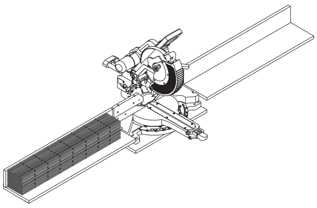
A5. SCANNABLE CODE

Unique scannable codes are produced for each building component to embed the digital construction information in the material.



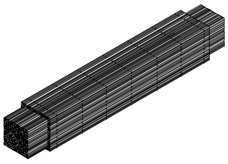
B3. REED BUNDLES

Each bundle is 1000 mm in length and can be stored for future use in construction, or used immediately after harvesting.



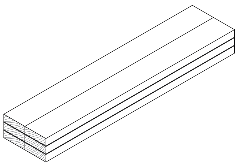
B4. CUSTOM LENGTHS

From the construction data and utilising an automated pushing machine, the reed bundles are cut to length.



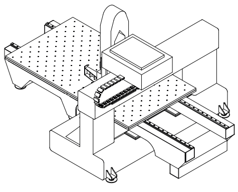
B5. SHAPING ENDS

The ends of the custom-length bundles are cut to accommodate wood connectors.



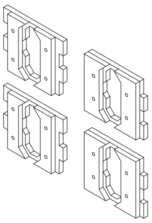
B3. WOOD SEASONING / STORAGE

The green wood is left to season over time and planks are stored for future use.



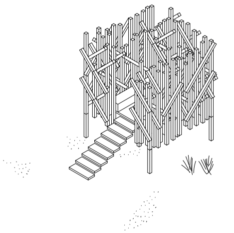
B4. CNC CUTTING

The wood planks are further milled using a CNC machine to accurately shape the end connectors.



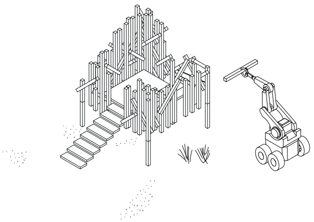
B5. WOOD CONNECTORS

Connectors are produced in two shapes. Four pieces are required to create one connector.



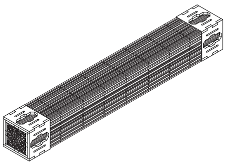
3. COMPLETED STRUCTURE

The completed nature observation structure allows visitors to engage with nature at a slower pace as the buildings encourage quiet, concealed observation of birds and natural features.



2. ON-SITE ROBOTIC ASSEMBLY

Components are assembled on site with an all-terrain robotic arm. The robot is equipped with cameras and scanners to accurately navigate the environment and identify the location of each component.



1. CUSTOM COMPONENT

The custom-length components are produced by combining the stitched, cut reed bundles with the wood end connectors. The end connectors are stitched through the reeds to form a tight connection.

4-5 Robotic Testing

A Universal Robots UR5 robotic arm was available for testing the proposed robotic assembly process. The UR5 is a medium sized collaborative robot. The robot has a reach of 850 mm and can lift a payload of up to 5 kg. RoboDK was used as the robot programmer for the simulation and physical testing.

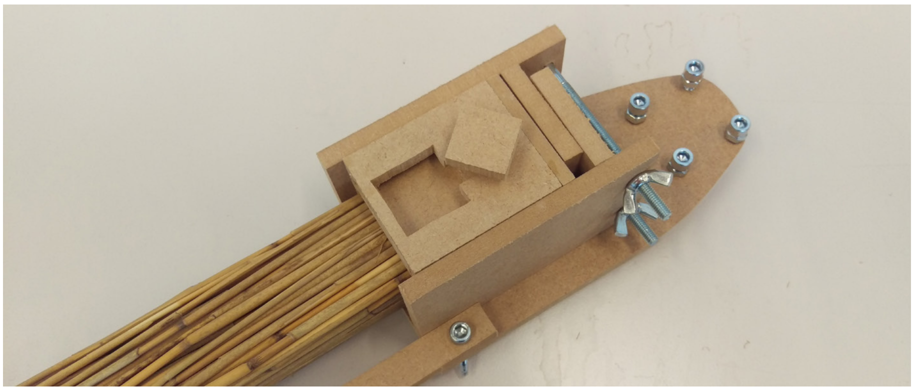
The challenge in assembling reeds with a robotic arm lies in the inconsistency of the natural material. In developing a design which could be robotically assembled, consistency had to be added in a way that would allow for easy assembly. The wood end connectors designed to join reed bundles together also provide an appropriate geometry for the robot to grip and move. For the purposes of testing, a manual gripper was built from MDF. The gripper utilises bolts with butterfly nuts to open and close the gripper around each part. In an ideal situation, an adaptive gripper, such as the Dahl DAG-M would be ideal for automatic picking of parts. Another important element is the inclusion of a part feeder, which would automatically place components in the same position, one after the next for the robot to grab. For the purposes of simplifying the testing, parts are placed manually in the gripper.

Initial testing focused on a simple task of placing one element at a 45 degree angle, as shown by the images on the following page. A simple component at 1:2 scale was used. Following this first test, a more elaborate setup was created consisting of six components. This sequence was programmed manually in RoboDK. As a next step for this project, a script would need to be developed for assembling elements in sequence. The main challenges here are in collision avoidance and sequencing of the assembly of parts.

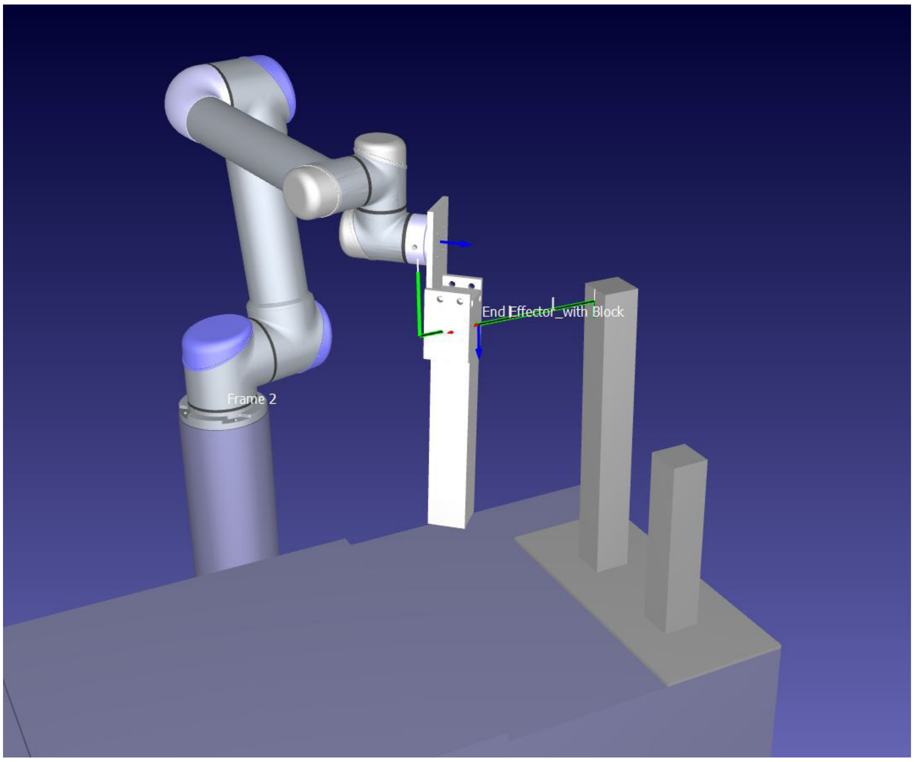
The most important take away from the robotic testing is that the design of a robotically assembled architectural joint must allow for tolerance. Even though at first it seems that a robot allows for more precision, small inaccuracies can quickly add up, resulting in a misaligned joint. These inaccuracies can result from the manufacturing of the components, computation of the weight or center of gravity, the mounting or calibration of the robotic arm, or in the setting of reference points from the physical setup. For further research, the joint would need some adjustment to include more tolerance for the assembly. This becomes particularly important when considering that the final design will be constructed in an environment that is much more unpredictable than a lab setup.

The first test setup for physical robotic testing aimed to place a bundle from the base position to a 45 degree angle and then slotted within the keyhole connection.

A custom end-effector is used to manually simulate the use of an automated gripping end-effector.



Preliminary test setup in the RoboDK Programmer



Robotic assembly test setup utilising the Universal Robots UR5 robotic arm with cutom built end effector.

Assembled 1:2 prototype

5 - CONCLUSION

5-1 Discussion of Results

The findings of the research can be categorised in relation to the research questions. The first question asked; *How can a digital design process reframe the use of reed in contemporary architecture*? The research answers this through the proposed digital design and production sequence. The result was largely influenced by the material characteristics of reed and the robotic assembly process.

Several factors limit the use of reed for long-term exterior exposure. In order to maximise the material performance, bundling reeds together is necessary. The use of an inconsistent natural material brings up many challenges for digital fabrication. While the digital fabrication aspect adds some limitations, it also opens up possibilities. Several parts of the fabrication could be achieved through handwork, but the benefit of a digital production chain is the data embedded in each of the components. This allows for each reed bundle to be a different, precise length and the assembly is rationalized through the location data.

One benefit of using a digital design process is that the architecture is immediately recognisable as a product of the current era. There are many deeply rooted associations when it comes to using natural materials. While a material such as stone feels rich and solid, plant fibers have traditionally been viewed as weak and inferior. The proposed project reframes reed as a digital material that is more relevant than ever in the present day.

The second research question asked; *How can this provide a solution for non-intrusive observation buildings in the natural landscapes of Texel Island in the Netherlands*? The design of biodegradable structures that aesthetically merge with the natural environment provides a solution. The textural and spatial quality of the proposed structures create a blurry, diffuse architecture. The architecture is in dialogue with the surrounding landscape and is the result of analysing the context. The material comes from the same island and the building forms react to their specific siting and use. The buildings exist in the space of threshold, defining space and encouraging transition, but never committing to being either interior or exterior space. The spatial, sensory and experiential qualities of the proposed nature observation buildings are made possible through the forming and assembly of the material. Merging these aspects together required the design process to follow a highly iterative, nonlinear sequence, with simultaneous research and adjustment made to the architectural concept, material tectonics and digital strategies.

Beyond the initial research questions, the process led to other unanticipated findings. Although the project is focused on robotic assembly, the innovation lies in redefining the harvesting process and considering materials for construction starting from the source; how they are taken from the ground. By questioning the way that we process a construction material, new possibilities for use can be revealed. This is fundamental in exploring sustainable strategies for the future. The proposed machine that would harvest and stitch the reed bundles is the cornerstone of this project as it enables the production of . This questions the role of architects in these processes; we have to push for new processes to enable our sustainability goals.

The other innovative aspect of this project is thinking about reed as a material which can be broken into parts, instead of used as a mass such as in the case of thatch roofing. Instead the architecture is viewed as an assembly of discrete elements in which any adjustment to one element has an impact on the resulting form. This is why the project is explored at a multitude of scales, because it emphasizes the fact that everything is interrelated, a change on one scale impacts the other. It is interesting to take a material which is weak on its own and bundle it, pack it densely, create a component which is structural, insulative, and can act as cladding.

The research by design method was appropriate for this project and the production of physical models at various scales validates the results, as the 1:1 shows the system is self-supporting, the 1:2 enabled testing of the robotic assembly, and the 1:20 and 1:50 models display the aesthetic quality and possible design variations. In considering how the research could be improved, testing of the robotic assembly should have been performed at an earlier stage in the research to better inform the design of the connection between components.

5-2 Limitations and Further Research

There are many ways in which this research could be developed beyond the limitations of a Master's thesis. The research focused on the design of the reed components to enable a robotic assembly process. Additional study would further verify the viability of the proposal as an adequate solution for nature observation buildings or other alternative structures.

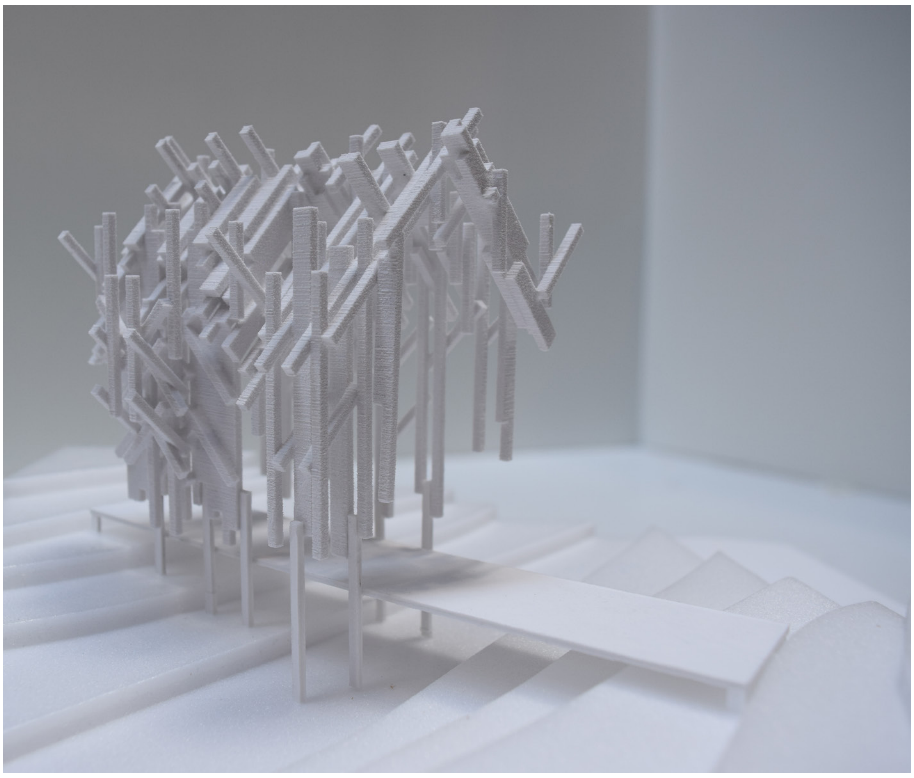
Testing the structural performance of the system would be necessary to ensure the ability to withstand the conditions on Texel Island. The 1:1 prototypes prove the reed bundles can be connected into self-supporting structures, however the addition of other loads should be considered. Wind loading is of particular concern due to the low weight of the reed bundles.

In order to evaluate the sustainability of the proposed process, calculations need to be made to determine the energy efficiency of the harvesting and manufacturing machinery. The proposed process includes several machining and robotic processes. It is important to use clean energy sources and low emission machines to further the sustainability agenda. The lifespan of the system is difficult to predict, especially if the reed is maintained through periodic replacement of the outer layers. In order to determine this, long-term testing would be required.

The robotic testing was focused on the use of a robotic arm as the best available method. It would be beneficial to consider other assembly options, such as the use of drones to expand the ability to access higher, difficult to reach areas.

The use of wood connectors enabled a biodegradable structure. Some improvements can be made to the connectors. More tolerance is necessary to improve the viability of robotic assembly. Additionally, the connection between the reed and the wood could be further secured by adding more stitching holes along the base of the connector to ensure a tight connection. However, with the use of machine stitching, this may not be necessary. An improvement was made when the design proposal switched from solid timber parts that were CNC milled, to milling of planks which are later joined together as this greatly reduces material waste.

An alternative solution for end connectors would be to use epoxy resin poured into moulds with the reeds embedded. Epoxy resin is not bio-based or biodegradable, but the concept is worth keeping in mind as innovative materials develop in the future. A further option would be to produce the connectors from a more durable material that can be reused many times with replacement of the reeds. This would be ideal for using the structures for temporary installations, such as exhibitions or festivals.



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