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Advancing Reed-Based Architecture through Circular Digital Fabrication

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This paper presents a completed research project that proposes a new approach for creating circular buildings through the use of biodegradable, in situ resources with the help of computational design and digital fabrication technologies. Common Reed (Phragmites Australis) is an abundantly available natural material found throughout the world. Reed is typically 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. The use of a digital production chain was explored as a means towards expanding the potential of reed as a sustainable, locally produced, construction material. Following 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.

Keywords: *Phragmites Australis, Reed, Discrete Design, Robotic Assembly, Circular Design, Biodegradable Architecture*

INTRODUCTION

Background

In the simplest terms, a building is the result of materials being formed, combined and joined to create defined space. Consequently, building materials and the production and assembly methods chosen during design can to a large extent determine the sustainability of a building. 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 renewable materials in substitute for emission producing ones is an important challenge for architects. In the European climate, plant-based resources, such as timber and bamboo, have been broadly investigated as quality materials that offer good performance characteristics. Innovative applications of other plant fibers in building construction are less widely studied. Common Reed (*Phragmites Australis*) has traditionally been used for thatch roofing, providing insulation and a weather-tight exterior cladding. In other countries, such as Egypt, Peru and Iraq, traditional techniques of weaving and bundling reeds have long been used to create entire structures. The research presented here investigates the use of reed in architecture, beginning from reed growing and harvesting through to the development of a system of reed-based components.

The research aims to promote the use of reed as a sustainable construction material through the utilisation of a circular, digital production chain in order to improve quality, reduce labour costs and seek new architectural expressions. The use of digital tools in conjunction with consideration of the harvesting and processing of the material, enables a level of complexity that would not be achievable in traditional processes.

Problem Statement

Despite the abundance of plant fibers and their potential as circular, low cost construction materials, they are often perceived as primitive architectural materials, which has led to a decline in use in contemporary construction. 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, whereas other non-wood plant fibers, such as reed, hemp, flax, or straw, are rarely employed other than in composites or as insulation material. Reed offers a sustainable, low cost material for construction and is abundantly available in many countries, growing on every continent except Antarctica. However, the use of reed as a construction material has declined and exploration of new architectonic approaches, particularly through the use of digital design and fabrication, is uncommon.

Research Question

This paper aims to answer: how can digital design and fabrication technologies encourage the use of reed in contemporary architecture towards increasingly circular built environments?

MATERIAL RESEARCH

Material Characteristics

Common Reed (*Phragmites Australis*) is a species of grass from the Poaceae family. The native plant can grow in a wide variety of habitats although it is best suited to wetland habitats in fresh or brackish water. 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. 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 (Ikonen, 2007).

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. 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, between 1-3 years in Nordic climates, due to the high cellulose content and lack of nitrogenous proteins, resulting in a poor quality food for herbivores and detritivores (Ikonen, 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). Reed has excellent acoustic and thermal properties and is very lightweight. The thermal conductivity is relatively consistent, around 0.05 W/mK, and is not affected by geometry, the acoustic behaviour is primarily dependent on stalk configuration, with a longitudinal stalk layout particularly effective in sound absorption (Asdrubali et. al., 2016).

Harvesting and Processing

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 (Ikonen, 2007). Approximately 1,000 bundles of reed can be produced from a hectare of reed bed. In the European market, 60 cm diameter bundles of reed are typically sold in lengths ranging from 1m to 2.3m. The cost of a bundle of reed is in the range of 2-3 Euros, with locally harvested reed often being more expensive than imported reed because of higher labour costs (A. Prosman, personal communication, January 15, 2019). Reed sourced from further away requires more energy for shipping than reed sourced locally. Therefore, encouraging the use of local reed requires the development of less labour intensive processes.

The quality of reed 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. The best reed for roofing is harvested in winter when the stems are hard and the moisture content is low (Ikonen, 2007). Collecting reed is easier when the water of the reed marsh is frozen, allowing equipment access. Harvesting of reed is rarely done by hand as it is much more efficiently achieved with purpose-made human-operated machinery.

Use in Architecture

The use of reed in architecture can be found in several forms, particularly in traditional buildings. Thatch is the most commonly known application for reeds in the European context. In addition to thatched roofing, thatching the exterior walls of buildings has become common in contemporary architecture. Examples include the Yusuhara Market building in Japan, for which architect Kengo Kuma used thatch as a facade panel [1], and the Wadden Sea Center by Dorte Mandrup, with thatched walls [2].

The Mudhif, a traditional guest house built by the Marsh Arabs in Iraq, is constructed entirely from reeds (Broadbent, 2008). Bundled reeds form arches to support the structure and woven reeds of varying porosity create the enclosure. These buildings have been constructed for thousands of years and continue to be constructed today. The potential of individual reeds to act together as a structure was recently tested through the design and construction of a temporary experimental pavilion in Japan. The project, *Design and Construction of Temporary Pavilion Using Reed as Structural Material*, utilised straight, tied pieces of reed to form an arched structure. The utilisation of reed is seen as an important issue in regions of Japan, to preserve the culture and environment (Nagai, 2017). However, the resulting structure is extremely lightweight, requiring stabilisation from wind loads with sandbags.

Reed can also be used as insulation in the form of panels made from reed stems tightly squeezed together and sewn with wire by machines. The panels are fire resistant, lightweight, and insulate both heat and sound. Reed panels 30 - 50 mm in thickness have a Specific Heat Capacity of approximately 300 (c)(J/kg.K) (Piesik, 2017). 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 Totora reed that grows abundantly in Lake Titicaca (Ninaquispe-Romero, 2012). They construct houses and boats from reed mats and bundled reeds.

Maintenance and Fire Safety

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. 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. For roof surfaces, a pitch of 45 degrees or more is typically required to allow water to shed. Exposure to sun and wind allows the reed to dry out, thereby prolonging its life. Heavily shaded and 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.

Fire safety is a concern for reed structures, as fire can spread quickly through dry reeds. 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. It is the underside of the roof, where the material is dry that is most vulnerable to the spread of fire. Additionally, when reeds are tightly packed together, as in the case of insulation panels, a higher fire resistance is possible (Ikonen, 2007).

RESEARCH BY DESIGN

Relevant Research Projects

Recent digital design and fabrication research relevant to this research include; the design studio taught by Jan Buthke at Aarhus School of Architecture, *Experiments in Robotic Thatching* (Buthke, 2016). The *Ripple Wall* installation created for the Digital Arts Center at the University of North Carolina at Charlotte (Beorkrem, 2017). *Biomimetic Robotic Construction Process*, in which beaver dams inspired the concept of using an all-terrain construction robot equipped with a 3D scanner (Cheng, 2016). And the robotic timber construction projects at ETH Zurich, including *The Sequential Roof* (Willman, 2016) and *Robotic Fabrication of Bespoke Timber Frame Modules*, which explores robotic assembly processes with the aim of reducing the need for scaffolding and allowing for construction of non-planar geometries (Thoma, 2018).

Case Study Context

Returning to the main research question, the primary objective is to use digital design and fabrication technologies to encourage the use of reed in contemporary architecture. As the project is highly focused on sustainable, circular design, an ideal application is for projects which need to be inserted lightly in natural environments. As a case study, the design of a series of nature observation buildings is proposed for the National Park Duinen van Texel, an island in the Wadden Sea in the northern Netherlands. 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.

A building that is customised to a specific use and set of conditions is better suited to materials which can be disassembled, reused, or biodegraded. 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 adaptation as wildlife shifts to different locations, the landscapes change, and the number of visitors to particular areas fluctuates. Through this context, permanence in architecture is questioned.

Design Concept

The design concept is material-based; an increasingly common design model that experiments with the synthesis of new digital techniques and material design and fabrication technologies in an experimental design model (Oxman, 2015). Currently the design for the buildings is done manually (Figure 1), with the idea of future implementation of a parametric model. While digital design is considered as part of the process, the focus for this research is on the assembly process. The ideal parametric model would generate options for the form of each structure based on performative requirements and site characteristics.

Figure 1
Physical model of proposed discretized reed-based structure

Figure 2
Proposed reed-based component, 1:1 prototype

Reed is an inconsistent material; each stem varies in diameter across its length making it challenging to work with in digital fabrication. Additionally, reed performs best when bundled to form a block or surface; combining many individually weak pieces to create a strong component. Bundling the reeds into compact, manageable components emerges as the logical approach to working with the material in a digital fabrication process. 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). This methodology provides the basis for a proposed system of bundled reed components.

Components and Connections

Several geometries were explored for the reed components. The shape of the cross-section is largely determined by how the reeds 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. One of the design goals was to use fully biodegradable materials; therefore, a solution emerged utilising a wood sleeve to create standardised square sections and provide a point of attachment between adjacent bundles. Prototypes were built by hand utilising two types of reed; Chinese reed with a thin culm diameter and shorter stem, and Turkish reed with wider culm diameter and longer stem. The final 1:1 prototype was built with laser-cut wood end-connectors and hand-stitched reed (Figure 2).

The proposed system 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.

An octagonal joint was found to be ideal to allow for attachment of successive components at the desired angles of 45, 90 and 135 degrees (Figure 3). 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 wood ends are designed to connect the reed bundles to each other, but they also provide an appropriate geometry for a robot to grip and move during assembly, thereby regularising the material.

The proposed design consists of three parts; the stitched reed bundle, the wood end connectors, and hexagon-shaped pins used to join the components together. The system 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 organisation. The keyhole connection allows for future disassembly or reconfiguration.

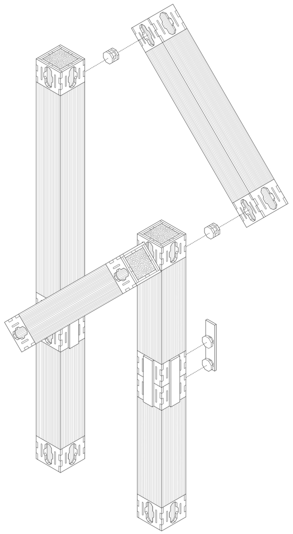

Figure 3
Proposed system assembly: Octagonal keyhole joints allow for standard end connectors that can be attached at 45, 90, or 135 degrees

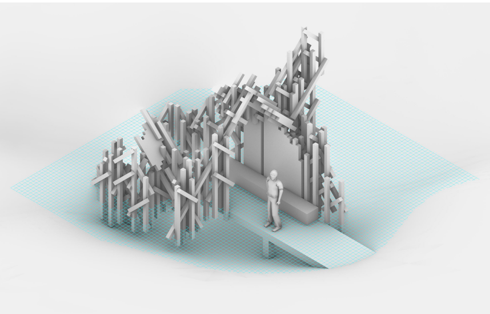

Figure 4
A digital model is required for the fabrication and assembly process to capture the length, location, and orientation information of each component

Design and Assembly Sequence

The design, construction, and lifespan of the reed structures are considered in a series of phases. The first phase is the development of a digital model representing the proposed building. The next phase is the fabrication of reed bundles and the connectors. The third phase is the robotic assembly of the structures, and the final phase is 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 and orientation of the component within the structure for robotic assembly (Figure 4). As described previously, this model is currently created manually, however a parametric model could be explored as a future step. Within the digital model, each discrete reed bundle is uniquely identified and contains information about its coordinates and length. 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.

Machines have been developed to automatically bundle reeds as they are harvested, producing 60 cm diameter bundles, which are the ideal size for a roofer to carry and work with. Additionally, large format sewing machines exist to produce reed mattresses and insulation panels. The automated harvesting and bundling of reeds for other uses in architecture has not previously been considered. The development of a new harvesting machine is proposed to combine the capabilities of these two existing machines. The machine is imagined to directly harvest reed and produce square, stitched reed bundles cut to custom lengths.

For the construction of the nature observation structures, the unique components would be assembled on site with an all-terrain robotic arm. The robot would require cameras and scanners to accurately navigate the environment and identify the location of each component. 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, as previously mentioned, this was achieved through the use of a square end-connector at the end of each reed bundle.

The process is considered from harvesting of reed through to the end-of-life of the structures (Figure 5). Through designing a complete system, a circular solution was achieved. Once constructed, the structures can later be expanded by simply adding more components. After the buildings are no longer maintained or used, they slowly fall apart or can be disassembled. The reeds will likely deteriorate before the wood connectors. However, the reed bundles can be maintained by removing the outer surface and applying a fresh layer of reed to protect the inner layers. It is difficult to predict the longevity of the structures as such a system has not been tested before, however it could be in the range of ten to twenty years.

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. With the limitation of the size and payload of the robot arm, a 1:2 scale model was built for use in robotic testing (Figure 6). In a real-world application, a larger, all-terrain robot would be required to assemble structures directly on site. The scaled model was built by hand and the assembly was semi-automated, with a focus on the customised positioning of each component. RoboDK was used as the robot programmer for the simulation and physical 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.

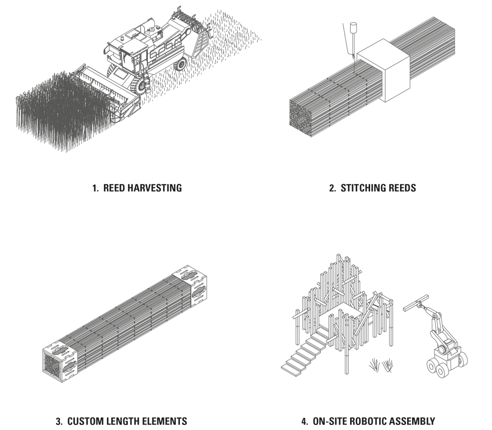

Figure 5
The harvesting, component production, and robotic assembly are designed as a complete system

Figure 6
Robotic assembly test setup utilising the Universal Robots UR5 robotic arm with custom built end effector

Testing began with simple tasks, such as joining one element at a 45 degree angle. Following this first round of testing, 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 based on the digital model. The main challenges here are in collision avoidance and sequencing of the assembly of parts. The most important takeaway 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 proposed design would be constructed in an environment that is much more uncontrolled than a lab setup.

CONCLUSIONS

Discussion of Results

The design process followed an iterative, nonlinear sequence, with research occurring simultaneously to design, resulting in continual adjustment to the architectural concept, material tectonics and digital strategies. Through this design-based research process, there were certain unanticipated findings. Although the project primarily focuses 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 towards the requirements of a robotic assembly process. Through questioning the way that a construction material is processed, new possibilities emerge. 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 localised production of a new type of building component.

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 use of an inconsistent natural material brings up many challenges for digital fabrication. However, while the digital fabrication aspect adds some limitations, it also opens up possibilities. Several parts of the fabrication could be achieved through handwork, but beyond the time savings, the benefit of a digital production chain is that data is embedded in each of the components. This allows for each reed bundle to be a different, precise length and the assembly is rationalised through the location data. The proposed project reframes reed as a digital material, capable of containing embedded data straight from harvesting.

Another innovative aspect of this project is considering reed as a material which can be discretized, instead of used as a mass, as is common with thatch roofing and insulation panels. Instead, the architecture is viewed as an assembly of components in which the overall form is impacted by any adjustment to a single component. A singular reed is inherently weak, but through dense bundling, components can be created that are 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 prototype showed the fabrication of components, the 1:2 model 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.

Limitations and Further Research

There are many directions in which this research could be further developed. 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. Wind loading is of particular concern due to the low weight of the reed bundles. 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. Additionally, study on the development of a new type of reed harvester and analysis of the costs is needed to determine the viability of the proposed system.

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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