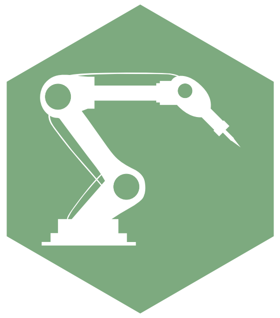
GREEN MEETS MACHINE

Green Meets Machine

Robotic Fabrication of Carbon-Negative Hempcrete

By

Ricky Frost



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ampd Lab

Mission Statement:

The following thesis is part of the Advanced Manufacturing and Prototyping for Design Research Lab. AMPD aims to investigate and define innovative techniques and methods of modern construction applicable to the architecture and construction sector through the use of advanced tools of design, fabrication, and manufacturing. The fourth industrial revolution is core to our research exploring methods of improving information flow from design to fabrication—across the digital continuum—to design architecture that builds wellbeing for people and the planet. We can't keep doing what we have always done—our research questions the status quo by designing and constructing prototypes. You should consider the thesis within the larger body of research that AMPD Research Lab undertakes. Each thesis has focused on an aspect of AMPD's aim.

Figure 1: Hemp hurds are processed to optimise the extrudable mixture

Abstract

Hempcrete is touted as a carbon-negative building material and can reduce the construction industry's vast share of global carbon emissions. However, conventional hempcrete construction is underutilised due to its laborious, time-consuming construction process. In response to these issues, Green Meets Machine uses design science research to explore how robotic fabrication can increase architectural expression in hempcrete construction while maintaining net negative embodied carbon in order to accelerate carbon-negative construction.

Direct extrusion and the design of an internal timber structure with parametric formwork aimed to to increase geometric variation in hempcrete construction. Evaluation of the designed artefacts revealed that, while direct extrusion requires further research before it is deemed a viable hempcrete construction method, the plywood structure and formwork module successfully increases architectural expression through its hybrid workflow. Combining the efficiency and mass-customisation ability of robots with the adaptability and problem-solving skills of human workers led to a streamlined construction workflow where robots and humans work together to realise a geometrically expressive, carbon-conscious architecture greater than what either could achieve alone.

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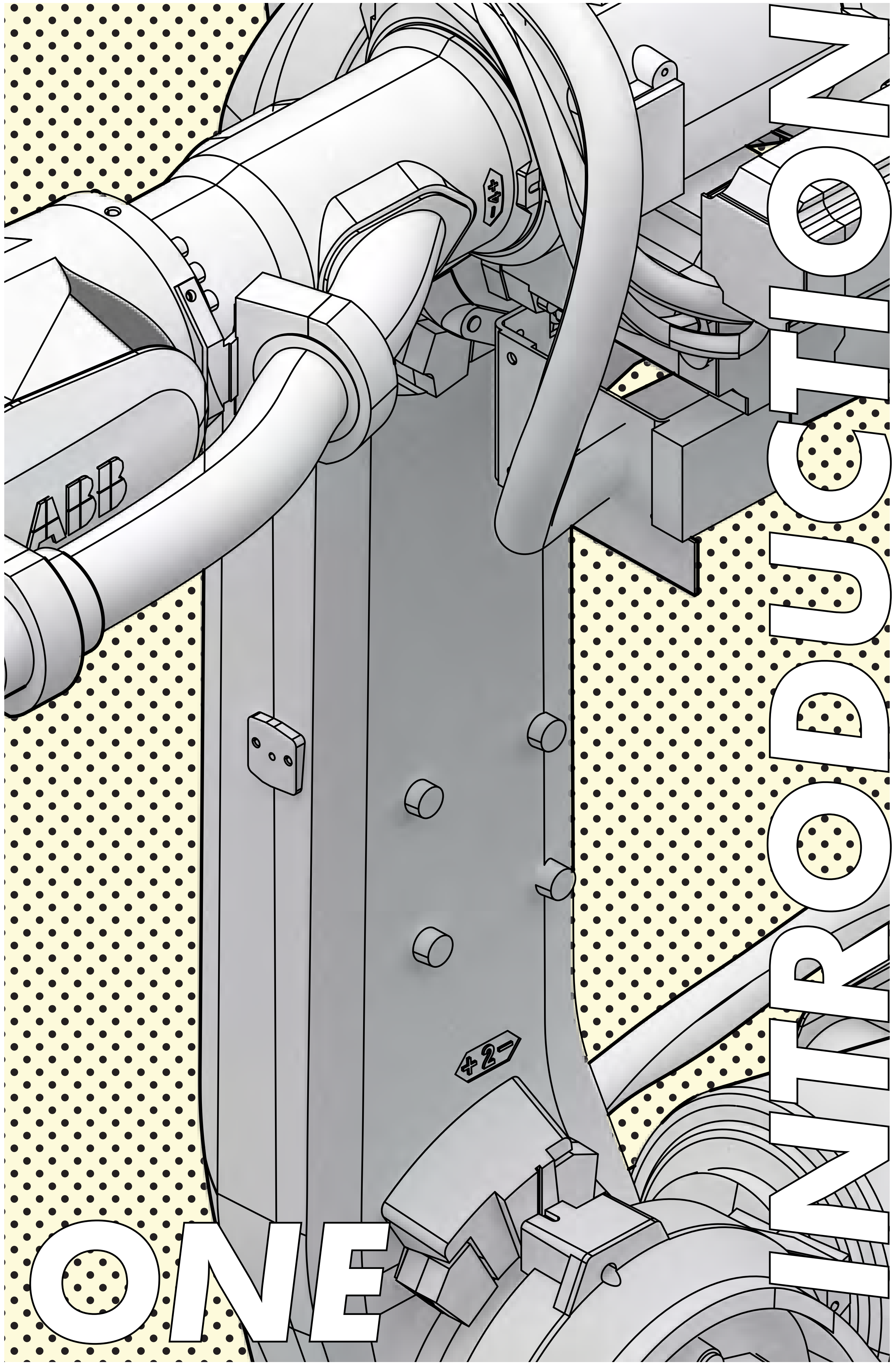
INTRODUCTION



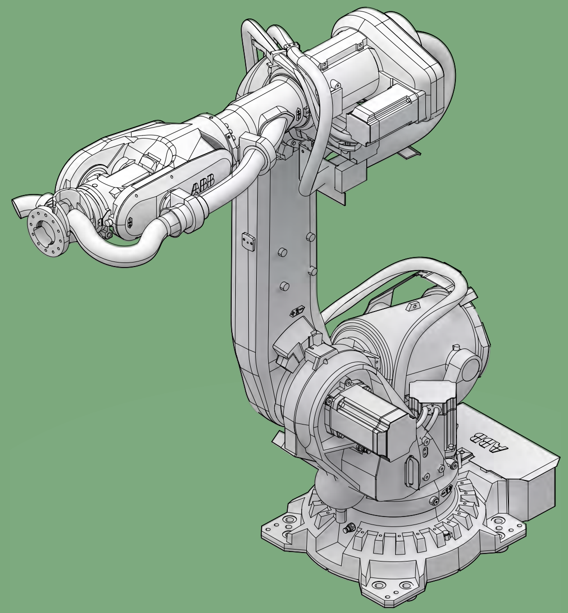
1.1.0 Research Background & Context

We are in a climate emergency. If we do not limit global warming to 1.5°C above pre-industrial levels, the effects of climate change will be irreversible (United Nations Environment Programme, 2020b; United Nations, 2019; Levin, 2018; IPCC, 2018). The IPCC's Sixth Assessment Report states that "limiting human-induced global warming to a specific level requires limiting cumulative CO_2 emissions, reaching at least net zero CO_2 emissions, along with strong reductions in other greenhouse gas emissions" (IPCC, 2021, p.36). Unfortunately, the construction industry is a massive contributor to global carbon emissions. The United Nations Environment Programme (2020a) reported that while the operation of buildings accounts for 28% of global CO_2 emissions, "the manufacturing, transportation and use of all construction materials for buildings resulted in energy and process-related CO_2 emissions of approximately 3.5 $GtCO_2$ in 2019, or 10% of all [global] energy sector emissions" (p.23).

A 2018 report by Thinkstep claims that, with a consumption-oriented view adjusted for international trade, New Zealand's built environment is responsible for 20% of its total carbon footprint (Thinkstep Australasia, 2018). However, with an ever-expanding population and in the midst of a housing crisis (McClure, 2021), New Zealand cannot afford to slow down construction. Enter hempcrete – a carbon-negative bio-composite building material with the potential to wind back the clock on climate change. However, due to misguided perceptions of hemp and the laborious construction process, only six hempcrete homes have been built in New Zealand as of January 2021 (Hemp Building Association New Zealand, 2021). While hempcrete does not require highly skilled labour – meaning almost anyone can do it – this can be a barrier to prospective clients and builders looking for a familiar construction method with a guaranteed outcome. Yet, if we continue building as we are, we are guaranteed irrevocable environmental destruction.

Counterintuitively, making a building warm, dry, and comfortable is seen as an obstacle to pure architectural expression. It is commonly perceived that meeting the building code is a mark of quality (BRANZ, 2021, p.4) and architects in New Zealand typically aim only to meet the minimum standards (New Zealand Business Council for Sustainability Development, 2008, p.5). As a result, 300,000 homes in New Zealand are uninsulated, cold, and damp (Habitat for Humanity New Zealand, 2019). This is because architecture is still heavily reliant on standardised building materials, mass manufacturing, complicated assemblies, and linear, regular geometries (Oosterhuis, 2012). These perpetuate cookie-cutter houses, leaky homes, high demand for skilled labour, and limited architectural expression.

However, recent advancements in robotic fabrication as a result of the Fourth Industrial Revolution have enabled architects to utilise technologies such as cyber-physical systems and parametric mass-customisation to efficiently fabricate bespoke designs, untethering architecture from its planar constraints and democratising design (Hack & Lauer, 2014; Greater Chattanooga, 2016). By combining robotic fabrication and hempcrete construction, exceptional building performance and design freedom can coexist without compromise, all the while reducing the construction industry's carbon footprint and doing right by our planet. This thesis explores how robotic fabrication can increase architectural expression in hempcrete construction to make carbon negative construction a more enticing option for those looking to build.



How can ***robotic fabrication*** increase ***architectural expression*** in ***residential hempcrete construction***?

1.2.0 Research Question

"How can ***robotic fabrication*** increase ***architectural expression*** in ***residential hempcrete construction***?"

1.2.1 Aim

The aim of this thesis is to democratise architectural expression in residential hempcrete construction by harnessing robotic fabrication to achieve an unconventional geometric outcome that is uniquely a product of its process.

1.2.2 Objectives

- Understand the context and implications of robotics in architecture, the fourth industrial revolution, the quest for carbon neutrality, and hempcrete construction
- Gain an understanding and mastery of the material properties and construction methods of hempcrete
- Demonstrate how robotic fabrication can be utilised in an architecture and construction context to increase productivity and diversify outcomes for hempcrete construction
- Reflect on the process and identify opportunities and constraints of the developed system

1.2.2.1 A note on carbon emissions

In his 2021 book *How to Avoid a Climate Disaster*, Bill Gates argues that:

> *The climate is like a bathtub that's slowly filling up with water. Even if we slow the flow of water to a trickle, the tub will eventually overflow. Setting a goal to reduce our emissions won't do it. The only sensible goal is zero.* (Gates, 2021, p.10)

Hempcrete is a carbon-negative construction material; however, this advantage mustn't be made redundant by other material or design choices within a proposed workflow. In line with what Gates (2021) and the IPCC (2021) say, merely reducing carbon emissions compared to other construction methods is insufficient. Good architecture considers and responds to context, and the bathtub analogy describes the context of the world we inhabit. As such, it is imperative that this thesis produces a carbon-neutral outcome.

Green Meets Machine assumes that the carbon emissions of the robot have a negligible impact on any workflow. Many promising studies have been conducted on minimising the energy consumption of robotic arm movements (Mohammed et al., 2014; Shah et al., 2019; Mostyn et al., 2020 & Vysocký et al., 2020) and this energy has the potential to be sustainably sourced. Furthermore, the embodied carbon of the robot itself is a fixed amount which will eventually be offset as it can theoretically fabricate infinite carbon-negative outcomes.

“The only sensible goal is ***zero***.

- Bill Gates

1.3.0 Scope

Green Meets Machine develops a hybrid workflow whereby the robotic arm works with a human labourer to produce a non-standard outcome for hempcrete construction (fig.2). An architectural outcome and associated workflow are developed through material testing, robot testing, modelling and simulation, and speculative design. A final design and workflow outcome is reached and documented accordingly.

This thesis aims to address a gap in existing literature by combining the two fields of hempcrete construction and robotic fabrication to achieve architectural expression. The research explores the materiality of hempcrete construction and its constituent parts to optimise it for robotic fabrication while maintaining net carbon negativity. The construction of a traditional hempcrete wall element aids the author's understanding of the materials.

Thermal and acoustic performance testing are outside the scope of this thesis. Rigorous structural analysis would strengthen the argument of the developed system; however, this is also outside the scope. Due to time and resource constraints, this thesis prioritises exploring the structure's geometric form over constructing a full-scale prototype. The author acknowledges that structure informs geometry and thus is a critical consideration within the system; however, this thesis's architectural outcomes seek only to support their own weight. While not within the scope of this thesis, there is potential for ongoing research into the structural, thermal, and acoustic performance of the developed system.

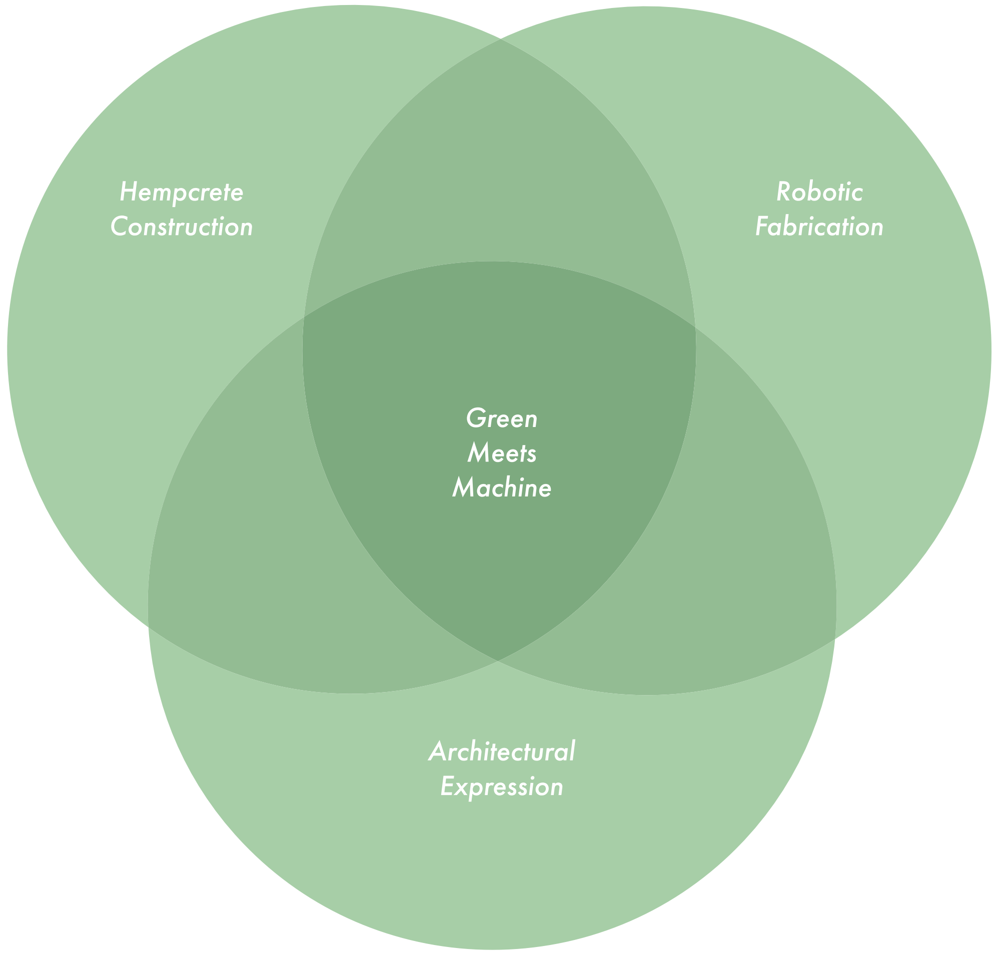


Figure 2: Green Meets Machine addresses the intersection of hempcrete construction, robotic fabrication, and architectural expression

1.4.0 Methodology

Design science research dictates the methodology of this thesis. Similar to – and often encompassing – action research (Collatto et al., 2017, p.250), design science research involves the development of an artefact to solve a specific problem and the evaluation of said artefact to extrapolate knowledge applicable to a wider context (Hevner, 2004, p.75 & Collatto et al., 2017, p.244). The researcher creates knowledge by reflecting on design rather than conducting design (Collatto et al., 2017, p.243). Design science research was initially criticised for lack of rigour (Carstensen & Bernhard, 2018, p.87), making evaluation and critical analysis imperative for this thesis. The main difference between design science research and natural science is the iterative process. Iteration in natural science is confounding as it changes multiple variables at once and makes the results unclear. Conversely, it is necessary in design science research which is about problem-solving rather than hypothesis testing (Kuechler & Vaishnavi, 2008, p.496). Design science research aims to refine or extend the kernel theories from which the research draws. Kuechler and Vaishnavi (2008) assert that creating a design theory through iterative development and evaluation of an artefact is directly linked to the refinement of its kernel theory (p.489).

The research follows Kuechler and Vaishnavi's design science research method (2008) (fig.3). Firstly, background research is conducted into principles and precedents from which suggestions are extracted and synthesised in a framework for robotic fabrication of hempcrete construction. These suggestions are direct extrusion and structure and formwork. Artefacts are developed for direct extrusion before being critically analysed and the research returns to the problem awareness stage. From here, a structure and formwork artefact is developed. Evauation encompasses the structural simulations in Fusion 360 for the first iteration of structure and formwork. Circumscription allows the author to approach the problem from a different angle, enabling the development of a plywood structure and formwork artefact. Robotic testing of joining details fulfls the evaluation requirement for this iteration, and subsequent conclusions are drawn.

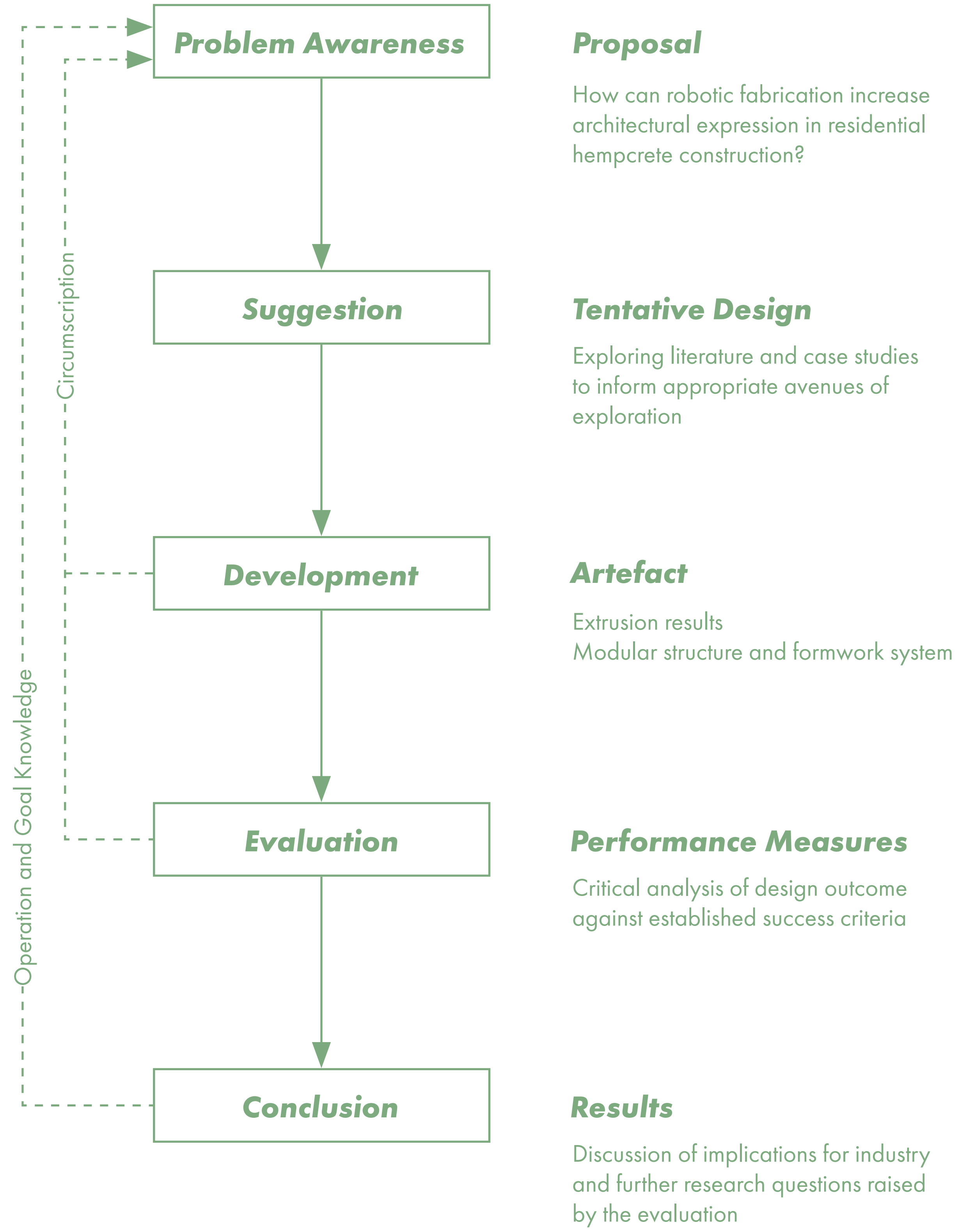
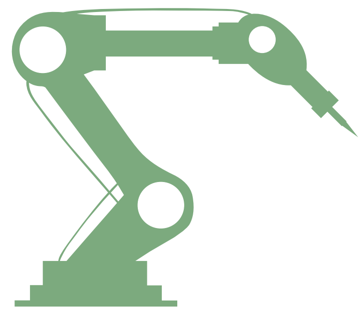


Figure 3: Methodology diagram adapted from Kuechler and Vaishnavi (2008)

As per design science research, the evaluation stage is where new knowledge is created. The use of design science research in this architecture thesis is validated by Aburamadan & Trillo (2020), the first authors to apply the design science research methodology to the development of an architectural artefact. They argue that "design science can be considered a novel framework for supporting the articulation of a scientifically sound architectural design strategy" (Aburamadan & Trillo, 2020, p.217).

There are two significant advantages of using the robotic arm as opposed to task-specific computer-controlled machinery. The first is the 6-axes of rotation that allow the robot to rotate around different angles on the same toolpath to create more complex outcomes. The second is the ability of the robot to carry out a multitude of different tasks depending on which end effector it is equipped with (Willmann et al, 2018). Due to these advantages, robotic fabrication increases the scope of design that architects can achieve compared to fabrication with task-specific machines. The robot is an integral part of this research as it has the unique ability to increase design freedom and workflow efficiency of hempcrete construction.

Simulation and modelling methods are a significant part of this thesis via Rhinoceros 3D (Rhino) and the Grasshopper visual scripting add-on. Rhino and Grasshopper bridge the gap between architecture and fourth industrial revolution technologies by enabling designers without a background in coding to access robotic fabrication by stringing together a series of components. In *Simulation research methods*, Kevin Dooley states that – while other research methods attempt to analyse and evaluate phenomena that have already occurred – simulation intends to predict what is likely to happen when certain variables are brought together (2002). It asks "what if?" rather than "what happened?" (Dooley, 2002). Of all the possible purposes of simulation in design science research, this thesis utilises computational simulation as a method of evaluation. Before engaging the robotic arm, the proposed toolpath for the robot to follow is simulated through Grasshopper and HAL to ensure there are no errors and the robot will operate as expected. Likewise, the structural simulation phase in Chapter 5 uses Fusion 360, another modelling and simulation software, to compare different framing designs and evaluates their performance to inform the design process. Furthermore, the final design outcome of this thesis is developed, explored, and presented through simulation and modelling.



TWO

LITERATURE REVIEW

2.1.0 Hempcrete

Hempcrete (fig.4) is a bio-composite building material comprised of hemp hurds mixed with a lime binder. While there is evidence that the hemp plant was used in construction as far back as the 6th century (Souza, 2020; Özdamar, 2021), hempcrete in its current form originated in France in the 1980s as an infill to repair damaged medieval half-timbered buildings (fig.5). Before the invention of hempcrete, surface repairs were conducted using Portland cement, which is not vapour permeable. As per Steve Allin (2005), "this meant the walls could no longer breathe and as a result moisture built up, causing the infill to swell and crumble and the render to pop off" (p.33). It was discovered that the cellulose properties of hemp hurds enabled vapour permeability when mixed with a lime binder to form a bio-composite building material. And thus, hempcrete was born. It was not long before the technology was used for new-builds due to its high thermal performance and insulative properties (Allin, 2005). Hempcrete offers advantages over other forms of sustainable construction. It has a better thermal performance than clay construction and better moisture resilience than straw-bale construction due to its cellulose properties (Bedlivá & Isaacs, 2014; Hemp Technologies, 2010). Hempcrete is not concrete in that it is not structural and is typically cast in forms around a structural timber frame. Despite this, it does provide some torsion resistance when used as an infill and prevents weak axis buckling of the timber frame (Mukherjee & MacDougall, 2013). Most importantly, hempcrete is carbon negative, storing 35kgCO_2/m^2, and continues to absorb carbon from the atmosphere for at least 100 years (Boutin & Flamin, 2013, p.308).

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Figure 4: Conventional hempcrete construction (Global Hemp Group, 2021)

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Figure 5: La Maison d'Adam in Angers, France, a medieval half-timbered building renovated with hempcrete infill in 1995 (Xorge, 2013)

2.1.1 Hemp

Before becoming marginalised in the 20th century due to its association with marijuana, hemp was used worldwide for various purposes. The first plant cultivated in China between 4000-6000 years ago, hemp's versatility lent itself to many applications, including clothing, textiles, rope, and paper (Demir & Doğan, 2020). The plant can grow to 4 metres in height in 12 short weeks, requires no herbicides or pesticides, and can be harvested up to four times per year. Subsequently, its carbon sequestration ability is four times greater than a traditional tree forest (Bedlivá & Isaacs, 2014). The hurds used in hempcrete come from the woody core of the plant's stem and are a by-product of hemp seed or fibre extraction (fig.6). Before the invention of hempcrete they were used primarily as animal bedding. A decorticator machine that requires little energy and no heat to operate extracts the fibre from the hurds (Mukherjee & MacDougall, 2013). Hemp has a small ecological impact due to nitrogen fertilisers used in its cultivation, but this varies depending on where it is grown (Pervaiz & Sain, 2003, p.24; Boutin & Flamin, 2013, p.308). Allin (2005) argues that seasonal crop rotation systems provide an ecologically friendly alternative to chemical fertilisers, as "hemp can be grown after a nitrogen fixing, green fertilising crop such as clover or alfalfa" (p.26).

A significant benefit of hemp is that it can be grown in most climates except where it is very cold (Magwood, 2016, p.6), which gives hempcrete construction almost anywhere the potential to be made from locally sourced materials. Unfortunately, the lack of infrastructure means this has not been possible in New Zealand, with early hempcrete projects importing hurd from overseas, negating its carbon negativity (Hemp Building Association New Zealand, 2021). Recently, Hemp NZ – the largest hemp producer in Aotearoa – partnered with NZ Natural Fibres and opened Australasia's first fibre facility in Christchurch (Stiles, 2021). As per Hemp Building Association New Zealand (2021), "the opening of the decortication factory in Christchurch is a game-changer for the newly emerging New Zealand hemp construction industry." The hurd produced here as a by-product of fibre extraction is sold to a Wanaka hempcrete builder (Stiles, 2021). However, there is little demand for hempcrete construction in New Zealand at present. In an interview with Carol Stiles of RNZ, Hemp NZ's CEO Dave Jordan said the hemp industry must focus on infrastructure and education if we are to see mainstream adoption of the stigmatised plant (2021). If the demand for hemp products in New Zealand grows, supply will rise to meet it.

Figure 6: Hemp hurds, the woody core of the hemp plant

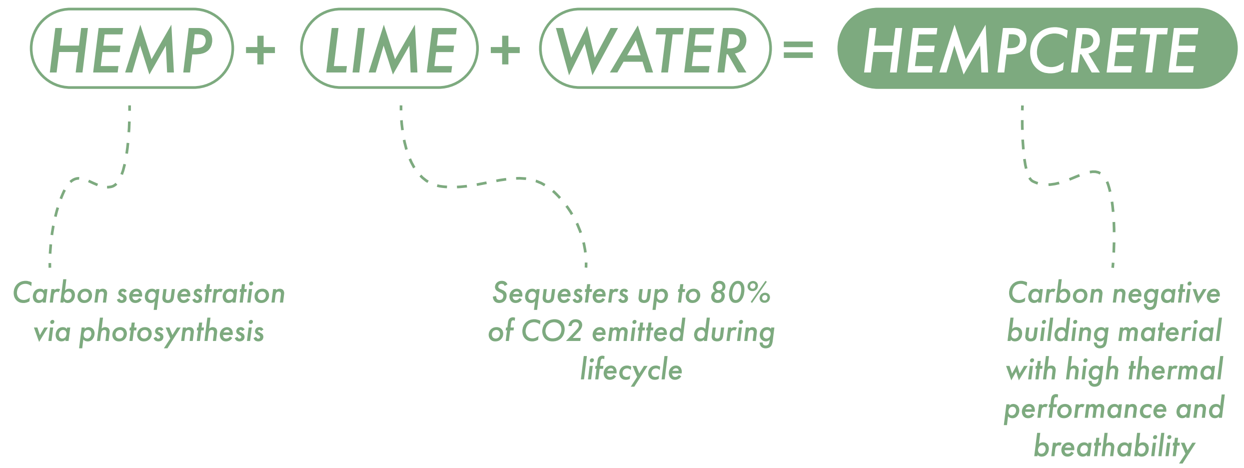

Figure 7: A carbon-negative bio-composite

2.1.2 Lime

The lime cycle, depicted in figure 8, enables us to understand how hempcrete construction can be carbon negative. While the processing of lime mortar requires heat, its carbon emissions are less than that of Portland cement, primarily because it only needs to be fired to 900°C as opposed to 1450°C (Busbridge, 2009). Furthermore, the amount of carbon emitted in the calcination stage is sequestered as it carbonates back into limestone (Florentin et al., 2017). First, limestone is fired to make quicklime, which is then slaked with water to produce hydrated lime. Hydrated lime dries through carbonation, turning back into limestone as it absorbs CO_2, and thus the cycle continues. Adding more water to hydrated lime makes lime putty, which slows down the process of carbonation due to its higher H2O content. Ultimately, the carbonation cycle is what enables hempcrete to be carbon negative and provides the opportunity to reduce the carbon emissions of the construction industry.

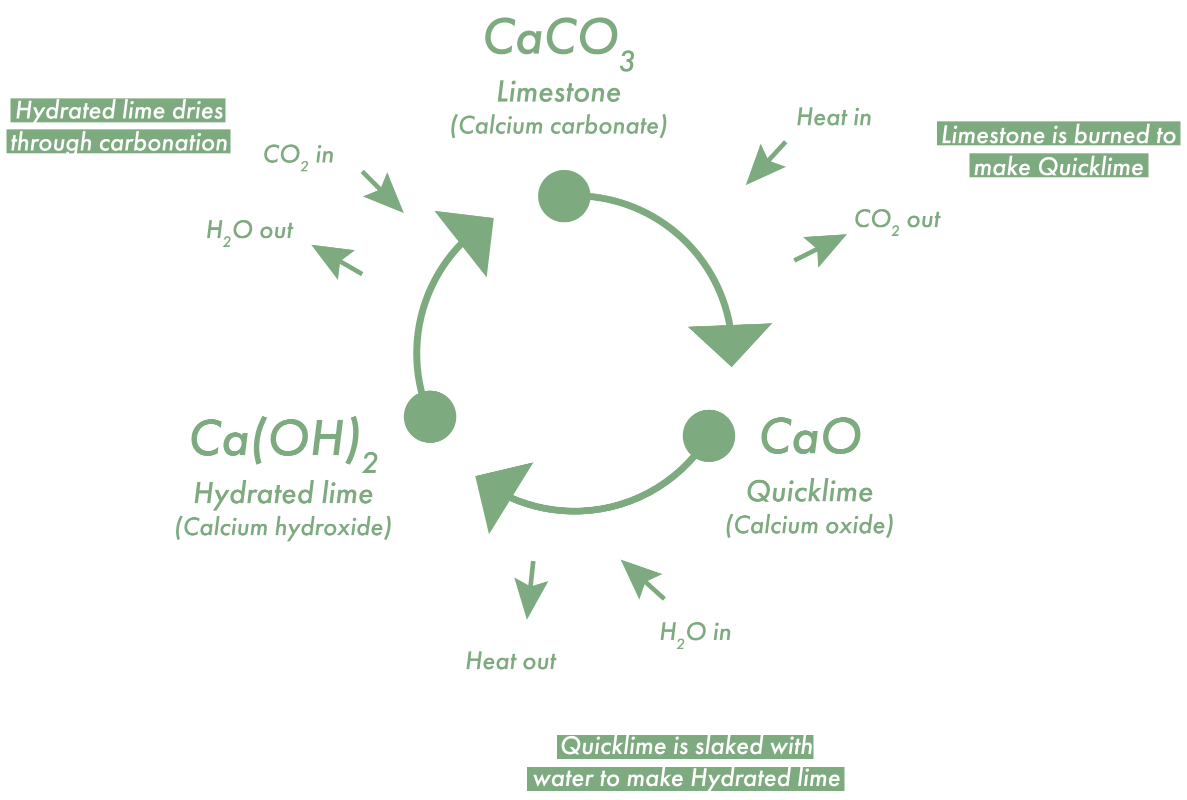

Figure 8: The Lime Cycle

2.1.3 Construction Process

The first hempcrete house in New Zealand was built in Taranaki in 2014 (Strongman, 2014), but only six hempcrete homes have been built in New Zealand as of January 2021 (Hemp Building Association New Zealand, 2021). This is likely due to misinformed perceptions of the hemp plant, with many associating it with its psychoactive cousin, marijuana. Or perhaps the apparent hesitation is due to the time-consuming and laborious hempcrete construction process.

Hempcrete is typically cast by hand in forms around a timber frame (fig.9). The forms are screwed to the frame, the hempcrete is deposited into the cavity and tamped down before the forms are relocated higher to build the wall up in gradual layers while enabling workers to reach in and tamp easily (Allin, 2005). As such, it is a slow process. Hempcrete can also be sprayed – a much faster method – however, this requires specialised equipment, making it inaccessible for mainstream builders. Spraying also requires more lime binder so that the hempcrete can stick to its host wall (Williams et al., 2017), which increases its embodied carbon.

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Figure 9: Hand placed hempcrete cast around a central solftwood frame (Sparrow, 2014)

2.2.0 Robotics in Architecture

Revolutionary innovations and technological advancements have widened the scope of possibility within architecture throughout history, reshaping our built environment over many years (Gross & Green, 2012, p.28). Just as the invention of ultra-strong Portland cement and BIM were revolutionary at their respective times, robotics will have a profound effect on architecture and construction (HMC Architects, 2019). Robotic arms have been utilised in industrial settings since the 1970s (Papageorge, 2018) and are typically used to carry out repetitive tasks with greater precision and efficiency than a human worker (Davila Delgado et al., 2019). They are responsible for automating many tasks that were once performed by humans (HMC Architects, 2019). The ABB IRB6700 industrial robotic arm used in this thesis can run specific commands with little effort via Grasshopper visual scripting. Its six axes of motion enable the robotic arm to access any point within the limits of its set envelope, limited only by its reach. Unlike typical 3D printers and CNC machines, which only operate on 2 or 3 axes, the robot can produce complex, fully formed geometries via additive or subtractive manufacturing. Robotic arms have the potential to revolutionise architecture if they are implemented more readily in the construction industry. It is time to move on from the manual stick-construction building methods that inhibit architectural expression and contribute to construction waste (Papageorge, 2018; Finch, 2019). The onus is on architects to adopt the technologies of the Fourth Industrial Revolution and design for robotic fabrication, rather than continuing to rely on conventional construction.

2.2.1 The Fourth Industrial Revolution

Architecture and construction are heavily reliant on the technology of the past (Oosterhuis, 2012). There have been three industrial revolutions since 1784, and it is widely believed that we are currently experiencing the fourth (Schwab, 2017) (fig.10). The second industrial revolution occurred in 1870 and brought about mass production – a cornerstone of modern architecture and construction (Davis, 2016). However, traditional mass-manufacturing processes limit the potential for architectural expression as they ensure that all units are standardised (Hack & Lauer, 2014). Recent advancements in robotic fabrication as a result of the Fourth Industrial Revolution have opened up a range of possibilities for mass-customisation within the construction industry (Oosterhuis, 2012; Hack & Lauer, 2014). Ultimately, robotic fabrication through algorithmic control of mechanical systems has the potential to revolutionise how we design and inhabit the built environment.

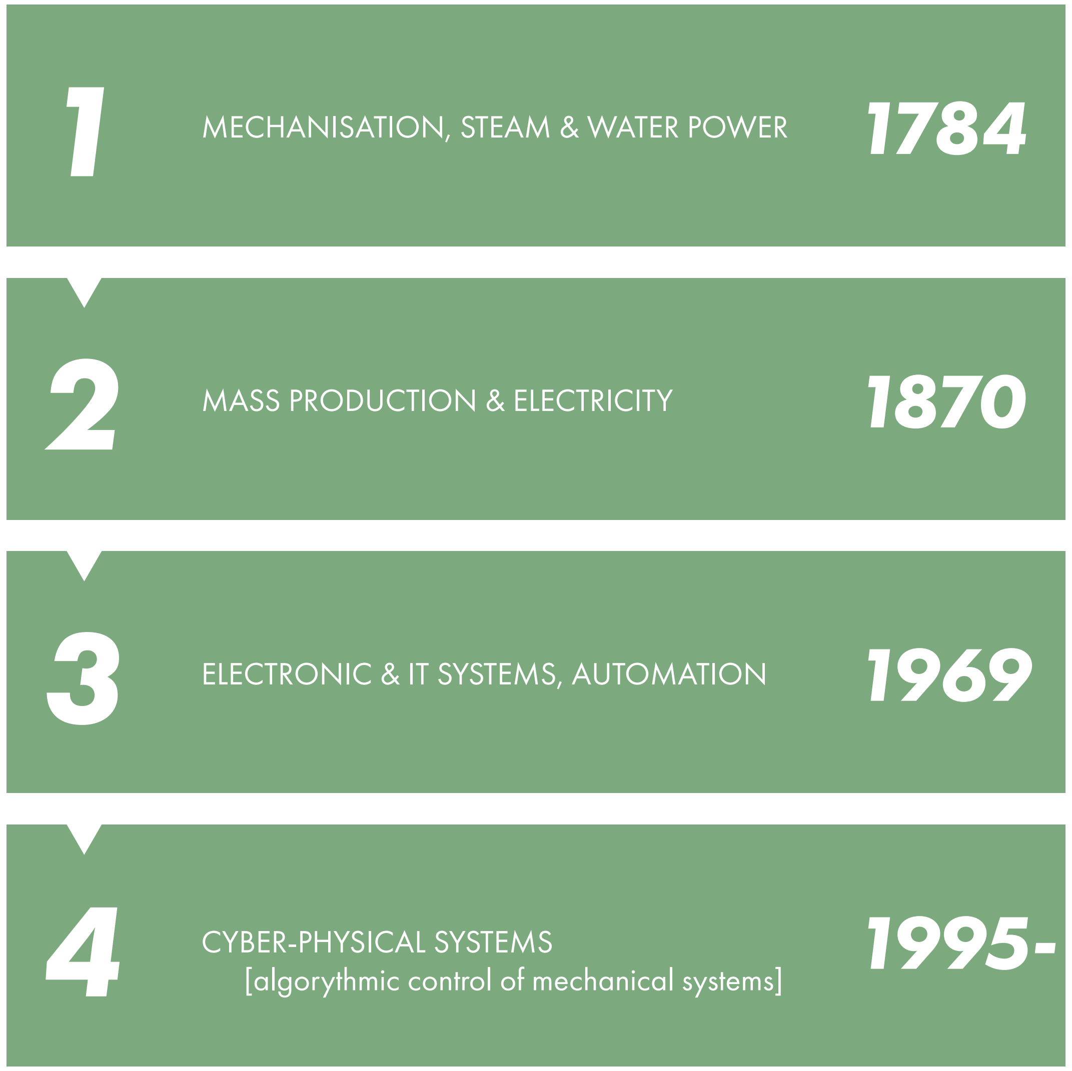

Figure 10: The four industrial revolutions

2.2.2 Robotic Fabrication Methods

Robotic fabrication methods for architectural application can be divided into two main categories – additive manufacturing and subtractive manufacturing. Additive manufacturing refers to robotic fabrication processes that build up material to achieve a formal outcome, while subtractive manufacturing refers to robotic fabrication processes that remove material from an object to achieve a formal outcome (Rathbone, 2018). Additive manufacturing, therefore, is inherently less wasteful than subtractive manufacturing, although this doesn't necessarily mean it is guaranteed to have less embodied carbon. Ultimately, the material choice determines the environmental impact of robotic fabrication. CNC clay routing, for example, is a subtractive manufacturing process while concrete 3D printing is an additive manufacturing process, but – due to the higher embodied carbon of concrete and the reusability of subtracted clay – the subtractive process has a lesser environmental impact in this instance.

Mass customisation is another advantage of robotic fabrication. Parametric design tools allow designers to capitalise on the mass customisation abilities of the robot by quickly iterating through design outcomes for fabrication. The reprogrammable nature of the robotic arm separates it from mass-manufacturing machines that are programmed to carry out a single repetitive task. Not only can robotic fabrication realise non-standard geometries, but it can fabricate virtually any form just as efficiently. This is the notion of democratised design (Greater Chattanooga, 2016). Mass customisation through robotic fabrication, or "complexity for free" (Gibson, 2017), leads to greater diversity of design outcomes, enabling increased architectural expression through geometric variation.

2.2.3 Robot-Human Collaboration

Fully automated robotic construction systems have largely failed as they automate tasks that are more efficient to perform manually (Hack & Lauer, 2014). Robots are good at tasks that require repetition and precision, whereas humans are good at decision-making and problem solving (Oosterhuis, 2012). It is widely agreed that the future of robotic fabrication in architecture involves robots working alongside humans to achieve a unified outcome greater than what either could achieve alone (Picon, 2014; Hack & Lauer, 2014). This notion is put into practice by freeform 3D printing specialists, Branch Technology. Co-founder Chris Weller says, "3D printing is really good at creating shape. Why do anything more with it than that? Why try to make 3D printing into what other conventional building methods already do very well?" (Greater Chattanooga, 2016, 0.56-1.08). As such, robotic fabrication informs the architectural expression of Branch Technology's designs, and conventional methods allow it to be implemented in a real world architecture.

Currently, robots are seen as slaves, automating once-manual tasks and putting people out of jobs (HMC Architects, 2019). There is a difference between automating a construction process and designing specifically for robotic fabrication. Rather than introducing robots at the construction phase, architects must begin designing for robotic fabrication. Mario Carpo, Reyner Banham Professor of Architectural History and Theory at the Bartlett School of Architecture, writes that "a meaningful building of the digital age is not just any building that was designed and built using digital tools: it is one that could not have been either designed or built without them" (Carpo, 2012, p.8). Robotically-native architecture should produce outcomes previously unachievable with a solely human workforce.

2.3.0 Precedent Studies

The following three precedents utilise robotic fabrication methods for concrete or bio-composite construction. The strengths, weaknesses, and implications have been critically analysed to inform a suggestion for the robotic fabrication of hempcrete construction as per Kuechler and Vaishnavi's design science research model (2008). The final precedent, Table Cape Hemp Home, is an example of architectural expression in hempcrete construction. The strengths, weaknesses, and implications of its architectural form and the methods used to achieve it are discussed and evaluated.

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Figure 11: Mesh Mould - freeform 3D extrusion for concrete formwork and reinforcing (Gramazio Kohler Research, 2016a)

2.3.1 Mesh Mould, Gramazio Kohler Research

Mesh Mould (fig.11) combines traditional construction methods with freeform printing technology to produce a reinforced concrete wall in which the reinforcing and formwork are one freeform 3D printed system (Gramazio Kohler Research, 2016a). The system acts as both a reinforcing and bleeding formwork that the concrete is pumped into and then spread smooth on the surface by hand with a trowel, merging robot and human workflows.

2.3.1.1 Strengths

- Mass customisation via robotic fabrication enables non-standard geometries without labour-intensive conventional bespoke formwork.
- Rather than automating the fabrication of conventional bespoke formwork, robots and humans work together in a new hybrid workflow to achieve the desired result via different means.

2.3.1.2 Weaknesses

- Latest iteration of Mesh Mould is an on-site incremental welding workflow. Dörfler et al. (2019) state that "the poorly structured nature of building sites requires mobile robotic systems to be equipped with advanced sensing and control solutions to contend with uncertain conditions found on-site" (p.53).
- Conflicts with the notion of allocating tasks based on the respective strengths of humans and robots.
- Still more practical than off-site fabrication and subsequent transportation of large reinforced concrete wall elements.

2.3.1.3 Implications

- Mesh Mould enables architectural expression in reinforced-concrete construction; this thesis aims to develop a workflow for greater architectural expression in hempcrete construction.
- Achieved through a common construction 'language' that allows humans to pick up where robots left off.
- The intention should not be to make the robot conduct tasks that a human can do more efficiently but rather to utilise the robot for tasks that are difficult or unachievable by humans to expand the scope of construction.

2.3.2 TECLA, MC A & WASP

TECLA is an extruded clay dwelling designed and prototyped by Mario Cucinella Architects and WASP in Italy. It takes only 200 hours to print, and the clay is sourced directly from the construction site. The result is a striking dome-shaped ensemble with ribbed walls that is uniquely a product of clay extrusion for sustainable construction.

2.3.2.1 Strengths

- Acknowledgment that the curved envelope geometry is not conducive to standardised furniture, which is accounted for by integrating amenity.
- The form is inherently structural due to the ribbed envelope, which seems to provide adequate bracing perpendicular to the wall.
- Horizontal striations resulting from layer-based additive manufacturing give the dwelling an aesthetic unique to robotic fabrication: the architecture is influenced by and a product of the process that created it.
- While restricting the ability of fully enclosed forms, the step effect - an inherent implication of layer-based additive manufacturing - provides an opportunity for skylights which the architects have taken full advantage of (fig.12).
- Sourcing clay from construction site avoids transport related carbon emissions.

2.3.2.2 Weaknesses

- TECLA was built in-situ in Italy in a hot, dry climate (Parkes, 2021). Although it claims to be weather resistant, it is unproven in wet conditions where the clay could be affected by humidity or moisture.
- While clay-based construction is carbon-neutral, it is a non-renewable resource.
- The carbon emissions inherent to the operation of the gantry printer makes the construction carbon positive, conflicting with the commitment of this thesis to a carbon-neutral construction workflow.

2.3.2.3 Implications

- Provides an insight into the aesthetic and spatial properties of a layer-based additive manufacturing construction workflow.
- Demonstrates the speed and consistency of layer-based 3D printing with clay.
- Shows how geometry can influence structure – while hempcrete itself is not structural, 3D printing can produce ribbed walls and dome forms that seemingly increase its load-bearing capacity.

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Figure 12: *Layer-based extrusion of dome forms results in skylight design (WASP, 2019 [edited])*

2.3.3 Robotic Clay Molding, Gramazio Kohler Research

Robotic Clay Molding was a workshop at IAAC Barcelona in 2012 where students developed physical and digital tools to shape the surface of a block of clay contained in a shallow tray as a reusable, minimum-waste formwork for the fabrication of mass-customisable concrete panels (Gramazio Kohler Research, 2016b) (fig.13,14).

2.3.3.1 Strengths

- Provides a waste-free formwork for the mass-production of highly articulated concrete panels.
- Rejects conventional formwork that is subtractive or material-intensive and cannot be easily reconfigured.
- Provides an opportunity for a reusable, reconfigurable formwork into which the designer can imprint or manipulate the surface of the clay to generate a desired outcome.

2.3.3.2 Weaknesses

- The clay is only manipulated on one horizontal plane, resulting only in the surface texturing of the resultant concrete panel.
- The overall dimensions of the resultant panel are constant, having no spatial implications on a proposed architecture. It merely textures the surface of a simple concrete panel.
- While this is interesting, there is more potential in the manipulation of geometric form and the architectural implications of a reusable, reconfigurable formwork system.

2.3.3.3 Implications

- Spatial qualities could be influenced by combining the Robotic Clay Molding and TECLA workflows and utilising layer-based clay extrusion to create geometrically diverse 3D forms for prefabricated hempcrete construction.
- The reusability of unfired clay maintains the carbon-neutral credentials of traditional Hempcrete construction while foreseeably allowing greater freedom of form.

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Figure 13: *Robotic Clay Molding workshop run by Gramazio and Kohler (Gramazio Kohler Research, 2016b)*

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Figure 14: *Robotic Clay Molding (Gramazio Kohler Research, 2016b)*

2.3.4 Table Cape Hemp House

Dr Roger Bodley's hemp home in Table Cape in the northwest of Tasmania was the first hempcrete house built in the southern hemisphere (Wood, 2010). As such, it is a significant milestone in the quest for carbon-neutral construction.

2.3.4.1 Strengths

- Combines architectural expression and high-performance housing in a carbon-neutral construction.
- Proves that hempcrete construction has the potential to form irregular, curvaceous geometry.

2.3.4.2 Weaknesses

- Encountered many difficulties during the construction process. Leaching, cracking, warping, and shrinking due to poor moisture management had adverse effects on the finished home (G. Flavall, personal communication, April 20, 2021).
- While the final design is slightly curved, initial concept plans were significantly more geometrically ambitious but could not be realised (International Hemp Building, 2018) (fig.15).

2.3.4.3 Implications

- Table Cape is effectively one curved structure while this thesis aims to achieve many curves.
- Green Meets Machine will focus on the human-scale architectural expression rather than the silhouette of the building.

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Please refer to the figure list for further details.

Figure 15: *Table Cape Hemp House (Hempcrete Australia, 2012; International Hemp Building, 2018 [edited])*

2.4.0 Suggestions

Drawing from the synthesis of existing knowledge conveyed in the literature review and learnings through analysis of relevant case studies, the following roadmap shows the suggestions this design science research will explore—all suggestions centre around creating and developing a hybrid workflow for the robotic fabrication of hempcrete construction.

Hempcrete bricks are already a well-established method of hempcrete construction (Noe, 2019; IsoHemp, 2019). As such, the decision has been made to limit exploration in this thesis to direct extrusion and structure and formwork.

The aim of this thesis is to democratise architectural expression in residential hempcrete construction by harnessing robotic fabrication to achieve an unconventional geometric outcome that is uniquely a product of its process.

Direct Extrusion
3D printing a self-supporting structure

Structure & Formwork
Robotically fabricated components for filled formwork

Modular Bricks*****
Robotically fabricated and assembled bricks

Problems addressed: carbon-zero construction, skill shortage, housing shortage, architectural form and character.

*Already commonplace in industry so not explored in this thesis

2.4.0.1 Hempcrete Bricks

While hempcrete bricks can foreseeably be manufactured and assembled to form an architecture by a single robotic arm, this system has inherent problems. Hempcrete is not a structural building element, requiring an internal structure to support it. For bricks to work, they need a structural host, which limits their geometric potential. As a result, existing hempcrete brick products are typically utilised primarily for their insulative properties, overlaid on timber-framed walls. There are some structural hempcrete bricks on the market, but these are already developed far beyond what is achievable with the time and resources available for this thesis (Noe, 2019).

Practically, a mortar would have to be used to bind the bricks together as they are laid (fig.16). In a hybrid workflow, the human worker is best qualified to spread the mortar while the robot places the bricks. This alternating workflow disrupts the ability of the robot to operate efficiently in a closed-loop system, as it introduces uncertainty due to the limited accuracy of the human worker.

Despite the greater articulation of form achievable by a system of small, modular components, the finished aesthetic of such an architecture would be negated by a finishing coat of lime render, which would hide the visual interest of the bricks. The wall would look homogenous and smooth, much like many existing hempcrete and other carbon-conscious material dwellings. Direct extrusion or structure and formwork can impart the influence of the robot onto the architectural outcome more explicitly, which justifies exploring them over bricks in the pursuit of uniquely robotic architectural expression.

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Please refer to the figure list for further details.

Figure 16: *Mortar bonds hempcrete bricks (IsoHemp, n.d.)*

2.4.1 Success Criteria

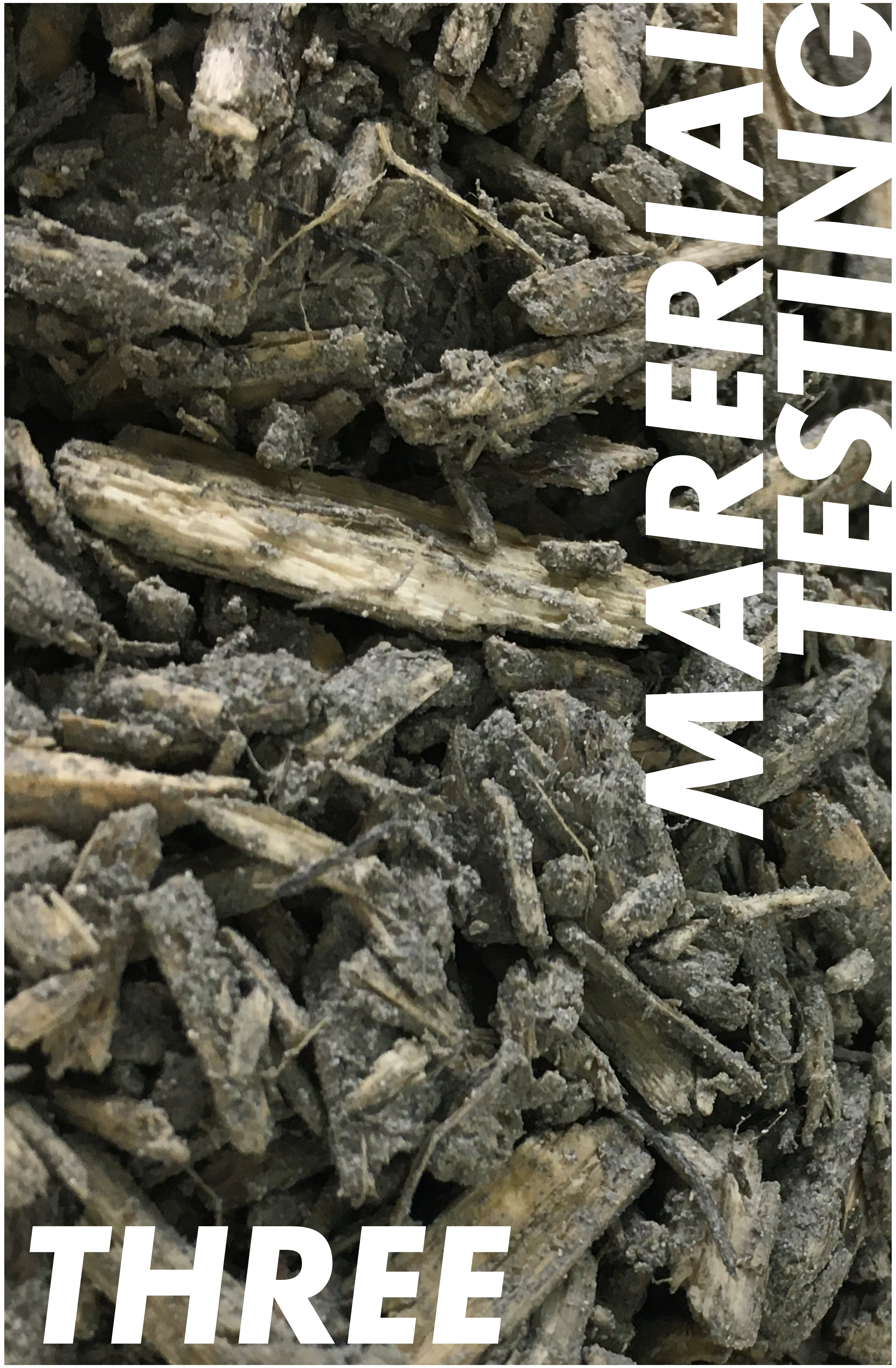
To be deemed successful, outcomes of this thesis must:

- Demonstrate how robotic fabrication can be utilised in an architecture and construction context to increase productivity and diversify outcomes
- Make hempcrete construction more accessible by assisting human labour
- Make hempcrete construction more desirable by increasing design potential
- Maintain the carbon negativity of hempcrete construction
- Produce an architectural outcome that is unique to the robot and improves upon conventional outcomes by answering the question – how would a robot build a house of hemp?

Figure 17: ABB IRB6700 Robotic Arm

THREE

MATERIAL TESTING



3.1.0 Introduction

This chapter details the experiments conducted regarding material testing to determine the extrudability of a hempcrete composite. Via email correspondence with Greg Flavall of Hemp Technologies Global (April 20, 2021), it was established that 3D printing with hempcrete has been attempted by many before – including when he was involved in building the Table Cape Hemp House - and proven unsuccessful. This is due to the "snowball" consistency of a typical hempcrete mix, compared to the slurry consistency of fresh concrete that enables it to be "printed" (G. Flavall, personal communication, April 20, 2021). The high moisture content of a hemp-lime mix required to produce a slurry, combined with the ability of the hemp hurds to hold water and the sealing properties of the lime, inhibits the printed composite from drying below the 19% moisture content threshold required to prevent dry rot (G. Flavall, personal communication, April 20, 2021). The resultant product is not suitable for construction and needs significantly more research. The author acknowledges this and knows that the 9-month duration of this thesis and the limited resources available make it unlikely that a breakthrough will be reached. However, the idea of a 3D printed hempcrete construction cannot be ignored. Experimenting with the material to optimise extrusion has also helped provide a deeper understanding of how different variables affect the outcome of the mixture and resulted in a better understanding of the hempcrete material composition.

3.2.0 Slump Tests

As a starting point, slump tests were conducted as a visual determination of extrudability. A range of different mixtures was tested. The typical hempcrete construction mixture ratio of 4:1:1 by volume (hemp:lime:water) was used as a baseline measurement (G. Flavall, personal communication, April 20, 2021). As these mixtures were closer to the "snowball" end of the spectrum, they did not actually slump, and it was clear that they would not extrude. However, as this was the author's first hands-on experience with hempcrete, valuable insights were gained from these tests.

Figure 18: Various hemp-lime mixtures

3.2.1 Critical Analysis

It was evident that hurd size impacted the density of the mix and the aesthetic outcome of the tests. Operating on such a reduced scale (400ml cup) exacerbated any imperfections and highlighted the material behaviour. The weight varied noticeably with the lime binder ratio, which is significantly heavier than the hemp hurds.

SLUMP TESTS

Figure 19: Slump Tests

3.3.0 Hemp Processing

To make the hemp more conducive to a slurry mix as opposed to that of a snowball – and so that it would pass easily through the extruder nozzle without jamming – the particles needed to be significantly smaller. A 1000W food processor was purchased to chop the hemp hurds into smaller granules. Initially, dry hemp hurds were processed at high speed for 30-second intervals and examined between each interval. This was conducted in the WFADI workshop's high dust room, as the process produced a lot of dust that escaped the hopper every time the lid was removed.

Dry processing achieved little success. After eight total minutes of processing, the hurds varied greatly in size due to granular convection – whereby the smaller particles sift to the bottom and the larger particles rise to the top (fig.20,21). The larger fragments were sifted out, and the appropriately sized hurds were incorporated into a hemp-lime mixture.

Subsequently, four tests were conducted where hemp hurds were soaked in water in a ratio of 1:1 for 24 hours, 48 hours, 72 hours and 96 hours respectively. Once soaked, the hemp was processed in the food processor for five total minutes in 1-minute intervals. The results were significantly better than the dry processing. However, there was no discernible difference in the final granule size of the hemp across the 24-, 48-, 72- or 96-hour tests. As such, it was determined that 24 hours was sufficient for soaking the hemp hurds prior to processing.

Of note is the apparent effect of water content on the ability of the food processor to process the hemp. If there was too much liquid, the wet hurds tended to stick to the walls of the hopper, avoiding the spinning blade of the processor for the entire 1-minute interval. These hurds were manually scraped off the sides and pushed into the middle after each minute, but this made little difference as they seemed to immediately return to the side walls as soon as processing resumed. It was discovered that a drier mix meant that the hurds were less likely to stick to the walls and were chopped up by the blades at a higher frequency and more efficiently, resulting in a damp breadcrumb-like mixture.

Figure 20: Hurds before processing

Figure 21: Hurds after processing

Figure 22: Hemp hurds are chopped up in a food processor

3.4.0 Preliminary Extrusion Tests

Before using the robot, it was important to ascertain whether a particular mixture was likely to extrude. Preliminary extrusion tests were conducted via manual extrusion with a caulking gun. Mixtures were made up with the processed hemp, hydrated lime and water; packed into the caulking gun; the nozzle replaced, and extrusion attempted. It was immediately evident that the mix could not be forced through a funnel despite the size reduction of the hemp hurds. Even when the opening was increased, the cellulose nature of the hemp stopped it from extruding. Instead, this action merely squeezed the liquid from the mixture that had been absorbed by the hurds, leaving a compacted mass in the caulking gun tube and a pool of liquid on the bench.

Testing was continued with the nozzle removed from the caulking gun. Effectively, the shape of the extrusion would be predetermined inside the tube and merely pushed out, with no end effector to manipulate the shape of the extrusion. It was theorised that when translating this to a robotic workflow, a large PVC pipe with an elbow joint at the end would be used – as the elbow would maintain the diameter of the extrusion but restrict the flow of hemp-lime mixture to prevent it falling out unless actively extruded. Due to time and resource constraints, the existing WFADI concrete extruder was used in this thesis. With the nozzle removed, it has a tubular end that approximates the geometry of the caulking gun. Combined with the internal rotating auger, it was expected that the funnel-shaped hopper would not cause a blockage, and the hemp-lime mixture would instead pass smoothly through the extruder.

Figure 23: The first extrusion test in which the caulking gun was refilled multiple times

Figure 24: The extruded object is comprised of two and a half layers and forms a "C"

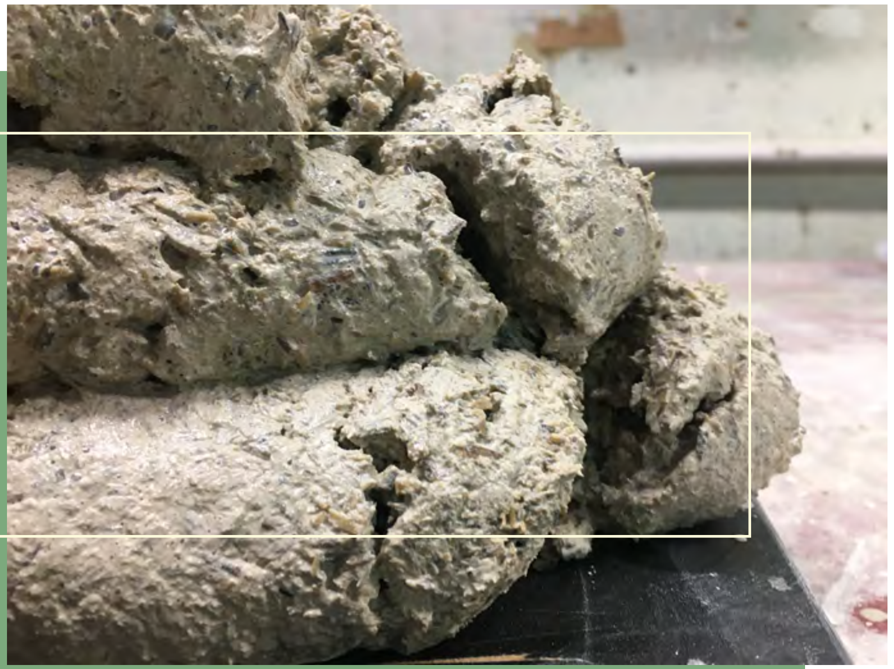


Figure 25:

The mixture would often crack coming out of the caulking gun, leading to variation in wall thichness and structural integrity

Figure 26:

Large chunks had a tendancy to crumble off, especially as the structure grew in height

Figure 27:

In some places the mixture was too wet, leading to less structural rigidity and more of a slump

3.5.0 Mixture Optimisation

The next step was to calculate the baseline ratio of hemp to lime to maintain the carbon zero credentials of hempcrete construction (Florentin et al., 2017). These calculations provided limitations for the material testing phase and ensured that the following experiments complied with the carbon-conscious research principle.

3.5.1 Simple Carbon-Neutral Ratio

Hemp hurds – prior to soaking – and hydrated lime were weighed at a volume of 400cm^3, and the resultant values were used to calculate the appropriate volume ratio for a baseline carbon-neutral mixture (see Appendix section 10.1.0 for calculations). For these particular variables, the ratio was calculated as:

1.91:1

Hemp:Lime

This ratio maintains the carbon-neutral credentials of hempcrete as a building material. However, this figure relies on 100% carbonation of the hydrated lime. In her Master's thesis that explored clay as a substitute for lime in hemp construction, Ruth Busbridge (2009) states that the lime's process emissions cannot be reabsorbed, only its calcination emissions:

> *Proponents of lime argue that it reabsorbs the carbon dioxide liberated from the raw limestone after construction and therefore the net CO_2 output is far lower than cement. However, at most 60-80% of the total CO_2 emitted is eventually reabsorbed and that is only if the lime fully carbonates. Furthermore, carbonation may take years to fully complete if indeed it ever does. Samples of lime mortars in ancient buildings have been shown to contain uncarbonated lime deep in the body of a wall.* (Busbridge, 2009, p.31)

While a 60-80% carbonation factor could be applied to the calculations, Green Meets Machine assumes that the hemp-lime mixture achieves 100% carbonation to give it the best chance of extruding successfully. Process emissions – which make up the other 20-40% of CO_2 – result from burning fossil fuels in the firing process. Although this might currently be standard practice, renewable energy sources will decrease and eventually nullify process emissions. Locally sourced agricultural biomass fuels, for example, are "considered carbon-neutral because the carbon released during combustion is taken out of the atmosphere by the species during the growth phase" (Chinyama, 2011, p.280). As such, it is expected that 100% of the lime's CO_2 can be sequestered. Additionally, the higher the lime content of the mixture, the more likely it is to extrude. The primary goal at this stage was to achieve an extrudable hemp-lime mixture.

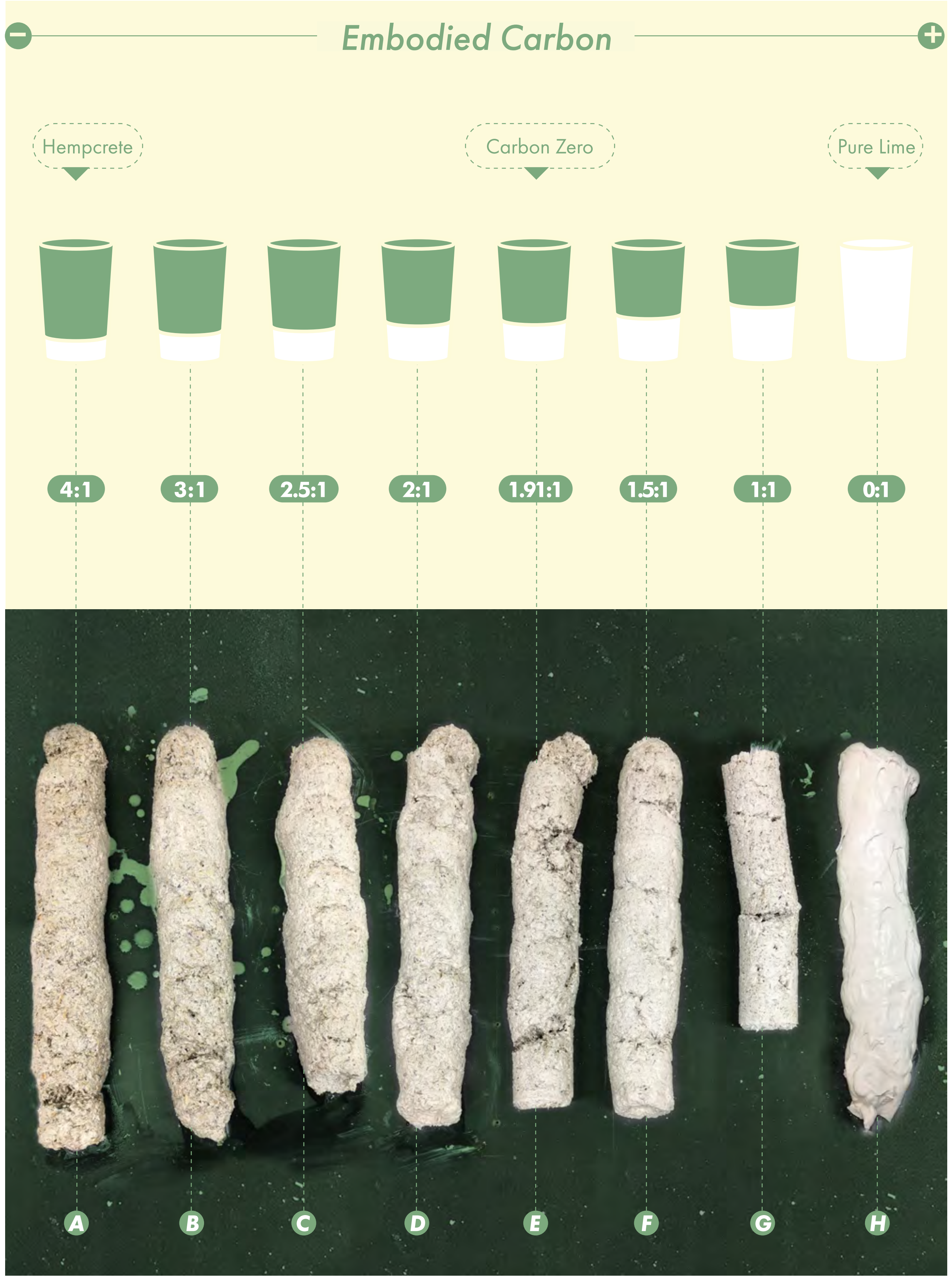


Figure 28: Testing different mixture ratios

3.5.2 Range of Extrudability

To observe the effect of lime in the mixture, eight different mixtures ranging from traditional hempcrete to pure lime plaster – including a carbon-neutral mixture – were set up to showcase a spectrum of outcomes (fig.28). Of particular interest were the two mixtures either side of the 1.91:1 hemp:lime carbon-neutral mixture – a 2:1 hemp:lime and a 1.5:1 hemp:lime mixture. The variation between the consistency of these three mixtures would indicate how much of a structural sacrifice mitigating the lime content of the mixture in an extruded hempcrete construction would be.

The tests were conducted and documented. While all the hemp had been soaked in a 1:1 hemp:water ratio, it was observed that the moisture content had more of an effect on the lime in the mixtures than on the hemp hurds, as hydrated lime reacts with water to form the lime plaster. In this particular experiment, changing the hemp:lime ratio also changed the lime:water ratio. As such, mixtures with a high hemp content were oversaturated, while the high lime content mixtures were crumbly. To fix this, two solutions were proposed: soaking the hemp hurds in the appropriate amount of water to produce the ideal lime binder, or squeezing the excess liquid out of the hemp hurds before adding to a pre-mixed lime plaster. First, however, the optimal lime:water ratio had to be determined.

Figure 29: The pure lime mixture cracked as it contracted during drying

Figure 30: 800cm³ of hydrated lime mixed with 300ml, 400ml, and 500ml of water respectively

3.5.3 Lime:Water Ratio

It was clear from experimenting with hydrated lime that the ideal lime:water ratio for a stiff lime plaster was somewhere in the vicinity of 2:1. Three containers were each filled with 800cm³ of hydrated lime before 300ml, 400ml, and 500ml of water were added respectively and combined by stirring with a knife. The 300ml mixture was too dry, and the 500ml mixture too runny, while the 400ml container was able to be mixed into a workable plaster (fig.30). Subsequent testing on different days revealed 2:1 was not always perfect, with environmental humidity playing a role in how stiff the mix became. As a general rule for ongoing experiments, it was determined that water should be added initially at ~45% by volume of hydrated lime before mixing, and then gradually as necessary until the desired consistency was achieved. For simplicity in calculations, the approximate ratio of 2:1 was used.

Figure 31: Manually extruded pure lime plaster

3.5.4 Reintegration of Hemp Hurds

With a lime plaster established, hemp could be added back into the mixture. First, a test was conducted where hemp hurds were soaked in the appropriate amount of water for their lime:water and hemp:lime relationships. Hemp:lime mixtures of 2:1, 1.91:1, and 1.5:1 were selected for this phase of testing as it was expected they would provide the most useful insight into the effects of water close to the critical zone of the embodied carbon spectrum. The three containers were set up as follows:

- For the 2:1 hemp:lime mixture, 800cm³ of hemp hurds were soaked in 200ml of water.
- For the 1.91:1 hemp:lime mixture, 764cm³ of hemp hurds were soaked in 200ml of water.
- For the 1.5:1 hemp:lime mixture, 1200cm³ of hemp hurds were soaked in 200ml of water.

After 24 hours of soaking, the hemp hurds were added to the food processor and chopped up smaller. However, as mentioned in section 3.3.0, the water content had a drastic effect on processing efficacy. In this instance, all three mixtures were still very dry as the small volume of water relative to the volume of hemp hurds was soaked up, not saturating the hurds and breaking down their structural integrity to prime them for processing. When the hydrated lime was mixed in, the resultant mixtures were dry and crumbly due to most of the liquid having been absorbed by the hemp hurds and unable to bind with the lime. It was evident from this phase of the experiment, by process of elimination, that soaked and squeezed hemp hurds added to a pre-mixed lime plaster would provide the best possible outcome for extrudability of a carbon-neutral hemp-lime bio-composite.

This theory was tested by soaking hemp hurds in the established 1:1 ratio of hemp:water for 24 hours, before draining off the excess liquid and processing for five total minutes in 1-minute intervals. Once chopped up, the hurds were removed from the food processor and squeezed by hand to remove as much remaining liquid as possible. The damp processed hurds were then added to the pre-mixed lime plaster in a ratio of 1:91:1 hemp:lime by dry volume – calculated prior to soaking. Finally, the resulting mixture was loaded into the caulking gun and manually extruded.

Figure 32: Developed workflow to achieve an extrudable hempcrete mixture

Figure 33: Manually extruded hempcrete mixture

3.5.5 Evaluation

The carbon-neutral mixture was successfully manually extruded with minimal surface imperfections (fig.33). The workflow developed details a robust framework for creating a seemingly extrudable hempcrete mixture. While the processing required would be difficult to perform without negating the carbon-neutrality of the final product on a large scale, it was suitable for the small scale tests conducted in this thesis. This process was used for all further extrusion of hemp-lime bio-composite. Having optimised the material, it was time to move on to testing at scale with the robot.

FOUR

ROBOT TESTING

4.1.0 Introduction

With an optimised hempcrete mixture, it was time to begin extruding with the robot to determine its viability. The plan was to extrude the 1.91:1:0.5 hemp:lime:water mixture with the WFADI's concrete extruder tool with the end nozzle removed on the ABB IRB6700 Robotic Arm in the WFADI workshop (fig.34).

4.1.1 The Robotic Working Environment

The concrete extruder consists of a larger funnelling hopper that feeds into a tube similar in diameter to the caulking gun used for manual extrusion. When in operation, a large auger turns inside the hopper, pushing the contents out the end of the tool.

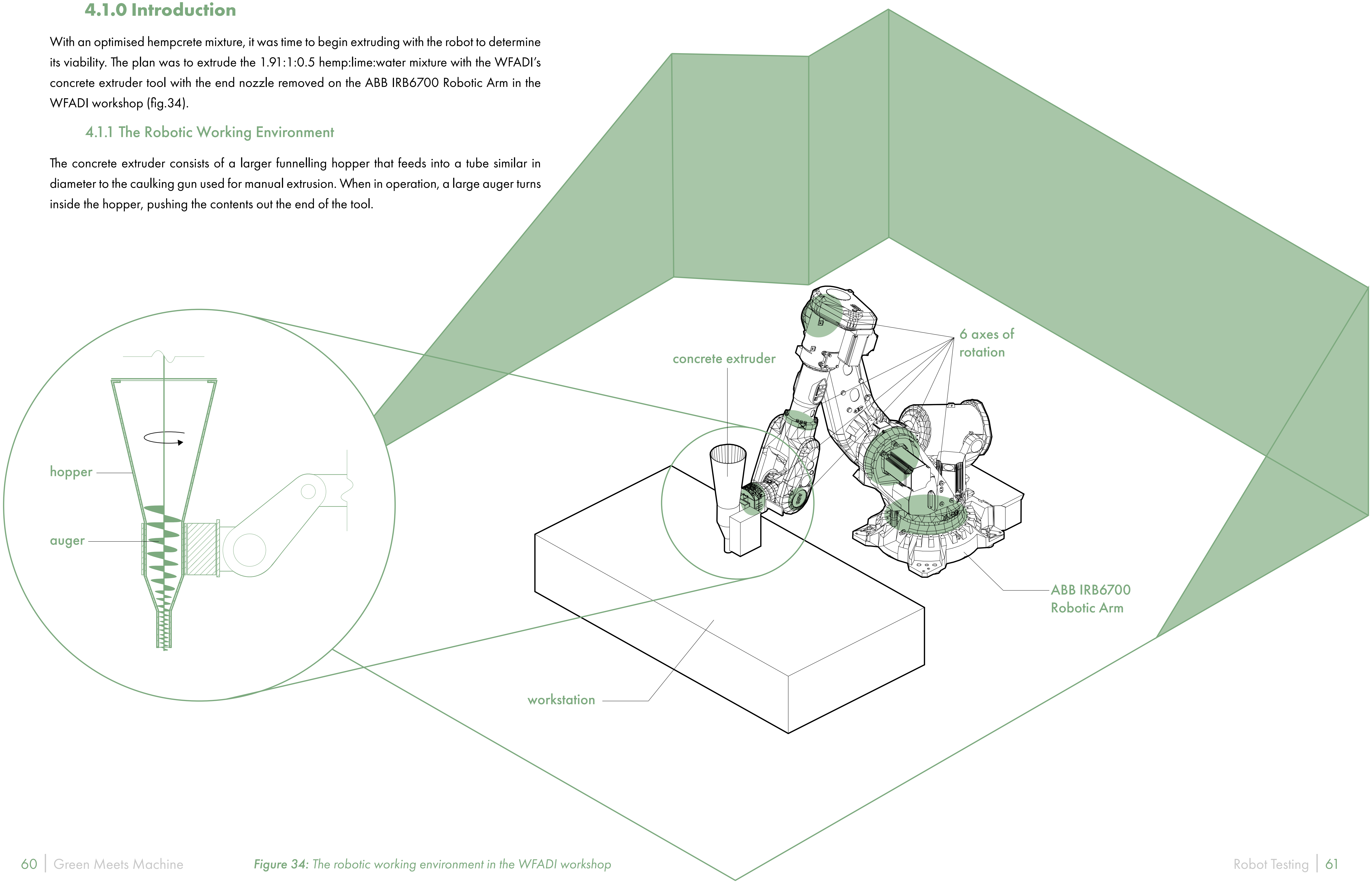


Figure 34: The robotic working environment in the WFADI workshop

4.2.0 Extrusion

Before extruding with the robot, criteria were set out to determine the experiments' success and establish a roadmap for subsequent exploration.

The pursuit of an extrudable hempcrete construction would be abandoned for the remainder of this thesis unless all three of the following conditions were observed:

- The robot extrudes the hemp-lime mixture
- The hemp-lime mixture forms a continuous line with no big holes or breaks
- The hemp-lime mixture stacks on top of itself and supports its own weight

If the first two criteria were observed but the mixture was unable to stack successfully, there would be the potential to extrude bricks for robotic assembly rather than extrusion of entire prefabricated wall elements. Dry hempcrete would be lighter and more readily stackable, and the robot would reduce the human workload and introduce its own unique geometric variation via mass-customisation. However, as with 3D printing, this would be limited by the inherent structural shortcomings of hempcrete.

There was also the potential to extrude a pure lime plaster mix as a lost formwork for conventional hempcrete casting, that would double as additional weatherproofing in the absence of a conventional lime-based render or wash.

The method was as follows:

- Robotically push mix through the concrete extruder into a bucket while stationary
- Set up Grasshopper script and pair with HAL file, enter Tool Centre Point values
- Extrude pure lime mixture
- Extrude hemp-lime mixture

Scan the QR code below to view the extent of robotic experimentation for hempcrete extrusion.

https://youtu.be/cM3upTQLpNI

Figure 35: Robotically extruded hempcrete and lime plaster mixtures

4.3.0 Analysis

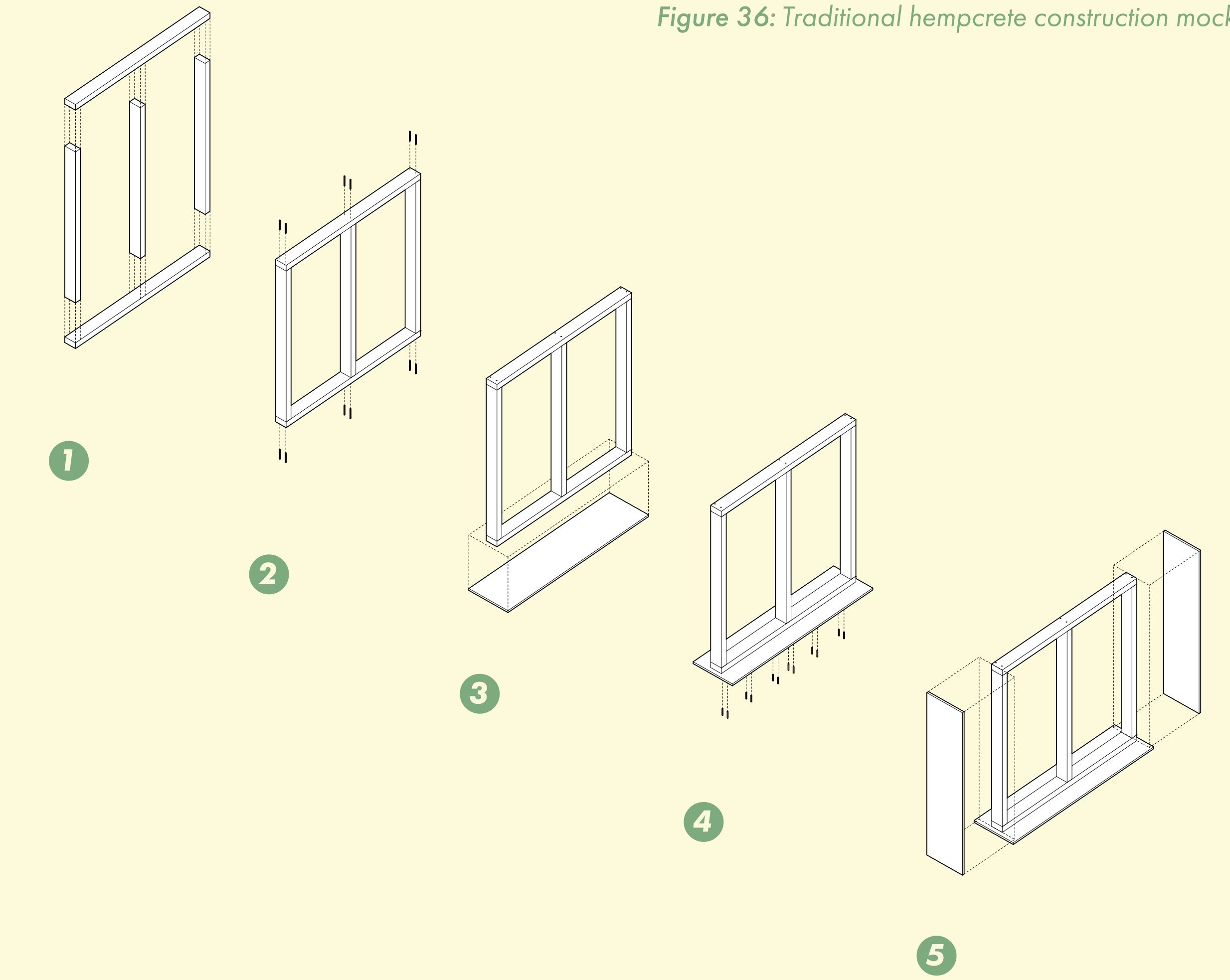
Extrusion of the optimised mixture demonstrated that the methodology has potential; however, several factors limited the result. Firstly, the modified concrete extruder did not produce clean geometry deposition. Unfortunately, it was the only tool in the workshop that could foreseeably extrude the hemp-lime mixture. The auger protruded from the end of the concrete extruder when the nozzle was removed, so the extruded mixture did not conform to the shape of the chamber as was expected. It is assumed that extending the end of the extruder chamber beyond the end of the auger would rectify this issue and result in a cleaner extruded geometry; however, such investigation is beyond the scope of this research.

Another limiting factor is the inherent moisture content of the optimised hempcrete mixture. This was discussed previously regarding its vulnerability to dry rot, but it should be noted that, experimentally, extruded hempcrete will take around a week to set in ideal conditions. This limits the potential production of precast hempcrete 3D printed building elements as they would be challenging to relocate inside a workshop to aid productivity.

While unsuccessful at 3D printing for construction with hempcrete, this research has highlighted some avenues for further investigation. Optimising the end effector and reducing drying times would result in a more suitable product that could one day see 3D printed hempcrete implemented in architecture and construction. These problems fall within the fields of material science and engineering rather than architecture and are outside the scope of this thesis. As such, the remainder of Green Meets Machine focuses on using robotic fabrication to increase architectural expression in hempcrete construction via different means.

FIVE

STRUCTURE & FORMWORK



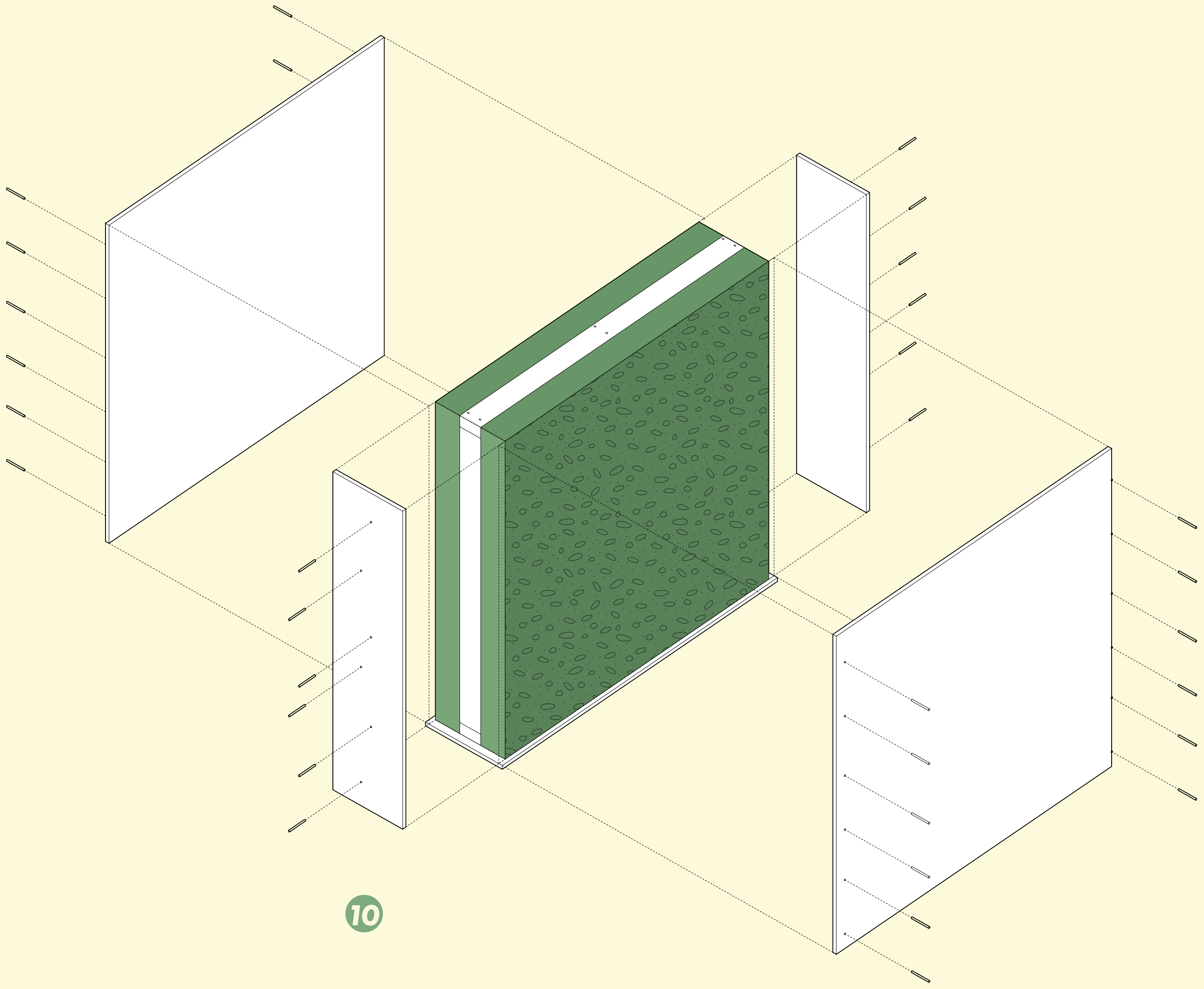
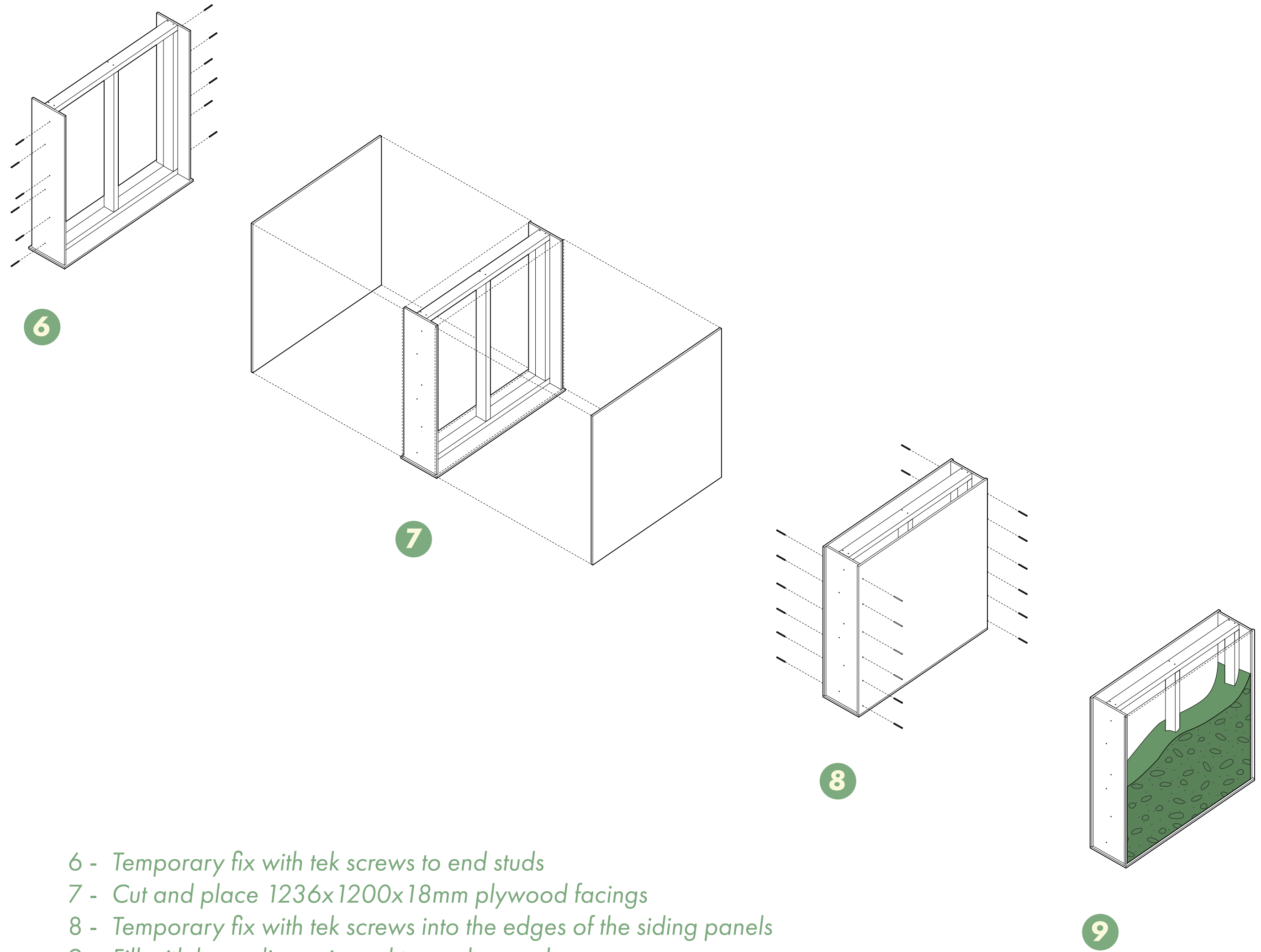


Figure 36: Traditional hempcrete construction mock-up

TRADITIONAL HEMPCRETE CONSTRUCTION MOCK-UP

1 - Cut and assemble a 1200x1200 module - bottom plate, top plate, and studs
2 - Permanent fix with nail gun through bottom and top plates
3 - Cut and place 1236x336x18mm plywood base
4 - Permanent fix with nail gun to bottom plate through bottom of module
5 - Cut and place 1200x300x18mm plywood sidings



6 - Temporary fix with tek screws to end studs
7 - Cut and place 1236x1200x18mm plywood facings
8 - Temporary fix with tek screws into the edges of the siding panels
9 - Fill with hemp-lime mix and tamp down edges
10 - Remove temporary formwork once hemp-lime mix has set

5.1.0 Proof of Concept

The next step was to revisit conventional hempcrete construction to optimise a structure and formwork model for increased architectural expression via robotic fabrication. Firstly, it was decided that constructing a 1200x1200x300mm module of a conventional hempcrete wall would aid the author's understanding of the material, workflow, and relevant processes. Figure 36 on the previous page depicts the proposed construction sequence for the module, following the 'cast and tamp' method for hempcrete construction detailed in section 2.1.3. After consultation with the workshop technicians, the size of the proposed module was reduced to 600x600x300mm, which would save time and material resources while still providing scalable time and resource data on which to base future workflow assumptions. For example, if comparing the time and material resources for a 1200x2400mm wall element, the 600x600mm module results can be multiplied by a factor of 8.

5.1.1 Structure and Formwork

Figure 37 depicts the as-built construction and assembly of the structure and formwork module, whose logic varies slightly from the initial proposal. Rather than the facing panels abutting the edges of the end panels and being screwed through, they sit between the end panels and are screwed through from each end. There is no reason for this other than it suited the scrap materials that were at hand and used for the construction; however, this does not affect the outcome of the hempcrete module. Another difference is the use of purlin screws instead of gun nails to construct the framing components. A nail gun was not available in the workshop, and – somewhat fortuitously – this enabled the accuracy of the frame to be adjusted during construction without having to pull out nails.

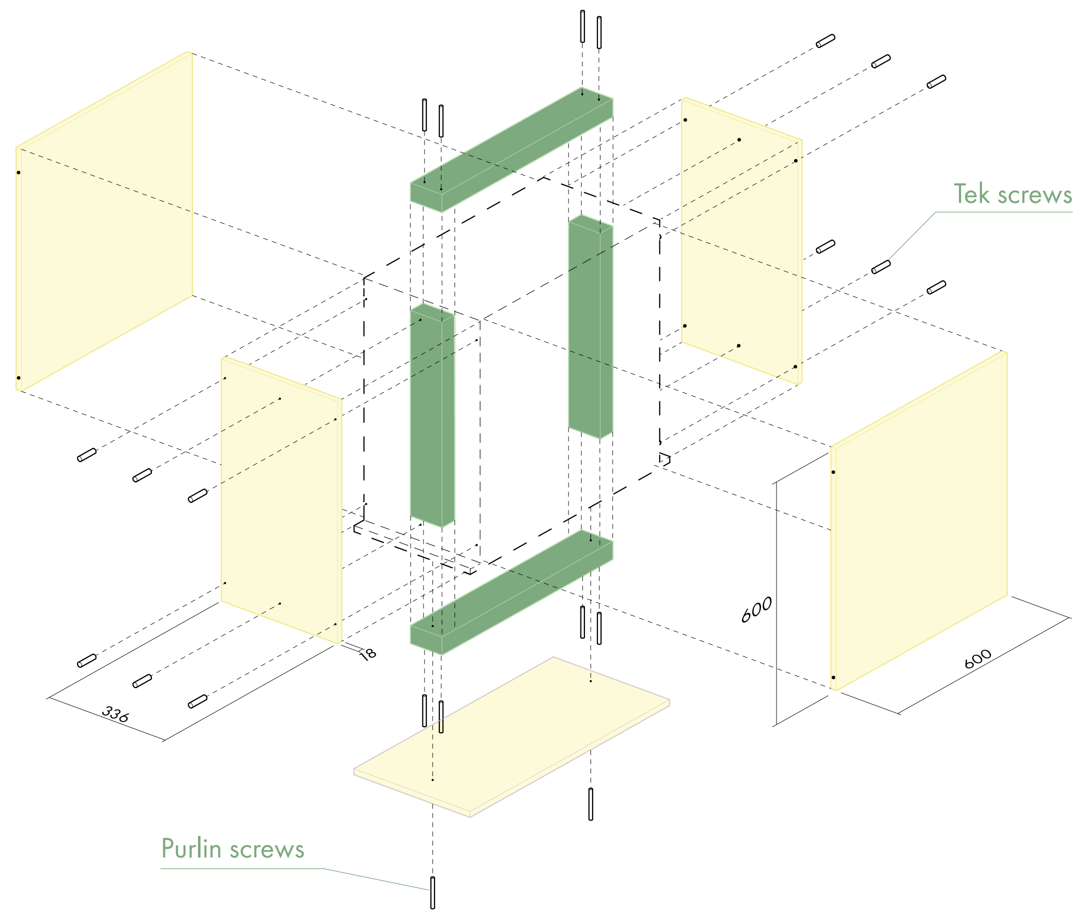


Figure 37: As-built structure and formwork module

5.1.2 Hempcrete Mixture

Once the structure and formwork were assembled, the hempcrete could be mixed. Per the advice of Gregg Flavall of Hemp Technologies Global, 10% by weight of regular builder's cement was added to the mixture to increase the effectiveness of the binder (G. Flavall, personal communication, April 20, 2021). This provided a realistic view of the final hempcrete wall module. Hempcrete construction overseas uses a commercial lime binder, consisting of more than just hydrated lime. This decision was reinforced by Allin (2005), whose DIY recipe for lime binder mix prescribes "7 parts hydrated lime, 1.5 parts hydraulic lime, 1.5 parts cement" (p.146). As Allin's cement ratio is 15% by volume and Flavall's is 10% by weight, Allin's advice was followed as it was more practical to measure. With no access to hydraulic lime and the inherent safety risks associated with such a volatile, caustic substance, the lime binder for the 600x600 module substituted hydrated lime for the hydraulic lime component. Firstly, 8.5 parts hydrated lime and 1.5 parts cement were mixed in the concrete mixer until combined. Water was added, and mixing continued until a consistent slurry was achieved. Finally, the hemp hurds were added to the mixer. The lime binder tended to stick to the bottom of the drum and collect a dense mass of sodden hemp hurds, while uncoated hurds were tossed around above. Intervening with a mixing stick between mixing intervals was necessary to ensure all the hurds were coated in the lime binder and helped the general consistency of the mixture. Mixing continued until it was deemed that all the hemp hurds had been sufficiently coated in the lime binder.

5.1.3 Cast and Tamp

The next step was to fill the structure and formwork module with the hempcrete mixture using the cast and tamp method. Two 9.6L buckets were filled approximately ¾ and deposited into the formwork before being spread out and tamped around the edges with a framing timber offcut. The mixture was left 'lofted' in the middle of the wall to optimise its insulative properties, as thermal performance is inversely proportional to density (Hempitecture, 2018). This process was repeated until the hempcrete mixture was used up. Another batch of hempcrete was mixed in accordance with the steps detailed in section 5.1.2. The cast and tamp process was resumed until the hempcrete reached the top of the formwork, where it was levelled off and packed down. The module was stored indoors to set.


Figure 38: Mixing hempcrete


Figure 39: Casting


Figure 40: Tamping


Figure 41: The hempcrete is left lofted in the centre

5.1.4 Removal of Formwork

As the weather was cool and damp, it was decided to wait longer than the 24 hours recommended by Hemp Technologies (2010) before removing the formwork. Having completed the casting and tamping on a Thursday, the formwork was removed four days later on the following Monday. Although some mixture came off with the forms, the longer wait time proved beneficial as the resultant surface finish of the wall was satisfactory (fig.42,43).

5.1.5 Critical Analysis

Aesthetically, the hempcrete module showcases the defined corners achievable with the cast and tamp method in a removable formwork system. Tamping around the edges was integral to achieving a smooth surface finish, as the compressed top is significantly less smooth than the sides of the module. While consisting of a series of straightforward tasks that most DIY enthusiasts could undertake, the construction of the hempcrete module proved to be a very time-consuming process. It took approximately 6 hours in total across multiple days, including clean-up. It is easy to see why hempcrete has not seen mainstream adoption in New Zealand. It is laborious, time-consuming work that results in a homogenous, boxy architecture. Mainstream builders have no incentive to use it as there are more time-efficient ways to build. Despite the bohemian dream of having a community that helps build each other's houses out of ganja, this is not a priority for most New Zealanders. Green Meets Machine must reduce the human labour required to build with hempcrete while increasing architectural expression to accelerate carbon-neutral construction.

Figure 42: Unscrewing the formwork with an impact driver

Figure 43: 600x600x300mm conventional hempcrete construction module

1. Mix

2. Pour

3. Spread

4. Tamp

5. Disassemble

6. Finish

Figure 44: Conventional hempcrete construction workflow

5.2.0 Structure and Geometric Variation

The internal structure of a hempcrete wall defines its geometric limitations. In a conventional hempcrete wall, vertical studs at 600 centres span between a top and bottom plate. Structure is the primary driver of form as the formwork is offset from the structure, typically with PVC spacers (fig.45), before the resulting cavity is filled up with hempcrete mixture (Hempitecture, 2018). If adequate care has been taken, the finished wall face will be the same horizontal distance from the internal timber frame at all points, reflecting the structural geometry.

The structure must be manipulated beyond its current planar constraints to increase geometric variation in a hempcrete wall. Dividing the vertical members provides smaller sections that have unique plane orientations. The structural implications are compensated for with the addition of dwangs to support the vertical joints. Figure 46 depicts the manipulation of the base geometry plane of a 3600x2400mm timber frame, with an appropriate arrangement of 90x45mm framing timbers fitted to the wall as best as possible. This logic of finding the best fit for a linear timber member against a curved surface is developed later in this thesis once the formwork logic is established.

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Figure 45: PVC spacers help maintain even distance between formwork and structure (Sparrow, 2014)

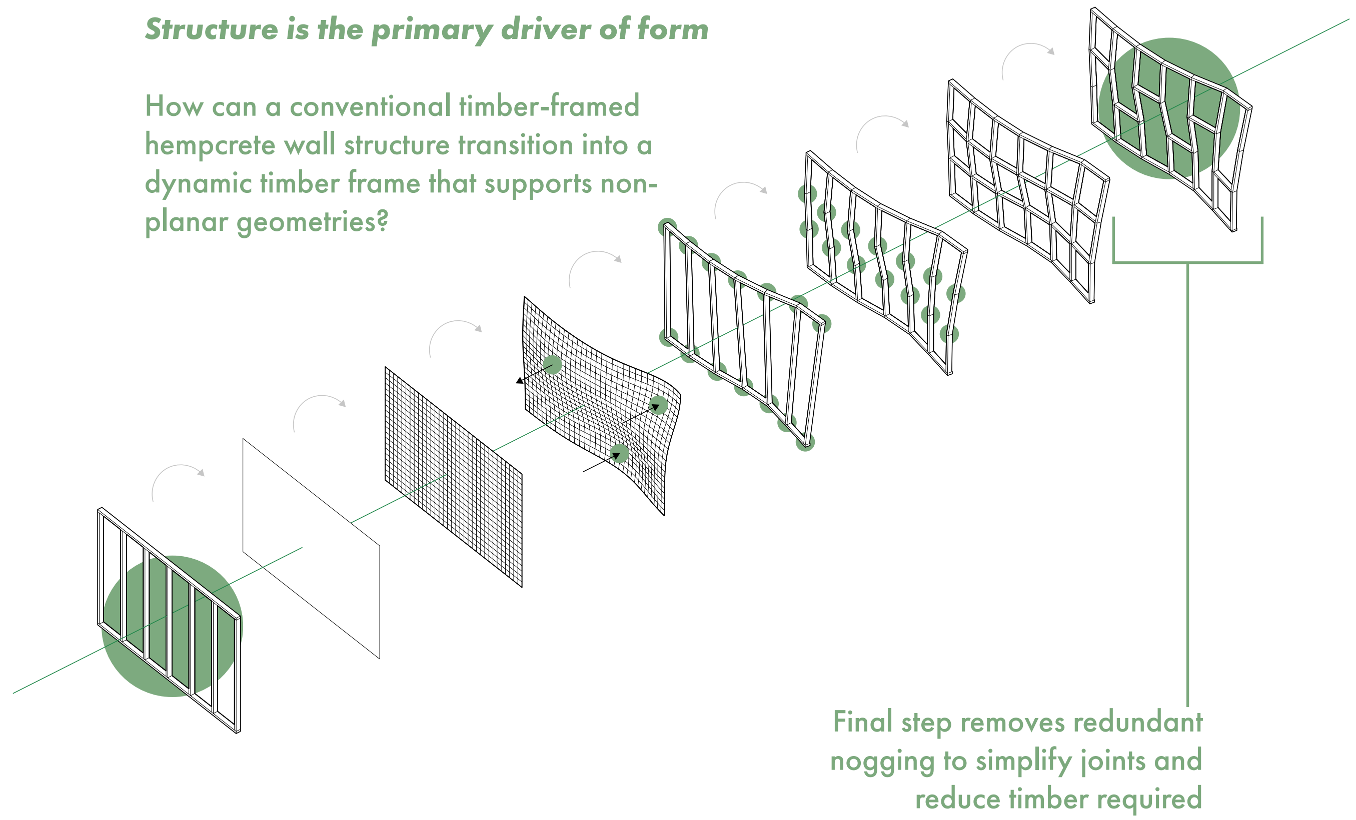

Figure 46: Generating geometric variation via articulated timber framing

5.3.0 Formwork and Architectural Expression

This section explores different formwork systems and evaluates their relative effectiveness at achieving increased architectural expression for hempcrete.

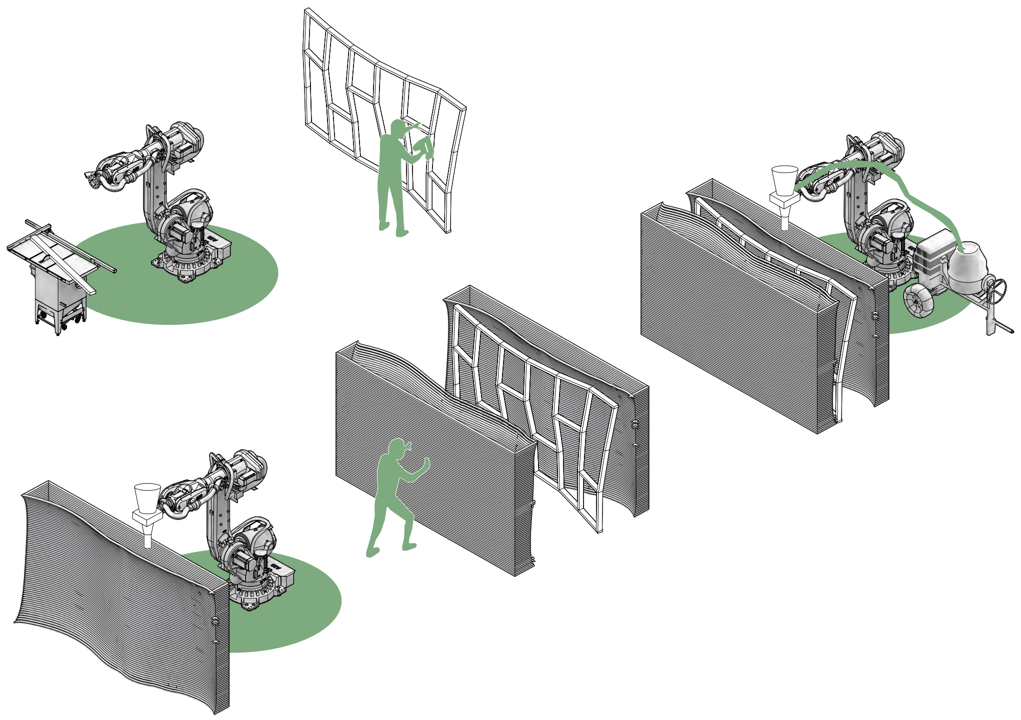

Figure 47: Proposed workflow for an extruded clay formwork

5.3.1 Clay

Systems and workflows for clay extrusion with the robotic arm already exist in the WFADI workshop. Chapter 2 evaluates TECLA as a precedent for what an extruded clay formwork might look like and the processes involved. In Gramazio and Kohler's Robotic Clay Molding workshop, once the concrete had set the clay was removed and rehydrated to be used again; in theory, ad infinitum (Gramazio Kohler Research, 2016b). While clay itself is not renewable, its ability to be recycled indefinitely is an attractive quality that would help mitigate the embodied carbon of a workflow involving casting hempcrete in an extruded clay formwork.

5.3.1.1 System Logic

Figure 47 depicts the author's proposed workflow for an extruded clay formwork. First, it is proposed that the robotic arm would use the gripper tool to position framing timbers in relation to a table saw to cut each piece at the desired angle (Hensel, 2021; Søndergaard et al., 2016). Secondly, a human worker would assemble the framing timbers into an irregular, non-planar frame enabled by the parametrically-defined angled timber. Concurrently, the robot would fabricate large clay volumes via layer-based extrusion to define the formwork on either side of the frame. The human worker would then locate the layered clay volumes in relation to the frame. Finally, the robot would pump a hempcrete mixture into the cavity between the clay formwork volumes.

5.3.1.2 Critical Reflection

Upon reflection, there are many problems with this workflow. Firstly, there is no precedent for clay as formwork for hempcrete. In her Master's thesis, Centre for Alternative Technology graduate Ruth Busbridge advocates for clay as a binder for hempcrete by arguing that lime does not sequester as much carbon as its proponents claim (Busbridge, 2009). While Busbridge provides a compelling argument for clay over lime regarding its environmental credentials, lime remains superior due to the thermal performance and vapour permeability it affords hempcrete (Bedlivá & Isaacs, 2014). The point, however, is that, unlike concrete, the hempcrete – when applied to the formwork – is likely to bind to the clay if it is still wet. Conversely, waiting for the clay to dry would choke up the workflow. In the Gramazio and Kohler Research workshop, the clay could be washed off the finished concrete panel, but it is unlikely this would be as effective with hempcrete. Additionally, clay extrusion at the scale required would prove time-consuming with the tools available in the WFADI workshop and would likely need human supervision to load more clay once the extruder barrel has been emptied. Furthermore, it is unrealistic that a human worker would be able to easily relocate the large clay volumes, which take up a significant amount of space compared to the finished wall. While clay extrusion can generate the geometric variation this research aims to achieve, its application as a formwork system for hempcrete construction is seemingly impractical.

5.3.2 Fabric

Fabric formwork has been used for large concrete shell structures and articulated columns due to its ability to find form (Veenendaal et al., 2011). It is capable of producing intriguing, organic form determined by its material properties. P_Wall by Matsys (2013) (fig.49) is an example of how fabric formwork can create interesting geometries and affect the spatial characteristics of an architecture. It provides interest and intrigue, changing how people inhabit the space.

5.3.2.1 System Logic

In the proposed fabric formwork workflow for hempcrete shown in figure 48, fabric would be loosely pinned from the underside of an articulated timber frame – laid horizontally – at nodes along the framing. Gravity would allow the fabric to find its form. Hempcrete would then be packed into the formwork and smoothed off manually once the framing is covered. Finally, the wall would be erected and the fabric formwork removed.

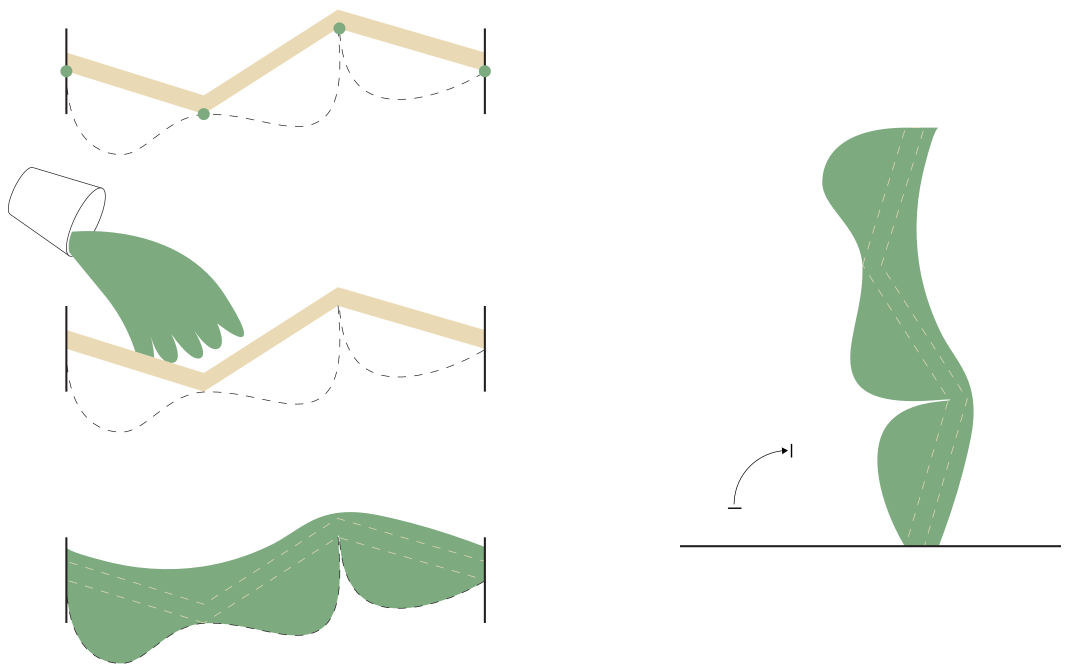

Figure 48: *Proposed fabric formwork fabrication workflow*

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Figure 49: *P_WALL by Matsys. An example of a fabric formed concrete wall (Matsys, 2013)*

5.3.2.2 Critical Reflection

While fabric formwork can produce sufficient geometric variation, the workflow above results in a highly variable wall thickness. This affects material optimisation where the thickness exceeds 300mm, and thermal performance where the thickness is less than 300mm. Furthermore, it is difficult to imagine where the robot fits into the fabric workflow. Arguably, the robot has already defined the geometry of the framing which has an impact on the final form that the fabric takes, but this is a tenuous link. Studies that develop flexible formwork have used pneumatics to parametrically control the geometric variation (Veenendaal et al., 2011), but this is beyond the capabilities of a single robotic arm.

5.3.3 Timber

Timber is the conventional formwork for hempcrete construction, but it is also able to generate geometric variation. Structure and formwork constructed from the same material has added benefits, as it can operate as a single cohesive system.

5.3.3.1 System Logic

To conform to the geometry of the frame, an array of triangular timber panels would be CNC milled by the robotic arm, offset from either side of the frame, and fixed through PVC spacers as per conventional hempcrete construction (Hempitecture, 2018) (fig.50). The cavity created between the two sides of the formwork would then be filled with hempcrete – either with the robot or by hand – and tamped down to ensure the desired smooth surface finish. Finally, the formwork panels would be removed once the hempcrete has taken shape.

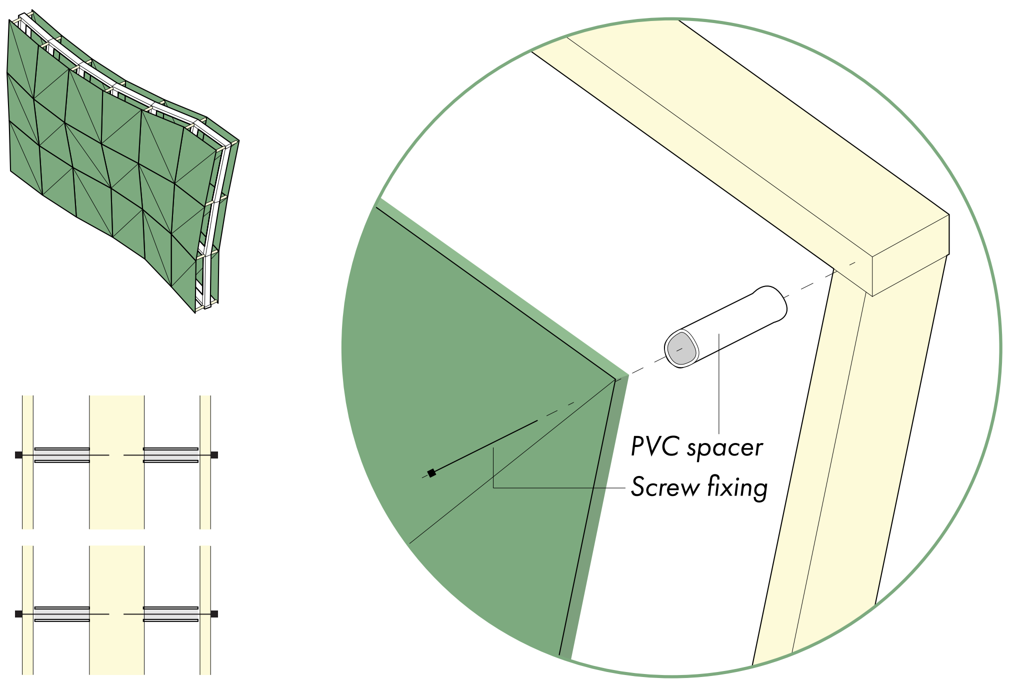

Figure 50: *Proposed timber formwork system to enable geometric variation*

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Figure 51: *Hempcrete construction with timber formwork panels (Ricketts, 2020)*

5.3.3.2 Critical Reflection

As the workflow above is a subtractive process – whereby the material geometry of timber is already defined as unitised panels – introducing geometric variation inherently increases the system's complexity. To achieve a high resolution of architectural expression within the wall, the panels need to be smaller and more plentiful for the system to conform to an irregular geometry. The resultant wall is the product of its process, as it would be different for clay and different again for fabric. This is an advantage of timber, as the internal timber frame of the proposed system is also made of timber and thus shares the same geometric limitations. Different materials have different geometric limitations, so reducing the number of materials used in a system reduces the number of geometric limitations. A timber system can push the geometric potential of timber instead of negotiating a geometric compromise between multiple materials. While timber sheet material is limited to planar geometries, this can produce a unique outcome that reflects the construction process.

5.3.3.3 WoodSkin Case Study

WoodSkin is an interior lining or furniture system that comprises a nylon mesh textile sandwiched between CNC routed chamfered plywood triangles (fig.52-54). It benefits from the flexibility of the fabric and the rigidity of the plywood. It is highly customisable, reprogrammable, and flat-packable, making it easy to store and transport. WoodSkin "bridges the gap between virtual design and real construction" (Taylor, 2013).

In terms of WoodSkin's applicability to this thesis, it would be difficult to accurately fabricate such a system as each plywood panel must correspond directly to another plywood panel on the back. The nylon mesh also introduces another material component which is counterintuitive when the goal is simplicity.

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Figure 52: WoodSkin finding form under gravity (Mammafotogramma, 2013)

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Figure 53: WoodSkin furnishing the front counter at AllezUp climbing wall in Montreal (Mammafotogramma, 2013)

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Figure 54: Close-up of WoodSkin's CNC-routed plywood triangles (Mammafotogramma, 2013)

5.3.4 Sprayed Application of Hempcrete

In addition to the cast and tamp method of hempcrete construction used for the 600x600x300mm module, hempcrete can also be sprayed into a wall cavity with a pump. Allin (2005) states that spraying hempcrete "has several advantages over the manual method other than speed, in that the mixture requires less lime and water in the mix which increases the insulation value and lessens the drying time" (p.156). This would imply that sprayed hempcrete has less embodied carbon than manually cast and tamped due to the lower lime content, ignoring the operational emissions. However, Williams et al. (2017) claim that projection-formed (sprayed) walls have "a higher density as well as the more energy intensive process" (p.7) and use a greater quantity of lime binder. The differences in mixes and methods make them incomparable. Despite this, it can be safely assumed that sprayed hempcrete remains carbon negative due to the ratios of the binder mixture. Even if the cement content of the mix is increased as Allin (2005) recommends for sprayed application, there is still a significant portion of lime to mitigate the increase in embodied carbon. This thesis assumes that sprayed hempcrete has more embodied carbon than cast and tamped hempcrete but is still carbon negative.

While a denser hempcrete wall would theoretically have reduced thermal performance, a study conducted at the University of Bath comparing the thermal and mechanical properties of precast and projection-formed (sprayed) hempcrete to the conventional onsite casting method concluded that "projection formed material may afford the thinnest wall section and lowest embodied energy but a reduced mechanical performance" (Williams et al, 2017, p.7). This is due to the orientation of compression, which is perpendicular to the wall. Nguyen et al. (2010) state that the "[hemp hurd] particles are anisotropic due to the capillary structure of the woody core part of the stem from which they are cut" (p.556). They conclude that "in perpendicular direction of compaction, the thermal conductivity can be 50% higher for a given apparent dry density" (Nguyen et al., 2010, p.559). This means that a thinner sprayed wall can achieve the same thermal performance as a thicker cast and tamped wall, despite its higher density. Using sprayed hempcrete can increase the usable space within a dwelling compared to cast-and-tamped hempcrete without compromising thermal performance. Once filled, the exposed surface of a sprayed hempcrete wall is float finished manually (Allin, 2005), while the formwork can be removed or left as part of the wall. The following section explains lost formwork in more detail.

	Cast & Tamped	Sprayed
Advantages	- Less lime = carbon negative - Greater articulation of form - Greater material consistency - Greater thermal performance	- Faster, more efficient - Can be done by the robot - Requires less formwork - Formwork can provide bracing
Disadvantages	- Slow and laborious - Imperfections in formwork are reflected in outcome	- Thermal performance varies - Requires specialty equipment - Increased embodied energy and carbon* - Lost formwork is not reusable

*Increased embodied carbon due to higher concentration of lime binder. Embodied carbon is negligible over time due to carbon negativity of product offsetting carbon produced by robot in its manufacture.

5.3.5 Lost vs. Reusable Formwork

In *Building with Hemp*, Steve Allin (2005) details the different framing implications of opting for sprayed application. As opposed to the conventional centred framing and offset formwork typical of cast-and-tamp hempcrete construction, sprayed application utilises half the amount of formwork, leaving one side of the framing exposed to be sprayed onto (fig.55,56). The formwork is often directly fixed to the opposite side of the framing, as the sprayed hempcrete envelopes the entirety of the framing and prevents any thermal bridging. Sprayed hempcrete is applied at such a velocity that the mixture sticks to the formwork, removing the need for manual compression. Allin writes:

> *If the hempcrete is to be sprayed with a pump into the framework and when a permanent facing of strandboard or plasterboard is fixed to the interior surface of the wall, there is no need of battens to be fixed down the sides of the uprights to provide a key for the hempcrete, as the force of the compressed air sticks the material firmly against these surfaces.* (Allin, 2005, p.142).

If the formwork is to be removed, it is advised that a polythene sheet be placed between the shuttering and the wall cavity to be filled in order to prevent the hempcrete mixture from bonding to the surface of the shutters as it is sprayed (Allin, 2005). This enables the removal of the shutter boards without damaging the surface of the wall.

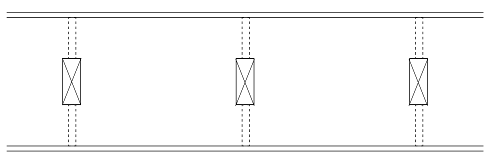


Figure 55: *Conventional offset formwork*

Formwork offset from structure with PVC spacers to allow hempcrete to be cast and tamped around structure before formwork removed.

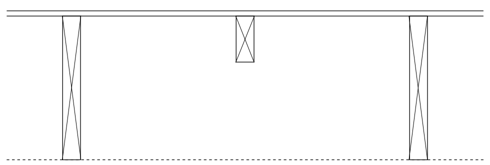


Figure 56: *Lost formwork for sprayed hempcrete*

Direct-fixed formwork on one side only allows hempcrete to be sprayed at the host wall where it sticks and solidifies. Guides help determine when the wall has been sufficiently filled.

5.3.6 Critical Analysis and Evaluation

Timber is the best choice for a formwork system in the context of this thesis as it has the same geometric limitations as the timber framing to be used. While other structural options could be better optimised for clay or fabric formwork systems, Green Meets Machine is concerned with increasing the geometric potential of hempcrete construction via robotic fabrication. Unlike hempcrete, timber is widely used in the construction industry, which will help encourage owners and builders to adopt the proposed system. In conjunction with a timber formwork system, sprayed hempcrete reduces the formwork requirements and enables the robot to assist in the hempcrete phase. It must be noted that while there was a clear link between the robotic process and the potential outcome during the extrusion phase detailed in Chapter 3, the robot will have less impact on the aesthetic outcome of a structure and formwork system. During extrusion, the robot directly manipulates the hempcrete by informing where it is extruded and at what speed. Conversely, in a structure and formwork system, the robot is responsible for fabricating the structure and formwork, which – in turn – inform the geometry of the hempcrete element. The robot, therefore, does not deal directly with the hempcrete mixture but can still inform the geometry through manipulation of the structure and formwork. While the robot can spray hempcrete onto the host wall, this is a significantly less precise deposition method than direct extrusion. It is ultimately the formwork that decides where the hempcrete ends up. The analysis of Mesh Mould and TECLA in Chapter 2 highlight the difference between a direct extrusion outcome and a formwork-derived outcome. While it is evident that TECLA was constructed with layer-based extrusion, it is difficult to determine the fabrication method of a finished Mesh Mould wall element. Regardless, the robot has informed the outcome through manipulation of the underlying structure and formwork.

5.4.0 Structural Simulations

Drawing inspiration from the WoodSkin case study, further explorations of possible structural systems were conducted. As discovered in the formwork assessments, form reflects structure. In order to generate a highly articulated non-planar formwork out of a planar sheet material, triangulation must occur (fig.57). Since structure is the primary driver of form, it is imperative that the structure mimics the form of the intended outcome. Thus, triangulated framing methods were explored through modelling in Rhino and Grasshopper. Three alternative systems that enabled articulation of form were then tested against each other via stress simulation in Fusion 360. Two types of connection logic were modelled for each system – hierarchical and non-hierarchical. For the sake of comparison, the systems were stress simulated in a planar configuration in order to compare results with conventional planar framing (fig.58-64). The results are documented in Appendix section 10.2.0.

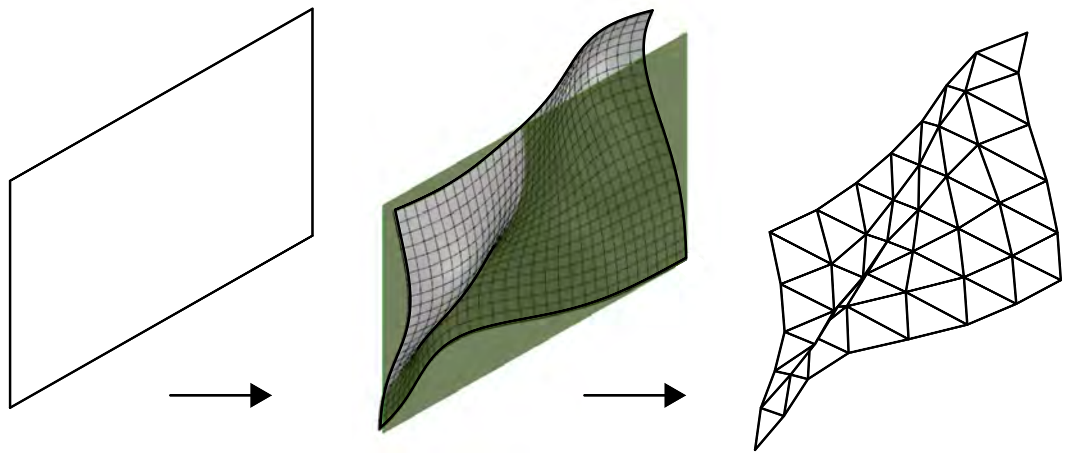


Figure 57: Triangulation of planar material to approximate non-planar geometry

5.4.1 Limitations

While useful for comparing the differences between each design, the quantitative results of the simulations were inaccurate due to the inability to simulate the behaviour of radiata pine. Timber is an anisotropic material, meaning it behaves differently depending on the direction of the grain. To counter this, the stress simulations were conducted with the members of the frames modelled as particleboard, assuming the behaviour of the system under stress would be sufficient to indicate the relative behaviour of radiata pine framing across designs.

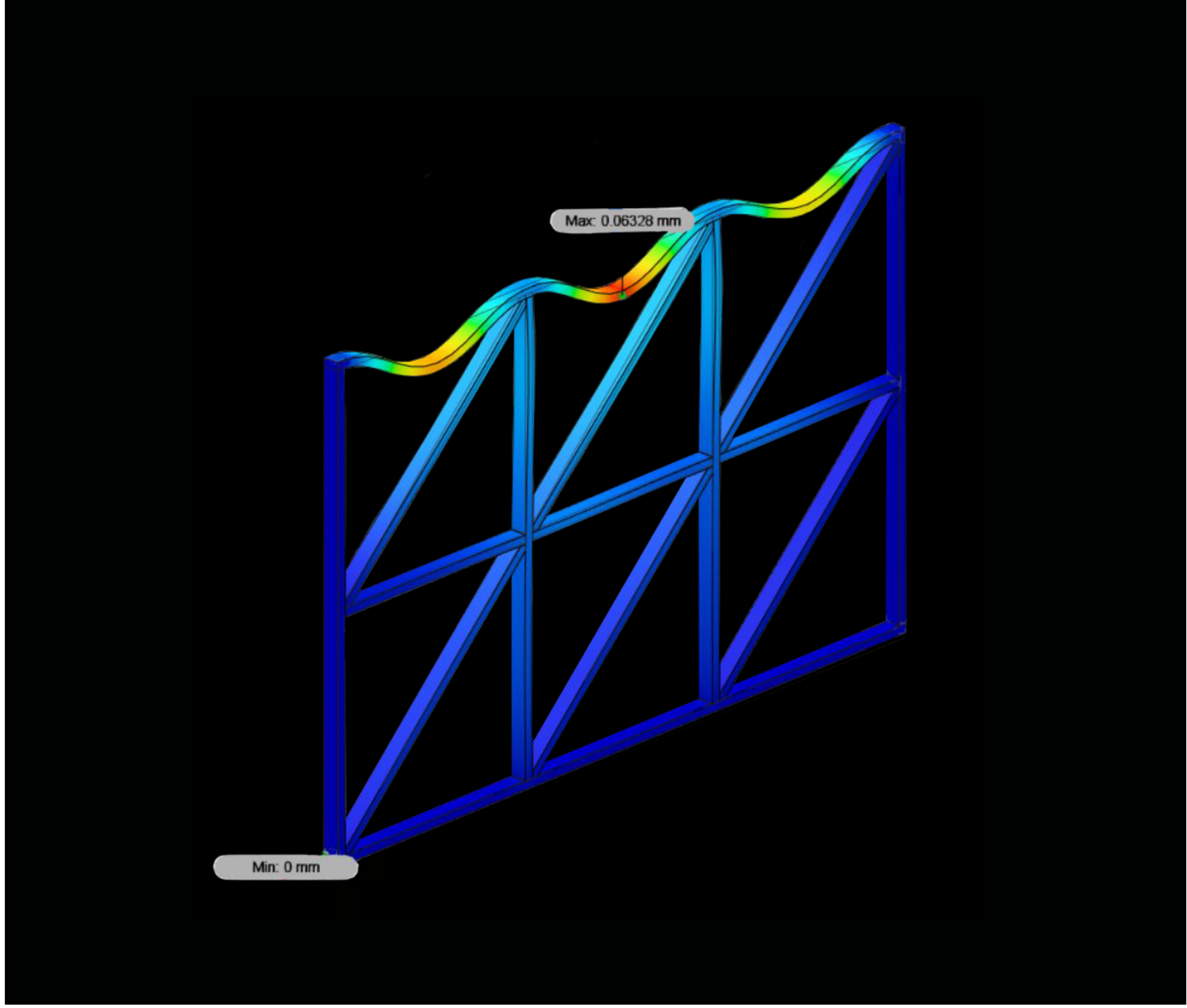


Figure 58: N frame under 100N gravity load

Figure 59: N frame architectural implementation

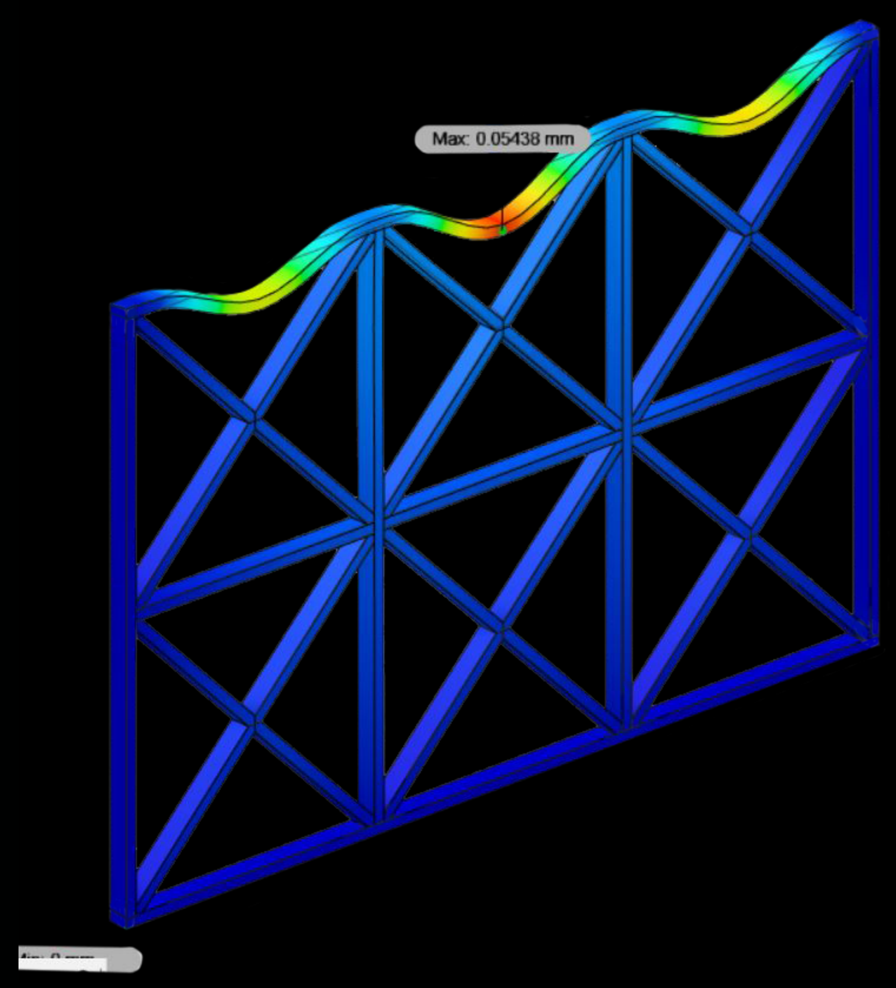


Figure 60: X frame under 100N gravity load

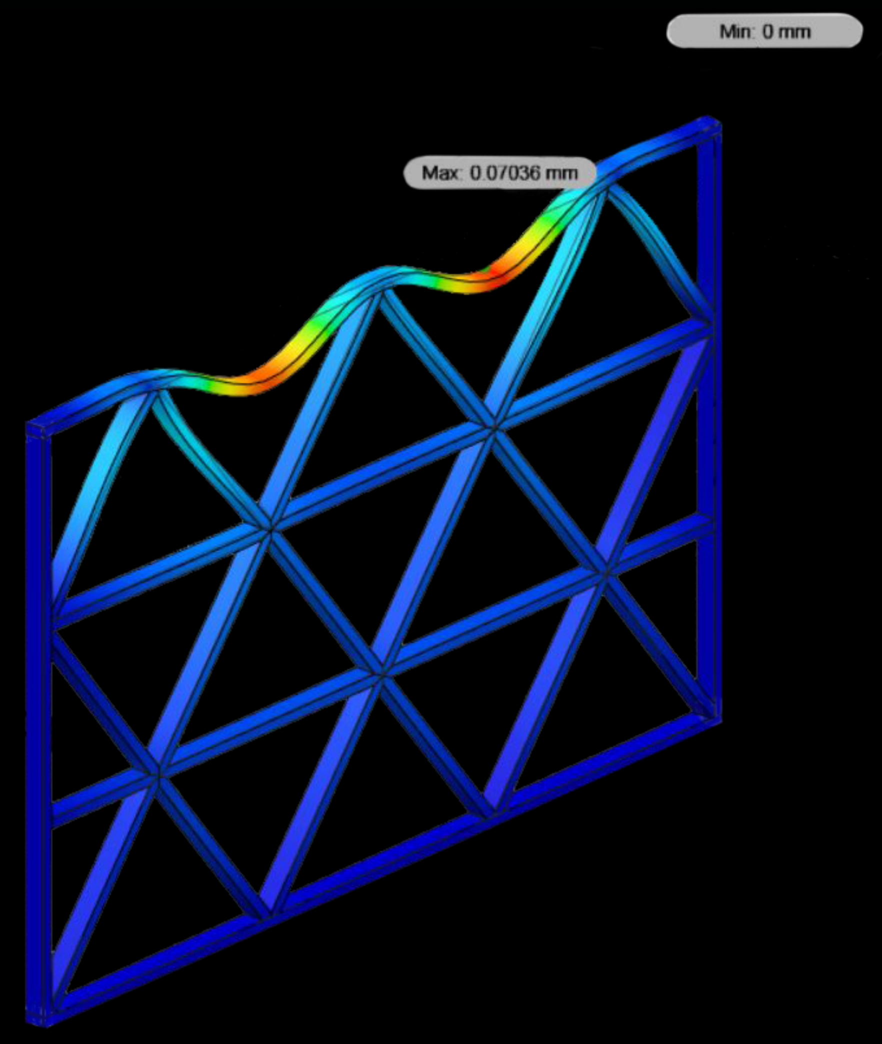


Figure 62: Hex frame under 100N gravity load

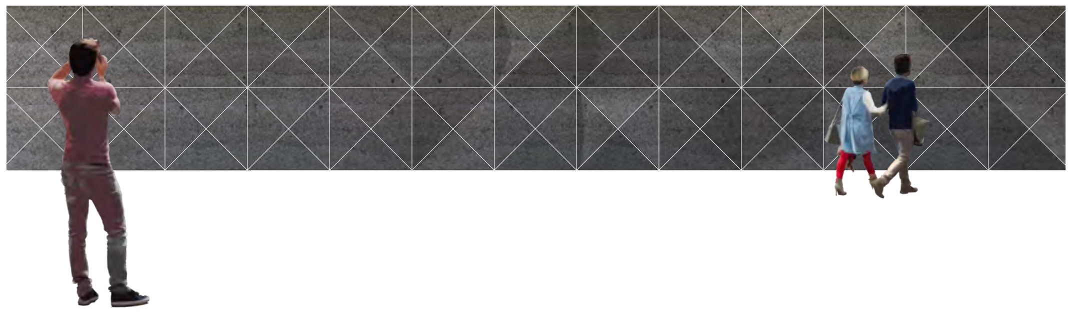


Figure 61: X frame architectural implementation

Figure 63: Hex frame architectural implementation

5.4.2 Results

It was clear from the simulations that the non-hierarchical connections tended to perform worse than the hierarchical connections. The frames with vertical members performed better under gravity load, while the frames with horizontal members performed better under lateral load. Upon this revelation, the *Hex* module was adapted by rotating the hexagonal pattern 90 degrees (fig.64). This increased the gravity load performance of the system at the expense of the lateral load performance. While unable to beat conventional vertical studs at 600mm centres in gravity load performance, the vertical *Hex* system still provided better lateral load performance than the conventional frame and better gravity load performance than the horizontal *Hex* system (see Appendix section 10.2.0). As such, the rotated *Hex* frame provides an acceptable middle-ground between gravity and lateral load performance.

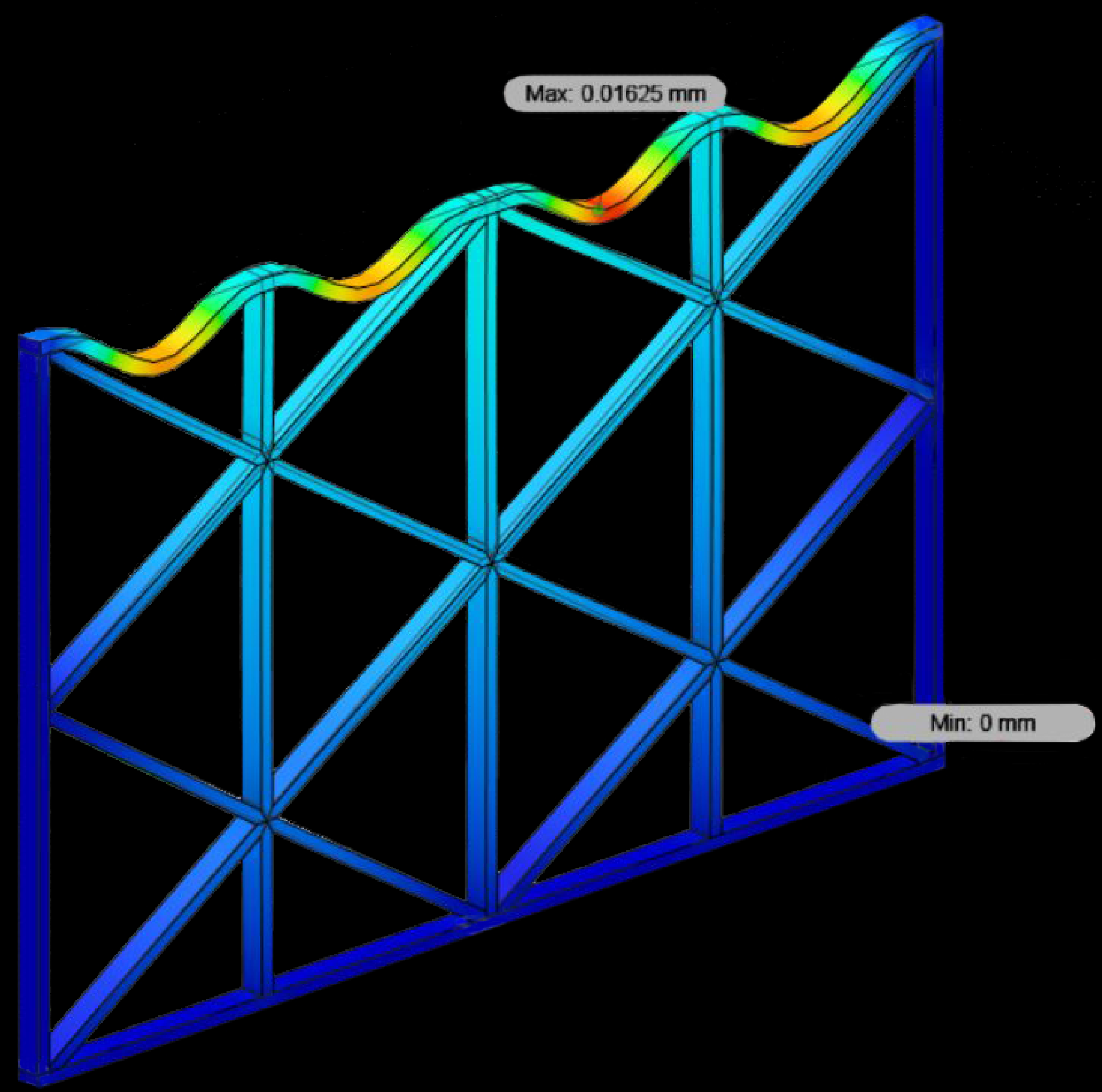


Figure 64: *Flipped hex frame under 100N gravity load*

5.5.0 Proposed System

The proposed design for a non-planar structure (fig.65) and formwork (fig.66) takes the form of a corner module, where two articulated frames intersect. Figure 67 shows how geometric variation is driven by the connection nodes of framing timbers and their distance from the normal. The corner itself is expressed as a vertical column (fig.68). Operating under the assumption that sprayed application of hempcrete would be used to manufacture the wall, a lost formwork consisting of plywood triangles CNC milled by the robot is affixed directly to one side of the plywood frame. It is proposed that this be the interior face of the wall and a lime plaster applied to the finished hempcrete exterior as weatherproofing so that the plywood does not need treating.

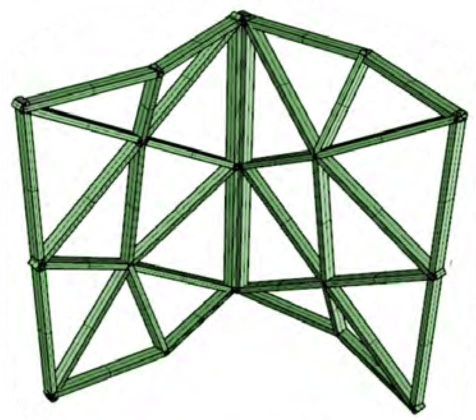


Figure 65: Non-conventional structural framing timber in vertically justified hexagonal pattern

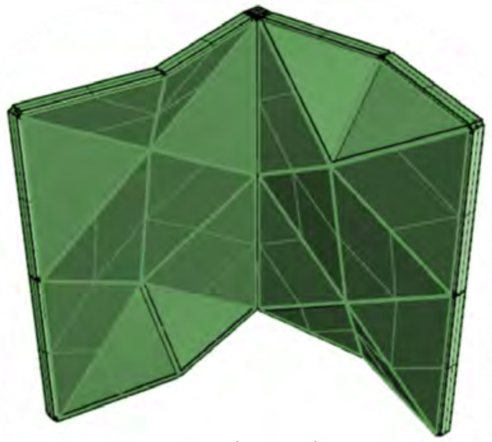


Figure 66: Formwork panels, interior

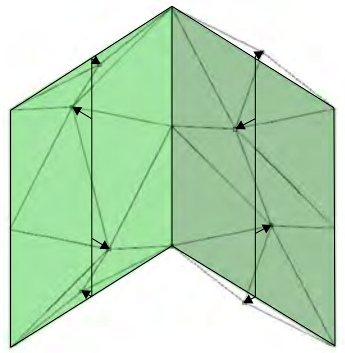


Figure 67: Points in relation to wall normal

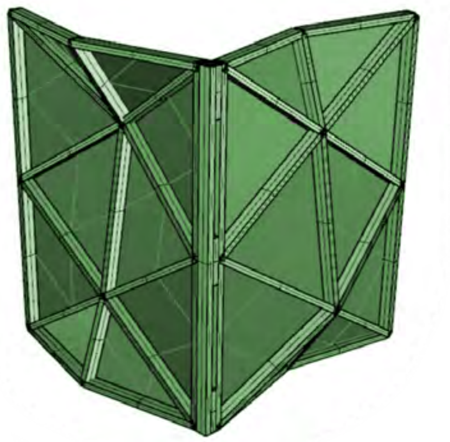


Figure 68: External corner of timber structure prior to sprayed hempcrete application

5.5.1 Workflow

The workflow for this system comprises of the robot cutting the framing timbers and triangular shutters, a human labourer aiding in the assembly of the frame and formwork, and the robot spraying the hempcrete mixture – mixed by the human worker – onto the wall before the surface is raked smooth by the human worker (fig.69).

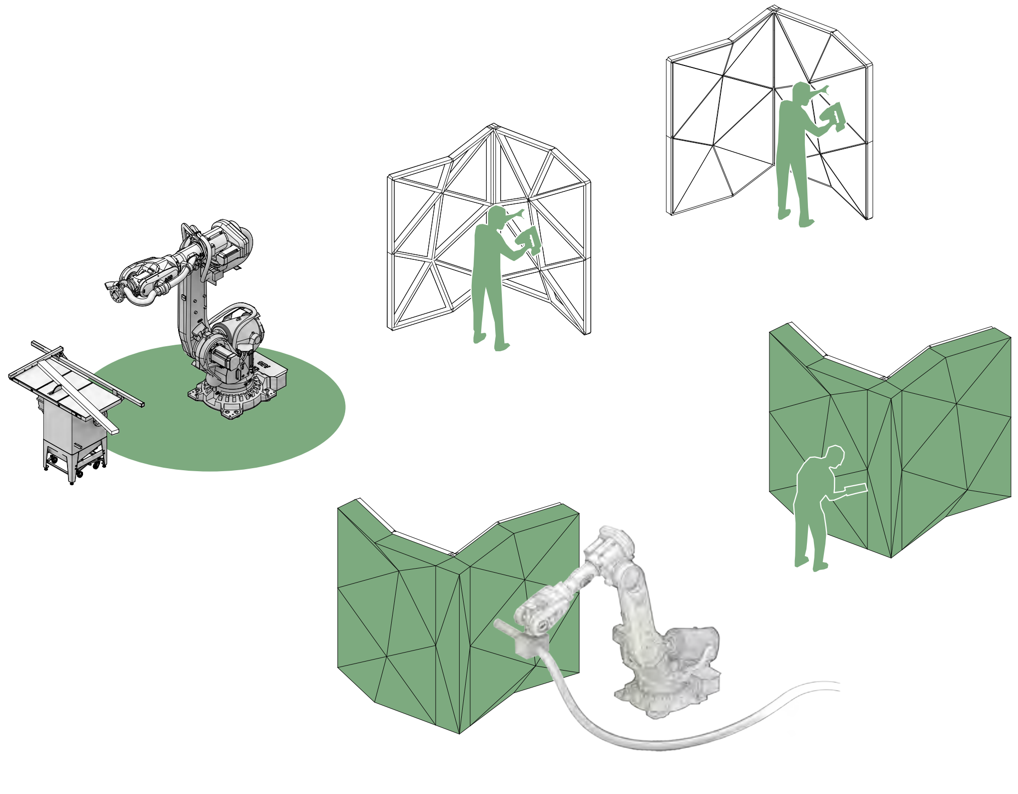


Figure 69: Proposed workflow for articulated timber structure and formwork that increases architectural expression in hempcrete construction

5.5.2 Application

Figure 70 is the author's artistic impression of what the proposed system would look like in an architectural context. The interior walls of the residence are exposed hempcrete, providing visual interest and warmth, while the overall form of the walls cut planes at different angles and dictate how people interact with the space.

Figure 70: Author's artistic impression of the architectural implementation of the proposed system

5.5.3 Critical Analysis

There are some glaring problems with the system in its current state. The first is the problem with members intersecting at different angles, causing overlap at the joints. This is inevitable with a non-hierarchical system; however, it can be remedied in the hierarchical system by introducing another hierarchy in terms of member cross-section size. This was done successfully by Hensel (2021) and Søndergaard et al (2016, p.196). This is not necessary for aesthetics but instead to simplify the assembly, as the timber frame will eventually be covered with hempcrete. Coincidentally, assembly is another issue with the system. It cannot be assembled on a flatbed as it is not two dimensional, so assembly must be constructed in mid-air. The robot could foreseeably help with this but would be hampered by unknown construction tolerances and human error. Problems also arise when attempting to determine how much hempcrete should be applied to the wall as there are no guiding features that assist the human worker in ascertaining when the 300mm minimum thickness has been applied to the wall. With these issues in mind, it was time to go back to first principles.

ROBOTIC VERNACULAR

SIX

6.1.0 First Principles

The initial research question can be boiled down to a more explicit directive: how would a robot help build a hempcrete house? To answer this question, one must consider the tasks the robot can perform. The ABB IRB6700 robotic arm in the Wellington Faculty of Architecture and Design Innovation workshop can perform a multitude of functions; including, but not limited to, pick and place operations, CNC milling, incremental forming, freeform 3D extrusion, clay extrusion, and concrete extrusion – utilizing a range of supplementary end effectors. This thesis has already explored an adapted concrete extrusion workflow optimized for hempcrete – but now the tasks applicable to a timber-framed wall element filled with hempcrete must be identified and evaluated for their relevance in order to devise a robotically native concept (fig.71).

CNC milling enables the robot to manufacture mass-customised timber elements with no loss in efficiency. This allows increased formal expression and irregular geometry within a potential hempcrete wall through complex multi-planar CNC milled connections.

Grippers enable pick and place operations to assemble complex modules out of individual components. This facilitates robotic assembly of the frame elements of a hempcrete wall to a high level of accuracy, reducing human labour.

While not currently available in the WFADI workshop, it is foreseeable that the robotic arm could assist in applying hempcrete infill to a timber wall module with a spray applicator end effector. This would speed up the process of applying the hempcrete mixture, which would free up human labour for other tasks.

6.1.1 Critical Reflection

Ultimately, the robot can perform a multitude of tasks. Its versatility creates a closed system workflow for manufacture and assembly, simplifying the process by removing the need for other machinery. While a mixing machine is still required to combine the hempcrete mixture, when compared to the conventional workflow the robot can effectively take the place of the table saw and drop saw while supplementing the work of the human labourer.

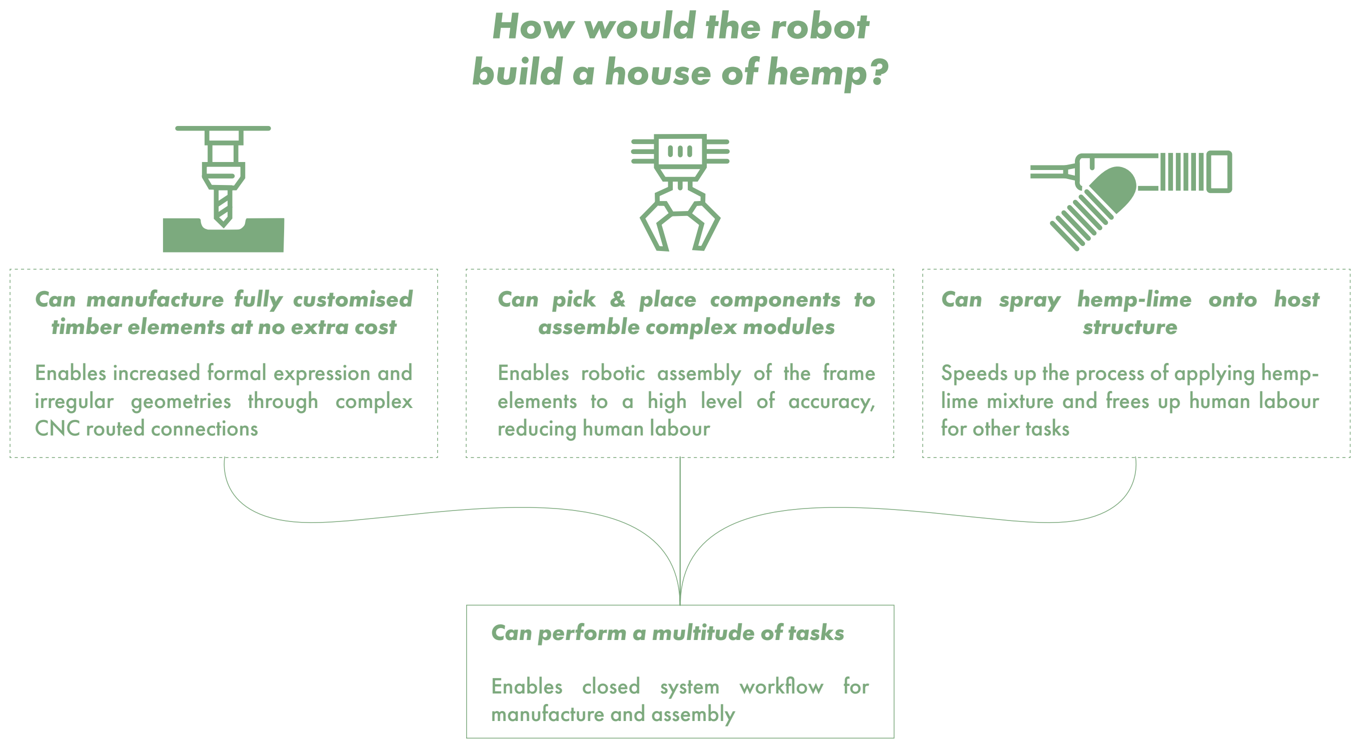


Figure 71: The relevant capabilities of the ABB IRB6700 Robotic Arm

6.2.0 Designing for Robotic Fabrication

The revised concept draws on the robot's strengths to optimise the hybrid workflow and ultimately accelerate the uptake of hempcrete construction (fig.72).

- All 18mm plywood CNC milled by the robotic arm with spindle end effector

- Slotted connection detail to allow friction fit assembly by robot

- Double 100mm structure with 100mm gap to prevent thermal bridging

- 300mm deep sidings to accommodate hempcrete infill

- Triangular plywood lost formwork panels direct fixed to framing

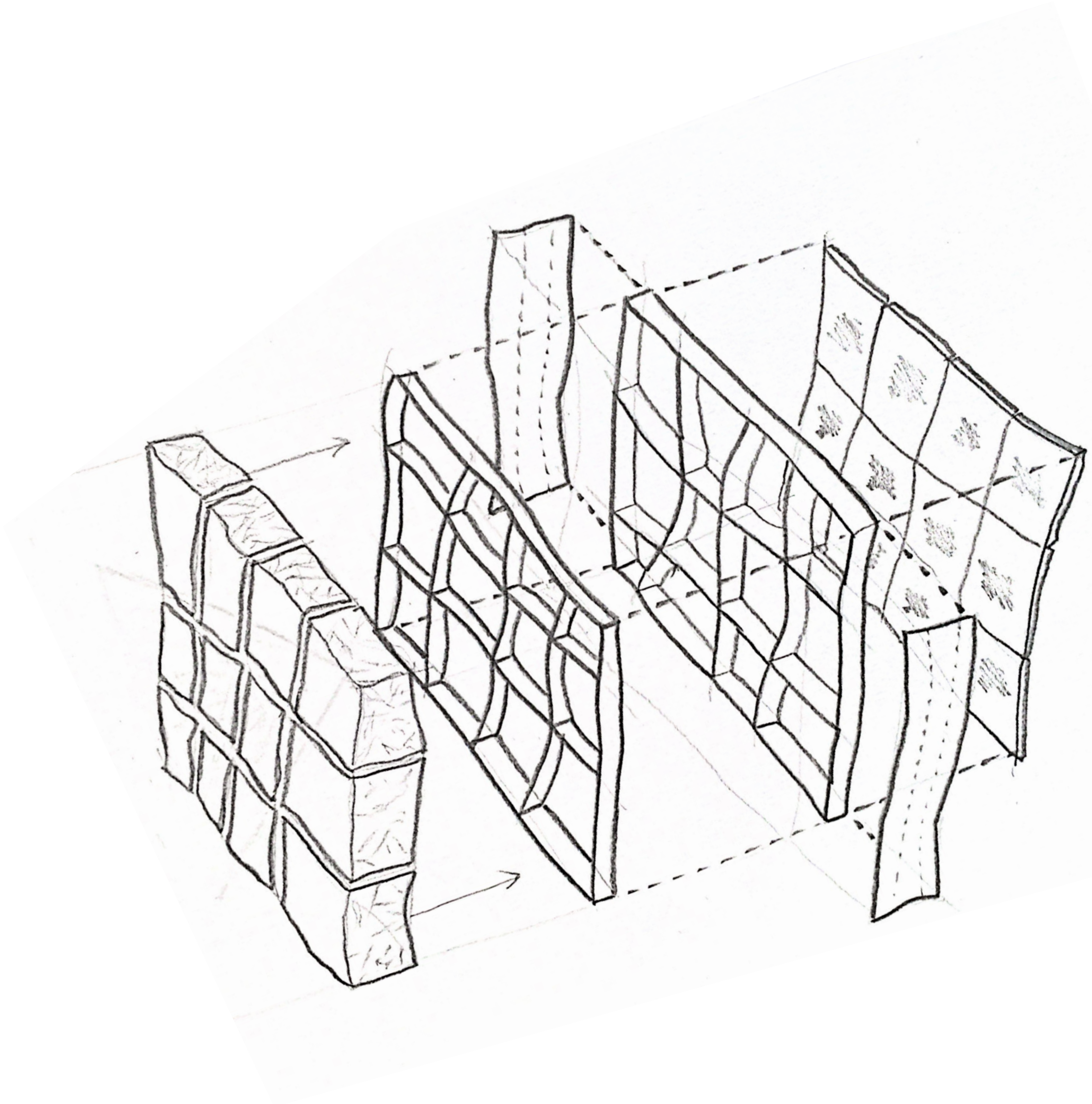


Figure 72: The new design is a thermally broken, friction-fit plywood raft

6.2.1 Joint Complexity

The slotted connection details of the plywood raft structure present a challenge. Having multiple intersecting members will increase the complexity of the joint and weaken the individual components as well as the entire system at each node. To accommodate three intersecting members, 66% of the width must be removed from each member, leaving only 33%, which creates a significant weak point and reduces the durability of the individual components. A member might flex or sag at the weak point when picked up by the robot, affecting the robot's ability to position the member and assemble the module accurately. By simplifying the structure and allowing only two members to intersect at a given point, only 50% of the width must be removed from each member, resulting in much more durable individual members and a stronger system.

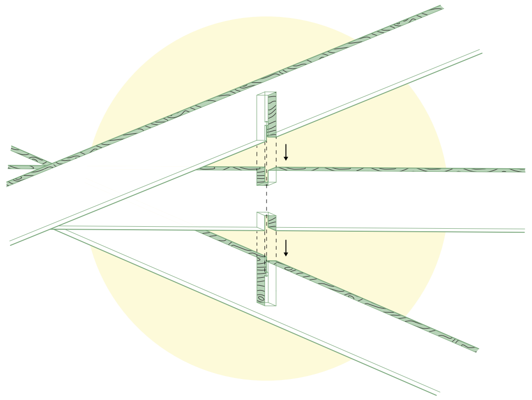


Figure 73: Three intersecting members creates complexity in the joint and makes each individual member weaker as the slots in each component must be deep enough to accomodate the extra component

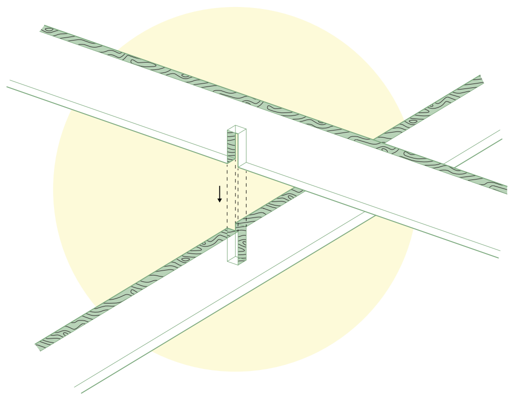


Figure 74: Simplifying the connection by avoiding having more than two members intersecting at any given point stengthens the system as a whole by ensuring that the slots need only cut halfway into each component

6.2.2 Structural Logic

The double crosshatch layout was chosen to avoid more than two members intersecting. Although not structurally tested, this was deemed to have the most potential for design complexity while maintaining structural integrity. The double lines provide support for all the intermediate formwork panels without sharing supports with adjacent members and requiring fixing too close to the edge of the panels (fig.75). This is important not only for durability but also for the aesthetics of the finished system, as the plywood formwork is the interior finished face.

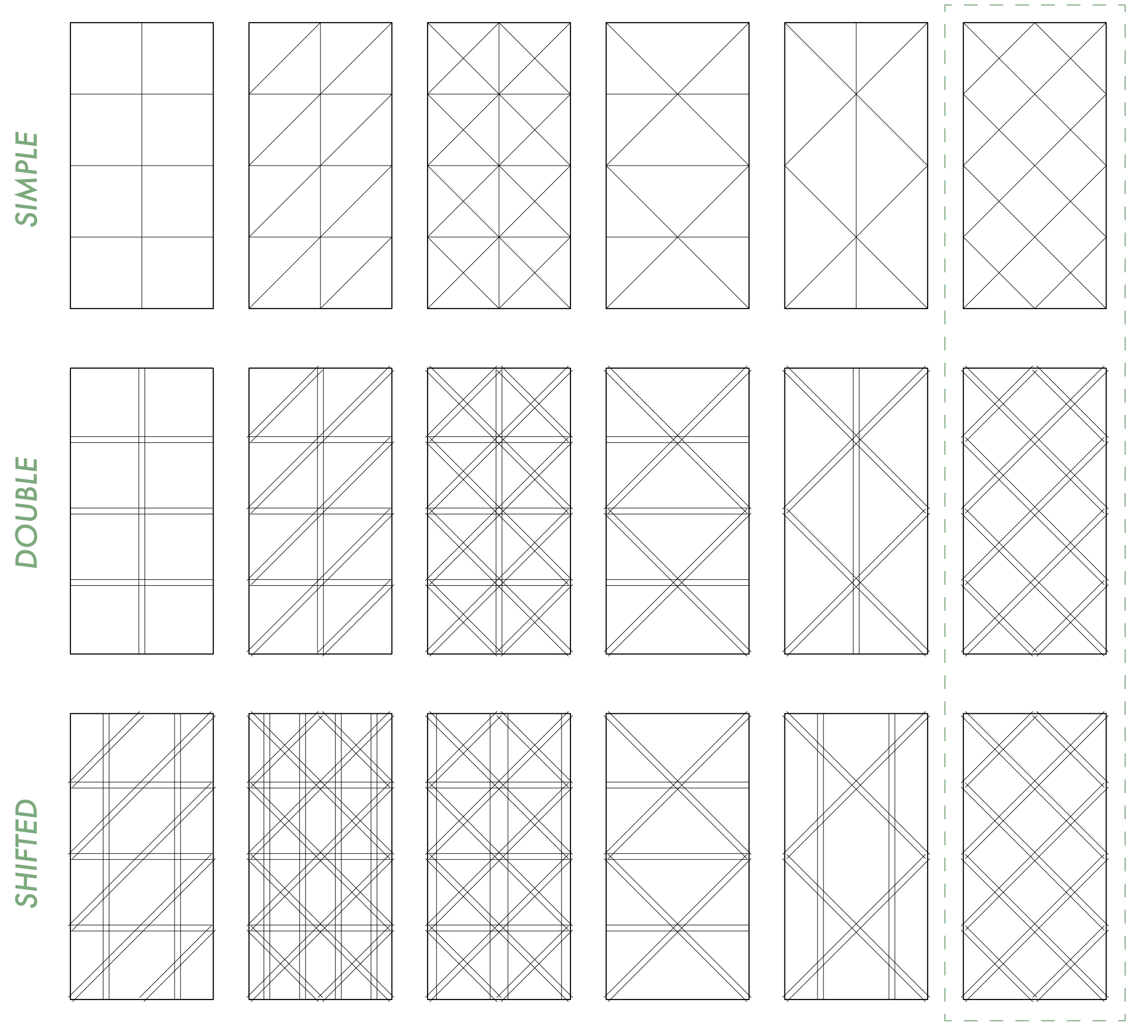
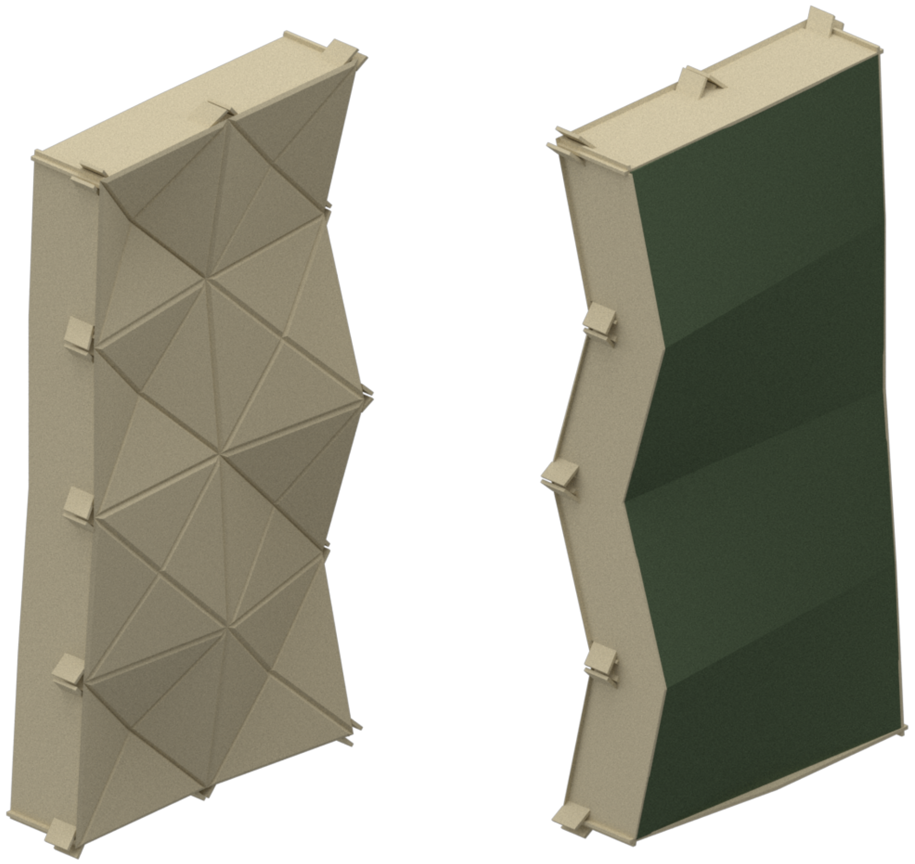
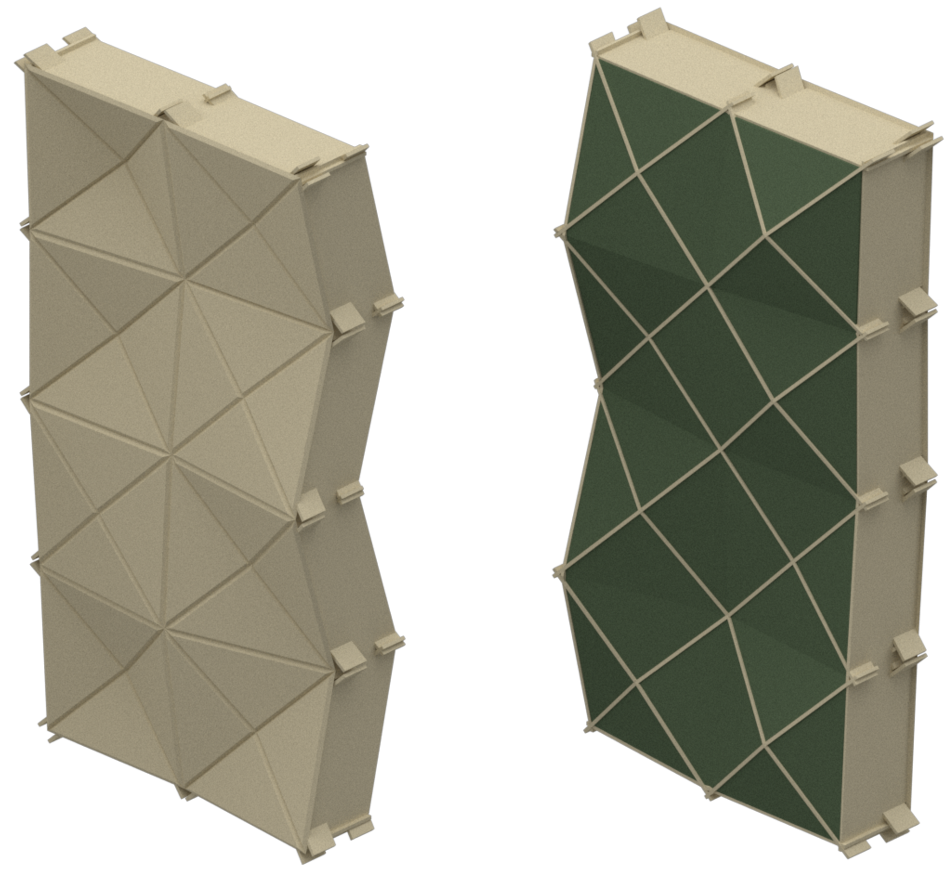


Figure 75: A range of structural layouts were explored but the double crosshatch was chosen as it avoids intersections of more than two members



Option 1

Ruled surface



Option 2

Compartmentalised surface

Figure 76: Ruled surface

Figure 77: Compartmentalised surface

6.2.3 Assembly Sequence

The proposed system would be assembled primarily by the robot with assistance in the initial stages by a human worker. For ease of assembly, the module would be laid flat on the ground. Firstly, the side boards would be slotted together, followed by the double crosshatch members before the triangle formwork panels would be fitted and fixed. In the compartmentalised design, the module would be flipped to complete the assembly of the guide rails on the external side. In the final step for both the ruled (fig.76) and compartmentalised (fig.77) designs, the module would be stood up, positioned in-situ, and sprayed full of hempcrete mixture by the robot.

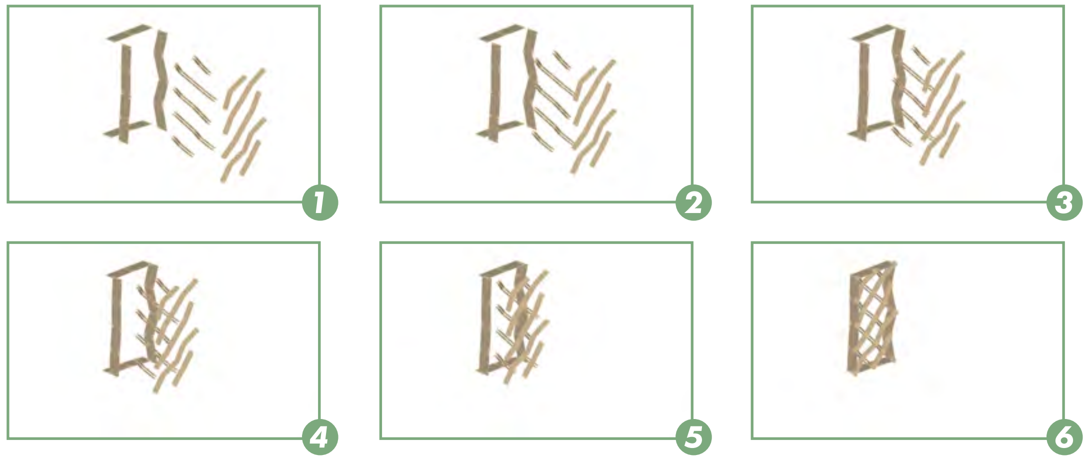


Figure 78: Assembly of frame

Figure 79: Assembly of panels

https://youtu.be/gZRewEF_bVs

Reverse side: Ruled surface

Figure 80: Addition of hempcrete

Reverse side: Compartmentalised surface

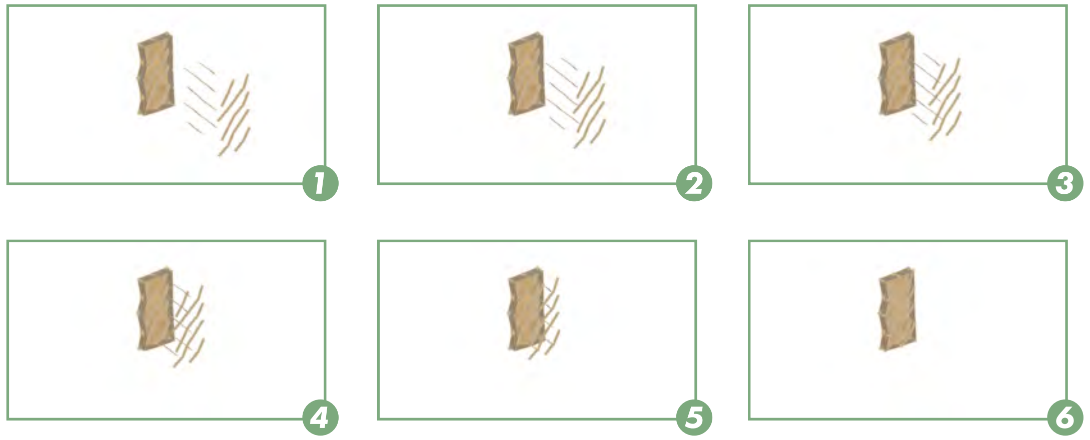


Figure 81: Assembly of frame

Figure 82: Addition of hempcrete

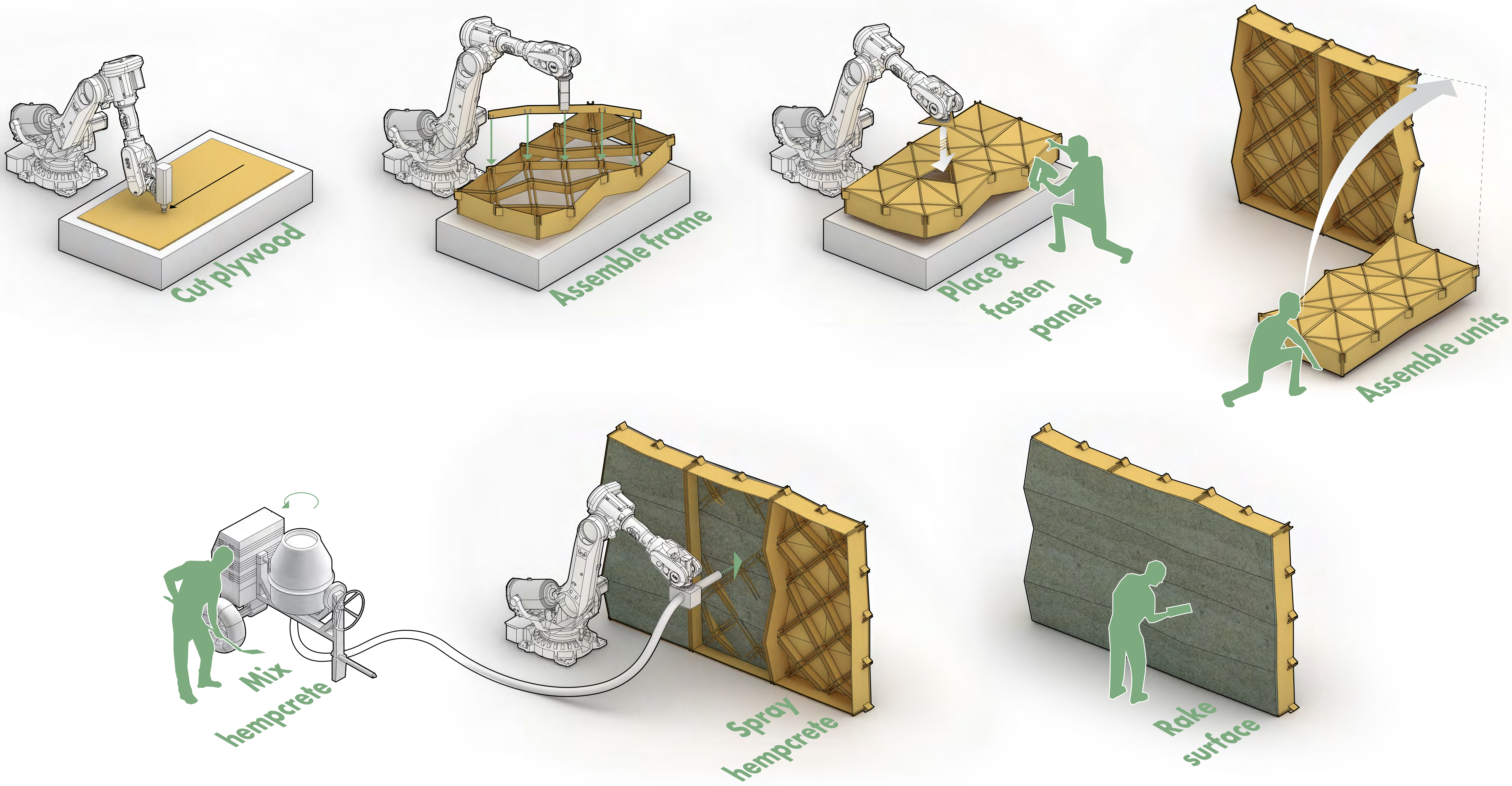


Figure 83: A hybrid workflow for hempcrete construction

6.3.0 Hybrid Workflow

With the frame and formwork now one synergistic system made entirely from plywood, the workflow for the manufacture and assembly of the geometrically variable hempcrete wall module is significantly more streamlined than that of the design proposed in Chapter 5. Firstly, the robot cuts the plywood shutters and frame members using the CNC milling spindle. Secondly, the human worker helps slot the sides together, and the robot assembles the frame. Once the shutter panels have been placed by the robot and fixed by the human worker, multiple units can be arranged to form a wall. Next, the human worker mixes the hempcrete for the robot to spray into the wall cavity. Finally, the human worker quickly smooths the surface with a trowel to ensure an even finish.

6.3.1 Prefabricated vs. In-Situ Workflows

There are some critical differences in the workflow depending on when the modules are transported to site. The workflow depicted in figure 83 is void of context in this regard, and the entire system looks to be fabricated and assembled in one place. This could be so, with the robotic arm being transported and stored on site. Transporting the modules to site once the plywood components are assembled and having an on-site robot spray them full of hempcrete is also an option, demonstrated in figure 84. Alternatively, figure 85 shows how the robot could still spray the hempcrete during off-site prefabrication provided that the human worker can still bolt through the side walls of the modules to connect them and then fill the gap with supplementary hempcrete to seal it up. While this seems excessive, completing the primary hempcrete phase off-site in controlled conditions makes for more consistent and predictable drying times and reduces uncertainty in the construction schedule – a problem encountered with conventional hempcrete construction (Sparrow, 2014). Ultimately, the workflow depicted in figure 83 provides a basic framework that can be adapted for convenience on a project-by-project basis.

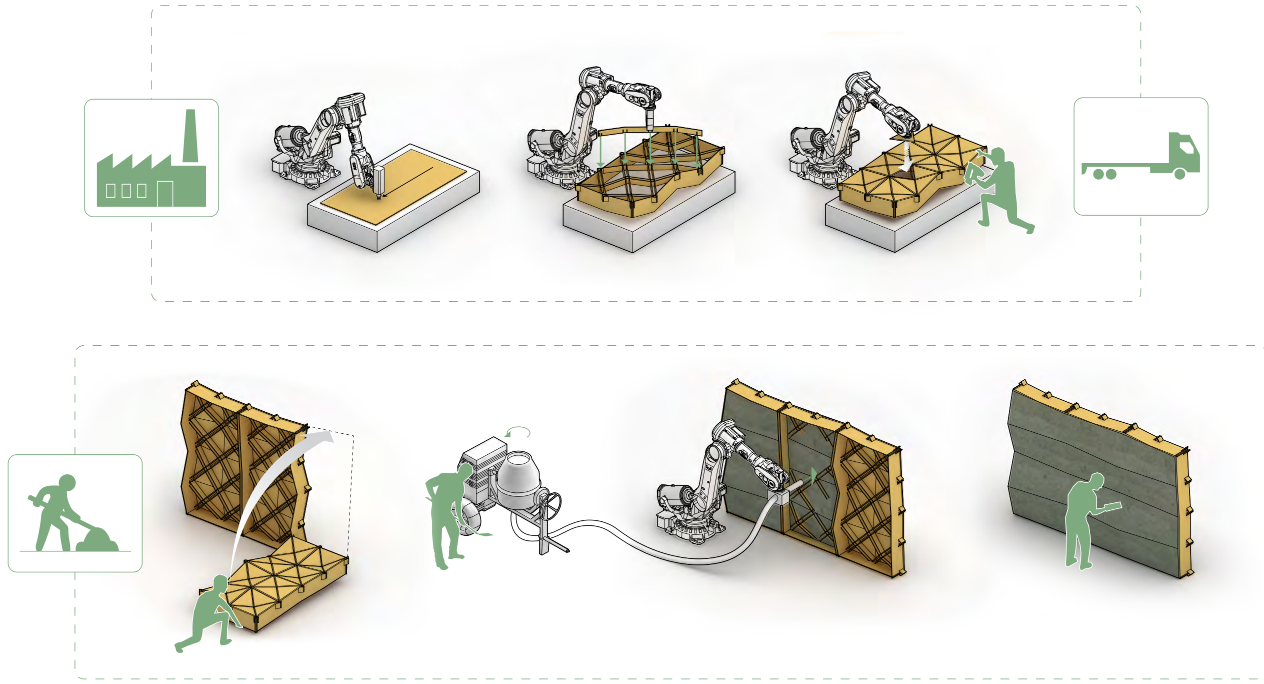


Figure 84: A workflow alternative where the robot conducts the sprayed application of hempcrete on-site

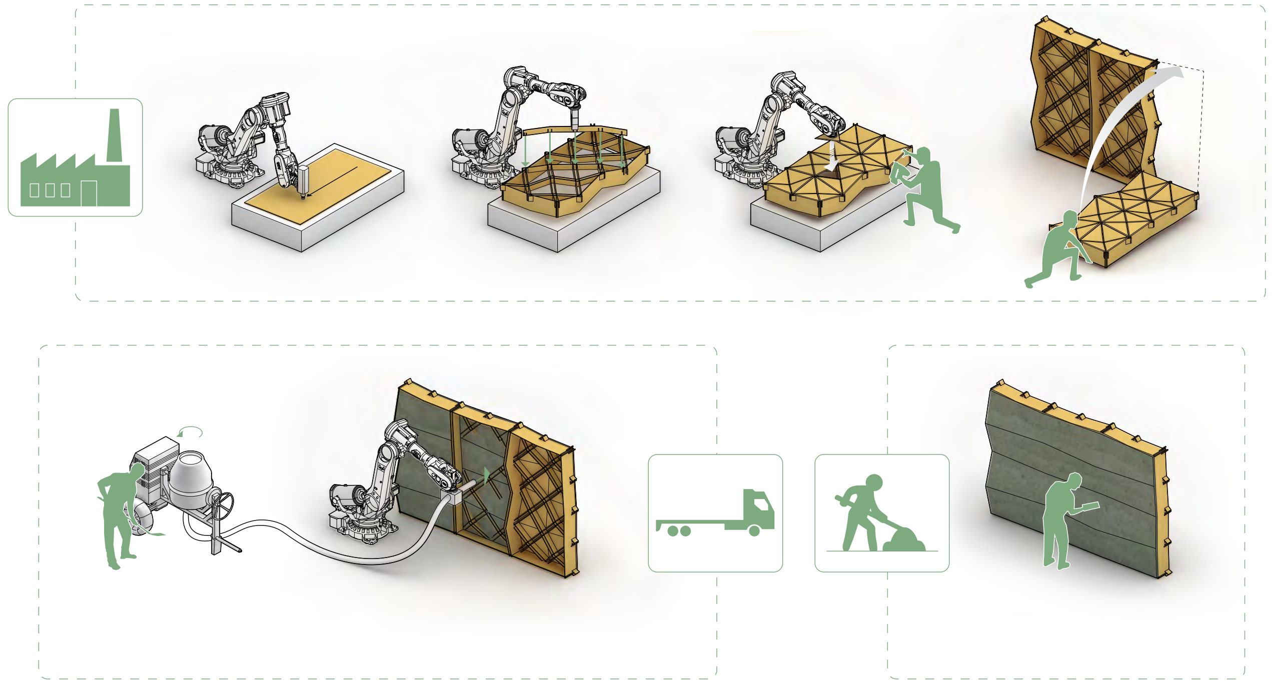


Figure 85: A workflow alternative whereby hempcrete modules are predominantly prefabricated

Conventional workflow

Task	Time (h)	Specialist Equipment
Measure and cut timbers by hand	0.50	Table saw, drop saw, PPE
Assemble frame	0.50	Impact driver
Assemble formwork	0.50	Impact driver
Mix hempcrete	2.72	Cement mixer, PPE
Cast and tamp hempcrete	5.28	Bucket, makeshift tamping tool
Remove formwork	0.08	Impact driver
Total	***9.58***	

Hybrid workflow

Task	Time (h)	Specialist Equipment
CNC route components with robot	4.00	CNC spindle, robotic arm
Assemble frame with robot	1.00	Robotic arm
Affix panels by hand	0.50	Brad gun
Mix hempcrete and...	2.72	Cement mixer, PPE
...spray hempcrete with robot	0.17	Hydraulic attachment, robotic arm
Rake finish surface by hand	0.17	Straight-edge
Total	***8.55***	
Human contact time	3.55	

6.3.2 Critical Reflection

The hybrid workflow successfully improves upon the conventional hempcrete workflow. Introducing the robot frees up human labour that can be reallocated for other on-site tasks, speeding up the construction process. A 1200x2400mm wall element is estimated to take approximately eight and a half hours to manufacture and assemble using the developed system, compared to nine and a half hours using the conventional method. The author acknowledges that this is a marginal difference, especially considering the figures are estimates based on the construction of the 600x600x300mm module in section 5.1.0. Furthermore, experienced hempcrete builders will be able to achieve faster results. However, it is in the human contact time where the actual savings occur. Of the eight and a half hours estimated for the hybrid workflow, only three and a half hours involve a human labourer. This frees up time for human workers to work on other tasks, speeding up construction overall.

The design of the plywood module resolves a lot of the issues of the LVL design. The edge conditions have been addressed – allowing a guide rail to indicate when enough hempcrete has been pumped into the module. Thermal bridging due to these edges has been mitigated due to the reduction of bridging elements, and the intention is that the exterior will be fully covered in hempcrete, as depicted in the workflow diagram (fig.83). The triangular panel design is carried through from the earlier design stages but takes the "X" arrangement due to the crosshatch structure. The panels themselves are only fixed on two edges. This would be unsuitable for a concrete formwork system but is sufficient as hempcrete does not slump or bow the formwork, especially when it is sprayed (Allin, 2005). The friction-fit system reduces the complexity of assembly and enables the robot or an unskilled labourer to carry out such a task. Overall, the design is aesthetically unique and only achievable at scale with the robot's assistance due to the angles that must be CNC routed into the plywood and the proposed robotic assembly that reduces human contact time.

6.4.0 Design Variations

There are two variations of the concept – one with a ruled surface (fig.86) and the other with a compartmentalised hempcrete surface (fig.87). To establish which module was worth developing, they were implemented into elevations and visually compared against each other and the success criteria. The ruled surface creates more of a sculptural aesthetic that implies a geometric shift, while the compartmentalised design appears to be an articulated surface rather than having any formal implications. The compartmentalised design also requires additional plywood and human contact time. The ruled surface, therefore, was the obvious choice to take into the development phase.

Ruled surface

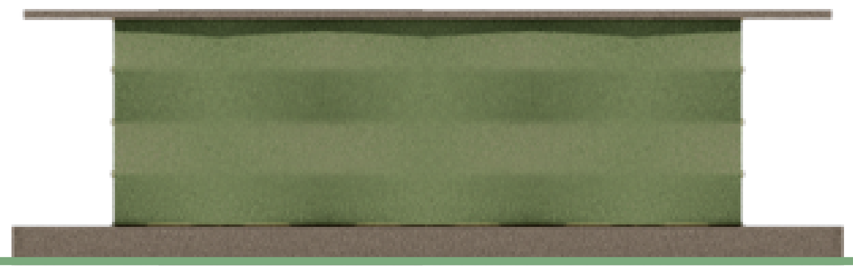


Figure 86: The ruled surface creates a sculptural aesthetic that is more of a geometric shift as opposed to an articulated surface

Compartmentalised surface

Figure 87: Breaking each face down into cells lends itself to better articulation but increases complexity of human involvement, as all cells must be individually raked

6.5.0 Design Development

In the design development phase, minor issues with the concept were addressed and resolved.

6.5.1 Edge Conditions

Firstly, the issue with the diagonal framing members extending past the side constraints of the module needed to be fixed for modules to be arranged next to each other and sit flat on the ground. This was an area of concern as the connections around the perimeter of the module technically exceed the 2-member intersection limit. This is avoided with the offset crosshatch design; however, it still presents some challenges. This was addressed by incorporating a nested sideboard, allowing members to connect to the sides while maintaining a flat surface on intermediary faces (fig.88).

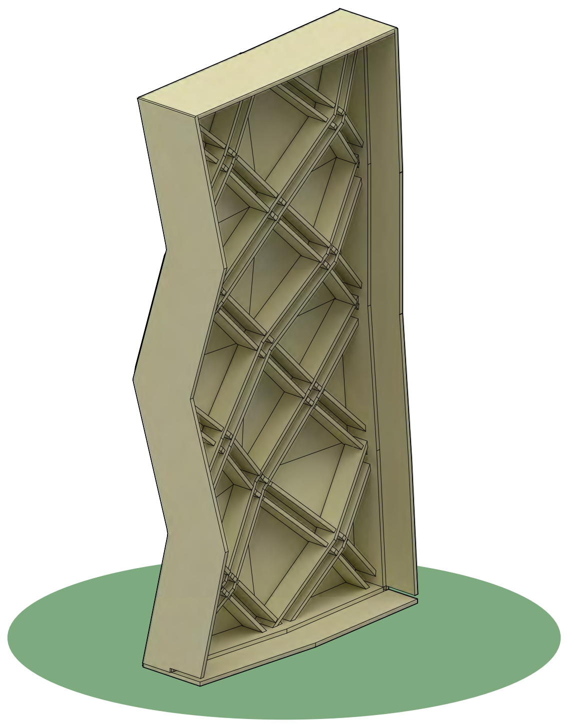


Figure 88: Double ply wall allows diagonal members to connect to the edges while removing the overlap and ensuring a flat surface for inter-module connection

6.5.2 Corners

Next, the joining of the boundary boards at the four corners of the module was addressed (fig.89). Overhangs were removed to ensure adjacent modules can be fixed side-by-side. While not friction fit, the boundary boards are affixed to their respective nested sideboards prior to assembly to become one piece in the workflow.

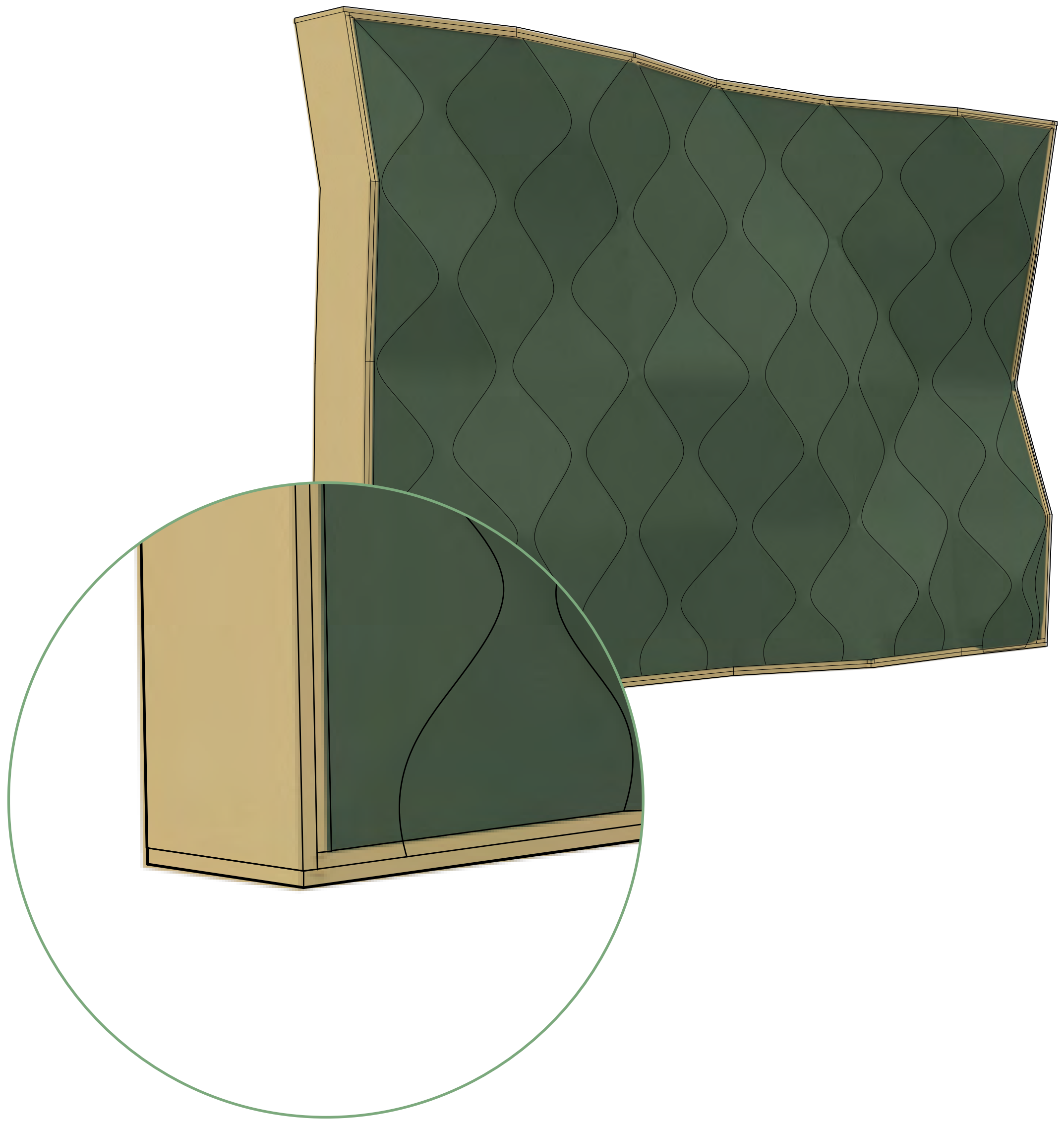


Figure 89: External corners consist of abutting boards to enable modules to sit flat on the ground and flush with adjacent modules

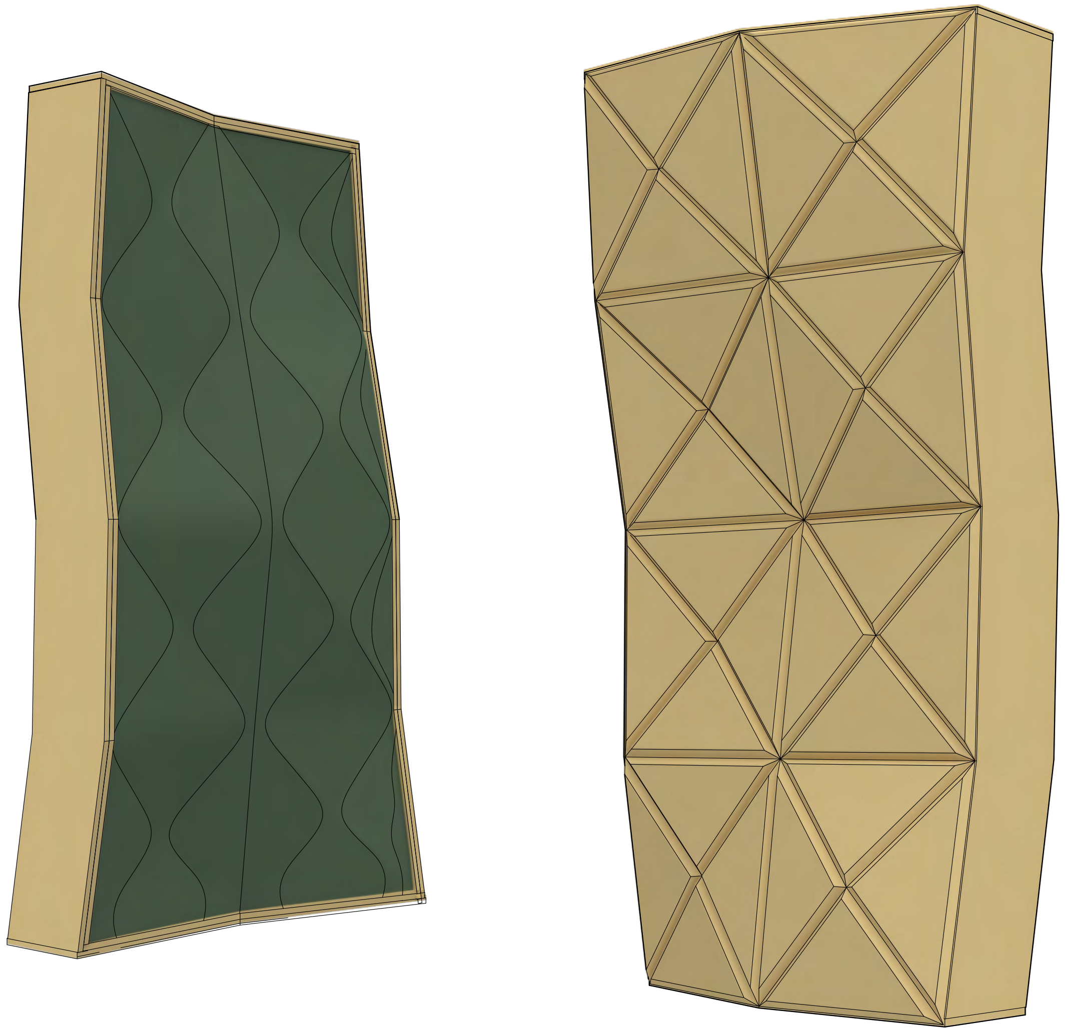


Figure 90: External and internal surfaces of single module

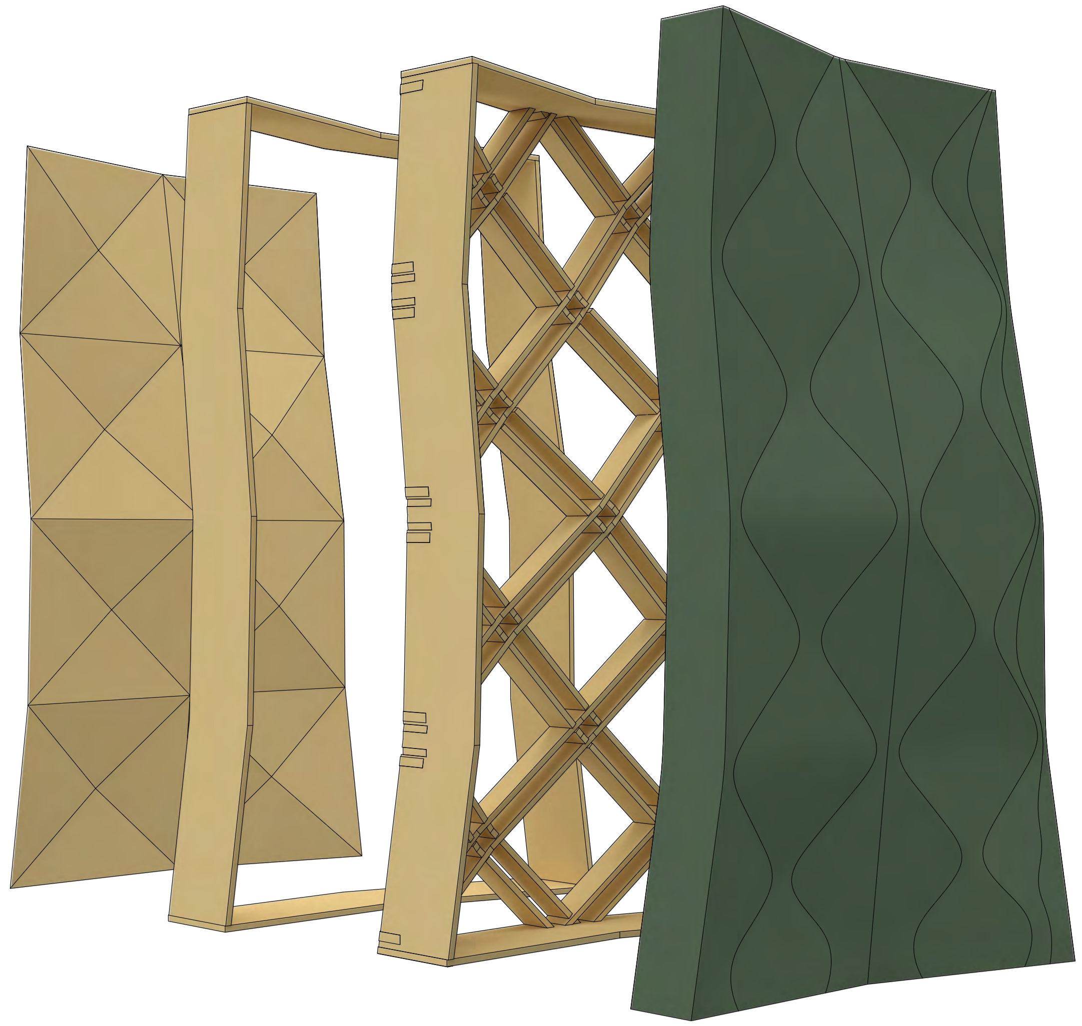


Figure 91: Exploded view of single module

6.5.3 Aesthetic

With the technical issues of the system ironed out, it was time to explore the geometric potential of the system. But not before testing how the developed design would look in architectural application (fig.92-94).

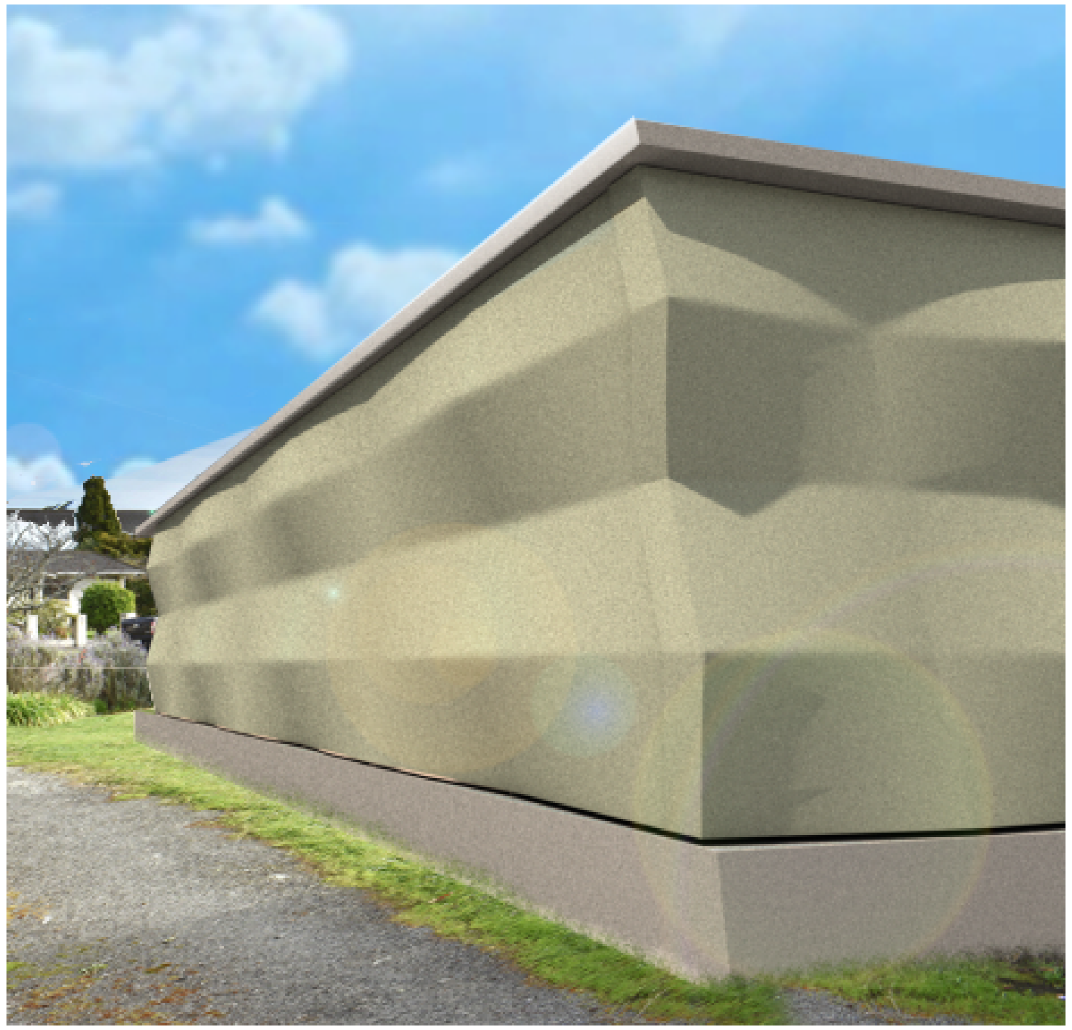


Figure 92: External corner of finished hempcrete module construction

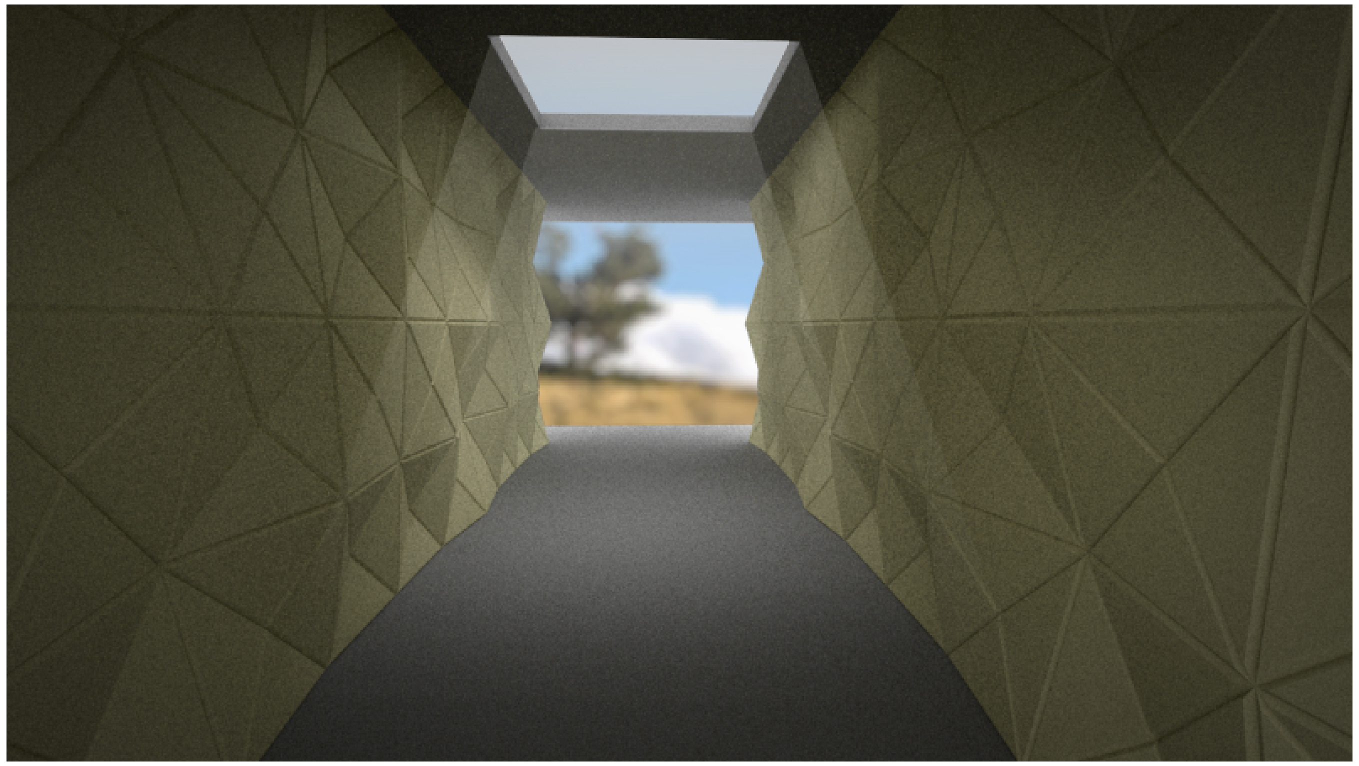


Figure 93: Interior hallway with hempcrete module walls, plywood internal face

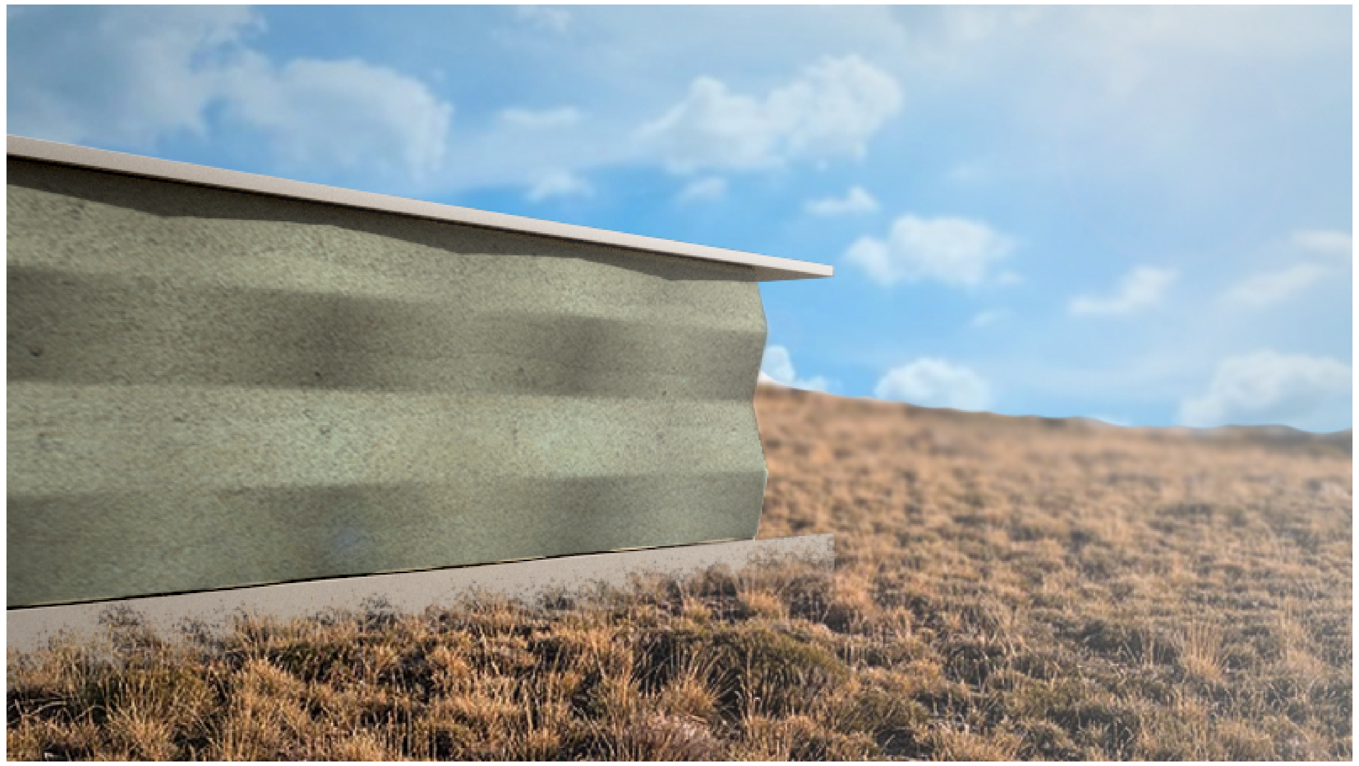


Figure 94: Exterior finish of hempcrete module construction


SYSTEM
DESIGN
SEVEN

7.1.0 Introducing Geometric Variation

The parametric Grasshopper script enables the designer to quickly iterate between point cloud arrangements to achieve architectural expression through geometric variation. Simply by changing the seed count, a range of designs can be generated. Figure 95 shows the versatility of the parametric system and a range of possible outcomes.

Figure 95: Geometric variations of a single module, generated quickly by adjusting the seed value to parametrically manipulate point attractor logic in the Grasshopper script

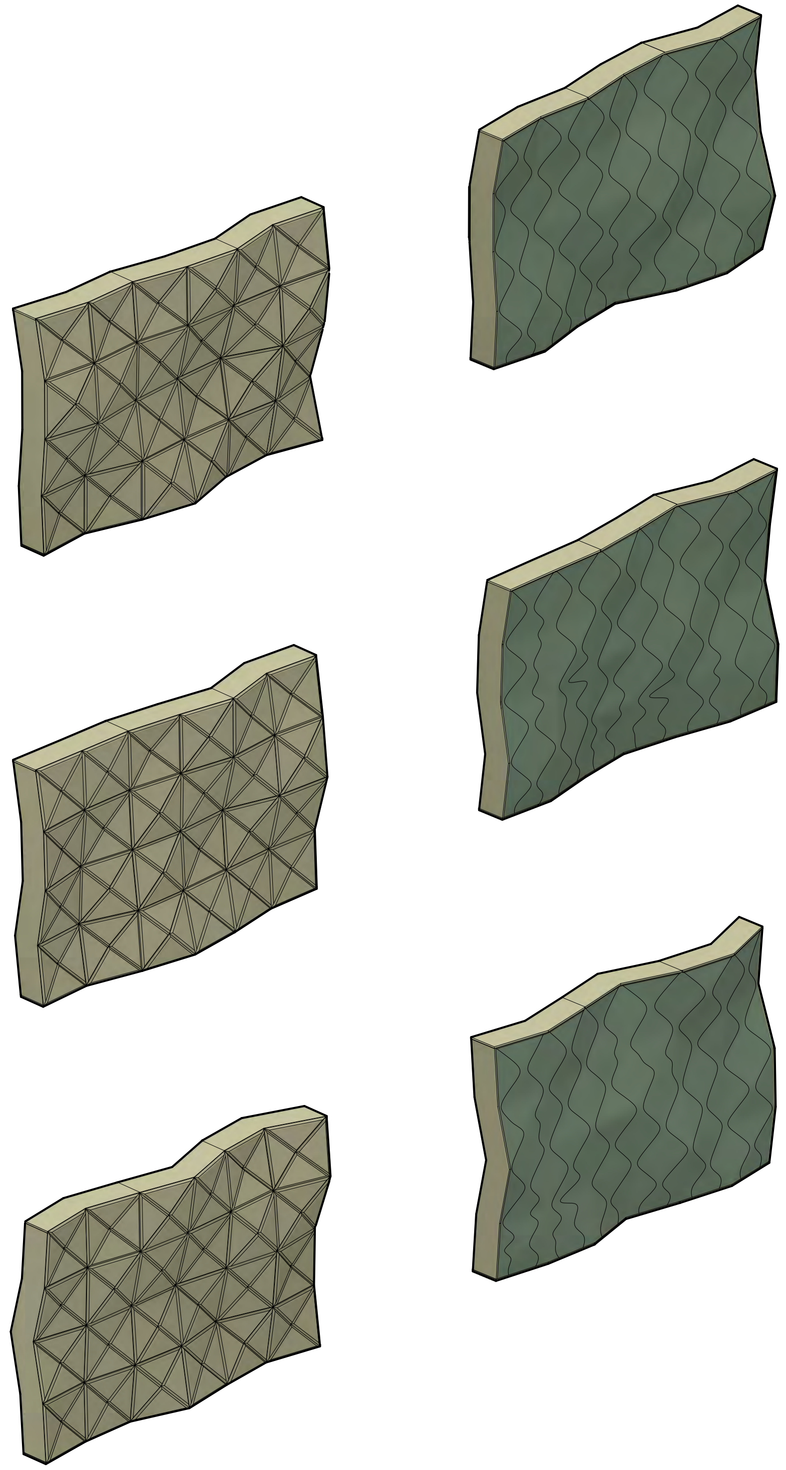


Figure 96: Three geometrically varied alternatives for a 3-module wall element

7.2.0 Corner Module

To achieve greater architectural expression through geometric variation, the system must be able to generate multi-dimensional solutions, or it will remain a surface articulation. By designing a corner panel, wall panels can be connected to form an enclosed space – form defining space is a key principle of architecture. A system that manipulates form as well as surface can dictate how users interact with and inhabit architecture.

Three options were explored for the structure of the corner module. The first option is a simple raft with vertical and horizontal members that fill the depth of the module, forming compartments (fig.98). This was too different from the diagonal logic of the base modules and created a lot of thermal bridges. Secondly, an attempt was made at a diagonal system similar to that of the base module (fig.99). Due to the two-dimensionality of plywood and the three-dimensionality of a curved corner, this had limited success. It is easy to see that a lot of material is required to fabricate some of the diagonal spans, and their curving nature increases waste when cut from a sheet of plywood. The third option reverts to the vertical and horizontal spans but introduces a thermal break between internal structure and external guide rails (fig.100). While these guide rails would be covered with a thin layer of hempcrete and not be visible in a finished architecture, they help the human worker define the curve of the corner.

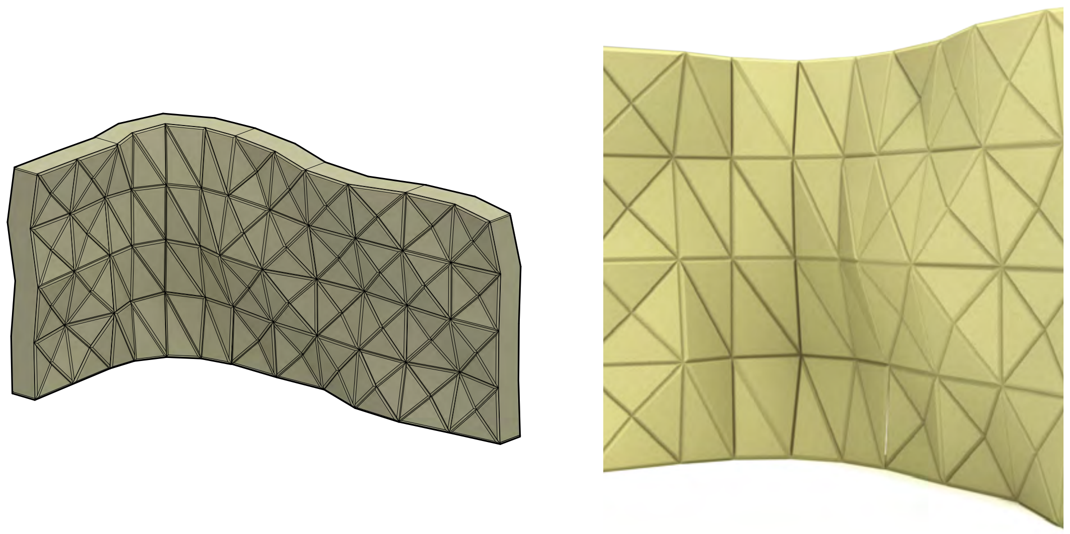


Figure 97: The plywood formwork panels on the internal corner approximate right-angled triangles as they must attach to the orthogonal structure within the wall

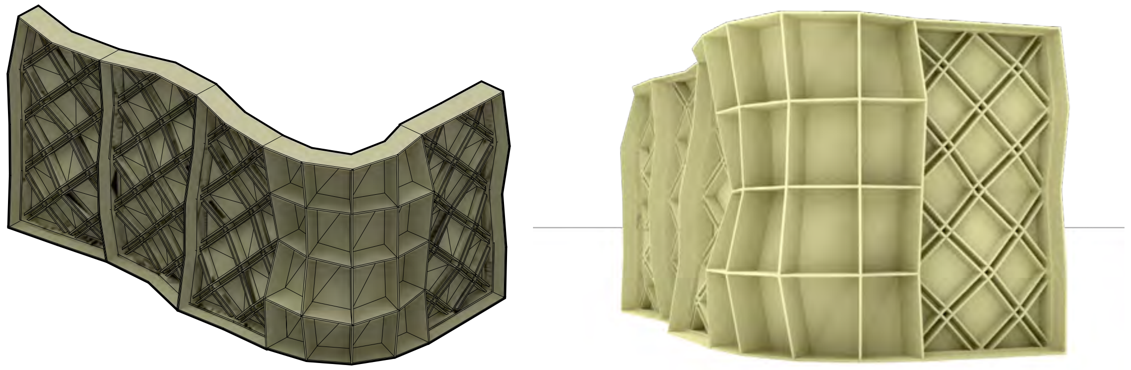


Figure 98: Option 1 - an orthogonal raft structure that fills the depth of the module

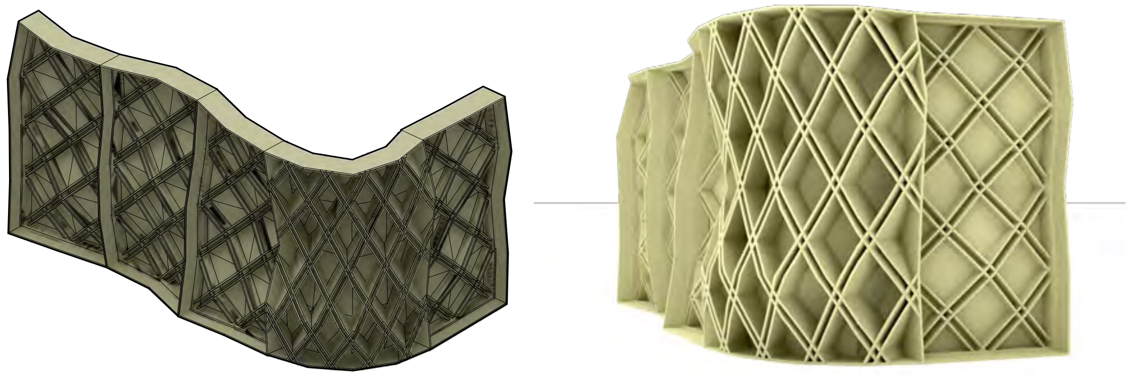


Figure 99: Option 2 - a diagonal crosshatch raft structure cannot account for the two planes of the corner

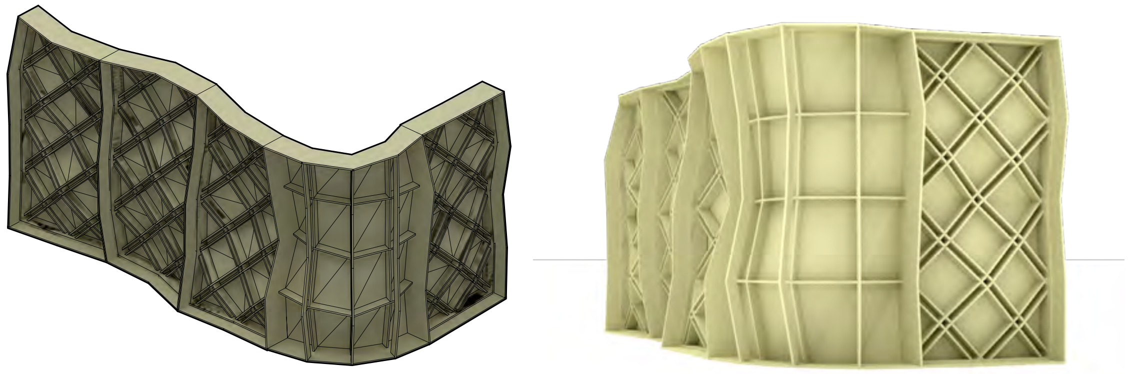


Figure 100: Option 3 - a thermally broken orthogonal raft structure provides guide rails to ensure the hempcrete is finished to the appropriate level

7.3.0 Robot Testing

Testing with the robot was carried out to aid understanding of the proposed workflow and iron out any design issues. Due to time constraints, this was limited to the 6-axis CNC milling of two facing panels as a proof of concept and to test the angled edge fabrication. The Grasshopper script converted the geometry into a toolpath comprised of a series of angled planes for the CNC milling tool to follow in a seamless sweeping motion. Scan the QR code below to see the robot in action.

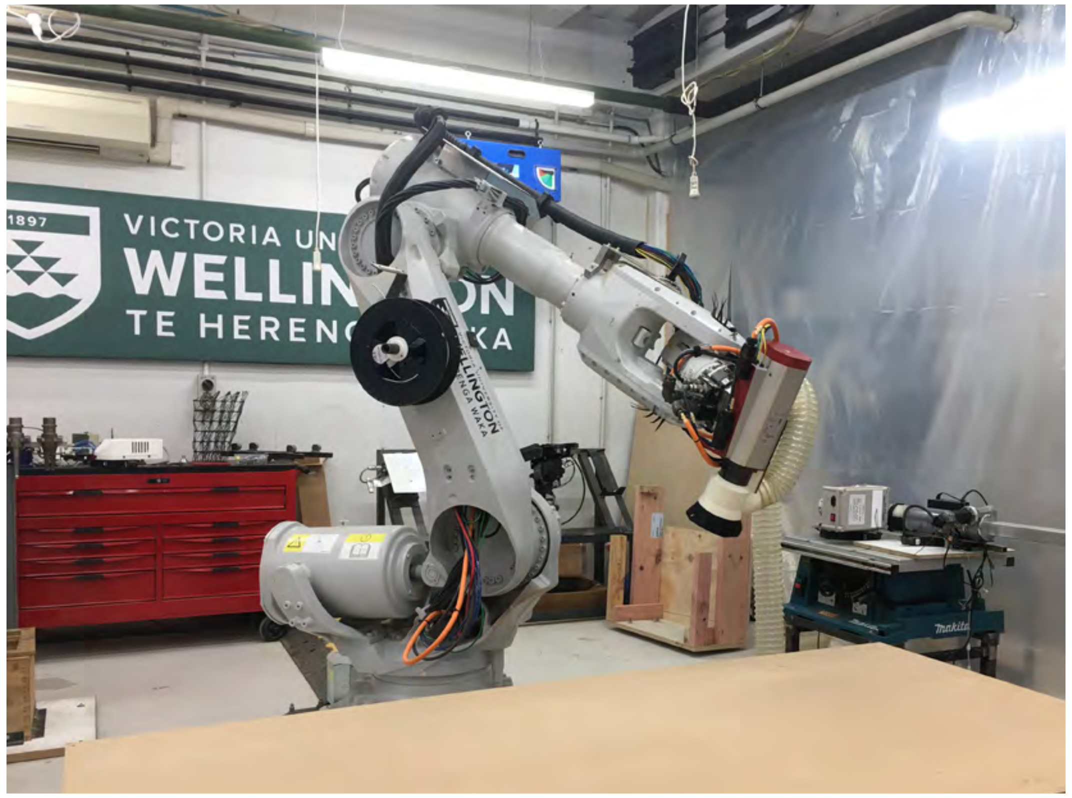


Figure 101: Robotic arm in WFADI workshop with CNC spindle tool and dust extraction vacuum attached

https://youtu.be/gkIADQnjZKI

7.3.1 Critical Reflection

The planes were angled to stop the stepped effect that would occur on an angled edge due to the 3mm contours of the toolpath. This is avoided entirely if the CNC milling bit is oriented parallel to the intended finished edge at 45°. However, simulations conducted prior to execution of the script showed that the maximum angle had to be reduced to 26° to avoid collisions between the robot and the table. As such, the step effect is evident in the finished panels (fig.102). 45° is theoretically achievable using a longer spindle, providing more space between the robot and the table. Alternatively, orienting the planes so that the spindle cuts perpendicular to the finished edge would reduce the required angle at the corners, but since the edges will still be cut at 45° they will remain stepped unless additional strategies are implemented. Nevertheless, robot testing provided valuable insight into the fabrication process that can inform further design development.

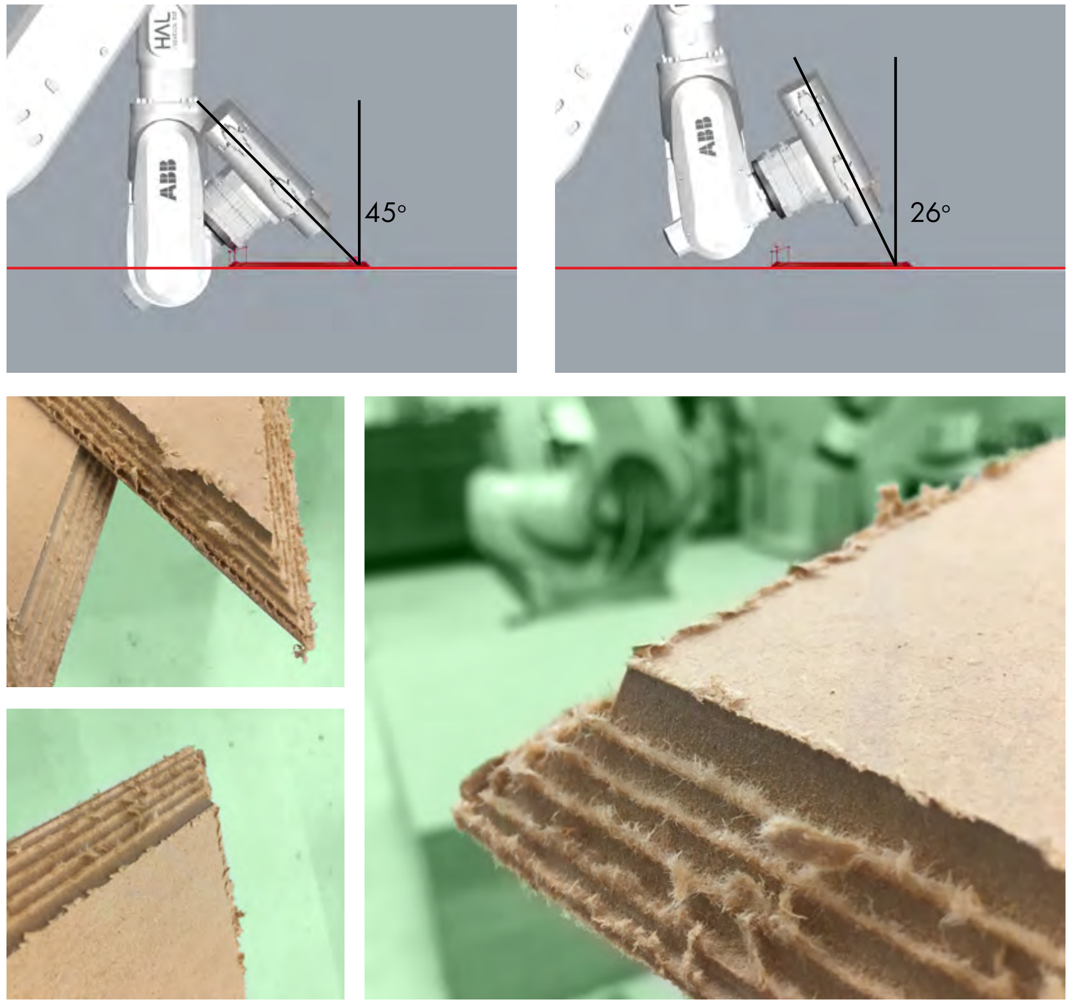


Figure 102: The angled edges of the triangular panels were approximated with an angle of 26° to avoid the robot colliding with the table

7.4.0 Design Alterations

Milling the panels revealed that the robot cannot accurately cut at angles greater than 26° from vertical. To account for this, the design of the panels can be adjusted to reduce the angles that need to be cut for any given panel regardless of the design iteration. Instead of a universal 45° angle on each edge that increases at the corners, edge angles should be determined by the angle at which it intersects with its neighbour. Moreover, all edges should be cut perpendicular to the wall normal so that there is no inherent assembly sequence (fig.104). This simplifies the assembly process and also means there are no angles greater than 45°, and for any angles still greater than 26° the strategies detailed in section 7.3.1 can be implemented.

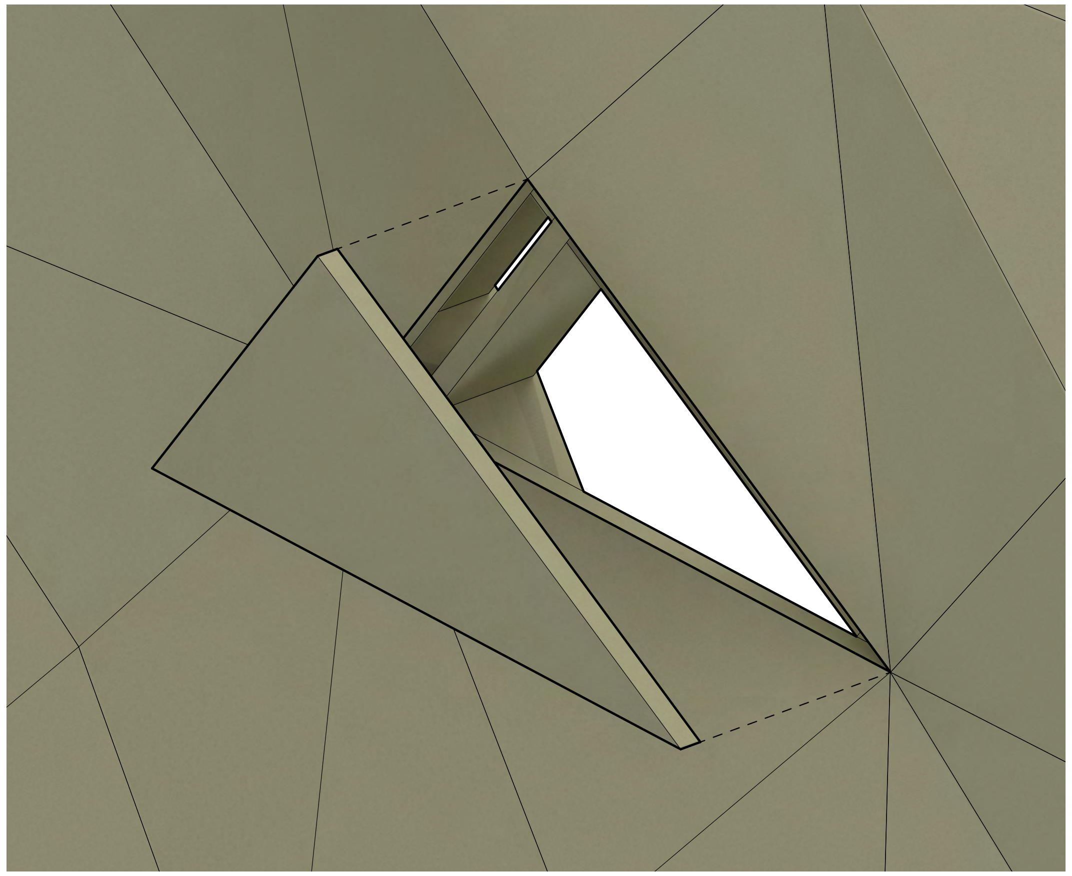


Figure 103: The edge angles of each triangular panel are perpendicular to the wall normal

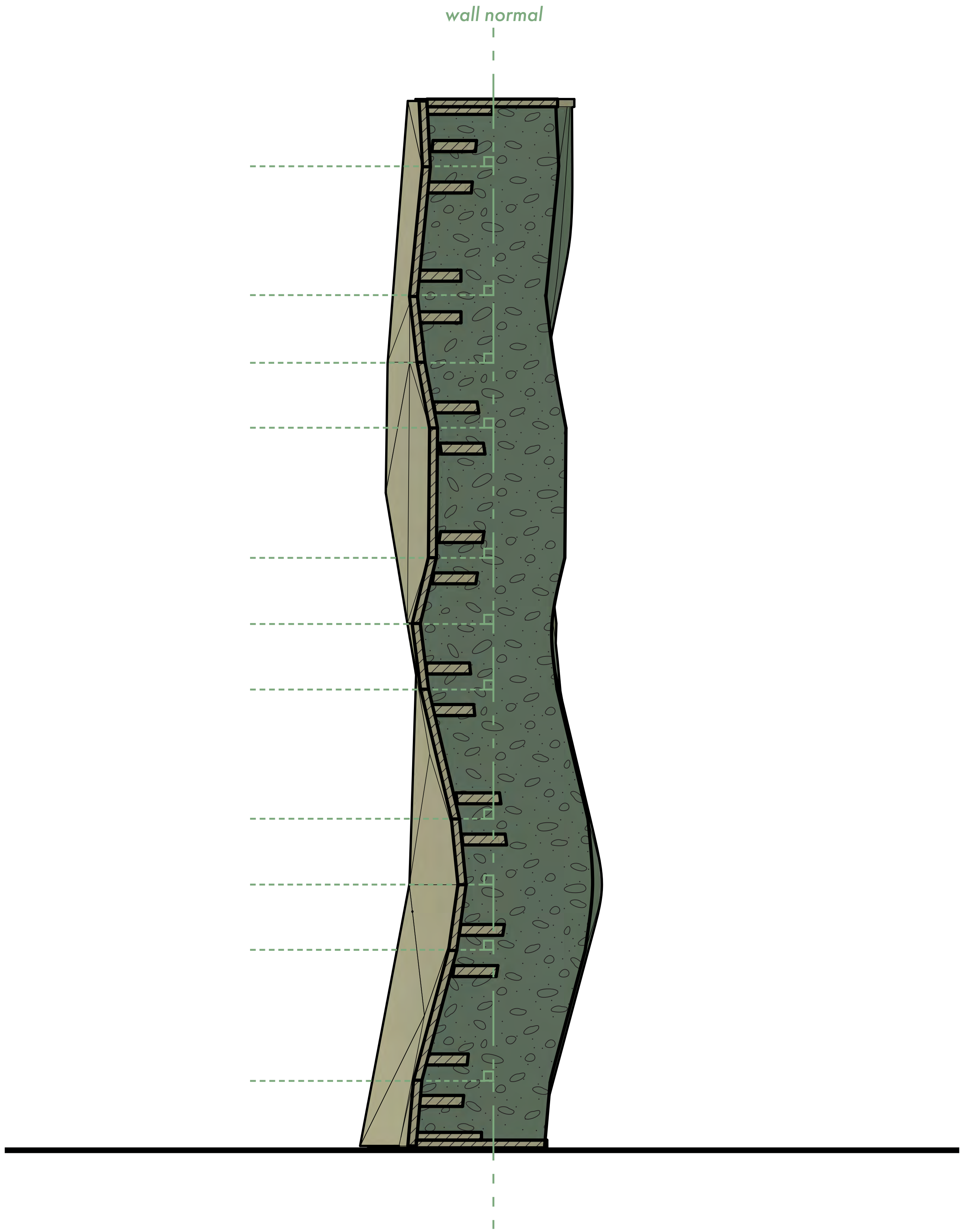


Figure 104: A cross section through the module shows the new panel logic

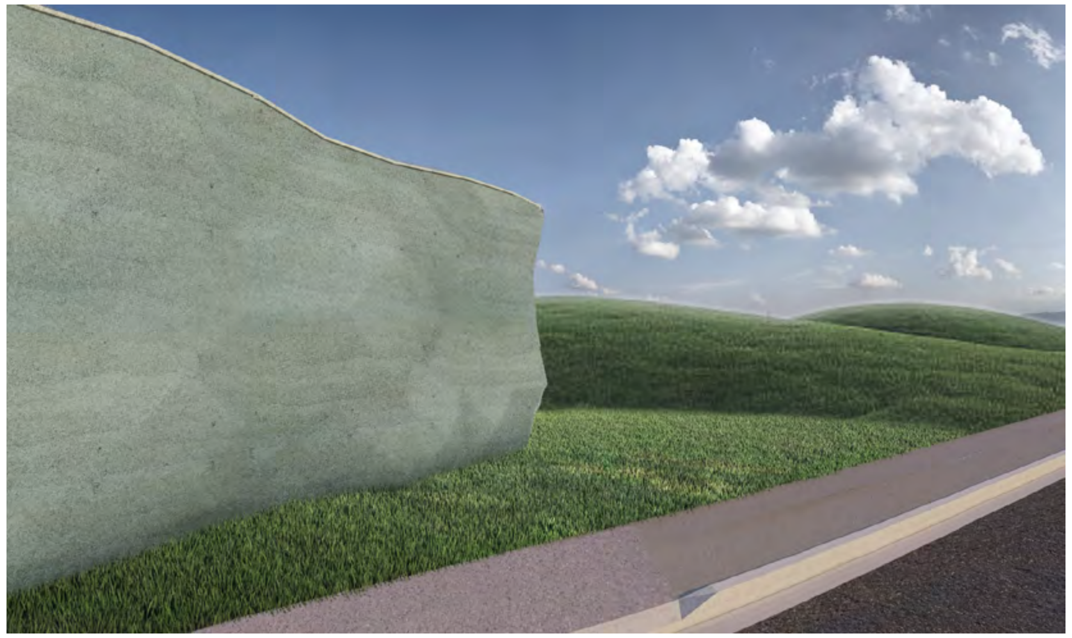


Figure 105: Architectural implementation of the modular hempcrete system

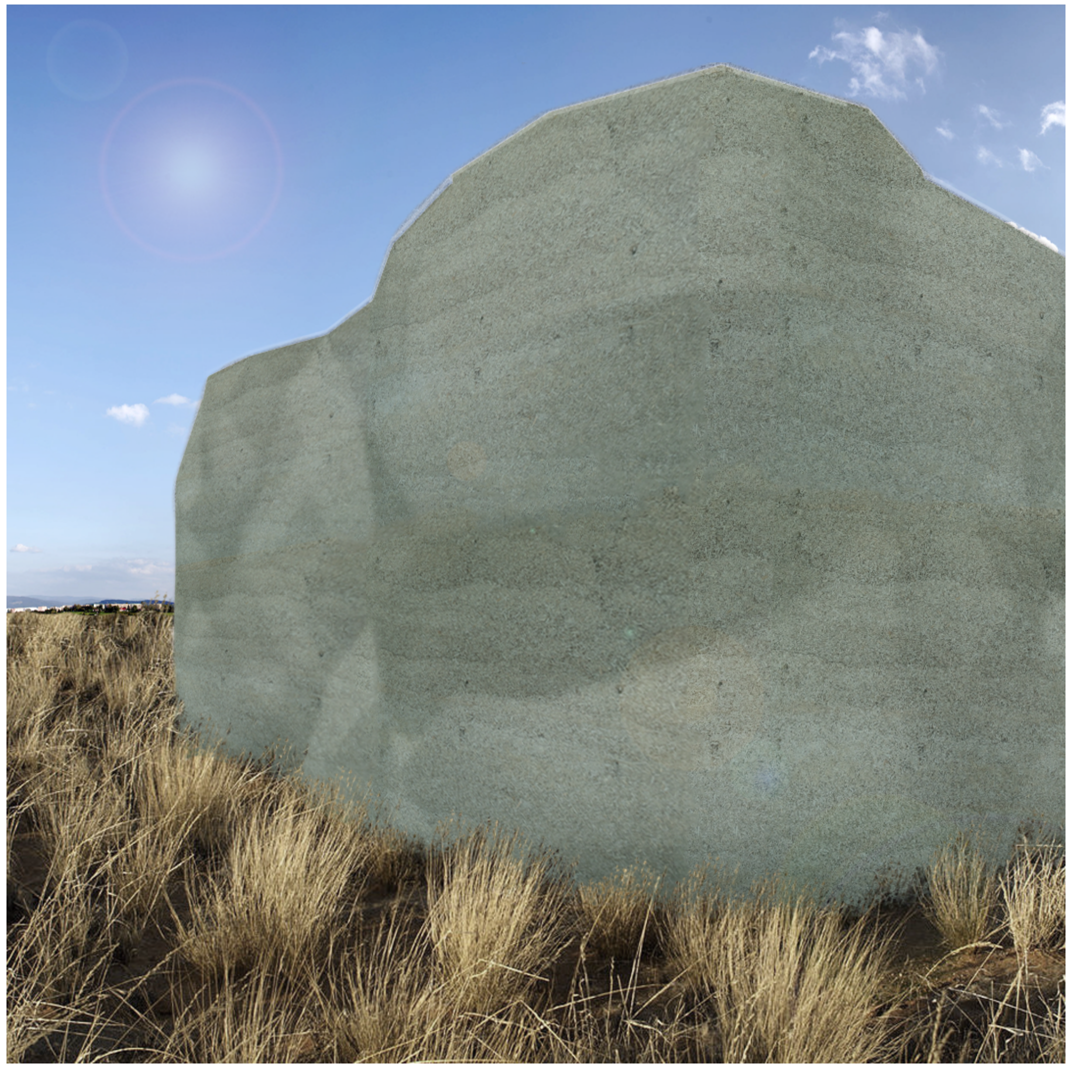


Figure 106: The external face of the corner module facilitates a flowing architecture

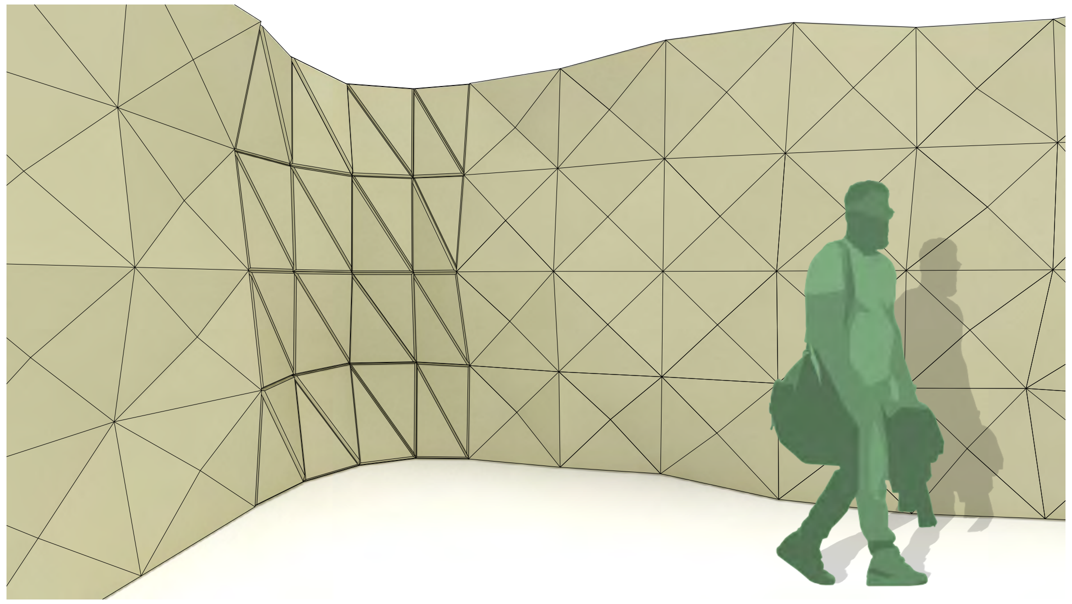


Figure 107: An interior perspective showcasing the corner module

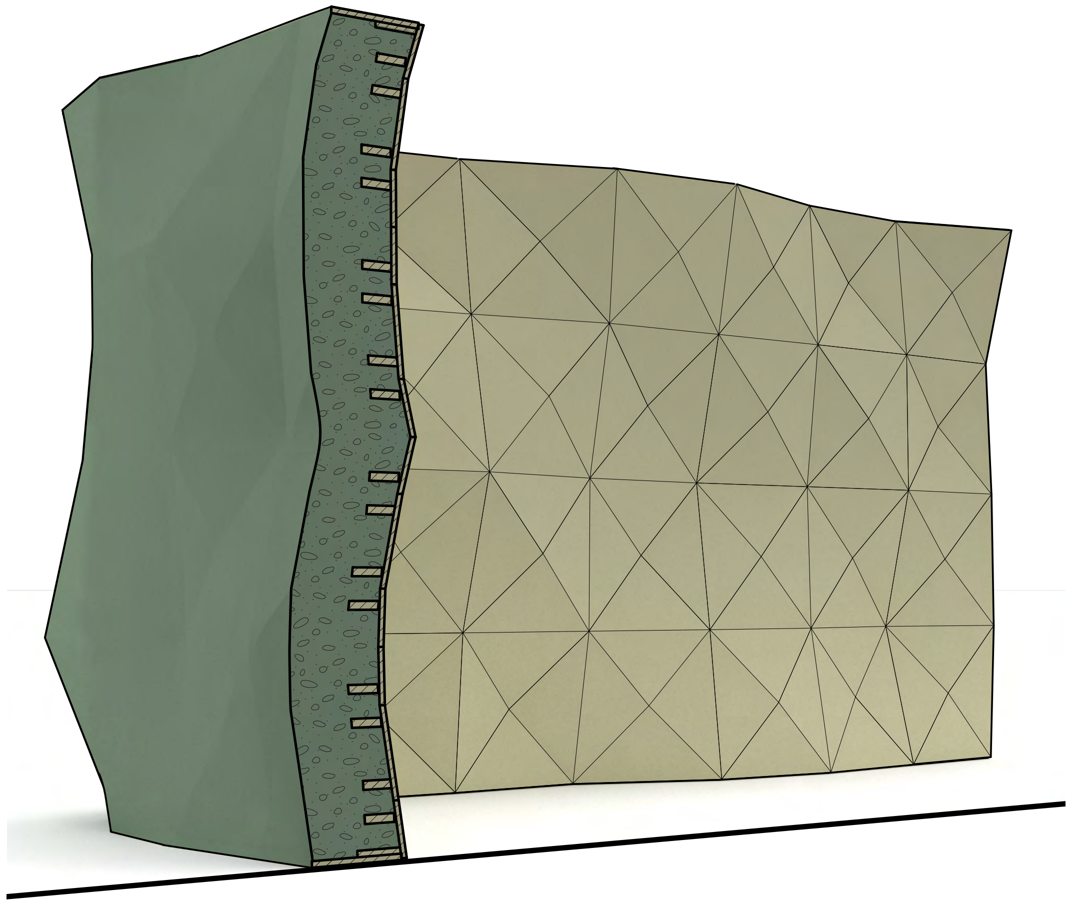


Figure 108: A perspective section juxtaposes the soft, fluid nature of the hempcrete exterior with the crisp angularity of the plywood interior

7.5.0 Workflow Alterations

Testing with the robot revealed that the workflow previously established could be improved to make construction more efficient. The plywood elements would be cut on a vacuum table to avoid the need for tabs so that the components are immediately accessible. The robot was previously responsible for assembling the module with the gripper tool but would not be able to pick up the plywood elements from flat. As such, the suction tool would be required to pick them up. The components would need to be placed in some sort of jig while the tool change occurs so that the grippers could then assemble the module. Therefore, for the construction of a small number of modules, it is proposed that assembly of the plywood elements be allocated to the human worker, who can do it quickly and with less hassle than the robotic arm. The human worker would need to be present for the assembly process anyway, as a single robotic arm requires a series of tool changes to carry out the assembly.

While the robot only completes two tasks in the revised workflow, the work it does is critical to the workflow as the system would not be able to be fabricated without the 6-axis abilities of the robotic arm. The friction fit plywood system enables fast and intuitive assembly that can be carried out by an unskilled labourer and is more efficient than the traditional stick-construction structure of a conventional hempcrete wall, which cannot achieve the same architectural expression.

Having a human worker assemble the plywood elements works well for a small number of module but it is not practical at scale. The tool change issue can be resolved by adding a second robot to the workflow. During assembly, one robot is equipped with the grippers and the other with the suction tool. Working together, the robots will be able to assemble modules with relative ease and minimal human intervention (fig.109). The human worker will still have to fix the perimeter boards to the nested edges and each other, but the robots can hold the components in place as this occurs, mitigating human error.

In both variations of the hybrid workflow, the robot completes tasks that the human worker can build upon rather than the other way around. As soon as the human worker is involved in the construction workflow, the potential for human error is introduced. Without sensors or real-time inputs, the robot is unaware of the human's involvement, and it is difficult to predict where each plywood element will be located and how it will be oriented. As established in the literature review, the robot is good at carrying out tasks that require precision, while the human worker is good at problem-solving and dealing with uncertainty. The revised workflow plays to the strengths of both parties. The robot precisely fabricates the friction-fit plywood elements – which the human worker assembles – and sprays the hempcrete into the wall cavity – which is finished by the human worker. The workflow is split in two, with the robot performing the initial tasks and the human worker completing the subsequent tasks. This makes for an efficient workflow as the potential for human error to cause bottlenecks is mitigated, and also reduces health and safety risks involved in human-robot collaboration.

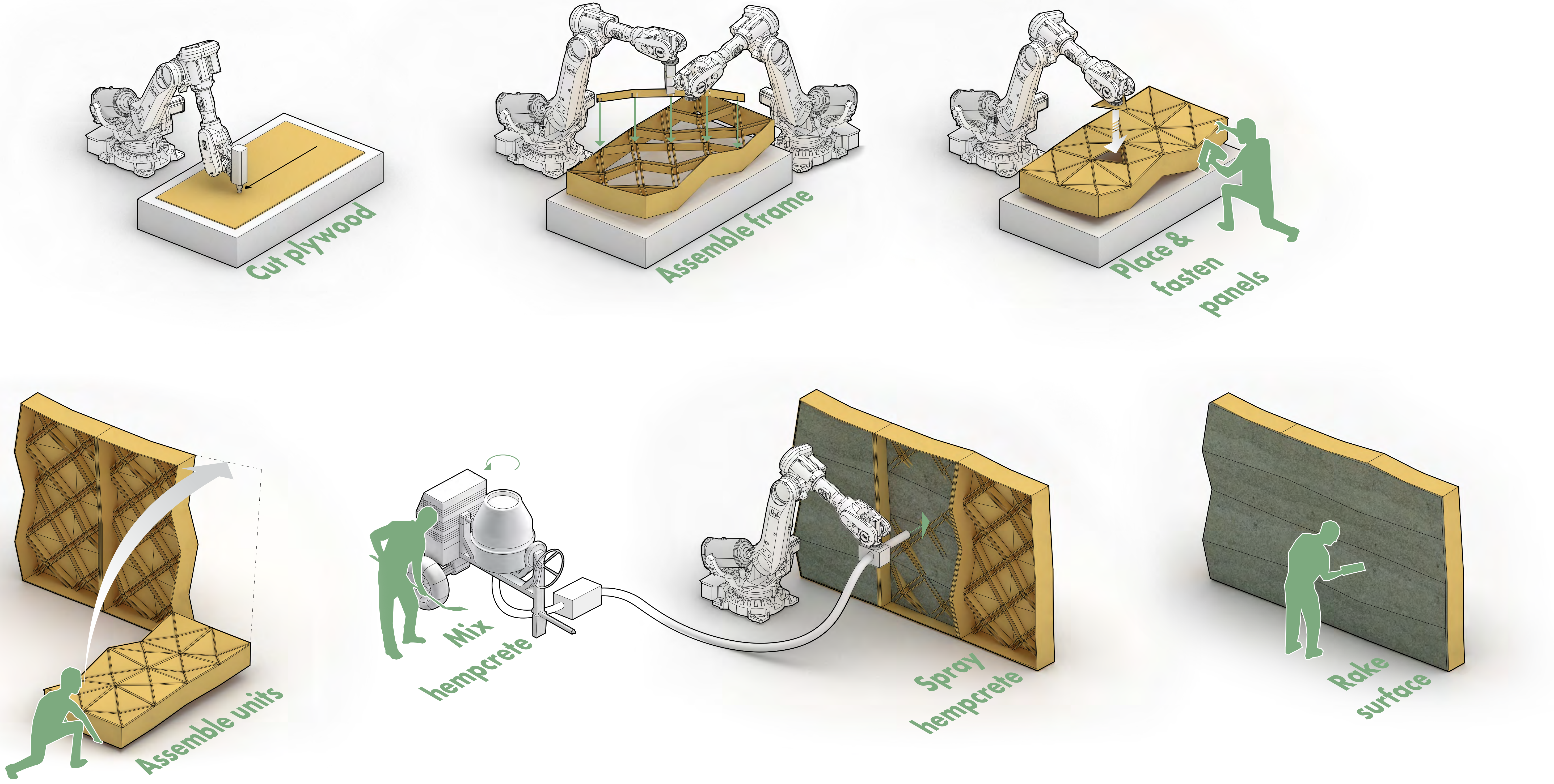


Figure 109: Green Meets Machine - a hybrid workflow for robotic fabrication of hempcrete construction


CONCLUSION
EIGHT

8.1.0 Evaluation

For this design science research to be concluded and make a meaningful contribution to existing knowledge in the fields of robotic fabrication and hempcrete construction, the artefact designed must be evaluated. The structure and formwork system designed provides a solution to reduce manual labour in hempcrete construction to accelerate carbon-neutral construction. A hybrid workflow that enables robotic arms and human workers to collaborate in manufacturing a prefabricated hempcrete construction module has been designed, developed, tested and tweaked. Rather than simply automating conventional hempcrete construction, Green Meets Machine has endeavoured from the start to produce an outcome that is unique to the robot, extending upon the possibilities and applications of hempcrete in architecture and construction. Although intended for single-storey residential applications, architects could foreseeably specify the developed module as internal partitions in high-spec green buildings on a commercial scale such as office spaces, apartments, or hotels (fig.110).

This content is unavailable.
Please refer to the figure list for further details.

Figure 110: There is potential for the modular hempcrete system developed in this thesis to be implemented in commercial architecture as well as residential (DB Interiors, 2018 [edited])

It is evident that the outcome produced in this thesis meets the criteria for success established in section 2.4.1 – Success Criteria:

✓- demonstrate how robotic fabrication can be utilised in an architecture and construction context to increase productivity and diversify outcomes

✓- make hempcrete construction more accessible by assisting human labour

✓- make hempcrete construction more desirable by increasing design potential

✓- maintain the carbon negativity of hempcrete construction

✓- produce an architectural outcome that is unique to the robot and improves upon conventional outcomes by answering the question – how would a robot build a house of hemp?

Productivity is increased by reducing the time spent by human workers on hempcrete construction as well as completing a range of specialty tasks with one machine – the robotic arm. Implementing parametric design systems enables a range of design options to be generated on a whim, diversifying design outcomes and increasing architectural expression. This makes carbon-negative hempcrete construction more attractive to people looking to build who may have been discouraged by the laborious conventional construction process. Additionally, the increased design potential due to the mass-customisation ability of robotic fabrication makes hempcrete construction more desirable as it is no longer limited to the boxy aesthetic typical of existing hempcrete houses. The system designed in this thesis has managed to maintain the carbon-negative status of hempcrete construction, although its exact carbon footprint is dependent on the mixture ratio, any mixture additives, the spray rate, and the resultant material density. The module is uniquely a product of the workflow as the mass-customisable nature of the parametric system that enables increased architectural expression is unfeasible to fabricate by hand or with a 3-axis CNC routing machine due to the angles that inform the geometric variation. Ultimately, the designed system provides a solution to the lack of architectural expression in hempcrete construction. Its associated workflow establishes a way to accelerate carbon-negative construction on a broader scale and reduce the construction industry's carbon footprint in New Zealand.

8.2.0 Design Limitations

While sprayed hempcrete is carbon-negative, the author acknowledges that utilising an electric powered robotic arm inherently increases the embodied carbon of the construction process. However, the proposed hybrid workflow makes hempcrete construction more accessible and desirable, making it more prolific, resulting in a net reduction in CO_2 emissions within the construction industry. The findings of this research are also limited by the lack of testing conducted for the proposed design solution. While the first half of Green Meets Machine thoroughly and methodically explores direct extrusion of hempcrete, the Structure & Formwork section was more speculative than experimental. Further testing and prototyping would strengthen the findings of this research and validate the conclusions.

There is little proof that the plywood structure of the system – with its friction-fit assembly logic – would work in its current iteration without additional fixings. While intermediary connections are bolted and the formwork panels are attached to the diagonal spans with brad nails, additional fixings may be required to strengthen the plywood structure. This research did not determine the tolerance that should be used for the interlocking slots to stop the system from falling apart while still enabling ease of assembly.

Although thermal bridging has been actively reduced in the design, the perimeter frame of each module spans the width of the finished wall. Although this can be covered with a thin layer of hempcrete once the edges have been used as guides to float-finish the external hempcrete surface, it remains the thermally weakest point of each panel.

The system's carbon negativity depends on the finer details of the workflow, such as the location at which specific tasks are carried out. As detailed in section 6.3.1, one option is to transport the robot to site and conduct the entire fabrication process. Alternatively, the modules could be prefabricated entirely off-site and transported to site, leaving the robot in the workshop. The finished panels would have a higher volume than the raw materials, so this option increases the embodied carbon of each module. The difference in carbon footprint, or whether the second option negates the carbon-negativity of the system, was not calculated in this thesis. However, prefabricating the hempcrete component in a controlled environment provides more certainty in the build schedule by ensuring consistent drying times. Project managers should consider the implications of each alternative on a project-by-project basis.

8.3.0 Research Limitations

Green Meets Machine was limited by the uncertainty surrounding New Zealand's Covid-19 pandemic response throughout 2021, which is a significant factor in why a full-scale prototype of the final wall module was not explored in this thesis. Access to the workshop was limited during alert levels 2-4. It was decided after the six-month review that the prototype was not necessary to communicate the design of the proposed system. Instead, the focus of the final stage of research was on design development and pushing the application of the system, resulting in the design of the corner module to offer greater design versatility. Ultimately, pursuing geometric variation is a more significant contribution than resolving technical issues of a scale physical prototype as the aim of this thesis is to increase architectural expression in hemcrete construction.

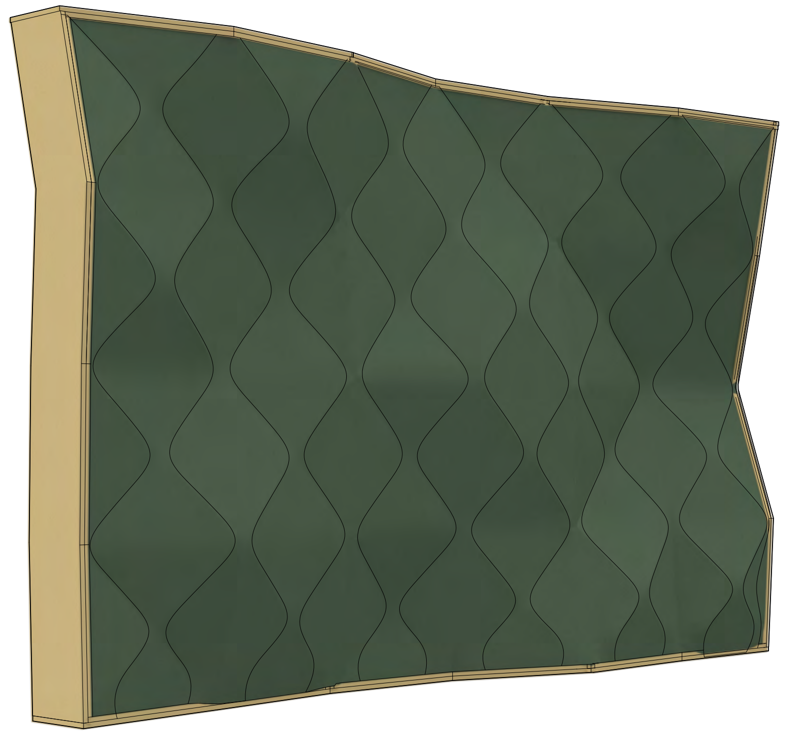


Figure 111: The modular hempcrete construction system developed by this thesis increases architectrual expression by rejecting planarity and harnessing the mass-customisation abilities of robotic fabrication

8.4.0 Further Research

Direct extrusion of hempcrete showed promise in the early stages of this thesis, but more research is needed to make it a viable additive manufacturing method. Ultimately, this should be conducted by material scientists and engineers as issues surrounding the moisture content and the extruder tool need to be resolved before architectural problems can be addressed. Regardless, direct extrusion of hempcrete shows promise for the future of carbon-neutral construction.

Further research involving structural testing of a scale prototype of the structure and formwork system developed in the second half of this thesis would help determine its suitability as a load-bearing structural element. A subsystem that enables perpendicular intersection of panels would prove useful as it would open up a range of design possibilities and enable effective division of space. The design could be pushed further to incorporate a roof system or dome form, removing the need to connect the designed wall to a conventional roof with standard flashing details. Also worth looking into is the inclusion of apertures to accommodate doors and windows. This raises the question of whether standard off-the-shelf doors and windows should be used or if they could be robotically fabricated and mass-customisable. In this way, the system could become a stand-alone architectural solution.

Further testing to directly compare conventional hempcrete construction and the system proposed by this thesis would validate the success of this research. Mixture ratios, additives, spray rates and resultant material densities could be explored to optimise the carbon negativity of the system. Ideally, lime and binder additives would be minimised to make it more carbon negative. If the mixture is more carbon negative than that of conventional hempcrete, a higher density would use more carbon negative mixture and thus result in a net increase in the carbon negativity of the system as a whole. Thus, a greater reduction of carbon emissions in construction would be achieved.

Overall, this research demonstrates how robotic fabrication can increase architectural expression in hempcrete construction through the design of a robotically fabricated hempcrete module and associated hybrid workflow. In a broader context, Green Meets Machine provides a pathway to accelerate carbon-negative construction and mitigate the construction industry's carbon footprint.

Figure 112: *The ABB IRB6700 Robotic Arm in the WFADI workshop*

NINE

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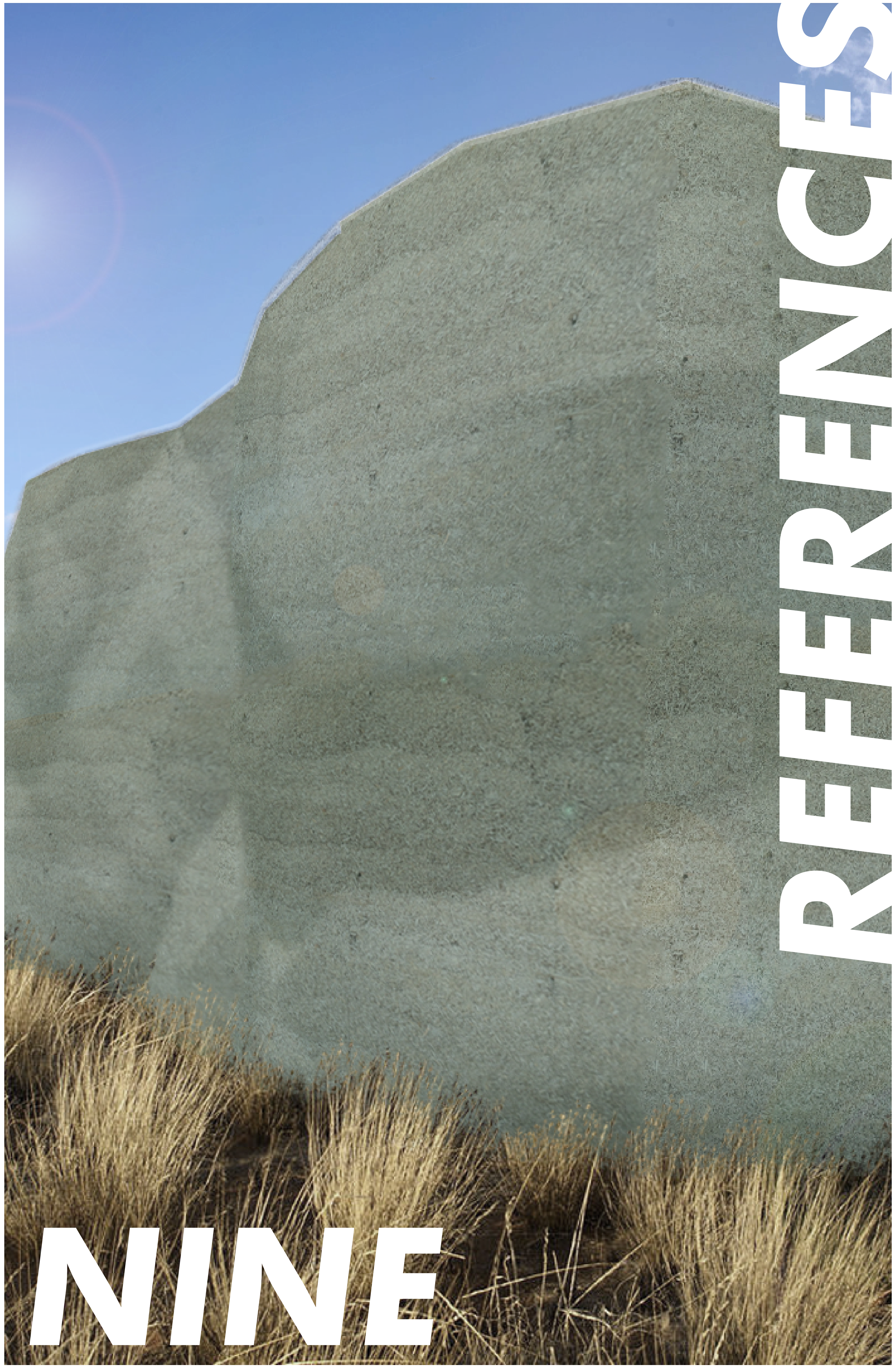

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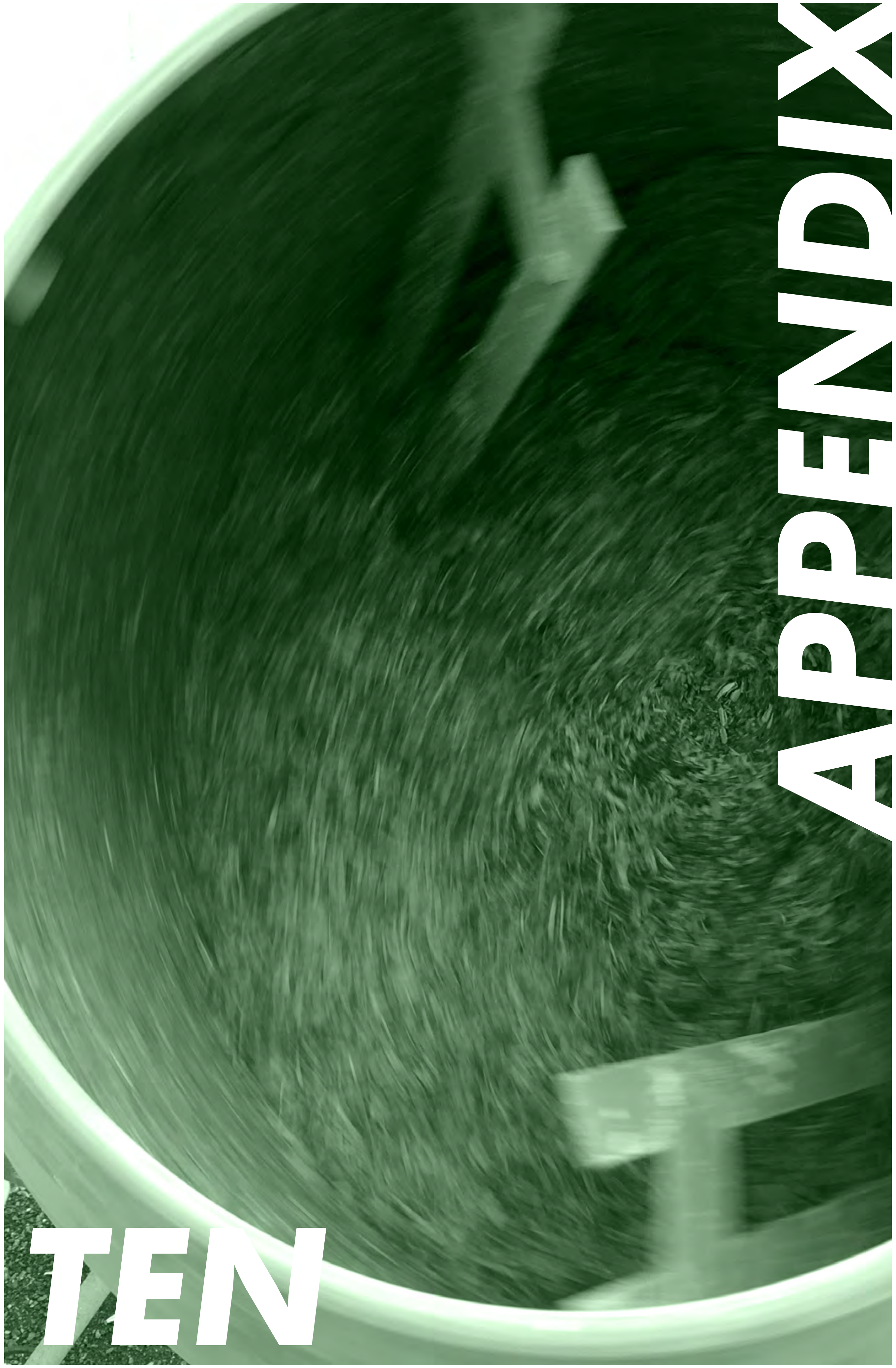
9.2.0 List of Figures

Unless otherwise stated, all figures are the author's own.


APPENDIX
TEN

10.1.0 Direct Extrusion Calculations

The following figures are derived from Florentin et al., 2017, p.299 and experimental data collected by the author at the WFADI workshop.

10.1.1 Embodied Carbon

Hemp: +0.085kgCO_2/kg, -1.8kgCO_2/kg = -1.715kgCO_2/kg

Lime: +0.73kgCO_2/kg, +0.7kgCO_2/kg, -0.7kgCO_2/kg (this assumes 100% carbonation) = +0.73kgCO_2/kg

Water: +0.00026kgCO2/kg = negligible

10.1.2 Carbon Neutral Ratio

Carbon neutral when produced = sequestered

> let lime = b, hemp = h

0.73b - 1.715h = 0

0.73b = 1.715h

b = (1.715/0.73)h

b = 2.35h

> baseline hemp:lime ratio = 1:2.35 by mass (assuming embodied carbon of water is negligible and 100% carbonation of lime occurs)

10.1.3 Material Density

Density was calculated by weighing a 400ml cup of each material and using p = m/v

Hemp:

p = m/v where m = 48.5g, v = 400cm^3

p = 48.5g/400cm^3

p = 0.12g/cm^3

Lime:

p = m/v where m = 215.5g, v = 400cm^3

p = 215.5g/400cm^3

p = 0.54g/cm^3

10.2.0 Structural Simulations

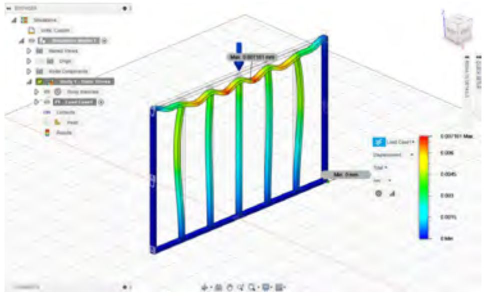


Figure 113: Conventional frame displacement under 100N gravity load

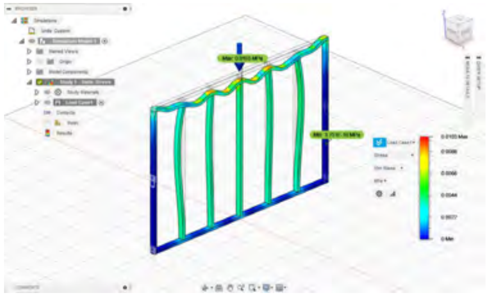


Figure 114: Conventional frame stress under 100N gravity load

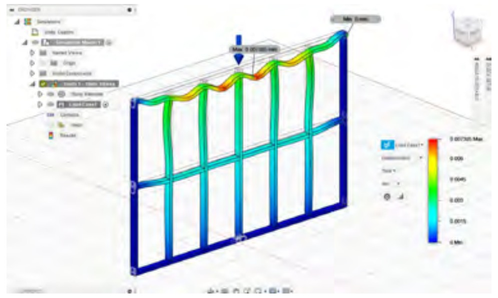


Figure 115: 1 dwang frame displacement under 100N gravity load

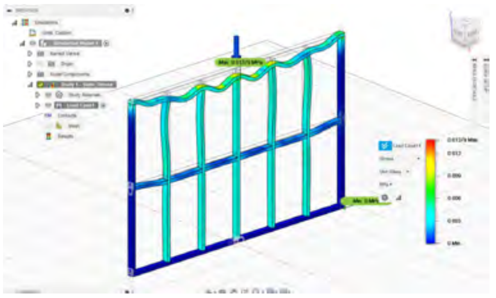


Figure 116: 1 dwang frame stress under 100N gravity load

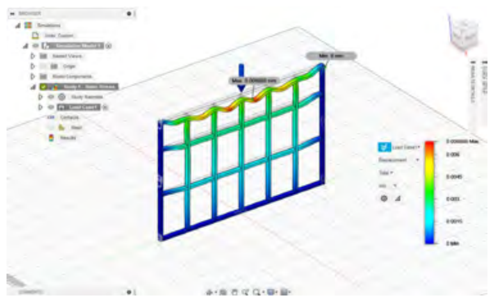


Figure 117: 2 dwang frame displacement under 100N gravity load

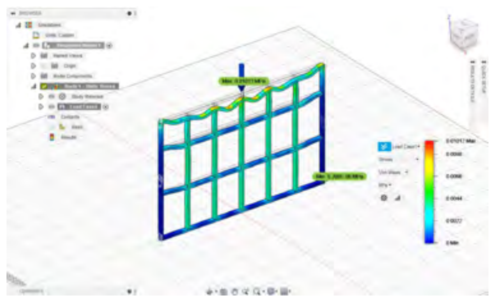


Figure 118: 2 dwang frame stress under 100N gravity load

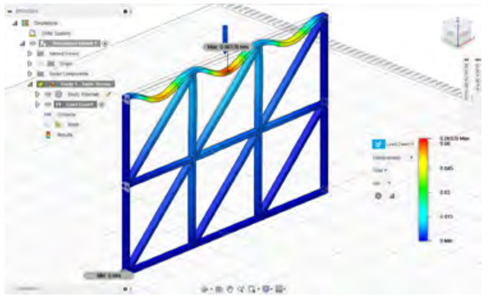


Figure 119: N frame displacement under 100N gravity load

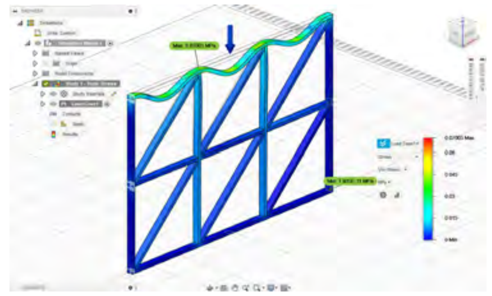


Figure 120: N frame stress under 100N gravity load

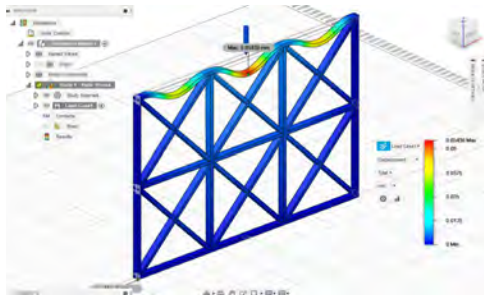


Figure 121: X frame displacement under 100N gravity load

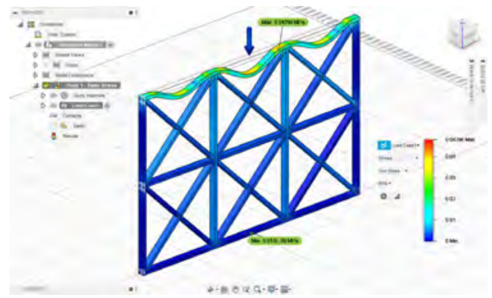


Figure 122: X frame stress under 100N gravity load

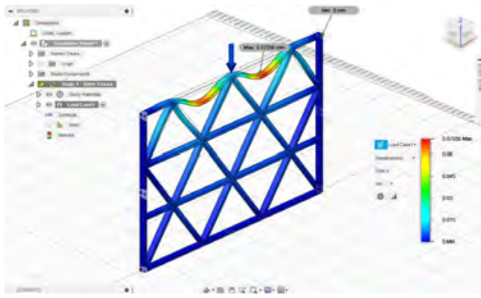


Figure 123: Hex frame displacement under 100N gravity load

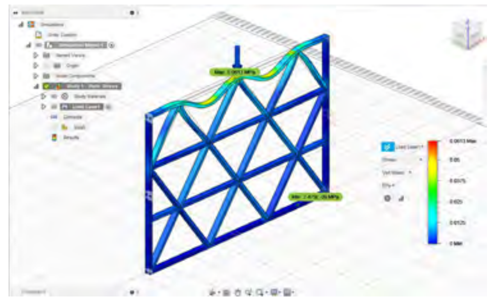


Figure 124: Hex frame stress under 100N gravity load

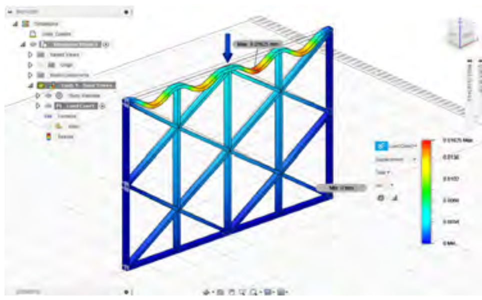


Figure 125: Flipped hex frame displacement under 100N gravity load

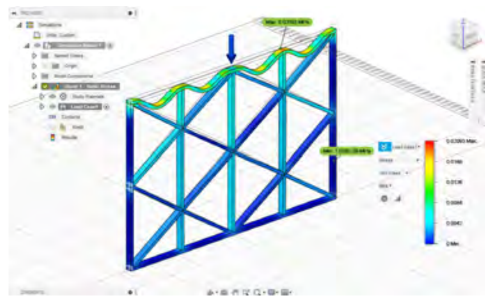


Figure 126: Flipped hex frame stress under 100N gravity load

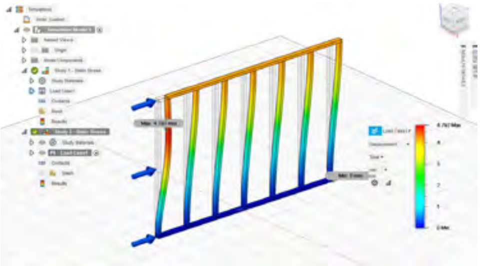


Figure 127: *Conventional frame displacement under 100N lateral load*

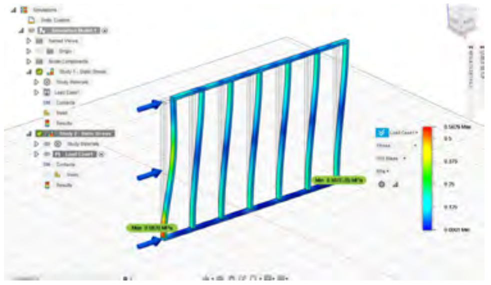


Figure 128: *Conventional frame stress under 100N lateral load*

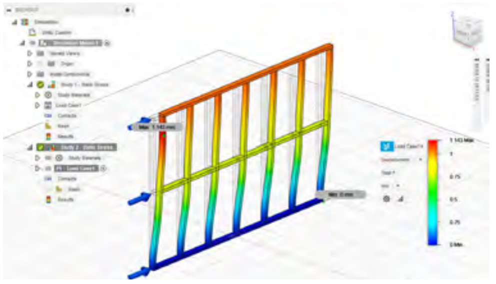


Figure 129: *1 dwang frame displacement under 100N lateral load*

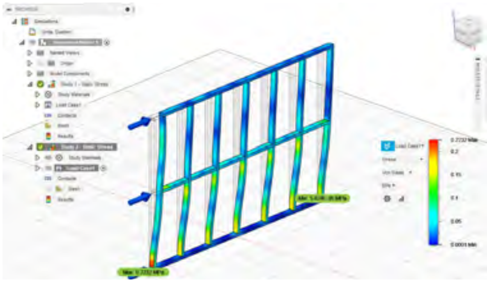


Figure 130: *1 dwang frame stress under 100N lateral load*

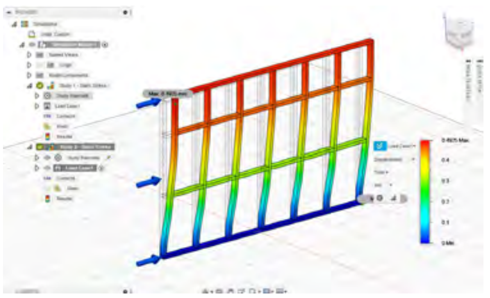


Figure 131: *2 dwang frame displacement under 100N lateral load*

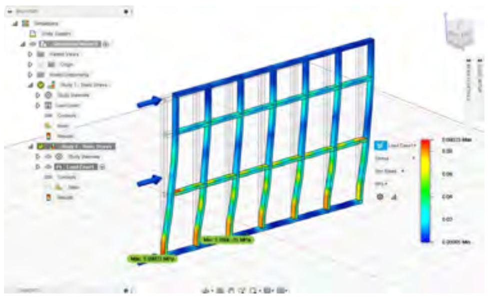


Figure 132: *2 dwang frame stress under 100N lateral load*

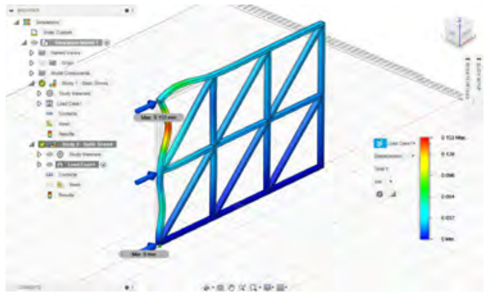


Figure 133: *N frame displacement under 100N lateral load*

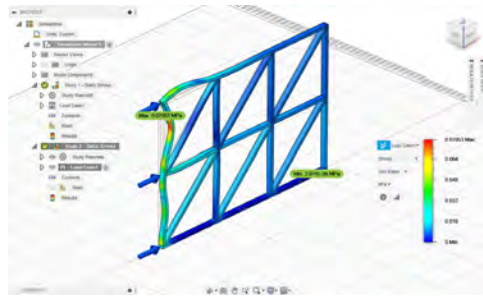


Figure 134: *N frame stress under 100N lateral load*

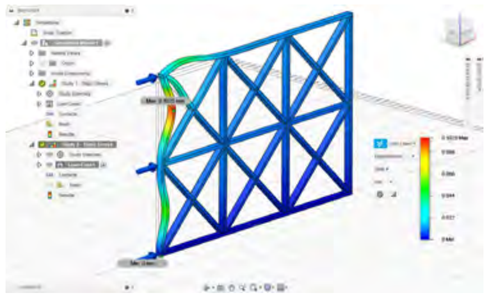


Figure 135: *X frame displacement under 100N lateral load*

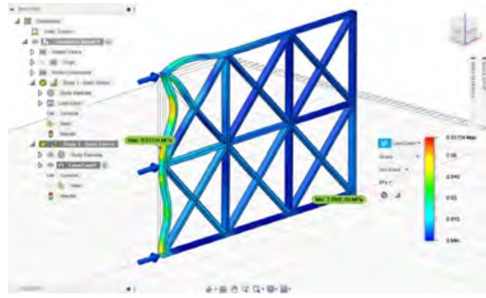


Figure 136: *X frame stress under 100N lateral load*

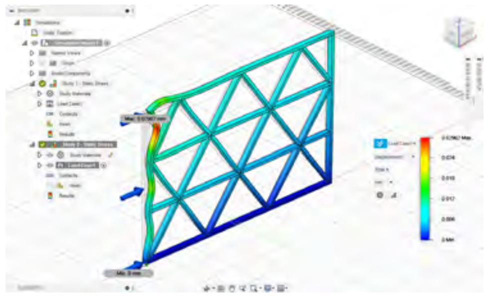


Figure 137: *Hex frame displacement under 100N lateral load*

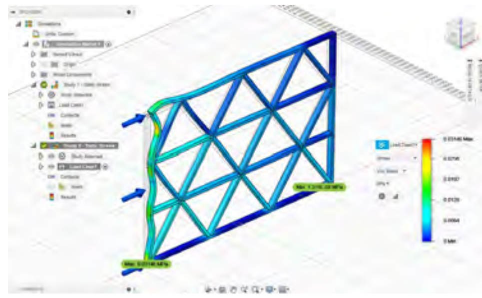


Figure 138: *Hex frame stress under 100N lateral load*

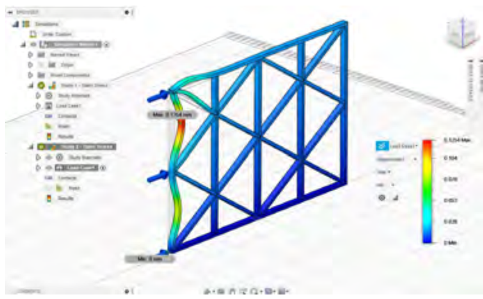


Figure 139: *Flipped hex frame displacement under 100N lateral load*

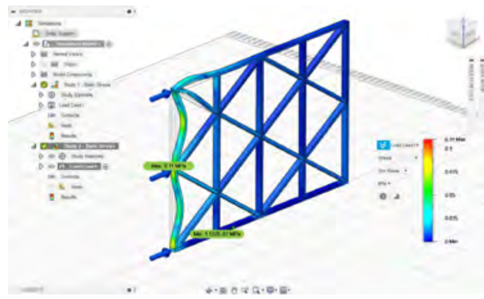


Figure 140: *Flipped hex frame stress under 100N lateral load*

	Control	Dwangs 1	Dwangs 2	N	N planar	N nonheirarc
Relative max stress under gravity	0.0103	0.01378	0.01012	0.06598	0.07003	0.07499
Relative min stress under gravity	3.75E-10	8.06E-11	5.30E-08	5.50E-11	1.94E-11	3.50E-10
Relative max displacement under gravity	0.007161	0.007424	0.006888	0.09293	0.06328	0.07657
Relative max stress under lateral load	0.5629	0.2232	0.09023	0.1118	0.07853	0.1152
Relative min stress under lateral load	8.37E-05	5.62E-05	5.10E-05	2.74E-08	2.61E-08	1.04E-07
Relative max displacement under lateral load	4.792	1.143	0.4925	0.1855	0.153	0.1813
Timber (m)	23.46	26.79	30.12	30.13	30.13	30.13
Joints	14	21	28	12	12	12
Max intersecting members	2	3	3	6	3	6
Members	9	16	23	23	15	23
Average length of members (m)	2.6	1.67	1.31	1.31	2.01	1.31
Complexity level of joint (max cut planes)	1	1	1	2	2	3
Vertical members	7	7	7	4	4	4
Operable joints that do not segment members	0	0	0	0		
Spans	19	32	45	23	23	23
Triangles	12	24	36	12	12	12

	X	X planar	X nonheirarchic	Hex	Hex planar	Hex nonheirarc	Flip planar	Flip nonheira
Relative max stress under gravity	0.05001	0.04796	0.06052	0.0451	0.0613	0.06054	0.02093	0.03501
Relative min stress under gravity	3.52E-11	8.01E-09	1.62E-09	2.79E-09	2.48E-09	2.69E-09	1.04E-08	2.47E-09
Relative max displacement under gravity	0.0386	0.05438	0.06886	0.05414	0.07036	0.08596	0.01625	0.02264
Relative max stress under lateral load	0.1197	0.07224	0.09614	0.08894	0.03146	0.04277	0.11	0.1001
Relative min stress under lateral load	2.97E-08	2.49E-08	1.34E-08	1.57E-08	1.31E-08	2.37E-08	1.54E-07	5.26E-08
Relative max displacement under lateral load	0.318	0.1023	0.1474	0.2561	0.02962	0.03388	0.1254	0.158
Timber (m)	39.45	39.45	39.45	36.28	36.28	36.28	35.29	35.29
Joints	18	18	18	18	18	18	17	17
Max intersecting members	4	4	8	6	6	6	6	6
Members	41	30	41	38	29	38	28	36
Average length of members (m)	0.96	1.32	0.96	0.95	1.25	0.95	1.26	0.98
Complexity level of joint (max cut planes)	2	2	3	2	2	3	2	3
Vertical members	4	4	4	2	2	2	5	5
Operable joints that do not segment members	6			5			5	18
Spans	41	41	41	38	38	38	36	36
Triangles	24	24	24	21	21	21	20	20

Figure 141: Attributes of various frame types

Ricky Frost

Master of Architecture (Professional)

2022

Green Meets Machine