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ARCHITECTURE FOR A CIRCULAR ECONOMY

G. FINCH | 2019

Defab: Architecture for a Circular Economy

by

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A thesis submitted to Victoria University of Wellington in partial fulfilment
of the requirements for the degree of Master of Architecture (Professional).

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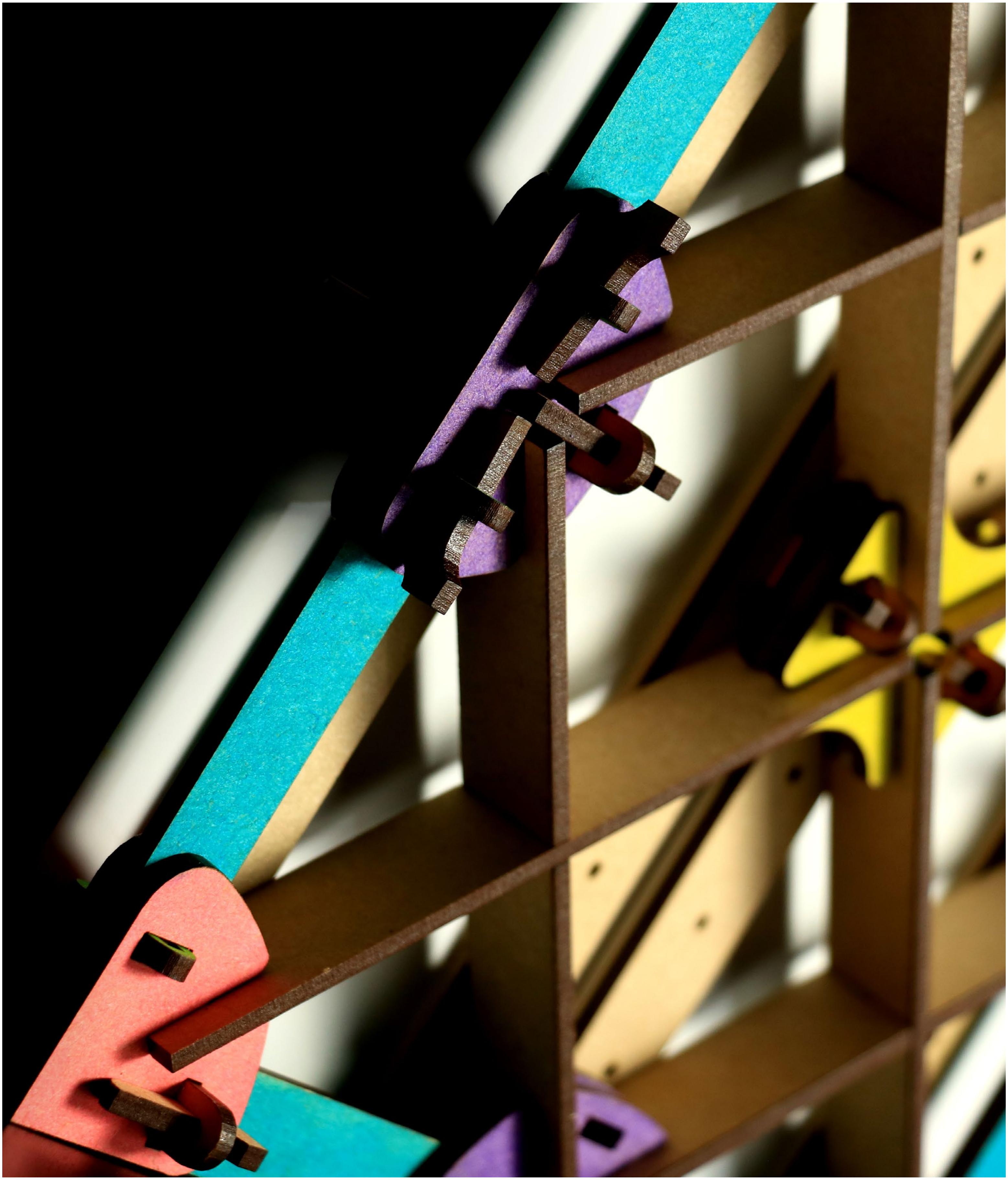


Abstract

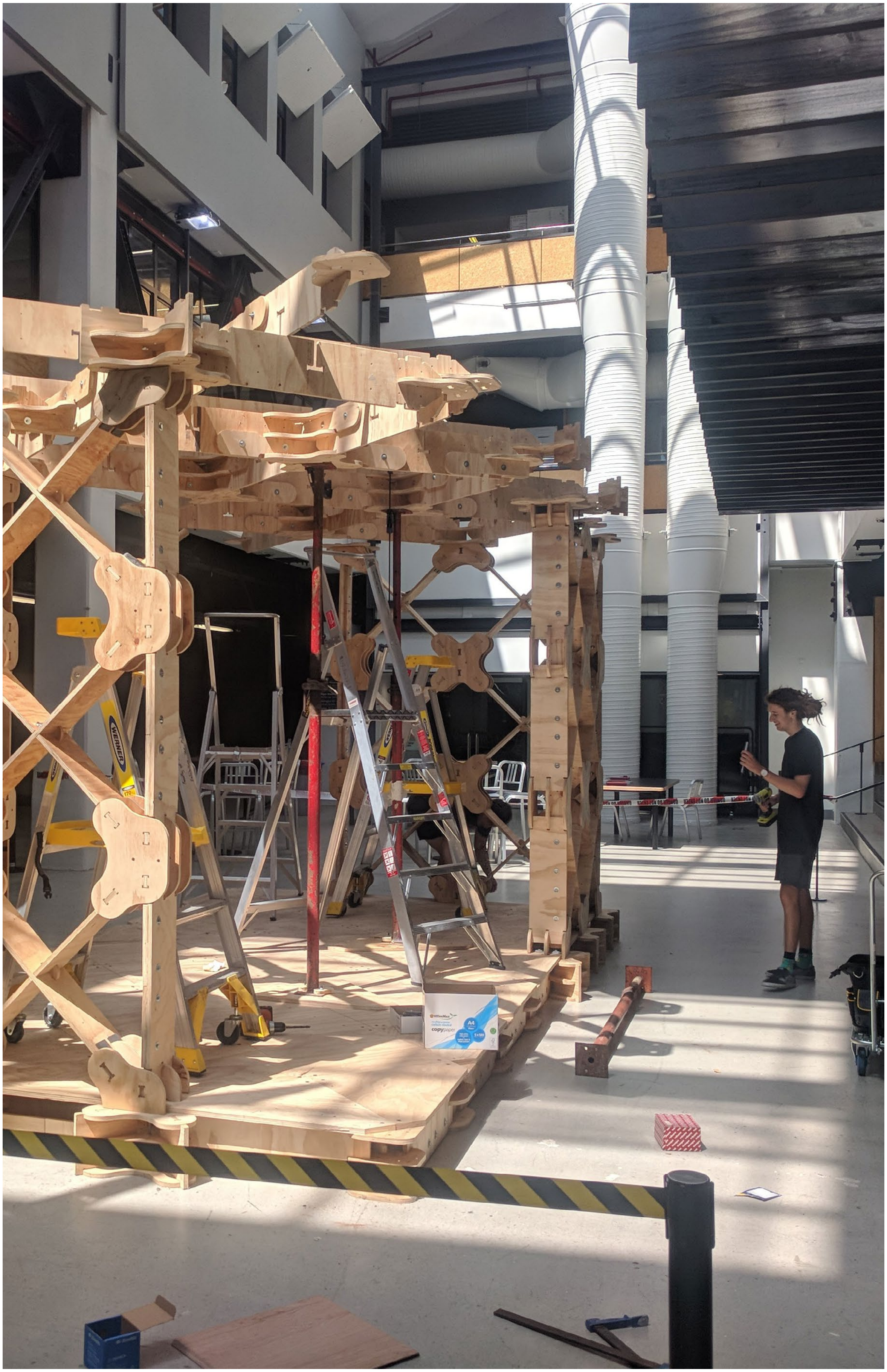
Mainstream construction practices result in the production of large quantities of toxic waste at all stages of a building's life cycle. This can be attributed to widespread adoption of irreversible fixing methods that prioritise rapid assembly, bespoke design practices and the increased use of 'low-value' materials. Unprecedented levels of consumption and waste production are set to continue as demand for residential housing in New Zealand grows rapidly. In response to these concerns, this thesis aims to develop innovative construction methods that facilitate the development of a Circular Economy for the building industry.

The resulting design proposal is a modular architectural construction system with integrated jointing capacity, redundant expansion potential and details that enable the effective separation of discrete building layers. This proposed assembly specification calls for the mass-standardisation of structural components to promote economically viable material retrieval and resale at the end of a building's useful life. Computer-aided manufacturing technologies are used to facilitate the incorporation of sophisticated reusable assembly parameters into connection details on a large scale.

Analysis of the proposed solution indicates that waste over an entire building's life can be reduced by more than 94% through the deployment of alternative architectural assemblies. Additionally, optimised assemblies enable deconstruction times to be reduced by up to 30% versus conventional light timber framing.

Figure 1. (cover)
X-Frame 7 pattern (A).

Figure 2. (left)
X-Frame 5 (A).



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I thank you.

Figure 3.
Deconstruction of X7 prototype (A).

Contents

Legal Liability

Advanced full-scale prototyping indicates that X-Frame exceeds all minimum code requirements for light timber framing. However, due to the experimental nature of this project, the author, project sponsors, research advisors and all individuals involved in the formation of this research accept no responsibility for the unsatisfactory performance of any experimental construction systems proposed in this publication. Individuals wishing to adopt or fabricate the structural, architectural and building systems proposed in this thesis do so at their own risk.


WAY

Introduction

The construction industry is responsible for up to 50% of all waste produced in New Zealand (REBRI, n.p., 2014; Inglis, p. 1, 2007). A focus on the economic performance of construction has meant the widespread adoption of single-use and composite materials (Curtis, p. 8, 2015). These materials – although adaptable, durable, quick to install and cost effective – have no reuse value as they are either irreversibly damaged on removal or are not approved by building codes for reuse (Storey et al, p. 18, 2005). Products such as plasterboard (drywall), treated framing timber and reinforced plaster monolithic claddings are all single-use materials that are found in 90% of residential structures built in New Zealand, and represent 85% of all demolition waste (Curtis, p. 6, 2015; EPA, n.p., 1998). These 'engineered' materials are fixed in a way that makes removal without damage an impossibility and are also difficult to recycle or reprocess without losing value (Chini, n.p., 2001). At the end of a building's useful life, the effort (cost) required to separate these materials exceeds the possible return for selling the recovered product.

Modern construction methods have also resulted in the dumping of increasingly toxic waste materials. Consumer and regulatory demand for long life and weathertight homes has led to the widespread adoption of composite and petrochemical-based materials. These materials are often treated with chemical stabilisers to prevent the ingress of water, for example: chromated copper arsenate (CCA) treated timber. When landfilled, these chemicals will delay the decomposition process, damage neighbouring ecosystems and potentially contaminate groundwater. The arsenic in CCA treated timber is readily leached into the environment in concentrations 500 times higher than safe background levels (Parisio, p. 18, 2006). Based on current

Figure 4.
Waste proportions in New Zealand's landfills and cleanfills (from top: commercial, industrial, residential, construction).

building trends, we should continue to expect the dumping of increasingly toxic building waste (Curtis, n.p., 2015; Keene and Smythe, p. 11, 2009). Furthermore, to achieve the stipulated performance of modern construction standards, silicone, adhesive-backed tapes and expanding foams are commonly employed. Subsequent alterations to the envelope result in huge quantities of waste, as uncontaminated separation of materials is all but impossible at the source.

In response to this unacceptable waste management record, this design-led research aims to make strides to reduce the impact of the construction industry on the environment and, specifically, to investigate how light timber framed (LTF) buildings might be redesigned to be more readily deconstructed into individual material components for reuse at the end of their useful life. The research evaluates why today's construction methods are responsible for producing such large quantities of waste and then addresses three critical architectural issues of designing for 'reuse':

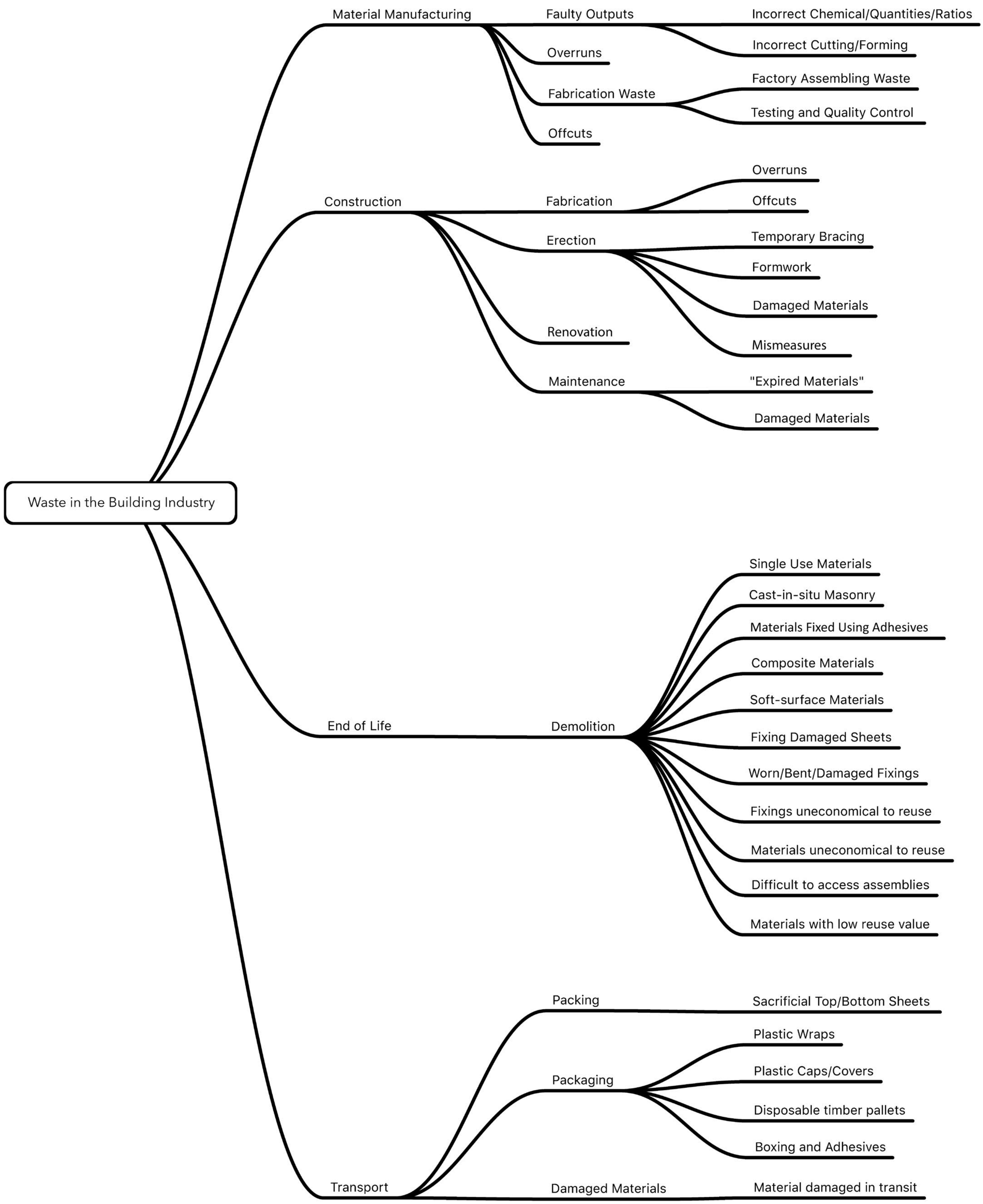
The materials we specify and their place in reuse life cycles;
How we assemble and fix the materials we specify;
How we cut, shape and form materials.

This research can be categorised by the following question:

How can light timber framed architectural assemblies be redesigned to integrate a circular economic model?

Figure 5.
Expanded foam blocks submerged in cement to provide added insulation (A).

Figure 6. (opposite)
Linear material consumption model (a).


Waste in the Building Industry
Material Manufacturing
Faulty Outputs
Incorrect Chemical/Quantities/Ratios
Incorrect Cutting/Forming
Overruns
Fabrication Waste
Factory Assembling Waste
Testing and Quality Control
Offcuts
Construction
Fabrication
Overruns
Offcuts
Erection
Temporary Bracing
Formwork
Damaged Materials
Mismeasures
Renovation
Maintenance
"Expired Materials"
Damaged Materials
End of Life
Demolition
Single Use Materials
Cast-in-situ Masonry
Materials Fixed Using Adhesives
Composite Materials
Soft-surface Materials
Fixing Damaged Sheets
Worn/Bent/Damaged Fixings
Fixings uneconomical to reuse
Materials uneconomical to reuse
Difficult to access assemblies
Materials with low reuse value
Transport
Packing
Sacrificial Top/Bottom Sheets
Packaging
Plastic Wraps
Plastic Caps/Covers
Disposable timber pallets
Boxing and Adhesives
Damaged Materials
Material damaged in transit

RESEARCH METHODOLOGY

The approach to design-led research within this portfolio is deliberately pragmatic in the sense that it aims to develop a construction assembly approach that is ready for the market today. From the outset of the research, the intention was to use cost economics, material analysis and real world assembly tests to iteratively develop an alternative method of assembly that could be easily adopted by the industry.

Experimentational Modes

To reflect the pragmatic intentions of the research, a design-led methodology was established that centred on the use of detailed scale and prototype models. This methodology reflects a need to explore a wide and diverse range of possible solutions as well as the pragmatic issues associated with designing for cyclic reuse. A process of reflecting upon existing conditions, digital sketch modelling and then rapid testing through the fabrication of computer numerically controlled (CNC) laser cut sketch models enabled expansive and unconstrained experimentation.

Figure 7 & 8.
Tactile engagement with architectural assemblies and reuse limitations (a).

Representational Mediums

It is important to note that the majority of visual material produced during the course of this research project was highly edited digital video and animation. The use of this medium enabled the analysis of design iterations throughout the assembly and disassembly process. Fluid documentation of the capacity of a jointing solution to operate repetitively and effortlessly (or only once and with great difficulty) led to a greater understanding of the potential of design experiments. Performance of a given solution could be quantifiably recorded from this moving image-based documentation of the 'construction' process.

On a more theoretical level, the use of video as a medium of visual evidence and documentation is evidence of how this study questions the established permanence of architecture. Typically the product of architectural research, or architecture in practice, is seen as fixed, permanent and finite object(s) in space. However if architecture is to truly transition to a waste-free model, this perception of fixed and bounded objects needs to change. If the product of architecture can, instead, be seen as a collection of materials arranged in a particular way at a certain point in time, a totally waste-free building industry can be conceived. As such, this research purposefully uses video to enhance the significance of flexibility and change over time – to ultimately question the static nature of the objects that we create.

1.0

Waste Solutions

1.1 CALLS FOR CHANGE

Significant publications have highlighted issues of sustainability and waste in the construction industry over the past three decades. In 2002 the New Zealand government published a national strategy for waste management and set the target of "reducing construction and demolition waste going to landfills by 50% of the 2005 figure by 2008" (Storey et al, p. 81, 2005). In 2009 the Ministry for the Environment (MfE) concluded in a separate report that although there had been a reduction in construction waste (8%), this was more likely to be a result of significantly less construction activity: notably "a 24% reduction of 'consented floor area' between 2004 and 2008" (MfE, p. 9, 2009). In 2005 a large proportion of Territorial Authorities in New Zealand also "set themselves the even more ambitious target of zero waste by 2015" (Storey et al, p. 81, 2005). An analysis of 2017 waste statistics indicate that not only was this goal never achieved but waste levels have steadily *increased* since 2008 (MfE, p. 20, 2017).

Climate scientists and sustainability experts have specifically pointed towards the building sector as a key area of concern in respect to waste. It is said that "achievement of the global sustainability agenda and prevention of impending negative

Figure 9.
Waste from a section of conventional light timber framing (A).

environmental impacts depends on how well the construction industry is able to reduce its CO^2 emission[s], virgin materials consumption and waste to landfill" (Ajayi et al, p. 185–186, 2015).

1.2 THE CIRCULAR MODEL

The pre-eminent solution to the waste problem is to eliminate the potential for the production of waste in all stages of a product's life cycle at the time of design. This approach is called 'cradle-to-cradle' or 'Circular E conomy' design and it is the underlying design criteria motivating this research.

1.2.1 Background

Attempts at the 'design-level' to address the management of artificial, chemically bonded and composite, hybrid waste materials were first implemented by Dutch Politician Adrianus (Ad) Lansink in 1979 (Watson, n.p., 2013). Lansink introduced what became known as 'Lansink's Ladder': "a simple schematic presentation of the order of preference for waste management options, with disposal at the bottom and prevention at the top" (Watson, n.p., 2013).

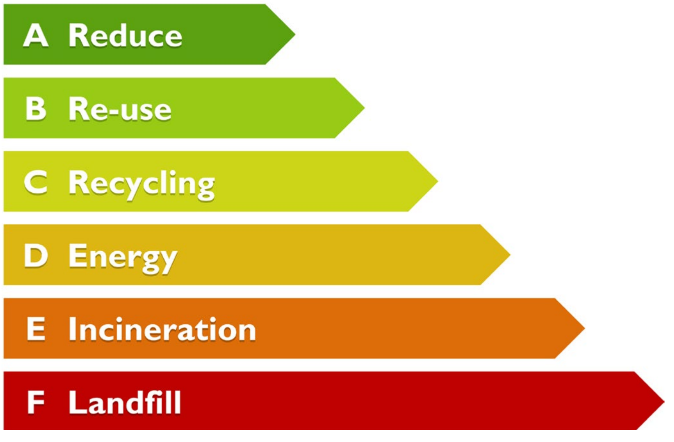


Figure 10.
'Lansink's Ladder' – today recognised as the waste hierarchy.

Lansink's 1979 proposal evolved into today's (2018) internationally recognised waste hierarchy/waste triangle (fig. 10). While Lansink's ranking highlighted the importance of managing waste streams at the highest possible level – that of prevention through design – these ideas failed to significantly influence manufacturers or consumers. Worldwide municipal solid and construction and demolition (C&D) waste levels have both continued to trend upwards from 1980 levels, with any significant reductions a result of economic fluctuations rather than changinging product design (as per 1.0) (EPA, p. 16, 2016; MfE, p. 9, 2017; MfE, p. 8, 2007; MfE, p. 3/36, 1997) (fig. 11).

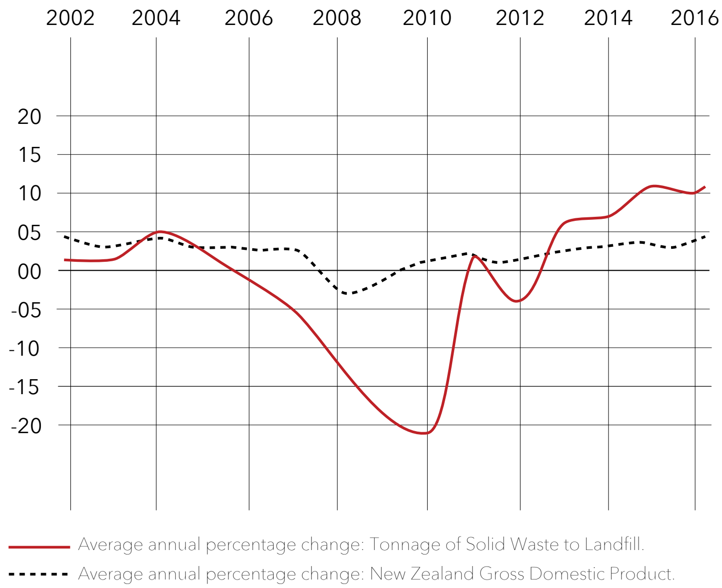


Figure 11.
Average Annual Percentage Change for New Zealand's Gross Domestic Product and Tonnage of Solid Waste to Landfill (2002 to present). Data from MfE, p. 9, 2017; MfE, p. 8, 2007 (A).

The Waste Hierarchy concept proposed by Lansink – although largely inconsequential on its own – helped to fuel a growing belief that designers should be doing more to prevent waste. In 2002, chemist Michael Braungart and architect William McDonough published *Cradle to Cradle: ReMaking The Way We Make Things*. This text again highlighted the need for designers to pre-emptively consider how their products will transition into valuable raw materials for other designers/needs. In opposition to the linear 'cradle-to-grave' cycle that continues to dominate manufacturing, 'cradle-to-cradle' represents the all-inclusive management of materials and byproducts of manufacture from extraction through to their integration into another product or life cycle. Braungart and McDonough are outwardly critical of the established principles of sustainability. It is argued that sustainable practices simply ask us to "substitute" one material for another that is "less bad" (Braungart et al, p. 61, 2009). Instead, the authors propose a 'cradle-to-cradle' approach that formalises the long-held idea that we as humans need to emulate natural processes in the way we manage materials over their life span to eliminate waste material (Braungart et al, p. 61–62, 2009).

'Cradle-to-cradle' ideas have inspired an entirely new agenda for sustainable designers and architects. Coined the 'Circular Economy', it represents a deliberate attempt to circumvent the 'take–make–dispose' consumption sequence that dominates the manufacturing industry and is responsible for the vast quantities of waste we as a society produce.

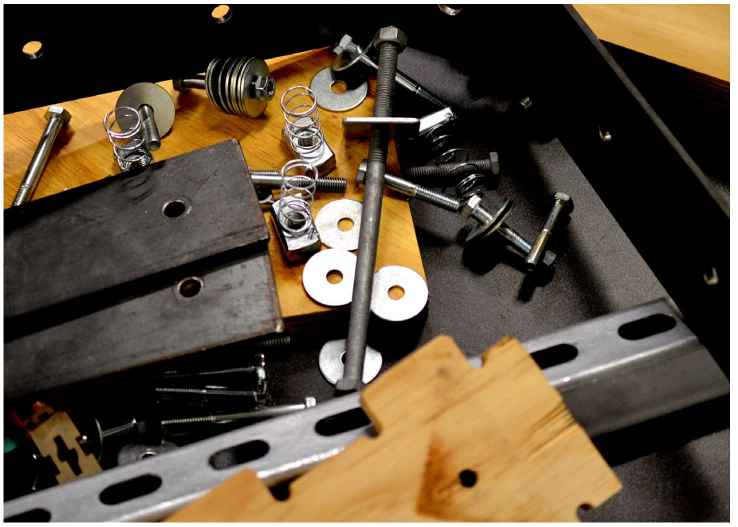
1.2.2 Material Categorisation

A key aspect of Circular Economy (CE) design is material categorisation and selection. Although material categorisation can be actively criticised as simply managing already compromised products; categorisation at the design level ensures that any medium with the potential to generate waste is effectively eliminated.

In its most basic form, the CE asks designers to be more selective in respect to the materials that they specify in design proposals. This means categorising materials based on their whole life performance together with their environmental impact from fabrication, and only selecting those that perform well in both categories. Materials sorted based on these measures will typically fall into one of three groups (Braungart et al, p. 109, 2009):

- "The Technical Metabolism" – refers to materials that are highly engineered and often energy intensive to fabricate. Materials with such properties include aluminum, PET plastic and steel.
- "The Biological Metabolism" – refers to materials that feed into a natural waste management process. Materials matching this description include untreated timber, lime-based plaster renders and unbound stone.
- Compromised or "Monstrous Hybrids" – refers to materials that are either designed poorly or compromised in some way over their lifetime. Treated timber is a leading example of a material that has a compromised potential to be effectively and safely disposed of.

Designers wishing to operate within the constraints of a CE would need to select materials from either the 'biological' or 'technical' categories. The designer would then need to ensure that no secondary material was added to the primary material in a way that restricted its long term reusability or recyclability. A common example of this problem is the application of treatments to structural timber elements. Untreated timber sits in the 'organic' category ordinarily but then moves to the 'compromised' category when a treatment product is added. This transition is complicated by the fact that this treated timber product could be considered a technical material capable of reuse depending on the way it is fixed and assembled into a structure.



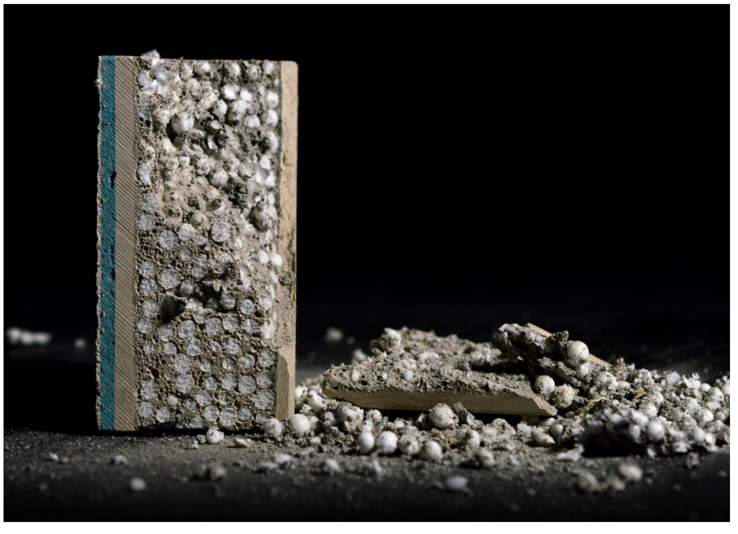


Figure 12, 13 & 14.
Common building and construction materials sorted by Circular Economy classification; examples of technical, biological and compromised materials (a).

1.2.3 Assembly and Geometric Parameters

Material categorisation does not guarantee effective waste management. If the product is not imagined as part of a greater system in which "materials and behaviors" are carefully considered, "there is very little point merely changing the design of a single product" through the selection specific materials (Baker-Brown, p.9, 2017). This statement is in recognition that the cost and usefulness of the materials or components within a given product will dictate if end-of-life disassembly takes place. For buildings, this means using components that are geometrically, functionally and aesthetically adaptable to a range of different uses across an extended time frame. Integrating components that meet these criteria (and that are also economically attractive throughout reuse cycles) is the key architectural challenge of designing for a Circular Economy.

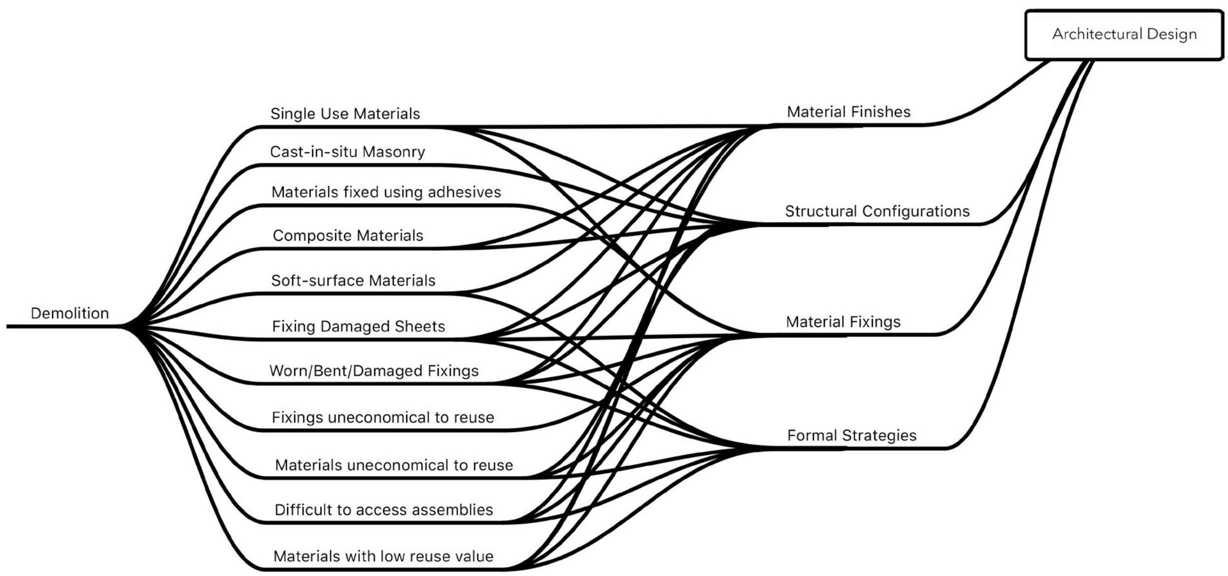


Figure 15.
The relationship between a range of architectural design decisions and the production of waste at the end of a building's life (a).

1.3 IMPLEMENTATION CHALLENGES

The design requirements of adopting Circular Economy ideals are considered by many businesses to generate "labour-intensive" practices with "insufficient effective demand" and "financial arrangements (for circular revenue models) [that] cannot compete with linear revenue models" (SER, p. 4, 2017). Contributing to this negative perception of the CE is a broad set of legislation that limits the potential value of upcycled and reused materials. In the building industry, strict regulations make it difficult to simply replace chemically enhanced building materials with natural or recycled alternatives. The widespread use of treated timber in New Zealand's buildings today reflects the recent 'leaky building crisis' where water penetrated the cladding and rotted un-treated structural timber framing (NZ Govt, p. 12, 2003; Murphy, n.p., 2003). Today, however, these barriers of adopting a circular model are beginning to shift. For the first time businesses are beginning to see the financial advantages of operating in a Circular Economy. An ever decreasing abundance of quality virgin materials is driving up manufacturing costs and adding volatility to the supply chain (MacArthur, p. 18, 2013).

Another significant barrier to the implementation of CE building practices is the perception that buildings have an indefinite design life. There is little motivation for CE design, as the positive implications are seen as too distant to have any significant economic benefit to the individual funding the project at the outset. This assumption, however, that buildings last indefinitely, is largely flawed. Internationally it is reported that 44% of all C&D waste is from renovation (EPA, p. ES-2, 1998). This figure suggests that there is significant remodelling activity that produces waste on an ongoing basis, regardless of the design life of the building itself. Appropriate CE construction systems could largely eliminate this 'mid-cycle' waste by ensuring all extracted materials are in a state fit for reuse. Furthermore it is widely reported that the proliferation of low quality building materials has significantly decreased the expected life span of light timber framed buildings. New Zealand's leaky building crisis, and resulting class action lawsuits against corporations whose building products performed poorly, is a notable example of long-term durability problems with modern materials (NZ Govt, p. 12, 2003).

Figure 16.
The circular economic model. Straw used for insulation in walls can be rapidly decomposed at the end of its useful life and used as fertiliser for the growth of more straw. At no point is waste produced (A).

Additionally, ongoing legal action regarding the substandard performance of building materials, and international research indicating the general shortened expected life-spans for buildings built today, suggests that our perception of buildings lasting 'forever' is misplaced (Divich, p. 48, 2016; O'Connor, p. 3–4, 2004).

1.4 SUMMARY

Research to date states that there is an urgent need for "education and research" to raise the "profile, to provide usable information and actively promote" waste elimination strategies such as deconstruction and a Circular Economy (Storey et al, p. 76, 2005). Industry sources support the notion that designing for reuse and deconstruction will lead to decreased waste; "if buildings and internal components were easier to disassemble, there would be greater materials salvage and possible reuse" (Storey et al, p. 75, 2005). Although early attempts to design-out waste following these parameters have had little impact on the industry, this research recognises the circular economic (CE) model as a viable solution based on the following parameters:

- CE transitions from a purely category-based approach for managing 'left-over' materials, to an applied theory of how buildings/products need to be designed so no 'left-over' materials exist.
- CE is a proactive, pre-emptive solution to totally eradicate waste. Any other option is attempting to reduce harm, not eliminate it.
- There is growing interest in the idea of a CE from business leaders that such a model may help to stabilise material supply chains and therefore, better regulate costs (MacArthur, p. 18, 2013).
- CE pre-emptive design ensures that those without the capacity to manage waste effectively are not required to do so.

2.0

Designing Out Waste

The following chapter is an in-depth assessment of various existing construction approaches, including positive variations (precedents) on standardised approaches and corresponding design experiments undertaken by the author. Preliminary studies involved the physical construction and then the deconstruction of various existing mainstream building systems alongside literature-based research. Physical cyclic analysis of existing solutions aided in grounding the research within a pragmatic scope while both reinforcing and dispelling initial assumptions. Analysis of innovative precedents, and the analysis of conventional methods, helped inform initial design responses also outlined in this chapter.

Chapter 2 contents:

- Analysis of different key categories of construction;
- Existing examples of best-in-practice design (precedents) within each category;
- Initial designed responses to identified problems;
- Ongoing evaluations of designed reponses;
- Identification of a 'design gap' – potential for innovation.

Figure 17.
New ideas (A).

A note on design-led research: This research project was constantly evaluating precedents, its own developments and performance indicators. In this sense the thesis has been organised to reflect a woven process where design experiments evolved directly from precedent examinations. Rather than divide the precedent studies and the conceptual development phase into two distinct chapters, this thesis attempts to merge the two into a constantly evolving body of knowledge and design potential. This is made possible by the specific focus on developing an architectural system rather than a building specific to a site.

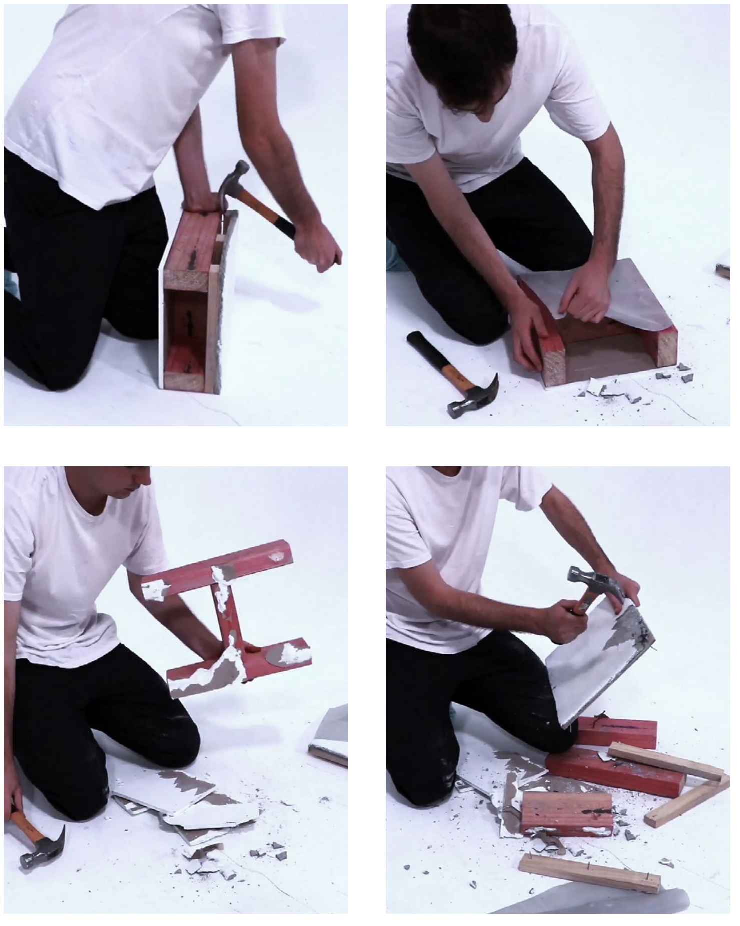


Figure 18.
Deconstruction of a conventional light timber frame architectural assembly (a).

Analysis of existing construction methodologies: Modern construction methods for residential and light commercial buildings can be separated into three categories: frame, panel and module. Each grouping has advantages and limitations in regard to their Circular Economy (CE) potential that are often determined by the way in which they interact with supplementary systems such as the architectural division of space, cladding and wall linings.

2.1 FRAME CONSTRUCTION

Traditional platform timber framing methods make up 87% of all newly built residential buildings in New Zealand (Buckett, p. 32, 2014). This light timber framing (LTF) method has remained largely unchanged since its widespread adoption in the 1930s (Isaacs, p. 99, 2010). Timber lengths, typically 90mm by 45mm in cross section, are cut and then nailed together to create a load bearing structural frame (fig. 19). The system is cost effective, highly flexible and heavily ingrained in building codes and compliance regulations in New Zealand. Structural timber members are chemically treated with boron to resist moisture-induced rot and insect attack. While this treatment does not affect waste levels by volume, or disassembly potential, it does mean that all timber waste from a building site today is now considered hazardous (fig. 19) (Environment Canterbury, p. 9, 2013).

A small 400mm high and 400mm wide wall section was built of New Zealand's predominant construction method to partially examine the disassembly and material reuse parameters.

Figure 19.
Boron treated timber extracted from a conventional wall assembly (a).

2.1.1 Waste and Deconstruction Observations

Existing literature suggests that although the structural reuse of framing timber is possible it remains an uncommon practice due to poor economic factors (Forbes, n.p., 2018). Key cost barriers include the expensive process of decontaminating timber (removal of screws, nails, clips and adhesives) and the need to structurally re-grade each timber member. Furthermore the deconstruction test carried out in this research reinforced the notion that conventional LTF is difficult to disassemble quickly without causing major damage to the materials being separated (fig. 18). The monolithic finishes (stucco plaster and plasterboard) and the way in which they are fixed to the load bearing frame require destructive separation that results in contamination and poor reuse values.

2.1.2 Alternative Framed Solutions

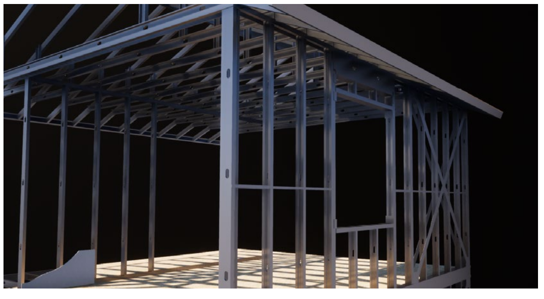


Figure 20. (top)
Platform light steel framing.

Figure 21. (bottom)
Adhesive application onto a light steel component for the fixing of linings.

Light-gauge steel framing: Platform LTF is only one of a range of lightweight framing methods certified for use in New Zealand. Light Steel Framing (LSF), which follows a nearly identical geometric frame pattern to that of platform LTF, is growing in popularity and is now used in approximately 10% of all new residential builds (Buckett, p. 32, 2014; AXXIS, n.p., 2018) (fig. 20). In most instances these steel framing methods suffer from the same deconstruction and reuse constraints as LTF, brought about by the use of monolithic finishes. As with timber frame construction, the use of adhesives between the studs and plasterboard materials exacerbates decontamination and makes reuse of the steel element more time consuming (fig. 21).

A note on industry precedents: Industry-leading architects have produced a range of alternative construction methods that help improve the reusability of various building components, or work to reduce waste. Interwoven throughout this analysis is the critical review of a range of key precedents that demonstrate outstanding innovations in this area. These are marked by a (P). Typically these precedents have been selected based on deliberate efforts to enable disassembly of materials at the end of the structure's life.

(P) Click-Raft (Moller)

Architect: Christopher Moller
Location: Various sites across New Zealand
Type: Small residential dwelling framing system
Date completed: Developed from 2008

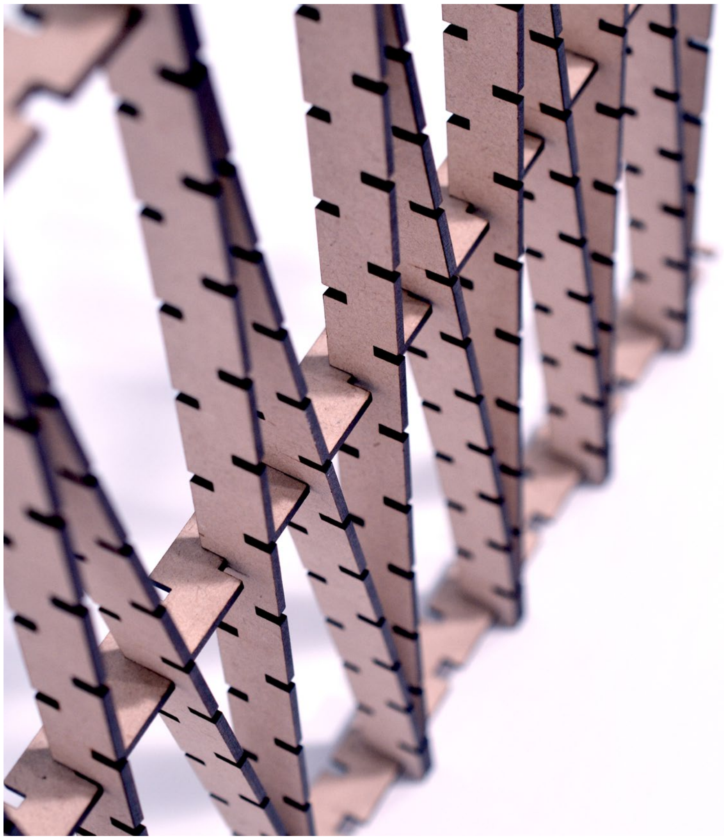
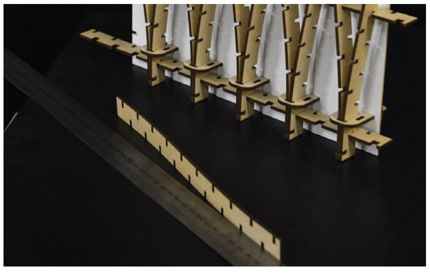


Figure 22.
Click-Raft structural plywood frame (a).

Details: Click-Raft was developed as an alternative light timber frame construction system by architect Christopher Moller. Click-Raft aimed to deliver "low cost, high quality, rapid assembly [and] flexible live/work environments" (Moller, n.p., 2016). Moller's final system is effectively a lightweight plywood frame that uses two principle members to create a structural woven grid of sinusoidal curves (fig. 22). The system typically uses 12mm-thick structural plywood and is structurally appropriate for load bearing floors and walls. CNC-routed slots along the edges of the plywood members allow Click-Raft to 'click' together without the need for fixings of any kind (fig. 23). Moller has also developed a cladding system for Click-Raft that forms "a completely separate outer skin" to leave the geometry of the system exposed internally (fig. 23) (Marriage, p. 687, 2016).



Observations: Click-Raft, although not specifically marketed for its circular economic advantages, offers significant improvements over conventional light timber platform framing. Notable advantages include the very limited number of discrete components that are required to construct a segment (two) and the flexibility of the identical modules in both vertical and horizontal structural elements (fig. 25). These factors make Click-Raft an attractive value-proposition for reuse, as large quantities of the same flexible module can be recovered and reused (Guy & Ciarimboli, p. 1, 2008).

Further advantages of Click-Raft over Platform Framing include the efficient use of sheet material at fabrication, potential to be flat-packed and easy transportability using dry and non-destructive jointing between all materials.

Figure 23.
Click-Raft structural plywood frame.

Figure 24.
Click-Raft after multiple reuse cycles (A).

Critique: There is some uncertainty as to whether the Click-Raft structure will sustain its rigid structural properties through multiple reuse cycles. Small scale model tests indicated a slight loosening of the frame as the deformed wood adjusted to its tensile form over time (fig. 24). Further testing, beyond the scope of this research, is required to identify the physical cyclic capacity of the structural frame. Conditional modulation of the Click-Raft structure and the system's ability to accept partial protrusions (windows, doors, etc.) could also be a key barrier for reuse. In most cases the Click-Raft 'Click-Leaves' are cut from the full length of a plywood sheet (2.4m long). The way in which these leaves are then assembled to create the rigid structure imposes a fixed length and no inherent capacity for partial modulation (fig. 25).

Figure 25.
Click-Raft enclosed space.

(P) ICEhouse™

Architect: McDonough and Partners
Location: Davos, Switzerland
Type: Suitable for light commercial and residential
System: Engineered light steel frame
Date completed: 2016

Details: ICEhouse™ (Innovation in the Circular Economy House) was conceived by William McDonough and Partners (McDonough co-authored *Cradle to Cradle*); an architectural design firm internationally renowned for industry-leading sustainable design practices and circular material management. The ICEhouse™ demonstrates the use of highly engineered technical materials arranged in a manner that facilitates "disassembly and reconstruction" (ICEhouse™, n.p., 2016). The house employs Wonderframe®, a highly modular multipurpose structural frame (fig. 26). The 'Wonder' frame for ICEhouse™ used engineered extruded aluminum components but was initially designed to allow local and low carbon materials to be used where possible (fig. 27).

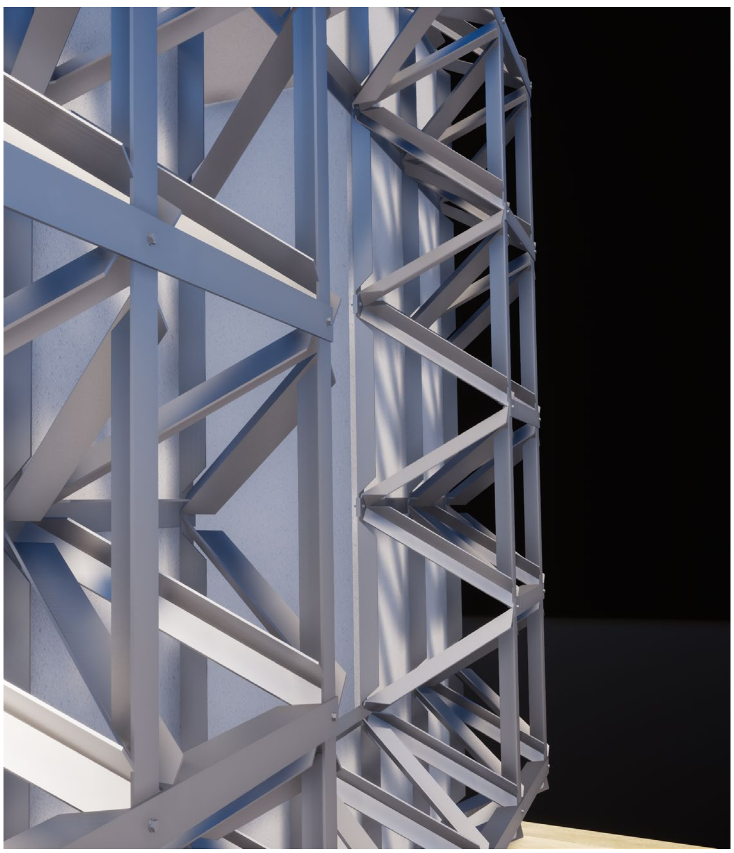


Figure 26.
Wonderframe® on exterior of ICEhouse™ using dry jointing.

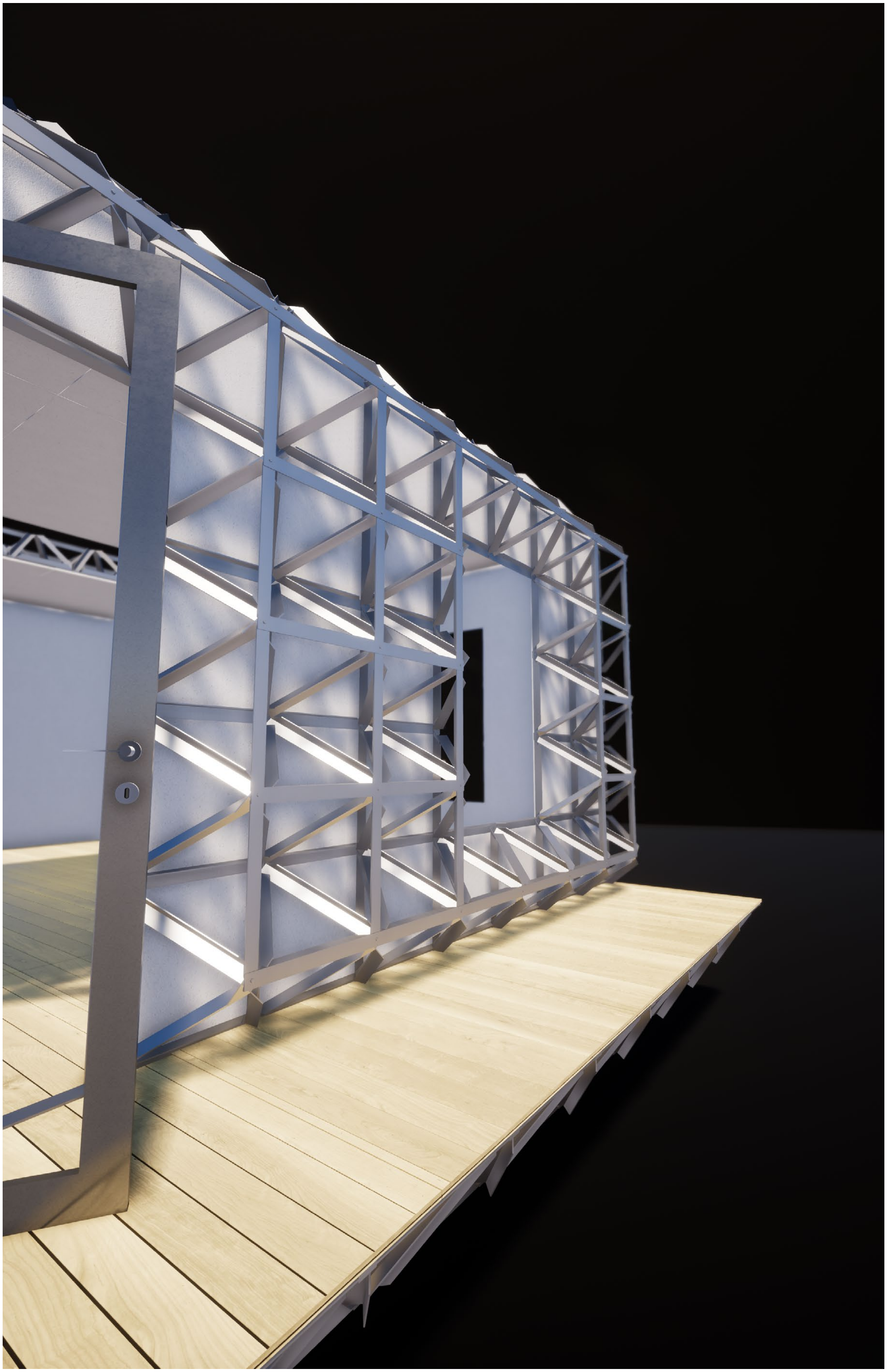


Figure 27.
ICEhouse™ with external frame and polycarbonate cladding.

Observations & critique: Wonderframe® is both the success and failure of ICEhouse™. The flexible, expandable, lightweight and adaptable frame is an ideal structural system for the Circular Economy. It represents highly efficient standardisation and a conscious effort to simplify the prefabricated frame. The current frame design, however, imposes a significant aesthetic condition on the building which may be restricting (fig. 27). The extensive use of highly engineered materials, notably PET plastics, is also unexpected for a 'product' that is advertised as the ultimate in 'sustainable design'. This tends to suggest that materials conventionally perceived as problematic can be used in CE systems, providing at the design level their entire life span has been considered.

(P) WikiHouse

Architect: Alastair Parvin at 00 Architecture Studio
Location: Teams in England and New Zealand
Type: Suitable for light commercial and residential
System: CNC-cut interlocking plywood frame.
Date completed: First developed in 2011.

Figure 28.
WikiHouse 'Wren' system being assembled.

Details: WikiHouse is an experimental 'open-source' alternative construction approach that utilises modern fabrication methods and low-cost building materials (fig. 28). The result is a structural timber frame made of plywood (or any other structural sheet material) that can be entirely digitally fabricated and requires no glue, screws or nails. The purpose of the system was "to lower barriers of time, cost, skill, energy and resources at every stage" of the building construction process, as well as meeting a wide array of social/environmental drivers (WikiHouse, n.p., 2017). Three of these drivers are significant in terms of (CE) design:

- Whole life design: including "maintenance, adaptation, disassembly and re-use;"
- Open materials: "cheap, abundant, standardised, sustainable, and ideally circular materials;"
- Avoiding black box products: owner/user can easily repair and adapt the end product.

Observations: The structural frame detailing ensures that joints are inherently reusable thanks to the simplicity of plywood-only jointing. Contamination of the structural material is avoided because of these timber jointing solutions. The Wren WikiHouse system ('Wren' refers to the fourth iteration of WikiHouse's structural system) also operates on a 300mm modular grid which enables modular expansion and adjustment with reduced levels of complexity (Wren, n.p., 2017). Unfortunately there are significant limitations in terms of material reuse and waste management. Downloading and editing the Wren WikiHouse digital model suggests that there is a large amount of waste at the point of fabrication due to an inefficient geometry pattern of the structure versus the dimensions of the sheet material (fig. 32).

Figure 29. WikiHouse Wren System (a).

Critique: WikiHouse states that the finished structure will aim to "incorporate ideas of adaptation, disassembly and re-use" – yet there is no evidence of such practices. Tests carried out on the WikiHouse Wren (4.0) system show that while the frame can be deconstructed (via hitting with a mallet), geometric parameters and the system's complexity make reuse economically unattractive (fig. 33). The biggest barrier is the fixed geometry that the WikiHouse structural configuration dictates. Corner and edge components are cut to form a 90° rigid shape which inevitably restricts the future use of these components in other locations (fig. 33). Finger jointing of the pieces in the Wren WikiHouse system also means that orientation is controlled, further restricting the flexible reuse of individual components.

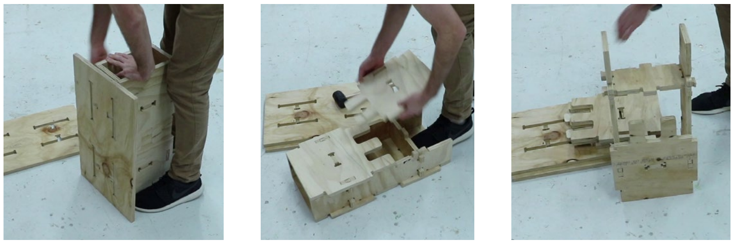


Figure 30.
Deconstruction of WikiHouse Wren system (a).

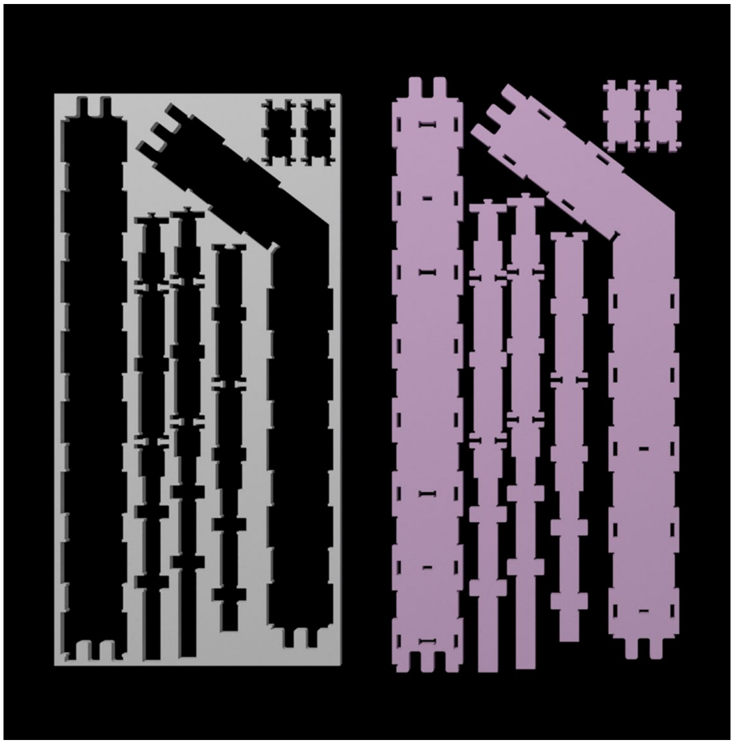


Figure 31.
Randomly selected sheet from WikiHouse Wren average build (A).

WikiHouse Wren	Sheet Area	Waste Area	Waste Ratio
Sheet (as above)	2.88 sq m	1.05 sq m	36%

Figure 32.
Fabrication waste statistics for a randomly selected WikiHouse Wren system cutting sheet (A).

Figure 33.
Imposed geometric parameters of the WikiHouse (A).

2.1.2 Author's Initial Design Experiments

Braced Platform Framing

Preliminary experiments by the author were designed to examine the existing way we build in a more 'reuse-friendly' manner. Detailing of a frame with junctions to enable reversible and non-damaging construction, without the addition of secondary materials, was proposed (similar to the Wonderframe® concept) (fig. 26). A reversible waterproof cladding/lining was also proposed – acknowledging the need for an integrated whole system design approach (fig. 34). This resulted in the complex detailing of jointing elements, a reduced level of structural stability and large quantities of disparate components (fig. 35).

Figure 34.
Braced platform frame assembly details (a).

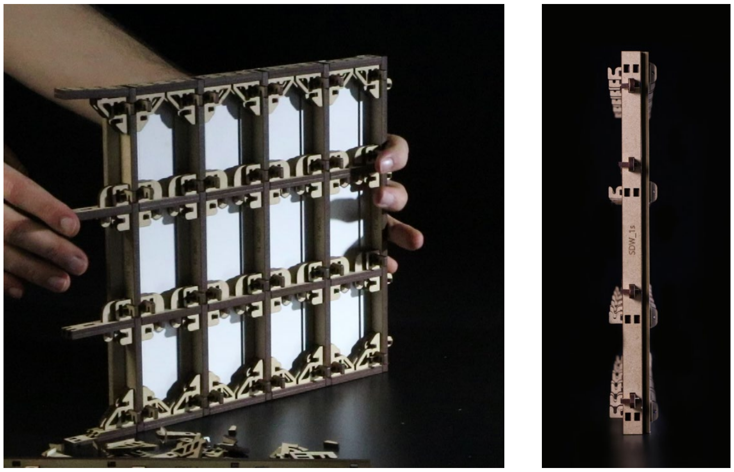


Figure 35.
Braced frame disassembly and elevation (a).

Locked Frames

Further preliminary experimentation, responding to conventional framing, included developing a post and beam system using traditional Japanese wood joining techniques (fig. 35). This is advantageous as it ensures no contamination of the timber with secondary materials and results in a significant simplification of the structural system. Limitations of this approach include the need for supplementary bracing and a fixed grid-based geometry that is not attractive to all building situations.

Figure 36.
'Locked Frame' post and beam frame with Japanese timber jointing methods (a).

Click-Lock Wall

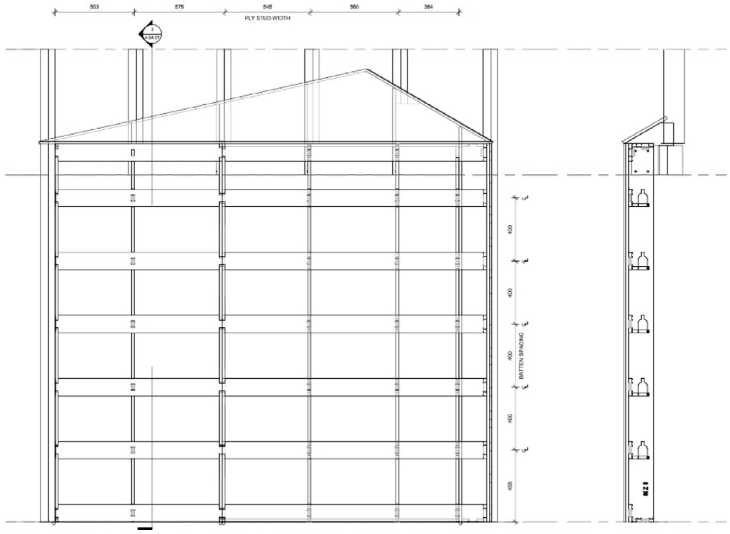
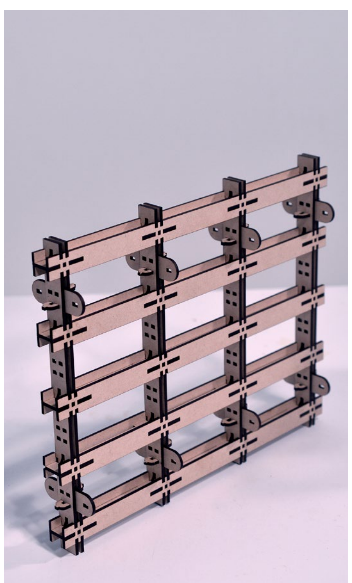


Figure 37.
Conceptual drawings of Click-Lock system by Marriage and Warrender (2016).

Marriage & Warrender: Another experimental frame approach with features facilitating material reuse was an LTF 'plywood-lego' solution published in 2016 (fig. 37) (Marriage, p. 691–692, 2016). Although never built, the orthogonal modular frame-like features, and the detailing of interlocking joints, suggested rapid disassembly potential. To test this hypothesis, a scale model of the interpreted system was fabricated (fig. 38 & 39). The author also considered the addition of compression-attached wall linings to eliminate the frame dependence on adhesive-fixed sheet materials for bracing.



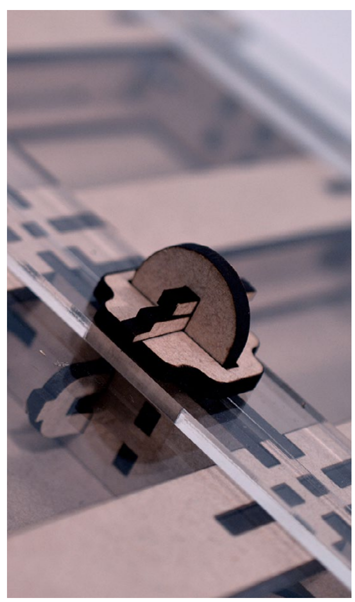


Figure 38. (left)
Click-Lock frame assembly (A).

Figure 39. (right)
Compression cladding detail for Click-Lock system (a).

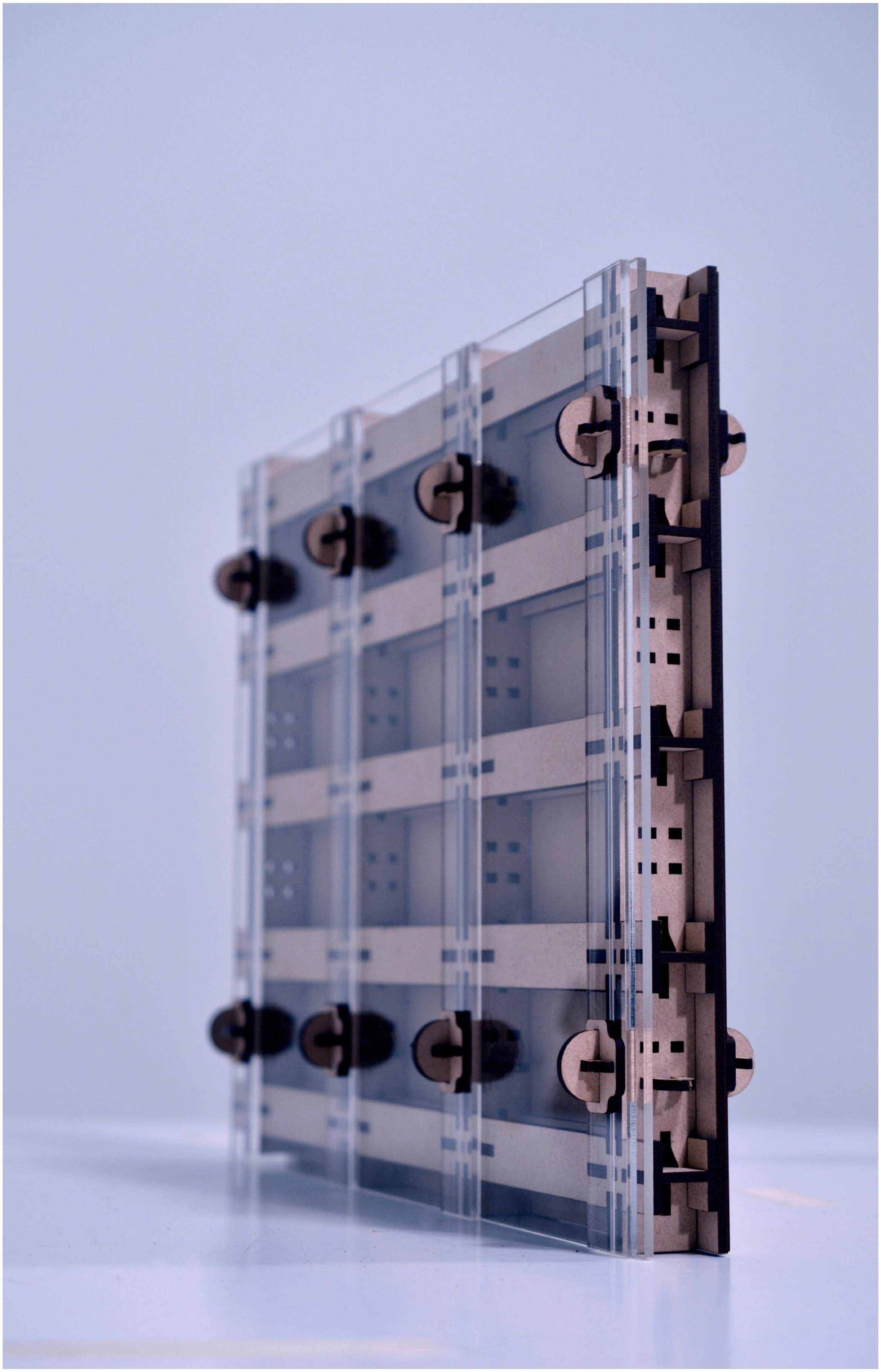


Figure 40.
Author's modified Click-Lock system with compression-fixed linings (A).

Testing & Analysis Methods: To understand the material and assembly performance of a construction system it was appropriate to investigate across a range of scale models. Smaller models (1:20) (fig. 38) were fabricated to determine the modular and geometric capacity of the system. 1:5 scale models were also constructed to explore the assembly parameters in a more complete and accurate manner (fig. 41). Finally, full-scale 1:1 models of key joints and material assemblies were built using the actual materials to examine the durability and cyclic performance of a given system (fig. 42).

Figure 41.
Intermediate scale model of Click-Lock assembly (A).

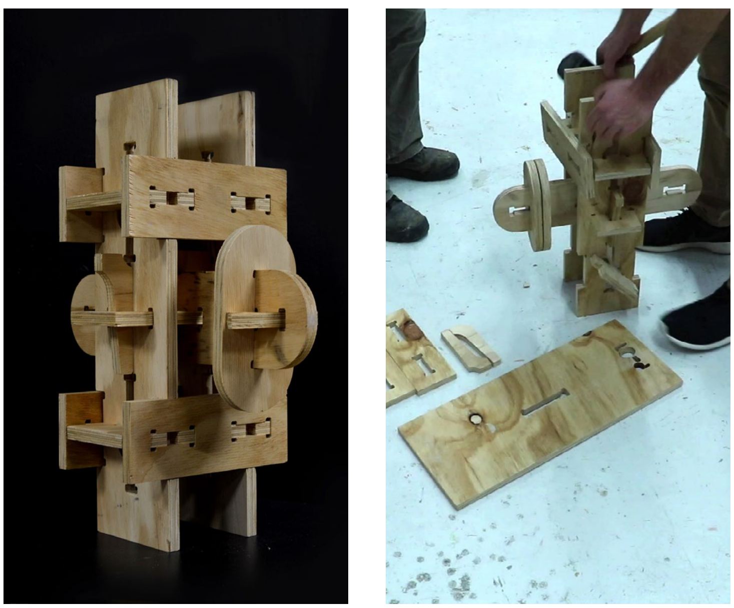


Figure 42.
Full scale model of Click-Lock assembly under deconstruction examination (A).

2.2 PANEL CONSTRUCTION

In this context, panel construction refers to 'Structurally Insulated Panels' (SIPs), solid cross-laminated timber (CLT) and other prefabricated structural panels. Panelised construction offers major advantages in terms of assembly speed (up to twice as fast than a comparable LTF building), building energy efficiency and an overall simplification of building elements (Burgess et al, p. 26, 2013).

Figure 43.
Installation of structurally insulated panels (SIPs).

2.2.1 Waste Potential

Panel construction can suffer the same CE limitations as LTF depending on how the structure is finished. To hide the oriented strand board (OSB/chipboard) product on the exterior of structurally insulated panels, timber battens will often be added and then a monolithic plasterboard finish applied (Burgess et al, p. 58, 2013). SIP construction also uses expanding foam sealant and adhesives around the perimeter of each panel to ensure a snug, airtight fit (fig. 44). This further complicates the reuse potential of SIP construction materials as expanding foam essentially contaminates the purity of jointing conditions and is problematic for a CE product.

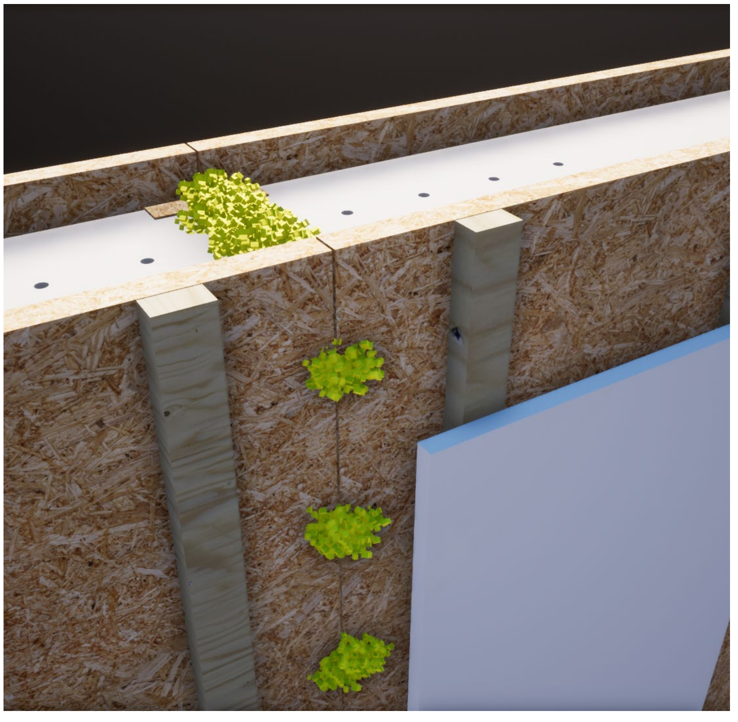


Figure 44.
SIPs panels with timber battens and expanding foam insulation at seams.

2.2.2 Alternative Panel Solutions

(P) Loblolly House

Architect: Kieran Timberlake Architects
Location: Taylors Island, Maryland
Type: Private residential dwelling
Date completed: 2006

Details: The Loblolly House project was completed by Kieran Timberlake Architects (KTA) in 2006 and represents a radical attempt to "improve the efficiency of construction processes" through the use of specialist building technology (fig. 45) (Kieran & Timberlake, p. 24, 2008). The building's use of Bosch Rexroth's Aluminum Frame is innovative in the sense that such framing would typically be restricted to industrial machine frames rather than residential buildings. The extruded aluminium system enables the dry and reversible jointing of all frame components, including lateral load resisting bracing. The extruded aluminum members come 'off-the-shelf' with a groove for a bolted clamp running down all four sides of the 'square' extrusion (fig. 47). KTA then modulated the enclosing panels to bolt into the aluminum frame. The result is a structure that is easy to disassemble quickly while preventing damage to the building components during the jointing and un-jointing process.

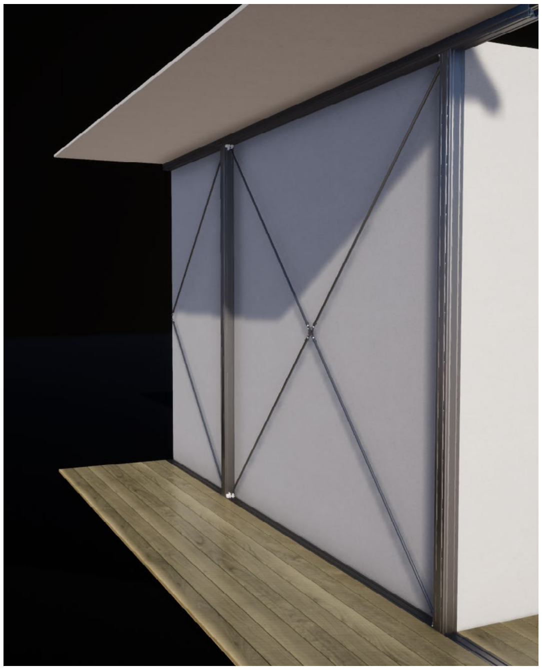


Figure 45.
Bosch Rexroth frame in the Loblolly House.

Observations: A key strategy used in the Loblolly project to promote mass standardisation was to remove any offset caused by the presence of materials (fig. 47). Evidence of this approach is provided by the exposed aluminum frame in the walls, floor and ceiling. In effect this supports reuse and simplifies complexity by reducing the number of varied panel elements. This in turn makes the assembly and disassembly process more straight forward as builders can easily locate key structural components and differentiate them from non- load bearing panels.

Critique: There are significant 'aesthetic' implications as a consequence of using this aluminum 'scaffold' system. The frame requires diagonal bracing to square itself and resist wind and earthquake loadings (Kieran & Timberlake, n.p., 2008). Hence diagonal steel cables tensioned between frame corners can be seen intersecting apertures throughout the building (fig. 46 & 47). Another drawback of Bosch Rexroth's Aluminum Frame for building construction is cost. It is estimated that the material costs upwards of $50 per metre for a 90mm x 90mm section (versus conventional 90 x 45mm timber framing member which costs $4.5 per metre) (Rexroth, n.p., 2017. Q1). The significant additional cost of this reusable structural grid is unlikely to be financially appropriate for mainstream housing.

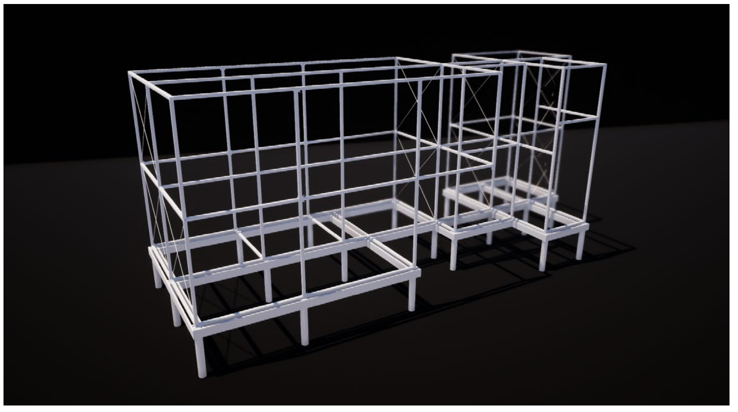


Figure 46.
Drawing of Bosch Rexroth structural frame for the Loblolly House.

A note on Panels and Frames: It is not uncommon for prefabricated wall and ceiling panels to be inserted into larger structural frames e.g. the Loblolly House. This forms a somewhat hybrid construction technique that arguably falls into both 'frame' and 'panel' construction categories. This construction approach removes the need for the panels to be load-bearing which can accelerate assembly processes.

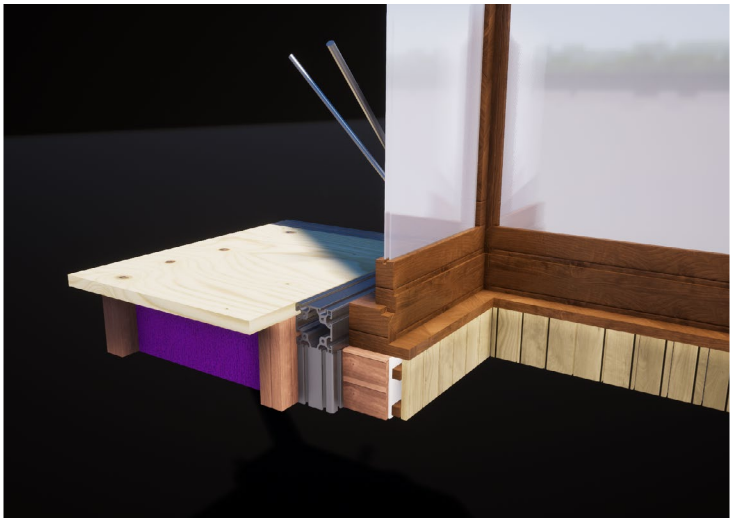
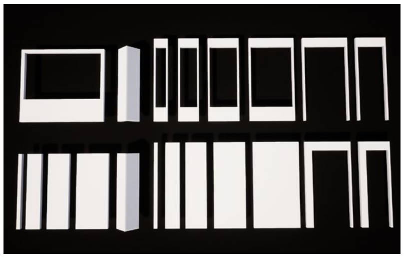
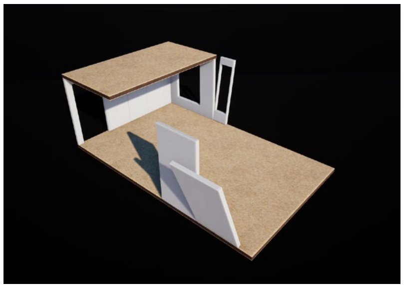


Figure 47.
Detail of Loblolly frame and panel junction.

(P) Industrialised Building Systems (IBS) and the *Sistema Moduli*





Details: IBS and *Sistema Moduli* are two prefabricated panelised building systems that emerged in the 1960s and '70s (fig. 48) (Pallasmaa et al, p. 2, 2013; Holden, p. 32, 2018). Although these two systems utilised different materials for their panel construction, they all exploited similar assembly geometries and methods (fig. 49). *Sistema Moduli* was developed in Finland by Kristian Gullichsen and Juhani Pallasmaa. The structure was a fixed module post and beam timber system using 1200mm wide wall/glazing/screen panels. The approach utilised a flat roof to radically simplify the modulation of the overhead waterproofing and reduce the number of varying components necessary to complete the building. Dry-trade construction was employed, and simplified assembly conditions were prioritised. For more information on the IBS system, refer to Holden, p. 32, 2018.

Figure 48.
Industrialised Building Systems (IBS) panel system.

Observations: Panelised construction has obvious reuse advantages in respect to disassembly economics. In fact the IBS system could be dismantled so effectively that the business offered a buyback scheme where damaged or older panels could be returned to the factory (Holden, p. 34, 2018). In a similar sense *Sistema Moduli* was designed to be a 'temporary summer house' erected and dismantled every year. Both systems however did have significant limitations. Fixed module widths and heights limited the spatial characteristics of the finished building and, due to the dry-jointing techniques, buildings were prone to leaking (Storey, n.p., 2017). Today both approaches would struggle to meet building code requirements for weathertightness and insulation.

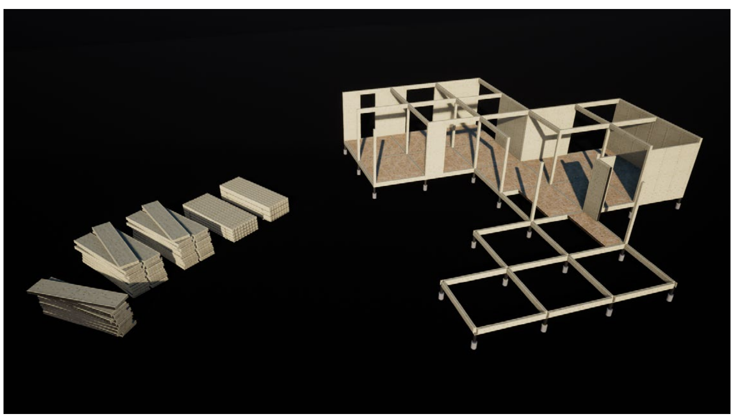


Figure 49.
Sistena Moduli frame and panel inserts.

(P) ModCell Prefabricated Straw and Glue-Laminated Timber Modules

Details: Another possible approach to eliminate the potential for construction waste is using unprocessed 'natural' materials. This means retaining the natural qualities of a given material so that, at the end of the building's useful life, it can be naturally 'recycled'. ModCell Straw Technology is an industry leading example of a modern prefabricated "carbon negative" construction approach that uses large quantities of natural "renewable, biodegradable, carbon sequestering materials" (ModCell, n.p., 2017). The ModCell system integrates a rectangular glue-laminated structural timber frame with straw (or hemp) infill (fig. 50). A "traditional 3 layer lime render" is then applied over the infill material (Pringle, n.p., 2017; ModCell, n.p., 2017).

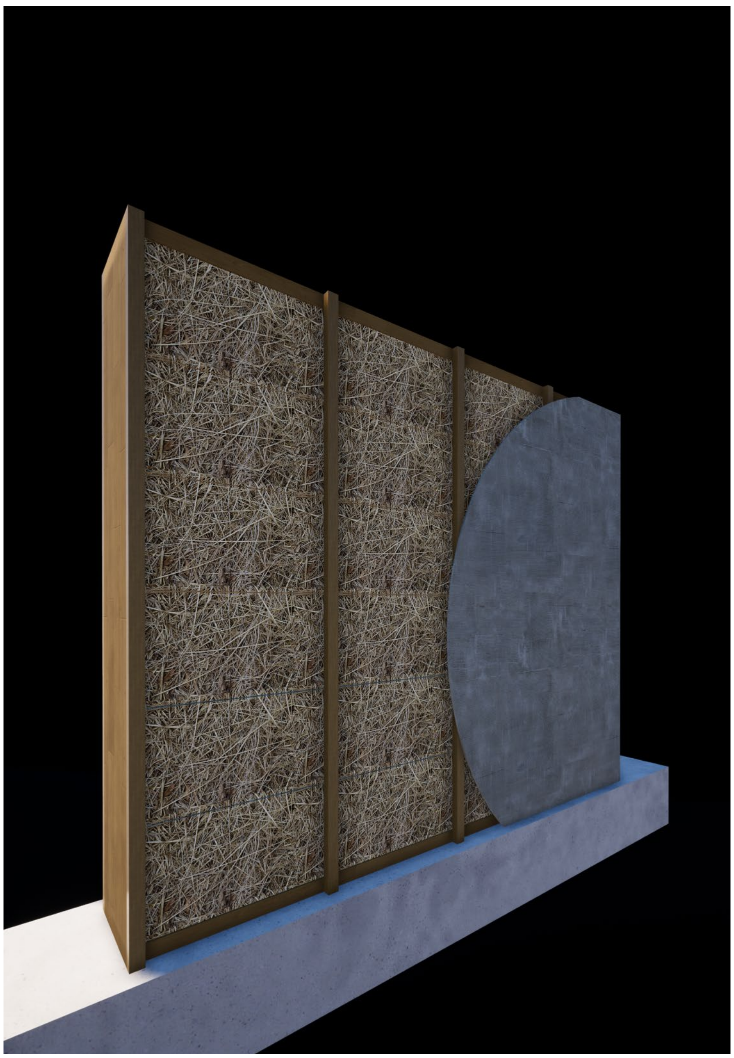


Figure 50.
ModCell – straw and laminated veneer lumber (LVL) panel system.

Observations: At the end of the building's life, it is foreseen that the infill material could be separated from the timber frame and mulched with the timber modules being deconstructable by hand (see 2.2.3). This composting process is dependent on the type of coating materials (paint) and the presence of reinforcement in the lime render. There are also maintenance concerns during the life of the product as any movement or cracking of the lime render could result in the decay of infill materials.

2.2.3 Initial Design Experiments

Modulated Straw Cells

Although deconstruction of the ModCell system is possible, the large glue-laminated frames require careful separation and exceed safe lifting guidelines (ModCell, n.p., 2017). A more material reuse-friendly solution considered by the author includes smaller modulations designed to separate into lightweight timber elements (fig. 51). This approach also improves the modular flexibility of a Straw Cell system (i.e. smaller modules). Concerns regarding how lateral bracing is implemented and how vertical modular flexibility is incorporated have not been fully resolved.

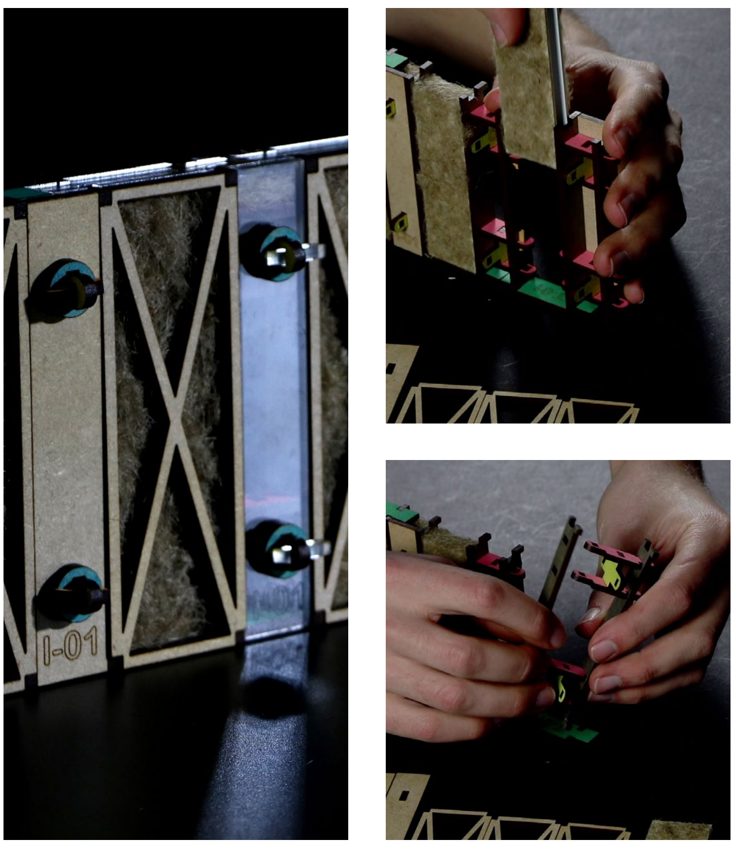


Figure 51. Modulated straw cells showing lining compression detail and disassembly process (a).

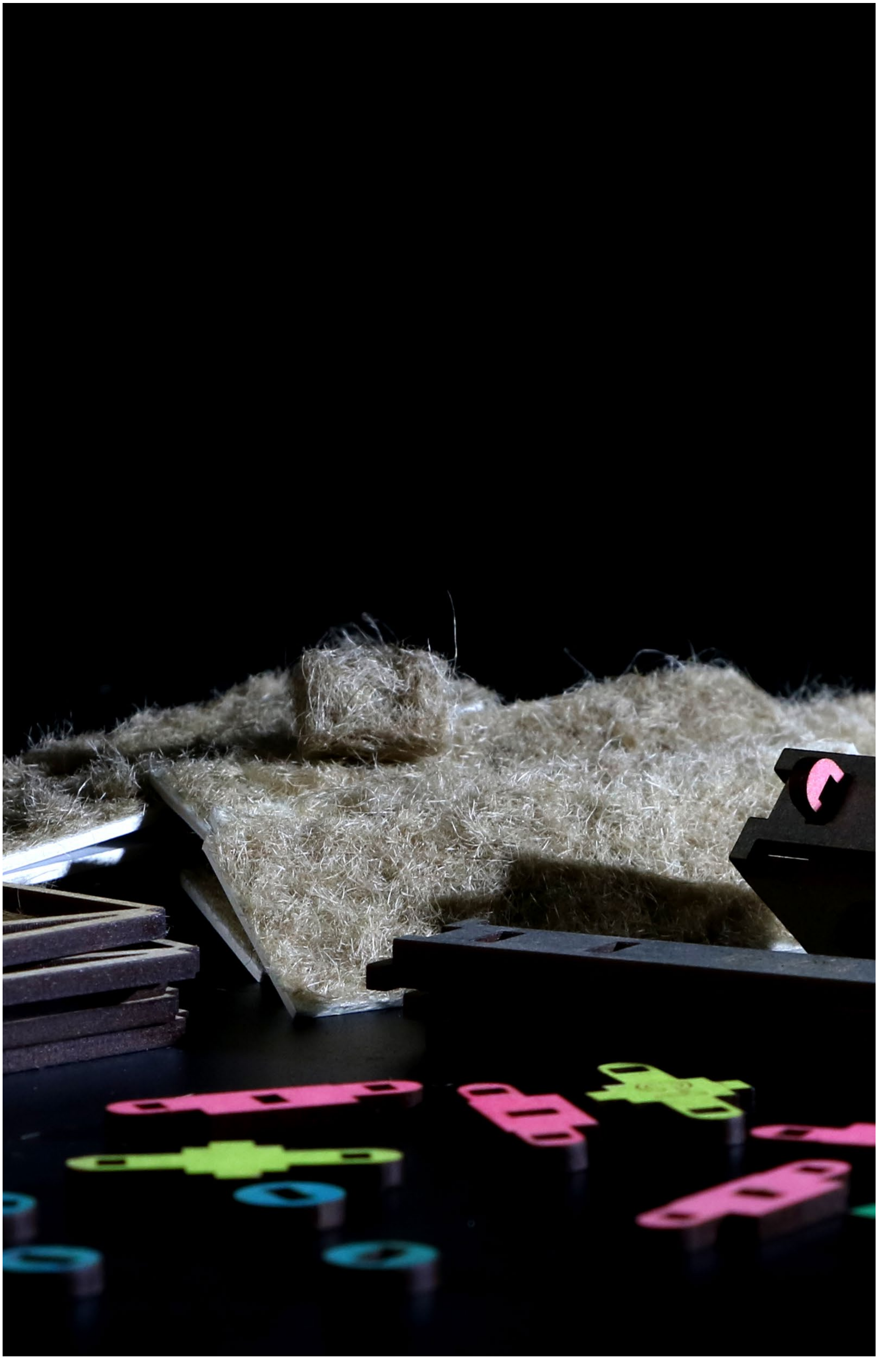


Figure 52.
Dissasembled modulated Straw-Frame components (A).

Stressed Skin Panels

To alleviate the moisture, thermal and expanding foam sealant issues of panelised systems used today, an overlapping and self-locking stressed skin panel solution was proposed by the author (fig. 53). The panel is completely homogeneous in its material construction and can be broken down in stages depending on the level of flexibility and material required. Surface detailing of the structural panel also enables the reversible fixing of aesthetic claddings and internal linings.

Full-height panelisation remains a reuse flexibility constraint of this proposal. Constructional complexity is also a genuine concern in terms of affordability and fabrication complexities.

Figure 53.
Expandable stressed skin panel using homogeneous materials (A).

2.3 MODULATED/HYBRID CONSTRUCTION

Modulated construction can refer to the use of clay brick, and more recently concrete block, to build load bearing structures from small repeating components (fig. 54). Today, however, modulated construction is often considered the large scale building of whole spaces in factory conditions, and then the transportation and assembly of multiple modules to form a complete building (Burgess et al, p. 74–75, 2013).

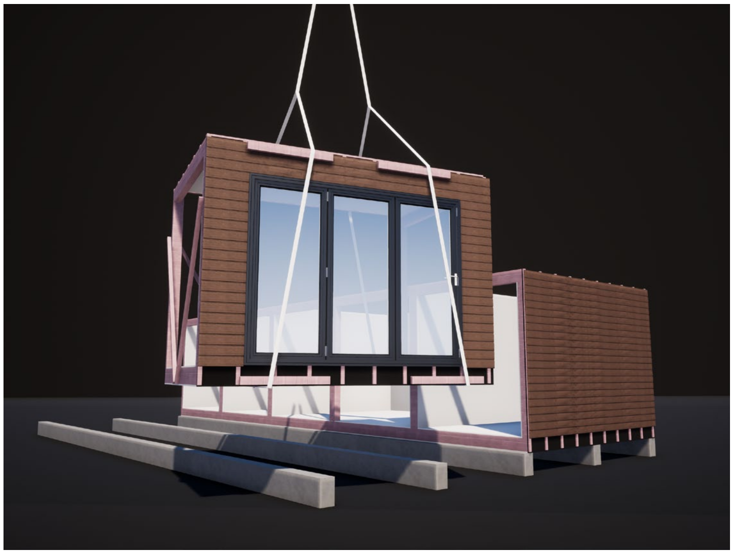


Figure 54.
Example of complete building element modulation.

2.3.1 WASTE POTENTIAL, DECONSTRUCTION AND OBSERVATIONS

In regard to waste production, deconstruction and material reuse, large scale modulated construction is believed to have the potential to enable full reuse and discrete building modules; yet there is a significant lack of evidence to support the assumption that these larger modules could be reused (Burgess et al, p. 11, 2013). Key assembly details, similar to the issues with frame and panel construction (monolithic linings, etc.), could ultimately lead to no significant waste reductions.

There is also likely to be a lack of economic potential for reuse brought about by fixed spatial and geometric conditions of large scale modulated construction. Welded steel box frames that can enclose whole spaces have a fixed width and height. Without careful detailing, the non-reversible nature of the welded joint would mean that anyone wishing to reuse the module would have to accept the exact spatial conditions being imposed. This is then likely to reduce the resale value of the large module as it is appropriate for a less diverse range of applications. A smaller modulation, however, like a traditional clay brick*, can be scaled up or down depending on the spatial arrangement desired and, therefore, arguably has a higher amalgamated reuse value.

***Bricks:** Clay Bricks have been used in construction for more than 3,000 years. The red clay brick still used today is a versatile and durable building solution that has only fallen out of popularity in New Zealand due to its seismic limitation (Salmond, n.p., 2010). Traditionally these bricks used a lime-based mortar that was significantly softer than the brick material itself. This allowed the non-destructive separation of the mortar from the bricks and direct reuse of the brick module. Today a concrete mortar that is significantly harder than the brick is used as a bonding material (Webster and Costello, p. 9, 2005). Although notably more durable, this material is much harder to separate from the brick and is likely to cause irreversible damage to the valuable building module (fig. 55). This is yet another example of economic and technical prioritisations leading to compromised materials.

Figure 55.
Decay of the brick module over reuse cycles (A).

2.3.2 Alternative Modulated Solutions

(P) Rigid Steel Frames

Details: F3Design, in collaboration with XLam New Zealand, have experimented with prefabricated steel box frames (named 'Boxus') to facilitate rapid construction and portability (fig. 56 & 57) (Wright-Stow, n.p., 2017). F3 have used this approach in a public art gallery space and for the construction of residential housing. Supplementary building elements are bolted to the welded steel frame.

Observations: In respect to material reuse, there are genuine concerns regarding the flexibility of the module in all directions. The fixed width and height of the spaces provided by the Boxus system limits the potential for diverse use of the system. This issue is highlighted in the ArtBox installation where air conditioning is required and there is limited capacity to facilitate its integration. Examining the Boxus concept further, the author experimented with double cube modules (fig. 58). The limitations identified with Boxus, in terms of attractive material reuse potential, translate directly into this brief study.

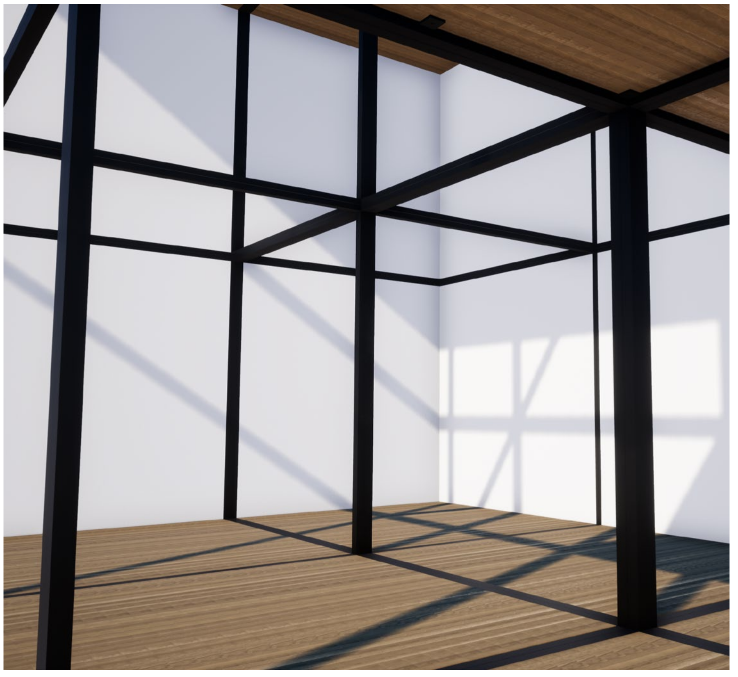


Figure 56.
F3Design & XLAM 'Boxus' module implementation.

Figure 57.
Double 'Boxus' module implementation.

Figure 58.
Experiments with double Boxus modulation for larger architectural systems (A).

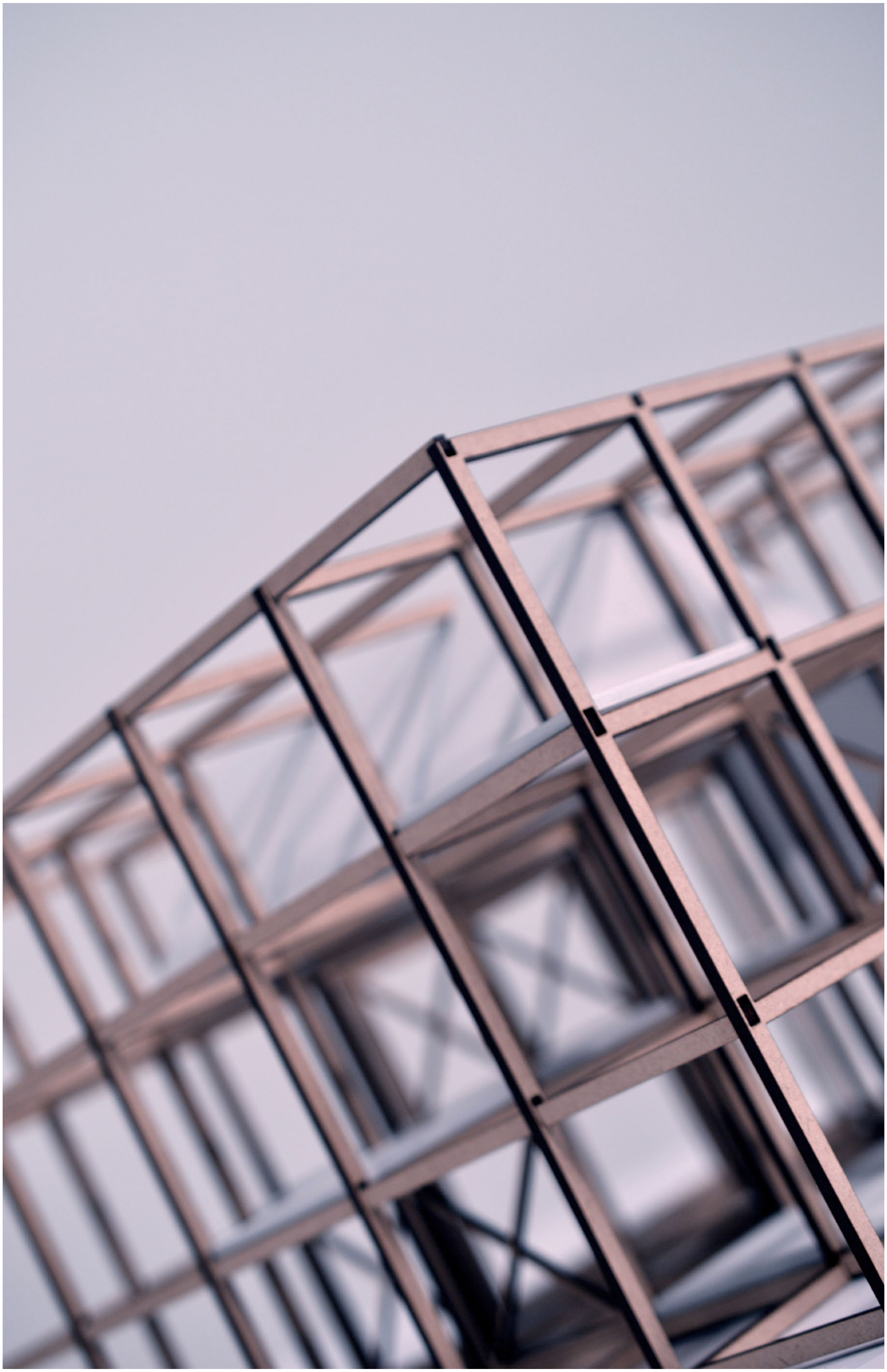


Figure 59.
Whole building redundant cell modulation (A).

2.3.3 Initial Design Experiments

Redundant Cell Modulation

The double cube modulation experiment evolved into a full building modulation experiment. This proposal incorporates frame, panel and module construction methods to propose a redundant grid in which panels can be inserted as required (fig. 59 & 60). This is advantageous over the single box module as it removes double, triple or even quad duplication of structural members where modules meet (fig. 56). However, this design calls for constrained formal potential and a level of redundancy that is arguably economically prohibitive.

Figure 60.
Elevation of redundant cell modulation (3 levels) (A).

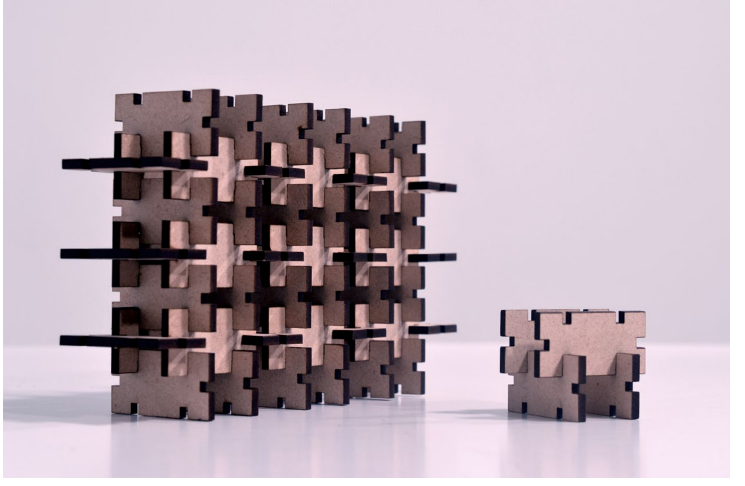


Figure 61.
Timber 'brick' module proposal (A).

Timber Brick Modulation

Referencing traditional modulation dimensions, this brief design experiment used a single prefabricated timber module to create a larger construction assembly (fig. 61). This experiment did not include whole wall reusable details such as waterproofing or insulation.

2.4 CRITICAL REFLECTIONS

Precedent & Preliminary Experimentation

To facilitate continued design research, these building approaches were collectively examined under three key performance measures of a successful Circular Economy as identified by Braungart, McDonough and Baker-Brown (p. 109, 2009; p. 4, 2017):

- Can the specified **materials** be reused directly or processed in a way that is not harmful or energy intensive?
- Does the method of **assembly** facilitate deconstruction without contamination, damage or compromise?
- Do the **formal properties** of the materials lend themselves to reuse in a wide range of situations?

After examining initial precedents, existing systems and preliminary design experimentation, these generic CE measures were expanded to relate directly to the built environment. This expanded list of performance criteria directly informed all further design investigations and enabled the author to critically reflect on the strengths and weaknesses of preliminary studies (next page).

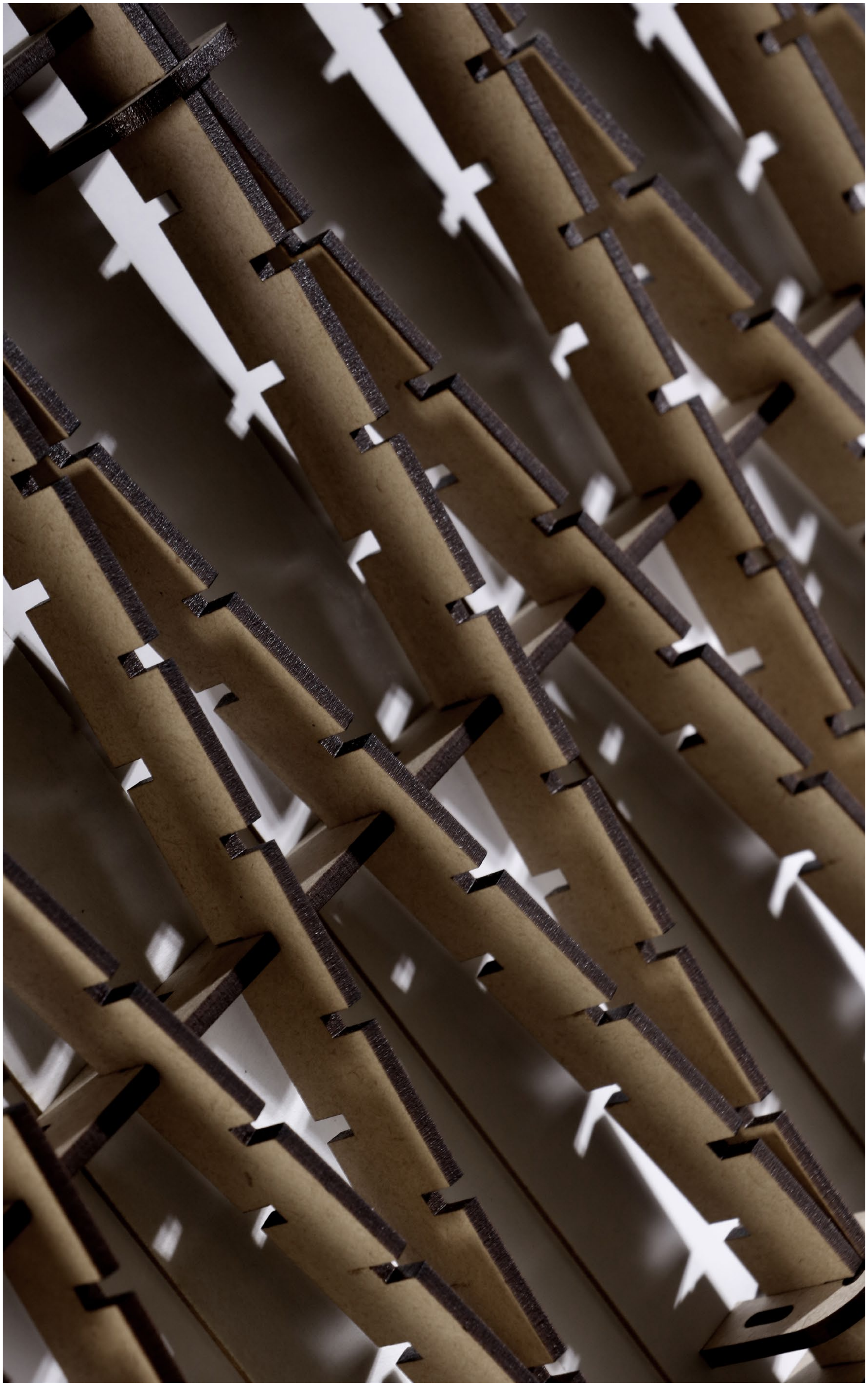


Figure 62.
Rear of Click-Raft system
with cladding (A).

Figure 63.
Performance criteria checklist.
Design & precedent solutions examined in chapter two compared against key Circular Economy performance criteria (authors solutions in red.) (A).

Geometry	G1	Modules and material components must be easily reconstituted or formed in a way that is economically attractive to reuse.
	G2	To achieve attractive reuse performance, deployed materials must be scalable based on a minimum divisible unit dimension.
	G3	Mass standardisation of components must be employed to improve direct reuse economic viability.
	G4	Functionally, the geometry must enable the independent layering of materials to facilitate easy separation.
Fixing	F1	Fixings must be exposed or have a sense of inherent logic to facilitate separation.
	F2	Fixings should either require no tools or be standardised to require only non-specialist tools and/or machinery.
	F3	Through design, fixings must be detailed to be removed/reversed without contaminating or inflicting irreversible damage to the primary materials.
	F4	Consequently no chemical, composite or adhesive-based fixings can be used.
Material	M1	Materials must retain performance through multiple reuse cycles or easily facilitate end-of-life management with minimal loss of value.
	M2	Materials must be detailed as to avoid the need for compromising bonded coatings or treatments.
	M3	To promote economic reuse, materials must remain aesthetically desirable or be easily restored to 'as-new' without complex processes.
	M4	The use of composite/compromised or inseparable hybrid materials must be eliminated.
Score		

	Light Timber Frame	Light Steel Frame	Click-Raft	ICEHouse	WikiHouse	Braced Platform Framing	Locked Frames	Click-Lock Wall	Structurally Insulated Panels	Cross Laminated Timber	Loblolly House	Industrialised Building Systems	*Sistema Moduli*	ModCell	Modulated Straw Cells	Stressed Skin Panels	Modulated Mass Construction	Rigid Steel Frames	Redundant Cell Modulation	Timber Brick Modulation
				✓		✓	✓	✓	✓		✓	✓	✓		✓	✓			✓	✓
				✓	✓		✓					✓	✓		✓	✓		✓	✓	✓
	✓	✓	✓	✓			✓					✓	✓	✓	✓					✓
			✓	✓		✓		✓			✓			✓	✓	✓			✓	
			✓	✓	✓		✓	✓	✓		✓	✓	✓			✓		✓	✓	✓
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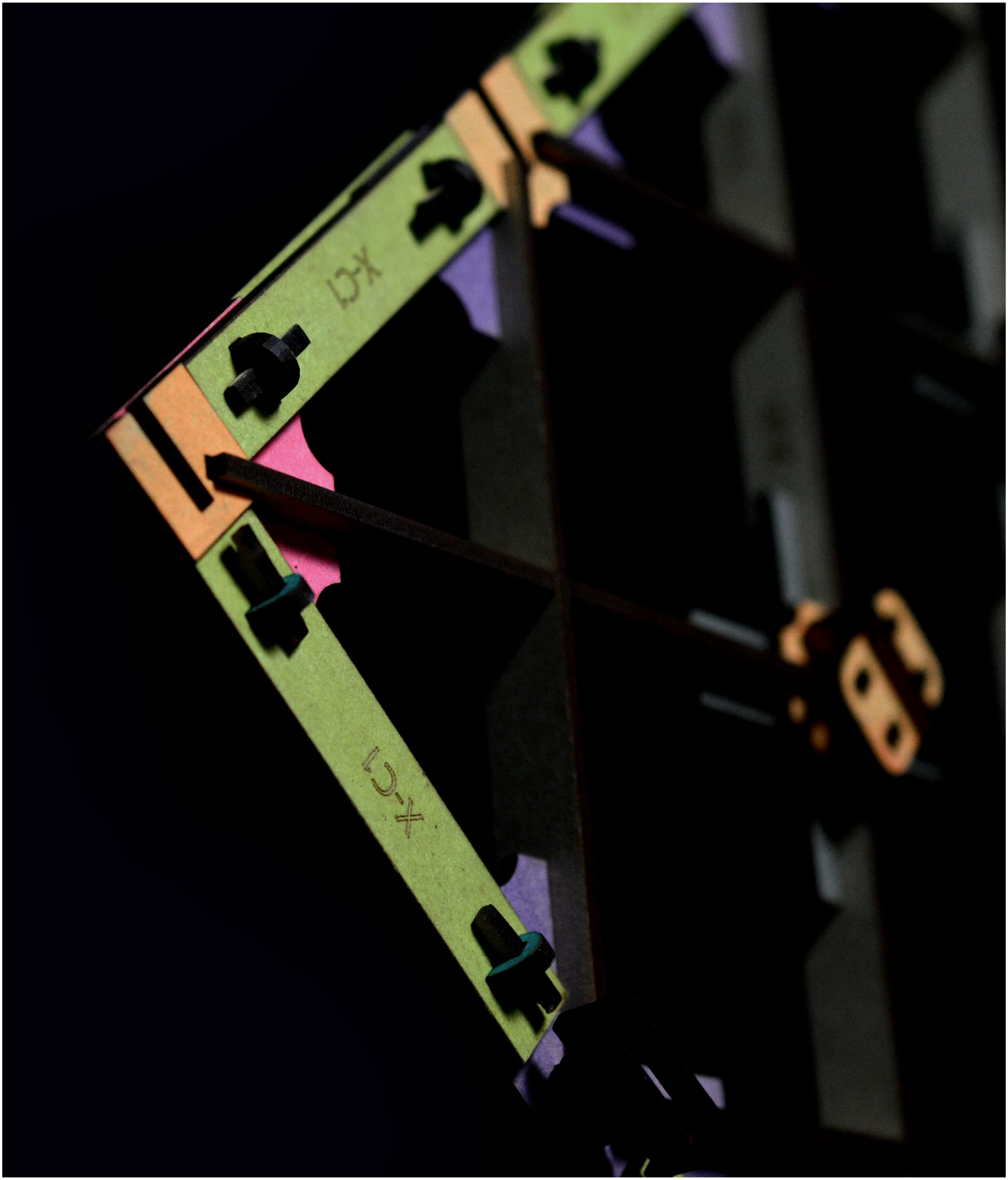
			✓	✓		✓	✓	✓			✓		✓	✓	✓					✓
	1	1	8	9	2	8	8	7	2	0	7	4	8	6	10	6	0	2	5	7

2.4.1 Development Direction

Frame and frame/panel hybrid construction methods were found to be generally superior to others in respect to modulation and fixing integration. The highest ranking frame and panel solutions: Modulated Straw Cells, Click-Raft and McDonough's Wonderframe®, indicated potential design development avenues that incorporate modulated frames and organic materials (fig. 63). Within these high-ranking solutions, material layering and damage or contamination caused to materials due to the fixing methodology remain significant re-use barriers. These issues appear to be a symptom of a poor relationship between material, module and fixing (see 2.1).

Further Observations

- No system performed perfectly or significantly better than others;
- Optimisations often depend on other contextual factors (material finishes/use/location);
- Mass production typically leads to more material reuse through standardisation;
- Neither natural materials or engineered materials have a significant advantage in facilitating reduced waste;
- Technology and computer aided fabrication does not guarantee reduced waste levels;
- Simplification of the structural system is critical and affects all other performance measures.



3.0

Ongoing Design Explorations

Experiments based on observations (2.5.1).
These experiments are evaluated in Chapter 4.

3.1 MODULATION EXPERIMENTS

Construction methods that employ structural frames were identified as a positive CE solution. However preliminary analysis also indicated that modulation of these frames is often restrictive: limited to a fixed height and horizontal expansion only. To ensure a more attractive reuse proposition, it was rationalised that a given frame should be modular both horizontally and vertically. Consequently, exploration of a module-based reusable frame geometry was undertaken in greater depth.

Figure 64.
Angled-Frame (A).

3.1.1 Experiments in Frame Design

Linear-Frame

Test: 'Linear-Frame' (fig. 65) was a direct response to the resulting over-complication of attempting to edit existing platform framing techniques for better CE performance (see 2.2.3). Linear-Frame sought to simplify a modulated timber grid through the use of members with integrated fastening capacity (fig. 66). This system treated the vertical structural element as a discontinuous member to increase modularity within a larger assembly (fig. 65).

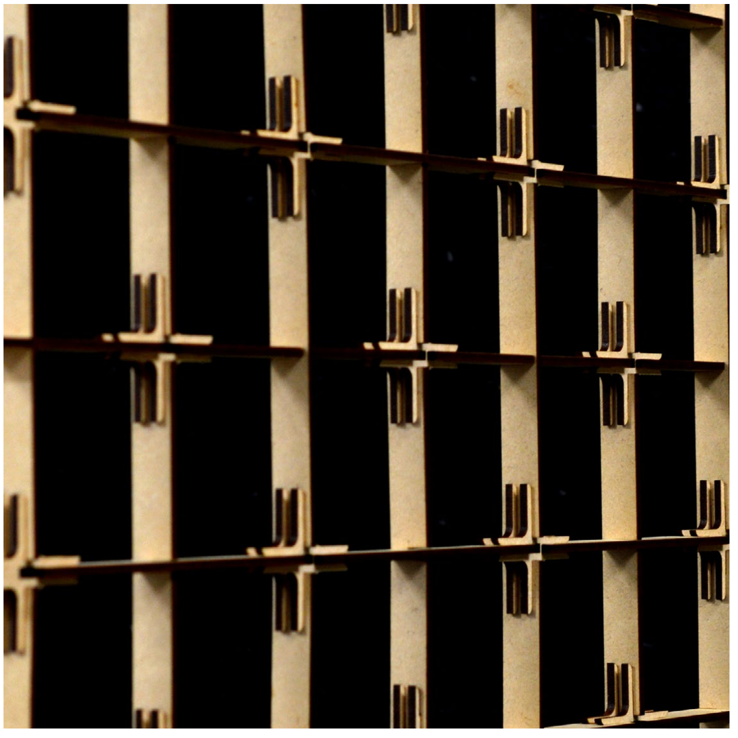
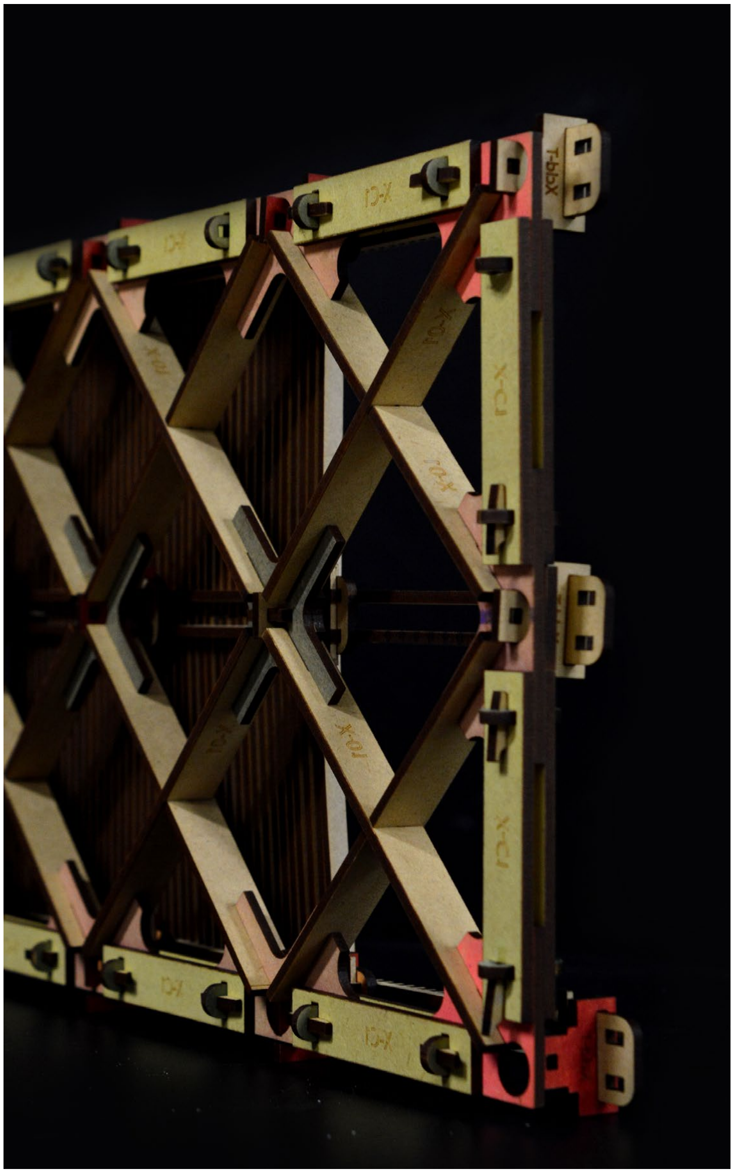


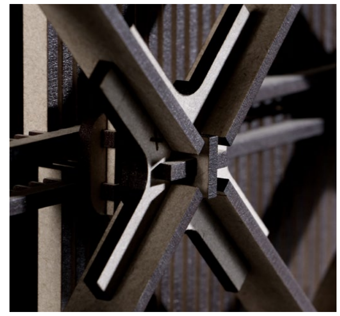
Figure 65.
Linear-Frame geometry and intersections (A).

Key Observations:
- Structural grid with two assembly components
- Modular (expandable)
- Offset at perimeter (i.e. unique members needed)
- No integrated lateral bracing capacity

Figure 66.
Process of deconstructing Liner-Frame. Note: two identical intersecting frames separating and then breaking down into smaller components (two separate elements (A).

Angled-Frame





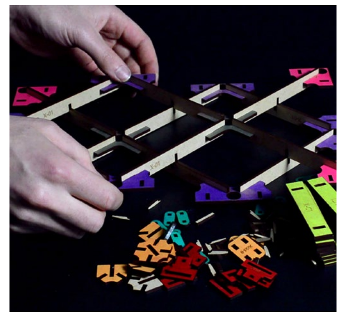


Figure 68. (top)
Angled-Frame intersection detail with cladding clasp through centre (A).

Figure 69. (bottom)
Separating reciprocal Angled-Frame elements (A).

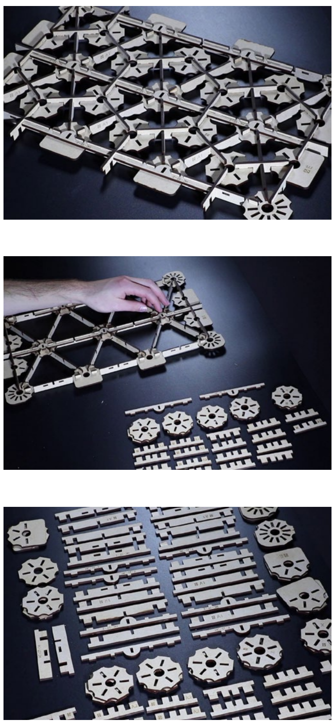
Figure 67.
Angled-Frame (A).

Test: Angled-Frame *(later referred to as 'X-Frame' – iteration 1)* was an iterative experiment derived from Linear-Frame adding inherent structural bracing capacity through an imposed diagrid geometry (fig. 67). The Angled-Frame structure also permitted more rigid sub-component jointing systems with provision for reversible cladding attachments (fig 68 & 69). Integrated lateral bracing capacity to aid in separation of discrete building layers was directly inspired by Moller's Click-Raft system (see 2.1.2).

Key Observations:
- Structural grid – three components
- Modular (expandable)
- Edge blending
- Integrated lateral bracing capacity
- Fragile joints

Pattern-Frame

Test: Pattern-Frame was an iterative experiment derived from Angled-Frame, designed to streamline component separation (fig. 70). Simplification was achieved by adopting a jointing system perpendicular to the direction of the spanning members (fig. 71). This change allowed a simplification of the disassembly process by enabling all components to be separated as singular, more compact, elements.



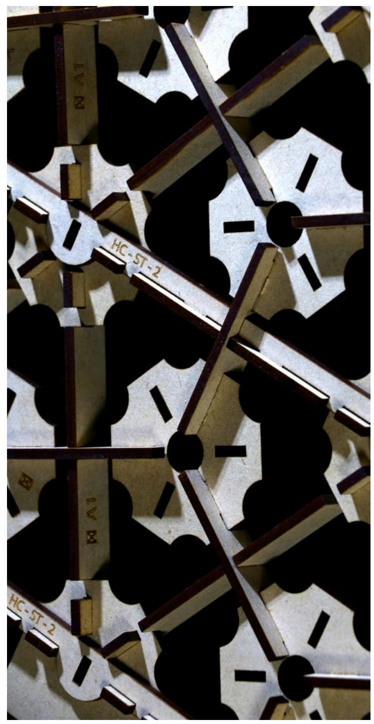


Figure 70. (left)
Pattern-Frame disassembly sequence through perpendicular separation (A).

Figure 71. (right)
Pattern-Frame detail (A).

Key Observations:
- Grid – five components
- Modular (expandable)
- Edge blending
- Integrated lateral bracing capacity
- Increased buckling potential
- Complexity issues

3.1.2 Experiments in Natural Material Integration

Straw-Frame (Truss)

Test: For increased modularity within a hybrid (natural and technical material) framework, a ModCell type system was tested that vertically modulated the structural components (fig. 72). This aimed to reduce the lifting weights inherent in the modulated straw cell system while also improving overall modular flexibility.

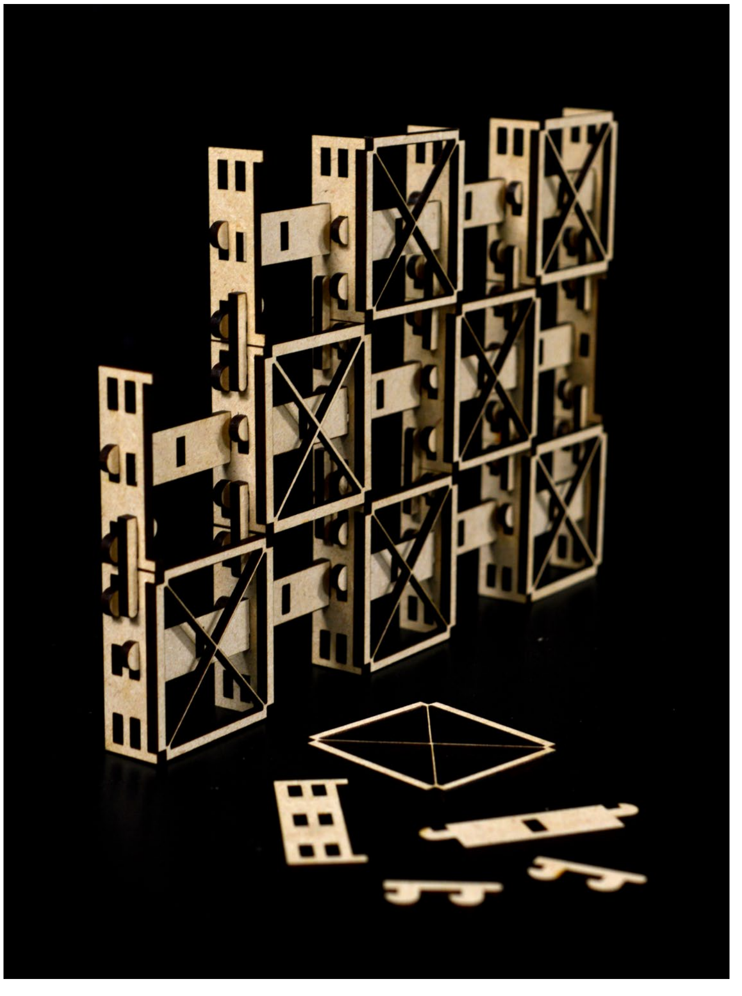


Figure 72.
Straw-Frame truss enabling vertical modulation of structural elements. Segments are 900mm high (A).

Key Observations:
- Vertically modular (expandable)
- Edge blending
- Complex waterproofing issues remain
- Complexity issues
- Limited lateral bracing capacity

3.1.3 Experiments in Horizontal System Design

Experiments up until this point typically dealt with modulating a reusable vertical structure only (e.g. walls). Economic reuse constraints – due to fixed lengths – on materials in the horizontal position (floors) are also prohibiting reuse factors. In an ideal situation both horizontal and vertical building elements (floors and walls) would be made out of the same components and thus equally modulated and suitable for reuse. The following tests experiment with the development of a simplified and expandable discontinuous horizontal construction system to test if this approach results in a system suitable for both uses.

Reciprocal Frame (1)

Test: Existing complex structural forms known as 'reciprocal frames' (RF) and '1.5 layer space frames' allow 'simple' discontinuous structural members to span significant distances horizontally (Larsen, n.p., 2008; Chen, n.p., 2014). An initial test explored the possibility of a modulated reciprocal frame (fig. 73). This system employed simple conventional 90 x 45mm timber members, however, if it was to be modulated vertically, a greater level of design detailing would be required (fig. 74).

Reciprocal Frame (2)

Test: A further reciprocal frame study aiming to create a linear system with simple perimeter detailing and rigid connections (fig. 75). This structure fell halfway between a reciprocal frame and a layered 1.5 layer space frame. To stiffen the system a quadruple pin jointing detail was integrated.

1.5 Layer Space Frame

Test: Adopting a full 'space frame' solution was thought to alleviate the issues with reciprocal structures (fig. 100). Unfortunately, the rigid jointing requirements were difficult to achieve while also incorporating reversible connections. The proposed structure was significantly more efficient, however, it reintroduced perimeter geometric limitations (fig. 76).

Key Observations: While the structure created an effective modular system, it required the design of joints with significantly less flexibility/deflection. The complex angular forms also presented difficulties in terms of edge connections.

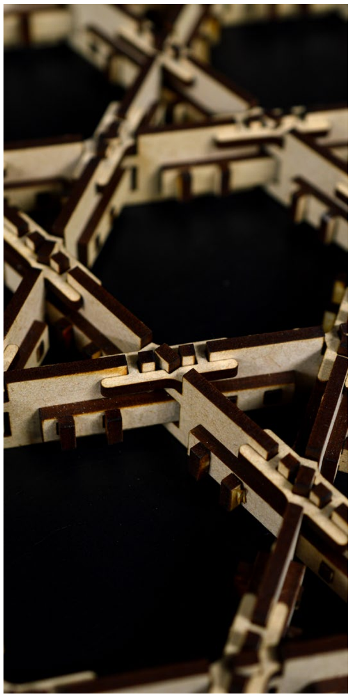
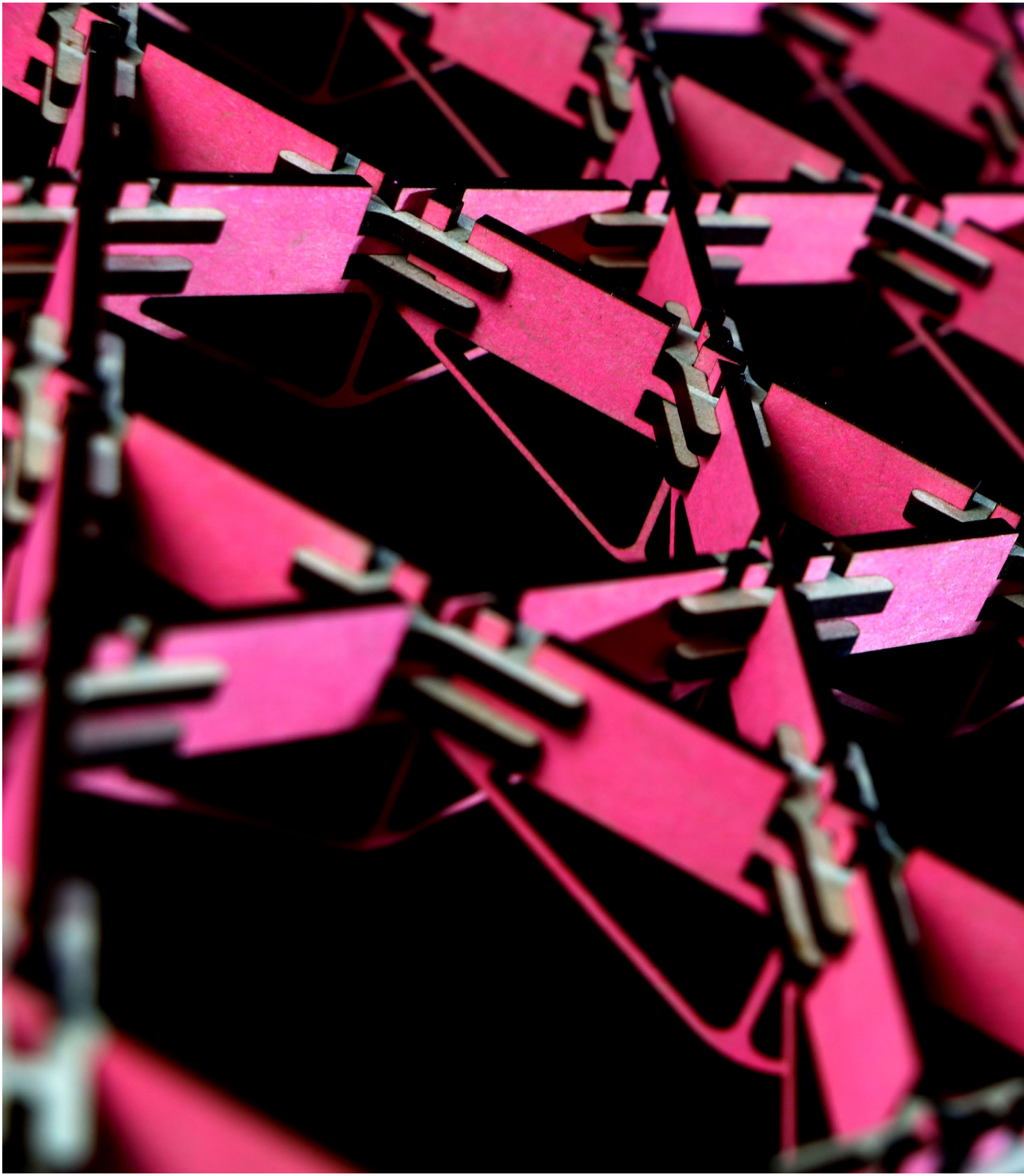


Figure 73 & 74.
Modulated Reciprocal Frame with quad pin jointing bridge (A).

Figure 75.
Modulated Reciprocal Frame with teeth-lock joint detail (A).



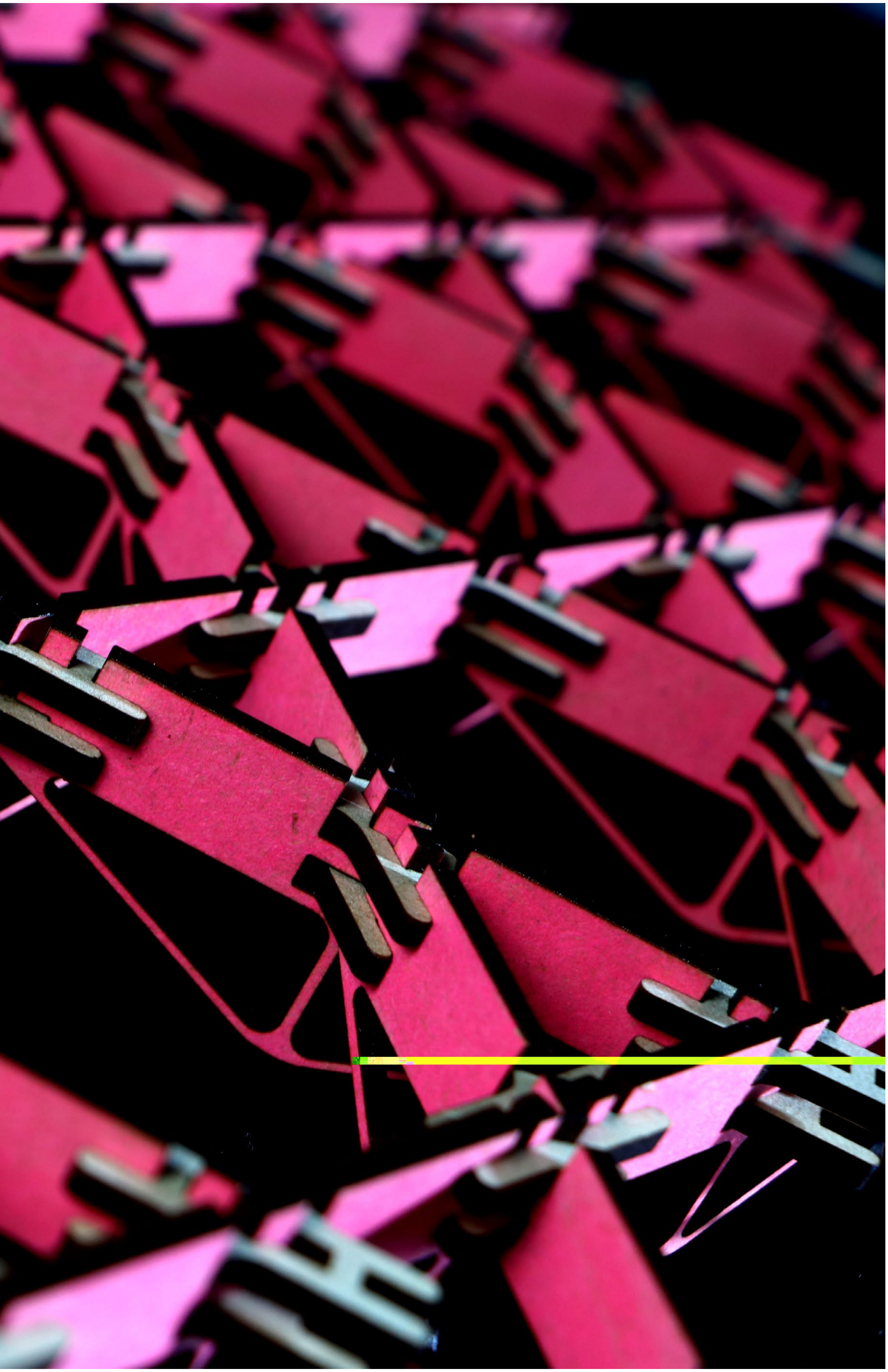


Figure 76.
1.5 layer space frame highlighting joint details and simplified component systems (A).

3.2 ASSEMBLY EXPERIMENTS

An integral aspect of the module design is the assembly specification of that given module. The way in which a geometry structurally interacts with another supporting geometry can render one or both of the materials inappropriate for reuse. The following investigations experimented with designing modules that could join to one another without causing irreversible damage.

As per all experiments, a detailed comparative analysis can be found in Chapter 4.

3.2.1 Reversible Friction Jointing

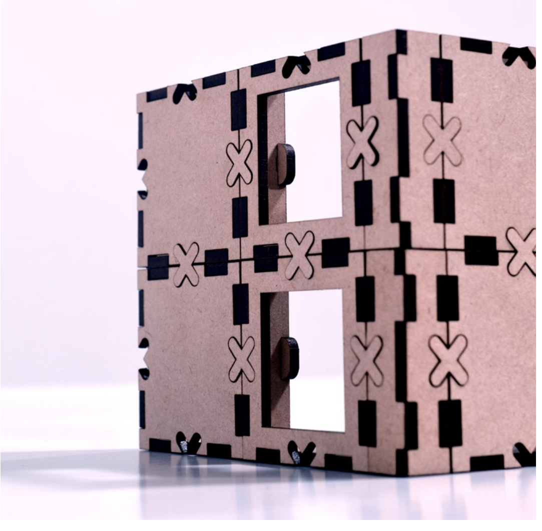


Figure 77.
EdFab plywood cassette system with butterfly connection (A).

(P) EdFab

Test: EdFab is a flexible module-based plywood cassette construction system that uses a plywood 'butterfly plug' at module intersections to unify the structure (fig. 77) (Chapman et al, p. 6–7, 2014). The system was developed by the University of Auckland's Department of Architecture & Planning, as an experimental construction system aiming to deliver rapid assembly times. The design results of the Auckland study have been represented here.

Key Observations: EdFab is somewhat advantageous in respect to reusability as it uses a single material and, typically, a single module to enclose an entire building. The butterfly jointing pin is also effective in creating a rigid connection between elements (fig. 78). However, as the butterfly component sits flush with the parallel module surfaces, the connection is not easily reversible.

Figure 78.
EdFab plywood system deconstruction (A).

WikiHouse Joint Variations

Test: EdFab and WikiHouse plywood systems both use integrated friction-based jointing methods that are difficult to separate. This is a result of the formal complexity of plywood components and the way in which smaller wooden components (pegs/pins) are locked into the greater system. It was hypothesised that changes could be made to the WikiHouse system would facilitate rapid disassembly. A scale model was built, testing the use of a traditional Japanese wood jointing method called Sao-shachi-tsugi (SST) in combination with conventional WikiHouse framing (fig. 79) (JAANUS, n.p., 2001).

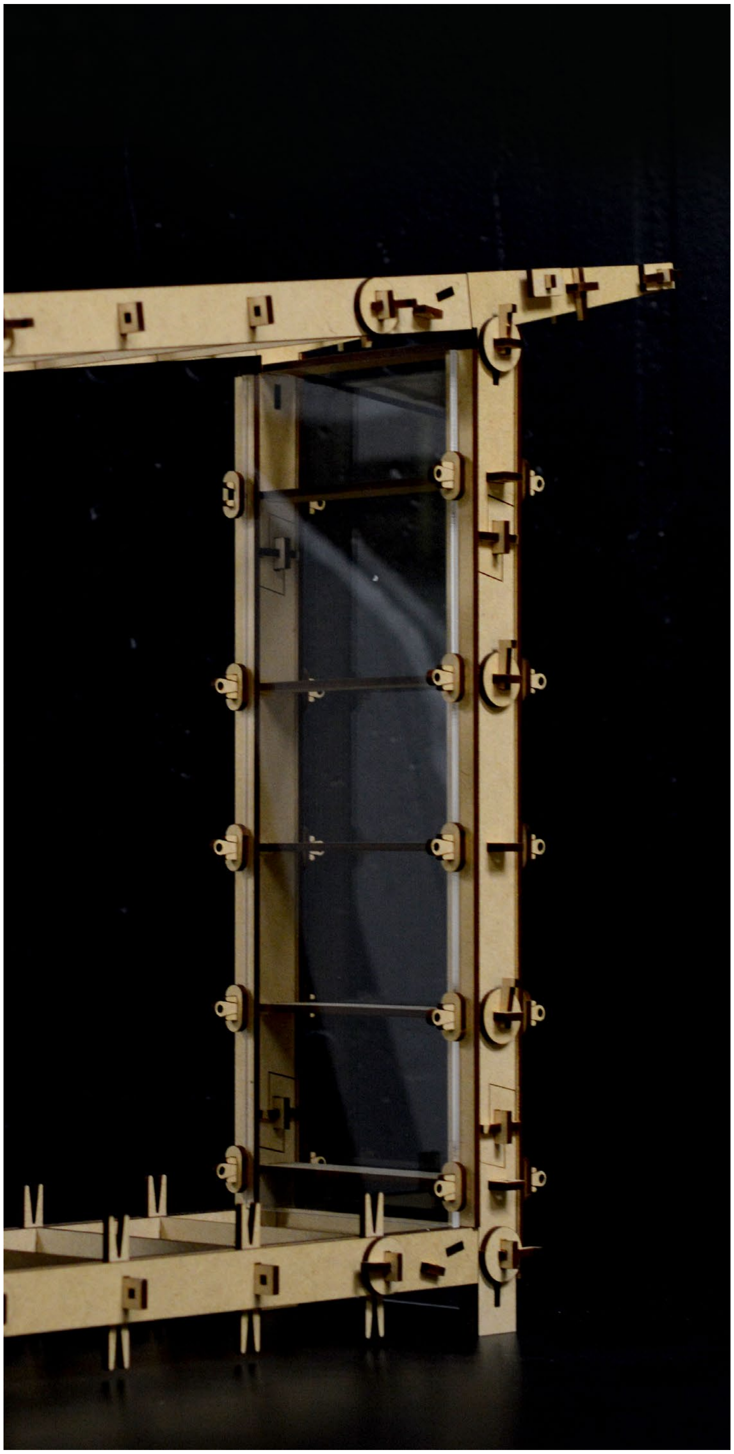


Figure 79.
Wiki-Finch – a combination of WikiHouse geometry V2, Sao-shachi-tsugi and friction mounted lining receptors (A).

Key Observations:
- Reversible pin joints (all timber)
- Reversible cladding
- Less rigid structural frame
- Fragile members

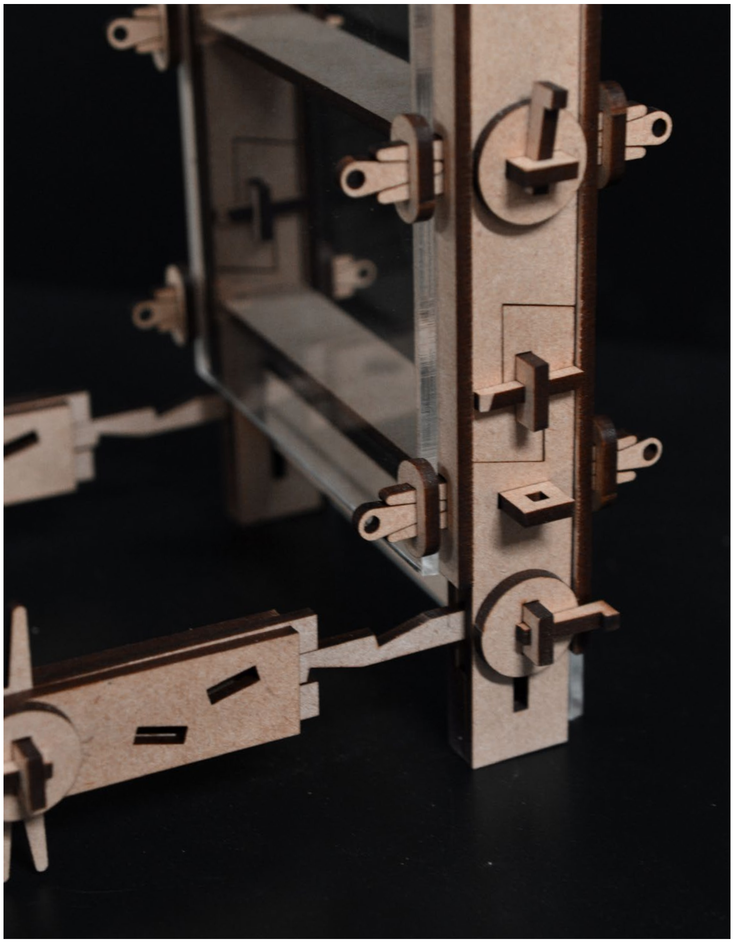


Figure 80.
Sao-shachi-tsugi joint and friction mounted lining receptors (A).

3.2.2 Assembly Integrated Frame Experiments

Bolty

Test: An experiment inspired by Kieran Timberlake Architects' (KTA) Loblolly House, 'Bolty' was a reversible wall assembly that used off-the-shelf components with a custom steel section. This simplified assembly approach was 'sketch-modelled' at full scale (fig. 81). The assembly experimented with the use of a single protruding bolt to create compressive joints, clamping the cladding and waterproof lining to the load bearing structure. It was foreseen that the vertical load bearing system would be a modified steel alloy 'C-section' extrusion (fig. 82).

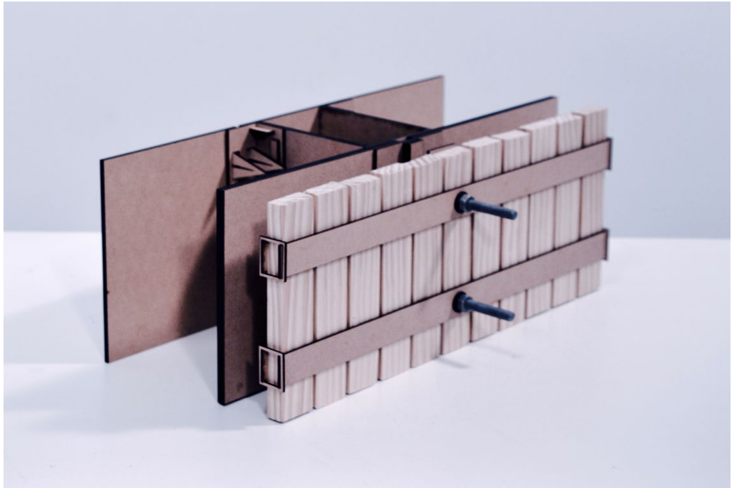


Figure 81.
Bolty – 1:1 section of wall with compression cladding and waterproof linings (A).

Key Observations: 'Bolty' was a diversion from radical structural changes to a simple layering system that enabled direct material reuse and fitted somewhat within conventional construction techniques. Notable issues/features include:

- Integrated reusable waterproof lining
- Reversible cladding
- Security hazard i.e. external dissaembly/entry possible
- Not vertically modular (expandable)
- No lateral bracing capacity

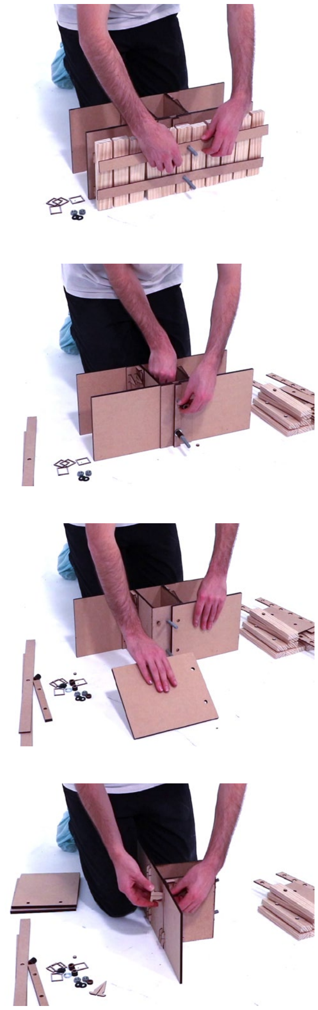
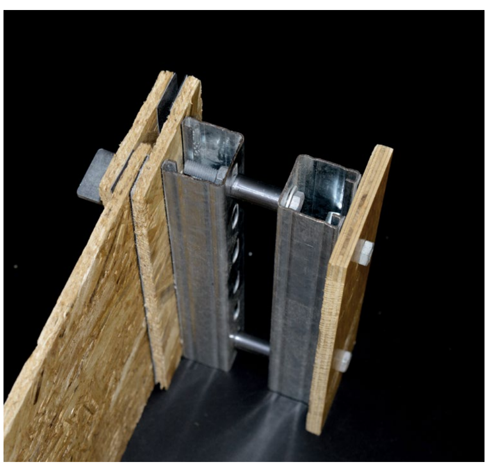


Figure 82.
Disassembly of 'Bolty' (A).

Unistrut

Test: Steel extrusions with an integrated fastening capacity, similar to the design proposed in 'Bolty', are already available on the market today. Unistrut is one such product, marketed as an "adjustable, demountable and reusable" structural fastening frame, typically used in manufacturing processes to support machinery and in the vertical service risers of buildings (fig. 83) (Unistrut, p. 7, 2017). Here Unistrut 'P1000®T' has been used to create a sandwiched structural assembly.



Key Observations:

- Integrated reusable waterproof lining
- Off-the-shelf components
- Security hazard i.e. external entry possible
- Not vertically modular (expandable)

Figure 83.
Unistrut stud and lining proposal. Section of wall with compression mounted waterproof lining, aesthetic rainscreen clasp and internal lining clamp (A).

3.3 CLADDING EXPERIMENTS

Waterproofing, internal lining and cladding layers and their integration with the structural system were identified in Chapter 2 (2.5.1) as areas of significant waste production and low reuse potential. To deliver a completely 'waste-free' product, new building envelope layers need to be designed that are fixed and modulated more effectively. The following section highlights key design details of proposed solutions.

3.3.1 Experiments in Waterproofing

Linear Frame Waterproofing

Test: A compression mounted rigid air barrier (RAB) system with overlapping seams sealed with reusable recycled rubber strips (fig. 84–86).

Figure 84. (left)
Waterproof layer on Linear-Frame compressed onto structural frame (A).

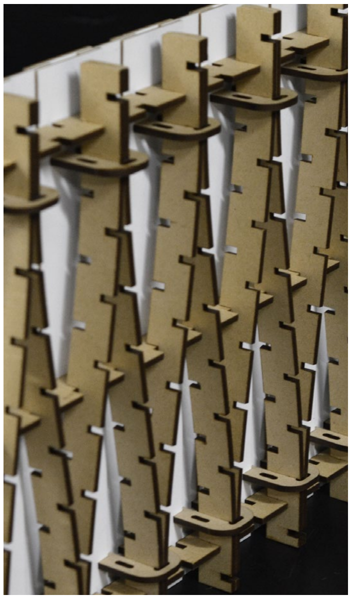
Figure 85. (right - top)
Waterproof layer detail (A).

Figure 86. (right)
Internal open-hook detail for internal lining fixing (A).

Key Observations:
- Reusable waterproof lining
- Off-the-shelf components
- Not vertically modulated
- Offset (requiring more individual components)

Click-Raft Compression Cladding

Test: A similar experiment to the previous, however, exploiting Moller's Click-Raft system as the structural underlay (fig. 88).



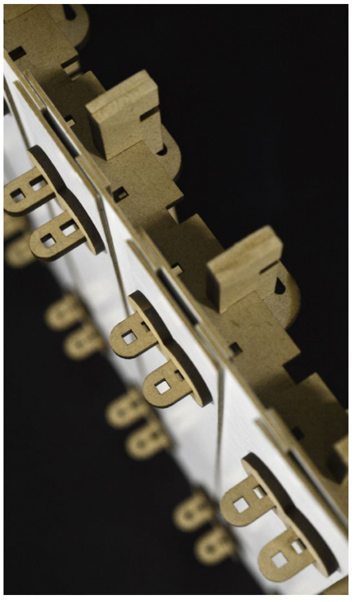


Figure 87. (left)
Rear of Click-Raft system with compression fixing holding lining to frame (A).

Figure 88. (right)
Compression lining fixing detail (top down) (A).

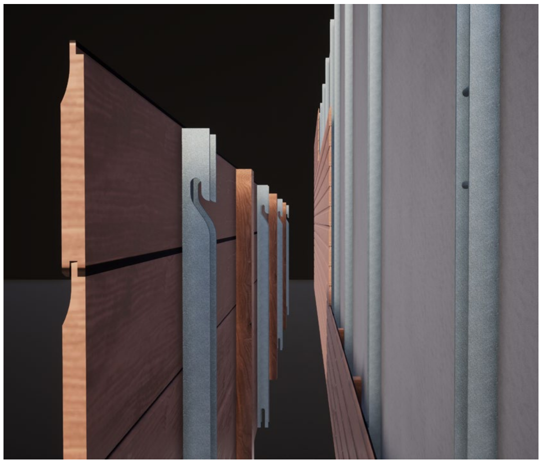
Key Observations: Similar issues; the modulation of the structural layer impacts the required modulation of the waterproof overlay. The vertical cap of this system is likely also a major modulation limitation.

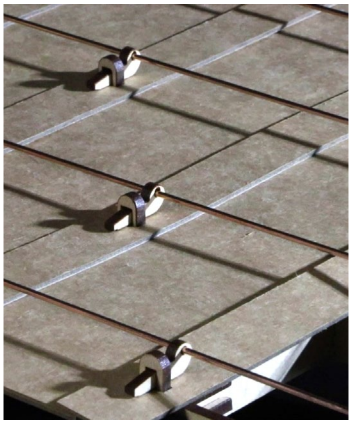
3.3.2 Reusable Aesthetic Cladding Experiments

Universal Cladding Interface

Test: The ideal solution for the reversible attachment of visual linings on buildings is a universal cladding interface (UCI). This interface would enable any panel, weatherboard, rainscreen or monolithic plaster-based cladding element to be mounted and unmounted without damage. Inspiration was taken from the 'First Light' project where a cladding system was developed that facilitated rapid assembly of a horizontal timber rainscreen (fig. 89) (Nuttall, p. 99–105, 2011: Marriage, p. 5, 2012). This concept has been further developed in a UCI and deployed onto a range of experimental systems (fig. 92).

Figure 89.
'First Light House' cladding interface with hook & bar.





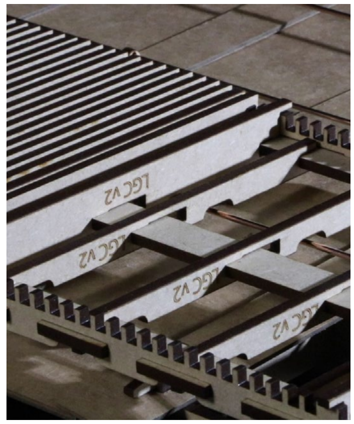


Figure 90. (left)
UCI bar mounted on building (Linear-Frame with compressed waterproof lining system) (A).

Figure 91. (right)
Cladding cassete mounted on UCI bar (A).

Outcomes: A universal cladding system of this nature could be considered economically unviable due to the extensive inbuilt redundancy. Positioning of the support components for the UCI horizontal 'bar' also needs to be thoroughly considered to avoid conflicts resulting in the need for more individual components.

Cladding Cassette One (UCI)

Test: A 'hook-and-lock' cladding cassette designed to hold vertical rainscreen members (inspired by Nuttall, 2012: Sutherland, 2014: Sutherland & Marriage, 2014) (fig. 89). Sacrificial softwood timber members are dowelled to a lightweight Accoya® frame with integrated slots to hook onto the UCI bar (fig. 92). To prevent lifting in extreme winds, the cassette is bolted to the UCI.

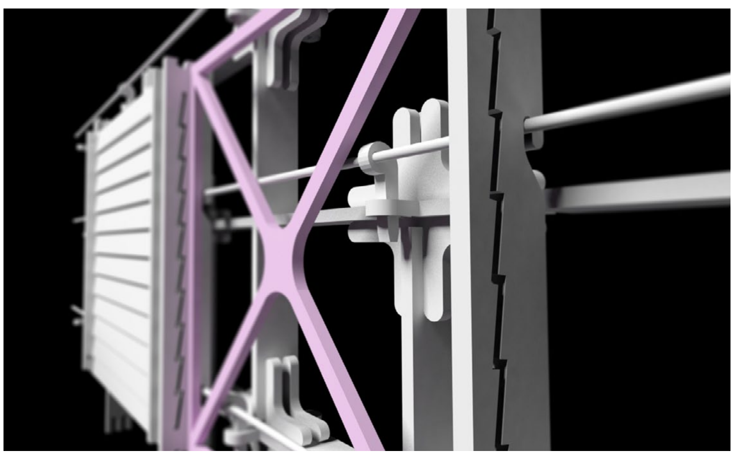


Figure 92.
Cladding cassete mounted on UCI bar (A).

Key Observations:
- Non-contaminating materials/non-toxic materials
- Invisible and seamless
- Supporting Accoya® frame is not flat-packed or efficient

Cladding Cassette Two (UCI)

Test: An iterative improvement to Cassette one. Cassette two uses the same mounting system but creates a less complex Accoya(R) frame that can be flat-packed and uses less material (fig. 93).

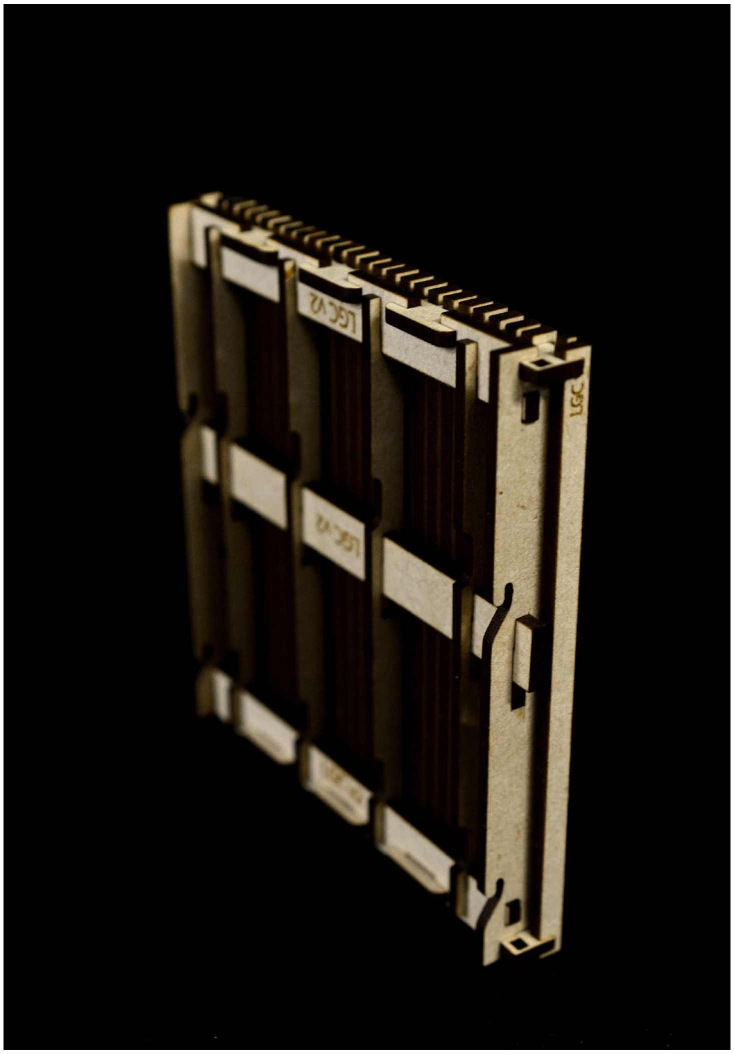
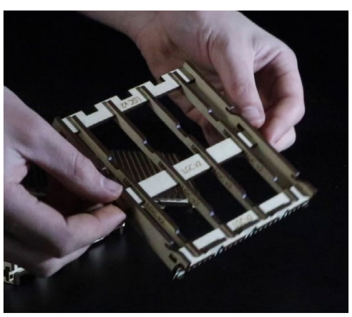


Figure 93.
Less complex cladding cassette (A).



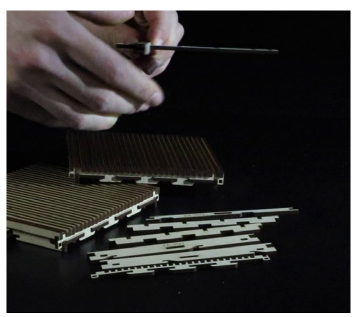


Figure 94 & 95.
Deconstruction of cladding system (A).

Figure 96.
Solid folded cladding panel for UCI (A).

Cladding Panel (UCI)

Test: Using the same attachment interface, a panel module was attempted to validate the potential of the UCI to provide an alternative aesthetic finish (fig. 96). A single piece of aluminum sheet can be folded to create a panel module that integrates hooks to fasten onto the UCI (fig. 97).

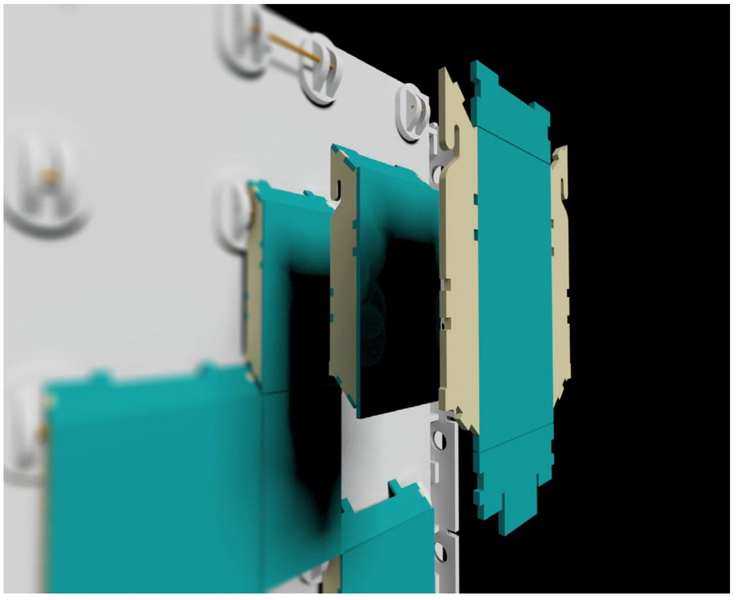


Figure 97.
Folded aluminum panel design and fixing (A).

Key Observations: This test aimed to demonstrate that a rapidly de-mountable (and reusable) cladding system can be deployed while meeting the 'aesthetic' and functional demands of the industry. The aluminum panel is not dissimilar to many metal cladding products in widespread use today.

3.4 MATERIALS

This research was centred on the use of timber and its role in establishing a Circular Economy in the building industry. The research did not however exclude the possibility of incorporating other materials to achieve a more effective solution. Providing the cyclic durability, hazard potential and end-of-life reprocessing requirements of a given material were evaluated and resolved a wide range of materials are appropriate for the design (see 1.4.1). Yet it was not in the scope of this research to identify new materials or quantify the full life cycle impact of a given material. Instead this work deals holistically with materials that are widely available today and the need to integrate a given product into a building system.

3.4.1 Experiments with Material Cyclic Durability

Plywood

Testing was carried out on 17mm structural *Pinus radiata* plywood to understand any issues that may arise over the life span of the deployed material. It was identified that plywood layers were prone to peeling and splitting when removed from friction-based joints (fig. 98). This was a concern as such damage had the potential to reduce the structural integrity of the frame components over time. It was also identified that slender plywood components were prone to snapping if protrusions exceeded more than 50% of their depth (fig. 100). Expansion and contraction, depending on the relative humidity levels, were also earmarked as an issue for friction-based jointing systems.

Figure 98 & 99.
Damaged plywood component (left) due to repetitive use of mortise and tenon joint. Undamaged version of the same joint (right) (A).

Figure 100.
Damaged plywood member due to cut exceeding 50% of depth of component (A).

Homogeneous Jointing Systems

The use of exclusively timber joints in a selection of design tests aimed to ensure a material palette that prevented material contamination. These joints needed to sustain adequate performance through multiple reuse cycles. Timber pegs were detailed to facilitate large amounts of adjustments while still retaining sufficient joint tension and incuded a tool slot to enable easier disassembly (fig. 101). These design decisions resulted in totally reusable jointing systems.

Figure 101.
Homogeneous plywood assembly (1:2 scale of Angled-Frame) (A).

Homogeneous systems: Homogeneous systems – systems that employ a single material – are seen as a superior CE choice (Guy & Ciarimboli, p. 42, 2008). This is largely due to the inherent purity and simplicity when managing materials at the end of a product's useful life. However, homogeneity does not guarantee reuse or recycling. A system using a single material may modulate that material in such a way that it requires complete reprocessing to be valuable again. This reprocessing might cost more than the purchase of new components and thus the existing materials are then landfilled. A system that uses multiple materials might facilitate modulation and direct reuse to prevent the need for new materials, waste or additional reprocessing energy costs.

Figure 102.
Various plywood pins and pegs tested for cyclic durability and disassembly convenience (A).

Conventional Framing Timber

Timber members used in conventional LTF are typically not reused as the recovery process is deemed not economically viable (Forbes, n.p., 2018). If these members were economically attractive to reuse, the structural damage from nail plates, nails and screws would need to be carefully evaluated to check if it impacts critical performance measures. For information regarding the potential structural reuse of *Pinus radiata* see Forbes, n.p., 2018.


SDW_1s

4.0

Conceptual Development Analysis & Evaluations

The following chapter undertakes a comparative quantitive and qualitative analysis (critical reflections) of design experiments from Chapters 2 and 3.

4.1 ECONOMIC ANALYSIS

To validate the practicality of the designed solutions, a detailed cost analysis and comparison with existing systems has been undertaken. This cost analysis utilised existing industry quantity surveying estimates and invoices from prototype fabrication. For a detailed breakdown of the resulting economic evaluation refer to Appendix (9.3).

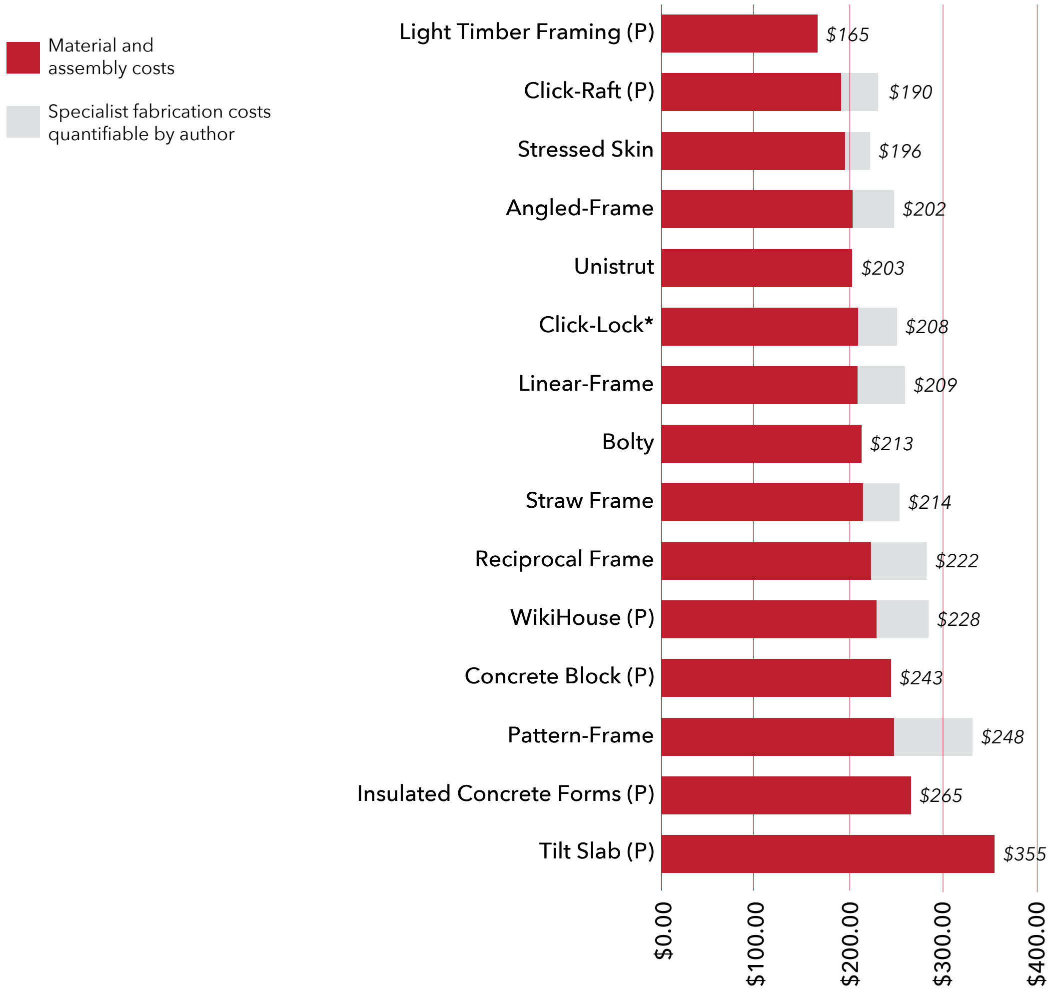
This economic study identifies the key implementation barrier for a reusable and modular architectural system: cost. Disregarding additional fabrication costs (see below) 'Conventional' platform LTF construction (2.1.1) was 10% more cost effective than its nearest competitor (Click-Raft) and was, on average, 30% more economical than the remainder of the proposed solutions (fig. 104).

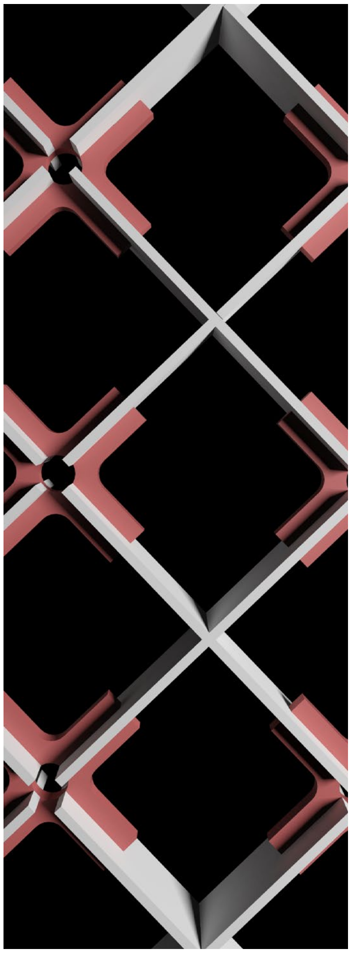
Fabrication costs in figure 104 represent 'non-standard' expenses imposed by the specialised fabrication methods that were used to 'fabricate' the final building components. Computer numerically controlled (CNC) routing is the predominant

Figure 103.
Collated conceptual designs (A).

contributor to this additional expense in the various systems. It is important to note that the cost of CNC routing can be *significantly reduced* through optimisations in the computer-aided design/manufacturing (CAD/CAM) process (Sutherland, p. 201–205, 2014). The greatest potential reduction in CNC manufacturing costs, however, comes at the component design stage. Changes between Angled-Frame and Pattern-Frame results in a cut pattern that requires less intricate routing (fig. 104 & 105) Consequently, Angled-Frame's manufacturing costs are 20% less than the Pattern-Frame proposal.

Figure 104.
Comparative cost analysis of existing and author-designed building construction options (per m²). Precedents and non-author designs notated with (P). * Click-Lock version here was a reinterpretation of the original design by the author (A).





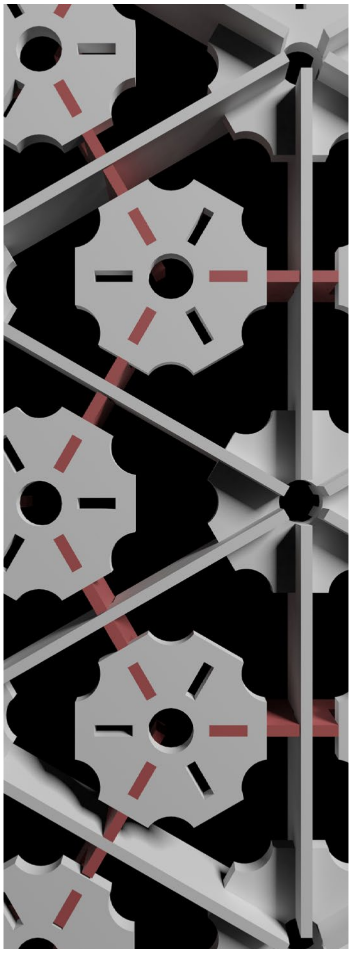


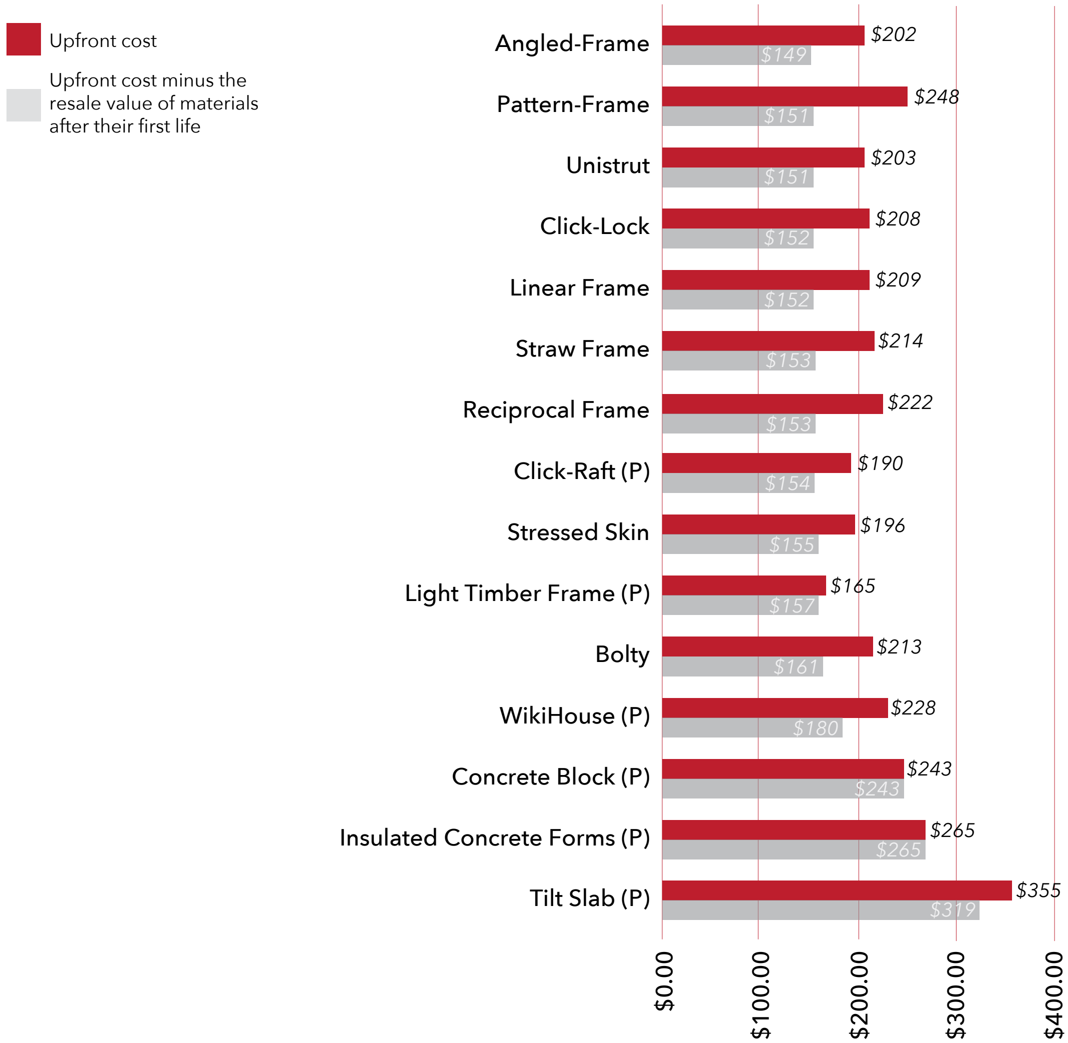
Figure 105 & 106.
Angled-Frame (left) and Pattern-Frame (right) (A).

23.1 metres of CNC routing per square metre of assembly.

33.4 metres of CNC routing per square metre of assembly.

Another way to measure the economic performance of a Circular Economy building solution is to estimate the resale value of the deployed materials at the end of their first use cycle, and then subtract that from the original material expenses (fig. 107). This quantifiably identifies the most economical building system over one full life cycle. To accurately implement this analysis, all materials in a selected construction system are evaluated for their direct reuse potential. Depending on the expected levels of damaged components, the end-of-life (EOL) value of these materials is estimated based on their original value. For example, if the structural framing component of an area of wall costs $100 but 10% of that is not appropriate for reuse (irreversibly damaged, contaminated, visually compromised) the effective EOL value is $90.

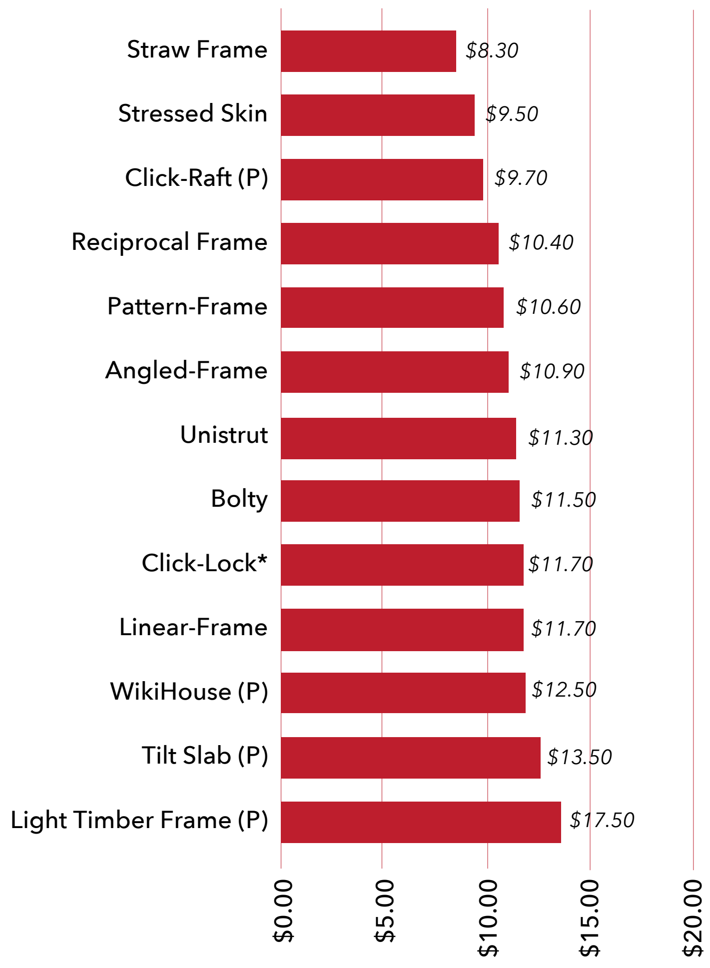
Figure 107.
Cost of system against cost of system less the resale value of the specified materials after first use cycle for existing (P) and author-designed building construction options (per m²). *See Appendix 1. Estimated end-of-life value based on retention of product's value/quality through first use cycle minus any damaged components. (A).*



This data quantifiably indicates the construction systems that have the most potential to be cost-attractive and have high levels of direct material reuse. Author-designed modulated frame systems perform well using this metric, yet upfront costs still pose a problem, exceeding LTF by 20% (fig. 107). Note that this 'cost after resale deductions' analysis has limitations. It does not account for the time taken to separate or remove materials and assumes that the given product retains its market value. This condition would require a more regulated architectural geometry, a largely singular approach to construction and an economy where the sourcing of new components was prohibitively expensive.

To further explore the economics of material reuse, the cost of deconstruction and material restoration, to an acceptable level of reuse, was estimated for a range of construction approaches (fig. 108). The cost to deconstruct and restore materials was identified as a key barrier to widespread material reuse (1.6).

Figure 108.
Cost of material extraction and preparation for reuse for existing (P) and author-designed building construction options per square meter. *See Appendix 1. Estimated based on quotes from industry and author's tests. Comparative only. Subject to real world variables. Area is per square area of wall surface – not floor area.*



Note: Concrete block and ICF were deemed too complex and expensive to determine realistic material extraction costings.

Straw-Frame's sacrificial integrated infill, internal lining and waterproof finish allows rapid separation of disparate materials (fig. 109) (3.1.1). The simple box frame construction can then be partially or fully disassembled and reused directly. Similar features in other systems, including large scale modularity and simplicity, enable significantly decreased deconstruction expenses. In some cases alternative cladding systems may increase deconstruction costs by 10% but add material resale value that exceeds the additional expenses. The impact of various cladding systems has been eliminated by using the same finishes for all construction options.

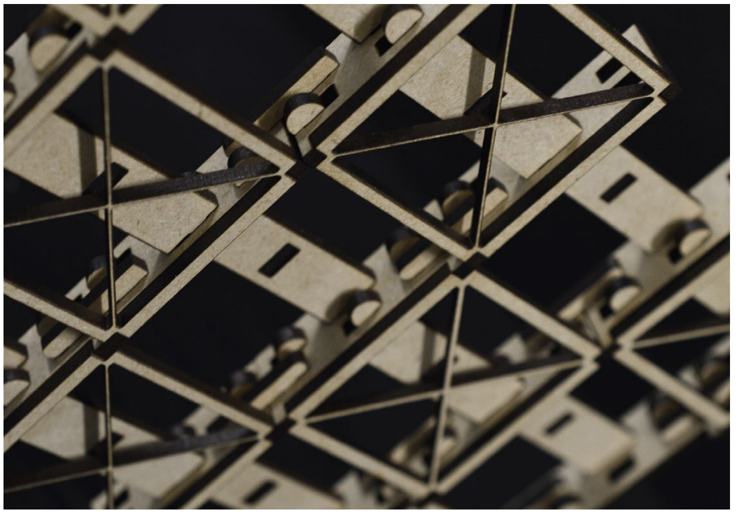


Figure 109.
Straw-Frame (A).

4.1.2 Costing Implications and Findings

Critical Reflections

Summary of key observations from the economic performance analysis of existing and proposed systems:

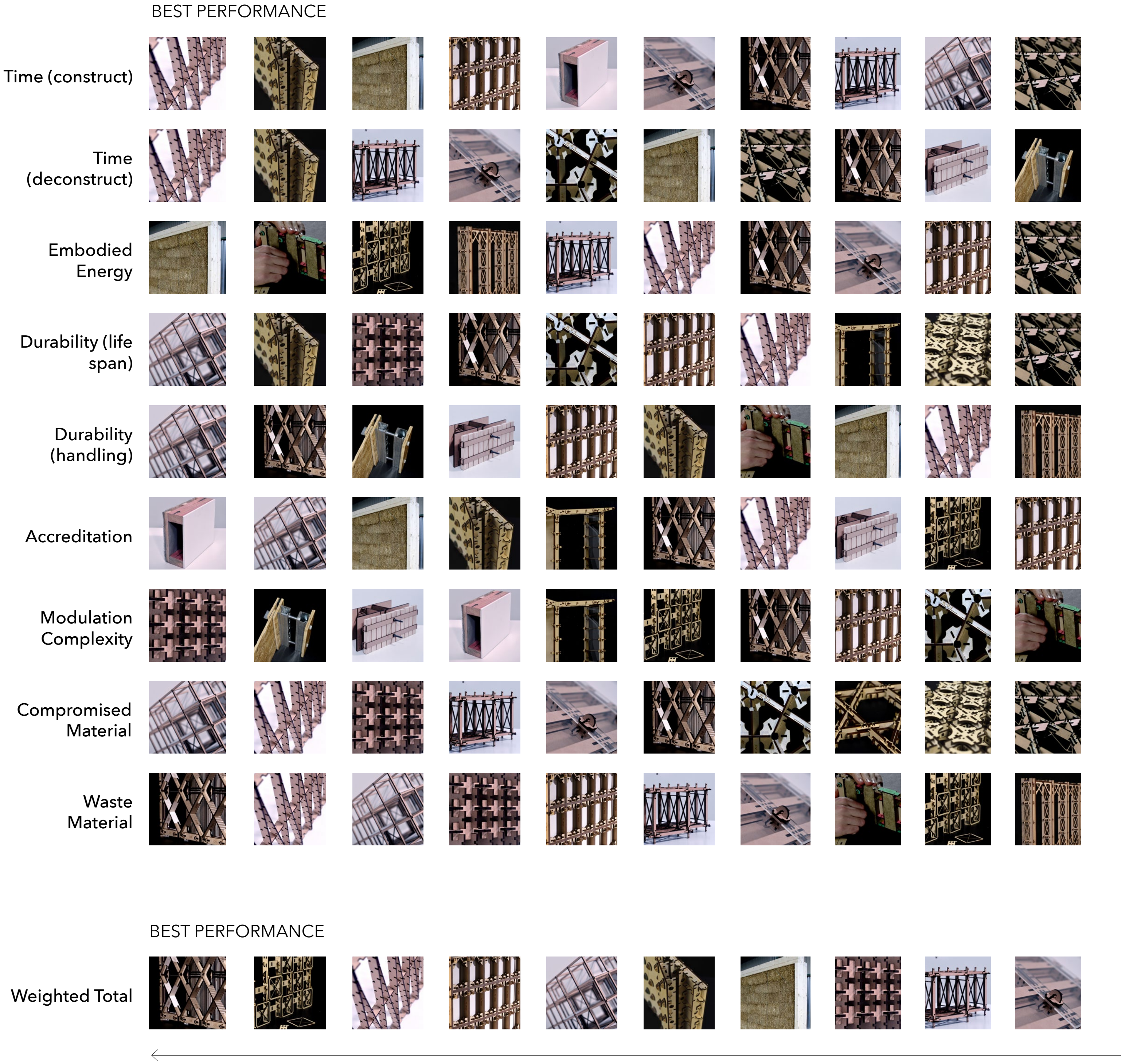
- Simplicity has a large impact on cost-effective reuse;
- CNC/specialist fabrication can be up to 20% of total material costs;
- Whole life cycle costs indicate author's proposals performing more cost-effectively than LTF;
- Click-Raft and author frame systems performed generally well;
- Proposals typically fall within fair cost margins (all in the range of existing solutions).

4.2 ENVIRONMENTAL PERFORMANCE MEASURES

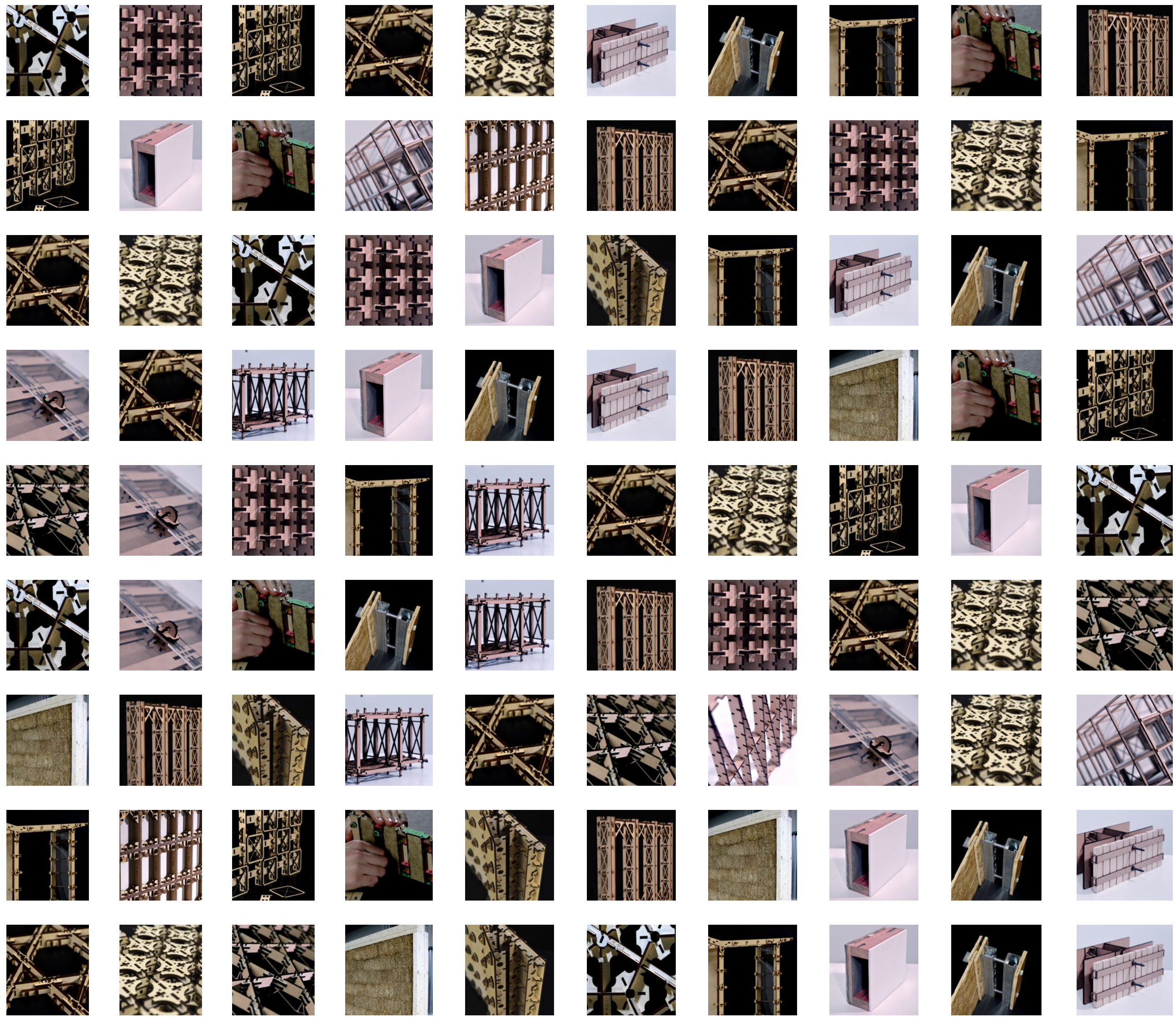
Economic performance is only one measure of success for a system designed to enable a circular economic model (CE). Improper modulation, prohibitive material durability and overall system complexity are also key barriers. To draw more effective conclusions, each system (and current solutions) has been ranked collectively below (see Appendix III for calculation; one unit of wall = $1m^2$ – averaged):

- Time up: estimated time taken to assemble structure only – per wall unit;
- Time down: estimated time taken to disassemble structure only – per wall unit;
- Embodied energy: collective embodied energy of structural materials per unit of wall;
- Material durability (during handling): collective for structural system – ranked;
- Material durability (during use): collective for structural system – ranked;
- Accreditation: collective for structural system – ranked;
- Modulation complexity; collective for structural system – ranked;
- Compromised materials: quantity of compromised materials collective for structural system – ranked;
- Waste material (structure only): per unit of wall, by %.

Figure 110. (next page) Tabled comparison of alternative performance measures for various design responses. Systems ranked from left (best performance, to right, worst performance) for each category (A).


BEST PERFORMANCE
Time (construct)
Time (deconstruct)
Embodied Energy
Durability (life span)
Durability (handling)
Accreditation
Modulation Complexity
Compromised Material
Waste Material
BEST PERFORMANCE
Weighted Total

WORST PERFROMANCE



Time (construct)

Time (deconstruct)

Embodied Energy

Durability (life span)

Durability (handling)

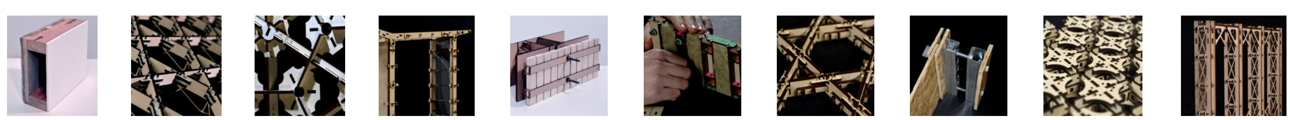
Accreditation

Modulation Complexity

Compromised Material

Waste Material

WORST PERFROMANCE



Weighted Total

Figure 111.
Performance criteria checklist. Design solutions proposed in chapter three compared against key Circular Economy performance criteria (A).

Geometry	G1	Modules and material components must be easily reconstituted or formed in a way that is attractive to reuse.
	G2	To achieve attractive reuse performance, deployed materials must be scalable based on a minimum divisible unit dimension.
	G3	Mass standardisation of components must be employed to improve direct reuse economic viability.
	G4	Functionally, the geometry must enable the independent layering of materials to facilitate easy separation.
Fixing	F1	Fixings must be exposed or have a sense of inherent logic to facilitate separation.
	F2	Fixings should either require no tools or be standardised to only require non-specialist tools and/or machinery.
	F3	Through design, fixings must be detailed to be removed/reversed without contaminating or inflicting irreversible damage to the primary materials.
	F4	Consequently no chemical, composite and adhesive-based fixings can be used.
Material	M1	Materials must retain performance through multiple reuse cycles or easily facilitate end-of-life management without loss of value.
	M2	Materials must be detailed as to avoid the need for compromising bonded coatings or treatments.
	M3	To promote economic reuse, materials must remain aesthetically desirable or be easily restored to 'as-new' without complex processes.
	M4	The use of composite/compromised or inseparable hybrid materials must be eliminated.
Score		

	Light Timber Frame (LTF) (p. 19)	Linear-Frame (p. 54)	Locked-Frame (p. 29)	Click-Lock (p. 30)	ModCell (p. 37)	Straw Partially Modulated (p. 38)	Straw Frame (Truss) (n.p)	Stressed Skin Cassetes (p. 40)	Modulated Steel (p. 45)	Timber Brick (p. 46)	Angled-Frame (X-Frame) (p. 55)	Pattern-Frame (p. 56)	Straw Fully Modulated (p. 57)	Reciprocal-Frame v1 (p. 58)	Reciprocal-Frame v2 (p. 58)	1.5 Layer Space Frame (p. 61)	EdFab System (p. 62)	WikiHouse/Sao-shachi-tsugi (p. 63)	Bolty (p. 65)	Unistrut (p. 65)
		✓								✓	✓	✓	✓				✓		✓	
		✓	✓							✓	✓	✓	✓	✓	✓	✓	✓			
	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
				✓		✓					✓		✓	✓	✓	✓			✓	✓
		✓				✓		✓		✓	✓	✓	✓				✓		✓	✓
		✓	✓	✓		✓				✓	✓	✓	✓				✓	✓	✓	✓
		✓	✓	✓							✓	✓	✓	✓	✓	✓			✓	✓
		✓	✓	✓						✓	✓	✓		✓	✓	✓	✓		✓	✓
		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
					✓	✓	✓			✓			✓							
		✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓			✓	✓
		✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓			✓	✓
	1	10	8	8	5	9	6	4	4	9	11	10	11	8	8	8	7	1	10	9

4.3 PERFORMANCE ANALYSIS

Ongoing Critical Reflections

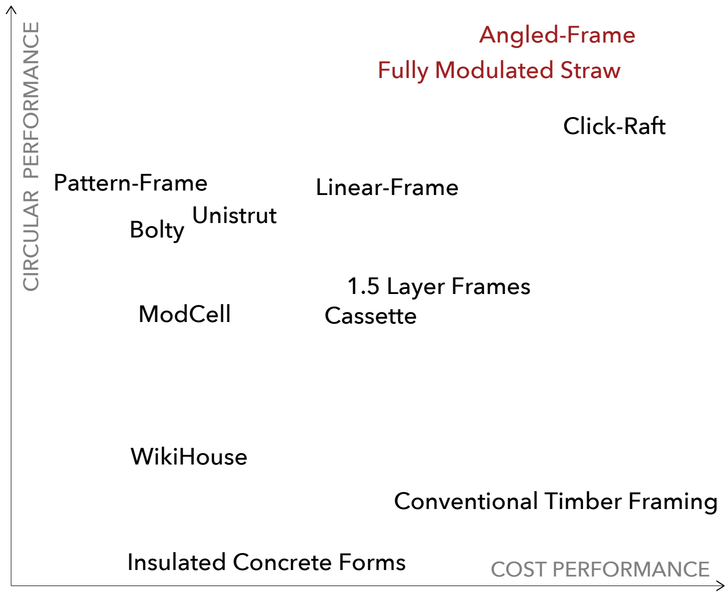


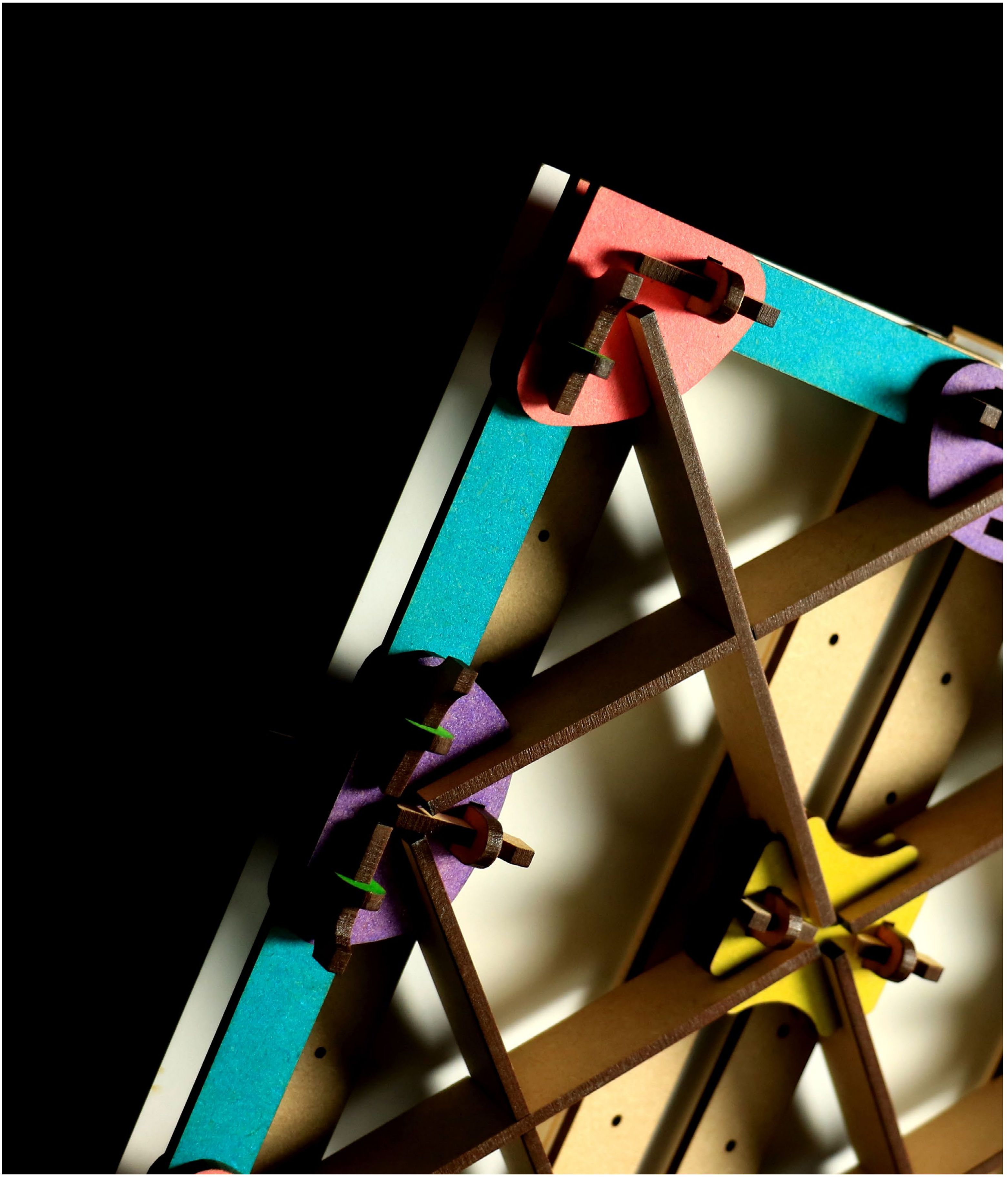
Figure 112.
Summary of performance tables (see 9.4) (A).

4.3.1 Leading Proposals

Angled-Frame: The Angled-Frame structure that resulted from simplified frame developments performed consistently well in both quantitative analysis and qualitative ranking (fig. 104–108). This is due to the full modular expansion and constant self-bracing capability of the frame. The 'X' structure ensures that, regardless of the size of the module, the frame will always have lateral load resisting potential. Consequently this means that any module can be used in any location without the need for specialist bracing components. This is economically advantageous in terms of manufacturing cost, deconstruction cost and end-of-life value.

Straw-Frame: Straw-Frame is a technical/natural hybrid con-struction solution that also performed strongly in all measures. The notable advantage of Straw-Frame is its ability to have a collective cladding/waterproof/moisture vapour/insulation/interior lining that is totally biodegradable and that uses quickly replenishable materials. Straw-Frame also has limitations in terms of its need for regular maintenance, large overhangs, thicker wall construction and a lack of lateral-load resisting bracing.

Figure 113. (opposite)
X-Frame (Angled-Frame iteration 2) (A).



4.3.2 A Material Problem

These leading proposals called for two significantly different solutions – either the design of a purely technical solution which relies on highly engineered products and the specification of many different unique components – or the design of a hybrid construction method that mixes both high and low energy materials.

Evidence from these studies suggested that there is not necessarily a clear 'best-case' solution when it comes to technical versus natural materials in a CE. This suggestion is supported by Baker-Brown who noted that the systems surrounding material selection ultimately defines the circular economic successes of a given product (p. 9, 2017). Evidence of this can be seen in the choice of materials for McDonough's ICEhouse™ where only products with established and efficient recycling schemes are employed. Consequently, the advantage of one material category over another is blurred.


X-C1

5.0
Developed Design

An integrated response based on Chapters 4's critical analysis.

5.1 FOUNDATION

Evidence supporting development direction

Qualitative and quantifiable evidence suggested that an iteration of the Angled or Straw-Frame design experiments (4.3) was the most successful solution resulting from the conceptual design phase of the research in respect to reducing building waste. Benefits included the potential total elimination of dependent building layers through the use of integrated compressive fastening systems (fig. 85) and the adoption of a technical, low carbon structural material (plywood) (Marriage, p. 421, 2017). Furthermore geometric properties of each proposal did not exclude the use of alternative material solutions. This suggested a possible amalgamation of the two systems into a hybrid technical and organic architectural assembly.

Figure 114.
Assorted systems from Chapter 3 and 4 conceptual design processes (A).

5.1.2 Notable Issues/Criticisms

Prior to the developed design phase of the research there were significant concerns regarding the inherent complexity of the Angled-Frame structure and the lateral bracing capacity of the Straw-Frame. These concerns stemmed from preliminary assembly and disassembly duration tests and a cross-examination of system complexity based on component variation (4.4). Although both of these factors impacted the potential success of the final developed design, they were identified as factors that could essentially be 'designed out'. Key aims of the developed design also included:

- Simplify the form of components;
- Integrate supplementary building systems;
- Economise & reduce the number of components required;
- Validate the cyclic performance;
- Achieve better performance metrics.

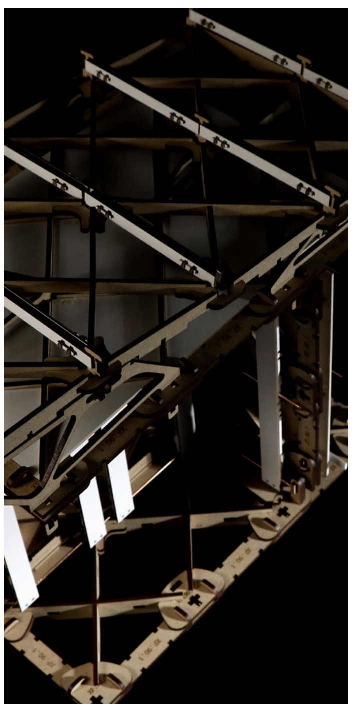
5.2 PRELIMINARY DEVELOPED DESIGN TESTS

To understand the holistic potential of each solution collated and integrated design experiments were undertaken: Organic Hybrid House and Technical House. These ideas emerged directly from a growing depth of knowledge regarding the appropriateness of materials and relative conflicts within circular economic models.

5.2.1 The Technical House

The Technical House (fig. 115) used entirely engineered/man-made/chemically enhanced materials in a flexible (modulated) and reversible fixing arrangement. Every material was formed in a way that permited reversible non-contaminating or non-damaging fixing processes. As an integrated solution the Technical House solution encompassed the entire principal wall construction elements: exterior aesthetic finish, exterior waterproof lining, structure, insulation and the internal aesthetic lining (fig. 117). Using a version of the Angled-Frame system, dubbed 'X-Frame', this structure was proposed as appropriate for horizontal and vertical load bearing systems.

Figure 115.
Technical House internal lining systems with modulated floor detail and homogeneous structural frame (A).



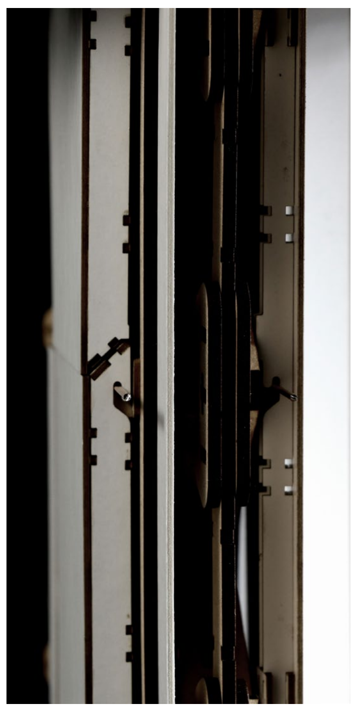
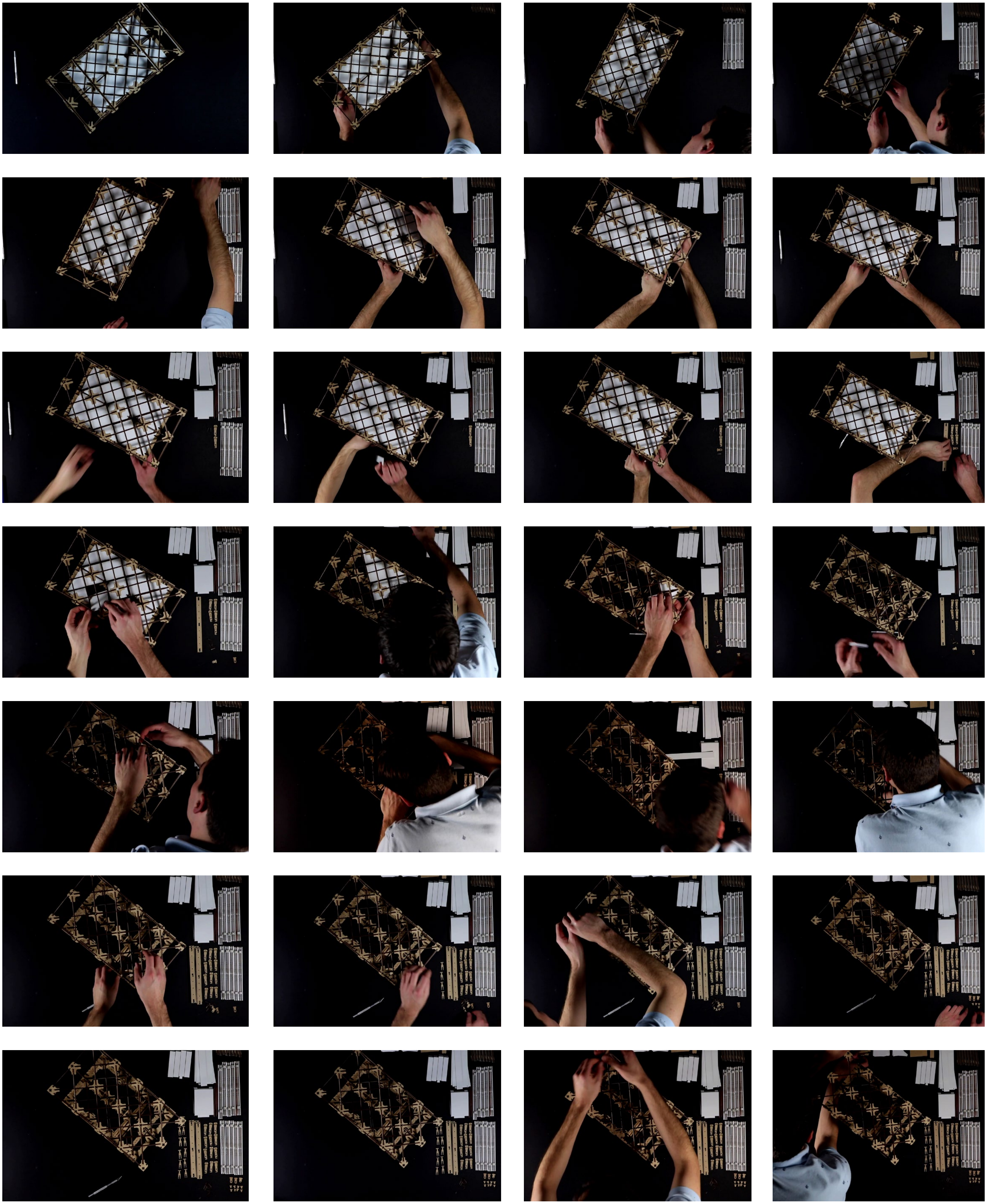


Figure 116. (Left)
Technical House assembly looking down at the roof and floor elements (A).

Figure 117. (Right)
Exterior to interior wall assembly indicating UCI cladding cassete, compression fixed rigid air barrier (RAB), structure and reversable internal linings (A).

Figure 118.
Technical House 'exploded components' highlighting the inherent complexity and redundancy problem of using only technical materials (A).



5.2.2 The Organic Hybrid House

The Organic Hybrid House (fig. 121) attempts to integrate materials that remain largely in their natural state. This allows the materials to be naturally processed without complication (at the end of the buildings useful life). Although this does not ensure a retention of value between 'use' cycles, it does secure a closed material loop thanks to natural decomposition processes. The primary natural material used is straw to double as wall infill and insulation. Packed straw can then be coated in a lime-based plaster and painted. This forms a waterproof and insulated wall assembly that includes no compromised materials. When dismantling the straw and plaster infill, it can be 'smashed' out of the load bearing structure, crushed into smaller pieces and then spread under vegetation as compost (Martin & Gershuny, p. 105, 1992). For more information about lime-based compost and its uses see chapter 6.

Figure 119. (previous page)
Disassembly of technical house (A).

Figure 120.
Detail of the Organic Hybrid House solution indicating the two parallel horizontal modular X-Frame elements (A).

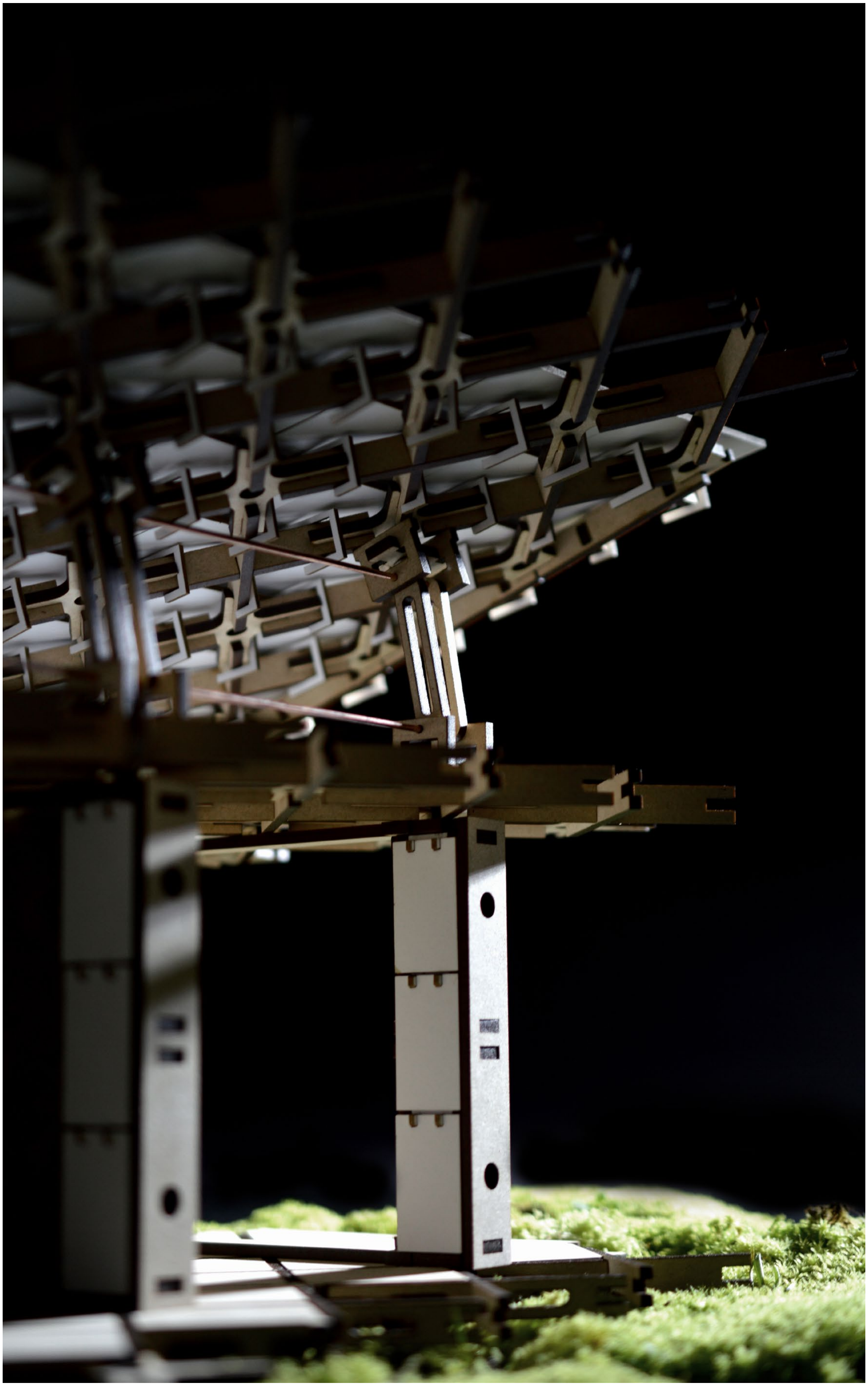
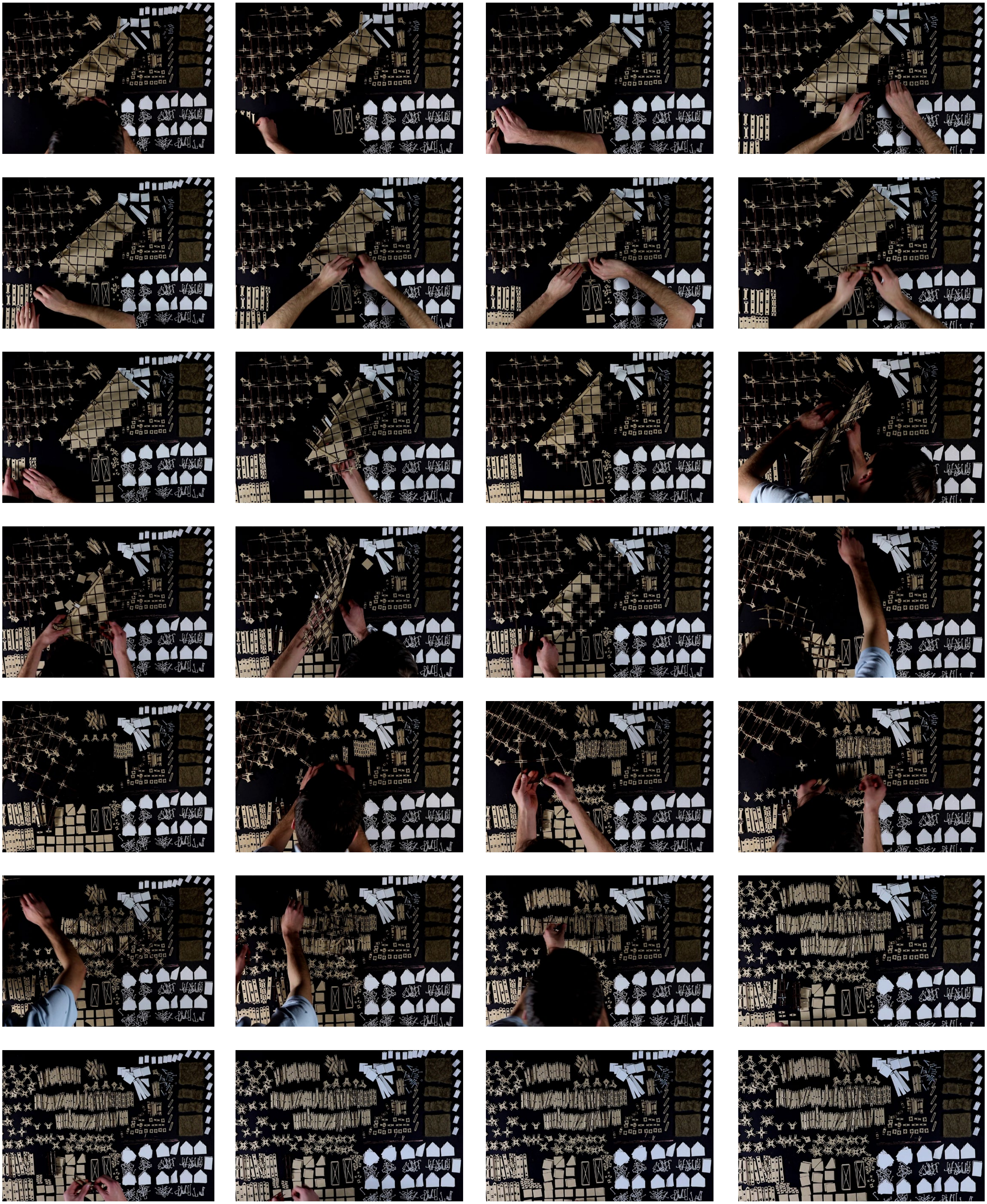


Figure 121.
The Organic Hybrid House using X-Frame in a horizontal configuration with infilled straw-plaster walls and partitions (A).

Figure 122.
Organic Hybrid House proposal (A).



A note of the Organic Hybrid House (5.2.2): While the significant point of difference between the technical and hybrid dwelling is the use of 'natural' materials, the entire structure is not made of unprocessed materials. There is potential for further research into the use of totally natural materials to form a 'wasteless' architecture but this extends beyond the scope of this research. Instead this investigation focuses on the capacity of timber, in association with other materials, to form an architecture assembly incapable of producing waste.

X-Post

X-Post was a response to the emerging concern that an inadequately designed X-Frame walling system could introduce levels of complexity that would make it unattractive for reuse or rapid disassembly. All vertical structure was therefore replaced with modulated posts to free up the floor plan and reduce the quantity of building components (fig. 124). This system provided a greater level of design freedom without adding complexity. The vertical structure was then modulated across an iteration of the X-Frame system. Inherent redundancy within the X-Frame meant that a vertical load bearing member could be fixed at any 900mm interval grid point (fig. 122).

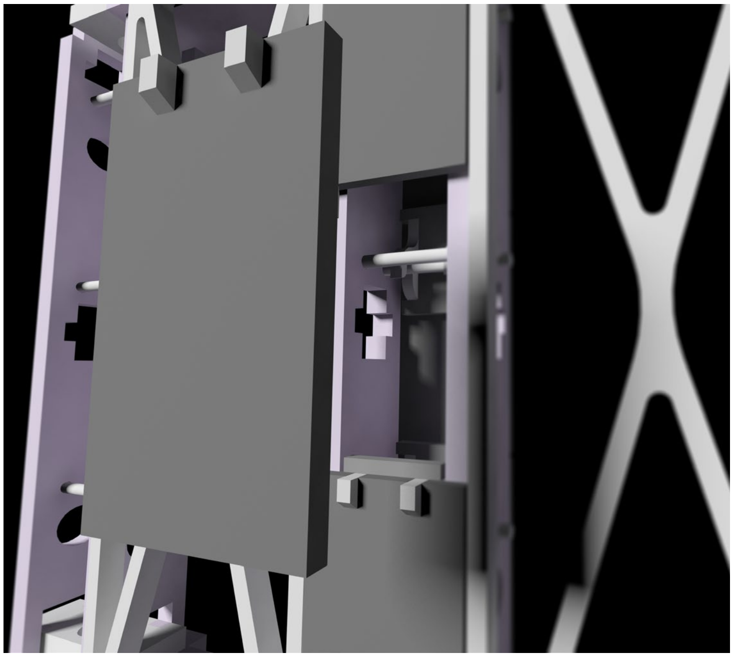


Figure 123. (previous page)
Disassembly of Organic Hybrid House (A).

Figure 124.
X-Post proposal. Panellised vertical structural element with facilities for service integration (A).

It is hypothesised that further testing and experimentation may identify X-Post as a superior solution to X-Frame in the vertical orientation.

5.2.3 ORGANIC VS TECHNICAL

Critical Reflections

The process of extrapolating an alternative construction solution over a larger and more complicated scale (5.2.1–2) led to the identification of major complexity flaws in the designs. Although the integrated technical house was possible in this iteration, the quantity of individual components (inherent complexity) would make full-scale construction and reconstruction problematic. A key concern would be the likelihood of needing to buy or specially order custom formed components for any future rebuilds. Furthermore, in this iteration, the system did not reject incorrectly fixed elements i.e. the system was not 'mistake-proof'. This is an issue when all components are designed to perform a very specific task and there are many components not largely dissimilar to one another.

	Technical House	Organic House
Vertical Modularity	✓	
Horizontal Modularity	✓	✓
Homogeneous Modularity	✓	0.5
Compromised Material Free	✓	✓
Non-damaging Fixings	✓	✓
Assist-free Construction	✓	
Dependant Layer Separation	✓	✓
Reprocessing Elimination	✓	✓
Inherent Assembly Logic	✓	✓
Total	9/9	6.5/9

Figure 125.
Organic Hybrid House vs Technial House (A)

It was noted that further optimisations of the X-Frame structure may help to reduce the number of varying components and that the 'organic' approach arguably introduced more component variation into structural elements (two discrete systems).

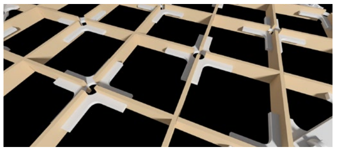
Design development direction: A transition from conceptual and hypothetical (scale models) to realised and detailed design was necessary to validate the research and eliminate poor performing design variations. This move aimed to bring the research direction in alignment with the original pragmatic aims. As a consequence of this realignment the viability of the X-Post solution in terms of cost (fig. 126), the number of varied components, a lack of preliminary testing and overall design flexibility was questioned. This consequently called for the implementation of an X-Frame system for all building elements (providing the offset caused when the X-Frame intersected itself could be eliminated). This lead to a series of advanced developed design iterations focused on improving the versatility and reusability of the X-Frame design.

(per square meter of structure)	Technical House	Organic House
Deconstruction Time	6 minutes	9 minutes
System Complexity	4 pieces	7 pieces
Cost	est. $202.00	est. $320.00
Fabrication Waste	2kg/m^2	1.5kg/m^2

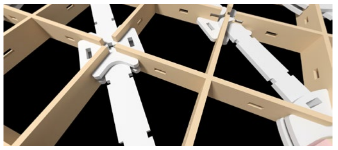
Figure 126.
Quantitive Analysis: Organic Hybrid House vs Technical House (A).

5.3 ADVANCED DEVELOPED DESIGN ITERATIONS

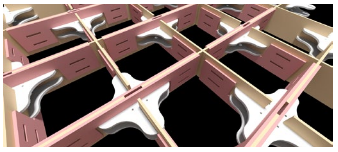
Reflecting upon the sucesses of these two house studdies the following design developments (X-Frame 3–7) culminate in the building of 'X7' – a full-scale proof-of-concept structure employing the most developed refinements of ideas researched in this thesis. X7 was built in the atrium of Victoria University of Wellington's School of Architecture on October 14th and 15th 2017. The finished structure measured 2.7m x 5.4m x 3.2m (WxLxH) and was disassembled in 4 hours and 40 minutes by five people on January 25th 2018. A prototype build of this scale is an effective outcome for this research project as it helps to validate the effectivness of the pragmatic design outcome. The prototype design demanded the resolution of key building details such as interior and exterior corners, floor, wall/ceiling junctions and reversible flooring finishes. The build effectively asks: is X-Frame a light timber framed architectural assembly capable of fully integrating into a circular economic model?



XFrame 1 & 2.
- Angled-Frame (version 1)
- Iteration 2 increased modular detail
- Addition of diagrid braces
- Single-slot connection

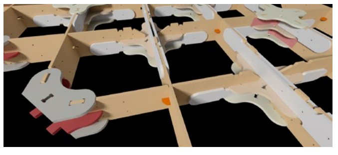


XFrame 3.
- As per Organic House
- Double-slot connection
- Interwoven spanning beams
- Basic perimeter detailing

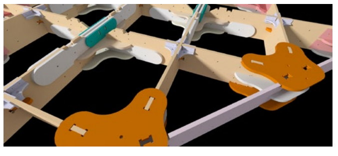


XFrame 4.
- Full structural detail design
- Horizontal spanning potential
- Addition of spanning brace
- Addition of locking peg

XFrame 5.
- Intersecting element detailing
- Double-bolted span details
- 3-layer-lock and slot detail
- 17mm material specification



XFrame 6.
- Floor and roof-join detailing
- Additional lateral load bracing
- Detailing steel junctions brackets
- Chamfering span corners



XFrame 7.
- Floor finish fixing details
- Hold down detail finalisation
- Perimeter span detailing
- Non-structural corner details

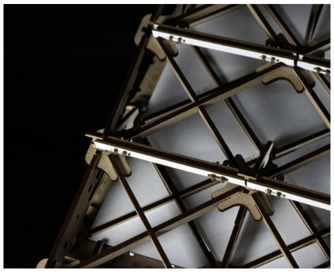
Figure 127.
Overview of the development of the X-Frame system (covered in depth on the following pages) (A).

5.3.1 X-Frame 3

X-Frame (3) was the final iteration of the woven Angled-Frame design tests developed in the preliminary design stage of this research (5.2.1) and forms the basis of the final developed design. The solution utilised two principal components: a 1200mm-long, 12mm-thick plywood span with a notched centre, notches on the ends and a four-pronged plywood cross designed to connect the spanning members (fig. 129). Preliminary analysis and advice from structural engineers suggested that this structure would be adequate for wall sections similar to those within the scope of NZS3604. However at this level of resolution the structure lacked effective perimeter detailing, structural capacity for spanning horizontally and evidence of suitable cyclic durability.

5.3.2 X-Frame 4

X-Frame 4 was the first fully detailed structural iteration of X-Frame. The structure was designed to work not only in vertical orientations but also horizontally as flooring or ceiling framing designed in consultation with a structural engineer. This included the addition of a spanning brace bolted across the four-pronged connection and detailing of the perimeter to ensure stresses were being evenly distributed (fig. 129 - white element). X-Frame 4 also adopted a plywood locking pin designed to hold the reciprocal frames together when oriented horizontally (fig. 129 - pink).



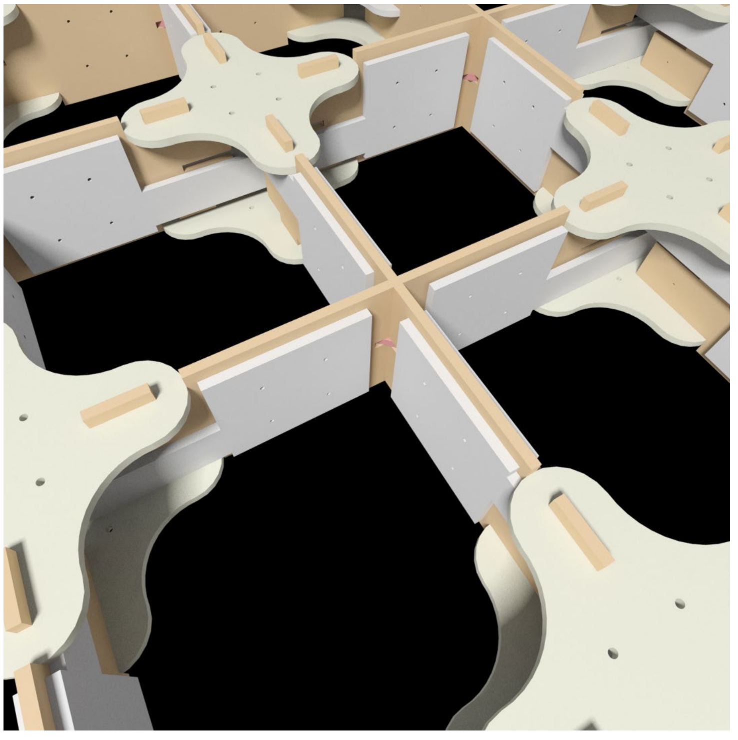


Figure 128. (above)
X-Frame 3 as intergrated into the Organic Hybrid House system (A).

Figure 129.
X-Frame 4 with capacity for horizontal spanning including central locking pin (A).

5.3.3 X-Frame 5

Corner Operations

Resolving the intersection of frame components at 90 degree junctions with the addition of a few new components and without inducing an offset was critical to ensure the frame was appropriate for reuse.

This required resolving corner, floor and ceiling joints in a way that reflected the intentions of the research. Various corner parameters were designed and tested (digital and physicals models) to identify a method of intersection that promoted rapid cyclic assembly.

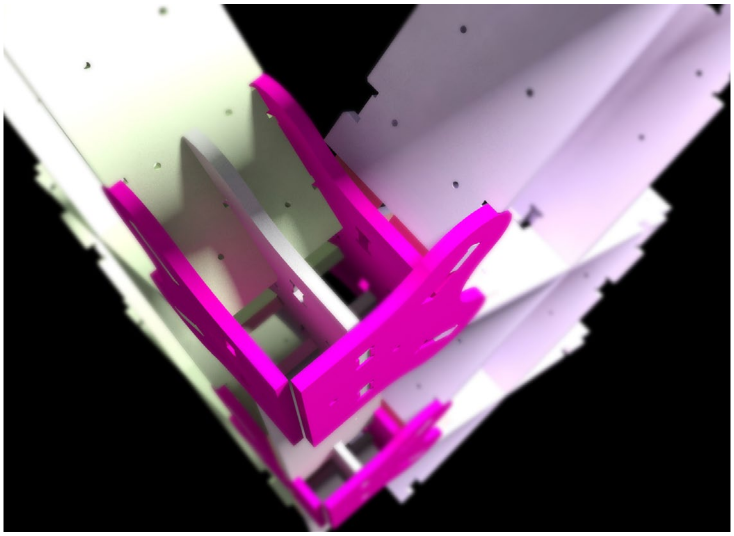


Figure 130.
Offset corners proposal. Results in the need for additional span member element (light pink) (A).

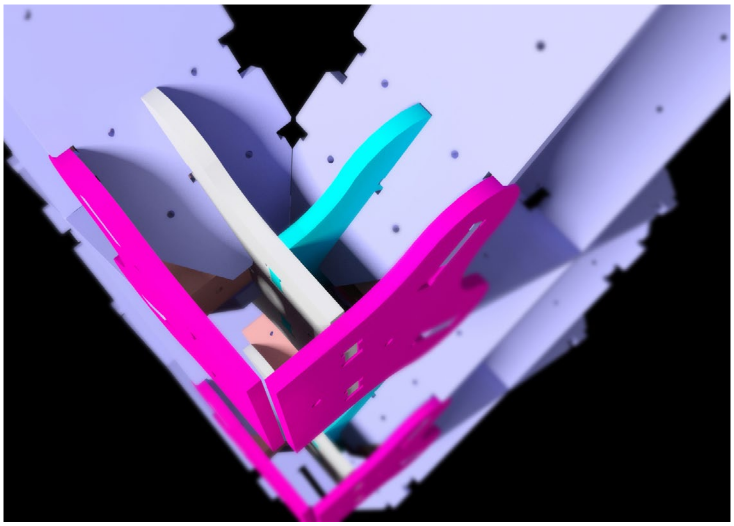


Figure 131.
Overlapping chamfered corners proposal. Chamfered corners on revised span component (purple) eliminate offset or the need for additional span members – fixed with plywood only tenon juntion elements (A).

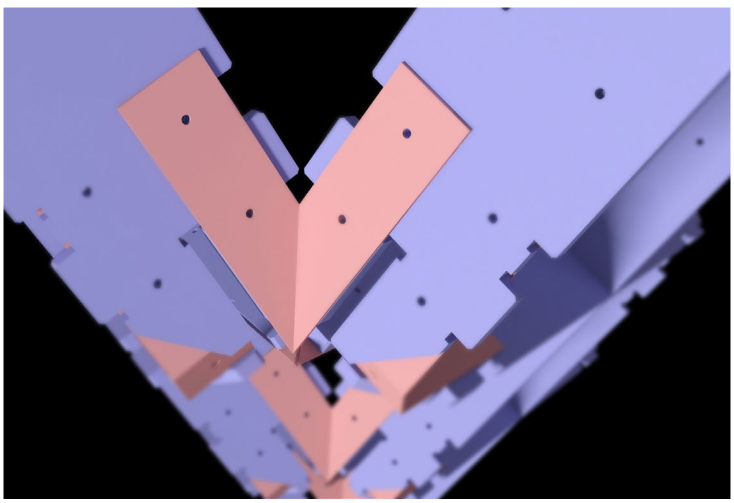


Figure 132.
Chamfered bracket corners proposal. Simplification of previous designs – introducing folded steel brackets and removing plywood elements (A).

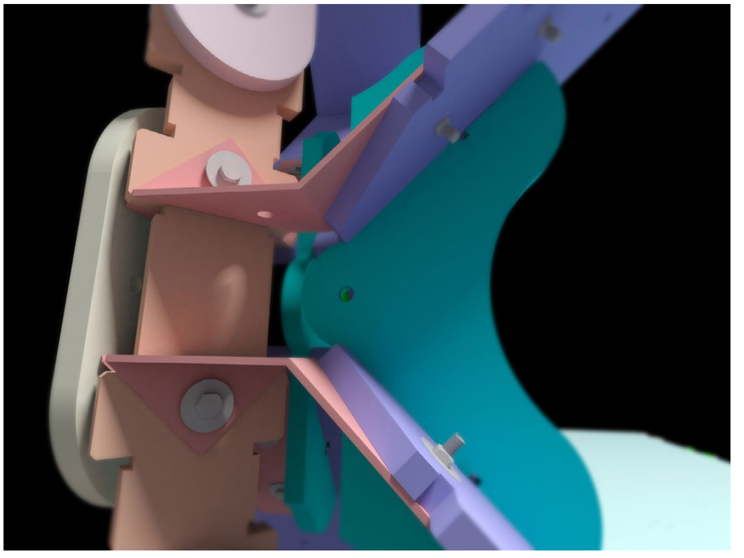


Figure 133.
Chamfered 45° corners (with cover plate off). Removes offset and ensures strength through a hybrid bracket and plywood connection (A).

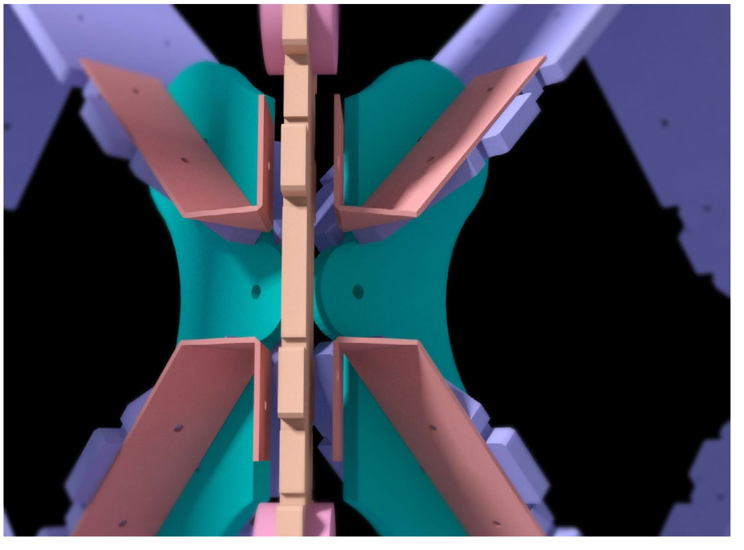


Figure 134.
Chamfered 45° corners proposal (with cover plate off) (A).

Motivations for selecting the chamfered and bracketed corner options were related to overall system flexibility and redundancy. Chamfering each corner of the X-Span component is a relatively minor operation that ensures no offset is required when two vertical assemblies intersect (fig. 134). Furthermore the chamfering ensures functionality of the X-Span component is not impacted when used elsewhere. Detailed digital simulations identified that the chamfered X-Span component would be faster to cut but would also produce more waste material (fig. 136). Other corner junctions tested introduced an extra X-Span length variation that would not be required in every design (depending on the number of intersections) and thus might result in eventual waste or cyclic barriers.

	# of Components	Expansion Potential
Offset	4	2
Overlapping Chamfered	3	2
Chamfered Bracket	1	4
Chamfered Angle Bracket	2	4

Figure 135.
Number of varied components and the ability for each design to expand further (*expansion potential* – more is better) (A).

	Chamfered Span	Square End Span
Cut Length (per piece) (m)	3.715	3.860
Total CNC Cutting Cost*	$1.16	$1.21
Total Waste Area (m^2)^	0.46	0.35
Waste Ratio (% per sheet)	16.03%	12.17%

*cost per span @ $75 per hour cutting at eight metres per 60 seconds
^waste area is the remaining material after best nesting condition for one sheet of spans

Figure 136.
Chamfered span vs square end span fabrication comparasion. An example of detailed fabrication analysis (A).

This information can be further detailed:

	Chamfered Span	Square End Span
Waste Ratio (% per sheet)	16.03%	12.17%
Bulk Waste (solid material)*	0.42	0.31
Sawdust Waste (powder)*	0.035	0.036
Bulk Waste %	14.81%	10.90%
Sawdust Waste %	1.23%	1.27%

*notated in square metre area -17mm deep.

Figure 137.
Detailed waste analysis of design variations (A).

Waste statistics: Analysis of waste quantities at the time of manufacture for different iterations suggests that optimisation of the formal properties of the object has the most significant impact on waste production at the time of manufacture. However, as stated, it is sometimes more efficient over multiple reuse cycles to have greater levels of modular simplicity than minimum levels of waste produced during manufacture.

Waste per Span:	Chamfered Span	Shortened Span
Fabrication & 1st Cycle	0.010	(none*)
2nd Cycle	0.0 (reused)	0.0 (reused)
3rd Cycle	0.0 (reused)	0.209^
Total Waste	0.010	0.209

Waste in square meter area 17mm thick.
*Dependent on nesting configuration.
^Area of a single piece discarded because of no appropriate place in new design cycle.

Figure 138.
Bracketed floor wall intersection detail was selected for its robustness and efficiency (A).

5.3.4 X-Frame 5 and 6

X-Frame iterations 5 and 6 represent refinements in structural integrity and cyclic use durability. Detailing of the perimeter to increase the stiffness of the frame when it spans horizontally and changes to ensure the diagrid is structurally stable under vertical loads (in consultation with structural engineers) were critical iterative developments to ensure real world compliance (fig. 139–142). These optimisations however were not purely structural. Reconfiguring the boundary condition of the frame enabled better jointing capabilities for claddings and internal linings as well as capacity for the reversible routing of building services.

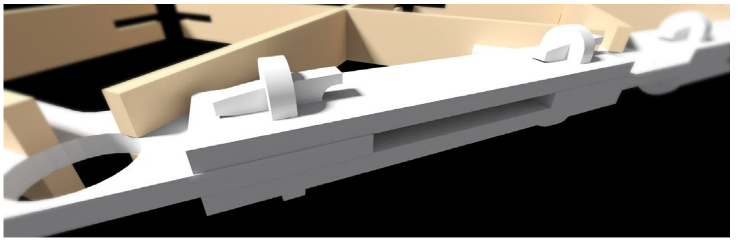


Figure 139.
Iteration 1 of X-Frame perimeter solution. Homogenus plywood connection perpendicular to span orientation (A).

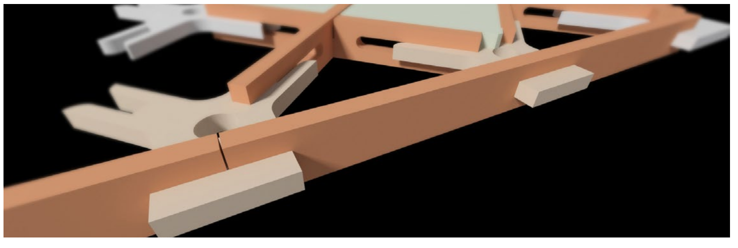


Figure 140.
Iteration 2 of X-Frame perimeter solution. Internally locked perimeter span (A).

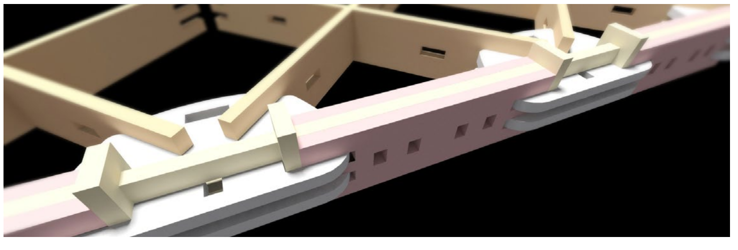


Figure 141.
Iteration 3 of X-Frame perimeter solution. Multi-component plywood locking system (A).

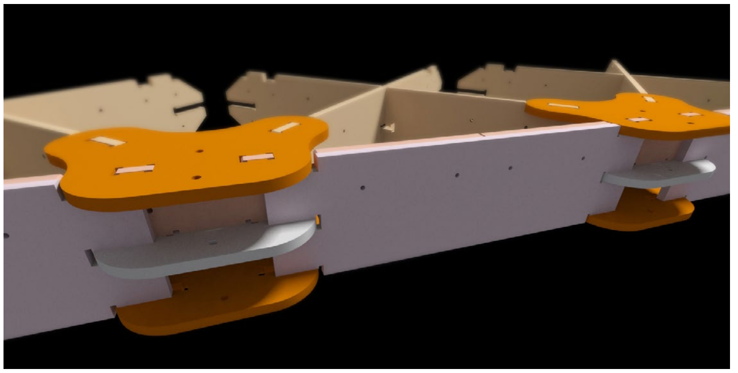


Figure 142.
Iteration 4 of X-Frame perimeter solution. Mortise and Tenon plywood ties bolted and centres (A).

Floor/Wall Iteration:	1	2	3	4
Number of Components	8	8	1	6
'Tie' Potential*	Y	Y	N	Y
Span Potential	Y	Y	N	Y
Perpendicular Connection	Y	N	N	Y
Lining Support	N	Y	N	Y

*Tie potential refers to the ability of the design to resist tension forces between spans.
^Span potential refers to the ability of edge systems to collect gravity loads.

Figure 143.
Comparison of X-Frame perimeter solutions examining salient structural features (A).

Floor/Wall Operations

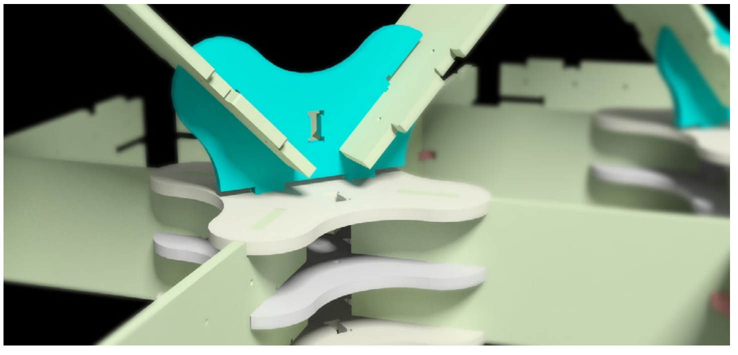


Figure 144.
Plywood tenon floor wall intersection detail (floor/wall 1). Solution was deemed too unstable and fragile (A).

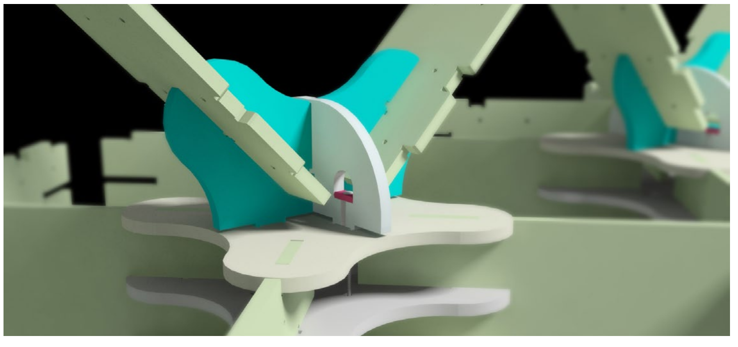


Figure 145.
Plywood slotted floor wall intersection detail (floor/wall 2). Solution had potential but was slow to implement and protruded from the finished wall surface (A).

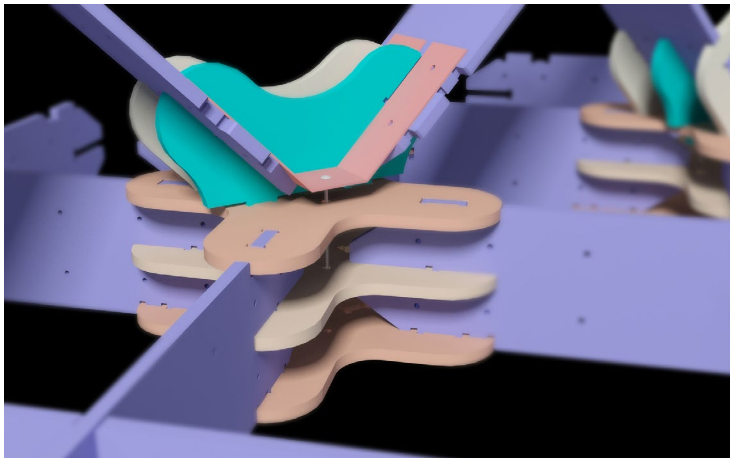


Figure 146.
Bracketed floor wall intersection detail (floor/wall 3). Was selected for its robustness and efficiency (A).

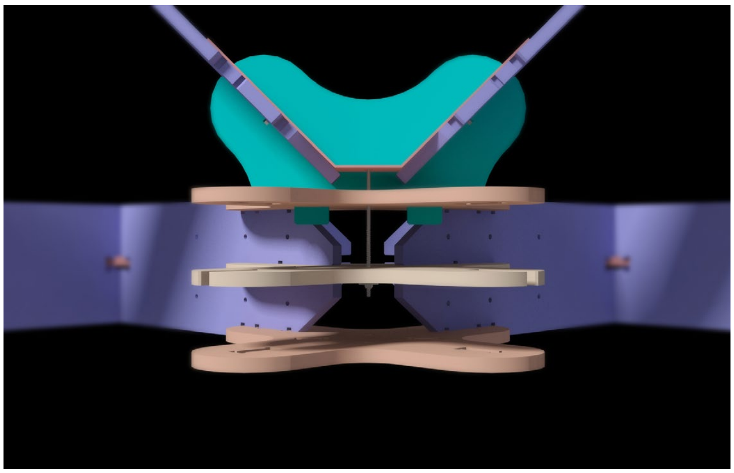


Figure 147.
Bracketed floor wall intersection holding too centralised 'X-Slot' component (yellow) (A).

Floor/Wall Iteration:	**Tenon**	**Slotted**	**Bracket**
Number of Components	1	4	7
Expansion Potential*	Y	N	N
Cost (per connection)	<$3.50	$8.78	$34.00^
Lateral Load Resistance	Y	Y	Y
Over-turning Resistance	N	N	Y
Homogeneous Materials	Y	N	N
Wall Intersection Potential	N	Y	N
Critical Structural Targets:	N	N	Y

*Expansion to a 2nd level of construction using the same jointing design.
^Proposed detail uses two folded steel brackets costing $16 each. It is expected that a single bracket designed to use less steel could be used. A pressure and steam bent plywood member could be used to further reduce costs.

Figure 148.
Quantitive comparison of floor/wall junction proposals (A).

X-Frame Internal Jointing Improvements

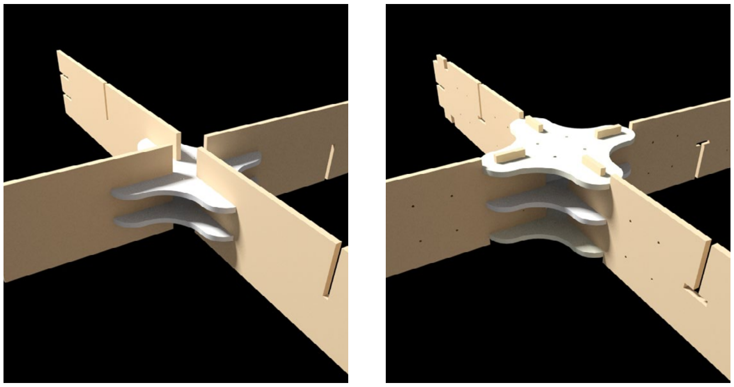


Figure 149 & 150.
Structural jointing improvements to the internal jointing between structural spans (A).

X-Frame Flooring Surface

The 21mm-thick plywood floor was modulated to match the geometry of the supporting X-Frame. Alternative module sizes were trialed, however smaller 600mm by 600mm (approx) squares proved to be the most flexible and easiest to handle (fig. 151). This dimension also maximised usage of the available sheet material to effectively produce only 'sawdust waste'. These panels were fixed into pre-positioned nuts locked into brackets flush with the X-Frame grid (fig. 154 & 155). The final assembly was entirely reversible without risk of damage to any components and could be effortlessly scaled.

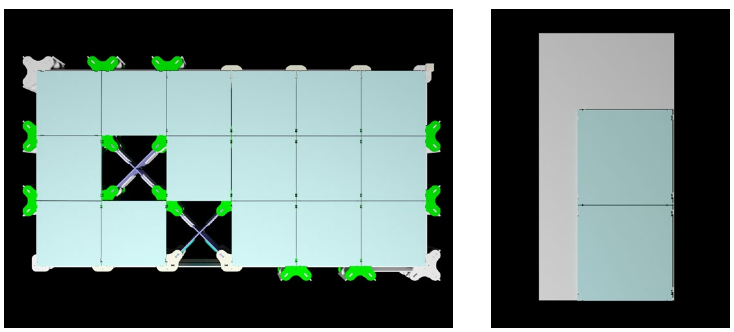


Figure 151.
900mm flooring grid module test (A).

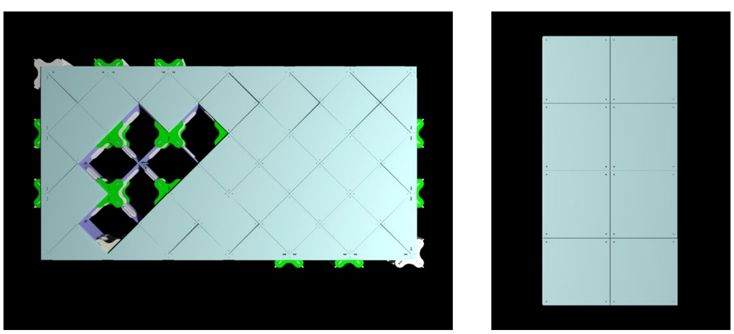


Figure 152.
600mm flooring grid module test (right) (A).

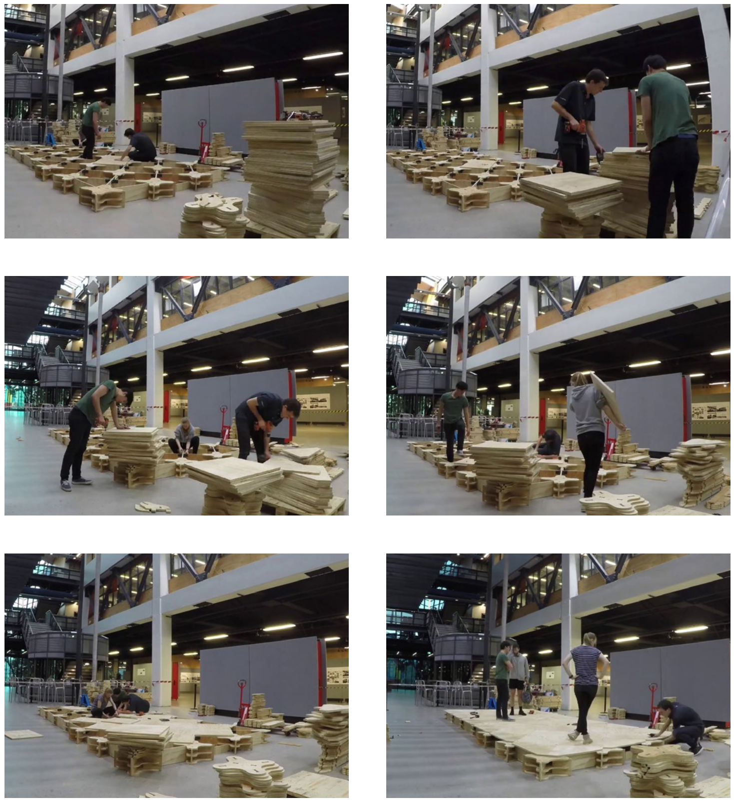


Figure 153.
Assembly of the 600mm floor grid module on the final X7 prototype (A).

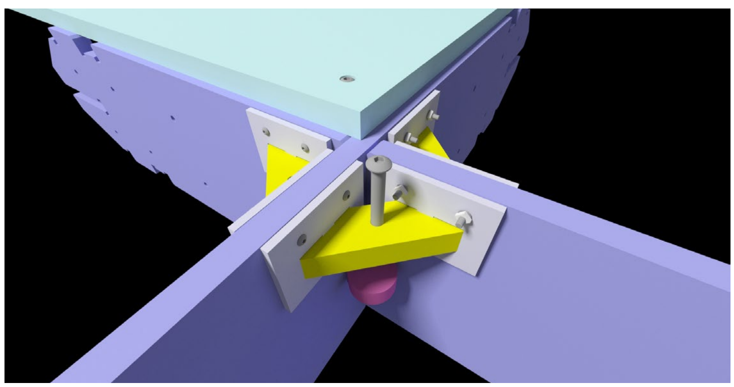


Figure 154.
Reversible floor hold down bracket at span intersections (selected iteration) (A).

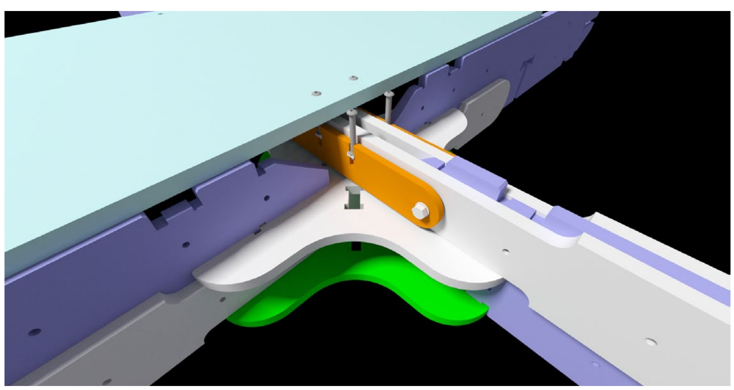


Figure 155.
Reversible floor hold down bracket at span join (selected iteration) (A).

Further Adjustments Required: Testing of the proposed design on a large scale highlighted a range of issues with the flooring attachment approach. An adjustment to the location of the open mortise hole in the X-Lock components is required to make the fixing of panels more efficient. Currently a hole must be drilled through the X-Lock plate approximately 8mm below the tenon location to allow the bolt to fasten (fig. 157). Relocating the tenon will be the most appropriate solution as it will retain the symmetricality of the panel being fastened. Stronger, faster and more flexible bracket attachments are also required to make the assembly and disassembly process more economical (fig. 156).

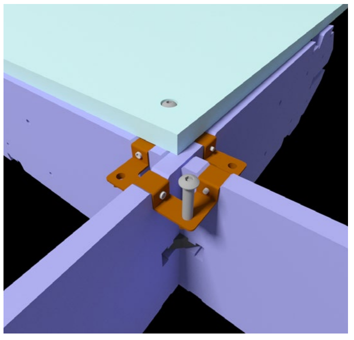


Figure 156. (left)
Superior hold down bracket at span intersection (selected iteration) (A).

Figure 157. (right)
Photo of the hole required to be drilled through the X-Lock component above the mortise (A).

Additionally, conflicts arose during the detailing of the floor/wall intersection and the structural flooring finish (fig. 158 & 159). To enable the seismic resisting wall-to-floor joint timber mortise fingers intersect the flooring finish and extend through into the X-Lock component (fig. 158). This required the shaping of a mortise in the flooring module where it intersects a wall and the custom shaping of the X-Lock component where two or more walls intersect (fig. 159). Adjusting the wall-to-floor joint to only require bolting will alleviate this issue, reduce fabrication costs and speed up assembly. However removing the mortise and tenon joint will reduce overall seismic strength and the accuracy of the alignment between vertical and horizontal planes.

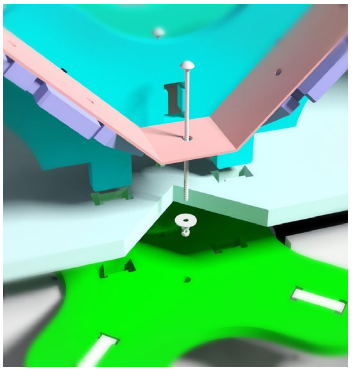


Figure 158. (left)
Render indicating tenons intersecting floor finish and X-Lock component (A).

Figure 159. (right)
Custom shaped X-Lock component with tenons for wall connection (A).

5.3.6 X-Frame Cladding

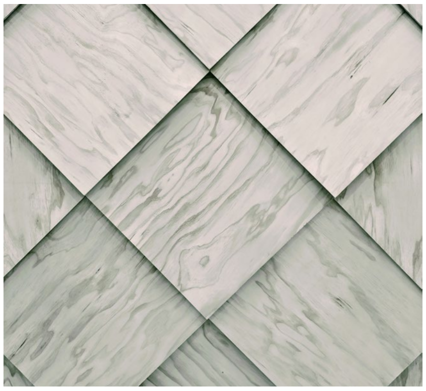


Figure 160.
Overlapping waterproof lining texture (A).

A proof of concept cladding solution was designed, fabricated and assembled (and disassembled) using the reversible fixing points available on the X-Frame diagrid (fig. 160–163). The intention was to demonstrate a weatherproof building envelope layer that was entirely reusable. Principles of overlapping and compression jointed building materials tested in conceptual development iterations were refined and applied. The finished timber modules followed the structural geometry to create a constantly overlapping skin that is fixed using large bolts through to the centralised X-Lock member (fig. 161–163). Weatherproof testing of this cladding is required to validate the approach. If it is found to be unsuitable X-Frame's 600mm grid allows conventional weatherproof and vapor barrier linings to be fixed without additional expense.

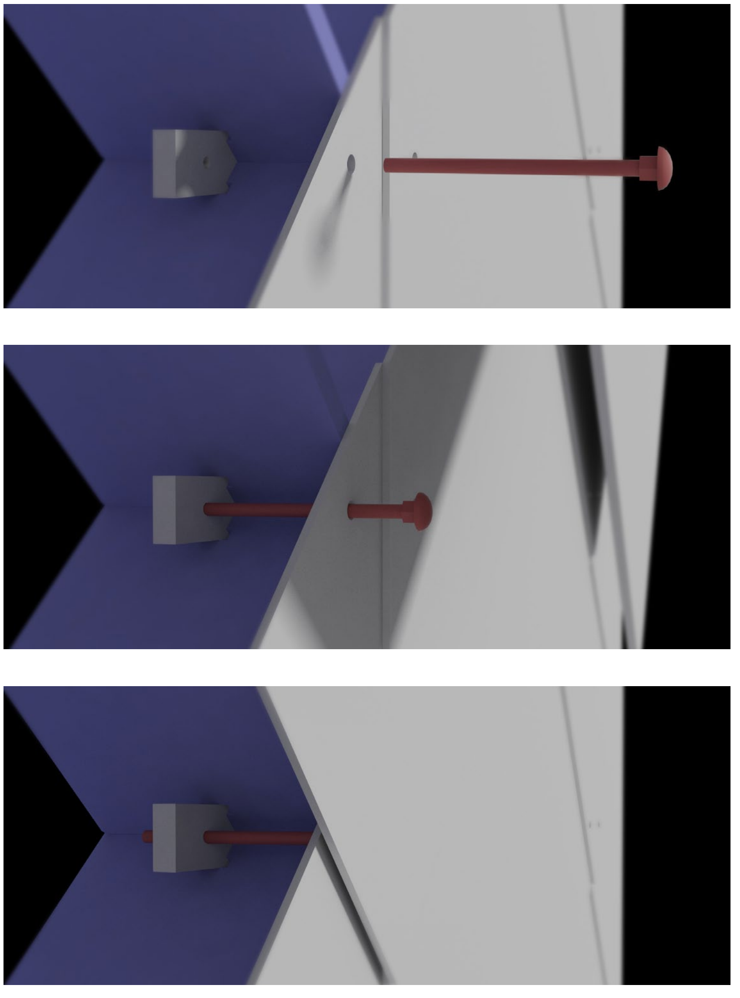


Figure 161, 162 & 163.
Cladding connection detail to X-Frame. Note the hidden fixing finish due to overlapping tiles (A).

5.3.7 Brackets

To protect the softer timber materials and ensure fully rigid jointing, steel brackets were required to transfer loadings between the walls and horizontal structural planes (as per fig. 158). These steel components were designed to be robust and easily fixed. Brackets were custom-made and to eliminate fabrication waste, have been formed from off-the-shelf 75mm x 4mm mild steel plates (fig. 164). Design experimentation to eliminate the need for these plates was extensive (5.3.3) however concerns expressed by the structural engineer, and time constraints prior to delivery of the full prototype '*X7*', led to the ultimate inclusion of structural steel plates.

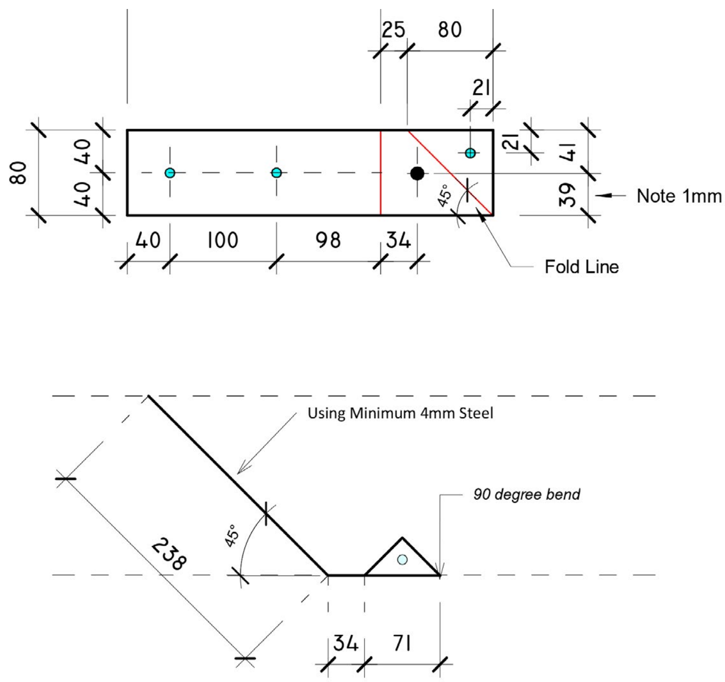


Figure 164.
Detailed technical drawings for specified steel brackets. Note efficient use of steel bar product (A).

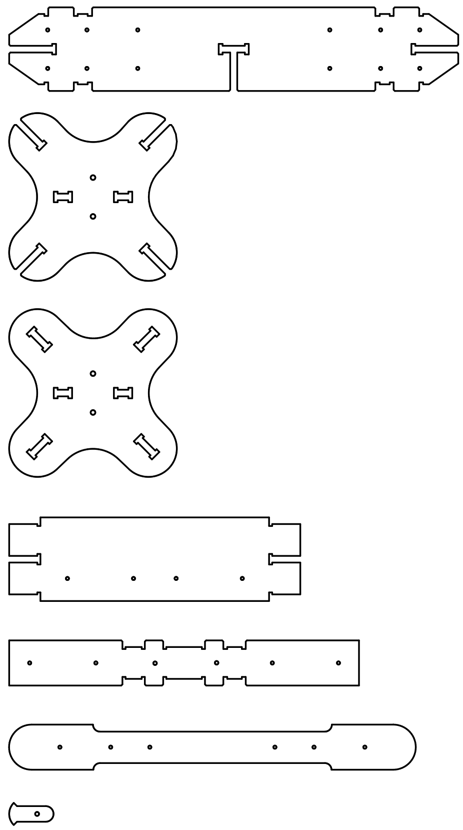
Figure 165. (left)
Fabricated steel brackets (4 variations) (A).

Figure 166. (right)
'V' bracket in place (A).

Figure 167.
Assembly process of full-scale X-Frame prototype test (6). Note integrated perimeter detailing but an absence of bevelled ends on key spaning elements (a).

5.3.8 X-Frame 7

Components



1. X-Span
Key structural spanning element for X-Frame.

2. X-Slot
Key structural connection element for X-Frame.

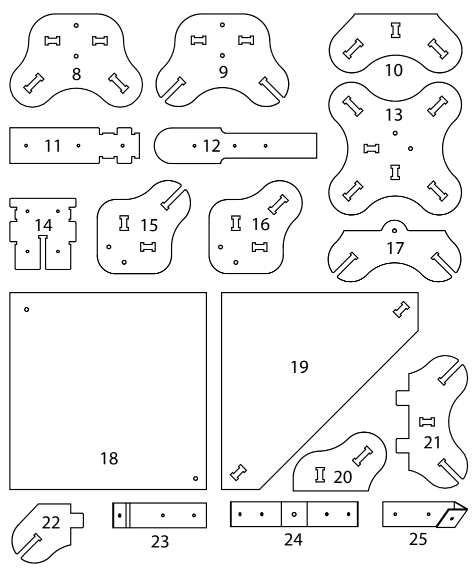
3. X-Lock
Key structural connection element for X-Frame.

4. Perimeter Lock
Edge spanning element.

5. Perimeter Span
Edge spanning element.

6. X-Brace
Spanning brace for horizontal configurations.

7. X-Pin



Additional components:

8. Edge Lock
9. Edge Slot
10. Wall Lock
11. Edge Half Span
12. Brace Half
13. Corner X-Lock
14. Edge Fill
15. Corner Slot
16. Corner Lock
17. Wall Join
18. Floor Square
19. Floor Edge
20. Wall Lock End
21. Wall Slot
22. Wall Slot End
23. Bracket End
24. Bracket Mid
25. Bracket Corner

Figure 168.
X-Frame (7) components (A).

Notable X-Frame 7 Features:

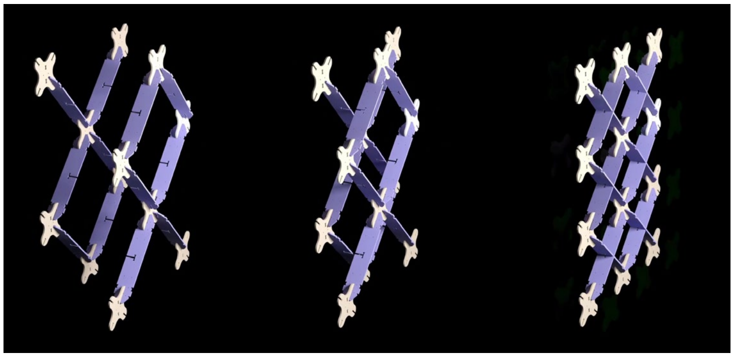


Figure 169.
Rendered sequence of X-Frame 7 wall frames assembling (A).

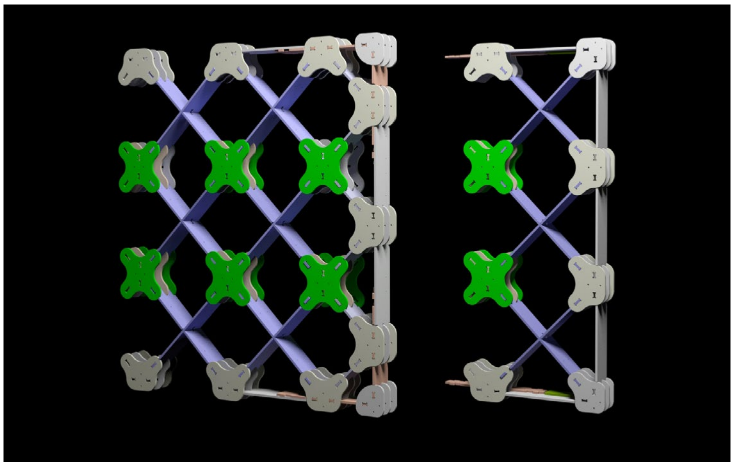


Figure 170.
Half-X Module allowing both 900mm (right) and 450mm (left) geometric modulations (A).

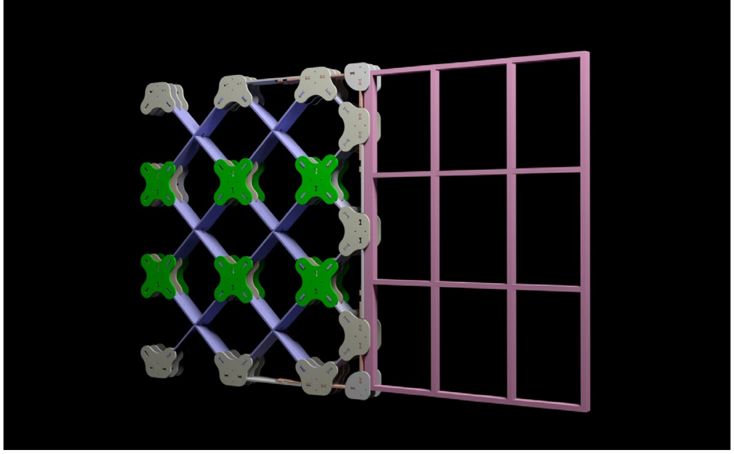
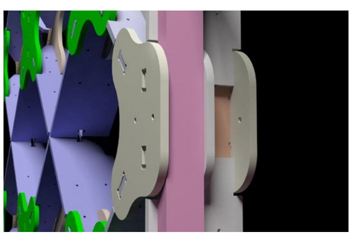


Figure 171.
X-Frame 7 allows conventional 90*45mm timber framing (pink) elements to be bolted at the perimiter of a framed area for further flexability (A).



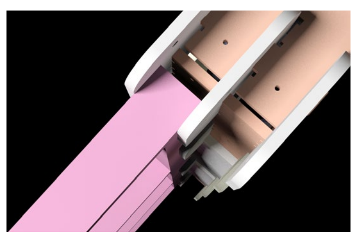


Figure 172 & 173.
Details of 90*45 intergration (A).

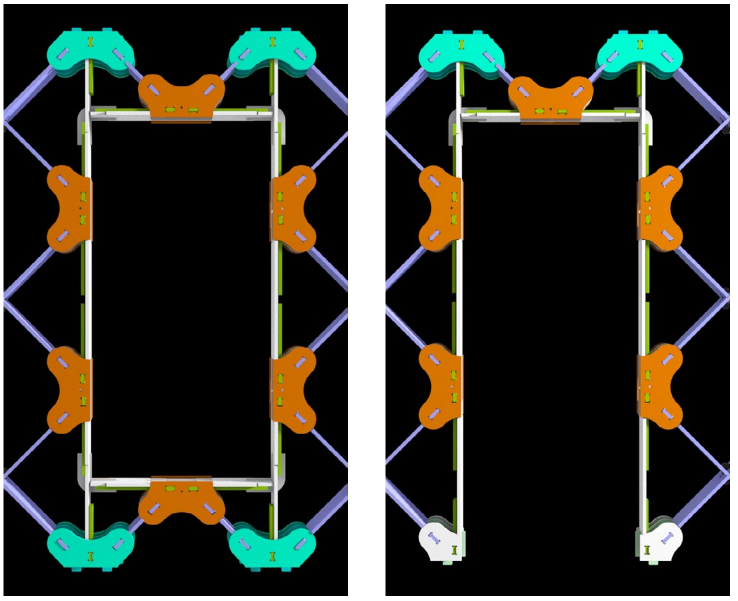


Figure 174 & 175.
Example of Half-X module used in conjunction with perimiter elements to frame a window (left) & door (right) cavity (A).

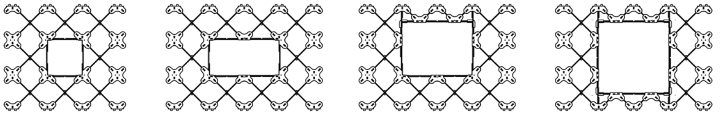


Figure 176.
A selection of alternative opening configurations (A).

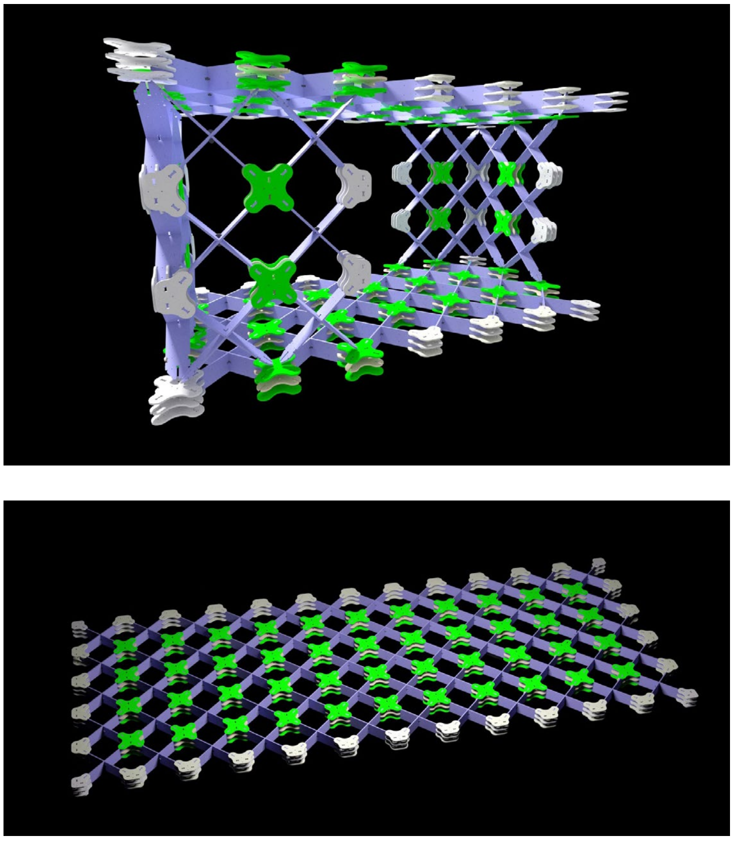
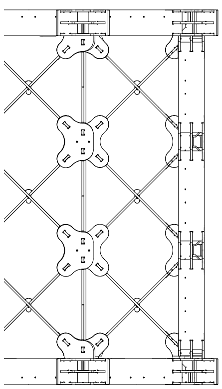


Figure 177 & 178.
Homogenous grid system i.e. wall and floor structural elements are the same and can be used interchangeably (A).

5.4 DEVELOPED DESIGN OUTCOME

The developed design outcome of this research thesis, X-Frame 7, was realised in the construction of a 1:1 scale prototype (named X7). X7 was funded by the New Zealand Instuite of Building's Charitable Trust with support from Carter Holt Harvey Ltd and was fabricated at Makers of Architecture and Victoria University of Wellington. The prototye was built in Victoria University's Faculty of Architecture Atrium in September 2017. X7 allowed the collection of accurate quantifiable data regarding the real-world performance of X-Frame.



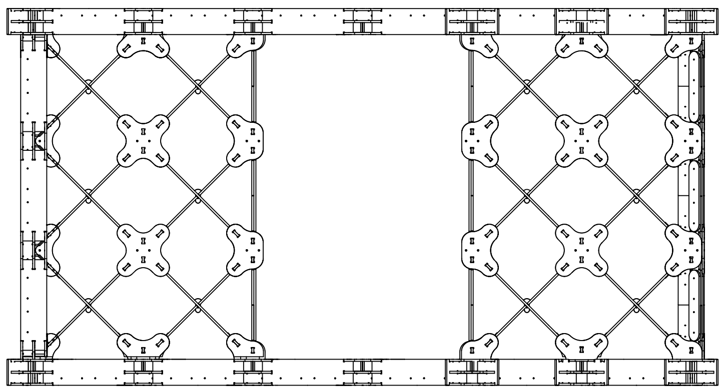


Figure 179. (left)
Partial elevation sketch of X7 (Short) (A).

Figure 180. (right)
Elevation sketch of X7 (Long) (A).

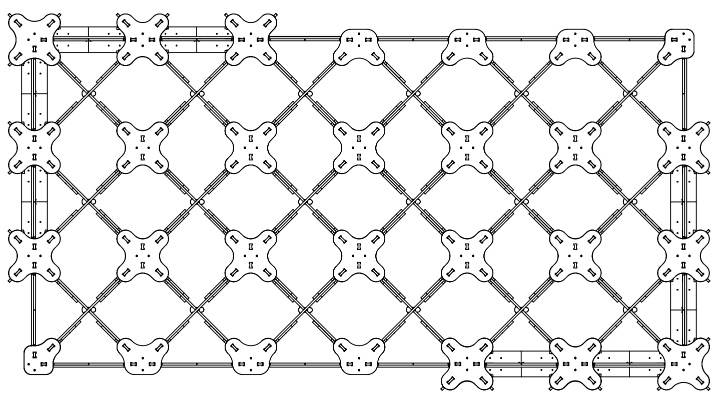
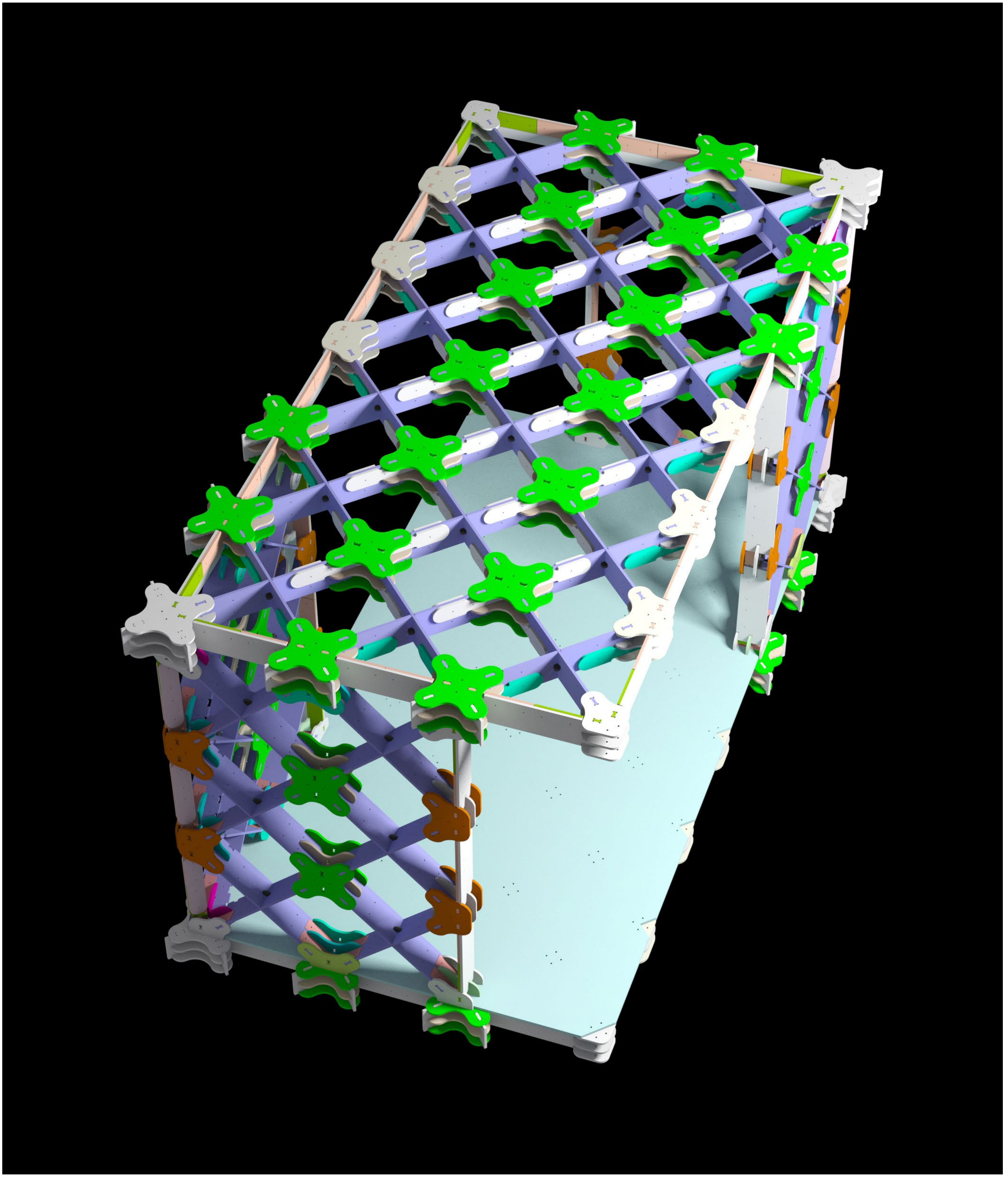


Figure 181.
Plan sketch of X7. Note walls in top left and bottom right corners (A).

X7 has been conceived to specifically test key common building parameters. This includes external and internal corners (and associated wall intersections), floor and wall intersections with structural capacity, structural spans and structural cantilevers.

Figure 182. (right)
Digital component render of X7 prototype using X-Frame (7) (A).



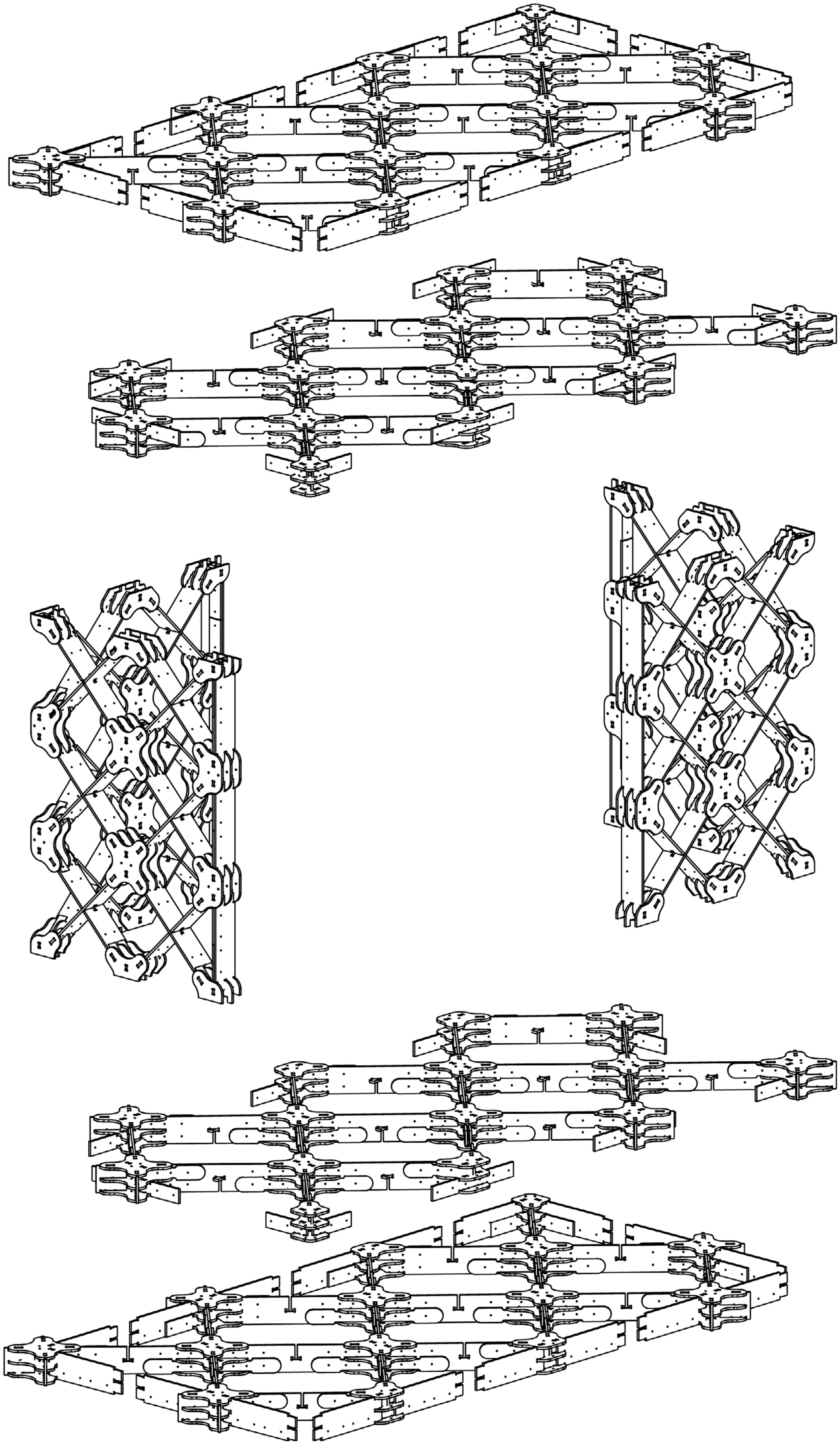


Figure 184. (below)
Quantity and cost of X7 components including fasteners and brackets. See appendix 2 for details (A).

	Number Of Pieces	Cost/Piece
	120	$17.95
X-Slot	44	$12.18
X-Lock	88	$12.51
	48	$11.30
	40	$10.07
	40	$9.70
X-Pin	60	$1.10
V-Lock	48	$8.69
V-Slot	20	$8.39
	28	$5.14
	32	$5.13
Wall Slot End	8	$3.53
Wall Slot	8	$5.92
Wall Join	8	$6.12
Edge Fill	44	$4.89
Floor Square	27	$21.64
Floor Edge	18	$15.91
	16	$17
	16	$17
	24	$17
50mm M6 Bolt	312	$0.25
60mm M6 Hex	16	$1.50
70mm M8 Bolt	36	$0.35
180mm M10 Bolt	40	$0.80
'Waste'	10% per unit.	$0.34
Total:		**$8,624.88**

Figure 183. (left)
Exploded drawing of key X-Frame components for X7 prototype assembly (A).

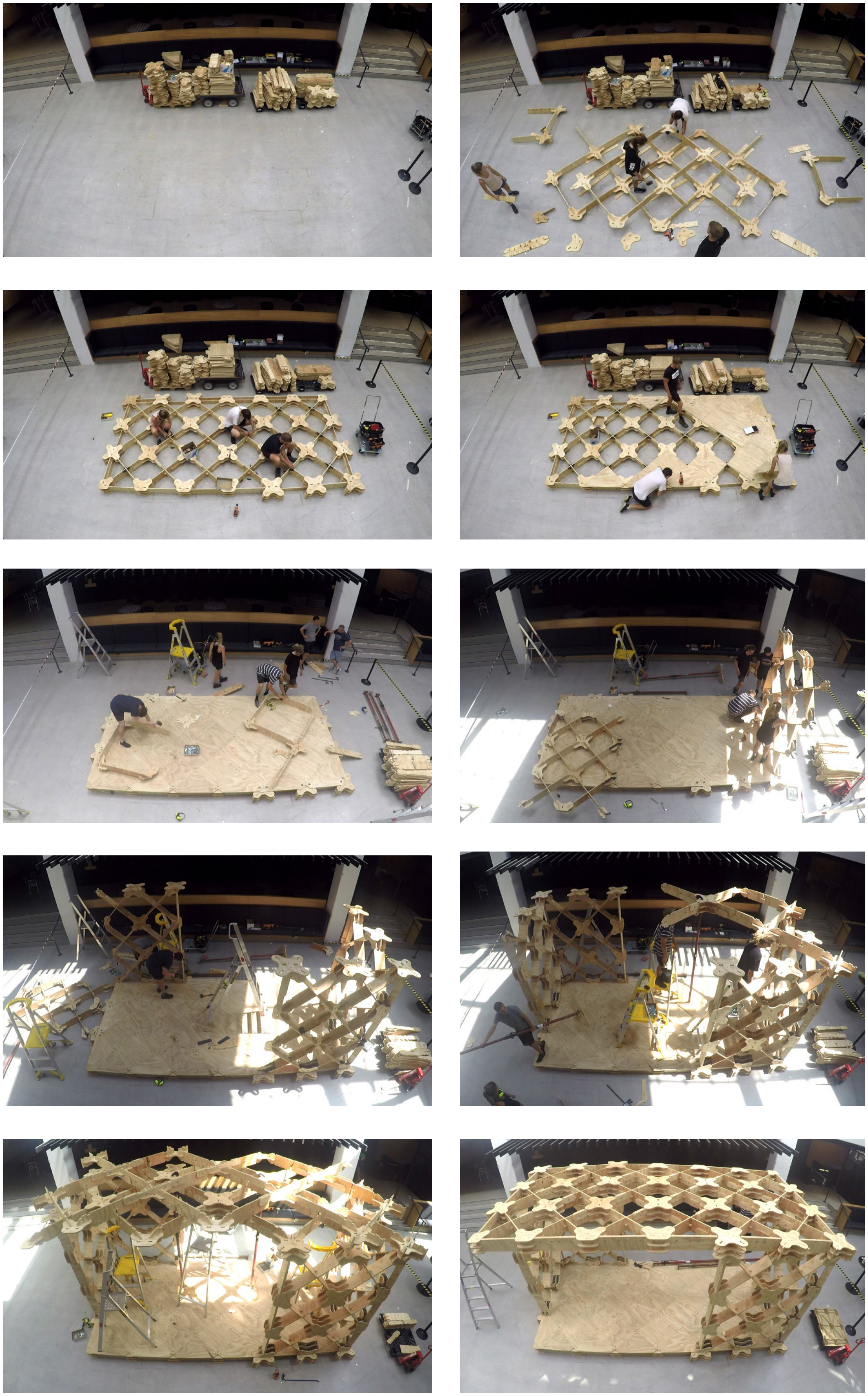


Figure 185.
Assembly sequence of X7 prototype (A).

Figure 186.
X7 wall system using X-Frame (7) showing X-Lock (centre) and key span elements (A).


LT 1

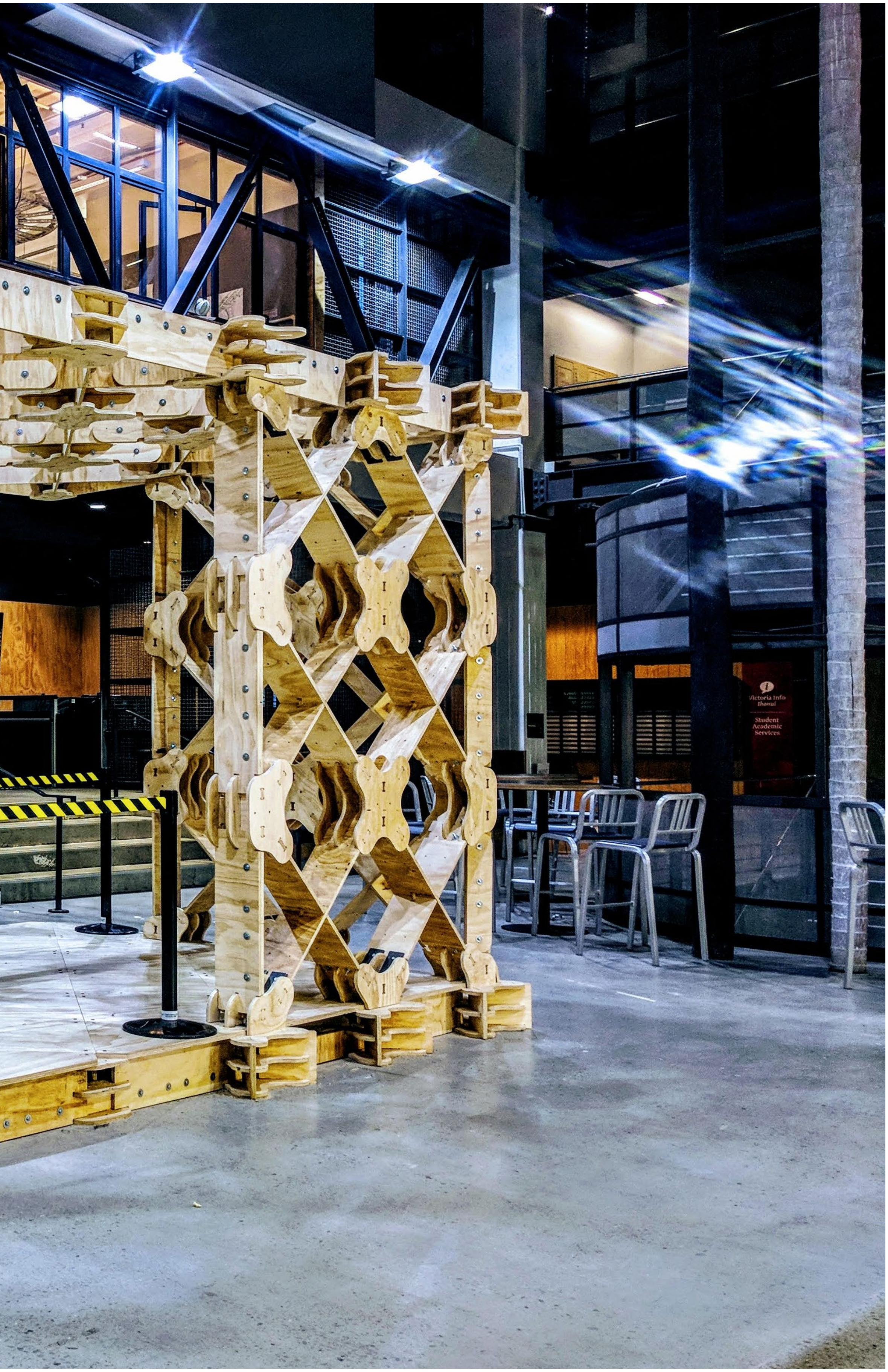


Figure 187.
X7 (A).

Figure 188.
X7 cladding test (A).

6.0

Critical Reflections

Chapter 6 collectively reflects upon the research and its scope, success, limitations and contributions to the discipline as a whole.

Figure 190.
Performance summary of X7 and X-Frame 7 Test (A).
(See Appendix 2 and 6.1 for calculation details.)

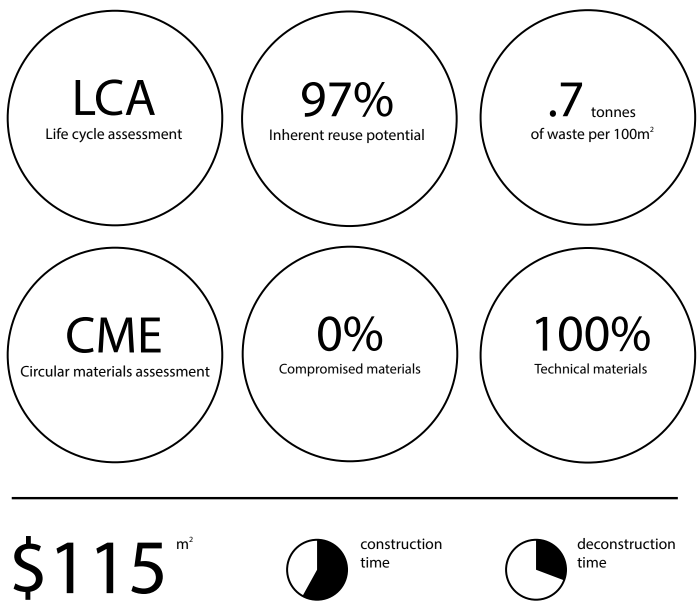


Figure 189.
Chipped waste
plywood material (A).

6.1 DESIGN

6.1.1 X-Frame 'X7' and 7 System Issues

Assembly optimisation, – the designing of jointing and fixing moments to enable rapid, logical and durable assembly, was a significant feature of the X-Frame system. Iterative refinements of X-Frame initially focused on such optimisations: decreasing the time taken to assemble and disassemble the structural frame. However throughout the final changes, a series of structural necessities dictated modifications to the jointing details that compromised earlier assembly optimisations. The primary example of these issues was demonstrated in the centralised plywood locking member, notated as X-Slot on drawings, which required the total separation of the interlocking frame before deconstruction was possible (fig. 191). While separating the structure in this manner was achievable, it becomes more difficult as the overall dimensions of the frame being disassembled increases. The way in which the X-Slot component is integrated not only makes disassembly longer but also increases the likelihood of damage to other components. Full-scale cyclic testing indicated that the X-Span members are most prone to damage due to this assembly requirement (fig. 192 & 193). These tests also suggested that frame assemblies (up to 4.8m in length and 1.8m wide) can be separated without damage by two unskilled labourers.

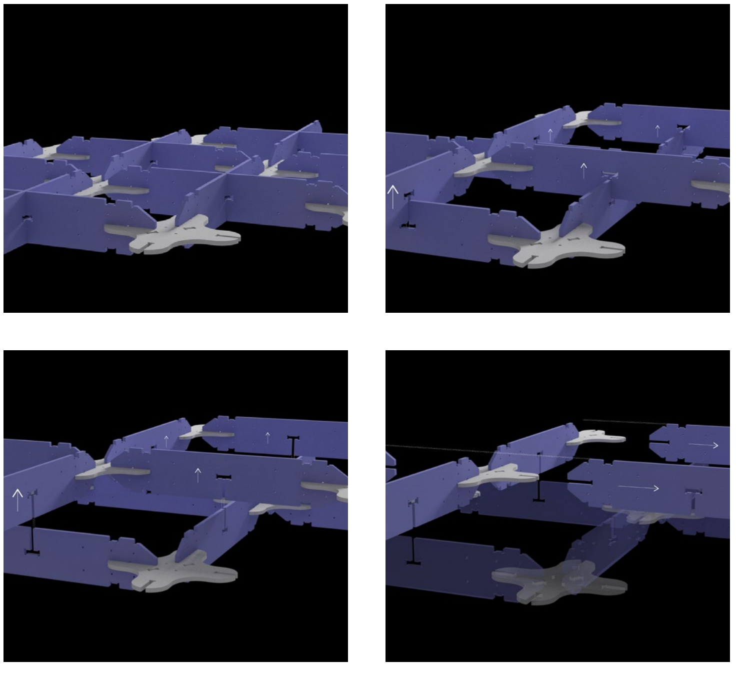


Figure 191.
CLOCKWISE FROM TOP LEFT

Progressive separation (deconstruction) of X-Frame elements. Note vertical separation must occur before lateral separation (A).

The X-Slot component also increased the amount of care – and therefore time – necessary for assembling the separate frame elements. The interlocking grid geometry of X-Frame, and the inclusion of the centralised X-Slot component, required the X-Span members to be deformed (bent) perpendicular to their length while inserting the final slotted joint (fig. 192 & 193). Repetitive or overstrained deformation could result in X-Span members snapping (fig. 193). Furthermore, of all the joints and connections within the X-Frame prototype, the centralised X-Slot component was the most difficult to disassemble. The ease of disassembly of this slotted component varied depending on discrepancies in the thickness of the plywood (due to moisture content and/or machining), applied loads and deflection during use cycles, and variations between CNC routing tolerances. Using a rubber mallet to knock slot components apart was time-consuming, but successful and it is yet to result in component failure (270 separate joints tested – 0 failures).

Figure 192 & 193.
Span and slot plywood members need to be deformed to complete full grid element (top) sometimes resulting in snapping of the span component (bottom) (A).

Other Key Evaluative Notes

Performance of Mortise and Tenon Joints: Timber is subject to thickness variations due to changing moisture levels as well as machining conditions, and as such perimeter spanning components were often extremely difficult to remove. The 'prolific' integration of these joints slowed down assembly.

Performance of Locking Pin: The locking pin introduced was also likely responsible for the occasional snapping of the 'X-Span' component in construction and deconstruction cycles during the construction of X7. Out of 120 X-Spans cut, three snapped in use cycles – 1 in construction, 2 in deconstruction (97.5% effective for reuse).

Performance of Steel Brackets: The performance of the steel brackets in practice was excellent. The resulting 90° intersection of structure was resilient and strong while also enabling rapid assembly and disassembly processeses. Where these brackets intersected at corners in walls, they helped to stiffen and align the frame without the need for significant external forces. Although none of these plates were damaged during the assembly process, they did sometimes damage the thread on intersecting bolts.

Figure 194 & 195.
Stiff mortise and tenon joints (left) and damage inflicted to X-Span elements due to locking pin integration (right) (A).

Figure 196.
Fabrication problems due to plywood sheets shearing and consequently generating more waste (A).

Figure 197.
CNC fabrication issues. Toolpath generating on the wrong side of a line – resulting in a component that is proportionally too small (A).

Figure 198. (left)
Preparation of components for use – removing tabs with a hand-held router.

Figure 199. (right)
Sanding edges for components cut at Victoria University – note that components cut at Makers of Architecture did not require sanding (A).

6.1.2 Category Based Analysis

	X-Frame 7	Platform LTF
Materials are easily reconstituted or formed in a way that is attractive to reuse.	✓	
Deployed materials are scalable based on a minimum divisible unit dimension.	✓	
Mass standardisation of components to achieve direct reuse economic viability.	✓	✓
Independent layerings of materials to facilitate separation and recovery.	✓	
Fixings are exposed or have a sense of inherent logic to facilitate separation.		
Fixings require no tools/are standardised to only require non-specialist tools.	✓	
Fixings detailed to be removed/reversed without contaminating or inflicting damage.	✓	
No chemical, composite or adhesive based fixings are used.	✓	
Materials retain performance through multiple reuse cycles without loss of value.	✓	
Materials detailed as to avoid the need for compromising bonded coatings/treatments.	✓	
Materials must remain aesthetically desirable or be easily restored to 'as-new' conditions.	✓	
Composite/compromised or inseparable hybrid materials are not permitted.	✓	
Score	11	1

Figure 200.
X-Frame (7) vs conventional platform light timber framing performance summary (A).

6.1.3 Quantifiable Performance Analysis

	Conventional	X-Frame 7
Construction Material Cost (per m^2 of wall - insulated & with RAB*1)	$94.00	$115.00
Deconstruction Labor Cost (per m^2 of wall - with claddings/linings*2)	$17.50	$12.00
Waste in Construction (kg) (no CNC or lime chip insulation*3)	3240	2505
Waste in Construction (kg) (with improved efficiency systems*4)	3,240	785
Weight of Structural Timber (kg) (timber weight*5)	10,368	17,940
Waste at End-of-Life (kg) (weight*6)	17,330	530
Full Life-Cycle Waste (kg) (combined weight*7)	20,570	1,315
Full Life-Cycle Waste Savings (%) (vs. conventional, with management systems)	-	**94%**

*Waste in construction calculated for a 180 square metre building. Calculations supporting these numerical results can be found in the appendix referenced to figure 201 and the corresponding Astrix.

Figure 201.
Summary of economic and waste measures for X-Frame 7 and conventional platform light timber framing (A).

6.1.4 Design Variations

Feedback during construction of the full-scale prototype suggested the extensive use of bolted fixings compromised the purity of the structural X-Frame system. The author consequently examined the feasibility of introducing plywood only connections to replace steel nuts, washers and bolts.

	Bolted	Plywood
Cost per Fixing (NZ$) (based on fabrication costs*1)	$0.45	$2.28
Cost for a 180m^2 Dwelling (extrapolated cost to use fixings)	$3,310	$16,050
Estimated Assembly Time (s) (per fixing - using appropriate tools*2)	14	15
Estimated Disassembly Time (s) (per fixing - using appropriate tools*3)	8	16
Building Assembly/Disassembly Time (hr) (extrapolated time for 180m^2 dwelling*4)	45	59

*Calculations supporting these numerical results can be found in the appendix referenced to figure 202 and the corresponding Astrix. Times based on experiments carried out in this thesis.

Figure 202.
Quantifying the impact of design variations: plywood fixings vs bolts (A).

Ongoing interest from the industry has seen further variations of the X-Frame system developed. X-Frame 9 is the most recent version that addresses many of the assembly limitations identified earlier in this chapter. This iteration was optimised for cost-performance, reduced deflection under load and immediate industry adoption.

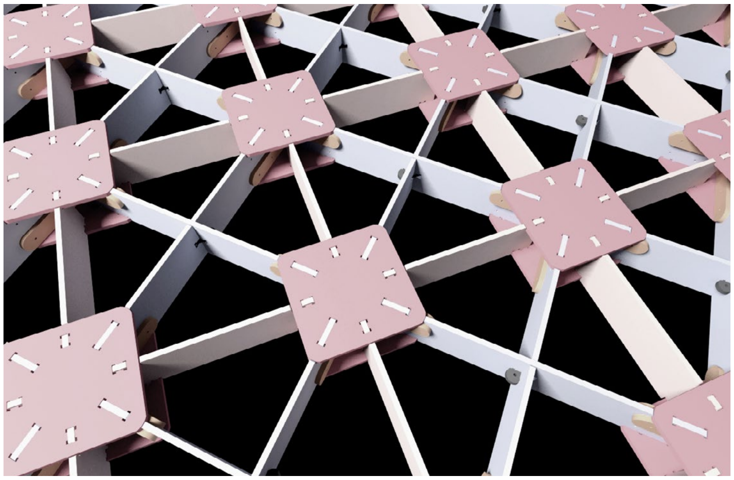


Figure 203.
X-Frame 9 proposal (A).

	X-Frame 7	X-Frame 9
Percentage Dust Waste/Sheet (average area of sawdust material/sheet)	14%	11%
Percentage Solid Waste/Sheet (average area of solid material/sheet)	9%	1%
Effective Sheet Area Used in Parts (percentage average area)	78%	88%
Total Perimeter Cut (m) (average total cut length of parts per sheet)	41.1	43.5
Cut Time (minutes @ 35mm/sec) (average time to cut all parts on sheet)	39	41
Total Cut Cost per Sheet ($0.04/sec) (average total based on cut time)	$97.80	$103.63
Area of Frame/Sheet (m^2) (area of X-Frame structure per sheet)	1.3	2.03
Cost/Square Meter (based on previous metrics)	$146.29	$93.68
Material Cost/Square Meter (based on frame area/sheet & material cost)	$56.15	$35.96
CNC Cutting Cost/Square Meter (based on frame area/sheet & $/sheet)	$90.14	$57.73

*Calculations supporting these numerical results can be found in the appendix referenced to figure 204 and the corresponding Astrix.

Figure 204.
Waste, fabrication and economic performance comparison between X-Frame 7 and 9 (A).

6.1.3 Waste in Fabrication

Reductive manufacturing technologies, such as CNC routing, inevitably produce large quantities of waste. This is a consequence of the pre-sized sheet material (in this instance 1200mm by 2400mm sheet plywood) conflicting with the desired forms being cut. Although the design was (see opposite) highly optimised to make use of the available material, there is always some degree of wastage (sometimes only the sawdust created by the thickness of the cutting piece). It was, therefore, necessary to identify a productive use for this waste material by-product.

Figure 205.
An example of solid and dust waste produced through the CNC manufacturing process (A).

	Sheet 1	Sheet 2	Sheet 3	Sheet 4
Colour Code				
Number of Components	28	11	18	25
Total Cutting Length (2 passes)*	40.1m	40.9m	31.8m	51.5m
Manufacturing Cost*[2]	$95	$97	$76	$122
% Area of Sheet Material Used	86.0%	83.3%	69.1%	72.6%
Dust Waste as a % of Sheet Area*[3]	13.6%	13.5%	10.5%	17.0%
Solid Waste as a % of Sheet Area	0.4%	3.2%	20.4%	10.4%

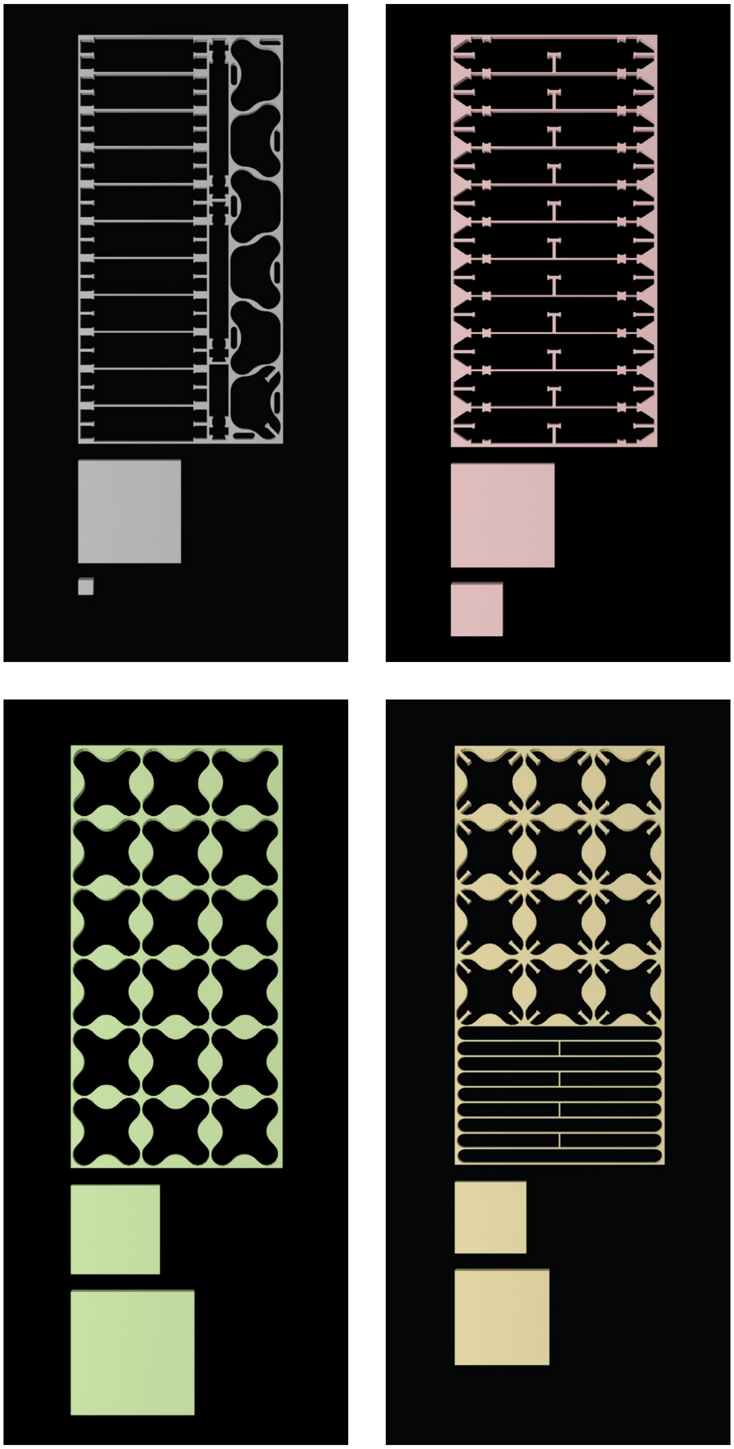
*Two passes required to cut through 17mm plywood without risking safety or compromising edge finish. *[2]. Costs calculated based on a CNC feed speed of 35mm/s and a cutting cost of $0.04/mm. *[3]. Dust = 9.5mm cutting bit multiplied by permitted cut.

Figure 206.
X-Frame 7 CNC cutting conditions and implications for manufacturing waste (linked to fig. 107) (A).

Figure 207.
Waste plywood from CNC manufacturing processes. Note that this is a consequence of choosing only to 'deploy' necessary material i.e material required to preform a given task (50mm around each hole in the plywood was specifyied by the structural engineer and this often dictated the shape of elements). Top square: 'dust' waste; bottom square: 'solid' waste (A).

Top square: quantity of waste that is sawdust

Bottom square: quantity of waste that is solid



Sheet 1
Dust Waste: 13.6%
Solid Waste: 0.3%

Total Waste: 13.9%

Sheet 2
Dust Waste: 13.5%
Solid Waste: 3.2%

Total Waste: 16.7%

Sheet 3
Dust Waste: 10.5%
Solid Waste: 20.4%

Total Waste: 30.9%

Sheet 4
Dust Waste: 17%
Solid Waste: 10.4%

Total Waste: 27.%

Waste Solutions

Of all the timber that is reused today, 38% goes into the production of low-density fibreboard (LDF), commonly known as chip or particle board, and medium-density fibreboard (MDF) (WRAP, p. 9, 2011). Unfortunately the final reconstituted product integrates petrochemical additives to bond the shredded timber together, ultimately resulting in a compromised composite material. The remaining 60% of recycled timber can be shredded ('chipped') and used as ground cover around plantings, as fuel for heating or energy generation and for bulking compost (WRAP).

Figure 208.
Chipping waste plywood (A).

There is historical evidence in Germany of chipped waste timber being used as insulation in walls and ceilings of buildings (Woolley, p. 27, 2006). In some variations of this method, the wood shavings were mixed with liquid clay to form an all- natural composite material, informally titled 'chip 'n' slip' (fig. 209) (Woolley, p. 27, 2006). This formula improved the thermal resistance of the insulation while also making the wood component more resistant to fire, moisture and rodents (Morgan & Scott, p. 18–19, 2003). Alternative modern construction techniques have replaced the chipped timber with hemp and added lime to essentially form a composite insulative material with the same basic ingredients (fig. 210) (Molloy, p. 85, 2016). In a Circular Economy, reusing timber waste as an insulation material is effective as only natural and non-toxic materials are being introduced to form the product. The end material, although 'composite' by nature, can be easily and naturally decomposed. Furthermore, this compost product is highly desirable for forest plantations where the growth of *Pinus radiata* leaves the ground acidic and in need of erosion resistance (Turner & Lambert, p. 89, 1987).

Figure 209.
Mixing 'chip 'n' slip' (lime) (A).

Figure 210.
'Chip 'n' slip' block (lime) (A).

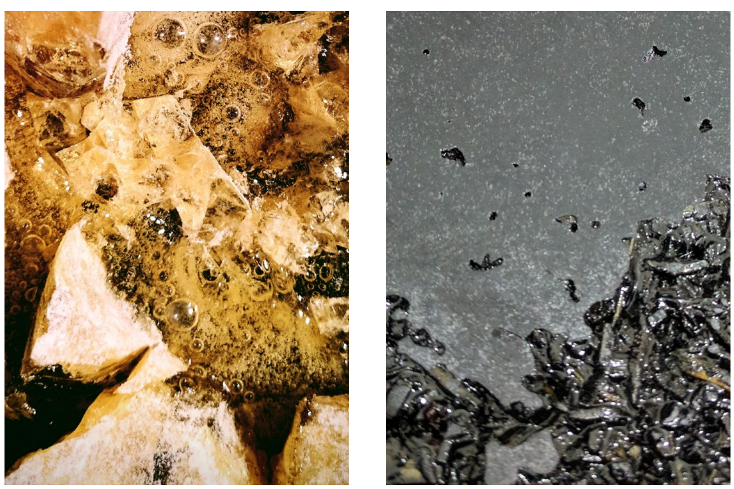


Figure 211 & 212.
Additional tests: mixing pine resin, charcoal dust and woodchips to create a natural sheet product (A).

Further research and implications: This is an area where the author would like to conduct further studies. The use of waste timber to create a high value 'Wood Fibre Insulation' product has been demonstrated internationally and more information is needed to ascertain why this product is not more popular and if waste CNC material can be processed into a fibre (Sutton et al, p. 1–4, 2011). Another area of potential research is the use of natural resins to create biodegradable LDF and MDF products. This second proposal was briefly tested using pine resin, charcoal dust and chipped waste timber (fig. 211 & 212). Although ultimately cost prohibitive to produce today, it is likely that the addition of beeswax to this mixture would result in a compressed sheet product suitable for the construction industry. Finally it is worth noting that although all of these processes do effectively 'close the loop' and minimise waste, they are essentially a mask for an inefficiency in the design. Any partial devaluation to the product entering the use cycle (even if it only happens in one cycle) is undesirable for a CE product.

Additive manufacturing: Additive manufacturing (such as 3D Printing) has real potential as a technology to eliminate waste produced at the manufacturing stage as material is only 'consumed' or 'delivered' where needed. So why hasn't additive manufacturing been used here? Typically when 3D printing a timber product, the printing filament is 30% wood pulp, 70% polylactic acid-based plastic resin (PLA) (ColorFabb, n.p., 2018). Although both of these products independently are biodegradable and entirely reusable without a loss of value, once they are combined, separating the thermally bound composite can be difficult (Sommerhuber et al, p. 235, 2017). This, and the current lack of a viable, large-scale, commercial pathway are key reasons why this technology has not been explored.

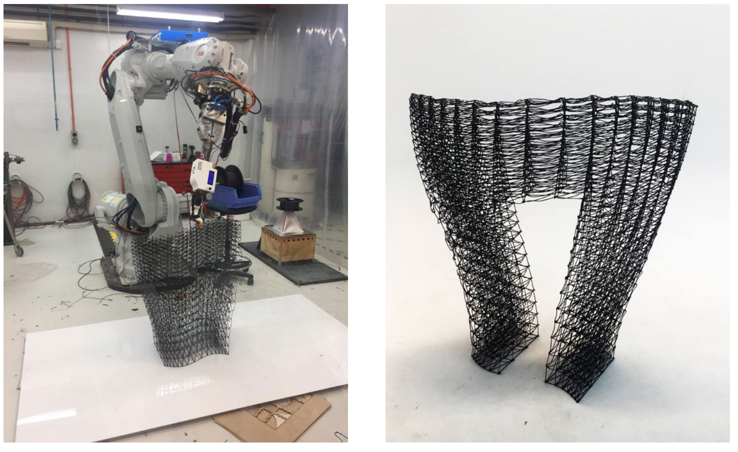
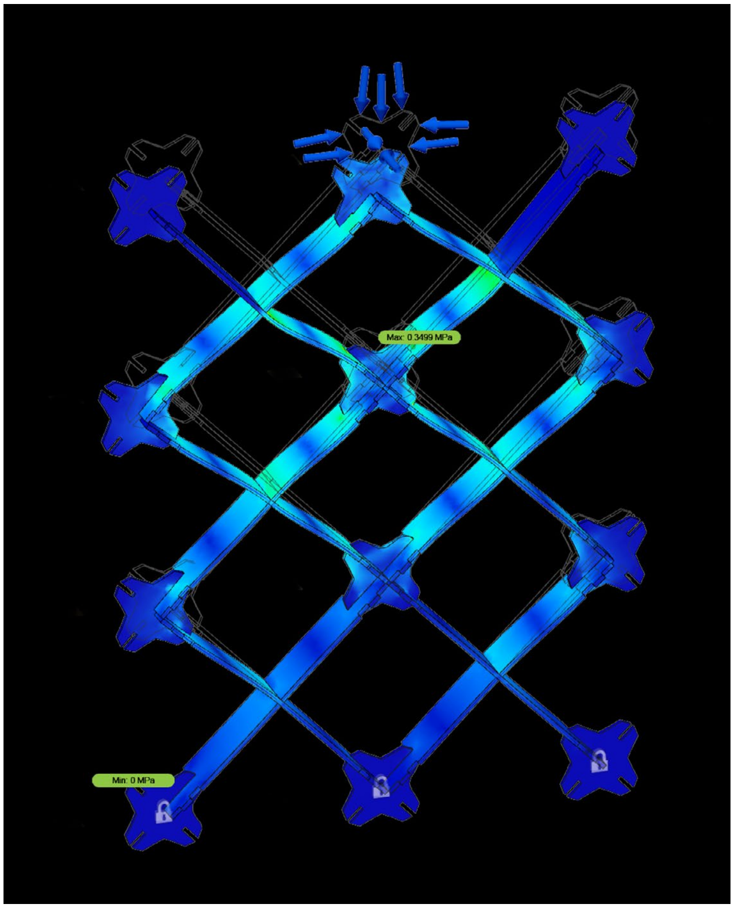


Figure 213.
Additive manufacturing examples (Image: Papageorge, 2018).

6.2 LIMITATIONS

6.2.1 Architectural Engineering



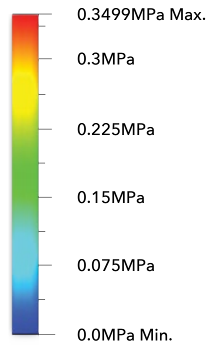


Figure 214.
Fusion 360 stress simulation (A).

Adapting and reinventing the way in which materials are assembled results in a range of conflicts with the structural design of a given building. For X-Frame, these issues have been discussed at length with two qualified structural engineers and other industry experts. However, these discussions do not represent full engineering calculations, or are a complete detailed structural analysis of the final proposed system. In this sense, the study's findings are limited as there is no quantifiable evidence that the structure meets New Zealand Building Code requirements. That said, the full-scale proof of concept prototype, comments from practitioners and the various tests all suggest that the X-Frame concept would exceed all relevant performance measures in New Zealand. The author hopes that the X-Frame prototype will be tested further to validate its performance.

6.2.2 Materials

In order to focus the scope of study, this research has focused on the use of timber and its capacity to eliminate end-of-life building waste. Although this parameter has been largely followed, the choice of timber has inadvertently eliminated potential design outcomes. Furthermore, within the range of timber products, the selection has remained narrow. This choice, again, enabled a more focused research scope and ensured that the final solution, X-Frame, was well resolved. The author acknowledges that more research is needed to determine if other timber products could provide a superior reusable architectural outcome.

6.3 SCOPE

Although the design research process can be tightly packaged, there was a significantly undetermined scope at the beginning of the research that led to a range of design operations that have very little relevance to the final outcome. More significantly however, some design experiments were rejected prematurely and it is likely that their potential contributions have not been fully realised. It is therefore very probable that further development of alternative solutions could result in similar performance levels. To measure the level of performance of various other solutions accurately, full-scale tests similar to those completed on X-Frame iterations (e.g. X7) are required.

6.4 PROCESS

Model & component design: The design research methodology reflects a need to explore a wide and diverse range of possible solutions as well as the pragmatic issues associated with designing for cyclic reuse. A process of reflecting upon existing conditions, digital sketch modelling and then rapid testing through the fabrication of CNC laser cut sketch models enabled expansive and unconstrained experimentation. The iterative design process was accelerated as the research worked to develop a small set of components that would then be scaled and repeated through a building. Likewise, by constructing highly detailed digital models and using automated object nesting software, multiple variations of a proposed design could be fabricated and tested simultaneously (fig. 215 & 216). The creation of detailed digital models also enabled design experiments to be tested at a range of scales without the need for further preparation. This scaled approach to testing design outcomes resulted in some iterations that were inherently inadequate, as they were designed at the scale of the physical model being produced. When scaled up to full-size, these design experiments often failed to form effective assemblies (fig. 218). Ensuring that all design operations were taking place at the appropriate scale, the limitations and material dimensions had to be identified at the outset of the design test. Ultimately the speed and fluidity of the design research methodology was highly effective in producing successful outcomes that were both experimental and appropriate.

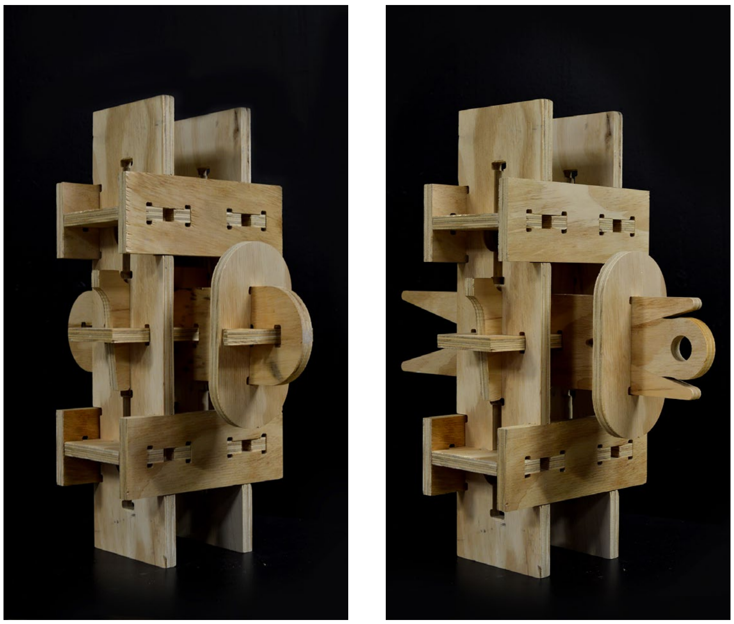


Figure 215 & 216.
Multiple variations of a proposed design (Click-Lock) fabricated and tested simultaneously (A).

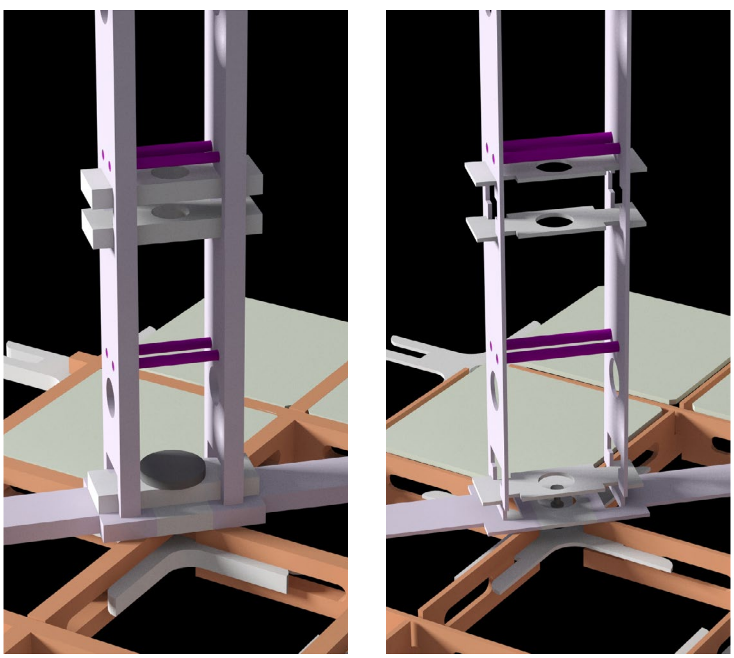


Figure 217 & 218.
Scaled design processes failing to translate to effective design solutions (inadequate material strength). 1:50 model using 3mm MDF (left) vs 1:1 system using 17mm plywood. (A).

6.5 KEY CONTRIBUTIONS

- **The identification of an adaptable, whole-building grid module that is structural and expandable.** The realisation of a building module that is more adaptable than traditional panellised prefabricated construction methods and is faster to assemble than brick-based construction is significant (see 5.5.1).
- **The successful separation of dependent building layers.** Separation eliminates dependency, cross-contamination and irreversible material damage, all while reducing disassembly time. The inherently lateral-load resisting frame enables all linings and claddings to be non-structural with easily reversible fixing details.
- **Using waste material to form an insulation product.** Finding a useful low-cost solution to the sustainable management of waste produced during reductive manufacturing of timber has wide-reaching implications. Not only does it address a key waste problem *immediately,* it also has the potential to provide extremely low cost, chemical-free insulation products to existing buildings.
- **A critical evaluation of various construction methods in New Zealand in respect to material reuse.** For the discipline as a whole, an integrated analysis of the advantages and disadvantages of various construction systems is important to raise awareness regarding end-of-life building waste.

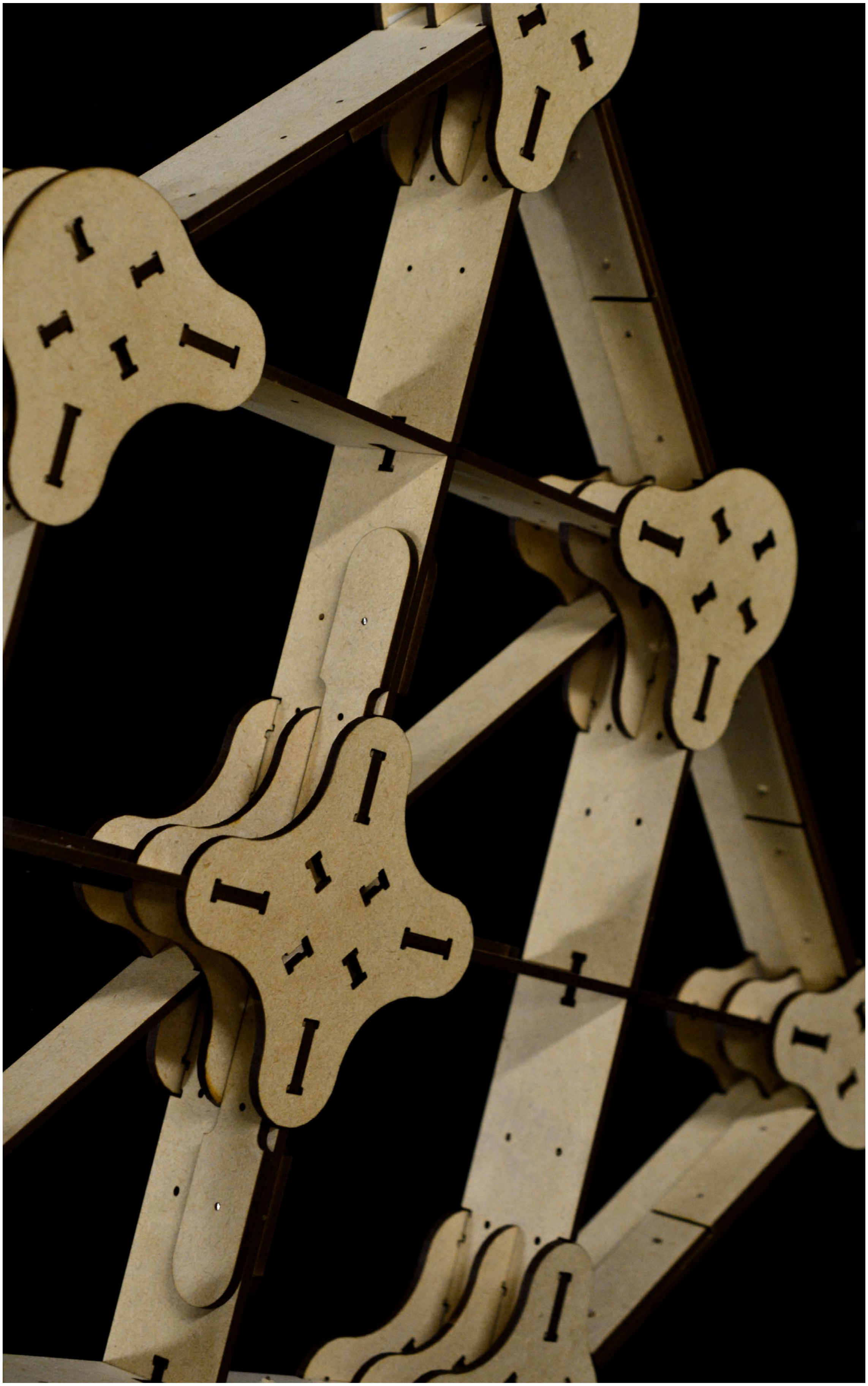


Figure 219.
X-Frame 6 scale model. Scale test demonstrating the effective structural and modular capacity of the diagrid solution (A).

6.6 ONGOING RESEARCH

The wide reaching impact of designing for a Circular Economy coupled with the poor performance of current construction methods suggests that there is significant potential for further research. This includes (but is not limited to):

- Detailing of the existing X-Frame design to accelerate deconstruction (eliminate X-Slot member).
- Refinements in the geometric patterning to improve cost effective fabrication and material deployment.
- Testing/developments to maximise the potential flexibility of the X-Frame system.
- Development of a more streamlined CAD/CAM process to enable mass-production of X-Frame.
- Updated X-Frame iterations to validate horizontal spanning capability.
- The exploration of additive manufacturing technologies to deliver 'wasteless' design.
- The testing of Scion (Crown-owned research institute) bioadhesive-based engineered timber products in CNC fabrication.
- Exploration and quantitative testing of modulated and reusable cladding infrastructures.
- Evaluations that prove/disprove X-Frame as an efficient/not efficient solution through detailed life cycle analysis (LCA).
- Investigations into the viability of unprocessed compostable materials being used in mainstream construction in an effort to eliminate waste.
- The investigation of the use of non-engineered timber materials in reusable systems.

The author acknowledges that there may be alternative construction methods that are more flexible, and economically more attractive to reuse, that have yet to be identified.

7.0

Final Remarks

This research set out to respond to the question: how can light timber framed architectural assemblies be redesigned to integrate a circular economic model?

While every other manufacturing industry has strived to ensure that their products can be recycled and reused, the building and construction sector has remained largely ambivalent. Today chemical modification and the irreversible adhesive-based fixing of materials remains prolific. With no clear leader in the industry to curb such practices, this thesis identifies it as the architect's responsibility to design and deploy less wasteful *architectural assemblies.* Leading by example, *Defab.* sets out to demonstrate that new types of experimental assemblies can be formed that strategically select, separate and modulate specified materials. The effective result of these new assemblies is an architecture that fully integrates into a circular economic model. Within this circular model, waste is pre-emptively eliminated by incorporating the capacity for reuse (or upcycling) at the time of design. This process ensures that no material is specified or integrated into the assembly in a way that prohibits reuse or upcycling of itself (or any adjacent material). To ensure that these 'reused' materials maintain value through multiple reuse cycles, this research has worked to identify a highly efficient structural frame module that can be utilised as a horizontal and/or vertical building element.

This research did not only set out to identify a method of construction suitable for a Circular Economy but also to identify

Figure 220.
Collated physical tests (A).

pathways to validate it as a viable and cost effective building solution. The full-scale fabrication and cost engineering of X-Frame is evidence of this pursuit. These practical assessments of performance argue that the cyclic performance of X-Frame makes it a superior value proposition versus conventional light timber framing. Ultimately X-Frame represents a 94% reduction in the quantity of waste produced by a building at the end of its life, and eliminates the potential production of compromised materials (see 6.1.3). Although the design outcome is largely successful, there is extensive potential for further research in the field of designing for reuse and a Circular Economy. Simplification of the modulated structure, more efficient manufacturing and the exploration of alternative materials are all required to ensure the successful adoption of Circular Economy building practices by the construction industry.

Figure 221.
X-Frame segment at Prefab New Zealand's CoLab conference, March 2018 (A).

8.0
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8.1

List of Figures

Examination Note:
(a) notates author's image assessed at 75% submission.
(A) notates author's image not previously assessed.

9.0

Appendix

9.1 SYSTEM COSTS

9.1.1 Estimating Material Costs

A wall section 10m long and 2.4m high was proposed. Final cost figures have then been adjusted to represent the average cost of a single square meter of wall. Standardised claddings and internal linings have also been applied to produce an all inclusive figure. The full scale fabrication of the final proposal aided in providing large amounts of accurate cost data that had a valuable contribution to the study's findings. As a consequence cost performance analysis of the final X-Frame iteration was used to re-estimate cost performance measures of earlier iterations and alternative CNC fabricated proposals.

Note: Because some construction systems have inherent bracing/insulation/waterproofing/cladding capacity the costing is for a wall product with the following specifications (unless stated):

- Unfinished internal aesthetic lining (typically 10mm unpainted/unstopped plasterboard*).
- Minimum insulation values of R 2.2 (some exceed this due to construction type).

- Lateral load resistance compliant with NZS-3604 (including hold-down hardware).
- Waterproofing to meet external moisture (E2) NZBC regulations.
- Visually finished external cladding (as part of meeting NZBC E2 regulations).
- Labour (unless stated).

Ensuring all systems have a minimum of these specifications enables a fair comparative study.

Note: Some proposed reusable linings/claddings have not been specified here to represent worst case scenario and enable a fair cost comparison between the modulated structures.

Table Appendix 1: Costing Data

Appendix: Table 1
Raw data used to calculate the cost of construction systems proposed in this thesis (A). See end of table for references.

Note: Reuse potential extent ratio marked on right-hand side. See 9.1.2 for details.

System	Material	Unit	Rate	
Insulated Concrete Forms (ICF)	200 Series Polyblocks supplied	m^2	$67.50	
	200 Series Polyblocks Laid. Baised on 1.1h/ m^2 for flat walls and 1.27h/ m^2 for general houses.	m^2	$64.90	
	100mm thick concrete filling with Vertical and Horizontal D10 @ 300mm CRS reinforcing.	m^2	$52.25	
	Three coat modified & coloured acrylic plaster to the exterior wall	m^2	$130.00	
	9.5mm Standard gib board glued to the interior wall	m^2	$7.75	
	Fix Gib board	m^2	$9.00	
Light Timber Framing (NZ Industry Conventional) (LTF)	100 x 50 H3 kiln dried wall framing	m	16.00	– Y 30%
	100mm DPC	m	$1.70	
	Bottom plate fixing anchors @ 900 centres	no	$1.85	
	Three coat modified & coloured acrylic plaster to the exterior wall	m^2	$110.00	
	Heavy duty building paper including strapping	m^2	$9.00	
	R1.8 Wall insulation (Pink Batts)	m^2	$16.95	– Y 20%
	9.5mm Standard gib board glued to the interior wall	m^2	$7.75	
	Fix Gib board	m^2	$9.00	

Concrete Block	200 Series Concrete blocks supplied	m²	$82.00	
	Two coat plaster to the exterior wall	m²	$47.00	
	100 x 50 Strapping	m²	$64.00	
	100mm DPC	m	$1.70	
	Ramsets	no	$1.85	
	50mm Polystyrene Insulation	m²	$14.35	
	9.5mm Standard gib board glued to the interior wall	m²	$7.75	
	Fix Gib board	m²	$9.00	
Tilt Slab	150 thick reinforced tilt panel including all labour & cranage	m²	$295.00	- Y 20%
	Three coat modified & coloured acrylic plaster to the exterior wall	m²	$110.00	
	100 x 50 Strapping	m²	$64.00	
	100mm DPC	m	$1.70	
	Ramsets	no	$1.85	
	50mm Polystyrene Insulation	m²	$14.35	
	9.5mm Standard gib board glued to the interior wall	m²	$7.75	
	Fix Gib board	m²	$9.00	
Click-Raft	2400*1200 12mm Untreated Structural Plywood	#	$69.99	- Y 80%
	CNC Machining of Plywood	mins	$1.67	
	100mm DPC	m	$1.70	
	Bottom plate fixing anchors @ 900 centres	no	$1.85	
	Three coat modified & coloured acrylic plaster to the exterior wall	m²	$110.00	
	Heavy duty building paper including strapping	m²	$9.00	
	R1.8 Wall insulation (Pink Batts)	m²	$16.95	- Y 20%
	9.5mm Standard gib board glued to the interior wall	m²	$7.75	
	Fix Gib board	m²	$9.00	
Angled Frame	2400*1200 17mm Untreated Structural Plywood	#	$79.00	- Y 95%
	CNC Machining of Plywood	mins	$1.67	
	Bottom plate anchors @ 900mm	#	$1.85	
	Three coat mofified & coloured acrylic plaster to exterior wall	m²	$110.00	
	Heavy duty building paper including strapping	m²	$9.00	

Angled Frame (continued)	R1.8 Wall Insulation (Pink Batts)	m²	$16.95	– Y 20%
	9.5mm Standard Gib Plasterboard glued and screwed to interior walls	m²	$7.75	
	Fix Gib Board	m²	$9.00	
	100mm damp proof chrod (DPC)	m	$1.70	
WikiHouse	2400*1200 17mm Untreated Structural Plywood	#	$79.00	– Y 50%
	CNC Machining of Plywood	mins	$1.67	
	--	--	--	
	Bottom plate fixing anchors @ 900 centres	no	$1.85	
	Three coat modified & coloured acrylic plaster to the exterior wall	m²	$110.00	
	--	--	--	
	R1.8 Wall insulation (Pink Batts)	m²	$16.95	– Y 20%
	9.5mm Standard gib board glued to the interior wall	m²	$7.75	
	Fix Gib board	m²	$9.00	
Click-Lock	2400*1200 12mm Plywood	#	$69.99	– Y 90%
	CNC Machining of Plywood	mins	$1.67	
	100mm DPC	m	$1.70	
	Bottom plate anchors @ 900mm.	no	$1.85	
	Three coat modified & coloured acrylic plaster to the exterior wall	m²	$110.00	
	Heavy duty building paper including strapping	m²	$9.00	
	R1.8 Wall insulation (Pink Batts)	m²	$16.95	– Y 20%
	9.5mm Standard gib board	m²	$7.75	
	Fix Gib board	m²	$9.00	
Stressed Skin Cells	2400*1200 17mm Untreated Structural Plywood	#	$79.00	– Y 80%
	CNC Machining of Plywood	mins	$1.67	
	100mm DPC	m	$1.70	
	Bottom plate anchors @ 900mm ct.	no	$1.85	
	Three coat modified & coloured acrylic plaster to the exterior wall	m²	$110.00	
	Heavy duty building paper including strapping	m²	$9.00	
	R1.8 Wall insulation (Pink Batts)	m²	$16.95	– Y 20%
	9.5mm Standard gib board glued to the interior wall	m²	$7.75	
	Fix Gib board	m²	$9.00	

Appendix: Table 1 (continued)
Raw data used to calculate the cost of construction systems proposed in this thesis (A). See end of table for references.

Note: Reuse potential extent ratio marked on right-hand side. See 9.1.2 for details.

Unistrut	Unistrut P1000T 41mm (2.5mm St)	m	$7.50	- Y 90%
	Oriented Strand Board (OSB)	#	$72.00	- Y 90%
	100mm DPC	m	$1.70	
	Compressive Fixings for OSB Unistrut Frame with thermal break.	no	$1.85	- Y 90%
	Bottom plate fixing anchors @ 900.	no	$1.85	
	Three coat modified & coloured acrylic plaster to the exterior wall	m²	$110.00	
	Heavy duty building paper including strapping	m²	$9.00	
	R1.8 Wall insulation (Pink Batts)	m²	$16.95	- Y 20%
	9.5mm Standard gib board glue fix	m²	$7.75	
	Fix Gib board	m²	$9.00	
Bolty	Extruded Light Steel U Section with Intg. Fixing Cap (600 cntrs).	m	$9.00	- Y 90%
	Oriented Strand Board (OSB)	#	$72.00	- Y 90%
	100mm DPC	m	$1.70	
	100 x 50 H3 kiln dried wall framing	m	$4.50	- Y 90%
	Compressive Fixings for OSB onto Unistrut Frame with thermal break.	no	$1.85	- Y 90%
	Bottom plate fixing anchors @ 900	no	$1.85	
	Three coat modified & coloured acrylic plaster to the exterior wall	m²	$110.00	
	Building paper with strapping.	m²	$9.00	- Y 20%
	R1.8 Wall insulation (Pink Batts)	m²	$16.95	
	9.5mm Standard gib board glue fix	m²	$7.75	
	Fix Gib board	m²	$9.00	
Straw Frame	2400*1200 17mm Untreated Structural Plywood	#	$79.00	- Y 85%
	CNC Machining of Plywood	mins	$1.67	
	Steel Bracking Components for Cell System	no	$56.71	- Y 90%
	Bottom plate fixing anchors @ 900 centres	no	$1.85	
	Large Pea Straw Bales	no	$40.00	
	2 Layer Lime Plaster to the exterior and interior walls	m²	$130.00	
	9.5mm Standard gib board glue fix	m²	$7.75	
	Fix Gib board	m²	$9.00	
	300mm DPC	m	$3.50	
	Steel bracing straps to achieve laterial load resistance.	m²	$12.00	

Pattern Frame	2400*1200 17mm Untreated Structural Plywood	#	79.00	- Y 95%
	CNC Machining of Plywood	mins	1.67	
	100mm DPC	m	$1.70	
	Bottom plate anchors @ 900mm ct	no	$1.85	
	Three coat modified & coloured acrylic plaster to the exterior wall	m²	110.00	
	Building paper including strapping	m²	$9.00	
	R1.8 Wall insulation (Pink Batts)	m²	$16.95	- Y 20%
	9.5mm Standard gib board glue fix	m²	$7.75	
	Fix Gib board	m²	$9.00	
Recirpical Frame	2400*1200 17mm Untreated Structural Plywood	#	79.00	- Y 90%
	CNC Machining of Plywood	mins	1.67	
	100mm DPC	m	$1.70	
	Bottom plate anchors @ 900mm ct	no	$1.85	
	Three coat modified & coloured acrylic plaster to the exterior wall	m²	110.00	
	Building paper including strapping	m²	$9.00	
	R1.8 Wall insulation (Pink Batts)	m²	$16.95	- Y 20%
	9.5mm Standard gib board	m²	$7.75	
	Fix Gib board	m²	$9.00	
Linear Frame	2400*1200 17mm Untreated Structural Plywood	#	79.00	- Y 90%
	CNC Machining of Plywood	mins	1.67	
	100mm DPC	m	$1.70	
	Bottom plate anchors @ 900mm ct.	no	$1.85	
	Three coat modified & coloured acrylic plaster to the exterior wall	m²	110.00	
	Heavy duty building paper including strapping	m²	$9.00	
	R1.8 Wall insulation (Pink Batts)	m²	$16.95	- Y 20%
	9.5mm standard gib board	m²	$7.75	
	Fix Gib board	m²	$9.00	

Appendix: Table 1 (continued)
Raw data used to calculate the cost of construction systems proposed in this thesis (A). See end of table for references.

Note: Reuse potential extent ratio marked on right-hand side. See 9.1.2 for details.

Citations:
Rawlinsons. *Rawlinsons New Zealand Construction Handbook 2011.* Rawlinsons Media Limited. p. 532, 491, 473, 547.
SuperFormNZ. *Cost Comparisons (ex Chch) as of April 2015.* SuperForm Building Systems New Zealand Limited. Availible from: superform.co.nz/frontend/technical.cfm?page=costcomparison. Accessed: 18.06.17.

9.1.2 Estimating Material Reuse Value

Opportunity values have been calculated based on the value of materials that can be salvaged completely undamaged from the original assembly. Any materials that can still perform their intended role that are non-visual but have been marked from the assembly and disassembly process are considered to have retained full reuse value. In most cases not all the materials originally used on construction will be reusable. To reflect this the percentage value indicated beside each material in Appendix Table 1 represents the percentage of usable materials i.e. 90% indicates that all but 10% of the originally specified materials can be reused. This material salvage value is deducted from the original cost to give a net figure for the effective cost of the product across two reuse cycles in ideal circumstances. The rates of possible reuse have been based on discussions with demolition contractors, industry reports and tests carried out within this research.

System:	Total cost/m² ($)	Recovered material value/m² ($)	Net Cost:
Conventional (LTF)	$165.98	$8.30	$157.69
TiltSlab	$355.01	$35.09	$319.92
Unistrut	$203.80	$51.93	$151.87
Bolty	$213.39	$52.20	$161.19
Straw Frame	$214.51	$61.00	$153.52
Pattern Frame	$248.73	$97.31	$151.42
Reciprocal Frame	$222.40	$68.67	$153.73
Linear Frame	$209.23	$56.82	$152.41
Click-Raft	$190.81	$36.16	$154.65
Angled Frame	$202.65	$53.53	$149.12
WikiHouse	$228.84	$47.94	$180.90
Click-Lock	$208.31	$55.99	$152.32
Stressed Skin Cells	$196.07	$40.37	$155.70
Concrete Block	$-	$-	$243.96
ICF	$-	$-	$265.84

Appendix: Table 2
Calculated recovered material value per square meter for a range of construction systems (A).

9.1.3 Estimating Deconstruction Costs

The estimated deconstruction cost is based on industry research that suggests strategic disassembly costs up to twice as much as demolition (Dantata, p. 13-14, 2005). This knowledge was coupled with quotes from undisclosed industry deconstruction contractors. These quotes were then translated into comparative figures by estimating the surface area of walls for a building with the quoted footprint. This was then translated into a area rate and time (in minutes) for a single unit of wall surface area. Unit time and cost formed the foundation of the quantifiable comparison. Once the base rate for conventional housing was established the 1:1 scale model tests were recorded (in duration) and multiplied out to match the given unit area of wall. As a LTF ('conventional') wall system was also deconstructed by the author the accuracy of the cost and time estimate from industry was cross examined. Industry estimates indicated 44 minutes per m^2 of LTF wall compared with 38 minutes from the authors test. This margin (14%~) is likely associated with the increased time taken to separate materials at junctions (wall/floor, wall/wall, wall/roof) and separate services in real world situations. All author tests have been increased by this differential (14%) to achieve an accurate representation as possible.

System:	m^2 of Wall Deconstructed/Hour	Deconstruction Rate/m^2 ($)
Conventional	1.37	$17.50
TiltSlab	1.78	$13.76
Unistrut	2.13	$11.29
Bolty	2.08	$11.51
Straw Frame	2.88	$8.33
Pattern Frame	2.26	$10.61
Reciprocal Frame	2.3	$10.42
Linear Frame	2.06	$11.67
Click-Raft	2.47	$9.72
Angled Frame	2.19	$10.94
WikiHouse	1.92	$12.50
Click-Lock	2.06	$11.67
Stressed Skin Cells	2.54	$9.46

Appendix: Table 3
Calculated cost to deconstruct (per square) meter for a range of construction systems. Rate based on labour costs of $24.00 (A).

Note: Labour rates based on unskilled construction labour of $24.00 per hour as per the Rawlinsons 2011 Construction Handbook and adjusted for inflation. Also note that further research studies are needed to quantify the time it takes to deconstruct various types of buildings. The lack of information in this area means that these costs should be considered largely comparative rather than reflective of real world costs. Regardless of this the consistent testing methodology meant that the ranking output was useful to determine key limitations of specific construction systems.

9.2 X-FRAME 7 ANALYSIS

	Conventional	**X-Frame 7**
Pay per hour (NZ$ - unskilled).	$24.00	$24.00
Structure Assembly Time Tests:		
Actual Measures: Wall Area	1	48.6
Actual Measures: Time (H)	0.722	15.493
Time/Wall m²	0.722	0.319
Cost/Wall m²	$17.33	$7.65
Notes (if any).	Services & Linings. One person. Materials restored.	No linings. No services. One person. Corner detail.
Cladding/Linings Time Tests:		
Actual Measures: Wall Area	N/A	4.86
Actual Measures: Time (H)	N/A	0.418
Time Per Wall Sq. M	N/A	0.086
Cost Per Wall Sq. M	N/A	$4.13
Notes (if any).	Linings and Claddings included in structure disassembly time.	X-Frame Plywood Cladding both sides - as per fig. 188. 1 Person.
Combined Estimated Deconstruction Time:		
Collective Total: (frame & linings per m²).	$17.33	$11.78
Cost Advantage: (% cheaper)	-	32%

Appendix: Table 4
Estimating the cost to deconstruct X-Frame 7 using knowledge from X7 (A).

System:	**Cost/m²**	**Notes:**
Conventional (90 x 45)	$94.00	Fibre-cement RAB. R2.2 insulation. No services. No labour hours. Raw materials only. Structural fixings.
Conventional (150 x 50)	$110.00	Fibre-cement RAB. R2.2 insulation. No services. No labour hours. Raw materials only. Structural fixings.
X-Frame 7 (220 x 17)	$115.00	Fibre-cement RAB. R2.2 insulation. No services. No labour hours. CNC fabrication*1. With fixings.

Appendix: Table 5
Material cost (per square meter) of X-Frame 7 (A).

Material sost ($)/sheet	$63.47	CNC cost/m²	$39.19
CNC cost ($)/hour	$65.22	Material cost/m²	$48.82
Sheets cut/hour	1.28	Fixings cost/m²	$3.13
Frame area/heet (m²)	1.3	Total structure cost/m²	$91.15

Appendix: Table 6
X-Frame 7 cost breakdown (GST exclusive) (A).

n.b. X-Frame costing in Appendix Table 5 includes RAB and insulation.

Material Waste Category	Conventional	X-Frame 7
Plasterboard (kg)	1040	0
Wood Based Products*1 (kg)	780	1720.43
Concrete and Masonry (kg)	490	0
Packaging (kg)	165	165
Metals (kg)	100	0
Insulation (kg)	25	0
Hazardous (kg)	20	0
Other (kg)	620	620
Total (kg):	**3240**	**2505.43**
% Waste Reductions:	-	23%
Total (with management systems*2) (kg):	**3240**	**785**
% Waste Reductions:	-	76%

Appendix: Table 7
Weight of waste by material during construction of a 180m² dwelling – X-Frame 7 vs. conventional platform framing (A).

*1 Wood based waste includes off-cuts, and in the case of X-Frame, CNC fabrication waste.

*2 Note that the untreated wood waste of X-Frame has not been included in the final waste count as the untreated plywood material is managed in assoiated X-Frame systems i.e. Lime-chip insulation.

Conventional waste from an 'average' 180sqm new residential dwelling as per itm.co.nz/pdf/ (accessed 09.09.17).

X-Frame 7: X-Frame Plywood Cladding both sides - as per fig. 188.

Note: Weight = 9.3kg per m² of 17mm plywood (timberwood.com.au)

Average waste area/sheet (m²)	0.288
Waste area/metre of frame area (m²)	0.21
Weight of waste/m² of frame (kg)	1.96
Area of frame in 180sqm building (m²)	880
Total Waste (kg)	1,720
Number of material sheets required	677
Weight of effective plywood per sheet	26.5
Weight of materials in system (kg)	17,935

Appendix: Table 8
Weight of waste and structural material for the X-Frame 7 system (A).

Material Waste Category	Conventional	X-Frame 7
Plasterboard (kg)	4578	0
Timber Cladding (kg)	1818	0
Framing Timber (kg)	10368	0
Timber Pile (kg)	337	0
Metals (kg)	28	0
Insulation (kg)	119	0

Appendix: Table 9
Waste produced at end-of-life of a given building system for a 180m² dwelling (A).

Material Waste Category	Conventional	X-Frame 7
PVC (kg)	81.7	81.7
Steel Roofing (kg)	10350	10350
Total (kg)	27679.7	10431.7
Total (with management systems*1) (kg)	17329.7	530
Damage Estimates*2 (kg)	Unknown	448

*1 – Waste managment systems as per appendix table 8.

*2 – Damage estimates for X-Frame are based on real world cyclic performance identified at 97.5%. Conventional retention rates remain unknown.

Conventional: Material weights from 'case study house' project. Calculated based on worst case waste management i.e demolition. Source: Aya Peri Bader. (2015). *A model for everyday experience of the built environment: the embodied perception of architecture*. The Journal of Architecture, 20:2, 244-267.

X-Frame 7: Weights from X7 prototype. No plasterboard used. Reusable X-Cladding used. X-Frame replaces timber. Screw piles specified. No single use metals. Lime-chip insulation block.

Appendix: Table 9 (continued)
Waste produced at end-of-life of a given building system for a 180m² dwelling (A).

	Conventional	X-Frame 7
Total Waste (kg)	20,570	1,315
% Waste Reductions:	-	94%
Waste per 100 m²	11,428	731

Appendix: Table 10
Waste produced at time of construction and end-of-life for a given building system (180m² dwelling – or as indicated) (A).

	X-Frame 7 - Bolted	X-Frame 7 - Ply Pegs
Fixings per sqaure meter	8	8
Area of frame	880	880
Cost per fixing	$0.47	$2.28
Total Cost	$3,308.80	$16,051.20

Appendix: Table 11
Cost of bolt fixing vs. cost of plywood peg fixing for a 180m² dwelling (A).

Area of timber required/peg (m²)	0.005
Total CNC line cut length (mm)	887.00
CNC cut passes	2
CNC cut time (s) (@35mm/s)	50
Total cost of materials ($)	$0.17
Total cost (fabrication time) ($)	$2.11
Total	$2.28

Note: Plywood pin system designed to test the viability of a totally plywood system. Cost estimates suggest that this would be prohibitive.

Reduced CNC manufacturing costs through increased cutting speed, a single pass and optimised geometry could reduce peg costs.

Appendix: Table 12
Calculation of plywood peg fabrication cost (A).

Appendix: Table 13
Assembly and dissasebly time for bolt fixing vs pins/ peg fixing (A).

	X-Frame 7 - Bolted	X-Frame 7 - Ply Pegs
Assesembly time (s)	15	14
Disassembly time (s)	8	16
Net time (s)	23	30
Fixings per m²	8	8
Area of frame (m²)	880	880
Total Time (hrs)	**44.98**	**58.67**

9.3 MULTI-SYSTEM PERFROMANCE

Appendix: Table 14 (part 1)
Record of calculations supporting quantifiable comparison of various construction systems (A).

	Time Up *1 (minutes)	Time Down *2 (minutes)	Embodied Energy *3 MJ/kg
Straw Frame (Modulated)	41	24	1.4 – Straw
Straw Frame (Mod-ModCell)	36	17	1.4 – Straw
Straw Frame (Truss)	48	19	1.4 – Straw
X-Frame	18	16	15 – Plywood
Linear frame	22	19	15 – Plywood
Pattern Frame	31	14	15 – Plywood
Reciprocal Frame 1	34	24	15 – Plywood
Reciprocal Frame 2	35	28	15 – Plywood
1.5 Layer Space Frame	26	15	15 – Plywood
Conventional	20	47	2 – Timber
Unistrut	39	43	25 – Steel
Click-Raft	16	12	15 – Plywood
Click_Lock	18	15	15 – Plywood
Stressed Skin Cassettes	12	8	18 – Treated Ply
Modulated Steel	24	18	25 – Steel
Timber Brick	35	41	2 - Timber
Locked Frames	27	28	15 – Plywood
Modell	15	25	12 – GluLam
WikiHouse 1	35	50	15 – Plywood
Bolty	36	9	25 – Steel

1* Construction time in minutes (for 1m² of wall). Using authors models.
2* Deconstruction time in minutes (for 1m² of wall). Using authors models.
3* Embodied energy based on principal material measured in MJ per kg. Material listed in table. Source: Hammond, G & Jones, C. (2008). *Embodied energy and carbon in construction materials.* Proceedings of the Institution of Civil Engineers - Energy. p.g. 93.

	Material Life Durability *4 (years)	Handling Durability *5 (years)	System Accreditation *6 (score)
Straw Frame (Modulated)	53	12%	7
Straw Frame (Mod-ModCell)	53	14%	5
Straw Frame (Truss)	53	18%	8
X-Frame	69	2%	4
Linear frame	69	2%	5
Pattern Frame	69	9%	6
Reciprocal Frame 1	69	37%	10
Reciprocal Frame 2	69	65%	10
1.5 Layer Space Frame	69	0%	10
Conventional	69	76%	1
Unistrut	83	4%	7
Click-Raft	69	0%	4
Click_Lockw	69	31%	6
Stressed Skin Cassettes	69	60%	3
Modulated Steel	83	5%	2
Timber Brick	69	3%	8
Locked Frames	69	45%	7.5
Modell	53	18%	2
WikiHouse 1	69	34%	3
Bolty	83	0%	4.5

4* Material lifetime durability of principal material based on literature in years (more is better). Source: Peixoto, V & Delgado, J. (2013). *Durability of Building Materials and Components.* e-tool Global. Availible at: etoolglobal.com/wp-content/uploads/2015/10/BuildingComponentLifeExpectancy.pdf. Accessed 19.08.17.

5* Durability of principal material based on the number of pieces damaged during scale tests through cycles for 1m^2 of structure (number of pieces damaged/total number of pieces).

6*Accreditation based on similarity to existing built solutions. Rank - (Best) 1 to 20. (less is better). Subjective measure.

Appendix: Table 14 (part 2)
Record of calculations supporting quantifiable comparison of various construction systems (A).

	Modulation Count *7	Compromised Materials % *8	Waste Material (fabrication - kg) *9
Straw Frame (Modulated)	5	0%	3.6
Straw Frame (Mod-ModCell)	6	0%	2.7
Straw Frame (Truss)	10+	0%	5.4
X-Frame	3	0%	1.9
Linear frame	2	0%	2.5
Pattern Frame	5	0%	4.5

Reciprocal Frame 1	10+	0%	6.5
Reciprocal Frame 2	5	0%	4.3
1.5 Layer Space Frame	3	0%	4.6
Conventional	6	78%	3.7
Unistrut	10+	23%	2.3
Click-Raft	2	0%	1.8
Click_Lock	3	0%	2.9
Stressed Skin Cassettes	1 (or 10+)	18%	3.8
Modulated Steel	3	23%	4.3
Timber Brick	1	8%	3.1
Locked Frames	4	8%	unknown
Modell	5	12%	2.9
WikiHouse 1	10+	6%	4.3
Bolty	10+	23%	unknown

Appendix: Table 14 (part 3) Record of calculations supporting quantifiable comparison of various construction systems (A).

7* Number of principal individual components/modules present in system. Count - 1 to 10+ (less is better). Quantifiable. Per m² of structure.

8* Percentage of materials that are composite or have no direct reuse path. Per m² of structure. Percentage - 1 to 100. (less is better). Source: Moffit, B. (2013). Composite Materials in Building and Construction. Presented at: ACMA's Corrosion, Mining, Infrastructure & Architecture Conference, Denver, USA, 2013. Availible from: compositebuild.com/wp-content/uploads/2013/07/Composite-Materials-in-Building-and-Construction-Applications.pdf. Accessed: 19.08.17.

9* Waste material in fabrication based on authors scale and 1:1 tests. Weight (kg). Less is better. Quantifiable. Per m² of structure.

9.4 MULTI-SYSTEM RANK

Performance Measure:	**Circular *1**	**Circular *2**	**Weighted Average %**
Xframe	44	11	88%
Straw Frame (Mod-ModCell)	49	11	86%
Click-Raft	54	8	71%
Linear frame	69	10	76%
Modulated Steel	71	4	48%
Stressed Skin Cassettes	75	4	47%
Locked Frames	79	8	64%
Click_Lock	79	8	64%
ModCell	81	5	50%
Timber Brick	85	9	67%
Pattern Frame	98	10	68%
1.5 Layer Space Frame	104	8	57%

Appendix: Table 15 (part 1) Record of calculations supporting quantifiable comparison of various construction systems (fig. 112, p. 88) (A).

Conventional	106	1	25%
Straw Frame (Modulated)	113	9	60%
Bolty	114	10	64%
WikiHouse 1	115	2	27%
Unistrut	117	9	58%
Reciprocal Frame 1	119	8	53%
Reciprocal Frame 2	128	8	51%
Straw Frame (Truss)	129	7	46%

1* Using data from appendix 9.3. Ranking each system in each category from 1 to 20 (number of systems tested). Sum total of rank represented here as raw data (lower is better).

2* Using Yes/No ranking criteria from p.61 & p. 86 (higher is better).

Weighted average used to locate system on the 'circular performance' axis on figure (fig. 112, p. 88).

Performance Measure:	**Rank *1**	**Rank *2**	**Rank *3**	**Average %**
Xframe	4	1	10	69%
Straw Frame (Mod-ModCell)	13	6	1	58%
Click-Raft	2	12	5	60%
Linear frame	7	4	13	50%
Stressed Skin Cassettes	3	13	4	58%
Click_Lock	6	5	14	48%
Pattern Frame	16	2	9	44%
1.5 Layer Space Frame	10	7	6	52%
Conventional	1	14	16	35%
Straw Frame (Modulated)	9	8	2	60%
Bolty	8	15	12	27%
WikiHouse 1	14	16	15	6%
Unistrut	5	3	11	60%
Reciprocal Frame 1	11	9	7	44%
Reciprocal Frame 2	12	10	7	40%
Straw Frame (Truss)	15	11	3	40%

1* Rank in 'Cost of Construction' (p. 78 - figure 104.)

2* Rank in 'Cost of Construction less resale value' (p. 80 - figure 105.)

3* Rank in 'Cost of Material Recovery' (p. 81 - figure 106.)

Weighted average used to locate system on the 'economic performance' axis (fig. 112, p. 88)..

Note: 4 systems removed due to unavailable cost analysis.

Appendix: Table 15 (part 2)
Record of calculations supporting quantifiable comparison of various construction systems (fig. 112, p. 88) (A).

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