NUTS & BOLTS

*An exploration of design for deconstruction and component re-use
in engineered timber construction*

+ GEORGE STRANG

NUTS & BOLTS

An exploration of design for deconstruction and component reuse in engineered timber construction

George Strang

A 120 point thesis submitted in partial fulfilment of the requirements for the degree of Master of Architecture [Professional].

*Victoria University of Wellington
School of Architecture
2021*

+ FRONT MATTER

This research is fuelled by the ever-increasing impact of global pollution and climate change, and the role the construction industry plays in it. Vast amounts of construction waste, needless manufacturing of single-use and composite products, and poor construction practices culminate in a linear economy model on which the world operates. It is a problem that can no longer be ignored and must be rectified. This research aims to develop and propose a construction system suitable for deconstruction and continued component reuse, using engineered timber products available in today's market. The system will be tested against several implementations across a variety of building scales. This research has the intention of enabling component reuse for a circular economy. A circular economy minimises waste produced. Less waste is good.

The resulting design proposal is a modular and prefabricated braced frame construction system to suit large and small scales, with removable foundations and adaptive spatial planning. Effective separation of building layers is achieved to allow for access, maintenance, and simple disassembly. Traditional Japanese timber joining techniques have also been researched and used to influence component connection design for deconstruction. This research eliminates irreversible fixings such as adhesives, nails, and screws. The system is then tested across commercial, residential, and small-scale implementations to test its feasibility.

It will serve as a case study that questions how we think of buildings and value their components. It aims to enable the same components to be useful across multiple building scales, minimising redundancy and waste.

+ACKNOWLEDGEMENTS

Where do I start?

Mum and Dad, I could not have done any of this if it were not for your inexhaustible love and support throughout these last five years (as well as the previous 17). Thank you, I am forever in your debt.

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The Neurosurgery team at Waikato hospital deserve a massive thank you for saving my life, however I doubt they read acknowledgements sections of architecture theses in their spare time. Rest assured I have said it in person.

Thanks also go out to my sisters, friends, classmates, pets, and many others for being yourselves and making life interesting. You too have contributed to the completion of this work.

To my Brain Tumour, Thanks for picking 2020 to come forward.

+ FRONT MATTER

+WORD COUNT

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+ FRONT MATTER

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+ INTRODUCTION

It should come as no surprise that the climate is changing. The planet is warming, oceans are full of plastic, air pollution is inescapable, and wildlife numbers dwindle. Non-renewable resources are quickly running out. To say that the architecture and construction industry do not play a significant role in this would be sheer ignorance. As of 2020, we are using the Earth's resources more than 50% faster than they can be replaced. This has increased by 26% in the last 10 years alone. Buildings are designed for linear lives, often ending in demolition and total waste. A lack of forethought and motivation from government, industry, and regulating bodies allows this to continue, partly due to the financial benefits of demolition and landfill. Once the significant need for a circular economy in construction is understood, how to achieve it can be explored.

How waste is minimised and managed is key. Luckily, waste management is very simple in principle. The priority is to reduce. Then reuse what you already have. Then comes recycling. These first three steps are the aim but unfortunately are not the reality. Using waste to produce energy, incinerating waste, and land-filling waste should be the absolute last resort. Unfortunately, these damaging methods are the most widely practiced throughout the modern world.

The concept of design for deconstruction and reuse is not a particularly new one. Traditional cultures built and designed for continual reuse and renewal using locally available materials. They did not waste because they did not have the luxury of waste. The importance of Design for Deconstruction is in its prioritisation of reuse compared to recycling. Recycling involves reprocessing and re-manufacturing recyclable products. This consumes time, money, and energy. Reusing something retains its value and integrity, saves energy, and eliminates waste by-products.

As a response, this research aims to investigate design for deconstruction and reuse through the design of a reusable construction system, made up of building components capable of use in varying building sizes and occupation types. In enabling reuse and minimising waste, we also minimise environmental damage. The thinking behind cross-scale utilisation is that adaptability and flexibility are vital to the success of a reusable system of building components. If a circular economy is to be established using durable materials and components, those components need to be suitable to a variety of shapes, sizes, and occupations.

This research assesses why it is necessary to be carried out, how the current industry operates, looks at suitable materials for use, and takes inspiration from traditional construction. The design investigation that follows seeks to address design for deconstruction and reuse, and some of the issues that surround it. Issues such as component assembly, the durability of components, transportation and storage, and variable implementations of a construction system.

+ RESEARCH QUESTION

“**HOW CAN AN ENGINEERED
TIMBER CONSTRUCTION
SYSTEM BE DESIGNED FOR
DECONSTRUCTION AND
BE REUSED OVER TIME AT
VARYING BUILDING SCALES?**

”

+ AIMS AND OBJECTIVES

Motivated by the alarming rates of climate change, construction waste, and needless consumption, the importance of material reuse through design for deconstruction has been realised. This research attempts to address how architecture for deconstruction and component reuse can be realised in New Zealand.

AIM

This research aims to propose a construction system that enables end of life deconstruction and component reuse across building scales and occupation types.

The aspiration of this research is for it to serve as a case study for sustainable and de-constructable design and construction in New Zealand. This research may serve as a starting point for further research, inform industry practitioners, or inspire students to research sustainable construction.

OBJECTIVES

- To research; Sustainable design and the circular economy, standard construction practices, engineered timber, and existing precedents.*
- To use engineered timber as a primary construction material, due to its more sustainable nature over traditional materials.*
- To research design for deconstruction key principles and use them to develop a set of success criteria to which this research can be compared.*
- To research and digitally model traditional Japanese joinery methods and use them to inform the construction system being designed as part of this research.*
- To use the knowledge gained from this research to develop a construction system that is fully assemblable and de-constructable.*
- To assess this system against the design for deconstruction success criteria developed in this research.*
- Refine the system based on assessment outcomes and against reflections based on research knowledge and expert appraisal (if possible).*
- To test this construction system against several implementations, of varying size, use, and occupation type.*
- Identify and discuss issues and shortcomings of the construction system and implementations, both inside and outside the scope of this research.*
- Use ongoing critical reflection and refinement throughout the development of the system and its implementations.*
- Create a viable example of design for deconstruction and component reuse based on the industry at present.*

**FIGURE 0.01 -
WHAT THIS RESEARCH IS**

THIS RESEARCH...

+SCOPE

WHAT THIS RESEARCH IS

This research is centred around the design and implementation of an engineered timber construction system, one that has been designed for deconstruction and component reuse over time. Traditional Japanese timber joinery has been implemented to influence joint and connection methods. This research deals in structure, design of building skin, and spatial planning for adaptivity and flexibility. The accommodation of services will be designed for, but services themselves will not be planned or designed in detail.

WHAT THIS RESEARCH IS NOT

This research is not without its limitations. While a primary focus has been on structural system design, this can only be taken so far. This is architectural research, not engineering research. As a result, the exact strength of components and the system cannot be determined. Best estimates and reasoning have instead been used from an architectural perspective. The design of 'stuff' or furniture is not within the scope of this research. People tend to furnish spaces with their own 'stuff', so the design of specific furnishings may counteract the idea of waste minimisation that is central to this research. This research is not site focussed either; rather it is regionally focussed on Wellington and the lower North Island. Part of Design for Deconstruction does involve transportation and storage for reuse. This can only briefly be speculated on in this research due to the time constraints in place. Design for transportation is seen as a separate area of research, and unfortunately cannot thoroughly be explored in this research. This research is interested primarily in engineered timber, due to its sustainable qualities and potential as a construction material of the future. Conventional materials such as steel and concrete are not relevant to this research.

CONCEPTUAL BY NATURE

It must be made clear that this research is conceptual, meaning that it will not be developed to a level that is ready for industry implementation. Understanding of component strength, treatment, and durability cannot be fully realised due to the time constraints of this research, which means that the system proposed in this research is unlikely to meet NZ building code or building act requirements.

This research is intended to be useful as a starting point for other researchers or practitioners, or the basis of other research on design for deconstruction.

SCOPING ISSUES

The scoping of this research has been a monumental challenge, due to the vast nature of sustainable design, and the infinite level of detail that can be delved into. The initial scope of this research started at what has been stated as 'multiple Ph.D.'s', after which I attempted to focus my scope on what was achievable. At the next review, it was deemed that I was still attempting too much, going too big, too zoomed out. Only then did I re-address the scope and refine the research into, what I think, is an appropriate level.

FIGURE 0.02 - SCOPING

Designed —
Facilitated ----

?

+ METHODOLOGY

METHODOLOGY EXPLAINED

The research methodology implemented is essentially NPD (New Product Development) in the context of Architectural research. It is implemented using the Double Diamond, following a five-step process of Discovery, Definition, Development, Delivery, and Evolution. It is still design research but does not adhere to 'research through design' or 'research for design'. The Double Diamond methodology follows more of a 'research then design' approach, research is intended to produce knowledge, design is work done to produce a solution for a problem. The design (work needing to be done to address a problem) is determined by the research, as research defines the problem (Design Council UK, 2015). In this case, research began with understanding climate change, construction waste, construction methods, and the circular economy model.

Cycles of exploration, reflection, and refinement are undertaken throughout each stage of the research, to ensure that problems are solved as they arise, and to ensure that the problem at hand is being solved. Linking research to design is done through the development of design principles, in this case DfD success criteria. The design is then explored and developed across stages 3 and 4 of the process. Stage 5 is an evolutionary stage, and in this case, is the design implementations of the construction system. Testing the construction system in several design scenarios is both an evolution and a reflection on the system and will be assessed as such.

Research is undertaken both through a literature review, precedent study and by modelling existing joinery techniques. Design is undertaken through both digital and analogue techniques, such as drawing, sketching, digitally modelling, and visualising. An overall pattern of divergence and convergence is formed.

This research opts for a micro to macro scale approach, starting small and resolving the system in detail, component by component, then testing it at the building scale. Consistent and regular critical reflection was undertaken to understand the shortcomings, weaknesses, and limitations of this research to strengthen it.

The logos associated with each stage of the research have been included throughout the text to help orient the reader.

+ SUMMARY OF TERMS

NZ	<i>New Zealand</i>
CAD	<i>Computer Aided Design</i>
CBD	<i>Central Business District</i>
NLA	<i>Net Lettable Area</i>
NFA	<i>Net Floor Area</i>
REBAR	<i>Steel Reinforcing Bar</i>
DFD	<i>Design for Deconstruction</i>
CED	<i>Circular Economy Design</i>
DFT	<i>Design for Transportation</i>
ENGINEERED TIMBER	<i>An Engineered Timber Product</i>
SIPS	<i>Structural Insulated Panel</i>
GLULAM	<i>Glue Laminated Timber</i>
LVL	<i>Laminated Veneer Lumber</i>
CLT	<i>Cross Laminated Timber</i>
PREFAB	<i>Prefabrication</i>
MODULAR	<i>Modular construction</i>
CO₂	<i>Carbon Dioxide</i>
KG	<i>Kilogram</i>
M	<i>Metre</i>
CM	<i>Centimetre</i>
MM	<i>Millimetre</i>

CHAPTER

LITERATURE AND PRECEDENT REVIEW

CHAPTER 1 STATEMENT

This chapter contains 9 subsections correlating to different areas of research that were undertaken. Underlying research motivations, construction methods, materials research, traditional joining, and precedents all lie within.

1.1 - SUBSECTIONS

CLIMATE CHANGE
CONSTRUCTION WASTE
RESOURCE SCARCITY
POOR BUILDING STANDARDS

“
**THE CONSTRUCTION
INDUSTRY CONSUMES 40%
OF GLOBAL RESOURCES
AND GENERATES ONE
OF THE LARGEST WASTE
STREAMS ON THE PLANET.**

(Cruz Rios et al., 2019)

”

FIGURE 1.01 - THE PLANET EARTH

Area: 510.1 Million km²

Population (human): 7.594 Billion (2018)

Age: 4.5 Billion years

Human ecological footprint (av): 1.75 Earths

0 1,000 2,000 4,000km

+ 1.1 RESEARCH MOTIVATIONS

GLOBAL CLIMATE CHANGE

Our planet is changing. It is doing so at a rate so fast that human activity cannot be denied as the cause. Carbon Dioxide levels are their highest in 650,000 years, Arctic sea ice has shrunk to its lowest extents on record, and seas have risen almost 180mm in the past 100 years. 19 of the 20 warmest years on record have occurred since 2001 (Jackson, n.d.).

The cause of these colossal changes is the rapid advancement of humanity since the industrial revolution. Populations have risen, cities have grown, and the natural environment has been decimated. As a result, humanity is now facing a near-future, self-inflicted extinction.

Unless massive changes are undertaken now, temperatures will continue to rise, water scarcity will increase, sea levels will rise, and life on earth will diminish.

CLIMATE CHANGE IN NZ

Understanding where the climate of our country - and our planet - is headed, is key to designing buildings that will serve a purpose both now and in the future. Climate change as a direct result of human activity is irrefutable, ignorance of its existence is no longer an excuse for inaction.

TEMPERATURE

Temperature is a significant factor when considering the lives of many New Zealanders. Temperature plays a significant part in the success of many aspects of life, including crops, livestock, tourism, leisure, energy use, and human comfort and health. Climate change and greenhouse gas emissions mean an increase in temperature, but they also mean greater uncertainty for temperature fluctuations. The "mid-range estimate for projected New Zealand temperature change is for an expected increase of about 0.8°C by 2040, 1.4 °C by 2090, and 1.6°C by 2110". While these predictions are relatively conservative, the possible ranges of increase are not. The worst-case scenario projections show up to 1.7°C by 2040, 4.6°C by 2090, and 5.0°C by 2110 (Mullan et al., 2018, p.13). The worst-case scenario projections would impact industries and businesses in a significant way as soon as 2040. Certain crops would no longer be suitable to hotter regions. Land may no longer be sustainable to irrigate. Ski seasons to air conditioning costs will all be affected by our inevitably changing climate.

RAINFALL

Rainfall projections show a greater variability across the seasons and regions. Winter and spring will show increased levels of rainfall on the west of both islands, while the east and north of the country will experience decreased rainfall. Summer seasons are predicted to be wetter for the east coast of both islands, and drier in the west and central North Island. Extreme rainfall events are predicted to increase in most areas, which could cause an increase in flooding and subsequent damages (Mullan et al., 2018, p.13-16).

FIGURE 1.02 - NEW ZEALAND AND CLIMATE CHANGE

TEMPERATURE INCREASE - 0.8°C by 2040, 1.4 °C by 2090, and 1.6°C by 2110.
DROUGHTS - Drought severity is projected to increase in most areas of the country.
RAINFALL - Extreme rainfall events are predicted to increase in most areas, which could cause an increase in flooding and subsequent damages (NIWA, 2018. p.13-16).
STORMS - It is predicted that maximum wind speeds and rainfall will experience an increase.
SEA LEVEL RISE - The current worst-case scenario for national sea level rise is 1.4m by 2100, with the extreme scenario being a 2.0m sea level rise.

+ 1.1 RESEARCH MOTIVATIONS

SEA LEVELS

A 2015 report by researchers for NIWA identified at-risk buildings, populations, and infrastructure based on sea-level rise predictions (Bell et al., 2015). The current worst-case scenario for national sea-level rise is 1.4m by 2100, with the extreme scenario being a 2.0m sea-level rise. Under the worst-case scenario predictions 68,170 buildings would be affected as would a residential population of 133,265 people nationally. 382 'critical-facility buildings' would be impacted, as would 5 airports. Over 2,000km of roads would be damaged. Whilst these predictions are for a worst-case scenario, they point to a definitively changing environment in New Zealand. Planning and risk mitigation needs to take place immediately, as the impacts from sea level rise will become reality within the next century (Bell et al., 2015, P.11-15).

CONCLUSION

Climate change predictions for New Zealand over the coming century paint a potentially dire picture for New Zealand. Temperatures will rise, Rainfall patterns will change, droughts will become more severe, storms will become less predictable and cause more damage, and sea levels will rise. New Zealand is facing an uncertain future with extreme climatic events a likelihood. Climate refugees will also become a reality, both nationally and globally. Planning and preparation are key for the continued health and well-being of the New Zealand people and economy. Architecture is no exception, and the sooner uptake on climatic design begins, the better of a position our built environment will be in.

“
**THE CONSTRUCTION
 INDUSTRY IS
 RESPONSIBLE FOR UP
 TO 50% OF ALL WASTE
 PRODUCED IN NEW
 ZEALAND.**
 ”

REBRI, 2014

CONSTRUCTION WASTE

The construction industry, at present, is not operating sustainably. Buildings are designed and constructed using a linear model from cradle to grave, using man-made and composite materials from non-renewable sources and with high embodied energy levels. Understanding how large of an impact the construction industry has is key in reducing it.

Construction waste in New Zealand is “often quoted as 17% of total landfilled waste”, however, this figure does not include “C&D waste taken to privately-owned clean fill dumps or illegal dumping of C&D waste” (Storey et al., 2005, p.7). It is recognised that clean fills receive most of the waste produced in the construction and demolition industry, highlighting the inaccuracy of the quoted figure. Clean fill dumping rates are significantly less than municipal landfill rates, contributing to this inaccuracy. REBRI (2014, n.p.), states that “the construction industry is responsible for up to 50% of all waste produced in New Zealand”, however, this is not something that can be approximated, as there are no accurate figures related to construction and demolition waste. A huge part of the problem is that nobody knows just how big the problem is, and in all likelihood, they don’t want to.

There is an opportunity in New Zealand to reduce our waste stream by up to 50% through the proper design, construction, and deconstruction of buildings. At present, 85% of demolition waste is made up of engineered materials such as plasterboard, timber framing, and plaster cladding (Curtis, p.6, 2015). Designing buildings to easily be taken apart and reused would have an immense impact in reducing New Zealand’s annual waste. It is staggering that there is little to no interest in this, let alone a government initiative for waste reduction.

“
**HUMANKIND IS
CURRENTLY USING
RESOURCES 50% FASTER
THAN THEY CAN BE
REPLACED. RESOURCE
CONSUMPTION HAS
GROWN BY 26% IN THE
LAST DECADE ALONE.**

(Cruz Rios et al., 2019), (McGlyn, 2015),
(Ellen Macarthur Foundation, 2013)

”

RESOURCE SCARCITY

The issue of resource scarcity is another that the construction industry has a significant role in. At present, humankind is using resources 50% faster than they can be replaced. Global supplies of non-renewable resources will continue to dwindle at an ever-increasing rate. By 2030, it is said that half of the world could face water scarcity (Cruz Rios, F., et al., 2019, p.120) (McGlyn, 2015). Water is a key resource in the mining and manufacturing of materials such as steel, concrete, plastics, and timber.

It would be bad enough if the world continued to operate and consume at the rate it does today, but sadly resource consumption is said to have grown 26% between 2010 and 2020, alluding to an ever-increasing rate of resource consumption (Ellen Macarthur Foundation, 2013). The global population is expected to grow to 9 billion by 2050, with another 3 billion people expected to join the middle class (Ellen Macarthur Foundation, 2013). This will put more strain on the earth than ever before experienced, with the construction industry playing a significant role in this. Currently, the construction industry consumes 40% of global resources (Pacheco - torgal, 2014, p.730) And generates one of the planet's largest waste streams (Zhao et al., 2010, p.377). The construction industry is one of the biggest users of global materials, and one of the biggest waste producers. The planet cannot continue to support the mass consumption and waste of single-use and composite materials, which are being used in buildings that are not designed to be taken apart or reused.

The absolute necessity of change in the construction industry becomes irrevocably clear once the magnitude of its global impact is understood. This research aims to contribute to this change through the implementation of Design for Deconstruction and material reuse.

FIGURE 1.04 - POOR BUILDING STANDARDS

+ 1.1 RESEARCH MOTIVATIONS

POOR BUILDING STANDARDS

Unfortunately, one does not need to look far to see problems within the New Zealand building and construction industry. From small scale to large, residential to commercial, and old to new, all have massive fundamental issues.

Most relevant to this research are the low building standards the industry is held to and has historically held itself to. Our homes are leaky, cold, mouldy, and damp (Hill, 2020), not to mention extremely expensive. The health effects of our housing stock are immeasurable, and uptake to solve these problems is extremely slow, in part due to extremely low minimum building standards (Le Page, 2019).

Wellington, not unlike the rest of New Zealand, is full of decrepit and abandoned properties that are not safe or fit for human occupation. An example of this is in the Gordon Wilson and McLean flats, which have been unoccupied since 2012 and are a constant threat to public safety due to their total structural ineptitude. Despite this they have recently been given category 1 heritage status (Wiltshire, 2021), leaving the site's future uncertain.

Similarly, Wellington City Library has also recently been saved from demolition, despite its seismic weaknesses and closure since 2019 (Davis, 2020).

In both cases, a large public outcry has led to the protection of these buildings, for their 'cultural' or 'historical' value. Discussion on the value of a building that does not effectively serve its purpose to house or shelter people could go on indefinitely, but the point remains that as a nation, we have extremely poor buildings at all scales.

FURTHER READING

House construction in New Zealand is a disaster – Tookey, John.
<https://thespinoff.co.nz/society/26-08-2017/house-construction-in-new-zealand-is-a-disaster-but-it-can-be-fixed/>

Push for drier, warmer homes – 'shock' at state of NZ housing – Hill, Ruth.
<https://www.rnz.co.nz/news/national/420461/push-for-drier-warmer-homes-shock-at-state-of-nz-housing>

Fixing the New Zealand Building Code – James le Page.
<https://www.consumer.org.nz/articles/fixing-the-new-zealand-building-code>

1.2 - SUBSECTIONS

HIERARCHY OF WASTE MANAGEMENT
CIRCULAR ECONOMY DESIGN

“
**THE ABSOLUTE NECESSITY
OF CHANGE IN THE
CONSTRUCTION INDUSTRY
BECOMES IRREVOCABLY
CLEAR ONCE THE
MAGNITUDE OF ITS GLOBAL
IMPACT IS UNDERSTOOD.**

(George Strang, 2020)

”

**FIGURE 1.05 - LASINKS LADDER /
WASTE HIERARCHY**

HIERARCHY OF WASTE MANAGEMENT

Understanding the hierarchy of waste management is key to circular economy design. Gerhardus Wilhelmus Adrianus Josephus ‘Ad’ Lansink is a Dutch scientist and politician who pioneered waste management and its relation to a circular economy. He organised waste management options preferentially, forming ‘Lansink’s Ladder’ in 1979. It is a simple concept, with disposal the last option and prevention the first (Watson, n.d. 2013). The best waste is that which we don’t produce. Only once every other option has been exhausted should we consider landfill.

FIGURE 1.06 - LINEAR AND CIRCULAR BUILDING LIFE CYCLES

+ 1.2 SUSTAINABLE DESIGN

CIRCULAR ECONOMY DESIGN

The concept of a circular economy is based around the notion of a closed-loop cycle of production and reuse. This, in theory, eliminates waste from a building's life cycle (Cruz Rios, F., 2018, p.i). This elimination of waste is at the core of circular economy design. Geissdoerfer (2017) defined circular economy design as "a regenerative system" achieved through "long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling" (Geissdoerfer et al. 2017, p.759). Understanding DfD is a significant part of circular economy design, as it actively eliminates waste through pre-planned material reuse. The importance of DfD lies in its prioritisation of reuse, compared to one of recycling. Retaining the value and integrity of a component by not reprocessing it is key to minimising waste.

1.3 - SUBSECTIONS

WHAT IS DFD?
EXISTING APPLICATIONS
CRITICAL SUCCESS FACTORS
MATERIAL CHOICE
DOWNSIDES TO DFD
STEWART BRAND'S SIX S'S
RESULTING SUCCESS CRITERIA

“

THE IMPORTANCE OF DFD LIES IN ITS PRIORITISATION OF REUSE, COMPARED TO ONE OF RECYCLING. RETAINING THE VALUE AND INTEGRITY OF A COMPONENT BY NOT REPROCESSING IT IS KEY TO MINIMISING WASTE.

(George Strang, 2020)

”

FIGURE 1.07 - DFD IN MANUFACTURING

+ 1.3 - DESIGN FOR DECONSTRUCTION

WHAT IS DFD?

DfD stands for Design for Deconstruction and represents a method of design that is implemented to facilitate the deconstruction of a building at the end of its useful life. DfD falls under the umbrella category of 'Sustainable Design', and its use facilitates many other facets of sustainable architecture and living. DfD adopts a cradle-to-cradle life cycle (Guy & Ciarimboli, 2005, p.1-4), a point of separation from the linear life cycle of a building that is widely applied today. A linear building cycle involves the design, construction, use, and eventual demolition of a building, resulting in immense amounts of construction waste. A cradle-to-cradle cycle supports a circular economy, one of continual material reuse and conservation. This in theory eliminates construction waste, which currently contributes immensely to overall global waste figures. Not only does DfD facilitate deconstruction, but it also facilitates adaptability that may result in the prevention of deconstruction (Guy & Ciarimboli, 2005, p.1-4).

EXISTING APPLICATIONS

DfD processes are already being implemented outside of the construction industry, most notably in manufacturing. Consumerism and excess have all but taken over society, waste creation being a primary by-product of this. European parliament issued Directive 2000/53/EC in the interest of producer responsibility, placing life cycle design in the hands of manufacturers. Car manufacturers, under this directive, are required to design for vehicle end of life, including component reuse and recycling. This benefits manufacturers and the environment, as there is a greater rate of material recovery and reuse, lesser waste being the result (Guy & Ciarimboli, 2005, p.1).

DFD has not yet become widely practiced in the Construction industry. DFD exists to reduce the consumption of new materials, reduce waste production, increase life span, and increase component reuse, benefiting clients and the environment alike (Guy & Ciarimboli, 2005, p.3). Implementation of DFD in contemporary construction would be of immense environmental benefit and aid in future-proofing the construction industry.

+ 1.3 - DESIGN FOR DECONSTRUCTION

**FIGURE 1.08 - DFD
SUCCESS FACTORS**

BUILDING MATERIALS RELATED FACTORS

- A. SPECIFY DURABLE MATERIALS**
- B. AVOID SECONDARY FINISHES**
- C. USE BOLTS/ NUTS JOINTS**
- D. AVOID TOXIC MATERIALS**
- E. AVOID COMPOSITE MATERIALS**
- F. MINIMISE BUILDING ELEMENTS**
- G. CONSIDER MATERIAL HANDLING**

HUMAN RELATED FACTORS

- A. ADEQUATE COMMUNICATION
AMONG TEAMS**
- B. PROVIDING THE RIGHT TOOLS**
- C. PROVIDING ADEQUATE TRAINING**

DESIGN FOR DECONSTRUCTION CRITICAL SUCCESS FACTORS

10 KEY PRINCIPLES

- 1. DOCUMENT MATERIALS AND METHODS FOR DECONSTRUCTION**
- 2. SELECT MATERIALS USING THE PRECAUTIONARY METHOD**
- 3. DESIGN CONNECTIONS THAT ARE ACCESSIBLE**
- 4. MINIMISE OR ELIMINATE CHEMICAL CONNECTIONS**
- 5. USE BOLTED, SCREWED, AND NAILED CONNECTIONS**
- 6. SEPARATE MECHANICAL, ELECTRICAL, AND PLUMBING (MEP) SYSTEMS**
- 7. DESIGN TO THE WORKER AND LABOR OF SEPARATION**
- 8. SIMPLICITY OF STRUCTURE AND FORM**
- 9. INTERCHANGEABILITY**
- 10. SAFE DECONSTRUCTION**

DESIGN RELATED FACTORS

- A. DESIGN FOR OFFSITE
CONSTRUCTION**
- B. USE MODULAR
CONSTRUCTION**
- C. USE OPEN BUILDING PLAN**
- D. USE LAYERING APPROACH**
- E. USE STANDARD STRUCTURAL
GRID**
- F. USE RETRACTABLE
FOUNDATIONS**

— Guy, B & Ciarimboli, N. (2005). *Design for Dissassembly in the built environment. The Hamer Center for Community Design, The Pennsylvania State University. USA.*

— Akinade, O., Oyedele, L., Ajayi, S., Bilal, M., Alaka, H., Owolabi, H., ... Kadiri, K. (2017). *Design for Deconstruction (DfD): Critical success factors for diverting end-of-life waste from landfills. Waste Management (New York, N.Y.), 60, 3–13. <https://doi.org/10.1016/j.wasman.2016.08.017>*

CRITICAL SUCCESS FACTORS

In conducting this research, two sets of critical success factors for DfD were uncovered. One is a set of 10 key principles developed by Bradley Guy and Nicolas Ciarimboli (2005, p.6). See Figure 1.08 for the full list.

Akinade (et al., 2017) developed a slightly more complex set of critical success factors, which can be divided into three main categories. The first category relates to material use. Materials should be durable, non-toxic, and non-composite. The second category relates to humans. The third and final category relates to design. Modular, off-site construction should be utilised wherever possible, as should an open building plan on a standard structural grid.

There are many commonalities between the sets of principles, together culminating in a cohesive and extensive set of design principles to apply to this research. The design investigations undertaken in this research will be assessed against a refined combination of these two sets of criteria to ensure research and DfD goals are being met.

MATERIAL CHOICE

There is a plethora of factors to consider around material choice. Embodied energy, material lifespan, susceptibilities, and cost to name a few. This research intends to design using engineered timber as the primary structural material, due to its low embodied energy, renewable nature, and abundance in New Zealand. The study of traditional construction precedents proves that timber, when properly designed with, can last indefinitely. Materials such as steel and concrete are non-renewable, highly processed, and energy-intensive. They may be more durable, but they are in no way more sustainable than timber.

DOWNSIDES TO DFD

Design for Deconstruction is a key component in Circular Economy design and the overarching principle of sustainable design. But it is not without its drawbacks. It can be a costly process, as it requires planning for the stage of a building's life that is not currently planned for. DfD places responsibility upon designers, contractors, and owners to consider and plan for something they will not be alive to see happen. This sits outside of most people's priorities in life. One of the most significant downsides to DfD is that it is largely untested. Despite being in existence for hundreds of years in traditional cultures, DfD has been lost in the modern world. A linear cycle of plan, build and forget dominates. As a result, its feasibility as a viable process is reduced. How would building consent work? How would you convince a contractor to take the risk? How many architects would bear the responsibility? How do you ensure that the deconstruction plans do not end up in the bin? The questions and doubts are never-ending, but that is not an excuse not to do something, especially with the increasing necessity of sustainable design.

**FIGURE 1.09 - STEWART BRAND'S
SIX S'S OF A BUILDING**

STEWART BRAND'S SIX S'S OF A BUILDING

As defined by Guy & Ciarimboli (2005, p.28), the categories listed as the six layers of a building are "meant to help describe buildings as shearing layers of change, that are in constant friction". These building layers change at varying rates. Faster changing layers like space plan are constrained by slow layers such as structure, which results in friction between the two layers (p.25). Understanding the six s's of a building can help designers and construction professionals understand that cycles of use, change, and wear exist, and can be planned for and mitigated. The result of utilising this knowledge is that buildings can be planned for change, minimal dysfunction and redundancy, cost control, and waste minimisation.

It is imperative that these building layers be appropriately separated for flexibility, adaptability, and ease of change or maintenance. See figure 1.09 for estimated layer life cycles, which allude to the importance of layers like structure and space plan for adaptability, skin and services for durability, and site for minimal impact by the built structure.

FURTHER READING

Design for Disassembly in the built environment.

Guy, B & Ciarimboli, N.

- p.39 **SITE**
- p.43 **SKIN**
- p.40 **STRUCTURE**
- p.46 **SERVICES**
- p.48 **SPACE PLAN**
- p.50 **STUFF**

**FIGURE 1.10 - DfD SUCCESS
CRITERIA**

- 1. DESIGN FOR COMPONENT REUSE**
- 2. DESIGN FOR OFFSITE AND MODULAR CONSTRUCTION**
- 3. DESIGN ACCESSIBLE AND NON-CHEMICAL CONNECTIONS**
- 4. SPECIFY DURABLE AND VALUABLE MATERIALS**
- 5. CONSIDER MATERIAL HANDLING**
- 6. USE A STANDARD STRUCTURAL GRID**
- 7. DESIGN FOR ADAPTABILITY**
- 8. MINIMISE BUILDING ELEMENTS, SIMPLIFY STRUCTURE AND FORM**
- 9. USE LAYERING APPROACH AND SEPARATE MEP SYSTEMS**
- 10. USE RETRACTABLE FOUNDATIONS**

+ 1.3 - DESIGN FOR DECONSTRUCTION

RESULTING SUCCESS CRITERIA

Having researched and understood existing DfD principles, a refined set of success criteria have been developed to design with and assess this research against. Some success criteria are broader than others but will be adhered to in the engineered timber context nonetheless.

This set of success criteria will serve as a 'checklist' of sorts throughout the research and will be heavily involved in the critical reflection process.

This set of success criteria was created, in part, due to the lack of cohesion between existing building rating systems and what is meant to be achieved in this research. The living building challenge is too high, and the green star system too broad. Circular economy construction needs its own rating system to gauge success.

+ 1.4 - STANDARD CONSTRUCTION

1.4 - SUBSECTIONS

**FOUNDATIONS
STRUCTURAL DESIGN
TALL TIMBER STRUCTURE
PARTITION WALLS
MEP AND SERVICES**

**FIGURE 1.11 - STANDARD
FOUNDATION SYSTEMS**

FOUNDATIONS

Foundations are vital when considering the stability, safety, and longevity of a building. They are “The most under-appreciated part of any building” (Marriage, 2020. p.118) and are considered a ‘sunk cost’ – meaning that once in place, there is no material recovery or return on investment. When it comes to the design and construction of tall buildings, pile foundations are the most relevant system to implement, commonly constructed from steel or concrete (Marriage, 2020. p.119).

FRICTION VS END BEARING

There are two options when considering foundation depth. One option is to build foundations that extend through soil and earth down to the bedrock, stably supporting building loads. These are called end-bearing piles and are dependent on geographical conditions. The other option is to construct piles down to a specific depth, compacting the ground beneath the pile and transferring loads through the soil. This system relies heavily on friction between pile and soil, as well as gravity forces. This system is known as friction piling and may be a viable option if soil quality is such that bedrock cannot practically be reached (Marriage, 2020. p.121).

**FIGURE 1.12 - STANDARD
FOUNDATION SYSTEMS**

MICRO-PILES

An alternative to installing one large pile is the use of multiple smaller piles known as micro-piles. These smaller piles provide “more friction, meaning that piles may not need to go down as deep”. They are then linked together using pile caps, commonly consisting of a thick reinforced concrete slab (Marriage, 2020. p.124).

HELICAL PILES

Helical piles, or screw piles, are a relatively new system in New Zealand despite being in existence since the early 19th century. They are typically constructed from hollow steel sections, with helices welded to the shaft. Helical piles are a ‘self-tapping’ mechanism and reduce soil displacement and ground disturbance when compared to more traditional methods. Shaft diameter ranges from 50mm to 600mm, and helix diameters can range from 150mm to 1200mm depending on strength requirements. The use of helical piles is fast, not invasive, durable, and retrievable. Their use is dependent on soil suitability and are currently made exclusively from steel. (BECA Ltd., 2015. p.2-7).

SUMMARY

In exploring prevalent practices in the construction industry certain facts become apparent. When it comes to foundations, concrete and steel dominate. Concrete is durable, relatively inexpensive, and easy to manipulate. Steel is strong and easy to install. But neither utilise sustainable materials or construction practices. They are put in the ground and left there. This presents an opportunity to design retrievable foundations constructed using sustainable materials.

**FIGURE 1.13 - STANDARD
STRUCTURAL DESIGN**

+ 1.4 - STANDARD CONSTRUCTION

STRUCTURAL DESIGN

Buildings, both large and small, often involve the use of concrete in New Zealand. At a residential scale, it is often used for in situ foundation slabs (Marriage, 2020, p.62). At commercial scale, concrete is often used for foundations, basements, columns, beams, floors, structural cores, even bracing.

What must be understood is the environmental impact of reinforced concrete, and how it fundamentally contributes to the construction industry's role in climate change. The production of cement is a terribly intensive process, producing one tonne of CO₂ per tonne of cement. This means that one cubic metre (m³) of concrete emits one tonne of CO₂ (Marriage, 2020, p.56-62). Then consider the amount of water and aggregate required to be mixed in to create concrete. This cubic metre of cement ends up weighing around 2500kg, meaning that 1500kg is made up of water and aggregate. Now consider that vast amounts of steel reinforcing still need to be tied into the equation. Virtually every building on a city street is made up of concrete and sits underneath virtually every house. As if to add insult to injury, this concrete is all single-use. It cannot easily be removed, disassembled, reused. Enormous amounts of time, money and energy must go into breaking up or cutting through concrete for it to be reused or recycled.

**FIGURE 1.14 - STANDARD
TIMBER CONSTRUCTION**

+ 1.4 - STANDARD CONSTRUCTION

TIMBER CONSTRUCTION

Lightweight timber-framed construction is the primary method of residential construction in New Zealand. Builders work and erect framing on-site, using irreversible fixings such as screws/nails, and bonded adhesives. This makes timber elements very difficult and laborious to re-use and causes significant damage to components, illustrated in figure 1.14. Even if these treated timber elements can be extracted for reuse, builders and tradespeople see no benefit to using them. Recycled timber is generally regarded by builders as being more difficult to use than new timber (Storey et al., 2005, p.34-36). This is a cyclic problem created by the past and present negligence and lack of foresight of construction professionals at all levels.

As a result, this research will look to implement non-structural wall systems to allow for bolted connections, enabling reversibility and reuse over traditional nailing methods.

**FIGURE 1.15 - STANDARD
PARTITION WALL DESIGN**

PARTITION WALLS

Typical partition wall systems (non-load-bearing) consist of either steel or dressed timber framing, with plasterboard sheets fixed to either side. The problem with these walls lies in the way in which they are fixed together. Irreversible fixings such as screws are most commonly used, which, by their nature, damage the material they go into. This damage results in the components they form becoming single-use materials, meaning that once installed, they cannot be removed and reused elsewhere (Storey et al., 2005, p.18). Figure 1.15 illustrates the typical removal and demolition of these partition walls in residential New Zealand. This is a major problem, as plasterboard, treated timber framing, and plaster claddings account for 85% of all demolition waste (Curtis, 2015, p.6). Considering that construction and demolition waste accounts for up to 50% of total waste produced in NZ (Storey et al., 2005, p.7), the scale of this problem becomes very clear. Designing non-structural walls that are adaptable, moveable, and reusable, is a crucial development the construction industry must undertake.

**FIGURE 1.16 - STANDARD
MEP SYSTEMS**

+ 1.4 - STANDARD CONSTRUCTION

MEP AND SERVICES

Every building needs services to function properly. Requirements vary greatly between residential, commercial, and industrial occupations, but the core problem of service design remains the same. The problem is that services (ducts, wiring, pipes) are attached in destructive and irreversible ways to other elements as illustrated in figure 1.16. Services must weave in, around, under, over, and through other building elements such as walls and structure. This also makes access and repair incredibly difficult, particularly when services are buried within walls (common in residential construction). Disentangling building services from one another, and from other building elements, is a monumental task for the tradespeople who must do it, but it does not need to be. How we design and integrate services into a building, at any scale or use, has a significant impact on the ease of repair, maintenance, and disassembly (Guy & Ciarimboli, 2005, p.46).

For detailed examples on how services typically work in commercial scale construction, see Marriage, (2020) pages 207-225.

1.5 - SUBSECTIONS

OVERVIEW

SAWMILLS AND PROCESSING PLANTS

REGIONAL PROCESSING AND

TIMBER WORKSHOPS

ENGINEERED TIMBER TYPES

QUALITY STATEMENT ON TIMBER

TIMBER AND FIRE SAFETY

TIMBER SPECIES SELECTION

“
**24.2 MILLION TONNES OF
CO2 WERE REMOVED BY
FORESTRY IN 2017 - A 30%
OFFSET OF OUR GROSS
ANNUAL EMISSIONS.**
”

(NZFOA & MPI, 2019, P.53)

FIGURE 1.17 - REGIONAL PLANTATION FOREST PRODUCTION IN NEW ZEALAND

1. Northland - 11%	6. Hawkes Bay - 6%	11. Tasman - 5%
2. Auckland - 0%	7. Manawatu-Whanganui - 12%	12. West Coast - 2%
3. Waikato - 11%	8. Taranaki - 11%	13. Canterbury - 6%
4. East Coast - 9%	9. Wellington - 9%	14. Otago - 6%
5. Gisborne - 2%	10. Marlborough - 5%	15. Southland - 6%

70% of NZ grown timber is produced in the North Island.
34% of that is in the central North Island.

061

+ 1.5 - ENGINEERED TIMBER

OVERVIEW

Forestry is one of New Zealand's five primary industries (NZFOA & MPI, 2019, p.1). As most native forests and publicly owned land cannot be harvested, most forestry takes place in privately owned forests. There are 1,725,476 Hectares of plantation forest in New Zealand, equivalent to almost 16 times the size of Auckland. Over 37 million cubic metres of timber were harvested in 2018, generating revenue of almost 7 billion dollars. Pinus Radiata is the most forested species of tree, making up 90% of trees in New Zealand forests. Douglas Fir accounts for a further 6%, the remainder being attributed to the forestry of native species (NZFOA & MPI, 2019, p.3-11).

New Zealand wood is predicted to be a 7 billion dollar export industry by 2022, largely due to interest from China. Over half of New Zealand's exports to China come from forestry, a relationship currently worth almost 3.5 billion dollars per year (NZFOA & MPI, 2019, p.6, 33). Forestry is vital to the New Zealand economy and is a dominant export, but it relies heavily on overseas interest and a flourishing Chinese economy.

+ CHAPTER 01

+ 1.5 - ENGINEERED TIMBER

+ CHAPTER 01

SAWMILLS AND PROCESSING PLANTS

Sawmills and timber processing plants tend to be concentrated around main centres throughout the country. The largest concentration appears to be around the Bay of Plenty and Waikato regions, optimal locations for national distribution. Only two sawmills exist in the Wairarapa region but are large enough to service the Wellington region. The Wellington region should seek timbers that were grown and processed as locally as possible, as far north as the Waikato and as far south as Nelson.

Engineered timber workshops create and fabricate engineered timber and timber products. They provide engineered timbers such as LVL, Glulam, and CLT. The main concentration of these workshops is around the Auckland region.

Location data courtesy of NZFOA & MPI (2019, p.37-38).

+1.5 - ENGINEERED TIMBER

+ CHAPTER 01

REGIONAL PROCESSING AND TIMBER WORKSHOPS WAIRARAPA

Towns such as Featherston, Carterton, and Masterton have low populations, which results in low demand for timber. Masterton houses the Juken New Zealand timber mill, however (NZFOA & MPI, 2019, p.37), a key industrial employer for the region. When it is considered that Masterton and Wellington are directly connected by rail, swift and local timber transportation becomes a reality. The JNL plant is in proximity to local timber plantation forests, creating a local supply chain of processed and engineered timber for the region.

KAPITI

Whilst Masterton and the Wairarapa can grow and process timbers, Kapiti and Levin are the only location in the region capable of engineering and producing specific members for use.

**FIGURE 1.20 - TYPES OF
ENGINEERED TIMBER**

+1.5 - ENGINEERED TIMBER

ENGINEERED TIMBER TYPES

Engineered timber has plenty of promise and will contribute to a more sustainable future. In New Zealand, engineered timber products are made from harvested *Pinus Radiata*, a fast-growing softwood that sequesters carbon quickly, but is a more vulnerable timber on its own. Processing *Pinus Radiata* and creating engineered materials with them essentially removes the natural vulnerabilities of the wood and results in a much more stable and durable material. Engineered timber is also very light (500 kg/m³) with a higher strength-to-weight ratio than steel and concrete (Marriage, 2020, p.76).

Plywood is a sheet material made from thin layers of veneer, which are glued and pressed together in alternating grain orientations for optimal strength. It typically comes in a 2400x1200mm sheet, and in thicknesses of 6,12, and 18mm. Plywood is well suited as a lining material and can act as wall bracing and in diaphragms (Marriage, 2020, p.79).

Glulam, or glue-laminated timber, consists of solid timbers oriented in the same direction and glued together. Smaller lengths are finger-jointed together. Glulam has great strength and stability characteristics and can be made to almost any desired size or shape. Glulam is well suited to beams, columns, and bracing elements (Marriage, 2020, p.79).

LVL, or laminated-veneer-lumber, has been heralded as a “material of the future” due to its high strength to weight ratio and versatility. LVL is made up of 3mm veneers being glued together, all with the same orientation. This provides it with high directional strength. It is well suited to the design of elements such as beams, columns, and braces. It generally carries a maximum length of 15m, with a 1m Max width and 300mm Max depth (Marriage, 2020, p.79-83).

CLT, or cross-laminated timber, consists of solid timber pieces being laid and glued in layers, in alternate directions. This gives it its two-way strength and desirability as a strong and lightweight floor slab. It is not suitable for beam or column design but can be used in shear wall design. It can be manufactured up to 3x11m in size, and up to 500mm thick (Marriage, 2020, p.79-85).

GLUES AND TIMBER TREATMENT

Unfortunately researching materials that are not manufactured with toxic chemicals or glues is outside the scope of this research. The inherent flaws involved with the current practices of the timber industry and their use of toxins and chemicals is acknowledged.

In particular, the use of epoxy and similar products are used in the creation of plywood, glulam, and LVL timber products. These materials are toxic and often carcinogenic.

MDF, which been has shown in research to be toxic and carcinogenic in its chemical processes, is essentially wood dust and waste product that has been mixed with epoxy/glue and pressed. Knowing this, the use of MDF has been excluded from this research. At least with engineered timber, the chemical damage is offset with high strength and durability properties. the same cannot be said for MDF.

For further information on this topic, see Parisio (p.18, 2006) and Curtis (n.p, 2015) as starting points.

**FIGURE 1.21 - FIRE
SAFETY**

+ 1.5 - ENGINEERED TIMBER

ENGINEERED TIMBER AND FIRE SAFETY

Contrary to what some laypersons may think, timber structures perform very well in fires. As Seike (1977, p.13) states;

“Wood does not begin to burn until it reaches a temperature of about 300° C. But since wood is such a poor conductor of heat, even when the surface temperature reaches 300° C the heart of a substantial building member is little affected and will continue to support the load it was intended to support. Hence, we can say that in a fire, wood construction is actually safer than steel frame construction, since steel is a very good conductor of heat, bending like Taffy at 800° C and warping badly at lower temperatures.”

**FIGURE 1.22 - TIMBER
SPECIES SELECTION**

+ 1.5 - ENGINEERED TIMBER

TIMBER SPECIES SELECTION

New Zealand is blessed with just over 10 million hectares of forests, 8 million of which are native. These 10 million hectares amount to roughly 40% of our total land area. This may sound like a large proportion of land, but prior to human arrival in New Zealand, more than 80% of the land was covered in native forests and shrubs. With colonisation came mass deforestation, the extent of which led to the mass protection and preservation of native timbers in the early 1900s. Plantation forestry of exotic *Pinus Radiata* was introduced, proving to be a fast-growing and successful product. Exotic pine has provided the country with its domestic timber needs since then (MPI, n.p., 2021).

Only under very specific conditions can a native tree be cut down, salvaged, or milled into a timber product. For this reason, and others relating to the respect of native timbers, native timbers will not be used or speculated on in this research. *Pinus Radiata*, forming engineered timber products, are the most suitable materials for this research and will be focussed on as a result.

For more information, please see the Ministry for Primary Industries, Ministry for the Environment, Native Plants Protection Act 1934, and Forests Act 1949.

1.6 - SUBSECTIONS

JAPANESE JOINERY
NATIVE AMERICAN TEPEES

“
**WHILE THE MOST HIGHLY
DEVELOPED MASON’S ART
IS TO BE FOUND IN EUROPE,
JAPAN UNDOUBTEDLY
ENJOYS THE MOST
ADVANCED TECHNIQUES
OF WOOD CONSTRUCTION.**
”

(Seike, 1977, p.11)

+ 1.61 JAPANESE JOINERY

WHY JAPAN?

Japanese carpentry is globally renowned for its beauty, precision, and perfection. Japanese wooden joinery has undergone development since 200 B.C. (Seike, 1977, p.8), with influence from Buddhist architecture and culture coming from Korea and China as early as the year 577 (Brown, 2013, p.16). This is known as the Asuka period (552-646) and is known as the second great revolution in Japanese joinery and architecture.

Japanese carpentry has endured over 1,500 years of practice, development, and survival. No traditional architectural culture serves as a better precedent for the potential of timber construction in New Zealand. Seike (1977, p.11) states that “While the most highly developed mason’s art is to be found in Europe, Japan undoubtedly enjoys the most advanced techniques of wood construction”, enforcing the concept that the study of Japanese carpentry is an inevitable part of any traditional timber research.

Traditional timber construction and craftsmanship in Japan features an abundance of joints and techniques, all with specific uses and suitability. They can be divided into two main categories: Splicing joints and Connecting joints. A splicing joint is essentially where two members are connected end to end, whilst connecting joints are when members join at an angle (Seike, 1977, p.93).

FIGURE 1.24 - YAKUSHIJI TEMPLE

+ 1.61 JAPANESE JOINERY

SUSTAINABLE, REUSABLE, DE-CONSTRUCTABLE

As discussed, climatic and geographic factors led to the widespread use of timber in Japanese traditional construction. This traditional yet advanced method of construction and joining is sustainable in its use and reforestation projects ensure supply meets demand. Structural timbers are not traditionally nailed together, making them highly reusable and de-constructable. An example of this can be found in Japan's Ise Shrine, where the inner sanctum of the shrine is dismantled and reconstructed every 20 years and has been done for over 1,300 years. Old, dismantled timbers are redistributed to other shrines for reuse, while the reconstruction process preserves knowledge and skill in traditional carpentry (Guy & Ciarimboli, 2005, p.4). Ise Shrine is a further example of sustainable traditional construction that was embodied by the Japanese people and sets a precedent for a more sustainable construction attitude that should be adopted by western culture.

SPlicing JOINTS

Splicing joints, or tsugite, are end-to-end connections. Splicing joints do require reinforcing, most commonly with screws, bolts, or plates (Seike, 1977, p.92). Adhesives have undergone recent developments; however, the use of glues and adhesives is not in the interest of this research, due to the permanence and lack of disassembly glued joints dictate. In addition to metal screws, bolts and plates are the use of wooden dowels, pins, and inserted splines to reinforce splicing joints. Without reinforcement “these joints are simply ways of aligning timbers and cannot transmit force effectively” (Seike, 1977, p.100).

The lap joint, or Koshikake-tsugi, is a hallmark splicing joint that is used widely throughout traditional Japanese construction. It defines the basis of a splicing joint, the differentiation between the male and female members. Member shape generally determines gender, with the female piece being the support, or seat, on which the male joint sits. Koshikake translates to mean “seat” and is sometimes what the female piece is known as in a lap joint (Seike, 1977, p.100).

The stub mortise and tenon, or Mechigai-tsugi, is not a legitimate structural joint itself, rather a contributor to the strengthening of other joints. When applied to another joint, the tenon becomes part of the male half of the joint, the mortise the female. The “increased contact surface of a stub mortise and tenon joint increases the firmness of the connection of its two members” (Seike, 1977, p.102).

Board jointing, or Hagi-tsugi, is not dissimilar to western construction. Straight joints, scarf joints, Bird’s mouth joints, ship-lap joints, tongue and groove, and splined joints are all relatively familiar to the joining of floorboards, panels, and external cladding. Tongue and groove joints are best suited to flooring and cladding, whilst joints more susceptible to splitting (such as bird’s mouth) are not (Seike, 1977, p.102-103).

The mortise and tenon joint is not to be confused with the stub mortise and tenon previously discussed. It is a legitimate joint for structural jointing and has many variations. The goose-neck mortise and tenon, or Kama-tsugi, is one such example. It is “specially devised to resist tension force” and is easily identified by its male member. The length of the neck can vary greatly and range from 12-18cm, however increased length does not correlate to increased strength. (Seike, 1977, p.104-105).

Figure 1.25

Figure 1.26

Figure 1.27

Figure 1.28

Figure 1.29

Figure 1.30

Figure 1.31

Figure 1.25 - Koshikake-tsugi - lap joint
Figure 1.26 - Ari-kake - dovetail
Figure 1.27 - Koshikake-ari-tsugi - dovetailed lap joint
Figure 1.28 - Mechigai-tsugi - stub tenon joint
Figure 1.29 - Mechigai-tsugi - stub tenon joint
Figure 1.30 - Koshikake-kama-tsugi-lapped gooseneck mortise and tenon
Figure 1.31 - Mechigai-koshikake-kama-tsugi-lapped gooseneck mortise and tenon with stub tenons

JAPANESE TRADITIONAL TIMBER SPLICING JOINTS

Figure 1.32

Figure 1.33

Figure 1.34

Figure 1.35

Figure 1.36

Figure 1.37

Figure 1.32 - Juji-mechigai-tsugi - cross shaped stub tenon
Figure 1.33 - Hako-mechagai-tsugi - blind U shaped stub tenon
Figure 1.34 - Kakuhozo-imo-tsugi - blind square stub tenon
Figure 1.35 - Kakushi-mechigai-tsugi - half blind stub tenon
Figure 1.36 - Kaneori-mechigai-tsugi - half blind L shaped stub tenon
Figure 1.37 - Chigiri-tsugi - inserted tenon joint

JAPANESE TRADITIONAL TIMBER SPLICING JOINTS

Figure 1.38

Figure 1.39

Figure 1.40

Figure 1.41

Figure 1.42

Figure 1.43

Figure 1.44

Figure 1.38 - Sao-tsugi - lapped rod mortise and tenon joint
Figure 1.39 - Mechagai-tsugi - stub tenon joint with pin
Figure 1.40 - Okkake-daisen-tsugi - rabbeted oblique scarf joint
Figure 1.41 - Daimochi-tsugi - oblique scarf joint with stub tenons
Figure 1.42 - Daimochi-tsugi - oblique scarf joint with stub tenons
Figure 1.43 - Kanawa-tsugi - mortised rabbeted oblique scarf joint
Figure 1.44 - Ken-isuka-tsugi - birds mouth or v joint

JAPANESE TRADITIONAL TIMBER CONNECTING JOINTS

Figure 1.45

Figure 1.46

Figure 1.47

Figure 1.48

Figure 1.49

Figure 1.50

Figure 1.51

- Figure 1.45- Ai-jakuri - end lap joint
 Figure 1.46 - Sammai-gumi - open slot mortise
 Figure 1.47 - O-dome - mitered open mortise
 Figure 1.48 - Hako-dome - rabbeted tenoned miter joint
 Figure 1.49 - Ari-dome - housed dovetail
 Figure 1.50 - Mechigai-dome - rabbeted stub tenon
 Figure 1.51 - Komi-sen - draw pin joint

+ 1.61 JAPANESE JOINERY

CONNECTING JOINTS

As previously discussed, connecting joints are those that occur at angles, that is, not end-to-end. Halving joints are a significant part of this joint family, due to their simplicity and reliability. However, it must be considered that when halving a beam, it becomes significantly weaker than if it were whole (Seike, 1977, p.113). The amount of material you remove from a structural member, the weaker it becomes.

Open slot mortise joints, such as the Wanagi-komi, are some of the simplest connecting joints. These can be used structurally and can consist of the smaller timber remaining whole and becoming the tenon.

Figure 1.52

Figure 1.53

Figure 1.52 - Ai-gake - cross lap joint

Figure 1.53 - Watari-ago - coggled lap joint

JOINTS OF NO INTEREST

Certain joints used in traditional Japanese carpentry do not apply to this research. The wedge joint, or Wari-kusabi, is one such example as they drive wedges through the top of a narrow tenon to split it and wedge it into the mortise opening. This inherently damages the timber tenon, which is sacrificial. This method of construction, while effective, does not facilitate deconstruction and further reuse (Seike, 1977, p.118).

Overly complex joints, such as the hogyozukuri-nokigeta-shiguchi, are also unsuitable due to the complexity, delicacy, and precision required, not to mention the structural ineffectiveness that results from its use. It may possess beauty, but it is not useful (Seike, 1977, p.125-126).

CONCLUSION

Japan is home to the “oldest extant wooden structures in the world”, the golden hall built in 679 and the pagoda built in 693 (Seike, 1977, p.9). They show that a timber structure can last indefinitely when properly built, maintained, and cared for. Japan’s climatic and geographic similarities with New Zealand make its traditional timber carpentry a perfect case study for this research. Understanding the Japanese perception and relationship to timber is just as important as understanding the joints and construction techniques themselves. The notions of sustainable, natural, de-constructable architecture are greatly strengthened by the integration of Japanese perspective and traditional techniques. Certain techniques, as discussed, will be disregarded from integration into the case study design, due to their weaknesses, permanence, and damage to timber members.

**FIGURE 1.54 - THE NATIVE
AMERICAN TEPEE**

+ 1.62 NATIVE AMERICAN TEPEES

DWELLINGS OF THE PLAINS TRIBES

The tepee is a large, cone-shaped dwelling formed from lightweight timber poles of pine or cedar (p.153), and tanned buffalo hides, as depicted in figure 1.54 (Nabokov & Easton, 1989, p.123). About 5-7 buffalo hides were required to make the tepee coverings, a covering that proved to be of surprising versatility. The hide coverings were fully waterproof and remained soft and pliable once dry (p.150). Tepees were not a true cone either, they were more egg-shaped to allow the rear side to brace against the prevailing westerly winds. Smoke flaps, or 'ears', at the top of the cone allowed control over the deflection of wind and the release of smoke from the centrally placed interior fires. Tepees were de-constructable, as they were regularly transported as the tribes moved from place to place. Tepees and their size directly correlated to transport units. They were transported by dogs prior to Spanish arrival, and horses after. This led to a doubling of tepee size (Nabokov & Easton, 1989, p.124). Tepees were a de-constructable, adaptive, and transportable housing system, the like of which has not been seen in western culture.

+1.7 ADDITIONAL PRECEDENTS

1.7 - SUBSECTIONS

TALL TIMBER

DFD

TRADITIONAL CONSTRUCTION

TIMBER - OTHER

**FIGURE 1.55 - TALL TIMBER
PRECEDENTS**

+ 1.7 ADDITIONAL PRECEDENTS

25 KING ST, BRISBANE

(Opray, 2017, n.p)

CLT

GLU

MJOSTARNET, NORWAY

(Block, 2019, n.p)

CLT

GLU

**FIGURE 1.56 - TALL TIMBER
PRECEDENTS**

+ 1.7 ADDITIONAL PRECEDENTS

BROCK COMMONS TALLWOOD HOUSE

(Hasan, 2017, n.p)

CLT

LVL

TALL

149 FEATHERSTON

(Iles, 2018, n.p)(Coulmann, 2017, n.p)

LVL

WLG

TALL

FIGURE 1.57 - DFD PRECEDENTS

+ 1.7 ADDITIONAL PRECEDENTS

MAISON TROPICALE, JEAN PROUVE

(Etherington, 2008, n.p)

DFD

PRE

DFT

R128 HOUSE, WERNER SOBEK

(Guy & Ciarimboli, 2005, p.31)

DFD

PRE

MOD

**FIGURE 1.58 - OTHER TIMBER
CONSTRUCTION PRECEDENTS**

+ 1.7 ADDITIONAL PRECEDENTS

HUT ON SLEDS, CROSSON CLARKE CARNACHAN

(Frearson, 2012. n.p)

TMB

SML

DFT

ALLMANNAJUVET MINE MUSEUM, PETER ZUMTHOR

(Archdaily, 2016. n.p)

TMB

SML

PRE

+ 1.8 - RESEARCH OUTCOMES

SUMMARY OF RESEARCH

So, what does this research tell us?

Climate change research tells us that we have not done a good job, by any means, as custodians of the earth. We are entering an age of great change and uncertainty, with architecture and construction being by no means exempt from this. Resources will become increasingly scarce, with particular emphasis on non-renewable building materials on which construction currently relies. Additionally, the knowledge that vast and immeasurable amounts of these resources are being wasted through linear construction and building demolition is unforgivable.

Sustainable design research has been undertaken, clearly exhibiting that reuse and recycling should be favoured over demolition and landfill. Circular economies need to be taken seriously. Design for Deconstruction provides a rather simple method for enabling a circular economy. Designing a building around how it can be taken apart and reused is a shockingly logical way forward once one realises the immense environmental impact our current construction methods create.

The significant potential of engineered timber can also be realised thanks to this research. It is strong, safe, and sustainable, even grown and manufactured here in New Zealand.

Traditional construction exhibits long-standing and well-developed methods of timber construction. Modern precedents, on their own, affirm the viability of tall, timber, DfD, reusable buildings.

The reality of our dire situation is evident in this research. Nationally and globally, both inside and outside the construction industry. However, as a result, we know exactly where we need to move as an industry to play our part in correcting human trajectory. What's more, we have examples of how to get there. It is a simple matter of combining and reforming different existing methods and ideas in a new way, to create an architectural solution to an existential problem.

TRANSITIONING INTO DESIGN

Now that motivations have been established, standard systems and practices have been researched, and materials are familiar, a design response can begin. Using Japanese joint research to influence this construction system will also be vital. The following chapter will document the iterative and cyclic design process that was undertaken to develop an engineered timber construction system.

CHAPTER

" THE SYSTEM "

CHAPTER OVERVIEW

2.0 - SYSTEM OVERVIEW

WHAT IS THE SYSTEM
INITIAL DECISION MAKING
MATERIAL CHOICE
BAY SIZE
RESIST SIZING

2.1 - DESIGN PROCESS

INITIAL IDEAS
DEVELOPMENT

2.2 - DEVELOPED COMPONENTS

FOUNDATIONS
COLUMN
BEAM
BRACE
FLOORS
WALLS
SERVICES

2.3 - REFLECTIONS

CHAPTER 2 STATEMENT

This chapter is a design response as a direct result of the research done in chapter one. It aims to be a structural system created from engineered timber, that can be constructed and dismantled a number of times, with cross-scale suitability.

In terms of the research methodology, this chapter involves defining, developing, and delivering the system.

This chapter illustrates the iterative design process undertaken to create this system, and some of the challenges resolved along the way. It is presented in a linear fashion for structural coherence, but in reality was far less so. Within the design process illustrated was a cycle of design, reflect, and improve. This led to the developed components that are later documented.

This chapter also documents the developed components that came as a result of the iterative process.

It then reflects on and critiques the system, and discusses where it could have been taken further.

WHAT IS THE SYSTEM?

‘The system’ is primarily the result of initial research into DfD, and understanding the importance of structure and the separation of layers. Designing a structural system that is separate from its services, outer skin, spatial plan, and stuff, became the basis of the system’s design. This structural system needs to consist of; foundations, columns, beams, bracing elements, and floors. Walls and windows (A.K.A building skin) will also be designed to attach and detach from the base system. Services need to be facilitated for attachment and detachment from the base system, but will not be designed in detail themselves.

Roofing elements will not be designed as part of the system, as roofing requirements are specific to the scale, implementation type (e.g. commercial, industrial, residential), location, and architectural intent of the implementation.

Building fixtures and interiors will not be designed either, as they fall under the category of ‘stuff’. The open and flexible spatial planning that the system allows needs to facilitate different types of furniture and fixture varying by occupation.

In summary, the system is a set of components forming a base structure, skin, and services. It will be made of engineered timber and will be designed for deconstruction and reuse across building scales and types.

+ 2.0 SYSTEM OVERVIEW

INITIAL DECISION MAKING

In undertaking this research and approaching 'the system', certain design criteria and decisions were immediately clear. Using engineered timber materials was one, utilising a braced frame system was another. Enabling deconstruction and cross scale suitability were natural considerations made.

Level height was initially designed at 4m floor-floor, as this best suited commercial and industrial spaces with extensive services, small urban residential spaces due to an increased perception of size and volume, and retail spaces with a need for flexible spatial planning.

Standardised structural bays as the basis of 'the system' came about from thinking about the largest scale first, being a large scale commercial development.

Modularity, regularity, and prefabrication were also logical considerations due to their sustainable design properties, and played significantly into the design of 'the system'.

Developing a set of recorded, standardised components also became clear as a result of initial research around documenting for deconstruction.

ENGINEERED TIMBER -----

BRACED FRAME STRUCTURE -----

DECONSTRUCTION -----

CROSS SCALE SUITABILITY -----

HIGH CEILINGS -----

STANDARDISED STRUCTURAL BAYS -----

MODULARITY -----

REGULARITY -----

PREFABRICATION -----

STANDARDISED COMPONENTS -----

FIGURE 2.01 -
THOUGHT PROCESSES

+2.1 DESIGN PROCESS

MATERIAL CHOICES

FOUNDATIONS

Foundations shall consist of LVL timber piles with stainless steel plates implemented where necessary.

COLUMNS

Columns will likely be Glulam with galvanised or stainless steel plates and bolts where necessary.

BEAMS

Beams will likely be LVL due to high directional strength, with galvanised or stainless steel bolts and plates where necessary.

BRACES

Brace components will likely be LVL or glulam in nature with galvanised or stainless steel bolts and plates.

FLOORS

Flooring components will likely consist of a CLT structural plate, with an insulated layer and plywood or other durable flooring layer.

WALLS

As walls are likely non-structural, they will likely be lightweight timber framed and insulated units, with ply internal linings, and necessary waterproofing and cladding externally.

SERVICES

Services themselves are not being designed in this research, but services mounts will be designed, most likely from galvanised or coated steel.

BOLTS/PINS

Bolts and pins will likely be galvanised or stainless steel, to endure both time and the elements.

PLATES

Bolts and pins will likely be galvanised or stainless steel, to endure both time and the elements.

RESIST SIZING

RESIST is an engineering software used to model and size structural members and systems for lateral loading (e.g. wind, earthquakes). It gives an initial idea of member sizes based on the size, scale, location, and type of structure proposed. As previously mentioned, sizing for commercial scale first made most sense, as it has the largest loading and structural requirements. This also allows for greater structural freedom at smaller scales, with the option of greater spans and fewer structural members. RESIST is designed as a preliminary tool, simply providing an indication on how things might work in reality (NZSEE, n.d.).

RESIST testing was undertaken on a 5-storey structure with a height of 20 meters. A rectilinear floor plan was used, with a 486 sqm floor area. Lightweight floor and wall types were input, as was a medium weight roof. Timber cross braced frames were used in both the X and Y directions. The site was input as a Wellington CBD site, coming with high wind and earthquake potential. Lateral load structure, in the X Direction, consists of 15 frames with three adjacent 5 metre bays. Columns have a 4-metre length, and a depth and width of 425 mm. Beams are 300x300 mm, braces are also 300x300 mm.

In the Y Direction, 2 frames consisting of 15 bays make up the lateral structure. Each bay is 3m wide. The required member depths were different in this direction, consisting of 250x200 mm beams, 500x500 mm columns, and 300x300 mm braces.

Analysis of this structure through RESIST resulted in a very safe building under both wind and seismic loads. Wind loads were between 1% and 2% of the maximum allowable, seismic loads ranging from 5% to 50% allowable ultimate, and 6% to 10% allowable serviceability. RESIST analysis resulted in a baseline model for a commercial structure, with plenty of room for adjustment. Using the member dimensions produced by RESIST, bay sizes/spans can be increased, and the member sizes themselves can be adjusted.

+2.1 DESIGN PROCESS

BAY SIZE

As previously mentioned, during the RESIST testing phase bays were sized at 3m by 5m. After further research and development, a symmetrical dimension was deemed to be more suitable due to its regularity and adaptivity.

6x6m was deemed to be more logical for a structural bay dimension, in part due to its ability to facilitate two parked cars underneath. It was also chosen due to the increased floor area it provides for only a slightly larger span.

FIGURE 2.02 -
BAY SIZING

FIGURE 2.03 - INITIAL IDEAS

FIGURE 2.04 - INITIAL IDEAS

Initial Braced frame design (two bays tall).

FIGURE 2.05 - INITIAL FOUNDATION IDEAS

How do you design a timer screen?

1 m^3 of Douglas Fir weighs 475 kg
 $0.5\text{ m} \times 0.5\text{ m} \times 5\text{ m}$ length of Douglas Fir
 weighs 625 kg
 Density of Doug Fir 0.53 (63 kg/m³)
 2 m length weighs 265 kg
 $265\text{ kg} \div 4\text{ men} = 66.25\text{ kg ea}$
 = Carryable
 1 m lengths = 132.5 kg

Switch to squared design

1 FOUNDATION DESIGN - JOINTS

FIGURE 2.06 - INITIAL FOUNDATION IDEAS

The diagram shows a precast concrete slab on the left, which is a square with an 'X' inside, suspended by three cables. To the right, a grid of floor plates is shown, consisting of a 3x3 arrangement of squares. Each square in the grid has a small square in its center. An arrow points from the text 'Floor plates - precast / prestressed' to the grid.

26.03.2020
Foundation des Sketches

VENICE SYSTEMS

**FIGURE 2.07 - INITIAL
FOUNDATION DEV**

**FIGURE 2.08 - INITIAL
FOUNDATION DEV**

FIGURE 2.09 - PILE CONNECTIONS

FIGURE 2.10 - INITIAL COLUMN IDEAS

FIGURE 2.11 - INITIAL BEAM

FIGURE 2.12 - BEAM DEVELOPMENT

**FIGURE 2.13 - BRACE
DEVELOPMENT**

**FIGURE 2.14 -
CONNECTION DEV**

**FIGURE 2.15 -
CONNECTION DEV**

**FIGURE 2.16 -
CONNECTION DEV**

FIGURE 2.17 - INITIAL FLOOR IDEAS

walls
thick

FIGURE 2.18 - INITIAL WALL IDEAS

WALLS

Window panel/wall connections

WALLS

FIGURE 2.19 - INITIAL WALL IDEAS

Floor slab connection/overlay - revisit

REMEMBER
- design for the
labourer / liftable
- transportability

FIGURE 2.20 - INITIAL WALL IDEAS

Need to think about Rain Louvers / Shading

WALL-WALL / WALL-STRUCTURE

FIGURE 2.21 - INITIAL WALL IDEAS

FIGURE 2.22 - INITIAL WALL IDEAS

FIGURE 2.23 - INITIAL SERVICES IDEAS

FIGURE 2.24 - INITIAL SERVICES IDEAS

FIGURE 2.25 - SERVICES DEVELOPMENT

THE DESIGN PROCESS

DEVELOPMENT PATTERNS

- Fewer pieces = Stronger system
- Larger components = Stronger system (also heavier system)
- Simpler components = Stronger components = Stronger system
- Less components = Less construction steps = Faster construction = Money saved
- There are always more problems to solve (the refinement process is endless)

ISSUES WITH THE PROCESS

The design process has been presented as a linear one, undergoing component-by-component iterative development, through sketch and digital modelling. The reality is that there was a lot of back and forth between components and design scales. Parts were not resolved one at a time, the system developed slowly as a whole. Decisions and changes were made as soon as the system moved from sketch to 3D modelling. These numerous decisions are difficult to record and represent retrospectively.

This research does not have enough space to document and discuss the development process in detail, an issue to be discussed in research reflections. The sketch process shown in this research is a mere representation of initial ideas, and the departure of developed components from these ideas shows just how much development has been undertaken.

DEVELOPED DESIGN

This chapter now shifts focus to the developed design of the system.

**FIGURE 2.26 - EXPLODED
AXONOMETRIC**

0 1m 5m 10m

+ OVERALL SYSTEM

The resultant system is a collection of components, that together form a braced frame construction system with CLT floors, internal and external walls, and retractable foundations. It is designed to be manufactured and partially assembled offsite (into whole components) and easily and quickly assembled onsite. It is then designed to be deconstructable and reusable at the end of its useful life.

- ① **COLUMNS** H1.2 min. treated glulam , 500W x 500D x 4000H (mm)
- ② **BEAMS** H1.2 min. treated LVL, features central fuse region, 250W x 300D (mm)
- ③ **BRACES** H1.2 min. LVL, 300W x 300D (mm) eccentric bracing system
- ④ **SHORT PILES** H5-6 treated glulam, 500W x 500D x 1000L (mm)
- ⑤ **EXT WALL BRACKETS** H3.2 min. treated LVL, attached to primary structure
- ⑥ **EXT WALL** Lightweight construction, modular with 1m,2m,3m width options
- ⑦ **FLOOR** CLT construction, insulation layer, variable surface coverings available
- ⑧ **FOUNDATIONS** H5-6 treated helical screw piles, connecting via pilecaps. LVL or glulam suitable as primary construction material.

**FIGURE 2.27 - SYSTEM
AXONOMETRIC**

0 0.5m 2.5m 5m

+ OVERALL SYSTEM

+ CHAPTER 02

The base system is designed to be adaptable to different building and occupation types, and as a result features a 4m floor to floor height, options for exposed ceiling services or suspended ceiling systems, and an adaptable 36m² floor space. The 4m floor to floor height enables a sense of verticality and grandeur, creating a larger sense of space. It also has the potential to be utilised for storage or split levels. Regular 6m by 6m structural bays enable consistency and simplicity in both the x and y directions, simplifying and streamlining the construction and assembly process, as well as standardising component dimensions.

- ① Columns, coming in 4m modules, can be added to reach any desired height or number of storeys.
- ② Floors can be left bare with the exposed plywood covering insulation, or can be concealed with carpet, flooring tiles, or hardwood timber floors.

FIGURE 2.28 - SYSTEM PLAN

0 0.5m 2.5m 5m

+ OVERALL SYSTEM

+ CHAPTER 02

This construction system consists of standardised components forming a regular bay module. Because of this, certain components are mirrored versions of others, forming opposite ends of the structural bay. This means that bays can be repeated in any direction as long as the correct components are used. Endless repetition is also enabled, useful for larger commercial or industrial structures.

This also means that two types of column exist, as well as two distinctly different end beams. Components used to create braces are the same.

All of the bolts used to fix components together sit within countersunk/recessed holes to ensure a high quality finish, durability of joints and bolts, as well as addressing safety concerns. This is most prevalent in flooring components, due to the tripping hazard that would otherwise occur.

- ① Column type A
- ② Column type B
- ③ Beam components A, B, and C
- ④ Countersunk bolt holes

**FIGURE 2.29 - SYSTEM
ELEVATION**

+ OVERALL SYSTEM

Visible in this diagram is the structural nature of the system, as well as component joining areas. Load paths and joint placement have been considered as well as practicable in this research, leading to the design of the central beam fuse region.

Also visible are the pre-machined slots in beams (above #2), which house hardwood pins that help secure the large CLT floor plates. The extension points for additional beams and braces can also be seen on the front side of the pictured columns and short-piles.

Detailed information on the Helical screw foundation system can be found later in the chapter.

Along the column edges, a series of components can be seen. These are recessed nuts ready for the installation of external walls.

+ CHAPTER 02

- ① Columns - H1.2 min. treated glulam , 500W x 500D x 4000H (mm)
- ② Beams - H1.2 min. treated LVL, features central fuse region, 250W x 300D (mm)
- ③ Braces - H1.2 min. LVL, 300W x 300D (mm) eccentric bracing system
- ④ Short-piles - H5-6 treated glulam, 500W x 500D x 1000L (mm)
- ⑤ Pile-caps - 2 layer system, lower being timber, upper being a stone barrier layer
- ⑥ H5-6 treated helical screw-piles, connecting via pile-caps. LVL or glulam suitable as primary construction material.

**FIGURE 2.30 -
FOUNDATION AXO**

0 250mm 1250mm 2.5m

+ OVERALL SYSTEM

WHOLE FOUNDATION SYSTEM

The foundation system designed in this research is partly informed by the design of traditional Venetian timber foundations, which can be seen in Appendix 1.

An upper pile-cap made of stone creates an effective moisture barrier between the helical piles and the upper short-pile, which is partially exposed above ground. The lower pile-cap and helical piles below it have no exposure to oxygen as a result, and are preserved in the muddy soil they sit in, preventing decomposition.

The helical piles consist of a treated timber body, likely LVL or glulam in composition. Galvanised steel helices are then fixed in, along with protection plates at pile joints.

Deep mortise and tenon joints based on Japanese joint types connect the piles together, ensuring maximum surface area contact between components for optimal strength and security. These joints are then further secured with four bolts at each join (2 in each direction) enabling disassembly and eliminating chemical joining.

COMPONENT LABELLING SYSTEM

Every component designed as a part of 'the system' has been labelled. This labelling system is designed to help contractors, designers, and engineers alike to identify and inventory components as necessary.

The labelling begins with broad categorisation:

FN - Foundation

SH - Short-pile

CL - Column

BE - Beam

BR - Brace

FL - Floor

WE - External wall

WI - Internal wall

SE - Services

Components are then assigned a type based on how many are in that category. E.g. FN.A, FN.B, FN.C etc.

Components are also numbered, based on how many identical components are being used in construction. E.g. FN.A.01, FN.A.02, FN.A.03 etc.

Additional categories also exist for wall components, which have cladding variants (CV) and window variants (WV). These are at the end of the component labels, and are also numbered.

**FIGURE 2.31 - BASE PILE
AXONOMETRIC**

0 50mm 250mm 500mm

FN.A.01 - BASE PILE

The base pile component features a pointed end for ground penetration, and rounded edges to reduce resistance as the pile rotates. Galvanised steel helices continue to dig the pile into the ground with minimal disturbance of surrounding soil. The helices attach to the centre of the pile to minimise any risk to the timbers integrity.

The component top has a galvanised steel cap for durability to ensure that components can be connected and disconnected over time with minimal component damage, ensuring reuse potential. Galvanised steel components also ensure rusting does not occur.

Treated LVL or Glulam timber are the envisioned engineered timbers to be used in the creation of this component.

The dimensions of this pile (see page 153) are designed based upon the traditional steel helical screw-piles, with size accommodations made for timber.

This component has been designed with the intention of being prefabricated and assembled off-site, allowing for straightforward assembly on-site.

**FIGURE 2.32 - BASE PILE
ELEVATION**

ALL MEASUREMENTS IN MM (MILLIMETERS)
SCALE 1:20 @A4

FN.A.01 - BASE PILE

- ① Cross shaped stub tenon connection to extension piles
- ② Japanese inspired joint connection between helix pieces
- ③ Prefabricated bolt holes through connection points
- ④ Galvanised steel helices fix through central points of timber pile
- ⑤ Pointed end for ground penetration

**FIGURE 2.33 - EXT PILE
AXONOMETRIC**

0 50mm 250mm 500mm

FN.B.01 - EXTENSION PILE

The extension pile component has been designed to fit to the top of the base pile component via the cross shaped joint cut into the base of the pile. This is then fitted with a galvanised steel protective cap.

The modular nature of the extension pile means that components can be attached for any desired depth, with the ability to be extended or shortened on-site as required.

The uppermost extension pile fits precisely into the bottom of the pile-cap, which covers a grouping of four piles.

Similarly to the base pile component, treated LVL or glulam are the intended engineered timbers to be used in the creation of this component.

Off-site prefabrication is intended, allowing for straightforward on-site assembly and installation.

Another advantage to the modular foundation system is that if a singular extension pile is damaged during its life or when being removed, it can be replaced without compromising the reuse potential of other components.

**FIGURE 2.34 - EXT PILE
PLAN AND ELEVATION**

ALL MEASUREMENTS IN MM (MILLIMETERS)
SCALE 1:20 @A4

FN.B.01 - EXTENSION PILE

- ① Cross shaped stub tenon connection to extension piles
- ② dovetail type joint connection between helix pieces
- ③ Prefabricated bolt holes through connection points
- ④ Galvanised steel helixes fix through central points of timber pile

FIGURE 2.35 - HELICAL SCREW CONNECTIONS

0 50mm 250mm 500mm

FN.A.01, FN.B.01 - HELICAL SCREW DESIGN

The helical screw system has been designed for straightforward assembly and disassembly, with strength and durability in mind. Galvanised 5-10mm steel plating has been envisioned and pictured throughout, however anodized or stainless steel may also be suitable, depending on use and durability. Another advantage of this system is that individual helix pieces can be swapped out if damaged during manufacture, assembly, or transportation. This also allows for optimal re-usability.

Connections between the helix parts are based on the dovetail joint, then fixed with steel rods and pins. As seen in the adjacent diagram, parts are secured in both the X and Y direction for maximum attainable joint strength.

**FIGURE 2.36 - PILE CAP A
AXONOMETRIC**

0 185mm 925mm 1850mm

FN.C.01 - LOWER PILE CAP

Pictured is the lower pile-cap component. It is designed to house the tops of the uppermost extension piles, again utilising Japanese joining methods for its surface area, strength, and stability.

The top of the cap implements a regular grid of repeating tenons that fit into mortises cut into the upper pile-cap that sits above. This is intended to maximise connection strength between pile-cap components.

Piles attach near each of the caps four corners. Width and spacing of piles is based upon research into standard foundation systems (See chapter 01).

Treated LVL or glulam has been envisioned for this component. This lower pile-cap has been designed to sit below ground, preserved in muddy soil with the helical timber piles.

**FIGURE 2.37 - PILE CAP A
PLAN AND ELEVATION**

ALL MEASUREMENTS IN MM (MILLIMETERS)
SCALE 1:20 @A4

FN.C.01 - LOWER PILE CAP

- ① 185x185mm tenons fit into same sized mortises on upper pile cap
- ② Extension pile housings utilising cross shaped stub tenon
- ③ 700mm spacing between piles ensures no pile shaft collapse or helix contact
- ④ 150mm contact depth between piles and pile cap ensures strong connection

**FIGURE 2.38 - PILE CAP B
AXONOMETRIC**

0 185mm 925mm 1850mm

FN.D.01 - UPPER PILE CAP

Upper pile cap to be made from locally sourced stone. Concrete should be used only as a last resort if natural materials are unavailable or unsuitable to ground conditions.

The primary purpose of the upper pile-cap is for it to serve as a moisture barrier and protective layer, separating the preserved lower foundation from the above ground environment. This prevents moisture from leaving the ground below, and oxygen getting in from above and decomposing wet timber piles.

As visible in the adjacent image, the pile-cap has repeating mortises that house the tenons of the lower pile-cap, ensuring a snug and secure fit. The short-pile component then fits into the centre of the stone upper pile-cap, connecting to the primary column structure. This system ensures proper load path distribution from building to ground.

**FIGURE 2.39 - PILE CAP B
PLAN AND ELEVATION**

ALL MEASUREMENTS IN MM (MILLIMETERS)
SCALE 1:20 @A4

FN.D.01 - UPPER PILE CAP

- ① 185x185mm mortises fit into same sized tenons on lower pile cap
- ② Shortpile housing also utilises cross shaped stub tenon design present in foundation system
- ③ 100mm contact depth between pilecap components
- ④ 150mm contact depth between shortpile and pilecap

**FIGURE 2.40 - SHORT PILE
AXONOMETRICS**

0 50mm 250mm 500mm

FN.E.01 - SHORT PILE - NORMAL
FN.F.01 - SHORT PILE - MIRRORED

As visible in the adjacent image, two types of short-pile exist, one the mirror image of the other. This ensures repeatable modules and standardised components.

Cross shaped stub-tenons have been implemented here for column connections, with seats for the beam connections.

Once beams are seated, bolts can run through the pre-machined recessed channels that are staggered vertically to ensure that bolts can run in both directions.

5mm galvanised steel plating caps the short-pile to protect the timbers and ensure durability and re-usability after the disassembly process occurs.

Weather treated Glulam is the primary envisioned material for this component.

**FIGURE 2.41 - SHORT PILE
PLAN AND ELEVATION**

ALL MEASUREMENTS IN MM (MILLIMETERS)
SCALE 1:20 @A4

**FN.E.01 - SHORT PILE - NORMAL
FN.F.01 - SHORT PILE - MIRRORED**

- ① Bottom of pile sits in upper pilecap, protected by 5mm galvanised steel plate
- ② 45mm recessed holes exist to house a 15mm bolt with 25mm wide head with accessibility space
- ③ staggered bolt channels to ensure all directions can be secured to
- ④ deep beam seat ensures strength and stability
- ⑤ Small mortise and tenon serves as a guidance joint as beams are placed
- ⑥ 5mm galvanised steel plate protects connection to column at top
- ⑦ Short-pile designed to prop building 1m high off the ground to ensure maintenance access and ensure adequate cross ventilation beneath the building, keeping timbers dry.

**FIGURE 2.42 - COLUMN
AXONOMETRICS**

0 50mm 250mm 500mm

CL.A.01 - COLUMN TYPE A - NORMAL
CL.B.01 - COLUMN TYPE B - MIRRORED

Similarly to the short-pile components, the large primary columns pictured opposite utilise the same joint types as short-piles, selected for their simplicity, strength, and stability.

Nuts to house external walls and their frames are pre-installed into the edges of columns for speed of assembly on-site.

5mm Galvanised steel plates protect the bottom brace joint, as well as the upper beam housing. The cross shaped stub tenon on top is used for additional columns/storeys, or bespoke roofing elements.

As columns have the potential to be visible and on display during the buildings life, countersunk and recessed bolt holes are used.

As previously discussed, the modular nature of the system allows for infinite repeatability in any direction, depending upon project requirements.

Treated glulam is the envisioned material to be used in this column.

This column component is designed to be manufactured and prefabricated off-site, then delivered and installed as a singular component. This minimises on-site assembly, saving both time and money.

FIGURE 2.43 - COLUMN
PLAN AND ELEVATION

ALL MEASUREMENTS IN MM (MILLIMETERS)
SCALE 1:20 @A4

CL.A.01 - COLUMN TYPE A - NORMAL
CL.B.01 - COLUMN TYPE B - MIRRORED

- 1 5mm galvanised steel protection plates
- 2 Nuts housing external wallframes
- 3 Staggered bolt holes so that both directions can be secured
- 4 45mm recessed channel to house 15mm bolt with 25mm wide head and nut
- 5 Large seat for beam to sit in
- 6 large mortise for brace to sit in, protected with a 5mm galvanised steel plate
- 7 Column width based on initial RESIST modelling to determine dimensions required for a large commercial implementation with maximum loading. This ensures that any lesser or smaller implementation can safely use the system.

**FIGURE 2.44 - BEAM
AXONOMETRIC**

+ BEAM DESIGN

BE.A.01 - BEAM TYPE A - END

BE.B.01 - BEAM TYPE B - SACRIFICIAL FUSE REGION

BE.C.01 - BEAM TYPE C - END

Three separate beam components exist. Two are end components, slotting and bolting securely into end columns. The third is a central fuse of sorts, designed to connect the two end beams and act sacrificially in a severe seismic event. The logic behind this is that designing one piece to fail ensures the safety and integrity of other components. This sacrificial piece can easily be disassembled and swapped out after such as event.

5mm galvanised steel plates protect both ends of the beam components, ensuring durability over the components lifetime.

The central holes that house large pins connecting to CLT flooring are also fitted with a 5mm galvanised protection plate.

As these beam components have the potential to be on display to building users during their lifetimes, they utilise recessed bolt channels for a high quality visible finish.

The two beam end components also house the top of the brace components, via a small mortise and tenon joint. This joint is cut into the underside of the beams.

Rabbeted oblique and scarf joints have been utilised in the design of these beams. Stub tenons have been added to beam ends for additional stability.

Treated LVL would be a suitable construction material for these components, as would glulam timbers.

**FIGURE 2.45 - BEAM
PLANS AND ELEVATIONS**

ALL MEASUREMENTS IN MM (MILLIMETERS)
SCALE 1:20 @A4

- ① Small tenons help installers guide pieces into place
- ② Pre-machined bolt channels run through all joins
- ③ Pre-machined holes for floor-pins to fit into align with similar holes in floor component
- ④ Mortise to house the top of brace component
- ⑤ Beam end designed to sit in opening at top of short-pile/column
- ⑥ Oblique scarf mirrored at each end of the fuse beam
- ⑦ End beam components are slightly longer than the central fuse region, however this is a nominal distance of roughly 150mm, and exists because the end beams have a large 150mm tenon at each end. As a result, all beams are essentially of the same dimension and strength.

**FIGURE 2.46 - BEAM PART
AXONOMETRICS**

0 1m 5m 10m

BE.A.01 - BEAM TYPE A - END

BE.B.01- BEAM TYPE B - SACRIFICIAL FUSE REGION

BE.C.01 - BEAM TYPE C - END

A total of 20 bolts run through each completed beam component. Eight bolts connect the three beam pieces, another eight connect to columns, and four connect to the upper brace tenons. This creates, in theory, a strong and rigid beam system that connects securely to other parts.

As previously discussed, the central beam component is sacrificial and can be replaced if it breaks under seismic loading. Its metal plates can be removed and reapplied to other components if this occurs.

**FIGURE 2.47 - BRACE
AXONOMETRICS**

0 300mm 600mm

BR.A.01 - BRACE TYPE A - LOWER

BR.B.01 - BRACE TYPE B - UPPER

As is visible in the adjacent figure, each brace consists of two components. This is for ease of manufacture, transport, storage, and installation. It also minimises the amount of machinery required to install it.

As each brace consists of an upper and a lower component, each can be interchanged if damage occurs to either one.

5mm galvanised steel plates protect the ends of each component and ensure a durable product with long life.

A high quality finish is to be used as timbers may be exposed for the duration of their lives. Countersunk and recessed bolt holes and channels have been used.

Treated glulam or LVL are the envisioned construction materials for these components. A variety of finishes can be used.

As previously discussed, the top of the brace slots into the underside of beams A and C, while the bottom of the brace slots into a large mortise built into the column components.

Cross shaped joints and mortise and tenons have been used due to their simplicity and strength properties, while also possessing an intriguing visual element.

+ BRACE DESIGN

**FIGURE 2.48 - BRACE
PLAN AND ELEVATION**

ALL MEASUREMENTS IN MM (MILLIMETERS)
SCALE 1:20 @A4

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BR.A.01 - BRACE TYPE A - LOWER
BR.B.01 - BRACE TYPE B - UPPER

- ① Tenon that fits into low end of primary column. Large for strength and durability
- ② Top of brace tenon that slots into underside of beams A and C
- ③ Cross shaped stub tenons have been used to connect brace components to each other
- ④ Brace spans entire height of system, from level to level
- ⑤ Pre-machined bolt channels run into column bolt channels, ensuring a strong connection

+ CHAPTER 02

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FIGURE 2.49 - FLOOR
PANEL AXO

FL.A.01 - FLOOR TYPE A - PLYWOOD LINING

FL.B.01 - FLOOR TYPE B - INSULATION LAYER

FL.C.01 - FLOOR TYPE C - CLT LEFT

FL.D.01 - FLOOR TYPE D - CLT RIGHT

FL.E.01 - FLOOR TYPE E - CONNECTING BEAM

The bulk of the flooring component consists of a 5 layer CLT panel, providing structural integrity and acting as a diaphragm, transferring loads to the structural frame. On top of the CLT sits a protected layer of insulating material. On top of the insulation sits the desired flooring finish. This can be hardwood flooring, plywood, carpet on top of ply, tiles, etc.

As the adjacent diagram shows, the bolts that connect the floor together run the entire depth of the floor, ensuring maximum achievable strength.

At each corner of the floor sits a crane attachment point for ease of installation and deconstruction.

Bolt holes and channels are recessed to ensure that there is no tripping hazard for building users.

The main flooring component sits on top of support brackets that are tied into the main columns, transferring some of the loads. Large timber pins also connect the beams and the floor to one another, transferring loads out and down the structural frame.

**FIGURE 2.50 - FLOOR
PANEL PLAN AND ELEV**

- ① Evenly spaced bolting locations to ensure even load distribution
- ② Bolts run entire floor depth to help secure it as a singular component
- ③ Crane/rope connection points in slab corners
- ④ Central beam that connects CLT components has its own pinned connections
- ⑤ Recessed bolt channels to ensure occupant safety

FL.F.01 - FLOOR TYPE F - FLOORING SUPPORT BRACKETS

Pictured in the adjacent figure are the support brackets that are fitted prior to the installation of flooring. These components tie into columns, as previously discussed. These support brackets also ease the construction process.

ALL MEASUREMENTS IN MM (MILLIMETERS)

SCALE 1:50 @A4

**FIGURE 2.51 - EXTERNAL
WALL OPTIONS**

0 300mm 1500mm 3000mm

+ EXTERNAL WALL DESIGN

- WE.A.01 EXTERNAL WALL TYPE A - 1 M**
- WE.B.01 - EXTERNAL WALL TYPE B - 2 M**
- WE.C.01 - EXTERNAL WALL TYPE C - 3 M**

There are three main external wall options, the main factor differentiating them being wall length. 1m, 2m, and 3m external wall options are available, with a total available wall length of 6m per structural bay.

Each wall comes to site as a complete, assembled component. This simplifies the construction and assembly process.

Each wall consists of a lightweight timber frame, insulation, a plywood internal lining, building wrap, vapour barrier and D.P.M, and external cladding. Cladding options are highly variable, as are window and door options.

Walls have three main connection areas. They connect to the top of the frame on which they sit, as well as the bottom. Wall components also tie into one another via recessed bolt channels. Large bolts connect the walls to each other and their frames.

The external walls are large elements, but remain as lightweight as possible via ply linings, insulated interiors, and minimal waste.

+ EXTERNAL WALL DESIGN

**FIGURE 2.52 - 1M WALL
PLAN AND ELEVATION**

ALL MEASUREMENTS IN MM (MILLIMETERS)

SCALE 1:50 @A4

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WE.A.01 - EXTERNAL WALL TYPE A - 1M

Adjacent is an illustration of the 1m wall option in its most basic form. The 1m wall is the narrowest wall option, and is pictured here with 90x45 timber cladding. This could be finished in a variety of ways to suit client preferences.

- ① Each external wall spans the height of each bay of 'the system'
- ② Wall to wall connections occur at the 2m mark - the midpoint of the wall
- ③ The core of each wall component is 180mm deep - enough for plenty of insulation
- ④ The mortise and tenons that interlock walls are as small as possible to maximise efficiency and aims to reduce thermal bridging

+ CHAPTER 02

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FIGURE 2.53 - EXTERNAL WALL VARIATIONS

0 300mm 1500mm 3000mm

+ EXTERNAL WALL DESIGN

- 1 WE.A.01.WV1.CV1 - EXTERNAL WALL TYPE A - WINDOW TYPE 1 - CLADDING TYPE 1
- 2 WE.B.01.WV2.CV1 - EXTERNAL WALL TYPE B - WINDOW TYPE 2 - CLADDING TYPE 1
- 3 WE.C.01.WV3.CV1 - EXTERNAL WALL TYPE C - WINDOW TYPE 3 - CLADDING TYPE 1
- 4 WE.D.01 - EXTERNAL DOOR - 1 M
- 5 WE.A.01.CV1 - EXTERNAL WALL TYPE A - CLADDING TYPE 1
- 6 WE.A.01.WV4 - EXTERNAL WALL TYPE A - WINDOW TYPE 4
- 7 WE.B.01.WV4 - EXTERNAL WALL TYPE B - WINDOW TYPE 4
- 8 WE.C.01.WV3 - EXTERNAL WALL TYPE C - WINDOW TYPE 4
- 9 WE.A.01.CV2 - EXTERNAL WALL TYPE A - CLADDING TYPE 2
- 10 WE.A.01.CV3 - EXTERNAL WALL TYPE A - CLADDING TYPE 3
- 11 WE.A.01.CV4 - EXTERNAL WALL TYPE A - CLADDING TYPE 4
- 12 WE.A.01.CV5 - EXTERNAL WALL TYPE A - CLADDING TYPE 5
- 13 WE.A.01.WV4.CV6 - EXTERNAL WALL TYPE A - WINDOW TYPE 4 - CLADDING VARIANT 6
- 14 WE.A.01.WV4.CV7 - EXTERNAL WALL TYPE A - WINDOW TYPE 4 - CLADDING VARIANT 7
- 15 WE.A.01.WV4.CV8 - EXTERNAL WALL TYPE A - WINDOW TYPE 4 - CLADDING VARIANT 8
- 16 WE.A.01.WV4.CV9 - EXTERNAL WALL TYPE A - WINDOW TYPE 4 - CLADDING VARIANT 9
- 17 WE.E.01 - WALL FRAME 1
- 18 WE.F.01 - WALL FRAME 2
- 19 WE.G.01 - WALL FRAME 3
- 20 WE.H.01 - WALL FRAME 4

As the adjacent figure illustrates, external wall design is highly variable, with a vast range of customisation achievable. Doors and windows are equally as catered to as walls. Windows range in size and shape, and the option of adjustable louvres are also available.

Cladding and internal ply linings are durable and paintable, allowing for strong and secure fixings without compromising reusability.

FIGURE 2.54 - EXTERNAL WALL EXPLODED

0 300mm 1500mm 3000mm

+ EXTERNAL WALL DESIGN

- ① INTERNAL PLYWOOD CLADDING
- ② INSULATION
- ③ BUILDING WRAP
- ④ DPM AND VAPOUR BARRIER
- ⑤ TREATED TIMBER FRAMING
- ⑥ BATTENS FOR CLADDING PANEL ATTACHMENT
- ⑦ EXTERNAL CLADDING

External wall panels consist of a number of layers, as illustrated in figure 2.54. Essentially, a lightweight timber frame houses insulation and water/weather proofing layers. Battens made from timber or steel are placed on the external face, for the attachment of desired cladding. The internal face is then lined with ply. Plywood is more durable, robust, and versatile when compared to gypsum lining, while also remaining relatively low cost.

FIGURE 2.55 - INTERNAL WALL AXONOMETRIC

0 300mm 1500mm 3000mm

+ INTERNAL WALL DESIGN

- ① **WI.B.01 - INTERNAL WALL TYPE B - 1M SACRIFICIAL UPPER**
- ② **WI.A.01 - INTERNAL WALL TYPE A - 1M LOWER WALL**
- ③ **WI.D.01 - INTERNAL WALL TYPE D - 2M SACRIFICIAL UPPER**
- ④ **WI.C.01 - INTERNAL WALL TYPE C - 2M LOWER WALL**
- ⑤ **WI.F.01 - INTERNAL WALL TYPE F - 3M SACRIFICIAL UPPER**
- ⑥ **WI.E.01 - INTERNAL WALL TYPE E - 3M LOWER WALL**

Internal walls differ slightly to their external counterparts, but are similar in nature. They feature an upper and a lower portion, the lower being 2.4m high to align with standard sheet measurements, with the intention to minimise waste produced during production. The upper portion is 1.6m high, and can be cut through or left out depending on services requirements and client needs.

Internal wall components fix securely to the ground plate as well as other wall components.

FIGURE 2.56 - INTERNAL WALL EXPLODED

+ INTERNAL WALL DESIGN

WI.C.01 - INTERNAL WALL TYPE C - 2M LOWER WALL
WI.D.01 - INTERNAL WALL TYPE D - 2M SACRIFICIAL UPPER

- ① Upper connection point, into ceiling
- ② Lower connection point, into lower wall
- ③ Connection bolts between wall components
- ④ Floor connection points
- ⑤ Wall to wall connection points, on both ends of the wall

The adjacent image shows a lot of wall cavities for the bolted connections to pass through. It should be noted that these can be covered with caps once installed, for a continuous wall finish.

**FIGURE 2.57 - SERVICES
STRUT PLAN**

0 300mm 1500mm 3000mm

SE.A.01 - SERVICES COMPONENT A

The services strut is a fairly rudimentary design, and exists as a housing for any and all services required in a building. It is similar in concept to a UNI-STRUT system, being an all purpose housing for mechanical, electrical, and plumbing system. This allows for the successful separation of building layers as outlined in the DfD success criteria. This strut attaches to the underside of the CLT floor plates, and runs in both the X and Y direction.

**FIGURE 2.58 - SERVICES
STRUT PLACEMENT**

+ SERVICES STRUT DESIGN

+ CHAPTER 02

- ① *Services attach to strut, strut attaches to CLT ceiling*
- ② *Any configuration of MEP services can be catered to with flexibility*
- ③ *Extra high floor to floor height allows greater vertical space for services to work in*

+ 2.8 REFLECTIONS

WHAT THE SYSTEM DOES WELL

The system is structurally logical, making use of an eccentric bracing system that minimises interruption between structural bays while remaining strong. The system is simple by nature, making it adaptive to different designs and uses. By being sized and engineered for commercial development in central Wellington, components are large, sturdy, and capable of withstanding heavy loads. This makes it adaptable to a large variety of uses. The system also:

- Uses strong and durable engineered timber
- Is completely de-constructable and reusable, eliminating waste and redundancy
- Uses large, solid, strong components, minimising the risk of damage and waste
- Uses traditional Japanese joinery to inform de-constructable connections and joints
- Based on the use of local materials
- Involves minimal impact to the site and surrounding environment
- System components are transportable and compact

WHAT THE SYSTEM DOES NOT DO WELL

- Not adaptable to non-linear forms
- Internal layouts are relatively limited
- Has the potential to be vastly over-engineered when used in small scale structures
- Components are large, bulky, and likely heavy
- Extra high ceilings work well for commercial, but may be under-utilised in residential developments
- Lacks delicacy and elegance
- Does not adapt to in ground or underground implementations well
- Shape and resulting forms are largely fixed and regular
- Curves are not possible

RESEARCH FAILINGS

- Researcher drew, 3D modelled, iterated, developed and problem solved, but did not take into the physical realm for testing. Physical modelling necessary to further develop connections and details.
- Counsel from an engineer or experienced architect was not sought for advice on system feasibility or shortcomings.
- Structural understanding was limited to the RESIST programme and its results.
- Overly ambitious in its designs to be a fully developed construction system
- Certain aspects necessary to a building have been overlooked. Roofing, joinery, and furnishings have been excluded and classified as 'design specific' or 'bespoke'.

TAKING THIS RESEARCH FURTHER

- Development is needed, both at the large scale and the small. Resolving connections and junctions, as well as additional components is needed.
- Needs to be physically modelled and tested at scale
- Discussion with an engineer or architect is needed to critique the structural weaknesses of the system

SUCCESS CRITERIA

All requisite criteria established in chapter 1 have been designed for and met, as they formed the basis of decision making when designing the system. The test will be to continue meeting this criteria as other aspects of the system are explored in the following chapters.

DOES IT MEET DFD SUCCESS CRITERIA?

1. DESIGN FOR COMPONENT REUSE	☒
2.DESIGN FOR OFFSITE AND MODULAR CONSTRUCTION	☒
3. DESIGN ACCESSIBLE AND NON-CHEMICAL CONNECTIONS	☒
4. SPECIFY DURABLE AND VALUABLE MATERIALS	☒
5. CONSIDER MATERIAL HANDLING	☒
6. USE A STANDARD STRUCTURAL GRID	☒
7. DESIGN FOR ADAPTABILITY	☒
8. MINIMISE BUILDING ELEMENTS, SIMPLIFY STRUCTURE AND FORM	☒
9. USE LAYERING APPROACH AND SEPARATE MEP SYSTEMS	☒
10. USE RETRACTABLE FOUNDATIONS	☒

CHAPTER

SYSTEM CONSTRUCTION

CHAPTER OVERVIEW

3.1 - STEP BY STEP CONSTRUCTION GUIDE

- STEP 1-10 - FOUNDATIONS
- STEP 11-14 - COLUMNS
- STEP 15-23 - BEAMS
- STEP 24-30 - BRACES
- STEP 31-35 - FLOORS
- STEP 36-40 - EXTERNAL WALLS
- STEP 41-45 - INTERNAL WALLS
- STEP 45-47 - SERVICES STRUT

3.2 - CRITICAL REFLECTIONS

CHAPTER 3 STATEMENT

This chapter is a straightforward step-by-step manual of how each component in ‘the system’ connects and comes together to form a structure and a building. The manual lists these steps in the order they should be constructed.

While this chapter is primarily delivery of the system (in methodology terms) it is also reflective and part of the continued development of the system.

This guide is not design specific, and does not illustrate how to build a complete building, instead it gives instructions on fitting each type of component as the designer intends.

STEP 1
FIGURE 3.01

Assemble foundation piles by bolting extension piles to the base pile. Attach the number of extension piles specified to reach the desired foundation depth.

NOT TO SCALE

STEP 3
FIGURE 3.03

Screw piles are to be grouped in fours, with consistent spacing of 700mm between piles.

NOT TO SCALE

STEP 2
FIGURE 3.02

Raise, align, and drill screw piles into place. Ensure all screw piles are drilled to the same depth. Vertical drilling is preferable to minimise the chances of connection failure.

NOT TO SCALE

213

STEP 4
FIGURE 3.04

Install the lower pile cap by lowering it onto the screw pile tops. Ensure proper alignment and placement of pile-cap joints.

NOT TO SCALE

214

STEP 5
FIGURE 3.05

Install the upper pile cap by lowering it onto the lower one. Ensure all mortise and tenon joints are in full contact.

NOT TO SCALE

215

STEP 6
FIGURE 3.06

Repeat steps 1-6 for each required foundation. Foundations should sit 6m apart from one another, and should be level to ensure a strong connection is made to the shortpile and columns.

NOT TO SCALE

216

STEP 7
FIGURE 3.07

Place shortpile cross-shaped tenons into the mortise opening in the top of the pilecap.

NOT TO SCALE

STEP 9
FIGURE 3.09

Slide bolts into place and fix securely in both directions to ensure a stable shortpile component.

NOT TO SCALE

STEP 8
FIGURE 3.08

Place a galvanised steel shortpile bracket on each face of the shortpile. Align pre-drilled bolt holes.

NOT TO SCALE

217

STEP 10
FIGURE 3.10

Repeat steps 7-10 for every foundation installed. Depending on component supplies and deliveries, construction may be fast-tracked by installing all components of the same type at the same time.

Also ensure that each shortpile has its mirror opposite placed adjacent to it.

NOT TO SCALE

218

STEP 11 **FIGURE 3.11**

Lift and place columns on top of shortpiles, ensuring proper alignment between mortise and tenon joins. The two should slide freely into place.

Then slide two bolts into the pre-drilled channels running in each direction and secure on the other side with a nut, thus securing the columns to the shortpiles

NOT TO SCALE

219

STEP 12 **FIGURE 3.12**

Ensure that adjacent to each column is its mirrored opposite. If not adhered to, proper beam and brace connections cannot take place and the whole system is compromised.

NOT TO SCALE

STEP 13 **FIGURE 3.13**

Once all column components are in place and secured, attaching beams and braces can occur.

NOT TO SCALE

220

STEP 14 FIGURE 3.14

Ensure a consistent column spacing of 6m is occurring in both directions.

Columns should be level, with all necessary bolts securely fastened.

NOT TO SCALE

221

STEP 15 FIGURE 3.15

Begin by attaching the lower beams first, which slot into the top of the shortpiles.

Pictured below is a component C being installed, but either A or C beams can be installed at this stage, as they do not yet connect.

Ensure that correct components are being installed, and that an A beam and a C beam sit at each end of the bay.

NOT TO SCALE

222

STEP 16 FIGURE 3.16

Pictured is the aforementioned C beam being bolted into place using the pre-drilled channels at the tops of shortpiles and columns alike.

Ensure the beam component is securely seated in the column opening before bolting.

NOT TO SCALE

STEP 18 FIGURE 3.18

Here is an A component being seated and bolted into place. Channels are pre-drilled into both the beam and column/shortpile, so installation should be straightforward provided alignment and placement is correct.

NOT TO SCALE

223

STEP 17 FIGURE 3.17

Pictured below is an A beam component, which can be installed before or after C components are installed, provided they are in the right place.

NOT TO SCALE

224

STEP 19 FIGURE 3.19

Beams of type B can now be fitted and bolted into place, between beams A and C.

Guidance tenons are placed at each end to assist with alignment and installation.

NOT TO SCALE

225

STEP 20 FIGURE 3.20

Once seated in place, four bolts can be slid through each end of the beam, and fastened.

The importance of correctly installing beams A and C should be apparent at this stage. If not, beam B will not be able to fit into place. Luckily, if this does occur, the out of place component can easily be removed and the correct one can take its place.

NOT TO SCALE

STEP 21 FIGURE 3.21

A secure, complete lower beam should now be in place.

Repeat steps 15-21 for each required structural bay, in each x direction.

NOT TO SCALE

226

Once all lower beams are in place, steps 15-18 can be repeated to create the end beams.

STEP 22 FIGURE 3.22

NOT TO SCALE

227

Repeat steps 19-21 to complete upper beams.

Ensure all required bolts are in place and securely fastened.

STEP 23 FIGURE 3.23

NOT TO SCALE

228

Connect brace components A and B to one another, using two bolts in each direction to secure the joint in place.

Components should be light enough for this operation to be carried out manually or with little mechanical intervention.

STEP 24 FIGURE 3.24

NOT TO SCALE

229

Lift and lower complete braces into place. The lower end slots into a large mortise machined into the column, and should fit snugly.

The top of the brace fits into a mortise on the underside of beam components A and C.

STEP 25 FIGURE 3.25

NOT TO SCALE

230

This is how the brace should look once properly in position. Note the alignment between the top of the brace and the end beam components.

The bottom of the brace sits low on the column, minimising placement angle and reducing stress on the brace as loading occurs.

STEP 26 FIGURE 3.26

NOT TO SCALE

231

Once in position, the bottom of the brace can now be secured. Four large bolts run through pre-machined channels that run continuously through the brace and column components. Secure with a nut once bolt is in position.

Braces and bolts can run in both directions due to staggered bolt channels.

STEP 27 FIGURE 3.27

NOT TO SCALE

232

STEP 28 FIGURE 3.28

The top of the brace can now be secured as well. Two bolts run through the beam, into the pre-machined channels in the brace tenon, and through to the inside of the beam.

If proper alignment occurs, the bolts should slide through freely.

STEP 29 FIGURE 3.29

Opposing brace components can now be installed to complete the eccentric braced framing system.

Construction may be fast-tracked by installing both braces simultaneously.

Ensure that steps 24-28 are repeated in their entirety for both brace components.

Below is an illustration of a complete and functioning structural system, one which successfully carries gravity and lateral loads from the frames, into the foundations, at which point they act on the earth.

This structural frame runs in both directions to ensure loads in both directions are being adequately mitigated.

STEP 30 FIGURE 3.30

NOT TO SCALE

235

Flooring component supports need to be installed prior to the CLT floor components.

These support components slot freely into the shortpile and column corners.

STEP 31 FIGURE 3.31

NOT TO SCALE

236

Flooring supports are lightweight and can be installed manually, by 1-2 workers.

Note the level at which flooring supports sit, which is just below the beams.

Ensure you DO NOT install upper flooring supports prior to installing the lower CLT slabs, otherwise the slabs will not pass freely down to the lower level.

STEP 32 FIGURE 3.32

NOT TO SCALE

237

STEP 33 FIGURE 3.33

Lower complete floor components into place. This step will need to be undertaken carefully to ensure the frame does not become damaged during the installation process.

The floor should slot securely into the tops of the flooring supports.

The pin holes in the side of the floor should also align with openings in the side of the beams.

NOT TO SCALE

238

Slide floor pins into place, through beams and into the CLT floor slab.

Three pins connect to each side of the slab.

These pins are designed to work in conjunction with the floor supports to disperse loads from the floor, to the outer frame and down.

STEP 34 FIGURE 3.34

NOT TO SCALE

239

Pins can now be bolted into place from the slab-top.

The flooring component is now securely in place. Repeat for all lower flooring requirements before installing upper floors/ceiling elements.

STEP 35 FIGURE 3.35

NOT TO SCALE

240

STEP 36 FIGURE 3.36

The framing components for external walls can now be installed. These components can be installed in any order as they do not overlap or intersect.

The primary corner supports have a large number of bolts that can be connected, however they may not all be necessary, depending on build location and environmental conditions.

NOT TO SCALE

241

STEP 37 FIGURE 3.37

This is one face of the system with a wall frame attached. Each external face will need to have these frames installed in order to place glazing, door, and wall components.

Ensure that the upper frame has protruding tenons, while the lower frame has mortise attachments.

NOT TO SCALE

242

External walls and wall components can now be installed. Components should be lightweight enough to be installed manually by two workers.

Ensure that the end of the first wall slots into the corner tenon as pictured below.

The face of each frame can house either; 6 x 1m walls, 3 x 2m walls, or 2 x 3m walls.

NOT TO SCALE

243

STEP 38 FIGURE 3.38

STEP 39 FIGURE 3.39

The top of each wall slots into pre-installed tenons, which are then secured with bolts. Ensure a complete connection for weathertightness and code compliance.

NOT TO SCALE

STEP 40 FIGURE 3.40

The bottom of each wall component has tenons that sit on the lower wall frame. These are then bolted through and fastened securely.

NOT TO SCALE

244

Once external walls are in place, installation of internal walls can begin. The 2.4m primary panels must be installed first.

These should be light enough to be carried and installed by 2 workers safely.

Once in place the panels can be locked into position.

STEP 41 FIGURE 3.41

NOT TO SCALE

245

Once in place the panels can be locked into position.

Locking wheels or bolted connections into floor panels are the envisioned method for securing these panels.

STEP 42 FIGURE 3.42

NOT TO SCALE

246

Upper sacrificial panels can now be carried into place. These can be installed by hand, using 1-2 workers.

Panels can be modified to allow for services before or after installation.

STEP 43 FIGURE 3.43

NOT TO SCALE

247

These upper panels can now be fastened securely into place at both the lower and upper ends, using bolts through pre-machined channels.

STEP 44 FIGURE 3.44

NOT TO SCALE

248

Repeat as necessary.

Internal wall panels should also be connected to one another laterally once in place.

To minimise the number of connections needed, use fewer large panels instead of more small ones.

STEP 45 FIGURE 3.45

NOT TO SCALE

249

Install the ceiling services strut.

This is a lightweight component that can be manually carried into place.

This component can be modified depending on floor plan and wall placement.

STEP 46 FIGURE 3.46

NOT TO SCALE

250

Once the services strut is in place, design specific elements can be introduced. Elements such as;

- Roofing
- Joinery
- Furniture
- Storage
- Services
- Decoration
- Painting walls

STEP 47 FIGURE 3.47

NOT TO SCALE

251

+3.2 - REFLECTIONS

WHAT THE SYSTEM DOES WELL

In exploring construction and system assembly, it becomes clear that the system is simple, straightforward, and logical. It highlights the large number of bolted and reversible connections, adhering to the DfD success criteria. The system is revealed to be well thought out, featuring pre-machined channels for bolts to pass through. These channels are staggered to allow for multi-directional connections. Overall, the construction process is streamlined and minimises work and problem-solving required on-site. This saves time, materials, labour, and money. It also minimises waste produced as nothing needs to be cut, sanded, planed, adjusted, or otherwise interfered with in any way.

WHAT THE SYSTEM DOES NOT DO WELL

The system fails to be successful in certain aspects. As previously discussed in chapter 2, this researcher is not an engineer, and cannot design with complete structural confidence. This system relies on bolted connections, which have the risk of shearing under excess load. There is also a large reliance on crane lifts to install components. Construction would be further streamlined by reducing or eliminating the number of requisite crane lifts. In exploring construction and how pieces go together, it is also revealed that certain problems are unresolved or have been overlooked. This is particularly apparent in the design of wall, floor, and services components. The construction system does not cover bespoke elements such as roofing, joinery, or finishing and furnishing, which could be a place for further development.

TAKING THIS RESEARCH FURTHER

As previously mentioned, certain elements of construction have been overlooked. Testing and developing components in the physical realm is needed to resolve some of these issues. Exploring and developing elements of a building that this research has not focussed on is needed, such as roofing.

Testing the strength of components and connections is needed, which would require assessment from an engineer or building scientist. Assessing the weight of components is also necessary to develop construction, as it would determine which elements can be installed by hand and which cannot.

Physical modelling, engineering consultation, detail development, and strength/weight testing would all improve how the system goes together in a real-world construction scenario.

WHAT HAS THE CONSTRUCTION PROCESS REVEALED?

No matter what you do, or how hard you try, you can only simplify the construction process so far. Construction is always a complex and painstaking process, that involves trial and error that may never be designed out. Understanding that a viable design that can actually be constructed takes a team of collaborating professionals years to develop is perhaps no surprise but can sometimes be forgotten. Testing this system through the construction process has been extremely useful in understanding its weaknesses and areas for improvement.

CHAPTER 4

DECONSTRUCTION

CHAPTER OVERVIEW

- 4.1 - RESEARCH
- 4.2 - DECONSTRUCTION
- 4.3 - STORAGE
- 4.4 - TRANSPORTATION
- 4.5 - REFLECTION

CHAPTER 4 STATEMENT

This chapter explores, outlines, and discusses steps and issues surrounding deconstruction and reuse of the system. It explores storage methods and places suited for storage, as well as transportation.

Reflections are undertaken on the issues and shortcomings of the explored deconstruction, storage, and transportation systems proposed. In methodology terms, it is design delivery as well as defining and questioning, due to the reflective and critical nature of the research.

**FIGURE 4.01 -
STANDARD CONTAINERS**

COMMON CONTAINER SIZING

Research into the common types of shipping container is essential in understanding common transportation/distribution systems and volumes. Exploring and understanding logistical hurdles is a key aspect in the success of this research.

The 20ft general container is assumed to be the most common container type, due to its compact length when compared to its 40ft counterpart. However, the system may not fit well within this dimension, due to the significant size of certain components.

The 40ft general container has double the cubic capacity, and is capable of a higher cargo weight. At 12m in length it can easily fit system components that may be too long for 20ft storage.

High cube alternatives exist for both 20ft and 40ft containers, and are well suited to any bulkier components such as floors or walls.

All container information sourced from - Mainfreight (2015)

**FIGURE 4.02 -
DECONSTRUCTION BASICS**

+ 4.2 - DECONSTRUCTION

DECONSTRUCTION STEPS

As previously mentioned, deconstruction of any building that uses the system follows a basic reversal of chapter 3 (construction). The following logic applies:

1. Remove all non-structural elements first, such as walls and MEP systems
2. Once stripped down to its structure, start removing uppermost elements and work your way down
3. Remove braces before beams and columns for obvious safety reasons
4. Foundations will be the last elements to be removed
5. Deconstruction will likely be occurring after a significant passage of time. Bolts may require cleaning, loosening, or mechanical assistance to be freed.
6. Keep all parts possible, including nuts and bolts

Components should be cleaned and checked upon dismantling, and any damaged parts should be set aside for refurbishment.

**FIGURE 4.03 -
STORAGE OPTIONS**

CRITERIA	WEATHER PROTECTION	THEFT DETERRENT	LONG TERM	MOISTURE PROTECTION	TRANSPORTABLE	SPATIALLY EFFICIENT	EXPENSIVE	SUITABLE?
STORAGE TYPE								
WAREHOUSE FACILITY	Y	Y	Y	Y	N	N	Y	N
SHIPPING CONTAINERS	Y	Y	Y	Y	Y	Y	Y	Y
OUTDOORS COVERED	N	N	Y	N	N	N	N	N
OUTDOORS UNCOVERED	N	N	N	N	N	N	N	N

STORAGE OPTIONS

Proper systems storage is vital to its longevity and reuse potential. It is inevitable that between deconstruction and reuse, a period of storage will need to take place. Storage options vary greatly. The adjacent matrix outlines four of the most viable options.

Weather protection is important in system storage, despite components being treated as per the NZBC. Components should not be left outside or exposed, at the risk of significantly reducing lifespans.

As the adjacent matrix shows, shipping containers are the most logical storage option. They meet all requisite criteria, with the only drawback being a high cost option. The cost implications of selecting container storage will be discussed in the chapter reflection.

Container storage offers strong, safe, and long term storage out of the elements. They come in standard sizes, are easy to stack and store, and unify storage and transportation systems well. How many containers are required to store the system needs to be explored.

**FIGURE 4.04 -
CONTAINERS IN STORAGE**

Storage of bulk amounts of containers is easily achieved at any port, warehouse, airport, or storage facility.

Facilities of this kind are highly secure and the risk of theft is minimal.

The cost implications of storing items at a facility such as this will likely be high, especially if it is for long periods of time.

**FIGURE 4.05 -
STORING THE SYSTEM**

+ 4.3 - STORAGE

STORING THE SYSTEM

With shipping containers affirmed as the logical and preferable system of storage, it needs to be figured out how many containers might be required for one bay of the system (6x6m grid). One bay of the system can form part of a larger structure or stand on its own as a small scale structure. One bay of the system consists of:

FOUNDATIONS

16x Base piles
32x Extension piles
4x Lower pile-caps
4x Upper pile-caps
4x Short-piles

BRACED FRAMES

4x Columns
8x Beam A
8x Beam B
8x Beam C
8x Braces

FLOORING

2x CLT plates, able to be separated into halves

EXTERNAL WALLS

6x 2m walls
12x 1m walls

**FIGURE 4.06 -
CONTAINER ONE**

40FT STANDARD SHIPPING CONTAINER

+ 4.3 - STORAGE

STORING THE SYSTEM

Container one is a 40ft general, with standard cube height. It fits all of the required base piles, all of the required extension piles, and both the upper and lower pile cap parts. It also fits the short piles that sit above ground. This container essentially houses the entire foundation system for one structural bay.

- ④ 4X SHORT PILES
- ③ 4X LOWER PILE CAPS
4X UPPER PILE CAPS
- ② 16X BASE PILES
8X EXTENSION PILES
- ① 24X EXTENSION PILES

**FIGURE 4.07 -
CONTAINER TWO**

40FT STANDARD SHIPPING CONTAINER

+ 4.3 - STORAGE

STORING THE SYSTEM

Container two is a 40ft general, with standard cube height. It contains the all structural elements required to create the braced frames. It also contains the CLT floor elements, split into halves in order to fit into the containers.

- 1 4X COLUMNS
- 2 8X BEAMS
- 3 8X BRACES
- 4 2X FLOORS

**FIGURE 4.08 -
CONTAINER THREE**

20FT HIGH CUBE CONTAINER

STORING THE SYSTEM

Container three is a 20ft high cube. It contains approximately half of the external wall requirement (for four sides). Six 2m wall panels are capable of covering 2 of the systems faces.

1 6X 2M WALL PANEL

**FIGURE 4.09 -
CONTAINER FOUR**

20FT HIGH CUBE CONTAINER

+ 4.3 - STORAGE

+ CHAPTER 04

STORING THE SYSTEM

Container four is a 20ft high cube. It contains the other half of the external wall requirement. It consists of twelve 1m wall panels, capable of covering 2 of the systems faces

- ① 6X 1M WALL PANEL
- ② 6X 1M WALL PANEL

**FIGURE 4.10 -
TRANSPORT LIMITATIONS**

+ 4.4 - TRANSPORTATION

ROADING

The New Zealand roading network is the most flexible and comprehensive system when compared to domestic shipping and rail. A 2019 report published by the Ministry of Transport outlines the current and future national freight demand. Road transport dominates by far, transporting 92.8% of all freight (R. Paling et al., 2019. p.ii), measured in tonnes. By tonnes per kilometre, roading is responsible for 75%. This is reported as a 16% growth from 2012 (p.3). The report estimates a total of 22.6 billion tonne-kms were transported by road in 2017/18. This shows that transportation of goods by road is definitively dominant in New Zealand and will likely remain as such for the foreseeable future.

Depending on a road network for freight and transportation is not without downsides. Road congestion is a significant issue in major centres and will only increase in severity with the population. New Zealand roads (outside of Auckland) are not sophisticated. Median barriers are rare, as are passing lanes and dual lane roads. Using roads to transport freight adds significant numbers of heavy trucks, which are slow and create safety concerns for civilian travellers. The carbon emissions caused by the road freight network is also of concern. Transporting freight by truck emits 0.136 tkm (tonnes per kilometre), roughly five times the emissions caused by rail (MfE, 2019. p.15-16).

Transporting freight by road is fast and reliable. It is a well-used and well tested method of transport, but it contributes significantly to road congestion and carbon emissions.

SHIPPING

Shipping is not a significant contributor to the transportation of freight in New Zealand. It currently accounts for 1.6% of goods moved nationwide (R. Paling et al., 2019. p.ii). Shipping in New Zealand is primarily for international import and export, with the Port of Tauranga being the busiest port in the country (R. Paling et al., 2019. p.10). Despite the lack of local interest, freight moved by ship domestically has grown 12% since 2012 (R. Paling et al., 2019. p.3), a potential indicator for future growth. Carbon emissions for transport by ship is also relatively low, at 0.045 tkm (tonnes per kilometre) of carbon dioxide (MfE, 2019. P.15-16).

Transportation by ship is unlikely unless goods are being transferred between islands, in which case goods will most likely stay on a transport truck and travel over the Cook Strait via ferry. An uptake in domestic shipping is not foreseeable, in part due to the significant overhead costs involved.

RAIL

Domestic freight transport via rail has declined 17% since 2012 (R. Paling et al., 2019. p.i), in part due to the Kaikoura earthquake of 2016. As a result, rail is only responsible for 5.6% of total freight movement in New Zealand. The New Zealand rail network is not expansive, nor is it flexible in nature. Rail does reduce road congestion, carbon emissions, road danger, and road maintenance, all by reducing the demand of heavy trucks. Carbon emissions are significantly lower than by road, at 0.028 tkm, the lowest emission rate out of the three transportation sources assessed. This is despite the fact that the national rail network does not possess electric or low emissions technology.

Transportation by rail is best suited to longer distances, being less sustainable and logical for shorter hauls. Part of the problem with rail is that New Zealand is a small country consisting of two islands, making the distances travelled by rail relatively short. Unless there is significant investment in the rail network and its capabilities, freight transportation will remain on the roads.

RAIL LINES IN NZ'S NORTH ISLAND
FIGURE 4.11

0 30 60 120km

City stop +
Rural stop •
Freight and Passenger line —
Freight only line ·····

PORTS, SHIP ROUTES, AND SH 1 IN NZ
FIGURE 4.12

Tasman Sea.

North Island.

South Pacific Ocean.

2. AUCKLAND

1. TAURANGA

4. NAPIER

6. WELLINGTON

3. LYTTLETON

5. OTAGO

Foveaux Strait.

South Island.

0 50 100 200km

State Highway 1 —
Shipping Route - - -

1. Tauranga 4. Napier
2. Auckland 5. Otago
3. Lyttleton 6. Wellington

1 State Highway 1 runs the length of New Zealand, and is the nations primary arterial road.

**FIGURE 4.13 -
BY TRUCK**

“

**92.8% OF FREIGHT IN NZ IS
TRANSPORTED BY ROAD.**

(R. Paling et al., 2019, p.ii)

”

**FIGURE 4.14 -
BY SHIP**

“

**SHIPPING IN NEW
ZEALAND IS PRIMARILY
FOR INTERNATIONAL
IMPORT AND EXPORT, WITH
THE PORT OF TAURANGA
BEING THE BUSIEST IN THE
COUNTRY.**

”

(R. Paling et al., 2019, p10)

**FIGURE 4.15 -
BY TRAIN**

“

**DOMESTIC FREIGHT
TRANSPORT VIA RAIL (IN
NZ) HAS DECLINED 17%
SINCE 2012.**

(R. Paling et al., 2019, p.i)

”

**FIGURE 4.16 -
BY AIR**

“

**BECAUSE YOU CANT GET
EVERYWHERE BY ROAD.**

”

THE GOOD

Exploring deconstruction has provided an awareness of what is required to take down, store, and transport the system nationwide. One bay alone is a significant task, let alone a whole building worth of components.

This research has also further enabled circular construction by theoretically exploring how these logistical tasks could be undertaken.

Proper storage can be identified as massively important in retaining the quality of components.

OPTIONS FOR REFURBISHMENT

After deconstruction, damaged components can be taken out of circulation and refurbished before being re-used. This is not something that would have been thought of if deconstruction research had not taken place. Refurbishment better allows components to be reused through routine maintenance, whilst also enhancing quality control.

COST IMPLICATIONS

It must be identified that cost implications became clear as deconstruction research was undertaken. The time and resources involved in deconstructing a building piece by piece cost exponentially more than traditional demolition.

There is also a large cost involved with storage. Shipping containers must be purchased, and a facility in which to store unused components must be paid for. These are significant upfront costs that would discourage most, if not all developers and contractors.

Transport costs are already a part of the industry and are a necessary cost to get materials to site, as a result transportation should not be seen as a negative factor.

LOGISTICAL ISSUES

Certain logistical issues have become apparent in this chapter. As previously mentioned, there are the high costs of deconstruction and storage, but there are hidden costs to be identified in relation to logistics. A nationwide supply chain would need to exist in order for components to be circulated effectively. An accurate inventory, a refurbishment centre, trucks, containers, employees, and digital systems would all need to be in place in order for the system to be successfully distributed.

TAKING THIS RESEARCH FURTHER

The storage and transportation of only one bay of the system has been explored in this chapter. As a result, there are major inefficiencies related to container storage and packing. If multiple bays of the system were explored for storage, containers could be packed far more efficiently.

Flooring elements were also very difficult to store. Re-designing these components for transportation would be beneficial in furthering this research.

Re-scoping internationally, calculating actual costs, further exploring refurbishment, and optimizing components for transportation would all be routes to furthering this research.

CHAPTER

COMMERCIAL IMPLEMENTATION

CHAPTER OVERVIEW

- 5.1 - INTRODUCTION
- 5.2 - SITE ANALYSIS
- 5.3 - PROCESS
- 5.4 - DRAWINGS
- 5.5 - RENDERS
- 5.6 - REFLECTIONS

CHAPTER 5 STATEMENT

This chapter is the first evolution of the system, and tests its implementation in a large scale commercial setting. This is 'the first lifetime' of the system being tested through theoretical implementation.

The implementation is then assessed against success criteria with its shortfalls identified. This chapter marks a departure from system delivery and refinement, instead testing it through experimental implementation. Reflections on shortcomings will help to strengthen the research.

**FIGURE 5.01 -
SITE LOCATION**

+ COMMERCIAL IMPLEMENTATION

WHO

This implementation is intended primarily for commercial use, however as it is sited in a prominent position on Wellington's waterfront, it will also be used and enjoyed by the public.

WHAT

A commercial office/mixed use building that fully utilises the system and its capabilities, designed in keeping with the scale and style seen on Wellington waterfront.

WHEN

This implementation is designed and intended for the site as of 2020/2021, as it is currently unoccupied and a perfect site to test and develop the system upon.

WHERE

Site 9, North Kumototo, Wellington waterfront/CBD.

WHY?

Central Wellington is the ideal testing ground for a structural system and how it might work, due to the region's high seismic and wind load requirements. The context of central Wellington also works to compare and contrast a commercial implementation against existing structures.

WELLINGTON TRANSPORT AND SOLAR ANALYSIS FIGURE 5.04

SUBSOIL OF WELLINGTON'S WATERFRONT FIGURE 5.05

HEIGHT RESTRICTIONS FIGURE 5.08

SITE RESTRICTIONS FIGURE 5.09

Net Area: 800-810m²

**FIGURE 5.10 -
PROCESS SKETCHES**

- Leaves on facade - adjustable
- or exposed structure
- Leaves adjustable sliding on front facade aligns with tube house exterior exclusivity.
- Exposed structure on sides rear of building

**FIGURE 5.11 -
PROCESS SKETCHES**

PUBLIC GALLERY/MUSEUM ADAPTION

AVIARY

**FIGURE 5.12 -
PROCESS SKETCHES**

**FIGURE 5.13 -
PROCESS SKETCHES**

+ COMMERCIAL IMPLEMENTATION

+ CHAPTER 05

- ① The proposed development sits at the forefront of Wellington's northern CBD.
- ② Arterial highways are adjacent to the site, and provide both an opportunity for exposure and a noise constraint.
- ③ Whitmore Plaza will undoubtedly be improved/completed with the addition of this implementation, sited between the PWC centre and Site 9.
- ④ Plenty of foot traffic will also pass in close proximity to the building, providing an opportunity for mixed use occupations at ground level.
- ⑤ As outlined in site analysis, the site does have significant challenges due to its placement on reclaimed land. The wet soil is optimal for the helical foundations however, working actively to preserve the water-laden timbers.

+ COMMERCIAL IMPLEMENTATION

+ CHAPTER 05

- 1 *Curtain wall façades provide views out to Wellington harbour while also providing north facing sun.*
- 2 *Vertical louvres work to mitigate the effects of overglazing.*
- 3 *Rooftop access provides building users an opportunity to make use of roof space, for a rooftop garden or activity area.*
- 4 *The ground floor main entrance is at the structural fuse between wings of the building, making use of existing pathways for foot traffic.*
- 5 *Exposed timber structure creates visual interest and serves as ornamentation of sorts.*

**FIGURE 5.16 -
STRUCTURE**

NOT TO SCALE

311

+ COMMERCIAL IMPLEMENTATION

+ CHAPTER 05

- ① *The base 6x6m structural system designed in chapters 2,3,4.*
- ② *Vertical building access*
- ③ *Double-glazed curtain wall façades*
- ④ *Central atrium allows for easy negotiation of the building, and is designed to house all circulation, as well as MEP services.*
- ⑤ *Secondary escape stair*

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**FIGURE 5.17
GROUND FLOOR PLAN**

Spaces within the system's 6x6m span are flexible to adjustment as well as spacious.

Central atrium provides a clear entry and exit point for the building.

Office layout is an example only. The absence of load-bearing walls means that spaces can be arranged and changed with ease.

A restaurant or retail space at ground level will undoubtedly attract interest and business from pedestrians.

Structural braces aim to be of minimal interruption to building users.

**FIGURE 5.18
TYPICAL UPPER FLOOR PLAN**

+ CHAPTER 05

The proposed building provides plenty of floor space for a large commercial structure. ①

Upper floors cantilever over Whitmore plaza. ②

Double-glazed curtain wall facades ③

Walkways provide building access at each level. ④

COMMONWEALTH WALKWAY

FIGURE 5.19
BUILDING SECTION

- ① Central atrium and walkway serve as the heart of the building, providing access and services.
- ② Rooftop can be used for a multitude of things, depending on occupant needs/desires.
- ③ 6x6m structural bays provide a clear and regular spatial separation.
- ④ Large cantilevers provide visual interest and showcase the capabilities of engineered timber.
- ⑤ Ramps allow wheelchair access to the building, despite the building being on shortpile foundations.

FIGURE 5.20
SERVICES INTERACTION

- ① 4m floor to floor height means there is no shortage of space for services to be installed.
- ② Angled braces can easily be worked around.
- ③ While internal walls are not pictured here, their 1.6m sacrificial upper section allows for easy services integration.
- ④ High ceilings ensure that office spaces do not feel cramped or small.

FIGURE 5.21
EXPERIENCE

FIGURE 5.22
EXPERIENCE

FIGURE 5.23
EXPERIENCE

FIGURE 5.24
EXPERIENCE

DOES IT MEET DFD SUCCESS CRITERIA?	
1. DESIGN FOR COMPONENT REUSE	<div>Y</div>
2.DESIGN FOR OFFSITE AND MODULAR CONSTRUCTION	<div>Y</div>
3. DESIGN ACCESSIBLE AND NON-CHEMICAL CONNECTIONS	<div>Y</div>
4. SPECIFY DURABLE AND VALUABLE MATERIALS	<div>Y</div>
5. CONSIDER MATERIAL HANDLING	<div>Y</div>
6. USE A STANDARD STRUCTURAL GRID	<div>Y</div>
7. DESIGN FOR ADAPTABILITY	<div>Y</div>
8. MINIMISE BUILDING ELEMENTS, SIMPLIFY STRUCTURE AND FORM	<div>Y</div>
9. USE LAYERING APPROACH AND SEPARATE MEP SYSTEMS	<div>Y</div>
10. USE RETRACTABLE FOUNDATIONS	<div>Y</div>

+ CHAPTER 05

DFD SUCCESS CRITERIA

As the system has already been designed and assessed against this criteria, the question is whether or not this implementation has jeopardised any of the criteria met. Most importantly, the separation of building layers and MEP systems, as well as maintaining accessible connections. These appear to be upheld in the proposed design, however could easily be undone by a tenant or client with differing design sensibilities.

THE GOOD

A relatively realistic commercial implementation of the system has been proposed, on a currently unused site in a prime location. It is prominent, but fits within the bulk and scale of its surroundings, enhancing the waterfront precinct. It is a striking and engaging structure, yet minimal and simple, in keeping with DFD values.

DESIGN FLAWS

The implementation is meant as a rapid means in which to evolve and test the system. This means that there are inherent design flaws and areas not fleshed out in the design. Bathroom design and variability in office layout are noticeably flawed, however the ideas that they represent are still sound. The large cantilever has not been engineered, and would likely be incredibly expensive to build with engineered timber on helical screw foundations.

TAKING THIS IMPLEMENTATION FURTHER

Further design development, resolution of layout issues, services design, engineering assessment, and physical modelling would all be beneficial routes for furthering this research implementation.

CHAPTER

RESIDENTIAL IMPLEMENTATION

CHAPTER OVERVIEW

6.1 - INTRODUCTION

6.2 - SITE ANALYSIS

6.3 - PROCESS

6.4 - DRAWINGS

6.5 - RENDERS

6.6 - REFLECTIONS

CHAPTER 6 STATEMENT

This chapter is the second evolution of the system, and tests its implementation in a large scale residential mixed use scenario. This is 'the second lifetime' of the system being tested through theoretical implementation.

The implementation is then assessed against previously established success criteria with its shortfalls identified. Testing how the same construction system works across commercial and residential use is the purpose of this chapter.

**FIGURE 6.01 -
SITE LOCATION**

+ RESIDENTIAL IMPLEMENTATION

WHO

This implementation is a test of the system's ability to adapt to a residential use, and is intended for a family or group of tenants. The ground floor will house a retail space as a source of income.

WHAT

A large residential structure in the heart of Wellington central, on Cuba Street. A pedestrian street, it is a significant precinct for the city's culture. The ground floor of the development will make use of foot traffic and house a retail/commercial space.

WHEN

This implementation is designed for present day/near future Wellington city. It is the 'second lifetime' of the system, and could be constructed from parts of implementation one.

WHERE

Cuba street, Wellington central.

WHY?

To test how the system works in a residential environment, showcasing adaptability and spatial flexibility. How the system looks and feels in a variety of uses. Central Wellington also works to maintain regional locality to the design implementations, in keeping with sustainable goals.

WELLINGTON TRANSPORT AND SOLAR ANALYSIS

FIGURE 6.04

June 21 - Winter Solstice
Sunrise 7:33 a.m.
Sunset 5:11 p.m.

December 21 - Summer Solstice
Sunrise 5:58 a.m.
Sunset 8:39 p.m.

+ Bluebridge Ferry Terminal
+ Harbour Ferry Terminal
+ Wellington Central Train Station
+ Wellington Bus Terminal

Soil type D
Soil type C

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FIGURE 6.05

SITE ANALYSIS

SCALE 1:500 @A4

340

FIGURE 6.06 -
PROCESS SKETCHES

FIGURE 6.07 -
PROCESS SKETCHES

FIGURE 6.08 -
PROCESS SKETCHES

FIGURE 6.09 -
PROCESS SKETCHES

**FIGURE 6.10 -
STRUCTURE**

NOT TO SCALE

345

+ RESIDENTIAL IMPLEMENTATION

+ CHAPTER 06

- ① 6x6m system bays.
- ② External walls, most likely consisting of 3m panels.
- ③ Double glazed facade facing street, with vertical louvres for sun and privacy.
- ④ Roofing consists of double glazed glass panels to maximise light and verticality on a narrow site.
- ⑤ Front door and retail entrance side-by-side but separate.

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**FIGURE 6.11 -
SITE PLAN**

+ RESIDENTIAL IMPLEMENTATION

+ CHAPTER 06

- 1 Residential implementation is sited in a busy area of Cuba street, its upper levels cantilevering slightly over the street to act as an awning for pedestrians.
- 2 Ghuznee street nearby is not an arterial road for the city, but is busy during peak hours.
- 3 Hotel Bristol, a bar and restaurant, is just across the road from the implementation, providing light and noise pollution to mitigate.
- 4 Large buildings flank either side of the implementation and limit the practicality of windows on the building's sides. This increases the importance of the front, rear, and top façades.
- 5 Glover park is also nearby and serves as the nearest green space.

**FIGURE 6.12 -
GROUND FLOOR PLAN**

- ① Dedicated residential and retail entries guarantee privacy and security.
- ② Cantilever acts as an awning for pedestrians, useful shelter from the rain.
- ③ Large and adaptable retail space, plenty of space for most inner-city small/boutique stores.
- ④ Changing rooms at the back to maximise security as well as privacy.
- ⑤ System structure can act as a useful spatial divider instead of an obstacle.

**FIGURE 6.13 -
FIRST FLOOR PLAN**

- ① Bedrooms are large, with enough room for a double bed, desk, and storage with plenty of room in which to manoeuvre.
- ② Bedroom 3, at the end of the hall, is slightly larger due to the absence of the hallway.
- ③ Bathroom is fully wheelchair accessible, yet compact.
- ④ Dedicated laundry space adjacent to bathroom means services are closer together and require less plumbing to operate.
- ⑤ The hallway is long, but this is largely unavoidable due to the shape of the site and resulting structure.

**FIGURE 6.14 -
SECOND FLOOR PLAN**

- ① Master bedroom is spacious, with a walk-in wardrobe and ensuite adjacent.
- ② Bedroom 4 is the same size as bedrooms 1-3.
- ③ The study could alternatively be used as a storage space
- ④ Rear window is floor to ceiling and illuminates the master bedroom with filtered light.

**FIGURE 6.15 -
THIRD FLOOR PLAN**

- ① Kitchen is large and spacious, with separate pantry.
- ② Office at the back could also be used as a guest room, or for storage.
- ③ 6x6m bay size is large enough to house a spacious dining area.
- ④ Open living/dining receives plentiful light from the glass roof above.
- ⑤ Front facade overlooks Cuba Street and Mount Victoria.

**FIGURE 6.16 -
CUBA STREET ELEVATION**

- ① *Facade louvres provide privacy against street level.*
- ② *Separate entry points, but residential entry still gets safety benefits from busy street/passive surveillance.*
- ③ *Building blends into its surroundings, being of similar size and shape to the building next to it.*

**FIGURE 6.17 -
LONGITUDINAL SECTION**

- ① The system can be seen clearly in the background, an active participant of the space.
- ② Vertical circulation will be well lit by front facade.
- ③ Open living floor will likely serve as the hub of the home.
- ④ Opportunity for informal spaces in cantilevered area

FIGURE 6.18 -
EXPERIENCE

FIGURE 6.19 -
EXPERIENCE

+ CHAPTER 06

FIGURE 6.20 -
EXPERIENCE

FIGURE 6.21-
EXPERIENCE

DOES IT MEET DFD SUCCESS CRITERIA?	
1. DESIGN FOR COMPONENT REUSE	<div>Y</div>
2.DESIGN FOR OFFSITE AND MODULAR CONSTRUCTION	<div>Y</div>
3. DESIGN ACCESSIBLE AND NON-CHEMICAL CONNECTIONS	<div>N</div>
4. SPECIFY DURABLE AND VALUABLE MATERIALS	<div>Y</div>
5. CONSIDER MATERIAL HANDLING	<div>Y</div>
6. USE A STANDARD STRUCTURAL GRID	<div>Y</div>
7. DESIGN FOR ADAPTABILITY	<div>Y</div>
8. MINIMISE BUILDING ELEMENTS, SIMPLIFY STRUCTURE AND FORM	<div>Y</div>
9. USE LAYERING APPROACH AND SEPARATE MEP SYSTEMS	<div>Y</div>
10. USE RETRACTABLE FOUNDATIONS	<div>Y</div>

+ CHAPTER 06

DFD SUCCESS CRITERIA

As the system has already been designed and assessed against this criteria, the question is whether or not this implementation has jeopardised any of the criteria met. This implementation calls to question accessible connections and adaptability. As the structure is sandwiched between existing buildings, fixing external walls would be impossible due to their external bolting system. Adaptability is limited, in part due to the site and its narrow nature. However, as internal walls are removable, the spaces could be adapted for other purposes. All other criteria have been upheld.

THE GOOD

An expansive large scale residential/mixed use design has been proposed, and a relatively realistic design has been created. Open and flexible living spaces have been created, as well as large bedrooms and sufficient amenities.

DESIGN FLAWS

Light would be a major issue in this implementation. Bedrooms and hallways would be very dark and artificially lit. The building may feel claustrophobic due to its narrow nature and long hallways. It would also be very expensive. A four storey family home on Cuba street is not entirely feasible, nor is a tenancy option for a structure that large and luxurious. The building would be very expensive to build, and the retail space would take a long time to offset this cost.

TAKING THIS IMPLEMENTATION FURTHER

Redesigning and compacting this implementation for a tenancy situation or individual apartment units, physical modelling, engineering the cantilever, resolving how to fix external walls, and figuring out how to get natural light into spaces would all be beneficial to taking this research further.

CHAPTER

SMALL-SCALE IMPLEMENTATIONS

CHAPTER OVERVIEW

- 7.1 - INTRODUCTION
- 7.2 - SITE ANALYSIS
- 7.3 - PROCESS
- 7.4 - DRAWINGS
- 7.5 - RENDERS
- 7.6 - REFLECTIONS
- 7.7 - INTRODUCTION
- 7.8 - SITE ANALYSIS
- 7.9 - PROCESS
- 7.10 - DRAWINGS
- 7.11 - RENDERS
- 7.12 - REFLECTIONS

CHAPTER 7 STATEMENT

This chapter is the third evolution of the system, and tests its implementation through two small scale rural scenarios. This is 'the third lifetime' of the system being tested through theoretical implementation.

The implementation is then assessed against previously established success criteria with its shortfalls identified. These evolutions of the system are testing how the system works in small scale, remote settings. It works in commercial and residential, making small scale the natural next test. Critical reflection will reveal how well the experimental implementation works.

**FIGURE 7.01 -
SITE LOCATION**

+ SMALL-SCALE IMPLEMENTATIONS

WHO

These small scale implementations largely serve to test the system's integration into New Zealand's natural environments. As a result, building users are those who utilise and enjoy those same environments. Skiers, trampers, travellers, are all part of the user demographic.

WHAT

This implementation is a small alpine hut, or ski chalet. It is meant for those staying on Mt. Ruapehu for skiing, snowboarding, mountaineering, or relaxing. It must provide all the expected necessities of a standalone hut, whilst also being comfortable and enjoyable.

WHEN

This implementation is designed as the 'third lifetime' of the system, meaning it has the potential to be constructed with pieces from the residential or commercial implementations. This said, its construction could take place centuries from now.

WHERE

The eastern face of Mt. Ruapehu, the North Island's only operational ski field. Mt. Ruapehu is also an active volcano, adding an avoidable risk factor for users and an unavoidable design constraint.

WHY?

To test how the system can integrate into small scale use and also work in New Zealand's natural environments. Assessing how well the system works at a small scale completes the research assessment on cross-scale suitability.

+ SMALL-SCALE IMPLEMENTATIONS

+ CHAPTER 07

- ① Large rocky outcrops in the area help to shelter the structure from wind.
- ② North facing glazing utilises natural light effectively.
- ③ Steep gradients require extensive foundation piles.

FIGURE 7.03 -
PROCESS SKETCHES

FIGURE 7.04 -
PROCESS SKETCHES

+ SMALL-SCALE IMPLEMENTATIONS

+ CHAPTER 07

- ① *North facing structure utilises natural light and maximises view shafts over central plains.*
- ② *No surrounding buildings to contend with.*
- ③ *Placement in a rocky area ensures ski routes are not interrupted.*
- ④ *Entry and exit point is at the south side of the building, facing the slope for practicality and accessibility.*

FIGURE 7.06 -
STRUCTURE

NOT TO SCALE

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- ① 6x6m structural system bays.
- ② Bespoke roofing structure and elements.
- ③ External walls consisting of 1m wide window panels, and 1-2m wall panels.
- ④ Wrap-around decking system attaches to primary structure.
- ⑤ North facing glazing system.
- ⑥ Foundations, made up of system components.

**FIGURE 7.07 -
GROUND FLOOR PLAN**

- ① Small bedrooms to prioritise living and social spaces. Small bedrooms are also easier to heat in winter.
- ② Large amount of storage space in hallway.
- ③ Kitchen and bathroom adjacent to group services requirements, lessening plumbing requirements.
- ④ Large living and dining space for occupants. Heating one large space is more efficient than a number of small spaces in the winter time.
- ⑤ North facing curtain wall with sliding door for deck access.
- ⑥ Separate laundry for washing and drying clothes.

**FIGURE 7.08 -
NORTH ELEVATION**

- ① Structure is elevated significantly from ground level at the northern end.
- ② Wrap-around deck allows for interaction between skiers and structure.
- ③ Sloping roof mitigates heavy rains while being strong enough to handle snow loads.

**FIGURE 7.09 -
LONGITUDINAL SECTION**

- ① Warm, dry, comfortable interior environment.
- ② Clear separation between social and private space.
- ③ Large kitchen and living spaces mean a large group of adults can be catered to.
- ④ Structural system contributes to architectural character of the space.

FIGURE 7.10 -
EXPERIENCE

FIGURE 7.11 -
EXPERIENCE

**FIGURE 7.12 -
EXPERIENCE**

DOES IT MEET DFD SUCCESS CRITERIA?	
1. DESIGN FOR COMPONENT REUSE	Y
2.DESIGN FOR OFFSITE AND MODULAR CONSTRUCTION	Y
3. DESIGN ACCESSIBLE AND NON-CHEMICAL CONNECTIONS	Y
4. SPECIFY DURABLE AND VALUABLE MATERIALS	N
5. CONSIDER MATERIAL HANDLING	N
6. USE A STANDARD STRUCTURAL GRID	Y
7. DESIGN FOR ADAPTABILITY	Y
8. MINIMISE BUILDING ELEMENTS, SIMPLIFY STRUCTURE AND FORM	Y
9. USE LAYERING APPROACH AND SEPARATE MEP SYSTEMS	Y
10. USE RETRACTABLE FOUNDATIONS	Y

+ CHAPTER 07

DFD SUCCESS CRITERIA

As the system has already been designed and assessed against this criteria, the question is whether or not this implementation has jeopardised any of the criteria met. This implementation is particularly concerned with durability of materials due to the harsh alpine environment, as well as material handling. Timber components would need to be treated to the highest possible level due to the cold, exposed, wet, snowy environment. Still, there would be significant wear on exposed components. This reduces lifetime and reduces the likelihood of reuse.

THE GOOD

A small, compact, realistic ski hut has been designed, with all amenities provided. It has been designed to perch on the side of the mountain and provide stunning views of the central plateau. Its wrap-around decks invite interaction with skiers and building users alike.

DESIGN FLAWS

Material durability is questionable, and how materials are handled and get to the isolated site has not been discussed. The hut itself would be warm, dry, and comfortable, however it is built on tall piles in a seismic/volcanic area. This makes the safety and logic of the structure a natural point of discussion. Building only one unit would also be a vastly expensive enterprise due to the isolated location and associated transport costs.

TAKING THIS IMPLEMENTATION FURTHER

Additional units, or a ski village could be explored. Exploring how components get to the isolated site and are handled. Specifying more durable materials/cladding or covering all timber components to increase lifespan. Physical modelling, alternative layouts, site selection, volcano-proofing, and engineering would all further this research.

**FIGURE 7.14 -
SITE LOCATION**

+ SMALL-SCALE IMPLEMENTATIONS

WHO

These small scale implementations largely serve to test the system's integration into New Zealand's natural environments. As a result, building users are those who utilise and enjoy those same environments. Skiers, trampers, travellers, are all part of the user demographic.

WHAT

This implementation is intended as a tramping hut or forest cabin. It is meant for hikers/ trampers, holidaymakers, or anyone who seeks to enjoy New Zealand native bush. It must provide the necessities of a home, whilst being spacious, comfortable, and enhancing to the native environment.

WHEN

This implementation is designed as the 'third lifetime' of the system, meaning it has the potential to be constructed with pieces from the residential or commercial implementations. This said, its construction could take place centuries from now.

WHERE

Aorangi national park is part of the Aorangi mountain range, near Cape Palliser, and is the southernmost mountain range in the North Island.

WHY?

To test how the system can integrate into small scale use and also work in New Zealand's natural environments. Assessing how well the system works at a small scale completes the research assessment on cross-scale suitability.

- 1 To maximise valley and river views, building should face east. North facing windows should provide necessary natural light.
- 2 Dense native forest surrounds and should be disturbed as little as possible.
- 3 River provides a flood risk factor, building should be elevated on piles to mitigate this risk.

FIGURE 7.16 -
PROCESS SKETCHES

FIGURE 7.17 -
PROCESS SKETCHES

+ SMALL-SCALE IMPLEMENTATIONS

+ CHAPTER 07

- 1 Primary glazing and views are to the east, with the addition of North facing windows.
- 2 Land is largely undisturbed
- 3 Butterfly roof channels water to the Northern side of the building for collection.

**FIGURE 7.19 -
STRUCTURE**

NOT TO SCALE

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+ SMALL-SCALE IMPLEMENTATIONS

+ CHAPTER 07

- 1** 6x6m structural system bays.
- 2** External walls, consisting largely of 2m and 3m panels.
- 3** Front balcony with folding glass curtain wall.
- 4** Double height atrium over social spaces.
- 5** Pile Foundations.
- 6** Entry point and rear balcony.

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**FIGURE 7.20 -
GROUND FLOOR PLAN**

- ① Large ground floor bathroom with a separate powder room off from the laundry.
- ② Feature staircase in double height internal space.
- ③ Front facade opens up to natural environment and provides deck access.
- ④ Large spacious kitchen with a spacious pantry due to increased stockpile needs as a result of isolated location.
- ⑤ Separated living and dining spaces that can be arranged to suit needs.

**FIGURE 7.21 -
FIRST FLOOR PLAN**

N.

① Open double height space dictates the upper storey.

② Large master bedroom with ensuite and walk-in wardrobe.

③ Small bathroom services the two smaller bedrooms.

④ Master bedroom has large double glazed window overlooking double height space and mountains beyond.

⑤ Private spaces are compact in favour of larger social and living spaces.

**FIGURE 7.22 -
EAST ELEVATION**

- ① Double height internal space.
- ② Folding glass facade integrates inside and outside.
- ③ Undisturbed natural environment surrounds the structure.

**FIGURE 7.23 -
LONGITUDINAL SECTION**

- ① Structural system contributes to internal and external architectural fabric.
- ② Social space prioritisation, with the kitchen at the heart of the home.
- ③ Facade makes the outdoor environment easier to enjoy.

SCALE 1:100 @A3

FIGURE 7.24 -
EXPERIENCE

FIGURE 7.25 -
EXPERIENCE

**FIGURE 7.26 -
EXPERIENCE**

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FIGURE 7.27 -
EXPERIENCE

+ CHAPTER 07

DOES IT MEET DFD SUCCESS CRITERIA?	
1. DESIGN FOR COMPONENT REUSE	Y
2.DESIGN FOR OFFSITE AND MODULAR CONSTRUCTION	Y
3. DESIGN ACCESSIBLE AND NON-CHEMICAL CONNECTIONS	Y
4. SPECIFY DURABLE AND VALUABLE MATERIALS	Y
5. CONSIDER MATERIAL HANDLING	Y
6. USE A STANDARD STRUCTURAL GRID	Y
7. DESIGN FOR ADAPTABILITY	N
8. MINIMISE BUILDING ELEMENTS, SIMPLIFY STRUCTURE AND FORM	Y
9. USE LAYERING APPROACH AND SEPARATE MEP SYSTEMS	Y
10. USE RETRACTABLE FOUNDATIONS	Y

+ CHAPTER 07

DFD SUCCESS CRITERIA

As the system has already been designed and assessed against this criteria, the question is whether or not this implementation has jeopardised any of the criteria met. This implementation is particularly concerned with adaptability of the design implementation, as well as component adaptability/reuse. A structure in an isolated forest environment has limited adaptability for other purposes. DoC huts are the only immediately obvious alternative.

THE GOOD

A relatively compact tramping hut or second home in the bush has been designed, providing spacious social areas as well as all required amenities. The design makes the most of the natural environment and makes full use of indoor/outdoor flow.

DESIGN FLAWS

Material durability is questionable. How long would treated timber components realistically last in a damp, dark, cold environment? And how reusable would those components be? A full height fold-able glass facade would be very expensive, and would not be a usable feature in winter. Large amounts of heat would also likely be lost through the glazing. The kitchen is perhaps too large, and the social spaces awkward and clunky. Part of this is the nature of conceptual implementations.

TAKING THIS IMPLEMENTATION FURTHER

Additional units, or forest development could be explored. Exploring how components get to the isolated site and are handled. Specifying more durable materials/cladding or covering all timber components to increase lifespan. Physical modelling, alternative layouts, and engineering would all further this research.

CHAPTER

FURTHER SPECULATIONS

CHAPTER OVERVIEW

- 8.1 - AGRICULTURAL
- 8.2 - BEACH BACH
- 8.3 - HUNTING LODGE
- 8.4 - SCHOOL PREFABS
- 8.5 - SHOWROOM/GARAGE
- 8.6 - DISASTER RELIEF
- 8.7 - REFLECTIONS

CHAPTER 8 STATEMENT

This chapter contains further evolutions of the system. It theorises how the system could be used in other scenarios, as a further exploration of its flexibility and versatility.

The implementations are then assessed against previously established success criteria with shortfalls identified. These implementations are not developed designs, rather they are further tests of the system, revealing success or failure in cross scale suitability. They also reveal future potential for the system and its research.

**FIGURE 8.01 -
AGRICULTURAL USE**

**FIGURE 8.02 -
BEACH BACH**

CHAPTER 08

**FIGURE 8.03 -
HUNTING LODGE**

**FIGURE 8.04 -
SCHOOL PREFAB**

CHAPTER 08

**FIGURE 8.05 -
SHOWROOM/GARAGE**

**FIGURE 8.06 -
DISASTER RELIEF**

DFD SUCCESS CRITERIA

These further speculations are nowhere near resolved enough to engage with the DFD success criteria. They simply suggest further uses for the system at a building level implementation. They would all need to be designed and developed before a discussion of their success as concepts can be made.

THESE ARE SPECULATIONS

Flaws in the designs of these speculations cannot be commented on, as there are no designs to speak of. Singular images depict how the system might work to provide further use in a variety of contexts. They are not good or bad, as they are not yet designed.

TAKING CONCEPTS FURTHER

These speculations could be further developed in order for them to interact and engage with the system. Design development, physical modelling, redesigning form, site selection, and interior design would all take these speculations and this research further.

These concepts also represent the future potential of the system and its potential uses.

CHAPTER

RESEARCH REFLECTIONS/CONCLUSIONS

9.1 - REFLECTIONS AND CONCLUSIONS

CHAPTER 9 STATEMENT

This chapter contains reflections upon the research as a whole, and discusses avenues for further research in the area.

This chapter and its reflections are not necessarily chapter specific. For in depth reflections upon research conducted in specific chapters, please see those respective chapters.

+ REFLECTIONS/CONCLUSIONS

WAS THIS RESEARCH SUCCESSFUL?

The success of this research can be judged by assessing whether initial aims, objectives, and questions have been addressed. The initial research question was “How can an engineered timber construction system be designed for deconstruction and be reused over time at varying building scales?”. This question was a starting point for the research, and all aspects of the question have been thoroughly explored. The work that has been done involves the use of engineered timber, is designed for deconstruction, and is then tested at various building scales. Similarly, the aim of the research has also been achieved. A construction system has indeed been proposed that enables end of life deconstruction and reuse. Different building types and occupations have been tested, with varying degrees of success. All research objectives have been achieved, apart from refinement based upon expert appraisal. Several factors did negatively impact the overall success of the research, which will be discussed in the following sections.

REFLECTING ON ‘THE SYSTEM’

The system designed and proposed in chapter 2 is the crux of this research. Without it, no implementations or tests could be undertaken. It is a logical system, designed based upon success criteria developed from the literature review. It is engineered to the extent that a single architectural researcher can achieve, but this has its limitations. As it has not been assessed by qualified engineers, it cannot be speculated that this is a viable structural solution, or that any of the following implementations are achievable. For this system and this research to go any further, expert consultation would need to be sought and refinements made as a result. The system is strong and achieves all that this research set out to do but remains entirely theoretical. In truth, it would be under-engineered for some scenarios and over-engineered for others. This begins a discussion on the nature of building itself, which is not the subject of this research. The system needs to be introduced to the physical realm. It needs to be tested at scale, tested through fabrication, and assessed and critiqued by industry professionals.

REFLECTING ON IMPLEMENTATIONS

The implementations detailed in chapters 5-8 are intended as evolutions, or tests, of the system and its capabilities. This was outlined from the start as the primary means of judging the success of the designed system. A variety of building scales were tested, as were occupations. Commercial implementation was perhaps most successful and was the original intention of the system’s design. Residential implementation was mostly successful, however, if the exposed structure is not to client tastes, then its success as a de-constructable system is significantly jeopardised. Small-scale implementations showed that the system does adapt to small-scale uses but is perhaps over-engineered. The system can also easily dominate these spaces and feel oversized. For more in-depth and resolved implementations, the system needs to first be refined. Implementations have been a useful tool in assessing the practicalities of the system, and how it looks, feels, and functions in a built space. The evolutions that these experiments represent have revealed shortcomings in system design and help in the future potential and future development of this research.

INITIAL QUESTION

How can an engineered timber construction system be designed for deconstruction and reused over time at varying building scales?

AIM

The aim of this research is to propose a construction system that enables end of life deconstruction and component reuse across building scales and occupation types.

OBJECTIVES

- To research; Sustainable design and the circular economy, standard construction practices, engineered timber, and existing precedents.
- To use engineered timber as a primary construction material, due to its more sustainable nature over traditional materials.
- To research design for deconstruction key principles, and use them to develop a set of success criteria to which this research can be compared.
- To research and digitally model traditional Japanese joinery methods, and use them to inform the construction system being designed as part of this research.
- To use the knowledge gained from this research to develop a construction system that is fully assemblable and de-constructable.
- To assess this system against the design for deconstruction success criteria developed in this research.
- Refine the system based on assessment outcomes and against reflections based on research knowledge and expert appraisal (if possible).
- To test this construction system against a number of implementations, of varying size, use, and occupation type.
- Identify and discuss issues and shortcomings of the construction system and implementations, both inside and outside the scope of this research.
- Use ongoing critical reflection and refinement throughout the development of the system and its implementations.
- Create a viable example of design for deconstruction and component reuse based on the industry at present.

FUTURE POTENTIAL

Assessment from engineers, significant refinement, physical modelling, 1:1 scale testing, cost assessments, and logistical issues are all avenues for furthering this research. Materials have also not been researched or implemented in significant detail and will play a crucial role in the durability and re-usability of the system and its components. Designing the system and optimising it for manufacture, transportation, and distribution also needs to be done before the system can play any role as a viable solution. These avenues were not possible due to the scope and limitations of a master's thesis.

This research has a great amount of future potential. It could be developed into a series of products suitable to the New Zealand market. It could form the basis of a circular construction company. Most realistically is its potential to be used as a starting point for other research, either at the masters or Ph.D. level.

AMBITION REALLY CAN BE THE ENEMY OF SUCCESS

One of the largest flaws in this research is the scope and breadth of the issues being dealt with. Sustainable design, design for deconstruction, engineered timber construction, structural design, material reuse, product design, off-site construction, and modular construction are all massive areas of research and development. This research sought to combine aspects of each of these areas and more, to create a solution to construction waste and problems on a global scale. No single one of these areas could be researched or resolved in detail, and this is largely why the system remains a theoretical one and not something real. This research was too ambitious in what it aimed to achieve, and as a result it is undeveloped and untested. But it can be a useful starting point for something bigger.

PERSONAL SETBACKS

This research was primarily conducted in 2020, beginning in March. Within one month of beginning this research, the world was flipped upside down by COVID-19. Lock-down ensued, and the research continued in isolation. This major event interrupted the building of momentum for the year ahead, and the research struggled to gain traction as a result. This was seen across the Master of Architecture cohort, and the university. In November 2020, I became very ill as I was preparing to leave my Wellington flat of 3 years. After multiple doctors and hospital visits, I was scanned and diagnosed with a brain tumour. I spent weeks in hospital and underwent brain surgery. 3 months were given to recover before the research was resumed at part-time. Finishing this research has been a challenge, largely due to circumstances outside of my control. It must be recognised that this research has been greatly impacted, and had it gone smoother, the research outcomes may have been different.

OTHER RESEARCH FLAWS

Over-ambition has been discussed, as have the setbacks that impacted the success of this research. There are many other shortcomings surrounding this research, some of which can be discussed here. The cost of the system is not something that has been researched in-depth, but due to the nature of large, intricate, three-dimensional engineered timber components, it can be assumed that the system would be very expensive to produce. Component weights are also likely to be very high, making storage options and transport an issue. This has not yet been resolved. Other up-front costs relate to storage and logistics and have been discussed in their respective chapters. Part of the issue is that the system sits outside of the model that the construction industry currently operates. It is a high-cost, circular system of renewal and reuse, with a high initial investment that pays off over time. The construction industry currently operates in a low-cost, linear fashion that ends in waste and destruction, with very little resource reuse. Changing the nature of an entire industry does not, and cannot, happen overnight. As a result, the system would likely fail if introduced to the market today.

WHAT HAS BEEN LEARNT?

This research has explored and uncovered a plethora of industry-related issues. It has successfully proposed a timber construction system for deconstruction and continual reuse. It is adaptive to a range of scales and occupation types. It engages with sustainable design, design for deconstruction, large timber construction, circular economies, manufacturing, storage, transport, material durability, and many other areas of construction. Most importantly, however, is that it raises more questions than it answers. It has opened up a pathway for further research and development, which may result in an actionable solution to major construction industry problems.

What has been learnt is that good things do take time. This research engages with massive industry issues it cannot solve on its own. Years of research, development, and testing would be required by a team of people to produce a market-ready solution to the problems motivating this research. But that does not mean that this research is not valuable. It is a step in the right direction. This research forms part of an important and ongoing discourse into solving problems that matter on a global scale, and for the future of our planet.

CHAPTER

END MATTER

10.1 - REFERENCE LIST
10.2 - LIST OF FIGURES

+ REFERENCE LIST

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