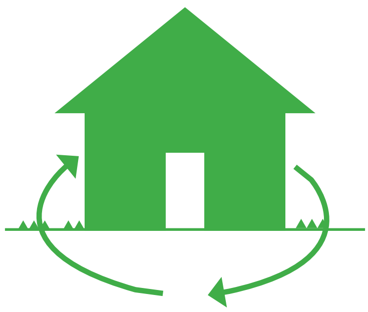
BIODEGRADABLE BUILDING:
A ZERO-WASTE MEDIUM DENSITY HOUSING DESIGN FOR NEW ZEALAND



Written by Jacob Coleman

2020

Abstract

New Zealand has a serious construction and demolition (C&D) waste issue. A Ministry for the Environment study from 2019 found that 2.9 million tonnes of C&D waste are disposed of at C&D fills nationwide every year (Ministry for the Environment, 2019). Averaged across the population this equates to nearly 600 kg per person. Auckland Council's 'Low Carbon Auckland' plan presents total landfill waste reduction targets of 30% by 2020, 60% by 2030, and 'zero waste' by 2040 (Auckland Council, 2014).

To achieve this goal of zero waste, building materials must operate within a closed loop (Baker-Brown, 2017; McDonough & Braungart, 2002). Materials can either be a part of a closed organic loop (natural biodegradable materials) or a closed technical loop (man-made cycle of reuse) (Baker-Brown, 2017; McDonough & Braungart, 2002).

This thesis aims to achieve a zero-waste medium density housing design for New Zealand that maximises the use of biodegradable building materials. However, it is hypothesised along with Sassi (2006) that both biodegradable and reusable components will be required to achieve zero waste. This thesis also seeks the most suitable biodegradable materials for New Zealand's climate and the optimum construction approach to support these materials. This research also contributes towards reducing the embodied energy and greenhouse gas emissions of the New Zealand building industry.

The most suitable biodegradable materials for New Zealand were selected based on availability and performance found to be untreated timber, clay plaster and, straw and wool insulation. In-situ construction, prefabricated wall panels and, standardised block modules were then compared to find the most suitable construction approach to support these materials and was found to be prefabricated wall panels. A building design was then pursued driven by the need to protect the biodegradable insulation materials from moisture infiltration. The design is then integrated within a site in Upper Hutt to address the demand for housing densification and demonstrate the potential for application of biodegradable materials to an urban setting at the scale of a medium density housing development.

A detailed BIM model of the building design was produced from which volumes of individual components were extracted and categorised regarding their biodegradability or reusability or lack thereof. This was done to determine the proportion and quantity of biodegradable materials and waste generated by the design. An identical design using conventional New Zealand materials and construction techniques was also produced for comparison.

Biodegradable materials made up 82% of the final design construction by volume and 91% of the construction by volume was diverted from landfill (reusable components made up 9% of the construction). This suggests that Auckland Council's goal of 60% waste reduction by 2030 is theoretically possible for developments of a similar scale to the final design. However, the goal of 'zero waste' by 2040 seems unobtainable even if significant improvements are made.

Acknowledgements

I would like to thank my supervisor Hans-Christian Wilhelm who generously poured out his time and energy weekly into my research. I would also like to thank my parents James and Julia Coleman who have supported and encouraged me throughout my studies and particularly during this thesis year. And I am forever grateful to my biggest supporter and wife Gabrielle who has never ceased supporting me at every step of the way. But above all, I am grateful to God, whose goodness and kindness has never left me.

Contents

1

1.1 Problem Statement

Construction and Demolition Waste

Construction and demolition waste is a global issue. In 2012, 40 countries collectively produced more than 3 billion tonnes of building waste and this figure has been increasing every year (Akhtar & Sarmah, 2018).

Despite the clean green image of New Zealand, there is a severe issue with the amount of building waste produced here and it is contributing to this global issue. In 2014, it was estimated that C&D waste represented 50% of all waste generated in New Zealand by weight (BRANZ, 2014). In 2018, Auckland Council released the region's Waste Management and Minimisation Plan (WMMP) in which it stated C&D waste to be the largest single waste stream for the region, at around 40% of total weight going to landfill, excluding rubble and concrete going to cleanfill and managed fill sites (Auckland Council, 2018).

Figure 1

Construction and Demolition Waste

Photograph by Jacob Coleman, 2020.

Waste Reduction Targets

Auckland Council's 'Low Carbon Auckland' plan presents total landfill waste reduction targets of 30% by weight by 2020, 60% by 2030, and 'zero waste' by 2040 (Auckland Council, 2014). Nothing has been published by the council to indicate that the 2020 target has been achieved. Previously to these targets from Auckland Council, in 2002, New Zealand set the goal of reducing C&D waste going to landfills by 50% of the 2005 figure by 2008 (Ministry for the Environment, 2002). By 2005, half of the Territorial Authorities in New Zealand aimed for zero waste by 2015 (Storey et al., 2005). The fact that similar targets have been set in the past and have not been met highlights our inability to change.

Linear Economy

The issue is in the way we build in New Zealand. Our building materials are not in a closed loop. Most of our building materials and components in New Zealand fall into a linear life system, where a material is extracted, produced, distributed, consumed, and finally disposed of. This linear system demands the constant production of new materials which places a strain on our planet's finite resources and this constant extraction and production damages our environment through the emissions of greenhouse gases (GHG).

Figure 2

Linear Economy diagram

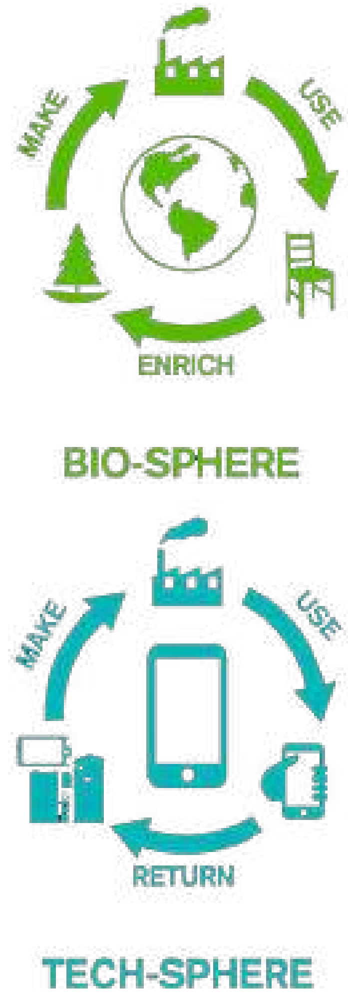
Reprinted from "Exploring the role of independent retailers in the circular economy: a case study approach" by T. Wautelet, 2018, p. 18. Copyright 2018 by Thibaut Wautelet.

1.2 Background

To achieve a zero-waste construction industry, architects must design with materials that operate within a closed loop (Baker-Brown, 2017; McDonough & Braungart, 2002). This means that the outputs of one system feed directly into the inputs of a new system resulting in no waste. There are two possible closed loop cycles that materials can be a part of (figure 3) (Baker-Brown, 2017; McDonough & Braungart, 2002).

Figure 3

Organic and technical cycle diagram



Reprinted from "The re-use atlas : a designer's guide towards the circular economy" by D. Baker-Brown, 2017, RIBA Publishing, p. 13. Copyright 2009 by Duncan Baker-Brown.

1. Bio-Sphere/Organic Cycle

This can be thought of as nature's cycle. This cycle is exclusive to plant-based materials that naturally regenerate and biodegrade such as wood or straw (McDonough & Braungart, 2002). The building materials produced from these natural resources often boast low embodied energies due to their lack of processing such as timber or straw bale. Although technically not renewable or biodegradable, earth will be included as material in the bio-sphere for this thesis. This is because earth is a natural material and produces zero-waste because it remains a natural resource not a waste material.

The term biodegradable in this paper is used to refer to materials that operate within the bio-sphere or organic cycle as defined by McDonough and Braungart in their book "Cradle to cradle: Remaking the way we make things" in 2002. Other suitable terms for these materials include bio-based, biological and organic. These are natural plant-based materials that are both renewable and biodegradable.

Biodegradation is a natural form of waste stabilisation (Haug, 2018). Biodegradation, decomposition or composting occurs when microorganisms (fungi and actinomycetes), macroorganisms (insects), and aerobic bacteria break down plant matter by ingesting and binding the particles together (Dougoud, 2018). The material that is biodegrading provides food for organisms in the form of carbon and nitrogen (Dougoud, 2018). It is important to note here that simply because biodegradable materials can biodegrade doesn't mean they will in any situation. Biodegradation requires special conditions of aeration and moisture to produce thermophilic temperatures (Haug, 2018). These specific conditions can easily be denied while the material carries out its operational life. Biodegradation is further defined for the purpose of developing specific assessment criteria later (see page 159).

2. Tech-sphere/Technical Cycle

This can be thought of as the man-made cycle of reuse. Any reused material participates in this cycle (Baker-Brown, 2017). This cycle is available to all materials or building elements, whether they be renewable, highly-processed, biodegradable or not. Given these materials or components can be carefully removed and disassembled and without causing damage, they can be reused continually until their integrity or suitability eventually becomes insufficient for application. windows and doors are examples of building elements with potential for reuse.

Both Spheres Can Be Combined

Both the bio-sphere and the tech-sphere can be combined. This can be thought of simply as the reuse of biodegradable materials. This approach means that the biodegradable component can remain in a technical cycle until it reaches the end of its useable life at which point it can return to its organic cycle and biodegrade (Sassi, 2006). This prolongs the life of the biodegradable material which will lower the frequency at which these materials reach the end of their lives and have to be dealt with.

Zero Waste Design Strategy

The strategy in this thesis to achieve zero waste is to:

1. Maximise the use of biodegradable building materials

2. Use reusable components where no biodegradable substitutive exists or is wise to use

3. Use deconstruction instead of demolition at the end of life of the building to ensure reuse of reusable components and separation of biodegradable reusable components.

1. Maximise Biodegradable Materials

Although both cycles technically result in zero waste, only materials in an organic cycle ultimately do so, as any technical cycle of reuse will still eventually end, thus resulting in building waste (Sassi, 2008). This is because, in contrast to the unending organic cycle, materials in a technical cycle need to constantly uphold their integrity to be suitable for reuse and cannot do this forever (Baker-Brown, 2017). All materials degrade. Once a material in a technical cycle degrades it cannot be reused, whereas biodegradation for a material in an organic is desired for zero waste to occur (Sassi, 2008). Materials in an organic cycle are superior to those in a technical cycle regarding their ultimate waste reduction potential (Ganotopoulou, 2014).

This is in line with Auckland Council's waste reduction strategy (figure 5). Auckland Council's primary strategy is reduction which can be achieved by increasing the use of materials in an organic cycle that biodegrade and produce no waste (Auckland Council, 2019). Auckland Council's second strategy is reuse of building components which can be thought of as utilising materials in a technical cycle (Auckland Council, 2019).

Maximising the use of natural biodegradable materials in our buildings is the best approach to eliminating construction and demolition waste. Sassi, a leading scholar in the field of biodegradable building materials, concluded in her study "Biodegradable Building" that using biodegradable building materials, indeed, offers significant waste reduction potential and that there are significant opportunities to substitute non-biodegradable building materials for biodegradable alternatives (Sassi, 2006). Use of biodegradable building materials in an organic cycle will, therefore, be sought primarily for the

Figure 5

Auckland Council's Waste Management Hierarchy

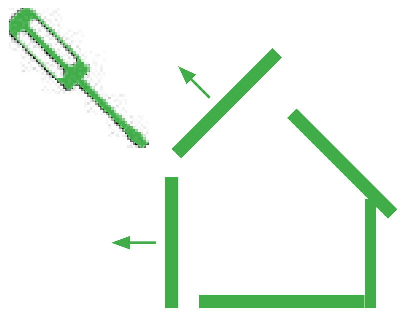
Reprinted From "Building Out Waste A guide for developers and building contractors" by Auckland Council, 2019, p. 2 (https://www.makethemostofwaste.co.nz/media/1534/building-out-waste.pdf). Copyright 2019 by Auckland Council.

2. Biodegradable and Reusable components

Research suggests that constructing a building entirely out of biodegradable materials in an organic cycle is not realistic or achievable in today's mainstream construction industry (Sassi, 2006). Essential materials such as glass used for windows or concrete for foundations do not have suitable biodegradable alternatives (Sassi, 2006). In these cases, it would also be imprudent to swap these materials out for inferior biodegradable materials. Other difficult to overcome sources of non-biodegradable waste include metal fixings, second fix electrical goods (e.g. socket outlets, switches) and plumbing pipes (Sassi, 2006).

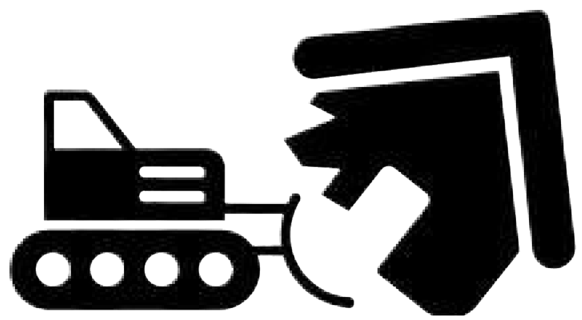
Building elements that have no biodegradable substitute should therefore be reusable and operate within a technical cycle to ensure zero waste. If designed to facilitate deconstruction all these non-biodegradable building elements can be reused. Wellington-based companies such as the Building Recyclers, No.8 Building Recyclers and Rummagers specialise in the reuse of building elements such as windows, doors, plumbing pipes, bathroom vanities, metal fixings, socket outlets, switches and many other building components. In addition, research into reusable prefabricated lightweight concrete foundations has been undertaken and deemed plausible (Llorens Duran & Pujadas Gispert, 2015).

Therefore, achieving a zero-waste medium density housing design is theoretically possible. Indeed, research suggests that a combination of biodegradable materials and reusable components is a realistic approach to achieving a closed material loop and zero waste (Sassi, 2006).



3. Deconstruction Not Demolition

However, with this approach, to ensure zero waste at the end of the building's life, demolition is not an option. For a 100% biodegradable building, demolition would be acceptable as all the material could be left to decompose leaving no waste. But when any non-biodegradable components are present, such as glass windows, concrete foundations or other non-biodegradable building elements mentioned above, overall biodegradability is compromised, and the building cannot be demolished and left to decompose. Therefore, deconstruction of building elements is required to allow the reuse of the inorganic components. Deconstruction is also recognised as part of the waste reduction strategy in the BREEAM building label assessment where it is rewarded over demolition. Because of the necessity of deconstruction, there lies an opportunity to reuse the organic components also. Deconstruction also allows for any biodegradable elements with compromised integrity to be separated for decomposition. A building must be designed to enable deconstruction. Building elements should be mechanically fixed, preferably with few fixings and easily accessible (Chini, 2001).



1.3 Objectives

1. Produce zero waste at the end of the design's life
2. Maximise the use of biodegradable building materials
3. Find the optimum biodegradable construction for New Zealand using locally available materials

1.4 Hypothesis

A dwelling construction can be made entirely zero waste using biodegradable and reusable components. This hypothesis is shared with Sassi from her paper "biodegradable building" in 2006.

1.5 Research Question

How can a medium density housing scale project be built best in New Zealand using predominantly biodegradable materials?

1.6 Relevance/Scope

Medium Density Housing

The architectural design output for this thesis is a medium density housing (MDH) development because:

1. Although many vernacular architectural typologies such as earth or thatch huts are entirely zero-waste and biodegradable, they are no longer the optimum living environments. MDH offers a housing typology suitable for the modern day.

2. The density of housing in New Zealand needs to increase. This is driven by the increase in population and demand for housing within a finite landscape. An estimated 30% of the total of all new dwellings in Auckland (35,000 houses) have been built in intensified typologies in the last decade (Syme, 2005). Wellington has also seen considerable intensification through both downtown apartment development and suburban infill in recent years (Bryson & Allen, 2017). Because MDH is a relatively new design typology for New Zealand and the demand for their development is ever increasing, applying the research from this thesis to this design typology is useful and relevant.

3. The MDH scale of 1-3 storey multi-unit dwellings provides the optimum scale and application for biodegradable building materials to be tested.

4. Medium Density Housing has also improved the environmental sustainability of our country's housing sector. MDH has reduced resource consumption in terms of land, infrastructure and energy (transport) (Witten et al., 2011).

Engagement With Tikanga Māori

The aspiration to achieve zero waste for the New Zealand construction industry aligns with tikanga Māori, and the tradition of kaitiakitanga to sustain and restore our collective resources to enhance the mauri (life force) of taonga tuku iho (heritage) (Environmental Choice New Zealand, 2020).

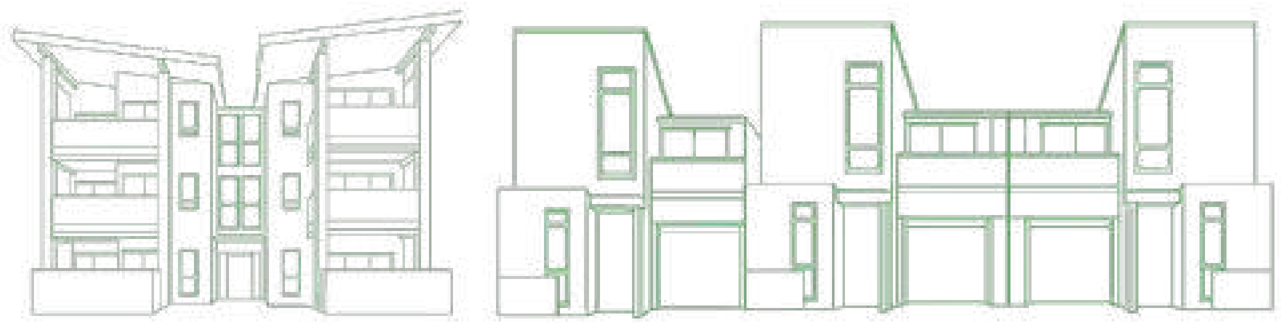
Before the arrival of the settlers, the vernacular architecture of Māori was entirely zero-waste and biodegradable. This thesis is striving to restore New Zealand architecture to the original environmental compassion present in its Māori roots.

Additional Benefits of Bio-sphere Materials

Bio-sphere materials not only reduce end-of-life waste but they reduce consumption of finite resources, energy consumption and greenhouse gas emissions. These areas of sustainability have been worked on extensively in the area of operational energy of buildings, but a lot of work is still to be done in the area of the embodied energy of buildings. However, the operation energy of a building also has the potential to be lowered by biodegradable insulation materials such as straw, wool or hemp.

Figure 4

Medium Density Housing diagram



Adapted from "Attitudes towards MDH" by BRANZ, 2017, RIBA Publishing, p. 1. Copyright 2017 by BRANZ.

1.7 Methodology

Methodological Process

1. This thesis begins with a precedent and literature review of biodegradable materials and construction techniques globally and in NZ. This is for the purpose of compiling a comprehensive list contemporary and vernacular materials and techniques.

2. It is from this list that the most suitable biodegradable building materials for New Zealand are determined. The most suitable biodegradable material is selected for the building elements of structure, insulation, cladding, foundations, flooring and roofing, as each element has unique performance requirements. Materials are selected based on availability and performance regarding the specific requirements for each building element.

3. The most suitable biodegradable building materials selected in the last step are used in this step to explore construction methods to find the most suitable approach for the materials. The construction approaches of In-situ construction, standardised block modules and prefabricated wall panels are then explored and reviewed. Wall build-up design proposals are produced for each construction approach and then the approaches are reviewed. The construction approaches are reviewed regarding how successful the approach has been in increasing the uptake of biodegradable materials, reuse potential and closeness to conventional New Zealand construction practice.
The final construction of the design is not designed at this stage but rather the construction approach decided. This is because a construction approach cannot be finalised before the design as the two aspects are inherently linked.

4. Once a construction approach is decided a building form is pursued that supports the use of biodegradable materials. The building form is mainly driven by the need to protect the biodegradable insulation materials from moisture infiltration. In this section, a suitable MDH design is also pursued based on MDH design typology research.

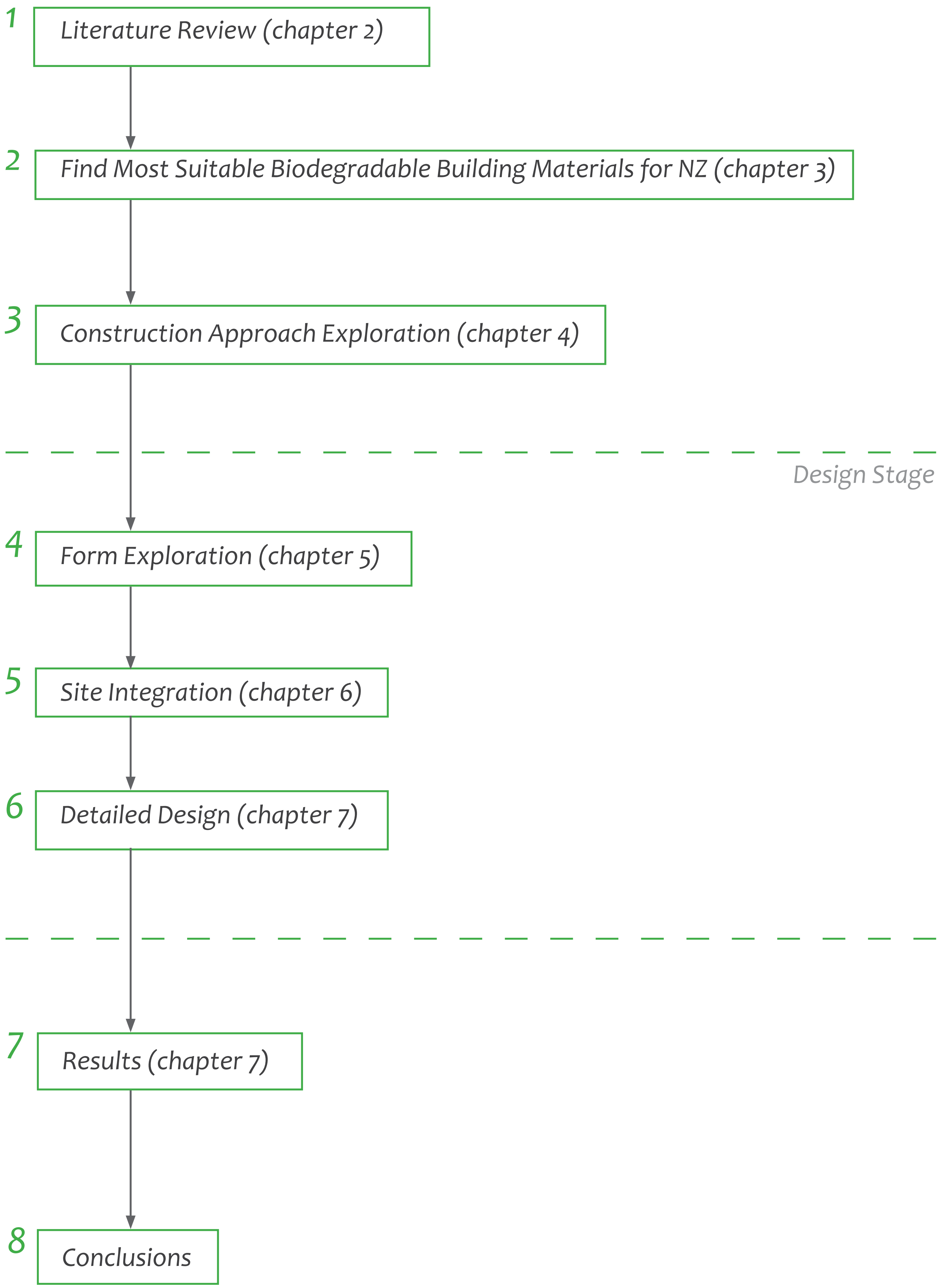
5. The design is then integrated onto a site in Upper Hutt. Although a sited design does not contribute to the thesis objectives, architectural design is never produced in isolation to its site. A sited design is used to demonstrate the potential for biodegradable building materials to be applied in an urban context as MDH development. In addition, a sited design is pursued because the selected architectural typology of Medium Density Housing requires careful consideration of the site and inter-unit relationships. However, a site development design is not pursued beyond the point of architectural sufficiency as the site development design merely architecturally justifies the building design. The building design is used as the architectural canvas on which the thesis objectives are pursued.

6. Once the architectural design of the MDH building has been resolved and integrated on site the building's construction can be designed in detail. A detailed BIM model of the design is produced to extract accurate volumes of the building components. The same is done for an identical design using conventional New Zealand materials and construction techniques. This is done to allow comparison.

7. The building components are then categorised regarding their biodegradability or reusability or lack thereof for both designs. This is done so that the proportion of waste and biodegradable materials can be generated and compared. Results regarding whether the design achieved zero waste through the use of biodegradable and reusable building components are presented. Furthermore, the degree of biodegradability of the overall construction is presented.

8. Final conclusions are then made as to whether the thesis objectives were achieved. Whether or not Auckland Council's waste reduction targets can be met is also addressed. Finally, further research opportunities are also presented.

Methodology Diagram



Objective Assessment Approach

Thesis Objective	Assessment Criteria	Metric	Criteria Objective
1. Zero Waste	Proportion of waste diverted from land fill	% by volume	100% Waste Diversion
2. Maximise Biodegradable Materials	Proportion of biodegradable materials	% by volume	As close to 100% as possible
3. Find Optimum Biodegradable Construction Approach for New Zealand	Availability of Materials	High=Produced in NZ Moderate = Raw materials available in NZ Low=Imported product	As high as possible
	Performance of construction in New Zealand's climate	Qualitative assessment of durability	As high as possible
		Thermal Resistance (m^2K/W)	As high as possible
		Vapour Resistance (MNs/g)	Informs vapour management
	Suitability of construction approach (In-situ, standardised block modules, prefabricated panels)	Most successful strategy in increasing the uptake of biodegradable materials	
		Greatest reuse potential	
		Closest to mainstream NZ construction practice	

In order to assess against the objectives of this thesis, measurable assessment criteria had to be developed. For the first two thesis objectives, existing metrics could be relied upon, but for the third thesis objective, original qualitative measures had to be developed. The first thesis objective uses the metric of the percentage of waste diverted from landfill by volume which is the metric used by BREEAM, the Declare label and The Living Building Challenge in its materials petal. For the second thesis objective, the proportion of biodegradable or compostable materials by volume is the metric used which is also used by the Living Building Challenge and the Declare label. The criteria used to assess the third thesis objective are the availability and performance of materials in addition to the suitability of the construction approach for the material. Availability is determined by original definitions where high availability refers to materials produced in New Zealand, moderate availability refers to raw materials that are available in New Zealand and low availability refers to imported materials. Performance is assessed qualitatively regarding durability and quantitatively regarding thermal and vapour resistance. Suitability of construction approach is assessed qualitatively regarding its ability to increase the uptake of biodegradable materials, its reuse potential and closeness to mainstream New Zealand construction practice.

Literature Review

2

Chapter Outline

The purpose of this literature review is to compile a list of vernacular and contemporary biodegradable materials globally and in New Zealand. Innovative international vernacular and contemporary precedents were briefly reviewed before New Zealand's biodegradable materials and construction techniques were reviewed more thoroughly. In the review of international precedents, the biodegradable material that is used innovatively in the project is extracted and is highlighted green in its title. Both vernacular and contemporary precedents were collected to gain an understanding of what materials have been used historically and what materials have endured to the modern day. An investigation into contemporary biodegradable precedents also reveals new biodegradable technologies. A specific investigation into the history of biodegradable building materials in New Zealand is undertaken to understand what materials have been used before. This literature review is undertaken to increase awareness of available biodegradable building materials so a process of narrowing the focus down to the materials best suited to New Zealand can begin in the following chapter.

2.1 Biodegradable Vernacular Architecture

In this section, international biodegradable vernacular precedents are reviewed. Vernacular architecture presents some of the most creative and effective examples of how humanity constructed with biodegradable materials in the past. Precedents were selected that used a biodegradable material in a manner that would seem innovative or unconventional through a modern lens. The review of vernacular precedents was not exhaustive but only the most innovative uses of material were selected because the review of New Zealand's biodegradable materials and techniques presented later in the chapter was the main focus. These vernacular buildings still dominate in many places in the world. It is estimated that between 30 and 50 percent of the world's population live in buildings constructed of earth (Rael, 2009).

Figure 6

Goahti Sod Houses, Arctic Region

Figure 7

Ma'dan Reed Houses, Iraq

Note. Reeds are wrapped in bundles and used to create columns, arches and walls. A reed house can be erected in just 3 days and can last up to 25 years with proper care.

Figure 8

Seaweed Roofed Houses on Læsø, Denmark

House with seaweed roof made using eelgrass from the ocean that is able to withstand decay for hundreds of years, thanks to the fact that they are impregnated with saltwater. 300 kilograms of eelgrass is required for every 1 square meter of roofing.

Figures retrieved from Archdaily (https://www.archdaily.com/805415/11-vernacular-building-techniques-that-are-disappearing) on 17 April 2020. Last updated in 2017.

Figure 9

Clay-plaster huts, Cliff of Bandiagara, Mali

Note. Also known as the Land of the Dogons, 289 villages of earthen buildings cover sandstone plateaus, escarpments and plains in the landscape of Mali.
Retrieved from Archdaily (https://www.archdaily.com/805415/11-vernacular-building-techniques-that-are-disappearing) on 17 April 2020. Last updated in 2017.

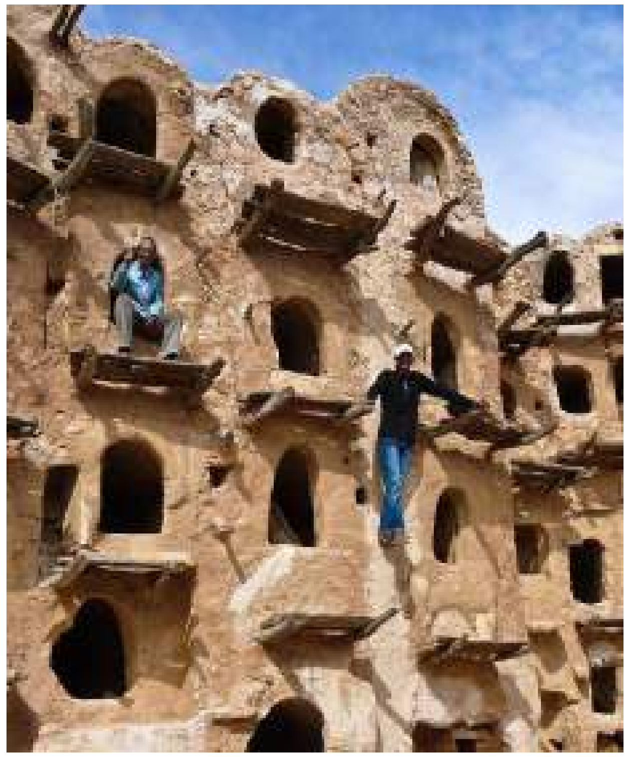
Figure 10

Adobe Brick, Beehive Houses of Harran, Turkey

Retrieved from Turkish travel blog (https://turkishtravelblog.com/the-beehive-houses-of-harran-turkey/) on 17 April 2020.

Figure 11

Cob, old granary in Nalut, Libya



Retrieved from Atlas of wonders (https://www.atlasofwonders.com/2011/04/libya-heritage-in-danger.html) on 17 April 2020.

Figure 12

Wattle and Daub, Mugsum Mud Huts, Cameroon

Note. Geometrically arranged reeds are covered in mud to produce the domestic mud huts. The huts are built in the form of a catenary arch, withstanding the maximum load with minimum material. The 9-meter-tall dwellings have practical footholds that also contribute to their aesthetic.
Retrieved from Design boom (https://www.designboom.com/architecture/musgum-earth-architecture/) on 17 April 2020.

Figure 13

Rammed Earth, the great Mosque of Djenné, Mali, West Africa

Photograph by Marco Dormino on 31 March 2015. Retrieved from Flickr (https://www.flickr.com/photos/un_photo/16992504601/) on 17 April.

2.2 Biodegradable Contemporary Architecture

In this section, international contemporary precedents are reviewed. Although technological advances can be blamed for environmental degradation in many ways, they have also produced innovations in the field of biodegradable materials. Precedents were selected that were deemed innovative in their production or construction of biodegradable materials. similarly, to the previous precedent review, this review is not exhaustive. The biodegradable used in the project is again highlighted in its title.

Figure 14

Cork House, Eton, Berkshire, UK

A

Photograph by David Grandorge, 2019.

B

Photograph by Alex de Rijke, 2019. Retrieved from Detail (https://www.detail.de/blog-artikel/ein-material-fuenf-pyramiden-cork-house-von-matthew-barnett-howland-34518/) on 17 April 2020. Last updated 19 August 2019.

This house was designed by Matthew Barnett Howland with Dido Milne and Oliver Wilton. The design was constructed in 2019 and was a contender for the 2019 Stirling Prize. The house is nearly entirely constructed out of the biodegradable material cork. Portugal, cork blocks are obtained from by-products and waste from cork forestry. The house consists of 1,268 interlocking cork blocks that do entirely without non-biodegradable glue or mortar. These blocks can be deconstructed at the end of life of the house and either be reused in a technical cycle or be left to biodegrade in an organic cycle.

The cork oak was brought to New Zealand by the early settlers with the earliest recorded tree planted in Symonds St, Auckland in 1855 by Dr Andrew Sinclair (Macarthur, 1994). The tree is well suited to New Zealand climates (Isaacs, 2015). Although the commercial production of cork did not develop, the cork oak can still be found in many parts of New Zealand (Macarthur, 1994).

Figure 15

Wood and Straw Thatch House, Kumrovec, Croatia

A

B

Photographs by Damir Fabijanic, 2014. Retrieved from Detail (https://www.detail.de/artikel/lokales-erbe-ferienhaus-in-kroatien-11897/) on 17 April 2020. Last updated 11 May 2014.

This project transforms a former agricultural building into a modern yet traditional holiday home. It was designed by PROARH, Zagreb and constructed in 2014. The design relies heavily upon the natural biodegradable materials of timber and straw. The use of steel and a Tyvek wall and roof underlay reduces the overall biodegradability of the building. However, the house showcases how natural biodegradable materials, such as untreated timber and straw thatch for roofing, can be used effectively in modern architectural design.

Figure 16

Wood and Straw Thatch Tij Bird Hide, Scheelhoek Nature Reserve, Stellendam, Netherlands


A

Photograph by Katja Effting, 2019.


B


C

Retrieved from Detail (https://www.detail-online.com/en/article/a-beached-ovoid-tij-bird-hide-by-road-architecten-34846/) on 17 April 2020. Last updated 30 October 2019.

This bird hide was designed by RAU Architecten, RO&AD Architecten and was constructed in 2019. It is located on the Scheelhoek nature reserve and uses a natural material pallet of stone, untreated wood and native reeds. The timber structure is made up of 402 prefabricated elements that can be dismantled at the end of life to either be reused in a technical cycle or left to biodegrade in an organic cycle.

Figure 17

Clay Gaia House, Massa Lombardo, Italy


A


B


C


D


E

Note. The Gaia House, built in October 2018, has a 3D-printed outer shell made from a mixture of soil and other biodegradable materials such as chopped rice husks. The house is 30m2 and uses timber columns as structure to hold up the timber roof.10/2018

Figures retrieved from Dezeen (https://www.dezeen.com/2019/02/27/gaia-wasp-3d-printed-house-biodegradable-video/) on 17 April 2020. Last updated on 27 February 2019.

Figure 18

3D-printed clay housing Concept, 2019 research project from the Institute for Advanced Architecture of Catalonia (IAAC)

Retrieved from IAAC (https://iaac.net/project/building-architecture-continuity/) on 17 April 2020.

Figure 19

TECLA Clay project, Designed by Mario Cucinella Architects (MCA) and engineered by WASP

Note. The first prototype was built in 2019 near Bologna in Italy. TECLA will be the first house to be entirely 3D printed using locally sourced clay. The houses will be 100% built of biodegradable materials resulting in zero waste.
Retrieved from MCA (https://www.mcarchitects.it/mario-cucinella-architects-and-wasp-start-on-site-with-tecla-a-prototype-3d-printed-global-habitat-for-sustainable-living) on 17 April 2020. Last updated 23 October 2019

Figure 20

3D-printed clay housing Concept, 2017-2018 research project from the Institute for Advanced Architecture of Catalonia (IAAC)

Retrieved from IAAC (https://iaac.net/project/digital-adobe/) on 17 April 2020.

In the last 3 years there has been significant research into the potential of 3D printing biodegradable houses out of clay coming out of Italy. There have been several design concepts produced (figure 18,19,20) and even a couple of prototypes built.

Figure 21

Hy-fi, a temporary outdoor pavilion constructed out of Mycelium blocks by New York based practice, The Living.

Photographs of Hy-fi were taken by photo by kris graves. Retrieved from Design boom (https://www.designboom.com/architecture/hy-fi-the-living-david-benjamin-moma-ps1-young-architects-program-2014-07-01-2014/) on 15 April 2020. Last updated 1 July 2014.

Figure 22

Tiny House, built in 2013, in New York by Ecovative uses mycelium as insulation

A B

Retrieved from Inhabitat (https://inhabitat.com/worlds-first-house-made-of-mushrooms-being-grown-in-new-york/) on 19 April 2020. Last updated 17 September 2014.

Mycelium can be thought of as the roots of a fungus. When combined with agricultural by-products like corn stalks, the mycelium grows and when it is all compressed and dehydrated an incredible material is produced. This material is more insulative than fiberglass insulation, it is fireproof, non-toxic, partly mould and water-resistant and stronger per kilogram than concrete. Mycelium as a building material is 100% biodegradable and can be produced in any form that a mould can be made for. Mycelium offers incredible potential to the building industry, however, at the moment it has only be used to create a temporary outdoor pavilion (figure 21) and for insulation in an experimental tiny home (figure 22).

Figure 23

Mud Shell, by MuDD Architects, London, 2018

A

Retrieved from Dezeen (https://www.dezeen.com/awards/2019/shortlists/mud-shell/) on 17 April 2020.

B

Note. The Mud Shell is a sturdy domed shelter constructed out of bags of hay attached to a wooden lattice that was then sprayed with a mixture of clay and fibre stabilised with lime using a drone.
Retrieved from MuDD Architects (https://www.muddarchitects.com/) on 17 April 2020.

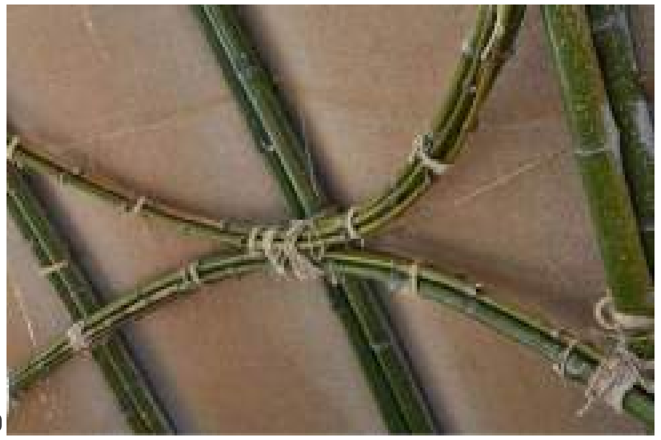
Figure 24

Clay, bamboo and rice husk, Terramia, by MuDD Architects, Milan, 2019

A

B

C



D

E

Note. The Terramia housing prototypes are entirely constructed out of the biodegradable materials of clay, bamboo and rice husks. The natural fibre fabric is sprayed by a drone with a bio-motar.
Retrieved from Design wanted (https://designwanted.com/architecture/mudd-architects/) on 17 April 2020. Last updated 24 January 2020.

The Mud Shell (figure 23) and Terramia (figure 24) by MuDD Architects demonstrate that achieving a 100% biodegradable dwelling is a genuine goal for some modern designers. Although in many ways modern advancements have made achieving a biodegradable building more difficult, MuDD Architects are exploring how it can make constructing a biodegradable dwelling easier.

Figure 25

Untreated timber, Woodcube, Designed by architekturagentur Hamburg, Germany, 2013

Photographs by Martin Kunze. Retrieved from ArchDaily (https://www.archdaily.com/421676/woodcube-architekturagentur) on 4 June 2020

The Woodcube is 5 storeys high and has 8 residential units with a net floor area of 900 m². The 32mm thick exterior wall and ceiling elements are prefabricated from unbounded non-coated cross-layered wooden boards which fixed together by traditional beech wooden dowel plugs.

The exterior wall elements are load bearing, thermally insulative and fire-resistant. To enhance the insulation performance of the wall system a 4 cm thick layer of wood soft fibreboard was added into the layers of the wall elements. Groves are engraved into the surface of the layered boards to create enclosed air cavities in the wall elements. The exterior walls boast a thermal resistance of R-12.8.

The entire timber construction was examined by building biologists and has no added chemicals or glues so is 100% biodegradable as well as being completely deconstructable and reusable.

2.3 Māori Biodegradable Vernacular Architecture

Figure 26

Raupo Hut, New Zealand

Retrieved from Auckland Museum (https://www.aucklandmuseum.com/collections-research/collections/record/am_library-photography-234474) on 17 April 2020.

Now that international biodegradable precedents have been explored the attention and focus will shift onto New Zealand. It is believed that Māori arrived on the shores of New Zealand from Polynesia in the late 13th century (Wilson, 2005). Māori were able to thrive in New Zealand's climate with shelters constructed solely of local biodegradable materials for centuries before non-biodegradable building materials arrived in New Zealand. It is therefore wise to seek wisdom from the vernacular construction techniques of Māori in New Zealand before the arrival of non-biodegradable building materials.

The Raupo hut (figure 26) is an example of New Zealand's vernacular architecture before the arrival of non-biodegradable building materials. Māori sourced their construction materials from surrounding forests and swamps (Salmond, 2010). Timber was used for structural poles, walls and ridge beams (Salmond, 2010). Rushes, bark or toetoe were used for thatching (Salmond, 2010). The thatching was often woven through mānuka battens (Salmond, 2010). All joints were tied or woven (Salmond, 2010). Reeds or slabs of tree ferns were used for walls

Biodegradable Materials of Māori

Timbers	mānuka	Other unspecified timbers				
Earthen Methods	Unspecified earthen methods					
Thatching Materials	Grass	Bark	Reeds	Ferns	Rushes	Toetoe

2.4 Biodegradable Architecture of the Early Settlers

Figure 27

The Cuddy, Waimate, New Zealand

Photograph taken by P McGahan on 11 December 2012. Retrived from Heritage New Zealand (https://www.heritage.org.nz/the-list/details/49) on 17 April 2020. Copyright: Heritage New Zealand

When European settlers arrived in New Zealand so did the first non-biodegradable building materials. "The Cuddy" (figure 27) was built in 1854 in New Zealand's early European history after the arrival of non-biodegradable building materials such as glass in New Zealand. The dwelling has Tōtara walls, a thatched roof and is lined with wattle and daub (Wilson, 2017). The chimney is constructed of adobe bricks (Wilson, 2017).

Local biodegradable materials were still heavily relied on for the early construction of settler's homes. In Wellington local Māori helped settlers build shelters of wood, reed, grass and bark (Salmond, 2010). In the 1840s and 1850s Settlers from the United Kingdom brought the techniques of wattle and daub, adobe brick, and cob to New Zealand (Hall, 2012). During this time New Zealand also saw construction sod, rammed earth, Kauri, Rimu, Tōtara and Matia (Salmond, 2010).

Timber was used for structural framing, cladding, flooring, foundations and roofing (Salmond, 2010). No building wrap layer, insulation or drainage cavities were present. Fern fronds, reeds and bark sheets were also used as roofing materials (Salmond, 2010).

Biodegradable Materials of Early Settlers

Timbers	Tōtara	Kauri	Rimu	Matai	
Earthen Methods	Wattle and Daub	Adobe Bricks	Cob	Rammed Earth	Sod
Thatching Materials	Grass	Bark	Reeds	Ferns	

2.5 Biodegradable Architecture in NZ Today

Figure 28

Earthship Te Timatanga, Hikuai, Waikato, New Zealand

Note. House constructed of Timber and earth rammed into old car tyres. Retrieved from Airbnb (https://www.airbnb.co.nz/rooms/10812145?source_impression_id=p3_1584396151_GjfgIl1LAT%2FZ83MP) on 4 April 2020.

Today the development of high-performing non-biodegradable building materials has dramatically increased and taken over the market. This has led to biodegradable building materials falling out of favour. This occurred in New Zealand and most of the western world after the industrial revolution. Constructions like the Raupo hut or The Cuddy are no longer being constructed. However, the use of biodegradable building materials is still being pursued by natural building enthusiasts who albeit represent a vast minority of the population.

The Earthship Te Timatanga (figure 28), is a modern-day New Zealand example of an attempt to increase the amount of biodegradable building materials used in buildings. The design is predominantly constructed out of timber and earth but contains metal roofing, aluminium joinery and waterproof membranes. Unfortunately, in our modern age, even natural building enthusiasts often have little motivation to find a biodegradable alternative for these common materials as they are cheap and effective (Kennedy et al., 2014). As a result, many modern-day examples of biodegradable buildings are only partly biodegradable.

However, a notable amount of mostly biodegradable buildings are still standing in New Zealand today. In Nelson alone, there are 144 dwellings built after 1945 constructed of earth and/or straw bales (Hall, 2012). In addition, the use of earth and straw bale for building houses has increased over the past 60 years and has dramatically increased in the last 20 years (Hall, 2012). The presence of the Earth Building Standards has also given earth building credibility in New Zealand (Hall, 2012).

2.6 List of Biodegradable Materials

Biodegradable Materials Globally

Vernacular	Contemporary
Cob	Cob
Adobe Block	Adobe Block
Rammed Earth	Rammed Earth
Wattle and Daub	Wattle and Daub
Bamboo	Bamboo
Clay Plaster	Clay Plaster
	Lime Plaster
	Straw Bale
	Earth Bags
	Cork
	Mycelium
Reeds	
Wood	Untreated Timber
Wool	Wool
	Hemp
	Cellulose Insulation
Seaweed	Seaweed
Thatch	Thatch
Sod	Sod
	Wood Fibre Insulation

Biodegradable Materials in New Zealand

Vernacular	Contemporary
Cob	Cob
Adobe Block	Adobe Block
Rammed Earth	Rammed Earth
Wattle and Daub	Wattle and Daub
	Clay Plaster
	Lime Plaster
	Straw Bale
	Earth Bags
Wood	Untreated Timber
Wool	Wool
	Hemp
Thatch	
Sod	Sod

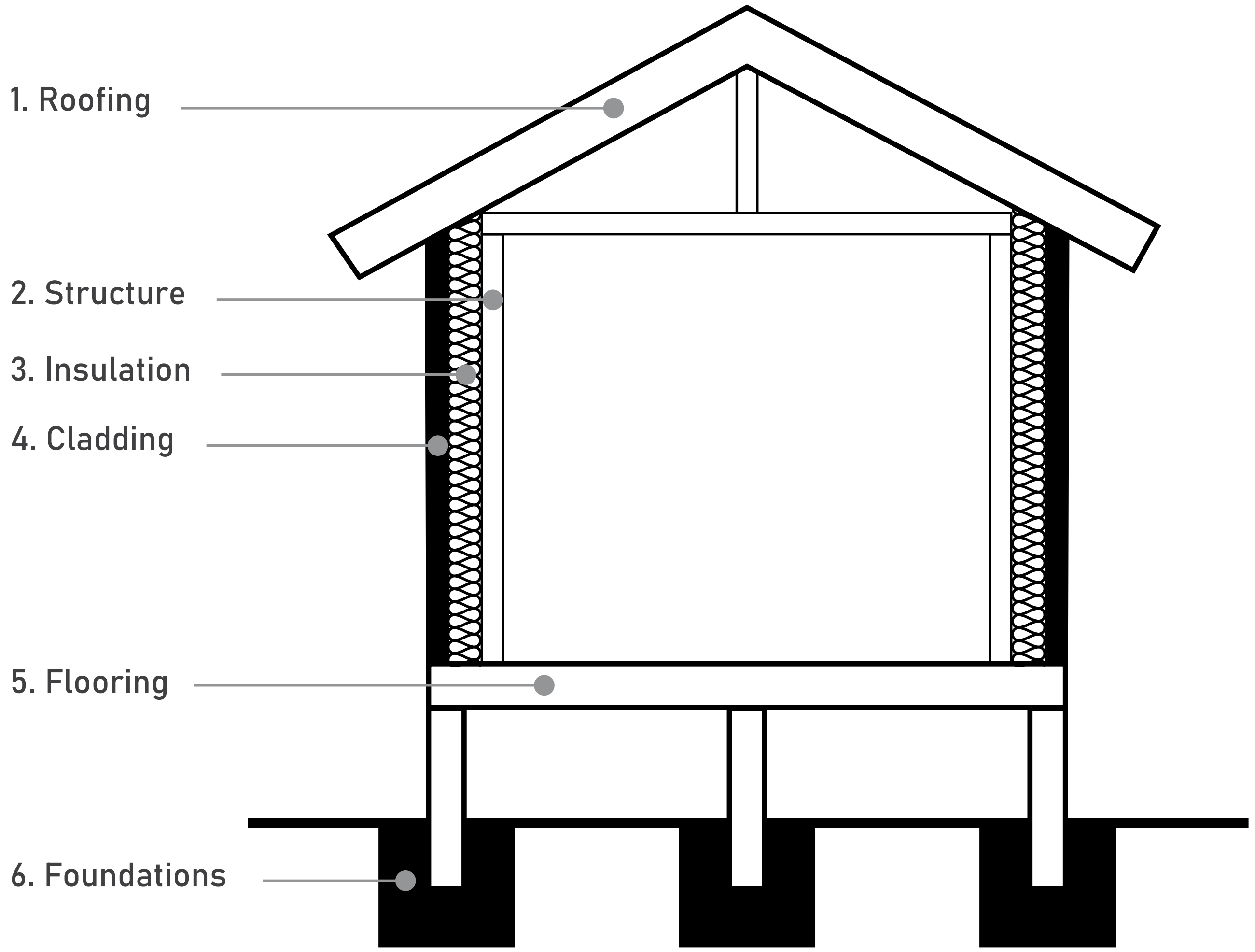
These tables list the vernacular and contemporary biodegradable materials internationally and in New Zealand. The list of international biodegradable materials were sourced from the precedent review and from "The natural building companion : a comprehensive guide to integrative design and construction", 2012 by Jacob Deva Racusin and "The Art of Natural Building- Second Edition", 2014 by Joseph Kennedy. The list of biodegradable materials used globally is not exhaustive but a useful background context for comparison against New Zealand's biodegradable materials. New Zealand's vernacular and contemporary biodegradable materials were sourced from the preceding literature review and based on the table of global materials. Both these tables are approximate but provide a useful indication of what materials have endured and been used in New Zealand from the global context. In the next chapter, the materials listed in the global biodegradable materials table are analysed thoroughly to determine their suitability for use in New Zealand based on availability and performance. Through this process, the most suitable materials for New Zealand from the New Zealand biodegradable material table will emerge.

Most Suitable Biodegradable Materials For New Zealand

3

Chapter Outline

The previous chapter produced a list of biodegradable building materials used in New Zealand and around the world throughout history. However, the suitability of these materials for application in New Zealand varies greatly. This chapter will therefore seek to find the most suitable biodegradable building materials for New Zealand using the list of materials produced in the previous chapter. The building's construction is broken down into six constituent elements - roofing, structure, insulation, cladding, flooring, and foundations. This is because each building element has unique performance requirements. The optimum biodegradable building material is then selected for each element based on its availability and performance in New Zealand. A summary of the most suitable materials for New Zealand is produced at the end of the chapter. This contributes towards the third thesis objective of finding the most suitable biodegradable construction approach for New Zealand.

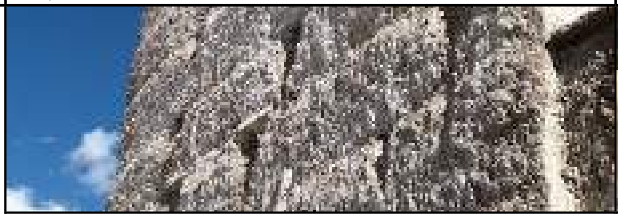


3.2 Structural Systems

Performance Requirement:

From NZBC B1 Structure "Buildings will withstand likely loads, including wind, earthquake, live and dead loads (people and building contents)."

AVAILABILITY KEY
High=Produced in NZ
Moderate= Raw materials present in NZ
Low= Imported product

Material	Vernacular Precedent	Contemporary Precedent		Availability	Strengths	Weaknesses	Overall Suitability
Cob	 Retrieved from Design boom (https://www.designboom.com/architecture/musgum-earth-architecture/) on 17 April 2020.	 Retrieved from This Cob House (https://www.thiscobhouse.com/cob-workshop-meadow-creek-mountain-ranch-part-1/) on 29 April 2020.		Moderate	- High compressive strength - High thermal mass - Earth building standard eases the consenting process	- Poor weather resistance - Heavy - Poor insulation coefficient - Poor performance in earth quakes	Low
Adobe Block	 Note. Mud bricks for building houses are sun dried at a Tonga fishing village on Lake Kariba, Zimbabwe. Retrieved from Alamy (https://www.alamy.com/mud-bricks-for-building-houses-are-sun-dried-at-a-tonga-fishing-village-on-lake-kariba-zimbabw) on 19 May 2020	 Retrived from Solid Earth (https://www.solidearth.co.nz/products-and-services/adobe-manufacture/) on 30 April 2020		High: produced in NZ by Solid Earth Adobe Buildings	-High compressive strength -High thermal mass - Earth building standard eases the consenting process	- Poor weather resistance -Heavy - Poor insulation coefficient - Poor performance in earth quakes	Moderate
Rammed Earth	 Note. Basgo fort, possibly constructed before 1357. Retrieved from ResearchGate (https://www.researchgate.net/figure/Basgo-fort-possibly-constructed-before-1357_fig1_273221030) on 19 May 2020.	 Retrived from Earth Homes (https://www.earthhomes.co.nz/Portfolio?mv_pc=6038) on 30 April 2020		High: Produced in NZ by Terra Firma and Down to Earth Building	-High compressive strength -High thermal mass - Earth building standard eases the consenting process	-Poor weather resistance -Heavy - Poor insulation coefficient -Requires steel reinforcing and cement stabilisers to provide adequate structure to resist lateral loads	Moderate
Clay or Lime-plastered Straw Bale	Baled straw wasn't produced until the late 1800s	 Retrieved from Simple Construct (https://simpleconstruct.net/natural-plasters/plastering-straw-bale/) on 19 May 2020		High: Straw bale produced in NZ High: Clay-plaster produced in NZ by Solid Earth Adobe Buildings	- Highly insulative - Resistant to lateral loads - Moderate compressive strength - Straw bale and clay plaster construction has been tested regarding seismic performance in Pakistan in 2009. The straw bale house performed extremely well.	-Not suitable for construction over 1-storey	Moderate

Structural Systems Continued

AVAILABILITY KEY
High=Produced in NZ
Moderate= Raw materials present in NZ
Low= Imported product

Material	Vernacular Precedent	Contemporary Precedent		Availability	Strengths	Weaknesses	Overall Suitability
Bamboo	 Retrieved from Edition (https://edition.cnn.com/style/article/vernacular-architecture-sustainability/index.html) on 19 May 2020	 Retrived from IBUKU (https://ibuku.com/sharma-springs-residence/) on 1 May 2020		Low	- Incredible tensile strength - Incredible compressive strength - Light - Flexible - Fire resistance (Kenedy et al, 2014)	- Prone to shrinkage - Low durability often requires chemical treatment for construction applications	Low
Cork blocks	No Vernacular Examples	 Photograph by Alex de Rijke, 2019. Retrieved from Detail (https://www.detail.de/blog-artikel/ein-material-fuenf-pyramiden-cork-house-von-matthew-barnett-howland-34518/) on 17 April 2020. Last updated 19 August 2019.		Low	- Water resistant - Light - Insulative - High compressive strength -Fire resistant	- Degrades and becomes hard and brittle over time	Low
Mycelium	No Vernacular Examples	 Photograph of Hy-fi were taken by photo by kris graves. Retrieved from Desing boom (https://www.designboom.com/architecture/hy-fi-the-living-david-benjamin-moma-ps1-young-architects-program-2014-07-01-2014/) on 15 April 2020. Last updated 1 July 2014.		Moderate: Raw materials available in NZ to produce Mycelium	- High compressive strength - Insulative - Fire resistance	- Poor weather resistance - Has yet to used in a habitable building	Low
Reeds	 Retrieved from Edition (https://edition.cnn.com/style/article/vernacular-architecture-sustainability/index.html) on 19 May 2020	No Contemporary Examples		Moderate	- Light - Moderate insulation coefficient - Flexible	- Poor strength - Poor durability	Low

Structural Systems Continued

AVAILABILITY KEY
High=Produced in NZ
Moderate= Raw materials present in NZ
Low= Imported product

Most Suitable

Material	Vernacular Precedent	Contemporary Precedent		Availability	Strengths	Weaknesses	Overall Suitability
Untreated Douglas Fir Heartwood	Kauri, Rimu and Matai were previously used as framing timbers in NZ but are no longer available	 Retrived from Douglas Fir (https://douglasfir.co.nz/net/buildwith/solutions.aspx) on 30 April 2020		High: highly produced in NZ	-Flexible to resist lateral loads -Light -High level of experience with the material in the industry - 20-30 life span without weather exposure - Modulus of elasticity 10 GPa - Bending strength 78 MPa (http://www.nzwood.co.nz/forestry-2/douglas-fir/)	- Moderate Durability - Use of untreated Douglas-fir structural timber beyond a single household unit of no more than two storeys is considered an alternative solution under the NZBC and will require quality detailing to get construction consented	High
Untreated Macrocarpa Heartwood	Kauri, Rimu and Matai were previously used as framing timbers in NZ but are no longer available	 Retrieved from NZ Wood (http://www.nzwood.co.nz/forestry-2/macrocarpa/) on 4 May 2020		High: Moderate production in NZ	-Flexible to resist lateral loads -Light -High level of experience with the material in the industry - 20-30 life span without weather exposure - Modulus of elasticity 5.79 GPa - Bending strength 87.8 MPa - Compression strength parallel to the grain 44.6 MPa - Shear strength parallel to the grain 12.7 MPa (http://www.nzwood.co.nz/forestry-2/macrocarpa/)	- Moderate Durability	Moderate

NZ Timber for Structure

Untreated Douglas-fir heartwood framing was found to be the most suitable structural system for New Zealand. This is because it is highly available in New Zealand and performs well due to its strength and workability Another species of timber that is considered durable enough to be untreated and have sufficient bearing capacity for structural application is Macrocarpa. However, Macrocarpa framing is not as available as Douglas-fir.

Since the arrival of the settlers to New Zealand, timber has been the predominant structural material, increasing from 79% of houses in 1858 to 90% in 1911 (Isaacs, 2010a). In 2017, 90% of new dwellings in New Zealand were still timber-framed (Brunsdon & Magan, 2017). It has been an enduring construction technique because of its availability, lightness, ease of use and its effectiveness against resisting earthquakes (Isaacs, 2010a).

Amendment 7 to B2/AS1 in April 2011, now allows the use of untreated Douglas-fir for roof, floor and external and internal wall framing in New Zealand buildings provided the conditions given in 3.2.2.2 of the Acceptable Solution are all met (BRANZ, 2020b). 3.2.2.2 requires that the framing is protected from weather or contact with the ground, that the building has a low complexity exterior, has a vented cavity and a simple roof of slope greater than 10° with eaves greater than 600mm (BRANZ, 2020b). Timber needs to be untreated as chemical treatment compromises the biodegradability of timber (see page 72).

3.3 Wall Insulation

Performance Requirement:

--Under the NZBC B2, Insulation must last at least 50 years
--Ensure exterior temperature as minimal effect on the desired interior temperature

AVAILABILITY KEY
High=Produced in NZ
Moderate= Raw materials present in NZ
Low= Imported product

Most Suitable

Material	Image	Availability	Overall Suitability
Straw Bale Reprinted from (Kennedy et al, 2014)		High	High
Pure Wool Reprinted from (Kennedy et al,2014)		High	High
Hempcrete Retrieved from: (https://thisnzlife.co.nz/build-house-hemp/) on 14 April 2020.		Moderate	Low
Cork Panel Retrieved from (https://www.ecopanel.co.nz/cork) on 15 April 2020.		Low	Low

Material	Image	Availability	Overall Suitability
Mycelium Retrieved from (https://www.buildinggreen.com/blog/greensulate---fungus-based-insulation-material-thats-grown-rather-manufactured) on 17 April 2020.		Moderate: Raw materials available in NZ to produce Mycelium	Low
Cellulose Retrieved From (https://www.detail.de/artikel/weg-fuer-biobasierte-daemmstoffe-bereiten-30179/) on 17 April 2020.		Low	High
Seaweed Retrieved from (https://www.designboom.com/design/kathryn-larsen-seaweed-prefab-thatch-panels-03-04-2020/) on 18 April 2020.		Moderate	Low
Straw-Based Products Reprinted from (Maxit, n.d.)		Low	Low

Wall Insulation Continued

Performance Requirement:

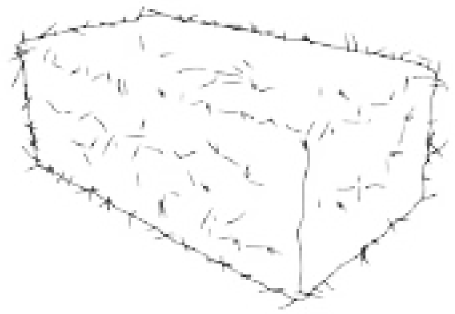
--Under the NZBC B2, Insulation must last at least 50 years
--Ensure exterior temperature as minimal effect on the desired interior temperature

AVAILABILITY KEY
High=Produced in NZ
Moderate= Raw materials present in NZ
Low= Imported product

Material	Image	Availability	Overall Suitability
Natural Fibre Insulation (Flax, Hemp, Jute) Retrieved from (https://www.detail.de/artikel/akzeptanz-von-baumaterialen-aus-nachwachsenden-rohstoffen-31767/) on 20 April 2020		Low	Low
Wood Fibre Insulation Retrieved from Stich Passive Design (http://stichpassivedesign.com/passive-house-products/wood-fibre-board/) on 9 June 2020		Low	Low

Performance criteria were not assessed for insulation. This is because thermal resistance and durability in terms of moisture resistance are the two main categories and all insulation materials have sufficient thermal resistance and most apart from cork and hempcrete have poor moisture resistance. Therefore, the availability of the biodegradable insulation material is the defining factor. Both straw bales and pure wool insulation are produced in New Zealand, but the production of straw bales is significantly greater than that of pure wool insulation. Therefore, straw bales are the most suitable biodegradable insulation material for New Zealand followed by pure wool insulation. The situation of biodegradable insulation materials in New Zealand, in general, is discussed later in this thesis (see page 71).

Straw Bale Overview



Straw bales are an abundant waste product of our agriculture industry. Straw bales are generally underutilised but are used for fertiliser, animal bedding and bio-fuel as well as a building material (R. Pringle, 2016).

Straw is the stem of the cereal plant from which the valuable head of wheat, barley, oats, rice or rye is harvested (Magwood, 2016). Bale sizes vary globally depending on the bailing machines used (R. Pringle, 2016). In New Zealand straw bales are generally 900-1000mm in length, 450mm wide and 350mm deep (Hall, 2019).
Straw is often confused with hay which is an agricultural product in its own right (R. Pringle, 2016). Hay is dried nutrient grass used as animal feed (R. Pringle, 2016). Hay contains much greater organic content than straw and is therefore not suitable for construction applications due to the risk of premature biodegradation. Both straw and hay are turned into bales by a bailing machine which is the probable cause of confusion.

Zealand's grain growing sector has the capacity to supply straw bales to construct 2,200 dwellings each year (Hall, 2019). Therefore, there is certainly the capacity for straw bale construction to grow in New Zealand. Currently, an estimated 20% of straw is simply burned after harvest (figure 29) (Hall, 2019). If this polluting and unsustainable practice were to cease even more straw would be available in New Zealand (R. Pringle, 2016).

Figure 29

Annual straw burn-off South Canterbury, 2012

Photograph by John Bisset, 2012. Retrieved from (https://unitec.researchbank.ac.nz/bitstream/handle/10652/4145/1410_Min_Hall.pdf?sequence=1&isAllowed=y) on 14 April 2020.

Straw bales have only been around since the first bailing machine which was invented in the late 1800s. Prior to that, however, loose straw has been used as a construction material for hundreds of years (R. Pringle, 2016). Straw bales were first used in construction in the 1890s in Nebraska, USA (Henry, 2012). Many of the buildings from this time are still standing, the oldest of which is the Burke house in Alliance, Nebraska, built in 1903 (King, 2006).

It was not until grain was first cultivated in New Zealand in the mid-1800s that straw became available (R. Pringle, 2016). It then took a straw bale revival in the USA in the 1990s for straw bale construction to finally gain enough interest to be used within New Zealand (R. Pringle, 2016). The first straw bale house in New Zealand was constructed in 1995 in Marlborough designed by Peter Kundycki, a landscape architect and urban designer (figure 30) (Hall, 2012). Since then, in 2015, it was estimated that there were 300 to 400 straw bale houses in New Zealand (Hall, 2015).

Most straw bale use in New Zealand is not load-bearing but used as infill amongst timber framing (BRANZ, 2015). This construction approach has the advantage of being able to construct the roof before the straw bale wall infill thus reducing the possibility of the bales getting wet. Significant pockets straw bale houses can be found in Northland, Waiheke Island, the Coromandel, Nelson, Tasman, Marlborough, South Canterbury and Central Otago (Hall, 2012). Statistics New Zealand's latest data from 2017 estimates that there are 1,729,300 in New Zealand (Statistics New Zealand, 2017). This shows that straw bale houses are a long way off even representing one percent of dwellings in New Zealand. However, although small, an industry for straw bale houses does exist in New Zealand with a handful of small companies specialising such as Straw Built Homes, The Little Pig and Strawmark. Sol Design is a New Zealand organisation that offers workshops on straw bale construction and other natural building techniques.

Figure 30

New Zealand's Fist Straw Bale House, Marlborough, 1995

Photograph by Min Hall, 2012. Reprinted from "Earth and Straw Bale: An investigation of their performance and potential as building materials in New Zealand" by M. Hall, 2012, Victoria University of Wellington. Copyright 2012 by Min Hall.

Figure 31

New Zealand's Straw Bale Construction Companies or Consultants

There are now companies in New Zealand that specialise in straw bale construction for homes such as Straw Built Homes, The Little Pig and Strawmark. Sol Design is a New Zealand organisation that offers workshops on straw bale construction and other natural building techniques. The presence of a competitive straw bale construction market is indicative of the construction technique's success in New Zealand.

It is essential that the straw bales remain dry over their whole life as the biodegradation process will commence in the presence of moisture (BRANZ, 2015). However, if the bales are kept dry they remain inert and can last for centuries. Straw has been found that is 7,000 years old (Kennedy et al., 2014).

The uptake of straw bale construction is limited in New Zealand due to the absence of a straw bale building standard (Hall, 2019). The absence of a design standard means that all building code clause B1 structural compliance design must be done by a chartered professional engineer (BRANZ, 2015). This adds time, cost and effort making straw bale construction less desirable. However, an informative straw bale construction appendix is likely to be present on the next revision of the New Zealand Earth Building Standards which, if accepted, will make the consenting process easier for all parties (Hall, 2019).

Pure Wool Insulation Overview

Figure 32

Pure NZ wool blown-in ceiling insulation from Envirowool

Retrieved from Envirowool (https://envirowool.co.nz/why-insulate/) on 13 September 2020.

The potential for pure wool insulation in New Zealand like straw bales is great. New Zealand is one of the largest producers of wool in the world producing 11% of the world's wool and taking 4th place behind Australia, China and the USA (Omondi, 2017). However, despite the abundance of wool produced in our country, only 30% remains in the country and of that wool very little is used in insulation (Nicol & Saunders, 2008). In addition, almost all of the wool used in insulation products in New Zealand is blended with polyester or combined with inorganic resins which compromises the biodegradability of the product. Manufacturers use inorganic resins or blend polyester with wool for durability and to help the product holds its shape (Isaacs, 2010b). Pure wool insulation that is not blended with polyester or inorganic resins is only available in New Zealand as loose blown-in roof insulation from Envirowool. The irony is that our wool is being used overseas in places such as the USA to produce pure wool insulation products. Havelock wool in the USA has made a partnership with Pāmu Farms of New Zealand to supply wool to produce their batt insulation (Hutching, 2018).

Wool is highly insulative, more so than straw. The crimpled nature of the wool fibres traps millions of tiny air pockets. The exterior layer of a wool fibre is hydrophobic (water-resistant) but its inner layer, its cortex, is hydrophilic (water-loving) (Tuzcu, 2007). This means that wool can absorb up to 30% of its weight in moisture within its cortex without feeling damp or compromising its insulative capacity unlike most bio-based or synthetic insulation materials (Tuzcu, 2007).

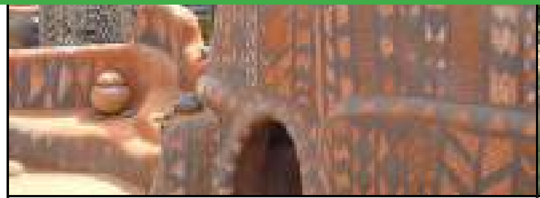
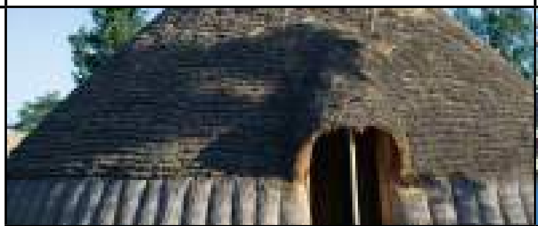
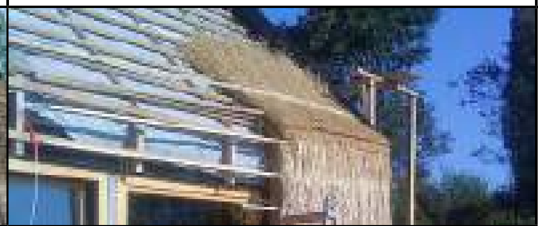
3.4 Wall Cladding

AVAILABILITY KEY
High=Produced in NZ
Moderate= Raw materials present in NZ
Low= Imported product

Performance Requirements

- Under the NZBC B2, cladding must last at least 15 years
- E2.3.2 Exterior walls must prevent the penetration of water that could cause undue dampness, damage to building elements

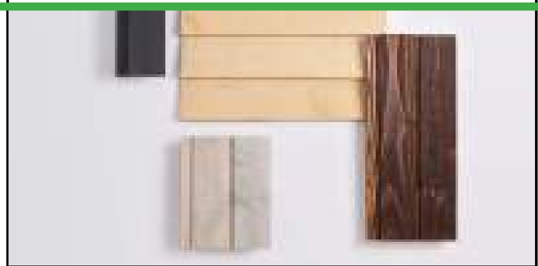
Most Suitable

Material	Vernacular Precedent	Contemporary Precedent		Availability	Strengths	Weaknesses	Overall Suitability
Clay-based Plaster (Weatherproofed with lime wash)	 Retrieved from Natural Homes (http://naturalhomes.org/timeline/gurunsi-house.htm) on 19 May 2020	 Photograph by Min Hall, 2012. Reprinted from "Earth and Straw Bale: An investigation of their performance and potential as building materials in New Zealand" by M. Hall, 2012, Victoria University of Wellington. Copyright 2012 by Min Hall.		High: Produced in NZ by Solid Earth Adobe Buildings	- Aids in keeping straw bales dry - Seals straw bales for air tightness and improved insulation - Provides bracing to resist lateral loads - Increases structural integrity of straw bale wall	- Poor durability without lime wash exterior finish - Low strength (less than lime-based plaster)	High
Lime-based Plaster	No Vernacular Example	 Owner-built lime-plastered straw-bale home, New Zealand, Designed by Graeme North Retrieved from Ecodesign (https://www.ecodesign.co.nz/examples/index.html) on 4 April 2020.		High: Produced in NZ by Earth Studio	- Provides some Aid in keeping straw bales dry - Seals straw bales for air tightness and improved insulation - Provides bracing to resist lateral loads - Increases structural integrity of straw bale wall	- Moderate durability - Moderate-High strength (less than cement-based plaster)	High
Seaweed	No Vernacular Example	 Retrieved from Dezeen (https://www.dezeen.com/2013/07/10/the-modern-seaweed-house-by-vandkunsten-and-realdania/) on 13 May 2020		Moderate	- Offers additional insulation - Salt from the seawater acts as a preservative and slightly increases durability	- The vernacular skills that brought success are essentially dead today and non-existent in NZ - Poor durability - Requires waterproof membrane for water tightness - Flammable	Low
Thatch	 Retrieved from Edition (https://edition.cnn.com/style/article/vernacular-architecture-sustainability/index.html) on 19 May 2020	 Photographs by Damir Fabijanic, 2014. Retrieved from Detail (https://www.detail.de/artikel/lokales-erbe-ferienhaus-in-kroatien-11897/) on 17 April 2020. Last updated 11 May 2014.		Moderate	- Offers additional insulation - History of use in NZ's vernacular architecture	- The vernacular skills are essentially dead today in NZ - Poor durability - Requires waterproof membrane for water tightness - Flammable	Low

Wall Cladding Continued

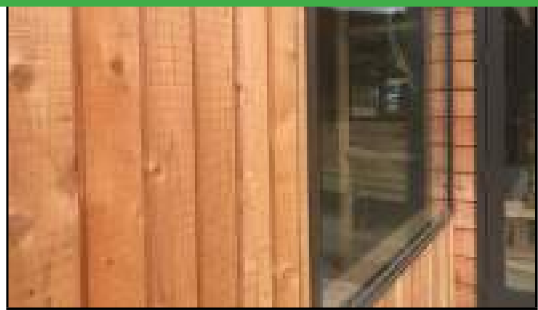
AVAILABILITY KEY
High=Produced in NZ
Moderate= Raw materials present in NZ
Low= Imported product

Most Suitable

Material	Vernacular Precedent	Contemporary Precedent		Availability	Strengths	Weaknesses	Overall Suitability
Cork Panel	No Vernacular Example	 Photographs by José Hevia 2016. Retrieved Lopez Rivera (https://lopez-rivera.com/project/two-cork-houses/) on 30 April		Low	- Moderate-high durability - Water resistant - Fire resistant - Provides additional insulation	- Waterproof membrane is common underneath to ensure water tightness	Moderate
Untreated Macrocarpa Heartwood Cladding (weatherboards	Kauri, Rimu and Totara were previously used as cladding timbers in NZ but are no longer available	 Retrieved from NZ Natural Timber (https://www.nznaturaltimber.co.nz/species/macrocarpa_cladding/) on 6 May 2020		High	- Moderate Durability - Will last 20-30 years when exposed to weather (http://www.nzwood.co.nz/forestry-2/macrocarpa/)	- Waterproof membrane is common underneath to ensure water tightness - Flammable	High
Untreated Douglas Fir Heartwood Cladding	Kauri, Rimu and Totara were previously used as cladding timbers in NZ but are no longer available	 Retrieved from Abodo (https://www.abodo.co.nz/products/timber/tundra-cladding) on 6 May 2020		High	- Moderate Durability - Durability class 3 - Will last 15-20 years when exposed to weather (http://www.nzwood.co.nz/forestry-2/douglas-fir/)	- Waterproof membrane is common underneath to ensure water tightness - Flammable	Moderate
Untreated Siberian larch Heartwood	Kauri, Rimu and Totara were previously used as cladding timbers in NZ but are no longer available	 Retrieved from Abodo (https://www.abodo.co.nz/resources/articles/siberian-larch-cladding-and-weatherboards-in-the-new-zealand-context) on 6 May 2020		Moderate: Limited NZ Supply otherwise imported from Russia.	- Moderate Durability - Durability Class 3 (https://www.abodo.co.nz/resources/articles/siberian-larch-cladding-and-weatherboards-in-the-new-zealand-context)	- Waterproof membrane is common underneath to ensure water tightness - Flammable	Low

Wall Cladding Continued

AVAILABILITY KEY
High=Produced in NZ
Moderate= Raw materials present in NZ
Low= Imported product

Material	Vernacular Precedent	Contemporary Precedent		Availability	Strengths	Weaknesses	Overall Suitability
Most Suitable Untreated Redwood Heartwood Cladding	Kauri, Rimu and Totara were previously used as cladding timbers in NZ but are no longer available	 Retrieved from NZ Natural Timber (https://www.nznaturaltimber.co.nz/species/redwood-cladding/) on 6 May 2020		High	- Durability is extremely variable - Moderate Durability - Durability class 3	- Waterproof membrane is common underneath to ensure water tightness - Flammable	High
Untreated Western Red Cedar Heartwood Cladding	Kauri, Rimu and Totara were previously used as cladding timbers in NZ but are no longer available	 Retrieved from Miproducts (https://miproducts.co.nz/Search/0/0/Rosenfeld-Kidson-Cedarscreen-Vertical-Shiplap-Weatherboard-i4f7ec8de-c2d4-41e6-81d7-2a4f5724ac0c-6400.htm) on 10 May 2020		Low	- Moderate Durability	- Waterproof membrane is common underneath to ensure water tightness - Flammable	Low
Most Suitable Untreated Red Beech Heartwood Cladding	Kauri, Rimu and Totara were previously used as cladding timbers in NZ but are no longer available	 Retrieved from Health Based Building (https://www.healthbasedbuilding.com/foreverbeech/cladding/foreverbeech-ht49-engineered-shiplap-cladding-brus?gn=Cladding&gp=2) on 10 May 2020		High	- Moderate Durabillty - Durable to Hazard Class H3.2 - Not prone to borer attack	- Waterproof membrane is common underneath to ensure water tightness - Flammable	High

Most Suitable Cladding Materials

Clay or lime-based plaster, as well as untreated Macrocarpa, Redwood and Red Beech were found to be the most suitable biodegradable cladding materials for New Zealand. Clay and lime-based plasters are more vapour permeable than timber claddings thus providing good dry out potential, but the timber claddings are more durable against weather. There is potential therefore to use both a plaster and a timber cladding over a vented cavity to uphold both durability and vapour permeability.

Plaster

Plastering straw bales is a traditional straw bale construction method (Racusin, 2012). Once the bales are sealed on both sides with plaster the tiny air pockets in the straw create effective insulation (Kennedy et al., 2014). The choice of plaster is crucial to ensure the bales remain dry. The main plaster types include earth, gypsum, lime and cement-based plasters although only earth and lime-based plasters are biodegradable (Kennedy et al., 2014). These plasters range from weakest and most hygroscopic (the ability to absorb moisture from the air and surroundings) with earth-based plasters to the strongest and least hygroscopic with cement-based plasters. Clay-based plasters are the best for straw bale walls as they are the most hygroscopic, which means that they will naturally wick moisture away from a straw bale wall, protecting it from moisture intrusion (Kennedy et al., 2014). They can absorb odours and soften sounds whilst also helping to maintain a constant and healthy humidity and indoor air quality (Racusin, 2012). The plaster also provides a layer of fire resistance (Kennedy et al., 2014).The layer of plaster on both sides of the bale wall adds structural strength and acts as bracing to resist earthquake and wind loads (Kennedy et al., 2014). Laboratory testing has shown that a well-built earth-plastered straw bale wall system can endure a very sizeable seismic event if there are strong connections between the walls, the floors and the ceiling/roof structure (Champion, 2009; Hsiaw, 2010).

Figure 33

A selection of tiles finished with tadelakt using all New Zealand materials, 2012

Reprinted from "Toward healthier, sustainable, medium density housing, through a return to natural materials" by S. Jaycock, 2012, Victoria University of Wellington. Copyright 2012 by Steven Jaycock.

Clay-plaster is not weather resistant and will erode if not protected. Lime can be applied as a weatherproofing layer to the exterior of a building through limewash. Limewash can be made in New Zealand and can be made in many different natural colours (figure 33) (Jaycock, 2014). Lime is a natural biodegradable material as it has the same chemical make up as limestone when it is set on a building (Racusin, 2012). However, it requires an energy-intensive process to produce where the mined limestone is heated to 900°C to produce the quicklime power used to create lime wash (Kennedy et al., 2014; Racusin, 2012). (Scan Lime Cycle Image). Lime is exceptionally weatherproof (Kennedy et al., 2014). When it is raining, an exterior lime render will absorb moisture until saturated (Racusin, 2012). This saturation prevents any further absorption of moisture, and the lime surface will repel water until the humidity level drops again, protecting the wall behind it (Racusin, 2012). Lime is also breathable and water permeable, allowing moisture in the clay-plaster beneath to evaporate into the outside air (Kennedy et al., 2014). It also regulates humidity by absorbing excess moisture from the environment, then releasing it as humidity drops (Kennedy et al., 2014). This makes lime ideal for interior surfaces in wet and humid areas such as kitchens and bathrooms (Kennedy et al., 2014). Lime is also physically flexible making it a suitable choice in seismically active areas such as New Zealand (Kennedy et al., 2014).

Timber

As of 2017, timber weatherboards have been the most popular cladding material in New Zealand (Brunsdon & Magan, 2017). Timber cladding is also used in straw bale construction (Kennedy et al., 2014; Racusin, 2012). Locally grown redwood, Red Beech and Macrocarpa are durable species that can be left untreated as cladding materials (T. Pringle, 2017). Each of these timbers is sufficiently durable leaving aesthetics as the only criteria for selection.

3.5 Foundations

AVAILABILITY KEY
High=Produced in NZ
Moderate= Raw materials present in NZ
Low= Imported product

Biodegradable Foundations

Performance Requirements

- The NZBC B2 requires foundations to last the life time of the building but at least 50 years
- Connect the building securely to the ground
- Dissipate loads into the ground
-E2.3.3 Walls, floors, and structural elements in contact with, or in close proximity to, the ground must not absorb or transmit moisture in quantities that could cause undue dampness, damage to building elements, or both.

Material	Image	Availability	Overall Suitability
Untreated Durable Timber Heartwood Piles (Totara has a history of use in NZ) Reprinted from "Stable Foundations" by N. Isaacs, 2009, BRANZ. Copyright 2009 by Nigel Isaacs.		Moderate	Low
Untreated Durable Timber Heartwood Post and Beam on Gravel Bed Reprinted from "The Art of Natural Building-Second Edition" by J. Kennedy, 2014, Copyright 2014 by Joseph Kennedy.		Moderate	Low
Untreated Durable Timber Heartwood Post and Beam on Grade Retrieved from Detail (https://www.detail.de/artikel/strohboid-klimafreundliches-strohhaus-34813/) on 17 April 2020. Last Updated 17 October 2019.		Moderate	Low
Earth Bag Foundation Reprinted from "The Art of Natural Building-Second Edition" by J. Kennedy, 2014, Copyright 2014 by Joseph Kennedy.		Moderate	Low
Cork Bock Foundation (has only been used in small scale experiments) Retrieved from Studio Bark (https://studiobark.co.uk/buildings-can-be-made-of-solid-cork-we-built-this-to-prove-it/) on 20 May 2020.		Low	Low

Reusable Foundations

Most Suitable

Material	Image	Availability	Overall Suitability
Stone Footings Reprinted from "Stable Foundations" by N. Isaacs, 2009, BRANZ. Copyright 2009 by Nigel Isaacs.		Moderate	Moderate
Precast Concrete Footings Reprinted from "Lightweight Recoverable Foundations on Suitable Ground", 2015, Green Building Council España. Copyright 2015 by Llorens Duran & Pujadas Gispert.		High	High
Precast Concrete Piles Reprinted from "Lightweight Recoverable Foundations on Suitable Ground", 2015, Green Building Council España. Copyright 2015 by Llorens Duran & Pujadas Gispert.		High	High
Precast Concrete Strip Foundations Reprinted from "Lightweight Recoverable Foundations on Suitable Ground", 2015, Green Building Council España. Copyright 2015 by Llorens Duran & Pujadas Gispert.		High	High
Steel Screw Piles Reprinted from "Lightweight Recoverable Foundations on Suitable Ground", 2015, Green Building Council España. Copyright 2015 by Llorens Duran & Pujadas Gispert.		High	High

Most Suitable Foundation Materials

Performance requirement E2.3.3 from clause E2 of the NZBC states that "walls, floors, and structural elements in contact with, or in close proximity to, the ground must not absorb or transmit moisture in quantities that could cause undue dampness, damage to building elements, or both". Unfortunately, this performance requirement cannot be satisfied with foundations constructed of biodegradable materials.

It is simply not wise to construct a building component as crucial as foundations out of a biodegradable material when it is in contact with the ground. The foundation will begin to biodegrade and severely compromise the stability of the structure. Untreated Totara piles have previously been used as foundations in New Zealand, but parts of the building would begin to noticeably sink over time as the piles slowly rotted (Isaacs, 2009). Isaacs shares in his paper, "Stable Foundations" that floors in parts of a 1908 New Zealand house on a relatively dry site sank over 90 years until the bottom of the laundry floor joists touched the ground (Isaacs, 2009). Although foundations constructed of biodegradable materials such as timber have served this nation and the rest of humanity well for centuries, larger structures are being built and a greater degree of longevity and durability is expected.

Reusable but non-biodegradable foundations such as precast concrete foundations can satisfy the NZBC's stringent performance requirements whilst maintaining the zero-waste objective. Precast concrete footings, piles and strip foundations, as well as steel screw piles, are all durable reusable zero waste foundation options for New Zealand.

3.6 Flooring

AVAILABILITY KEY
High=Produced in NZ
Moderate= Raw materials present in NZ
Low= Imported product

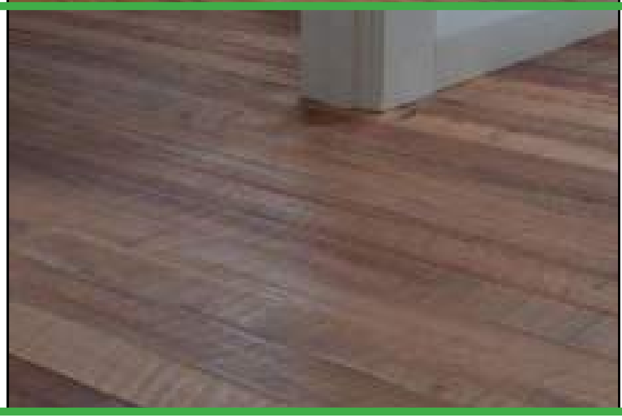
Performance Requirements

-Under the NZBC B2, Floors must last at least 50 years
-Provide habitable platform
- Perform under dead and live load

Material	Image	Image Source		Availability	Strengths	Weaknesses	Overall Suitability
Most Suitable Untreated Matia Heartwood Flooring		Retrieved from Saw Mill Direct (https://sawmilldirect.co.nz/category/matai-flooring/) on 4 May 2020.		High	- High dimensional stability and hardness make it excellent as a floor - Durability equivalent to Hazard Class of H3.1 - Light - Suitable for suspended and inter-storey floors	- Poor Insulation - Poor thermal mass - Flammable	High
Untreated DouglasFir Heartwood Flooring		Retrieved from Pinterst (https://www.pinterest.nz/pin/434034482809088328/) on 4 May 2020.		High: Available by special order in NZ	- Moderate durability - 20-30 life span without weather exposure - Light - Suitable for suspended and inter-storey floors	- Poor Insulation - Poor thermal mass - Flammable	Moderate
Most Suitable Untreated Macrocarpa Heartwood Flooring		Retrieved from Pankhurst Saw Milling (https://pankhurstsawmilling.co.nz/macrocarpa/) on 4 May 2020.		High	- Moderate durability - Will last 40-60 years without weather exposure - Naturally borer resistant - Light - Suitable for suspended and inter-storey floors	- Poor Insulation - Poor thermal mass - Flammable	High
Rammed Earth Floor		Retrieved from Earth Studio (http://earthstudio.co.nz/rammed-earth-floors/) on 4 May 2020.		High: Produced in NZ by Earth Studio	- High durability when sealed with natural oil and wax - High thermal mass - non-flammable	- Heavy - Only suitable for groud floors - Poor insulation as a isolated component	Moderate

Flooring Options Continued

AVAILABILITY KEY
High=Produced in NZ
Moderate= Raw materials present in NZ
Low= Imported product

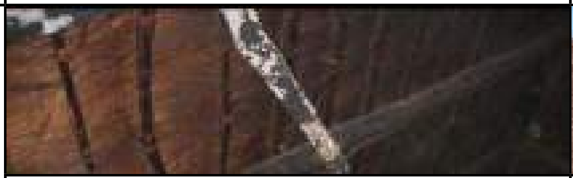
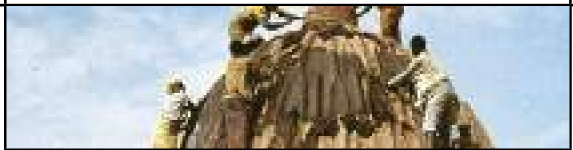
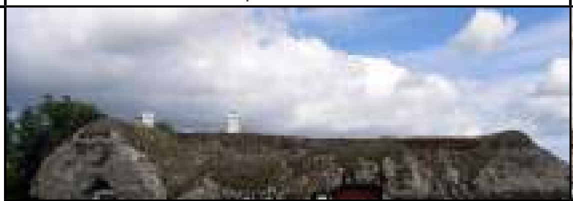
Material	Image	Image Source		Availability	Strengths	Weaknesses	Overall Suitability
Untreated Rimu Heartwood Flooring		Retrieved from NZ natural Timber (https://www.nznaturaltimber.co.nz/species/rimu/) on 4 May 2020.		High	- Moderately durable - Durability Class 3 - Light - Suitable for suspended and inter-storey floors	- Susceptible to borer attack - Poor Insulation - Poor thermal mass - Flammable	Moderate
Untreated Siberian Larch Heartwood Flooring		Retrieved from Siberian Larch Wood (https://www.siberianlarchwood.co.nz/gallery) on 4 May 2020.		Low: Imported from Russia	- Moderate durability - Durabiltiy Class 3 - Light - Suitable for suspended and inter-storey floors	- Poor Insulation - Poor thermal mass - Flammable	Low
Untreated Tawa Heartwood Flooring		Retrieved from NZ natural Timber (https://www.nznaturaltimber.co.nz/species/nz-tawa/) on 4 May 2020.		High	- Non-durable - Light - Suitable for suspended and inter-storey floors	- Poor Insulation - Poor thermal mass - Flammable	Low
Most Suitable Untreated Red Beech Heartwood Flooring		Retrieved from NZ natural Timber (https://www.nznaturaltimber.co.nz/species/nz-beech/) on 4 May 2020.		High	- Moderately durable - Durable equivalent to Hazard Class 3.2 - Not prone to borer attack - Light - Suitable for suspended and inter-storey floors	- Poor Insulation - Poor thermal mass - Flammable	High

3.7 Roofing

AVAILABILITY KEY
High=Produced in NZ
Moderate= Raw materials present in NZ
Low= Imported product

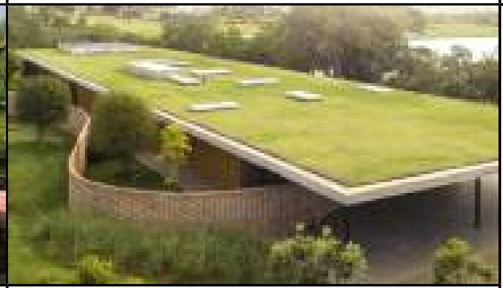
Performance Requirements

-Under the NZBC B2, Roofing must last at least 15 years though the roof structure must last for 50
- Divert rain water away from the building
- Ensure Airtightness
- E2.3.2 Roofs and exterior walls must prevent the penetration of water that could cause undue dampness, damage to building elements, or both.

Material	Vernacular Precedent	Contemporary Precedent		Availability	Strengths	Weaknesses	Overall Suitability
Thatch	 Thatch Roof, Esk Homestead, Canterbury, New Zealand, 1864 Photograph by Min Hall, 208. Reprinted from "Earth and Straw Bale: An investigation of their performance and potential as building materials in New Zealand" by M. Hall, 2012, Victoria University of Wellington. Copyright 2012 by Min Hall.	 Photograph by Damir Fabijanic, 2014. Retrieved from Detail (https://www.detail.de/blog-artikel/ein-material-fuenf-pyramiden-cork-house-von-matthew-barnett-howland-34518/) on 17 April 2020. Last updated 19 August 2019.		Moderate	- Provides some additional insulation if airtight	- Poor Durability - Requires waterproof membrane for water tightness	Low
Cork Panel	No Vernacular Example	 Retrived from NY Times (https://www.nytimes.com/2019/04/26/realestate/building-with-cork-sustainable-architecture.html) on 13 May 2020		Low	- Moderate-high durability - Water resistant - Fire resistant - provides additional insulation	- Requires waterproof membrane for water tightness	Low
Earth	 Mugsum Mud Huts, Cameroon. Retrieved from Design boom (https://www.designboom.com/architecture/musgum-earth-architecture/) on 17 April 2020.	No Contemporary Example		Moderate	- Provides thermal mass	- Poor durability - Poor insulation	Low
Seaweed	 **Note.** House with seaweed roof made using eelgrass from the ocean that is able to withstand decay for hundreds of years, retrieved from Archdaily (https://www.archdaily.com/805415/11-vernacular-building-techniques-that-are-disappearing) on 17 April 2020. Last updated in 2017.	 Retrived from Pinterest (https://www.pinterest.nz/pin/505740233152269555/) on 13 May 2020		Moderate	- Provides some additional insulation if airtight	- Poor durability - Requires waterproof membrane for water tightness	Low

Roofing Options Continued

AVAILABILITY KEY
High=Produced in NZ
Moderate= Raw materials present in NZ
Low= Imported product

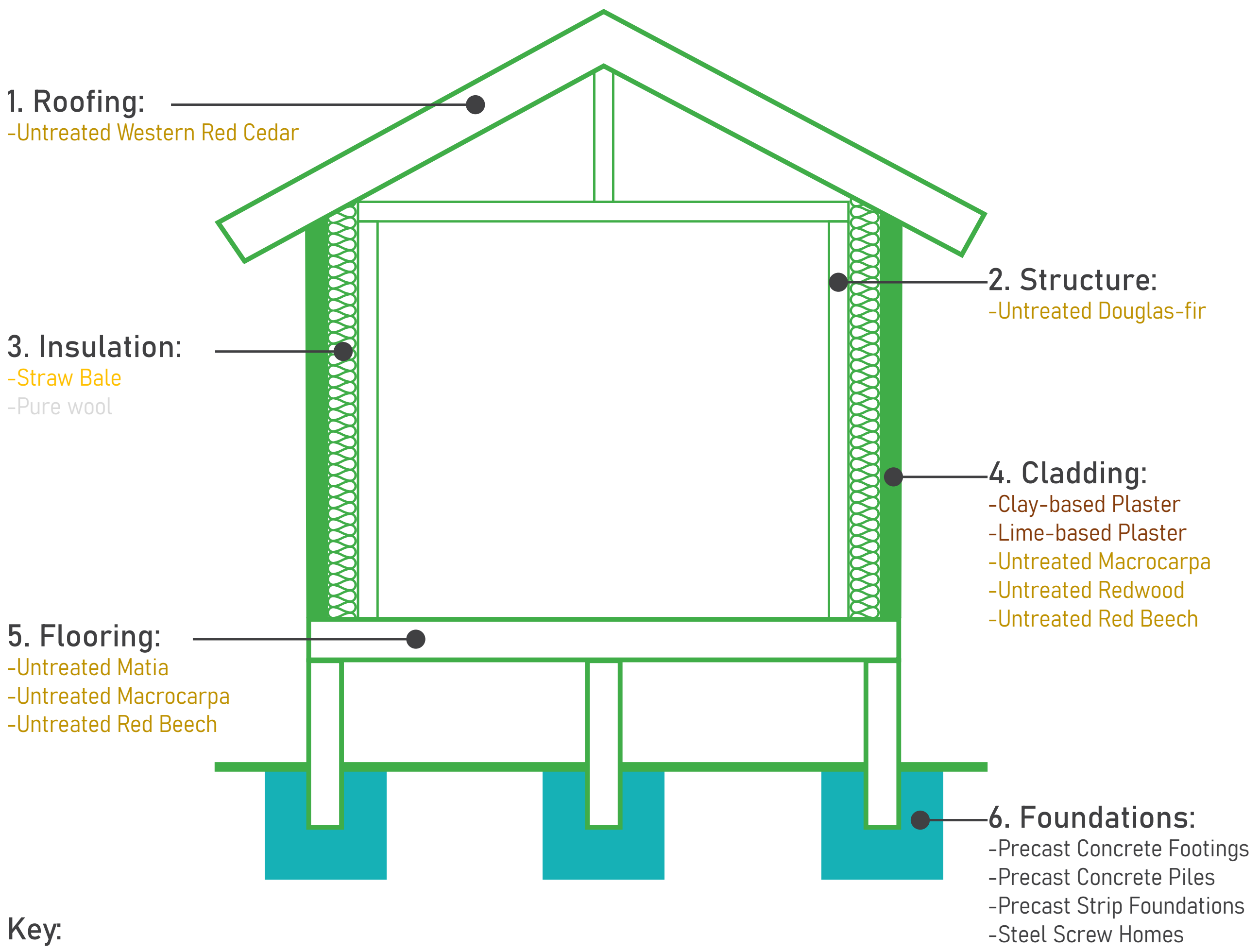
Material	Vernacular Precedent	Contemporary Precedent		Availability	Strengths	Weaknesses	Overall Suitability
Sod	 Retrieved from Flickr (https://www.flickr.com/photos/tjetjep/10511817545) on 16 May 2020	 Retrieved from Inhabitat (https://inhabitat.com/this-modern-solar-powered-retreat-is-topped-with-a-massive-green-roof/) on 16 May 2020		Moderate	- Moderately durable	- Heavy - Requires waterproof membrane for water tightness	Low
Untreated Alaskan Yellow Cedar Heartwood Roofing	Kauri, Tōtara and Kaikawaka roofing were previously used in NZ but are no longer available	 Retrieved from SPS Building (https://spsbuilding.co.nz/product/cedar-shingles-and-shakes-sps-timber/) on 10 May 2020		Low: Imported from Canada	- Moderate durability	- Requires waterproof membrane for water tightness	Low
Untreated Western Red Cedar Heartwood Roofing	Kauri, Tōtara and Kaikawaka roofing were previously used in NZ but are no longer available	 Retrieved from Rosenfeld Kidson (https://rosenfeldkidson.co.nz/ProductCategory/ProductDetails/32/cedar-shingles?cat=5&category=exterior-timbers) on 5 May 2020		High: Available from Rosenfeld Kidson	- Moderate durability	- Requires waterproof membrane for water tightness	High

Most Suitable

Timber Roofing

Untreated Western Red cedar shingles or shakes were found to be the most suitable biodegradable roofing material for New Zealand. Timber is the most durable biodegradable roofing material and Western Red cedar is grown and produced here in New Zealand. Timber shingles and shakes have been used as a roofing material in New Zealand for around 200 years (BRANZ, 2020a). Shingles are sawn and have relatively smooth faces while Shakes are usually hand split (although some are also sawn) and usually have a rougher textured surface on at least one side (BRANZ, 2020a). Both shakes and shingles have random widths and also taper in thickness (BRANZ, 2020a). Timber shingles and shakes are not covered by New Zealand Building Code Acceptable Solution E2/AS1, so they need to be consented as an Alternative Solution (BRANZ, 2020a). Western red cedar or Alaskan yellow cedar that is grown and processed in Canada represent the majority of timber shingle and shake roofs currently installed in New Zealand (BRANZ, 2020a). However, previously, redwood shingles and shakes were sometimes used (BRANZ, 2020a). Historically, New Zealand kauri, tōtara and kaikawaka timbers were used by European settlers for shingles or shakes, but these timbers are not now available in sufficient quantities for commercial manufacture (BRANZ, 2020a).

3.8 Summary of Zero Waste Materials for NZ



3.9 Biosphere Barriers

The majority of barriers limiting the uptake of biodegradable building materials stem from their decreased durability in the presence of moisture. This is because moisture is a catalyst of the biodegradation process.

Building Regulations

Fortunately, there are no barriers that directly prevent the use of biodegradable building materials in New Zealand. The durability requirements in clause B2 and the moisture resistance requirements in E2 of the NZBC do prevent some of the less durable biodegradable construction approaches from being used. These are often construction techniques found in vernacular architecture such as Raupo huts, untreated timber piles or entirely earth structures. But so many more sufficiently durable biodegradable construction methods exist that can be used. In fact, our performance-based building code in New Zealand means that unconventional or innovative construction techniques are welcomed given they can be proven to perform.

Perceived Low Durability

Amongst the general public the word biodegradable can cause concern when associated with building materials as people fear it means their house will rot away. In truth however, just because biodegradable materials can biodegrade does not mean they will. Biodegradation requires specific environmental conditions such as moisture and bacterial surroundings which can easily be denied while the material carries out its operational life. Biodegradable construction can last for centuries and in many cases last longer than our modern-day constructions; certainly, longer than the arbitrary mandated 50-year life-span mandated in B2 of the NZBC. The Lavenham Guildhall in Sudbury England, for example, is built out of exposed untreated timber and coated once every five years with limewash (figure 34). This building was built in 1529, nearly 500 years ago, and is still in everyday use. Our oldest known earth building in New Zealand is Pompallier House, in Russell built in 1841 (figure 35). This building is two-storeys tall and has endured over 150 years of our country's climate and withstood many earthquakes.

Figure 34

Lavenham Guildhall, Sudbury, England

Retrieved from Britain Express (https://www.britainexpress.com/attractions.htm?attraction=3663)

Figure 35

Pompallier House, Russell, New Zealand

Retrieved from NZ Herald (https://www.nzherald.co.nz/travel/news/article.cfm?c_id=7&objectid=11113338)

Biodegradable Insulation

Inorganic insulation materials dominate the NZ market. Fiberglass wall insulation occupies 90% of the market and the other share is mainly polyester insulation (Brunsdon & Magan, 2017). However, overseas in countries like Germany, organic wall insulation materials such as wood fibre, cellulose, hemp, flax, straw or wool are not uncommon, occupying up to 4% of the market (Götze & Naderer, 2019). Straw bale and wool are the only bio-based insulation materials produced here and represent an insignificant share of the New Zealand market (BRANZ, 2015, 2020). However, as recently as 2008 blown-in cellulose (macerated paper) insulation was being produced in NZ (McChesney & Cox-Smith, 2008). Bio-based insulation materials continue to battle building regulations around the world as they are deemed to have inferior durability due to their lack of moisture resistance (Sigmund, 2017). This is especially the mindset of the New Zealand construction industry following the leaky building crisis. However, thorough hygrothermal testing out of Germany over the last 10 years in the "11th edition of the FNR market overview of insulating materials" has shown these reservations unfounded (Kaiser et al., 2020).

Membranes and Wraps

Inorganic building wraps and membranes that keep a building watertight and/or airtight are one the most challenging aspects to find a biodegradable or even reusable solution for especially for roof construction. While the NZBC does not demand the use of a waterproof roofing membrane it does require that building materials and components are durable and that external water is managed so it does not damage the structural integrity of the building or impact the health of the occupants (T. Pringle, 2013). This is certainly difficult to ensure without a waterproof membrane however before their invention they were managed without for millennia. The Esk Head Homestead (figure 36) in North Canterbury built in 1864

Figure 36

Esk Head Homestead, North Canterbury, 1864

Photograph by Min Hall, 208. Reprinted from "Earth and Straw Bale: An investigation of their performance and potential
as building materials in New Zealand" by M. Hall, 2012, Victoria University of Wellington. Copyright 2012 by Min Hall.

is an example of how a watertight roof was constructed in New Zealand with biodegradable thatching before the invention of synthetic membranes and wraps. This biodegradable construction has lasted for nearly 150 years demonstrating the durability and longevity possible with a biodegradable roof construction. A watertight biodegradable roof construction without a membrane is therefore possible and is pursued in this thesis (see page 156).

Chemical Treatment of Timber

Timber, being a natural biodegradable material will begin to decompose in the presence of moisture. To avoid this occurring during the operational life of the building, instead of keeping the timber dry or able to dry out, chemical treatment is used in New Zealand to increase the moisture resistance of the timber and hinder the decomposition process.

Wet boric or boron salts timber treatments were first introduced in New Zealand in 1952 (BRANZ, 2013). Before that, untreated native timbers such as Rimu, Matia and Tōtara and some untreated radiata pine framing were used (BRANZ, 2013). From 2003 there was a period where all timber needed to be treated in New Zealand (T. Pringle, 2012). However, today, for some applications, NZS 3602:2003 lists a limited number of species that are considered durable enough to meet the requirements of the Building Code without the need for treatment such as macrocarpa, redwood and western red cedar externally and Douglas-fir, macrocarpa, rimu and matai internally (BRANZ, 2020b). Despite the slight loosening of restrictions around the need for chemical treatment however, chemical treatment of timber still dominates the industry in New Zealand.

Not only does chemical treatment of timber inhibit the biodegradation process but it also makes the timber inappropriate for reuse in domestic construction (Rhodes & Dolan, 2013). This results in our country's greatest biodegradable asset and the majority of our residential construction ending up in the landfill at the end of its life. When landfilled the chemicals also damage surrounding ecosystems and potentially contaminate groundwater (Parisio, 2006).

Cost

Unlike timber, the biodegradable materials of straw bale, clay-plaster and pure wool insulation are not conventional New Zealand construction materials. This often means a higher cost. The cost of straw bales as a raw material, for example, is low, however, the unfamiliarity of the material makes it difficult to get competitive prices from builders (Hall, 2012). In addition, construction with in- situ straw bale and clay plaster is labour intensive (Hall, 2012; Kennedy et al., 2014; Racusin, 2012). Unless the owner builds the dwelling themselves a straw bale house will unlikely be cheaper than a conventional New Zealand house (Hall, 2012). The cost is also increased by the need for more substantial foundations to support the heavy walls (Hall, 2012).

Construction Approach Exploration

4

Chapter Outline

This chapter contributes towards the third thesis objective of finding the optimum biodegradable construction approach for New Zealand. In this chapter, the construction approaches of in-situ construction, standardised brick modules and prefabricated wall panels are explored to determine which approach is the most suitable for biodegradable materials. The most suitable biodegradable materials for New Zealand found in the previous chapter are used to explore these construction approaches. For each approach precedents are analysed prior to the production of design proposals. The metrics of weight, thermal resistance and vapour resistance are used to compare design proposals for each construction approach. Data was sourced on the materials used in the proposed designs to calculate these metrics. The calculations were manually conducted. The weight for each design was calculated by multiplying the density of each material by its respective volume. The thermal resistance for each design was calculated by summing the depth of each material after being divided by its respective thermal conductivity. The vapour resistance of each design was calculated by summing the vapour resistivity of each material after being multiplied by its respective depth. Thermal and vapour resistance were calculated excluding the timber frame. The construction approaches are then reviewed based on their ability to increase the uptake of biodegradable building materials, reuse potential and proximity to conventional New Zealand construction practice.

Properties of Materials

Material	Density	Thermal conductivities	Vapour resistivities
Straw bale	128 Kg/m3 (Magwood, 2016)	0.085 W/mk (calculated from Hall, 2019)	9.71 MNs/gm (calculated from (Magwood, 2016)
Straw (Ecococon)	110 Kg/m3 (Ecococon, 2017)	0.0494 W/mk (calculated from Ecococon, 2017)	Straw bale: 9.71 MNs/gm (calculated from Magwood, 2016)
Pure wool insulation	25 Kg/m3 (Tuzcu, 2007)	0.033 W/mk (Tuzcu, 2007)	10.0 MNs/gm (Black Mountain Insulation, 2020)
Douglas-fir	462 Kg/m3 (Kimberley et al., 2017)	0.12 W/mk (TenWolde et al., 1988)	541.1 MNs/gm (calculated from Kordziel et al., 2020)
Clay plaster	1500 Kg/m3 (Morton et al., 2005)	0.66 W/mk (Morton et al., 2005)	26.3 MNs/gm (Vares et al., 2017)
12.7mm Exterior gypsum sheathing (DensGlass®)	708.7 Kg/m3 (DensGlass®, 2017)	0.128 W/mk (DensGlass®, 2017)	60.6 MNs/gm (DensGlass®, 2017)
13mm Interior gypsum sheathing (SHEETROCK® HD)	654 Kg/m3 (USG Boral, 2019)	0.178 W/mk (USG Boral, 2019)	38.5 MNs/gm (Overton, 2015)

4.1 In-situ Construction

In-situ construction is the most common construction approach in the residential sector in New Zealand. It has been the only method of construction before the introduction of prefabricated construction. In-situ construction is the process of assembling building components on site. All construction will be in-situ to some extent but in this case, it refers to the process of building where all construction occurs on site.

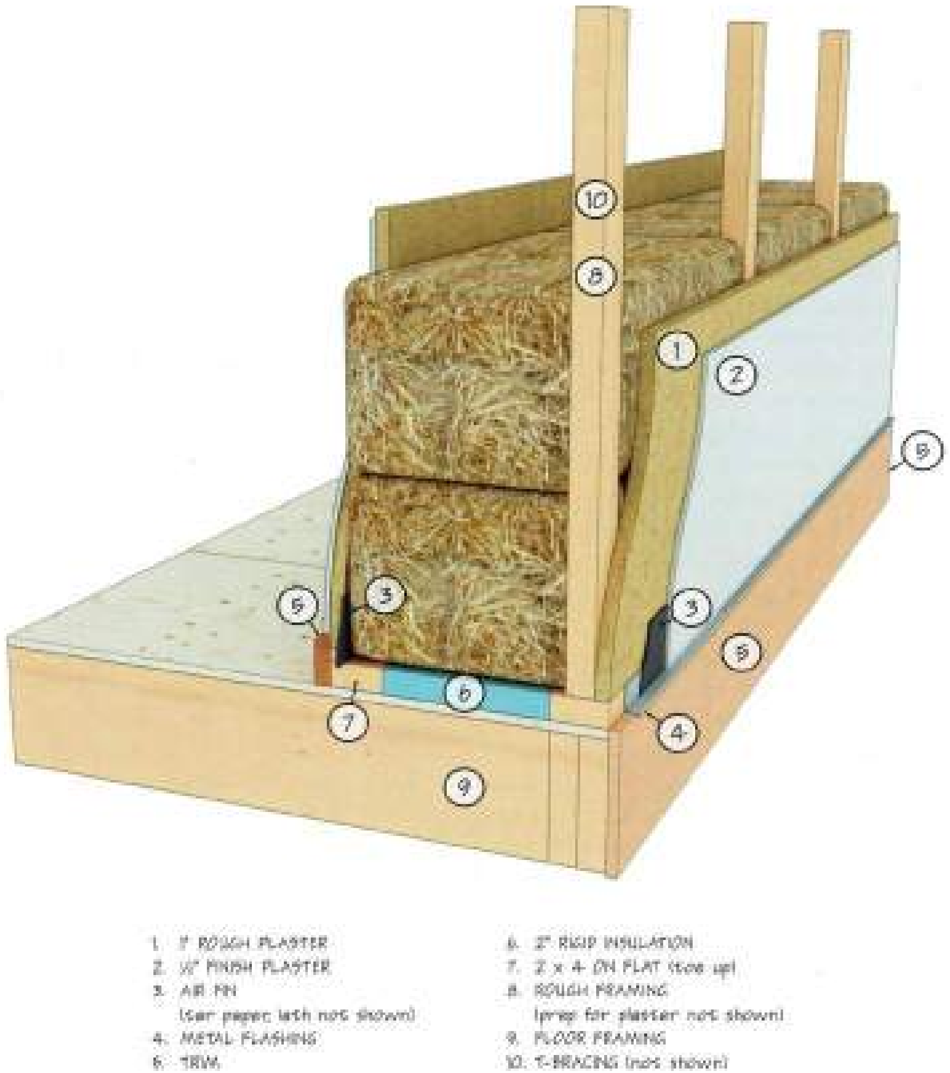
Precedent Review

There are already established in-situ construction methods using the biodegradable materials found to be most suitable to New Zealand in the tradition of straw bale construction. Straw bale construction uses straw bale, clay plaster, and timber, which are all biodegradable materials suitable to New Zealand. Pure wool insulation is not a material used in straw bale construction but in-situ constructions including wool insulation can be informed by straw bale construction techniques.

Bale Infill techniques

Figure 37

Bale infill with plastered exterior

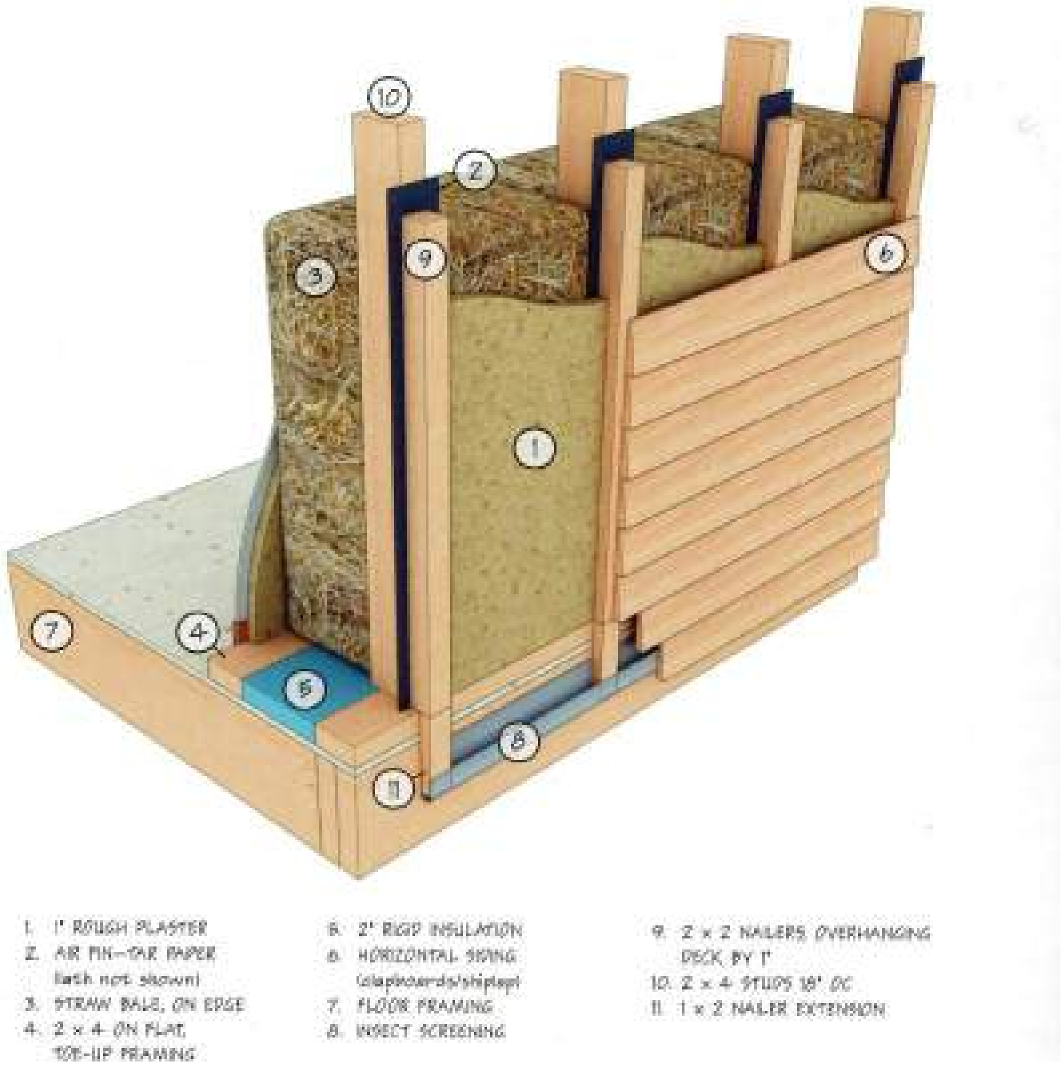


Reprinted from “The natural building companion : a comprehensive guide to integrative design and construction” by J. Racusin, 2012, Copyright 2012 by Jaco Deva Racusin.

Description	Strengths	Weaknesses
The structural stud are spaced such that a bale can be notched to fit cleanly into the cavity between the studs	- No thermal bridging - Simplicity and familiarity of conventional stud framing -Plaster is continuous	- Bales require notching - Presence of non-biodegradable components such as air fins, metal flashings, sealants and rigid insulation - Clay plaster adds weight to the construction - Clay plaster makes deconstruction for reuse or decomposition at the end of life difficult

Figure 38

Bale infill with timber exterior



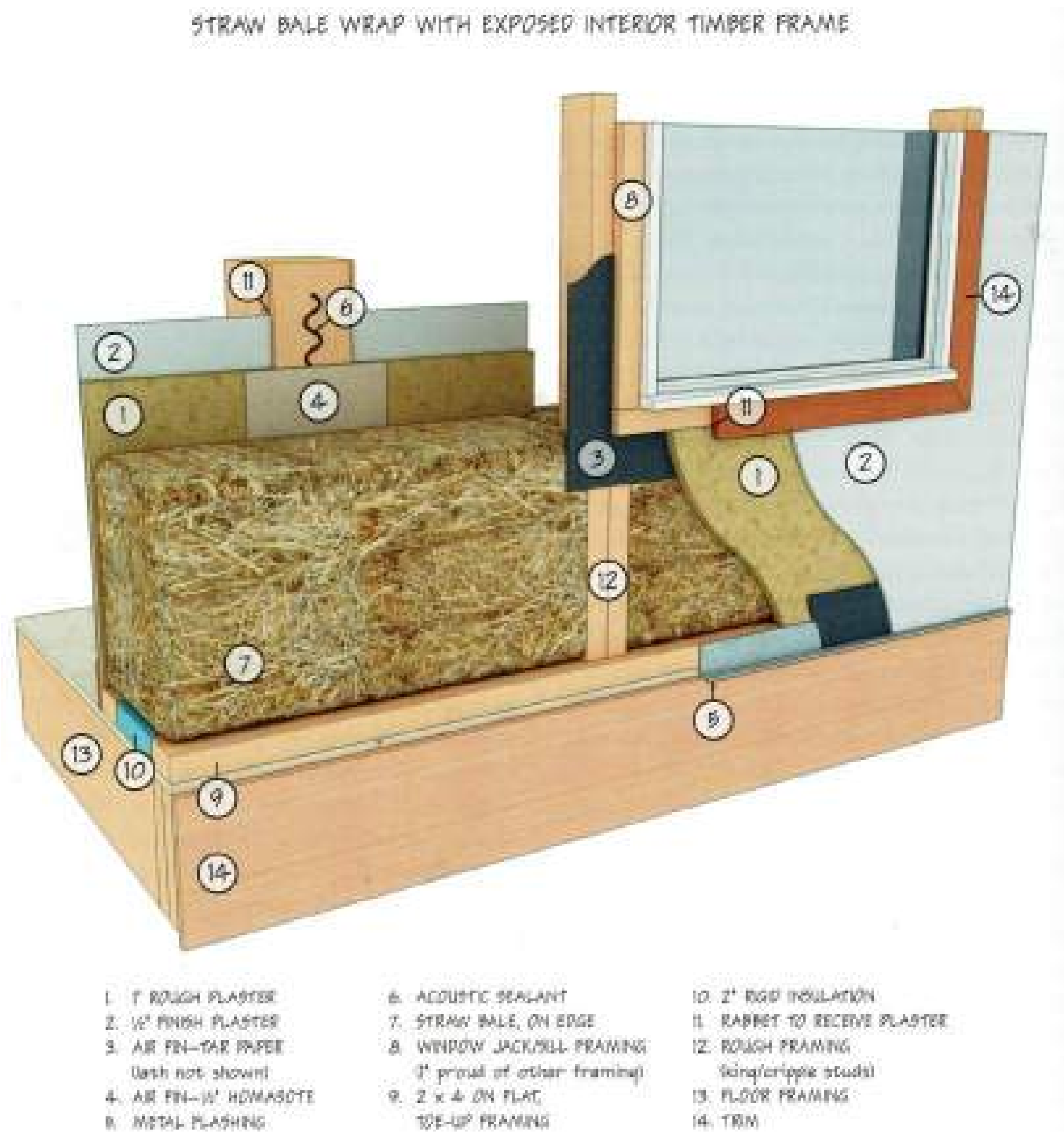
Reprinted from “The natural building companion : a comprehensive guide to integrative design and construction” by J. Racusin, 2012, Copyright 2012 by Jaco Deva Racusin.

Description	Strengths	Weaknesses
Structural studs can be any size or spacing as bales are pressed against their interior face. Plaster is applied on the interior face and exterior face between the studs. Timber cladding is present on the exterior over a vented cavity.	- No thermal bridging - Timber cladding over vented cavity provides more weather protection	- Bales require notching - Plastering between the battens on the exterior is time consuming - Presence of non-biodegradable components such as air fins, metal flashings, sealants and rigid insulation - Clay plaster adds weight to the construction - Clay plaster makes deconstruction for reuse or decomposition at the end of life difficult

Bale “wrap” techniques

Figure 39

Bale wrap with plastered exterior

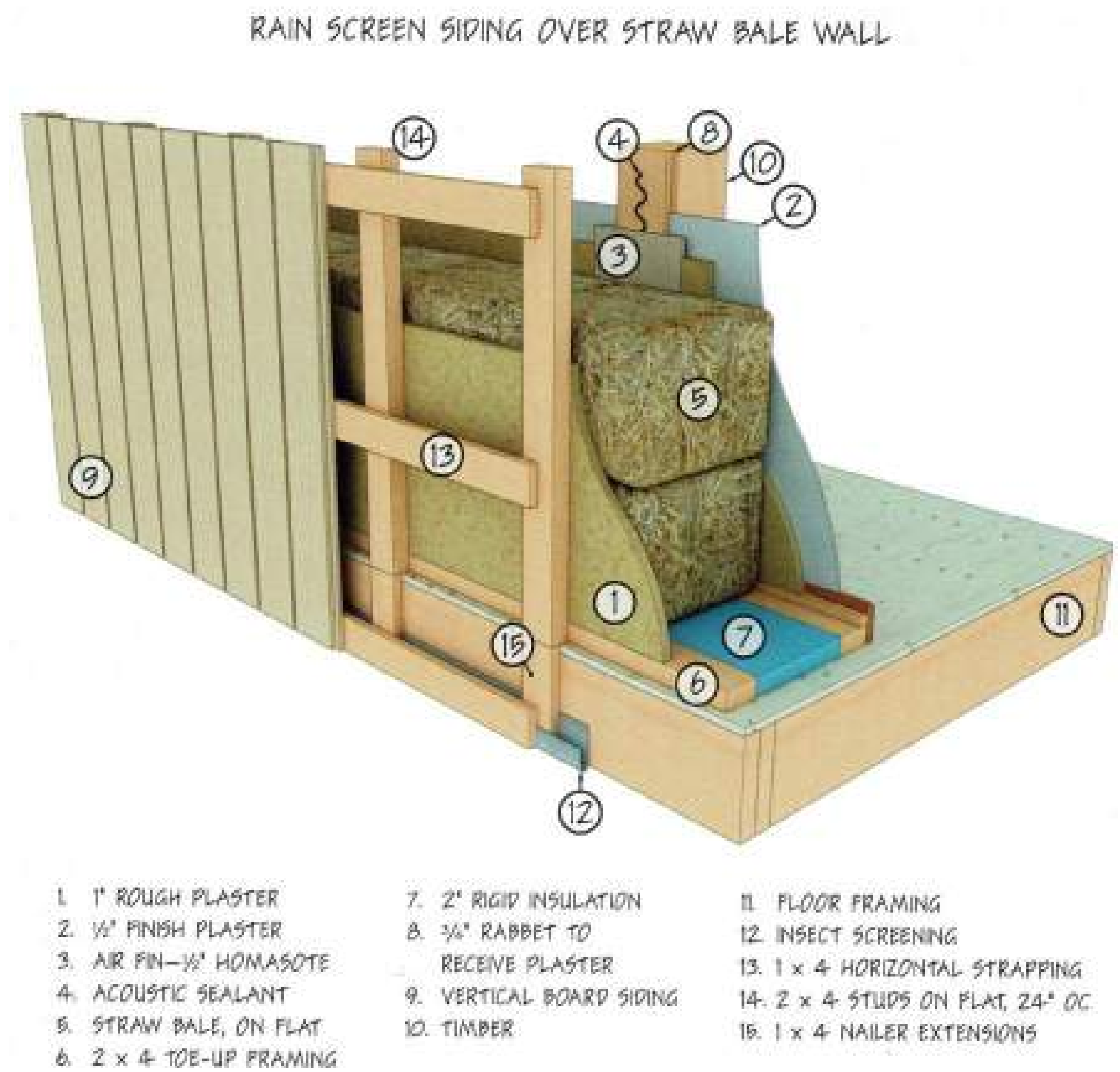


Reprinted from “The natural building companion : a comprehensive guide to integrative design and construction” by J. Racusin, 2012, Copyright 2012 by Jaco Deva Racusin.

Description	Strengths	Weaknesses
The bales and plaster wrap around the exterior of the structural timber frame, leaving the timber frame exposed on the interior.	- No thermal bridging - Exposed structure contributes to interior aesthetic - Flexibility to increase structure with larger studs at narrower spacings - Bales need no notching	- Presence of non-biodegradable components such as air fins, metal flashings, sealants and rigid insulation - Clay plaster adds weight to the construction - Clay plaster makes deconstruction for reuse or decomposition at the end of life difficult - Plastering between the studs on the interior is time consuming

Figure 40

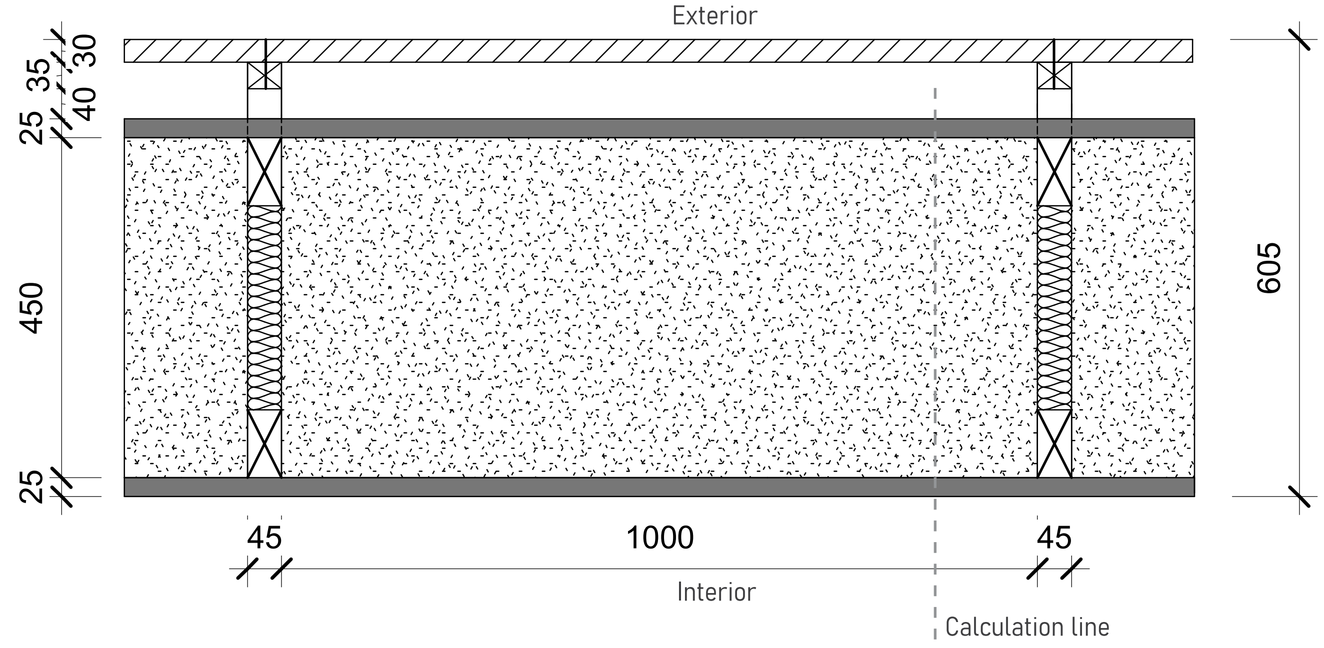
Bale wrap with timber exterior



Reprinted from “The natural building companion : a comprehensive guide to integrative design and construction” by J. Racusin, 2012, Copyright 2012 by Jaco Deva Racusin.

Description	Strengths	Weaknesses
The bales and plaster wrap around the exterior of the structural timber frame, leaving the timber frame exposed on the interior. vertical timber cladding is present over a vented cavity on the exterior	- No thermal bridging - Exposed structure contributes to interior aesthetic - Flexibility to increase structure with larger studs at narrower spacings - Bales need no notching - Timber cladding over vented cavity provides more weather protection	- Presence of non-biodegradable components such as air fins, metal flashings, sealants and rigid insulation - Clay plaster adds weight to the construction - Clay plaster makes deconstruction for reuse or decomposition at the end of life difficult - Plastering between the studs on the interior is time consuming

Wall Proposal 1
Scale 1:10



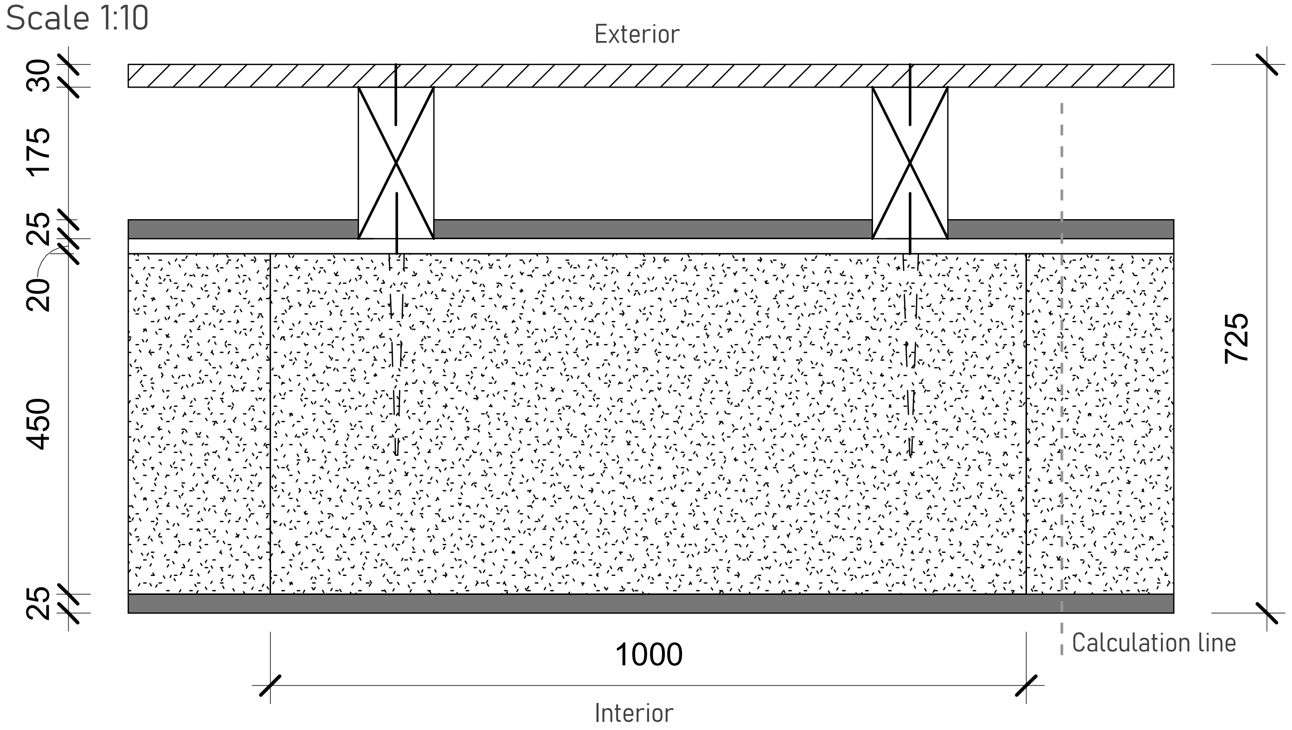
Material		Function
	Untreated Macrocarpa Cladding	Cladding
	Screws	Fixing
	Untreated Douglas Fir Cavity Batten	Provide vented cavity depth, provide place to fix cladding
	Clay Plaster	Protect wool insulation from condensation and moisture (vapour control layer) Provide air seal
	Untreated Douglas Fir Framing	Structure
	Straw Bale	Insulation
	Pure Wool	Insulation
	Untreated Douglas Fir Framing	Structure
	Clay Plaster	Protect wool insulation from condensation and moisture (vapour control layer) Provide air seal

Thermal Resistance	Vapour Resistance
5.37 m²K/W	5.68 MNs/g

The precedent analysis highlighted and literature also supports that including timber cladding over a ventilated cavity increases weather protection and reduces the chance of the bales getting wet (BRANZ, 2015). Therefore, timber cladding over a ventilated cavity will be used for every wall proposal.

Wall proposal 1 is a bale infill design. The precedent review revealed that having to notch the bales is a primary weakness of this construction approach. In addition, the non-continuous nature of the plaster between the cavity battens required for the timber cladding was also noted as a weakness. This wall proposal therefore seeks to eliminate notching and increase the continuity of the plaster whilst maintaining timber cladding over a ventilated cavity. The wall proposal places the structure in between the straw bales so no notching is required and used pure wool insulation to insulate the cavity.

Wall Proposal 2
Scale 1:10

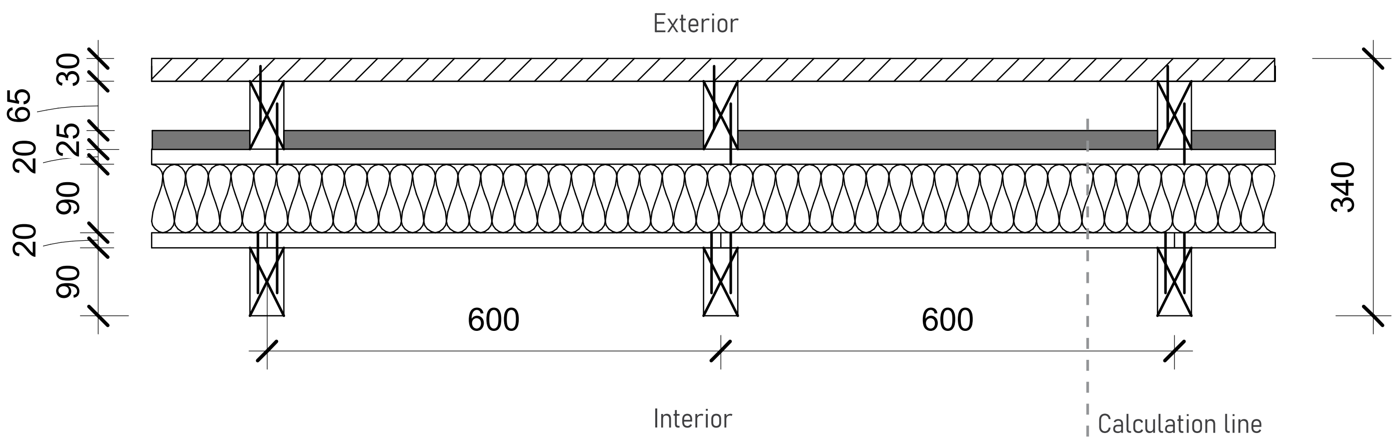


Material		Function
	Untreated Macrocarpa Cladding	Cladding
	Screws	Fixing
	Untreated Douglas Fir Framing	Structure, provide vented cavity depth, provide place to fix cladding
	Clay Plaster	Protect straw bale insulation from condensation and moisture (vapour control layer) Provide air seal
	Untreated Douglas Fir Boards	Provide substrate for clay plaster to be laid
	Untreated Douglas-fir Piercing Rods	Tie straw bales into structure
	Straw Bale Insulation	Thermal insulation layer
	Clay Plaster	Protect straw bale insulation from condensation and moisture (vapour control layer) Provide air seal

Thermal Resistance	Vapour Resistance
5.552 m²K/W	16.51 MNs/g

Wall proposal 2 is a bale wrap design. The design seeks to increase the resource efficiency of a typical bale wrap construction with timber cladding by using one timber member to provide structure and act as a cavity batten. The straw bales are pierced into place to fix them to the building's structure.

Wall Proposal 3
Scale 1:10

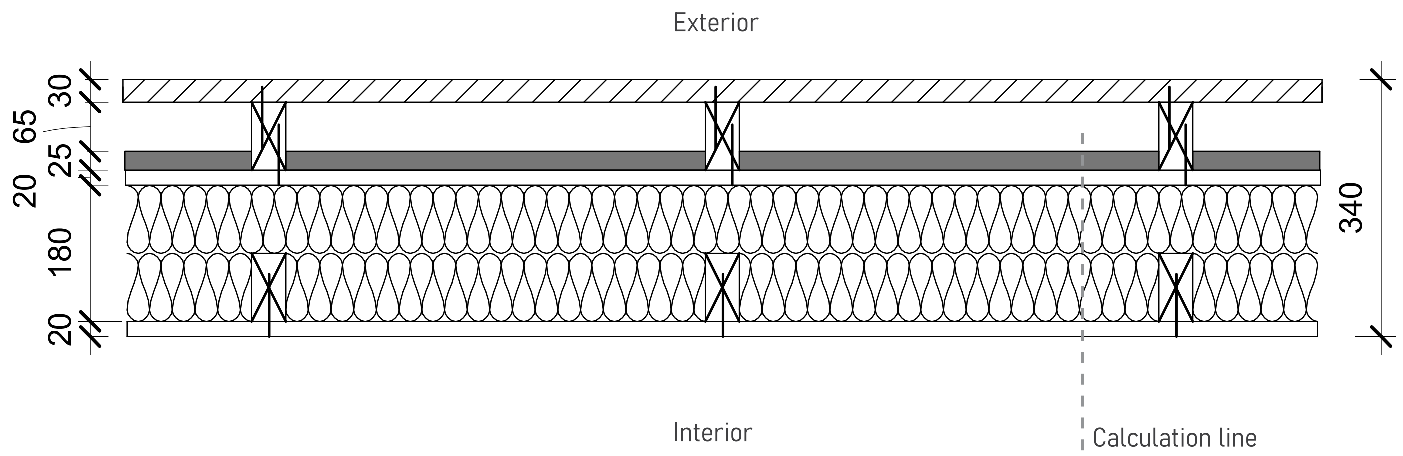


Material		Function
	Untreated Macrocarpa Cladding	Cladding
	Screws	Fixing
	Untreated Douglas Fir Framing	Structure, provide vented cavity depth, provide place to fix cladding
	Clay Plaster	Protect wool insulation from condensation and moisture (vapour control layer)
	Untreated Douglas Fir Boards	Provide substrate for clay plaster to be laid
	Pure Wool Insulation	Thermal insulation layer
	Untreated Douglas Fir Boards	Interior finsh
	Screws	Fixing
	Untreated Douglas Fir Framing	Structure, provide place to fix interior boards

Thermal Resistance	Vapour Resistance
3.10 m²K/W	23.20 MNs/g

Because wool insulation, unlike straw bales, has no structural capacity, in order to eliminate thermal bridging a double timber frame is required. However, one of the timber frames can double as cavity battens like wall proposal 2. In addition, wool insulation, unlike straw, cannot support clay plaster therefore in order to benefit from the hygroscopic and vapour permeability of clay plaster a timber substrate is required.

Wall Proposal 4
Scale 1:10



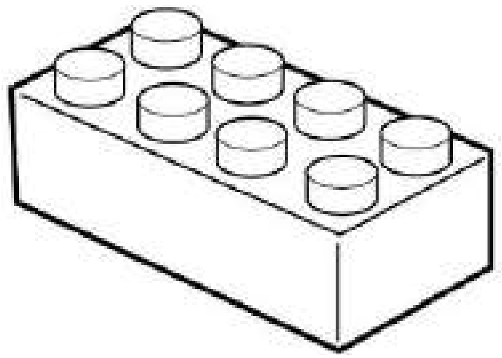
Material		Function
	Untreated Macrocarpa Cladding	Cladding
	Screws	Fixing
	Untreated Douglas Fir Framing	Structure, provide vented cavity deptth, provide place to fix cladding
	Clay Plaster	Protect wool insulation from condensation and moisture (vapour control layer)
	Untreated Douglas Fir Boards	Provide substrate for clay plaster to be laid
	Natural Wool Insulation	Thermal insulation layer
	Untreated Douglas Fir Framing	Interior finsh
	Screws	Fixing
	Untreated Douglas Fir Boards	Structure, provide place to fix interior boards

Thermal Resistance	Vapour Resistance
5.83 m²K/W	24.10 MNs/g

Wall proposal 4 is identical to wall proposal 3 except the structure is not exposed on the interior but instead used as an additional insulation cavity.

4.2 Standardised Block Module

Due to the fact that combining both the bio-sphere and the tech-sphere is the optimum waste reduction strategy a biodegradable and reuse construction module should be pursued. This research proposes a standardised prefabricated biodegradable construction brick, reminiscent of Lego. Such a brick can be simply deconstructed at the end of life and reused in an identical application in a future project. Research suggests that demountable standardised prefabricated modules could, indeed allow for a circular economy within the construction industry (Minunno et al., 2018).

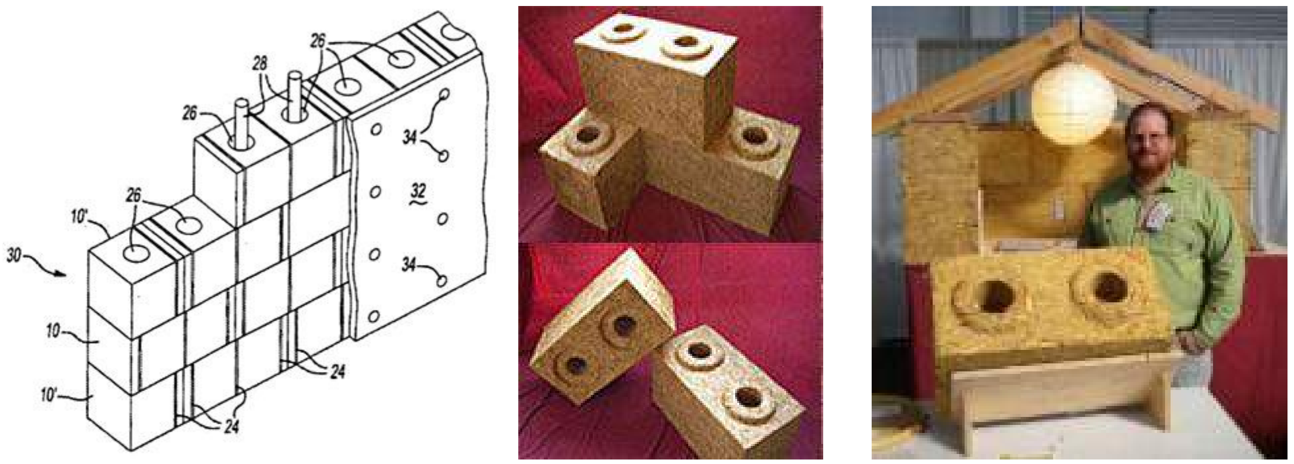


A biodegradable and reusable construction module

Precedent Review

Figure 41

Oryzatech Stak Blocks



Retrieved from Treehugger (https://www.treehugger.com/sustainable-product-design/oryzatech-strawbale-lego-blocks-for-grown-ups.html) on 2 June 2020

Description	**Strengths**	**Weaknesses**
- Made from compressed rice straw - 300x300x600mm - 2 locations of structural connection (1x2 brick)	- Load-bearing - Fire resistant - Reasonably light at 13.5 Kg - Highly insulative at R-8.8 - No thermal bridging	- Relieves heavily on the use of steel rebar rods - Undisclosed binder which may compromise biodegradability - Not weatherproof

Figure 42

Just BioFibre Hempcrete Building Block

Retrieved from Hempcrete Walls (http://hempcretewalls.com/2015/04/22/more-hempcrete-structural-building-block-info-vancouver-bc/) on 2 June 2020

Description	**Strengths**	**Weaknesses**
- Made from Hempcrete (hemp, lime and sand) with timber structural members - 300x300x600mm - 8 locations of structural connection (2x4 brick)	- Load-bearing up to 2 storeys - Fire resistant - Very light - Highly insulative - No thermal bridging	- Requires stainless steel fixings - Not weatherproof

Figure 43

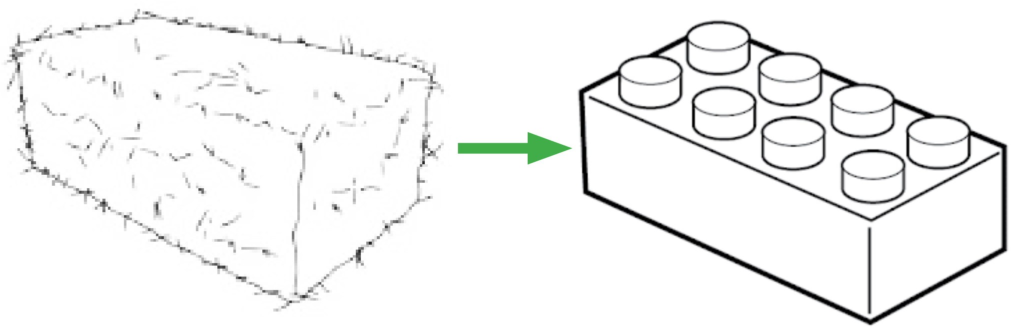
Gabloks

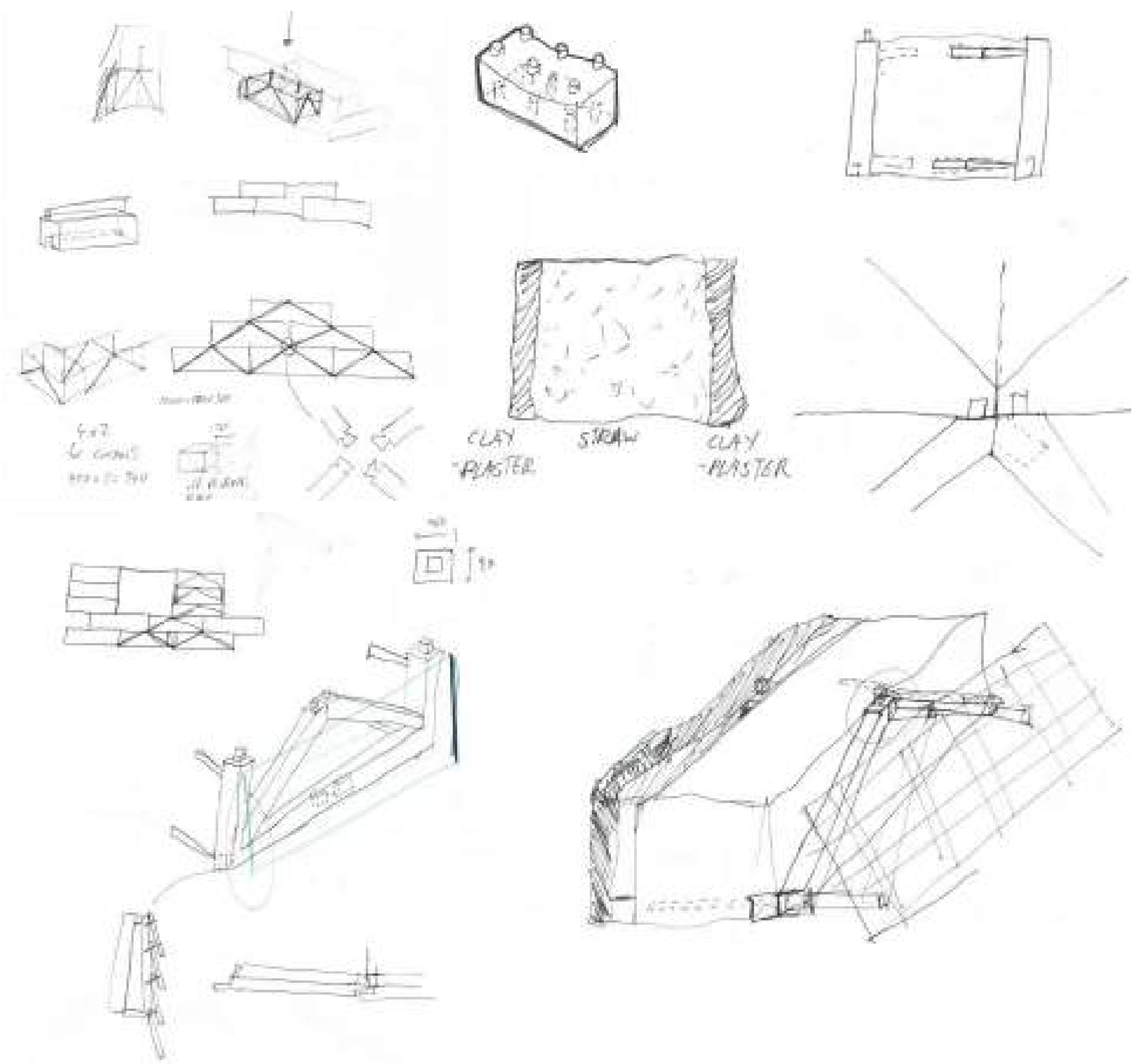
Retrieved from Linkedin (https://www.linkedin.com/company/gablok/?trk=similar-companies_org_title&originalSubdomain=ua) on 31 June 2020

Description	**Strengths**	**Weaknesses**
- 18mm wood chip panel casing with rigid EPS blocks inside - 300x300x600mm - 2 locations of structural connection (2x4 brick)	- Load-bearing up to 3 storeys - Fire resistant - Very light - Highly insulative - Weatherproof	- Wood chip panel uses glue which compromises biodegradability - Rigid EPS insulation is non-biodegradable and is essential for the structural intergrity of the design - Thermal bridging through timber casing

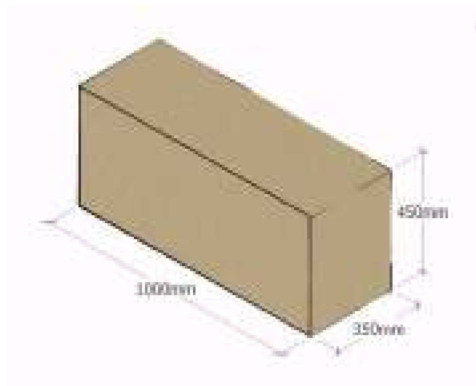
General Issues	Learnings
- Existing biodegradable modules are either not structural or weather proof.	- 1x2 or 2x4 or 4x8 ect modules allow modules to be used on corners

Module Concept Sketches

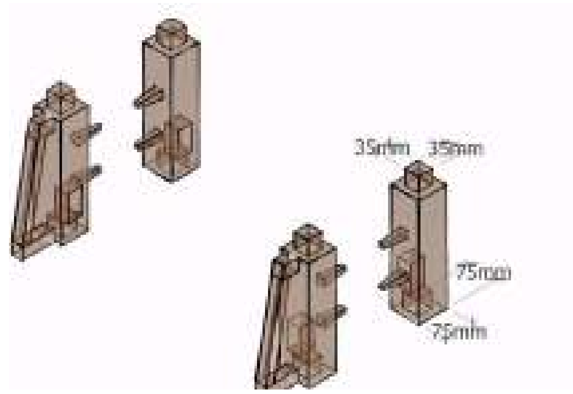




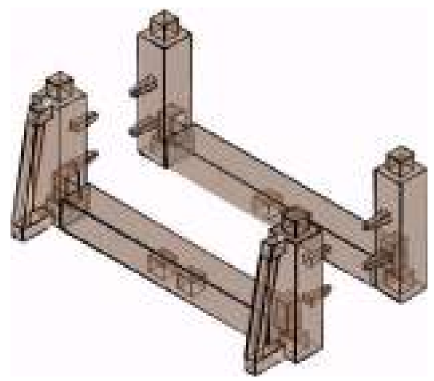
Standardised Block Concept



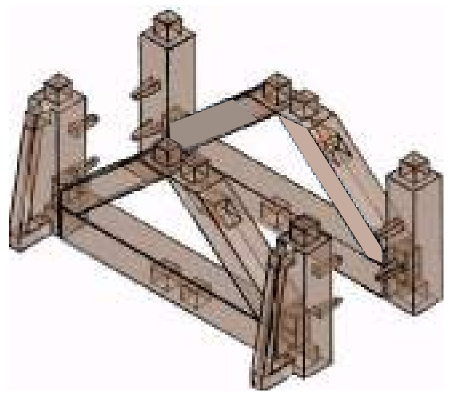
1. NZ standard straw bale



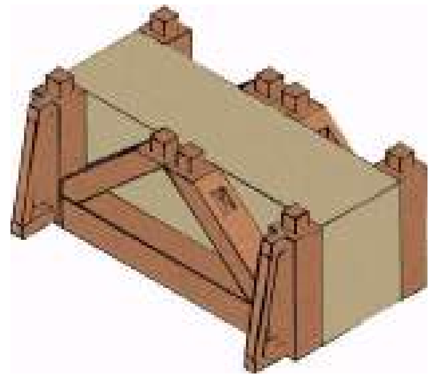
2. Vertical timber struts



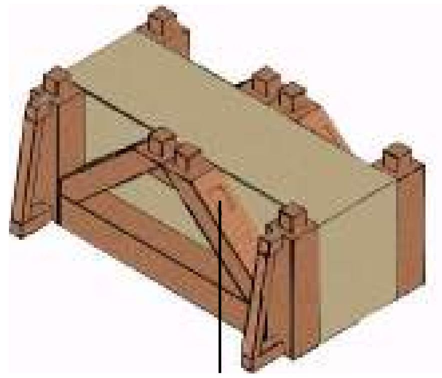
3. Slot in horizontal Douglas-fir member



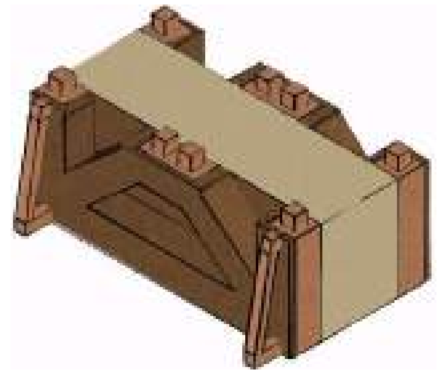
4. Slot in Douglas-fir cross braces



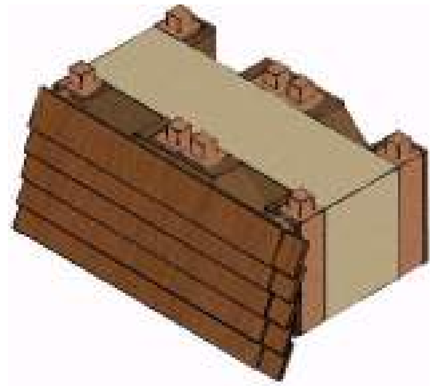
5. Pierce Douglas-fir exo-structure into straw bale



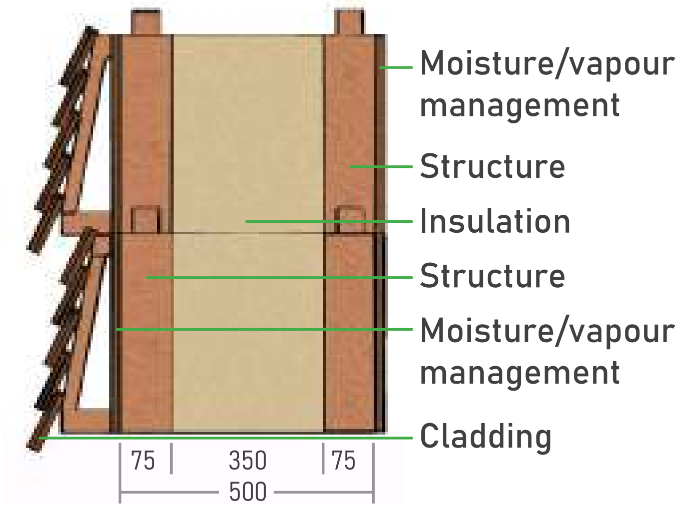
6. Slot in Douglas-fir brace peg member



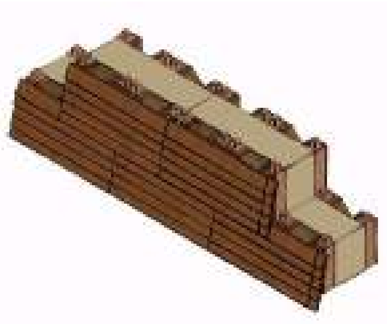
7. Coat exterior and interior faces with 30mm of clay plaster

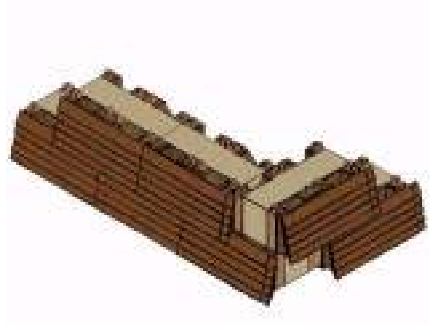


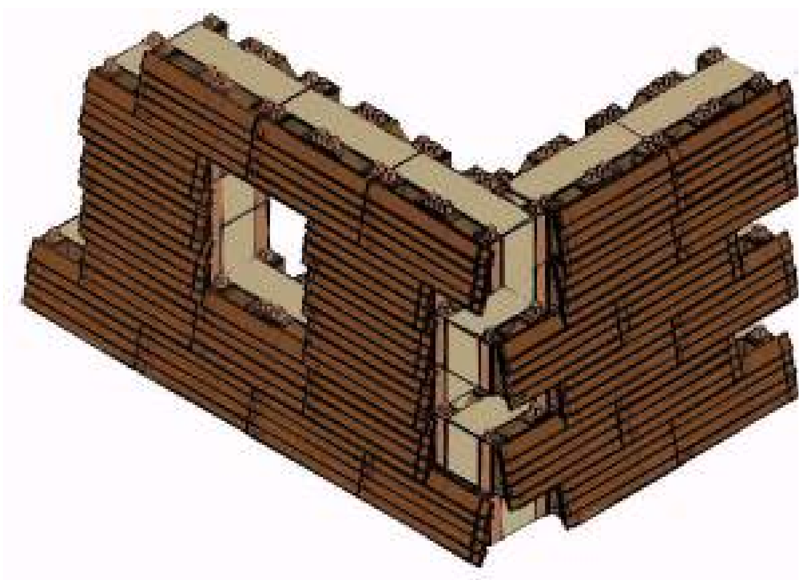
8. Screw in Macrocarpa weatherboards



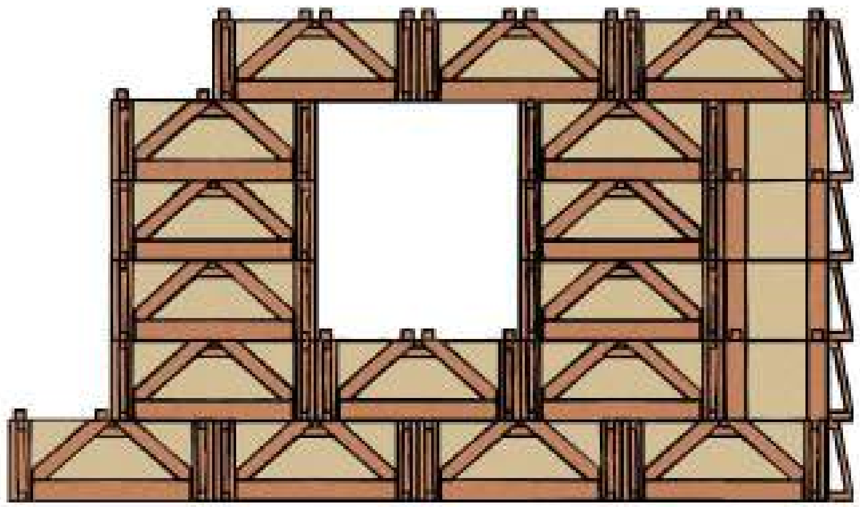
Weight	Thermal Resistance	Vapour Resistance
77.4 Kg	5.44 m²K/W	85.9 MNs/g



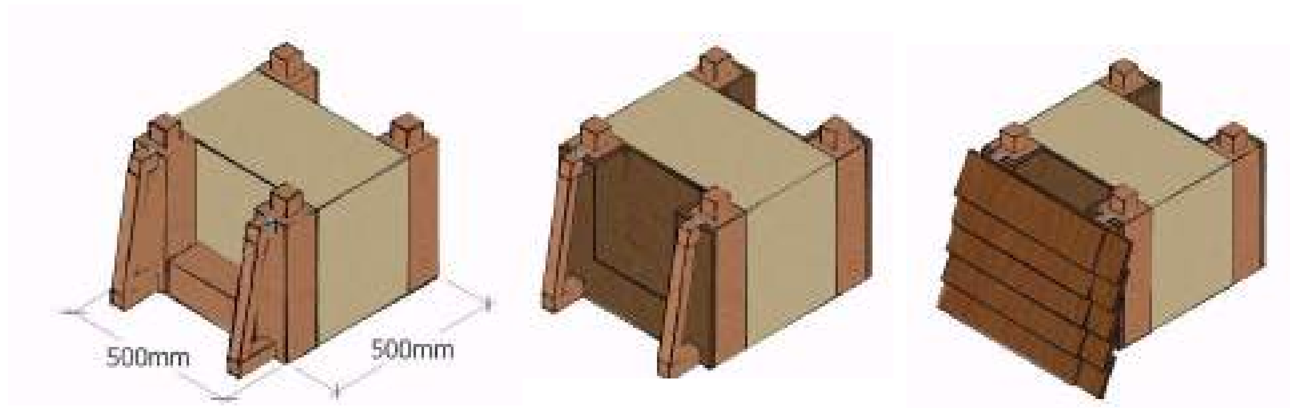


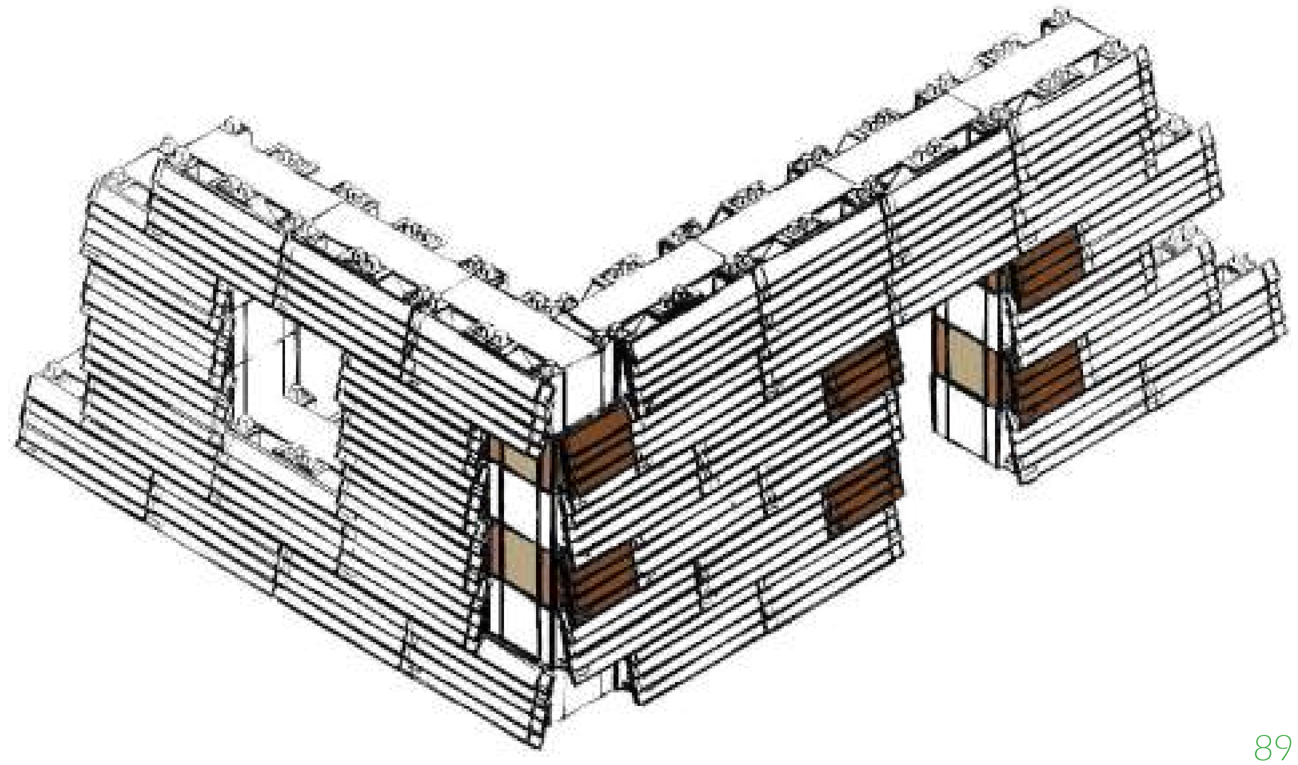


Structure Load Paths

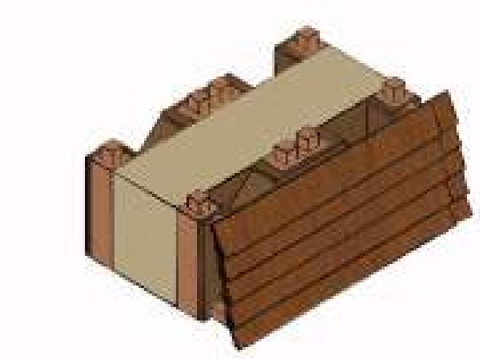


Half Brick for Corners and Openings



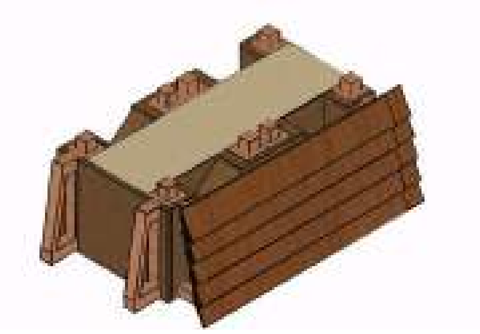


Corner Treatment



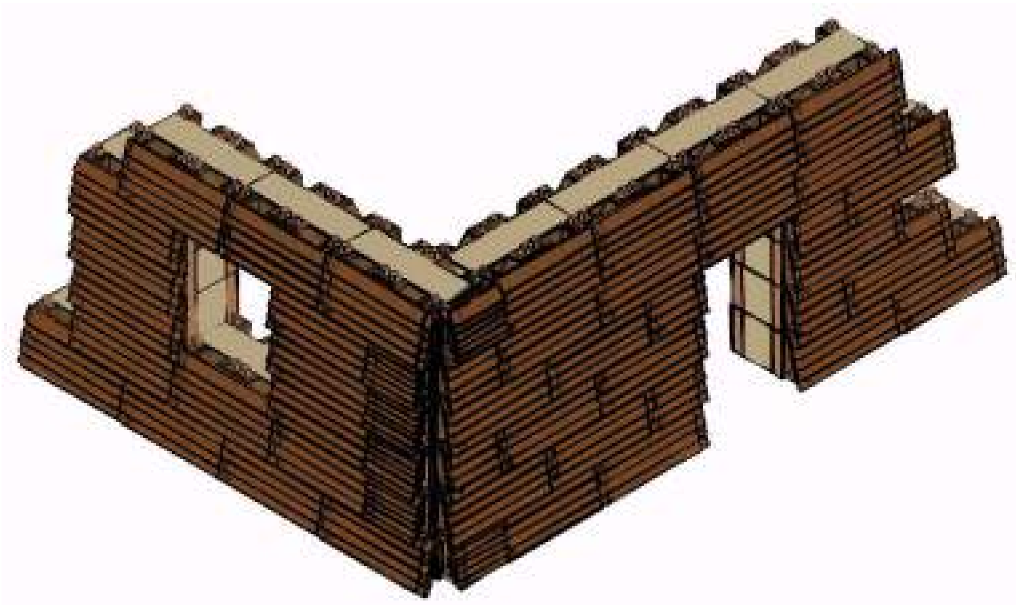
1. Standard Module

2. Screw in cavity battens



3. Coat in 30mm clay plaster

4. Screw in macrocarpa weatherboards



The construction brick is derived from dimensions of the standard New Zealand straw bale which is 350mmx450mmx1000mm (Hall, 2019). Identical timber framing is pierced into both sides of the straw bale so that the overall dimensions of the brick are 1000mmx500mm (2x4). This means that the block can be used on corners. The timber frames also provide structure and connection points to adjacent blocks. Clay plaster is present on both sides to protect the straw bales and timber weatherboards are fixed over a vented cavity. This structural insulated weathertight block can then be simply constructed and deconstructed and easily reused on similar future projects. Their small scale and standardised nature of the blocks means that the same block can be used to create a vast variety of building scales and layouts.

4.3 Prefabricated Wall Panels

Why do we need a prefabricated panel?

A prefabrication wall panel has the potential to lower the risk associated with using bio-based insulation materials and increase their uptake. The controlled and dry interior environment within the factory drastically lowers the chance of the bio-based insulation material being compromised through moisture. For straw bale construction specifically, prefabrication offers the benefits of the possibility of plastering all year round, improved quality of plaster and accelerated application (Hall, 2014). It is also more suitable for small urban sites and builders on rural sites can spend less time away from home (Hall, 2014).
The consistency and improved quality assurance of the product due to the interior factory setting will allow the straw or pure wool insulated panel to receive BRANZ CodeMark or Appraisal. This will allow the panel to gain acceptance in the mainstream market. In addition, prefabrication in general offers reduced site labour which can reduce costs.

No biodegradable prefabricated panel in NZ

No straw or pure wool insulated prefabricated wall panels exist in NZ. Straw-insulated prefabricated panels are produced in the UK and Lithuania by the companies ModCell® and Ecococon respectively but no prefabricated panels using pure wool insulation are produced anywhere. In New Zealand experimental prototypes of straw bale insulated prefabricated wall panels have been developed and prefabricated wall panels that use wool blend insulation are produced in New Zealand by Ecopanel. Straw bale prototype prefabricated walls have been developed in New Zealand by Sol design in 2011 and 2014 (Hall, 2014). In 2011, Sol Design constructed a 10m2 experimental prefabricated structure in Geraldine, Canterbury (Hall, 2014). They then began working on prefabricated straw bale panel and constructed a power shed for an off-grid property in Geraldine, Canterbury in 2014 (figure 44) (Hall, 2014). More recently, in 2019, Min Hall, a senior lecturer at Unitec, has produced four prototype straw bale wall panels at one-third scale, using different timber framing options including laminated veneer lumber (LVL), timber I-beams, sawn timber vertical trusses, and a 'C' frame where sawn timber and plywood are incorporated to form a channel section (Hall, 2019).

Figure 44

Experimental prefabricated straw shed Geraldine Canterbury, New Zealand, 2011

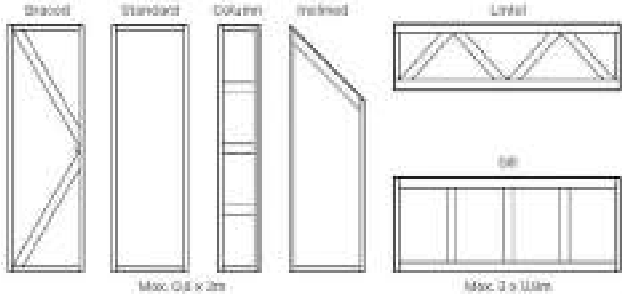
Reprinted from "Is there a place for natural building in New Zealand's conventional housing market? - a prefabricated straw bale case study" by M. Hall, 2014, Copyright 2014 by Min Hall.

Methodology

Prefabricated straw wall panel literature and precedents are reviewed to inform how wool insulation could be best be used within a straw a prefabricated wall panel. This literature also supplied suitable construction approaches for pure wool insulation as it is a material with similar moisture management requirements to straw. This informed three prefabricated wall panel designs. The Ecococon panel was used as a base for prefabricated explorations using wool in combination with straw insulation. This is because of their benefits over the ModCell® Panel. Compressed straw is used in the Ecococon panels instead of bales which allows the panels dimensional flexibility. This makes the panels adaptable to almost any design which keeps site labour cost low (Ecococon, 2020). Ecococon also produces a range of panels for different applications (figure 45). The design proposals are based on the standard (non-braced) wall panels from Ecococon with the intent that the lessons learned can be applied to the full range of panels. The panel designs are all of the consistent dimensions of 0.35m x 1.8m x 2.4m to allow direct comparison.

Figure 45

Ecococon panel types



Reprinted from "Planning Guide" by Ecococon, 2020, Copyright 2020 by Ecococon.

Prefabricated Straw Panel Literature Review

There are two processes for prefabricated straw bale panel construction- the wet process (figure 46) and the dry process (figure 47) (Magwood, 2016). The wet process uses plaster and the dry process uses a permeable magnesium oxide or gypsum sheathing on the interior and exterior faces (Magwood, 2016). The wet and dry process can be mixed with one face covered in plaster and the other in a permeable sheathing or combined with each face using both a plaster and permeable sheathing (Magwood, 2016). Clay or lime plaster is biodegradable, but magnesium oxide or gypsum sheathings are not. This means the wet method is the only biodegradable construction option for a prefabricated straw bale panel.

Figure 46

Wet Process

Reprinted From "Essential Prefab Straw Bale Construction: The Complete Step-by-Step Guide" by C. Magwood, 2016, p. 16. Copyright 2019 by Chris Magwood.

Figure 47

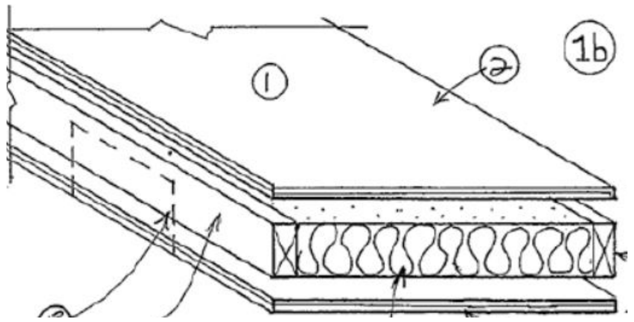
Dry Process

Reprinted From "Essential Prefab Straw Bale Construction: The Complete Step-by-Step Guide" by C. Magwood, 2016, p. 16. Copyright 2019 by Chris Magwood.

A hollow timber box beam for the top and bottom plates minimises thermal bridging and provides separate cavities that require insulation (figure 48) (Magwood, 2016). This provides an opportunity for wool insulation within a straw prefabricated panel.

Figure 48

Insulated bottom plate



Reprinted From "Essential Prefab Straw Bale Construction: The Complete Step-by-Step Guide" by C. Magwood, 2016, p. 16. Copyright 2019 by Chris Magwood.

Ecopanel uses plywood, RAB board, or oriented strand board over wool blend insulation (figure 49) (Ecopanel, 2018). However, pure wool insulation without the added moisture resistance of the polyester is more susceptible to moisture damage, to a similar extent as straw, and therefore requires different treatment. Straw is hygroscopic which means it will absorb and store water (Kennedy et al., 2014). This means straw bales require a vapour-permeable construction to ensure there is reasonable drying potential (Racusin, 2012). Wool is also hygroscopic (Tuzcu, 2007). A prefabricated wool wall panel should therefore be constructed in a similar manner to a straw wall panel and use a vapour-permeable sheathing as wool cannot support a plaster render. Gypsum sheathing is the most suitable sheathing material for this purpose as it is more vapour-permeable than a magnesium oxide sheathing (Magwood, 2016). Gypsum sheathing comes in two forms, one for exterior use featuring a fiberglass and/or waxed paper coating and one for interior use (Magwood, 2016).

Figure 49

Wool blend insulated Ecopanel

Retrieved from Ecopanel (https://www.ecopanel.co.nz/insulated-wall-panels) on 20 September 2020.

LVL panels are often used in prefabricated straw bale construction (Magwood, 2016). These timbers contain inorganic glues which slow down the biodegradation of the timber. However, these engineered timbers still biodegrade. New Zealand LVL is 43% degradable organic carbon which will decompose by 50% over 23 years (Love, 2010). Within timber framing, LVL has been rapidly taking share from pinus radiata timber in recent years in New Zealand (Brunsdon & Magan, 2017). Untreated douglas-fir LVL is available in New Zealand.

Figure 50

Ecococon Panel

Reprinted from "Is there a place for natural building in New Zealand's conventional housing market? - a prefabricated straw bale case study" by M. Hall, 2014, Copyright 2014 by Min Hall.

Description	Strengths	Weaknesses
- Timber perimeter, double timber frame, compressed straw infill	- Compressed straw allows for increased structural integrity, fire resistance, pest resistance, flexibility of scale	- Compressed straw is a more costly and involved process than using straw bales - Difficult to install services - Thick walls to achieve sufficient R-value - Heavy - Thermal bridging through timber casing - Panels can't be deconstructed at the end of life due to continuous claddings over the exterior surface

Figure 51

Project Pātūtū NZ 2019

Retrieved from Far.org.nz (https://www.far.org.nz/assets/files/blog/files/97780f8e-8b07-5d41-a8e4-12b036a2ca97.pdf) on 30 June 2020

Description	Strengths	Weaknesses
- Timber perimeter, double timber frame, mini straw bale infill	- Mini straw bales allow for lighter thinner panels units - Mini straw bales allow for a more conventional wall thickness	- Mini bales are resized standard bales which produces off-cut waste - Difficult to install services - Only moderate R-value due to thinner walls - Thermal bridging through timber casing - Size of bales dictates the size of the panel

Figure 52

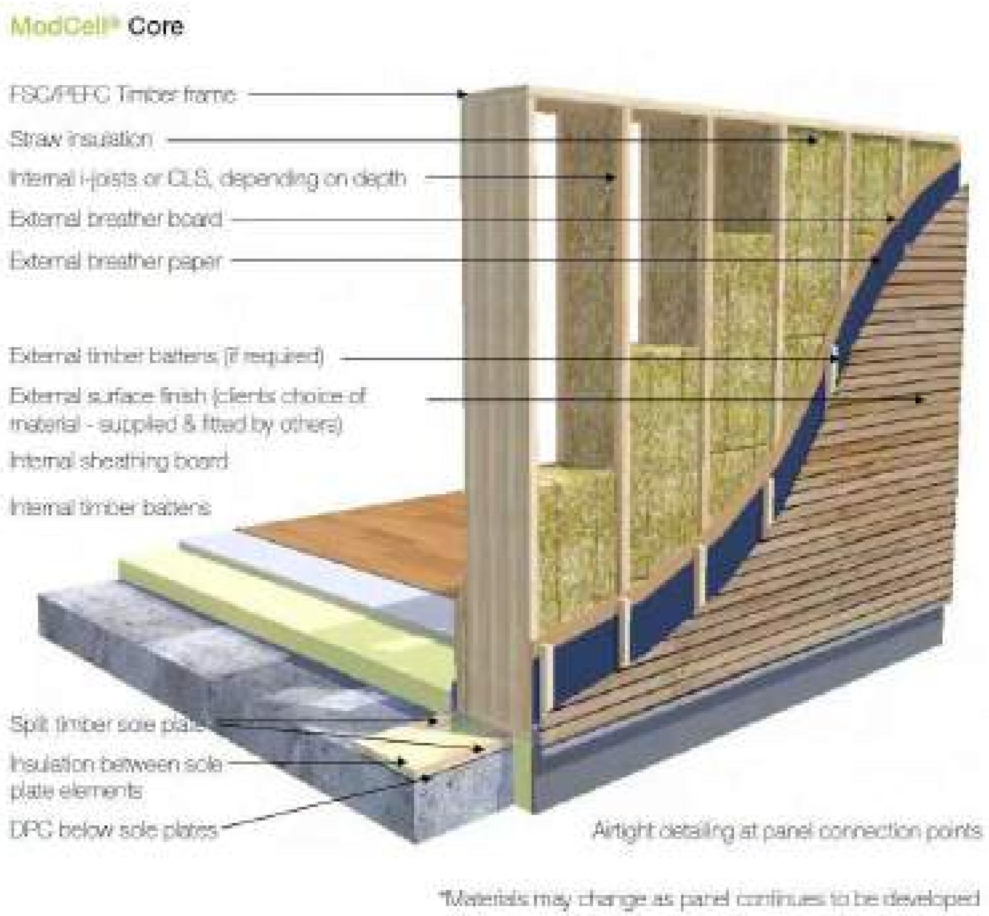
Sol Design prefabricated straw bale panels New Zealand, 2014

Reprinted from "Is there a place for natural building in New Zealand's conventional housing market? - a prefabricated straw bale case study" by M. Hall, 2014, Copyright 2014 by Min Hall.

Description	Strengths	Weaknesses
- Timber perimeter, double timber frame, straw bale infill, cement plaster	- Services are pre-installed in the panels	- Cement plaster is non-biodegradable and has lower vapour permeability than clay or lime plaster - Uses steel straps and steel mesh - Thermal bridging through timber casing and "buttered" bales - Size of bales dictates the size of the panel - Heavy - Thick walls

Figure 53

ModCell prefabricated straw bale wall panels



Reprinted from Modcell Technical Guide (https://www.modcell.com/files/3615/5066/3020/ModCell_Technical_Guide_2019v2r.pdf) on 18 April 2020.

Description	Strengths	Weaknesses
- Timber perimeter, timber I beam studs, straw bale infill, timber cladding	- Bales slot simply in between studs - Extra studs increases structural capacity	- Timber cladding has lower vapour permeability than clay or lime plaster - Uses non-biodegradable such materials such as DPC, synthetic insulation and external breather paper - Non-biodegradable sealing tape is required to fix the panels together - Lots of Thermal bridging through vertical timber members

Straw into Gold 2014 NZ Thesis

Figure 54

Straw into Gold, 2014

Reprinted from “Straw into gold” by R. Pringle, 2014, Copyright 2014 by Ryan Pringle.

Description	Strengths	Weaknesses
- Timber perimeter, double timber frame, straw bale infill, clay plaster (Based off Modcell panel)	- Services are pre-installed in the panels - Clay plaster has the highest vapour permeability of any plaster - Lack of full depth studs eliminates thermal bridging - Smaller panels increases flexibility of dwelling size _ Smaller panel size increases reusability potential as a module	- Uses steel corner braces - Thermal bridging through timber casing - Smaller panel size increase number of joints required between panels where there is high risk of leaks and air gaps - Clay plaster has low durability

Prefabricated Biodegradable Precedent Review Summary

General Issues	Learnings
- Thermal bridging through timber elements - Exterior plaster renders only have moderate durability - Exterior timber claddings have lower vapour permeability than plaster renders - Difficult to install services - Presence of non-biodegradable materials (Glues, membranes, metal meshes) - Panels are non-deconstructable at end of life - Heavy - Thick - Panel size dictated by bales - No Wool Prefabricated panel	- Compressed straw has increased structural integrity, fire resistance, pest resistance and flexibility of scale - Pre-installed services are preferred as services are difficult to install in straw bale - Clay plaster has the highest vapour permeability of any plaster - Lack of full depth studs eliminates thermal bridging

Design Proposals

A prefabricated timber frame was used for each design. The prefabricated frame is based on the minimum straw bale width of 900mm and depth of 350mm and the minimum stud height of 2400mm. This was done for the sake of simplicity. The timber frame weighs 169.5Kg. For each design, a pure wool batt insulation product that can hold its shape is proposed along with compressed straw.

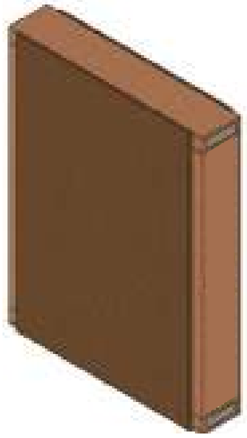
Panel 1 is the timber frame filled with compressed straw insulation with wool insulation present in hollow timber box beams used for the bottom and top plates. Panel 2 is identical to panel 1 apart from 150mm of pure wool insulation instead of straw in the centre. Straw is present on either side of the wool insulation as a substrate to support clay plaster. Rigid self-supporting compressed straw panels will be glued into the prefabricated timber frame on one face before the pure wool batt insulation is laid in the frame and sandwiched between identical straw panels on the other face. Panel 3 is entirely insulated with pure wool batt insulation with gypsum sheathing on the exterior and interior.

Panel 1 Construction and Assembly

1. Prefabricated douglas-fir frame using douglas-fir dowel joints

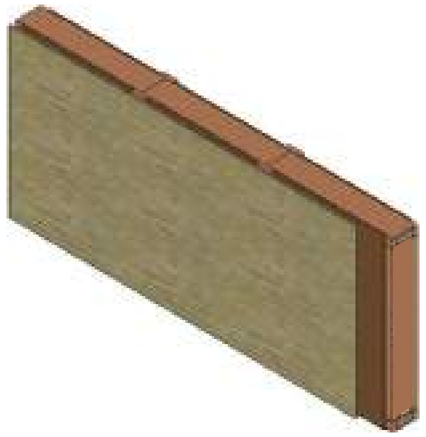
2. Pure wool batt insulation in cavities of top and bottom plate

3. Compressed straw

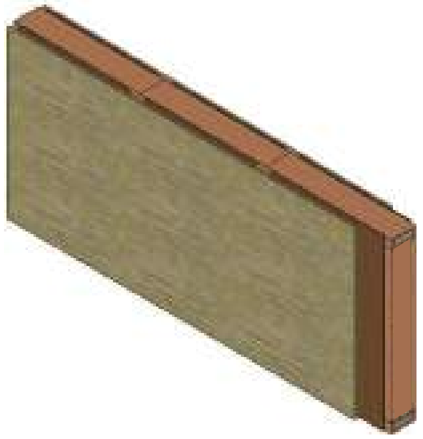


4. 25mm clay plaster on both sides

5. Fix panels together with douglas-fir joining battens and douglas-fir dowels on both sides

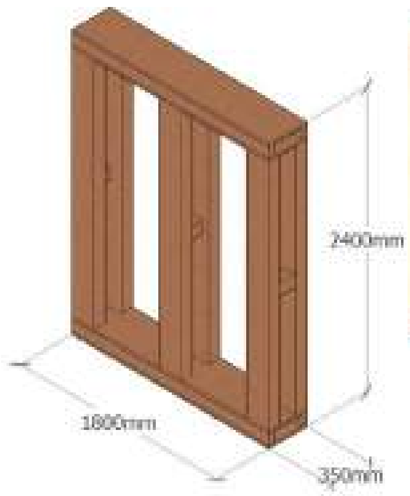


6. Macrocarpa cladding fixed over cavity to joining battens with douglas-fir dowels

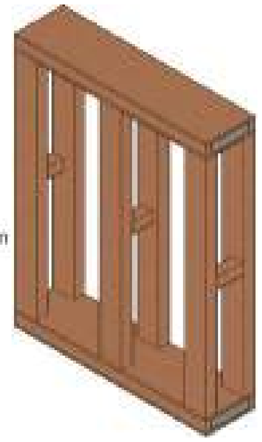


7. Optional fixing of interior lining to interior battens over cavity (cavity can be used for cabling)

Panel 2 Construction and Assembly

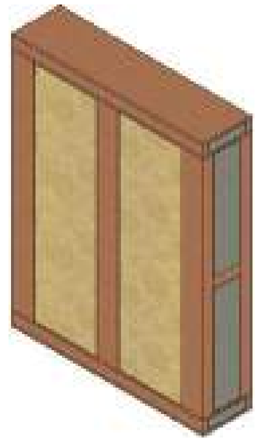


1. Prefabricated douglas-fir frame using douglas fir-dowel joints

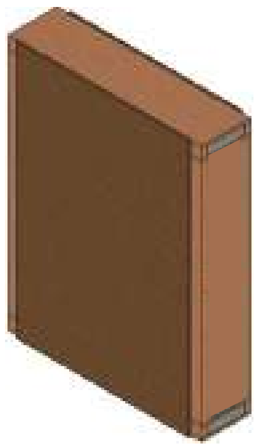


2. Pure wool batt insulation in cavities of top and bottom plate

3. Compressed straw rigid panels 100mm thick on both sides



4. Pure wool batt insulation, 150mm thick,
in the centre



5. 2.5mm clay plaster on both sides and fix douglas-fir side panels to the frame

6. Fix panels together with douglas-fir joining battens and douglas-fir dowels

7. Macrocarpa cladding fixed over cavity to joining battens with douglas-fir dowels

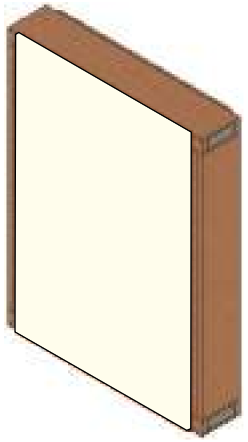
8. Optional fixing of interior lining to interior battens over cavity (cavity can be used for cabling)

Panel 3 Construction and Assembly

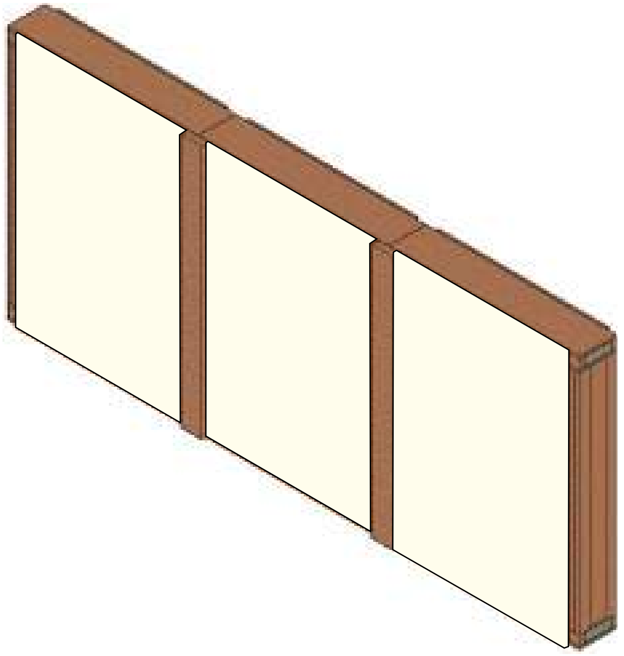
1. Prefabricated douglas-fir frame using douglas-fir dowel joints

2. Natural wool batt insulation in cavities of top and bottom plate

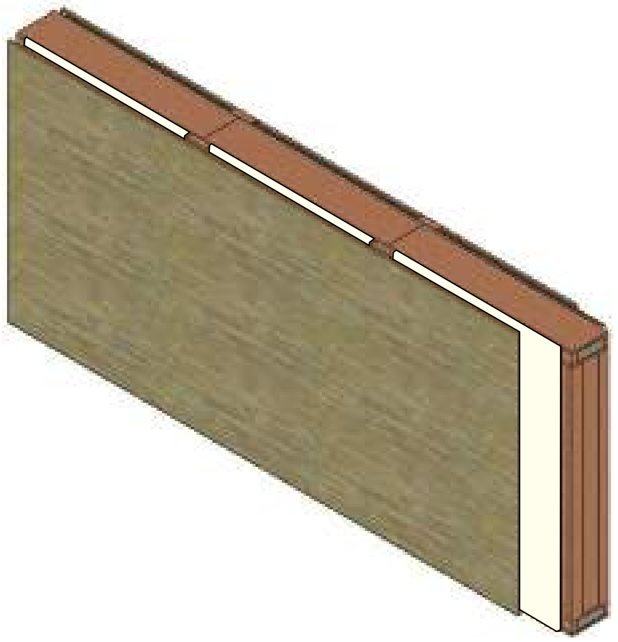
4. Pure wool batt insulation



3. Gypsum sheathing panels fixed on both sides with screws

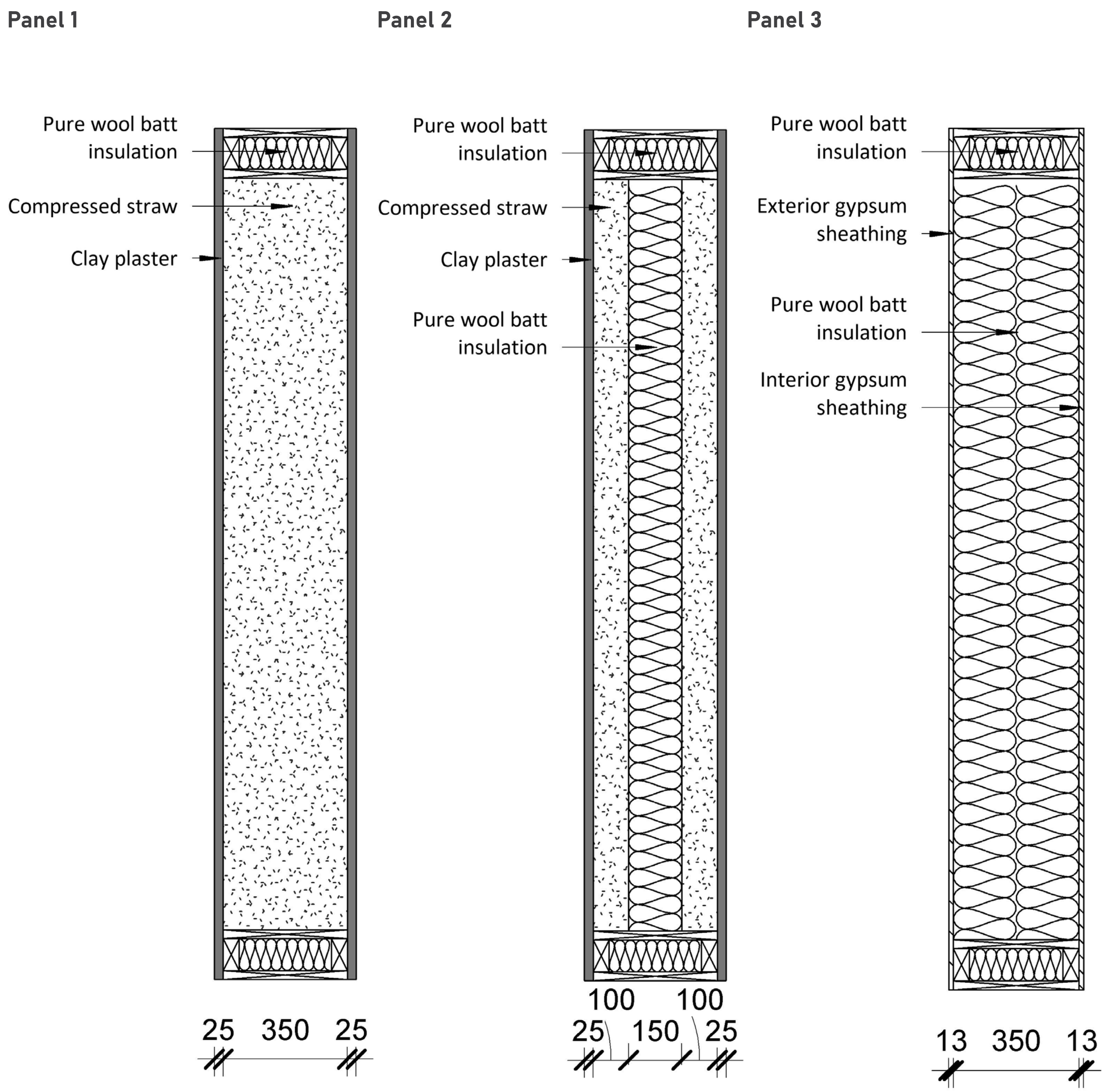


5. Fix panels together with douglas-fir joining battens and douglas-fir dowels



6. Macrocarpa cladding fixed over cavity to joining battens with douglas-fir dowels

8. Optional fixing of interior lining to interior battens over cavity (cavity can be used for cabling)



Properties of Panel Designs

	Weight	Thermal Resistance	Vapour Resistance
Panel 1	582.3Kg	7.2 m²K/W	4.716 MNs/g
Panel 2	528.1 Kg	8.7 m²K/W	4.757 MNs/g
Panel 3	273.8 Kg	10.8 m²K/W	4.774 MNs/g

Discussion

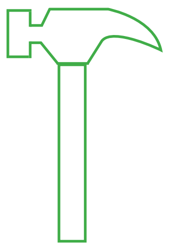
Panel 1 only makes a minor alteration on existing prefabricated straw panels such as Ecococon and ModCell® with the addition of pure wool insulated top and bottom plates. Panel 1 is, therefore, the least speculative of the 3 designs and has the most potential for real-world application. Panel 2 combines wool's low density and superior insulative properties with straw's ability to support the bio-based vapour permeable material of clay plaster. It is, therefore, more insulative than panel 1 and more vapour permeable than panel 3.

Panel 2 occupies a useful middle ground in terms of vapour and thermal resistance. The presence of the clay plaster on both panels 1 and 2 does make the panels significantly heavier however a crane will be necessary even without this additional weight.

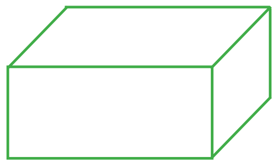
Panel 3 is a pure wool insulated substitute for the Ecopanel. As expected, panel 3 is the lightest and most insulative of the 3 designs due to the exclusive use of pure wool insulation. However, panel 3 forgoes total biodegradability and the ability to support clay plaster resulting in a mild reduction in vapour permeability compared to panels 1 and 2. The panels can support a timber rain screen over a vented cavity to improve weather resistance. These designs will be competing with many existing SIPs already available in NZ that do not use bio-based insulation materials.

Despite the thermal advantages and reduced weight of panels 2 and 3, panel 1 has the greatest potential for success. Panel 1 is the closest to successful real-world designs from Ecococon and ModCell®. Without physical prototypes to demonstrate the effectiveness of panels 2 and 3, which are inventive but still speculative, panel 1 presents the most reliable path forward.

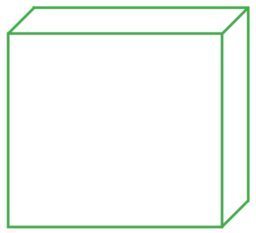
4.4 Review of Construction Approaches



1. In-situ



2. Standardised block Modules



3. Prefabricated Panels

Construction approach review

Most successful strategy in increasing the uptake of biodegradable materials	**Greatest reuse potential**	**Closest to NZ mainstream construction practice**	
1. Prefab	1. Modules	1. In-situ	3 points
2. In-situ	2. Prefab	2. Prefab	2 points
3. Modules	3. In-situ	3. Modules	1 point

Most successful strategy in increasing the uptake of biodegradable materials

Prefabricated panels have the greatest potential to increase the uptake of biodegradable building materials followed by in-situ construction and standardised block modules. The Ecococon and ModCell® panels demonstrate the success a prefabricated panel with bio-based insulation can have. Ecococon has built over 100 projects in the last 10 years (Ecococon, 2020). ModCell® has built 33 projects since 2001 (ModCell®, 2020). Conventional in-situ construction has produced all of New Zealand's biodegradable buildings so far. However, this has not been at the rate achieved by Ecococon overseas. Standardised block modules are increasingly being studied but are yet to enter mainstream construction (Galle et al., 2017). This construction approach therefore has the lowest potential of increasing the uptake of biodegradable materials.

Greatest Reuse Potential

Standardised block modules have the greatest reuse potential followed by prefabricated panels and in-situ construction. Due to the standardised dimensions and demountable nature of the block modules its reusability is the greatest. The prefabricated panels come in a range of sizes which increases design flexibility but decreases the reusability potential compared to the standardised block modules. This is because a prefabricated panel needs a specific application to be reused instead of a general application like a standardised module. For In-situ construction only the reuse of individual deconstructed elements is possible. This makes the application for reuse even more specific than that required for a range of prefabricated panels.

Closest to Mainstream Construction Practice

In-situ construction is the dominant construction technique in NZ. Prefabricated panels and standardised prefabricated construction modules occupy the vast minority of the market with standardised prefabricated modules occupying the smallest share.

Most suitable zero waste construction approach for New Zealand

Construction Approach	Total Points
1. Prefab	7 points
2. In-situ	6 points
3. Modules	5 points

With all these criteria considered prefabricated panels are the most suitable zero-waste construction approach for New Zealand.

Form Exploration

5

Chapter Outline

The previous chapter pursued the optimum zero-waste construction approach for New Zealand. This chapter primarily seeks a formal design that supports the use of biodegradable building materials and secondly a suitable medium density housing design. The integration of the design concept on site and detailed design occurs later in chapters 6 and 7 respectively. Biodegradable building design and medium density housing design were researched firstly to inform the design concepts. Design precedents were also used to inform and inspire each concept. Three concept designs were produced in an iterative design process where each design is reviewed to inform the next. The three concept designs are compared and reviewed at the end of the chapter in terms of their formal simplicity (exterior junctions/dwelling) and dwelling density (bedrooms/hectare). Formal simplicity is desirable for construction with biodegradable insulation such as wool or straw that are susceptible to moisture damage, as complex exterior junctions where leaks may occur are reduced. Formal simplicity is used as an assessment criterion for the first objective regarding the support of biodegradable materials, and dwelling density is used for the second objective regarding medium density housing. The most successful design concept is then selected for integration on site in the next chapter.

Chapter Objectives

1. Design to support biodegradable materials

2. MDH Design

Biodegradable Building Design Research

Many biodegradable buildings have been built by natural builders and many of them fail due to poor moisture management. Many straw bale buildings have failed using cement plaster which is non-vapour permeable and traps moisture within the construction (Kennedy et al., 2014). Moisture is the nemesis of biodegradable materials as it can cause premature decomposition. This is particularly true for biodegradable insulation materials including straw and wool used in this thesis. It is widely known that a straw bale building must be designed and constructed in such a manner that the straw remains dry throughout the entire building process and the lifetime of the building (North, 2002).

Some foundational design strategies have therefore been developed by natural builders to keep the rain away from the building and prevent excess moisture infiltrating the insulation. The roof is the primary means of achieving this as it is the first line of defence against moisture. Steep roofs with large overhangs are used to shed rain and minimise the exposure of the external walls (BRANZ, 2015). In straw bale construction this is often referred to as a "good hat" (Racusin, 2012). Shortly after the arrival of European settlers to New Zealand roofs were made with large eves to protect cob walls from rain (Salmond, 2010). In addition, roofs were also steep, often at least 30 degrees, to shed rain, and in the South Island even steeper roofs were preferred to shed snow (Salmond, 2010).

In straw bale construction a building not only needs a "good hat" but also "good boots" (North, 2002). This refers to a means of preventing moisture from entering the construction from the ground (Kennedy et al., 2014). This can be achieved by suspending the structure off the ground or using a thick non-porous foundation such as stone or concrete to give good separation between the ground and the vulnerable construction (Racusin, 2012).

With this understood, each design concept will therefore have a steep roof with large overhangs. This also supports the use of timber shingles (found to be the most suitable roofing materials in chapter 3) which are more effective at keeping moisture out at steeper angles. Each design will also be suspended off the ground through the use of reusable concrete footings (one of the most suitable foundations approaches found in chapter 3).

Medium Density Housing Design Research

There is no universally agreed-upon definition of Medium Density Housing (BRANZ, 2017b). For this project, however, clarity of definition is not essential if its position on the density spectrum is understood. Medium-density housing (MDH) sits between low-density housing (LDH) and high-density housing (HDH) on the density scale. In New Zealand, LDH includes stand-alone dwellings, generally 1–2 storeys, on independent sections typically between 400-800m2 (BRANZ, 2017b). HDH includes apartment buildings greater than 6 storeys (BRANZ, 2017b).

Medium-density housing has many typologies, including 1-storey units, 1–2-storey duplexes or triplexes, 2–4-storey terraced houses, and 3–6-storey apartments (BRANZ, 2017b). BRANZ divides these into three main categories (figure 55). The architectural typology of medium density housing was selected for this thesis for the purpose of constructing a 3-storey residential building that would push the limits of biodegradable materials. Therefore, terraced housing or apartments are the only available typologies.

Figure 55

Medium density housing categories

Reprinted from "What is medium-density housing?" by BRANZ, 2017, Copyright 2017 by BRANZ.

Surveys of NZ housing aspirations indicate the desire for the standalone home, including a private garage and backyard, as a preferred dwelling model and life-style (Bryson, 2017). This relates back to the 19th century when settlement promoter's advertised New Zealand with a rural vision - an image supported by the NZ Government well into the 20th century (Ferguson, 1994). New Zealanders also prefer a security and privacy-focused concept of safety rather than a community-focused one (BRANZ, 2017a). With this considered, a 3-storey apartment instead of 3-storey terraced housing would be preferable because the buildings can be separated giving more yard space, increasing security and privacy, and providing the aesthetic of standalone homes.

Apartments are usually 1-2 storey self-contained housing units within a larger building (Ministry for the Environment, 2012). There is usually common access to a core stairwell and private open space is a courtyard or garden on the ground floor or balconies on upper floors (Ministry for the Environment, 2012).

5.2 Concept 1

Precedent Review

Figure 56

King Tāwhiao's whare at Te Kūiti, 1885

Retrieved from NZ Historu (https://nzhistory.govt.nz/media/photo/king-tawhiaos-whare-at-te-kuiti) on 15 May 2020

Figure 57

Japanese Kirizuma Straw Roof

Retrieved from Bambubuild (http://www.bambubuild.com/en/traditional-roof-in-japanese-architecture/) on 15 May 2020

Figure 58

Straw Panel House, Poland, by LORENS Architects

Retrieved from Archello (https://archello.com/story/9705/attachments/photos-videos/1) on 16 May 2020

Figure 59

Nest, France, 1984

Retrieved from New Atlas (https://newatlas.com/nest-house-studio-1984/25134/) on 16 May 2020

King Tāwhiao's whare (figure 56) is an example of biodegradable māori vernacular architecture with a large steep roof. The Japanese kirizuma straw roof (figure 57) is a vernacular example of how a habitable space can be created under a large roof in an A-frame concept.

The Straw Panel House (figure 58) and Nest (figure 59) are both contemporary designs using straw. The Straw Panel House demonstrates the potential for skylights through thick straw bale walls and the pleasant aesthetic provided by the depth of the windows. Nest demonstrates the beauty of having the roof as a visually detached element and the benefit of improved access for maintenance that it provides.

Figure 60

Straw Biod, Austria, 2019

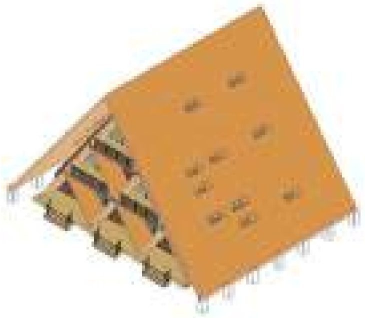
Photographs and renders by Straw boid, 2019. Retrieved from Detail (https://www.detail.de/artikel/strohboid-klimafreundliches-strohhaus-34813/) on 17 April 2020. Last Updated 17 October 2019.

Straw boid is the primary precedent for this concept. It uses the same materials that were found to be the most suitable biodegradable materials in chapter 3 of untreated timber, straw bales and clay plaster, and does so in an innovative manner.
The straw boid prototype was designed by architecture students Fritz Walter and Max Schade in their diploma thesis from the Institute for Structural Design at Graz University of Technology (Sigmund & Mijatovic, 2019). The prototype consists of a wooden structure that can be completely dismantled at the end of life and either be reused or left to biodegrade (Sigmund & Mijatovic, 2019). The timber structure is double layers to allow straw bales to slot in and occupy the voids (Sigmund & Mijatovic, 2019). The curved wood is achieved by moistening and heating the wood with water vapour which liquifies the lignin (plant-based) glue allowing it to be shaped (Sigmund & Mijatovic, 2019). A 25mm layer of clay plaster coats the straw bales on the interior to preserve and fireproof the bales (Sigmund & Mijatovic, 2019). An exterior layer of timber shingles is present to further weatherproof the construction (Sigmund & Mijatovic, 2019).

Design Proposal

No slanted straw walls

With slanted straw walls

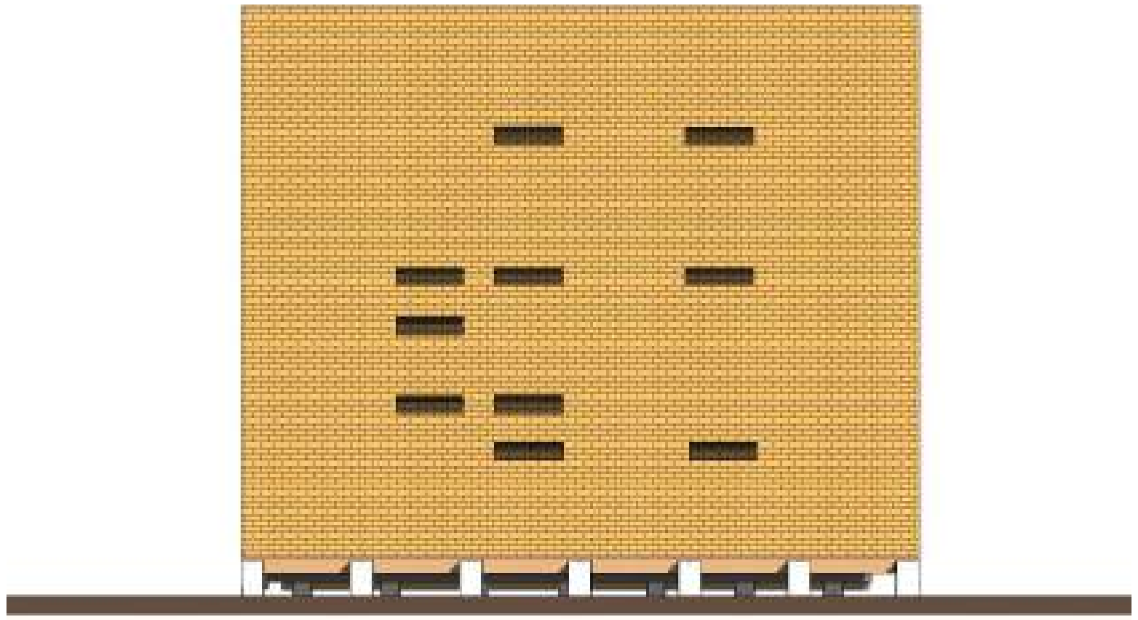


With added timber roof layer

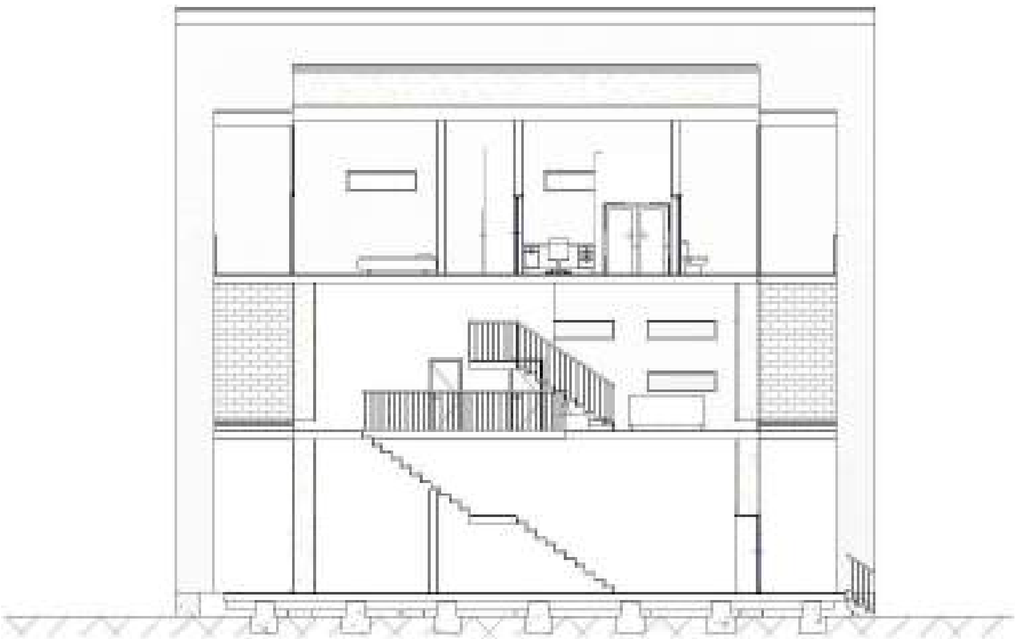
Front + Rear Elevation 1:200

Because the research revealed the importance of having a "good hat", the roof became the driving feature of this design. An A-frame form was arrived at similar to the Japanese kirizuma straw roof precedent. The skylights from the Straw Panel House inspired the apertures in the design's envelope and the roof from the Nest precedent inspired the secondary detached roof layer. Timber shingles are used on the exterior and glazing is used on the front and rear facades in reference to the straw boid precedent.

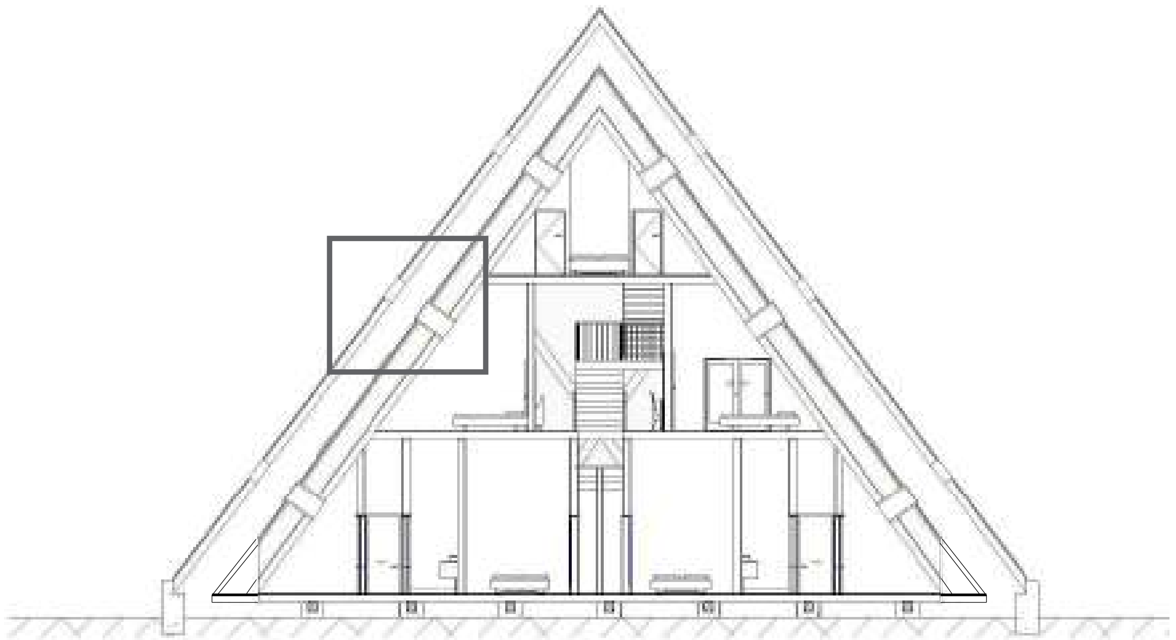
Side Elevation 1:200

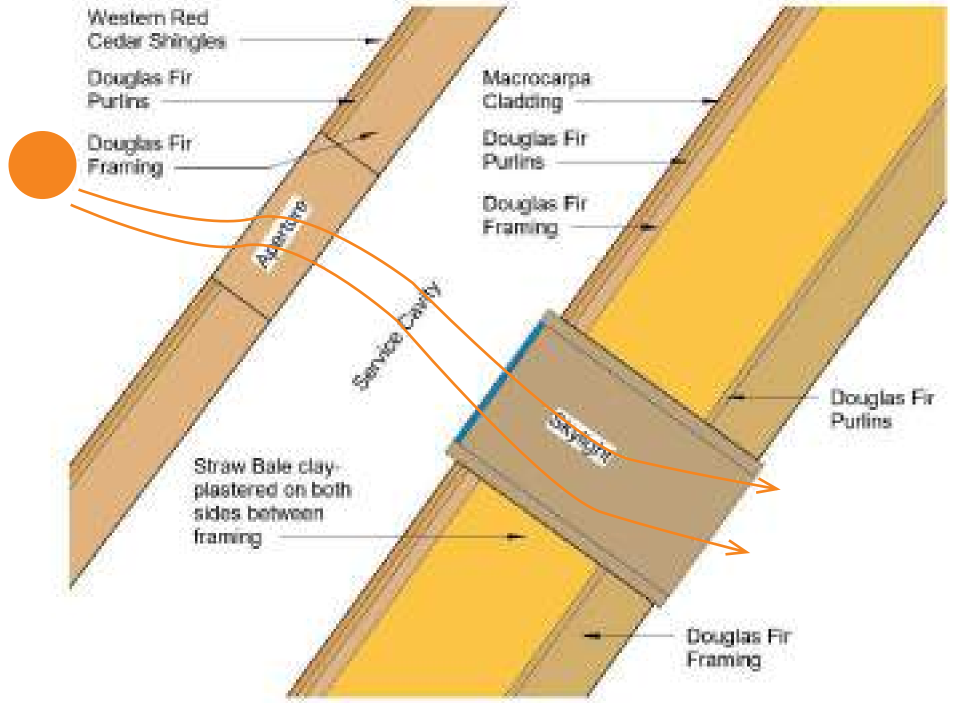


Long Section 1:200



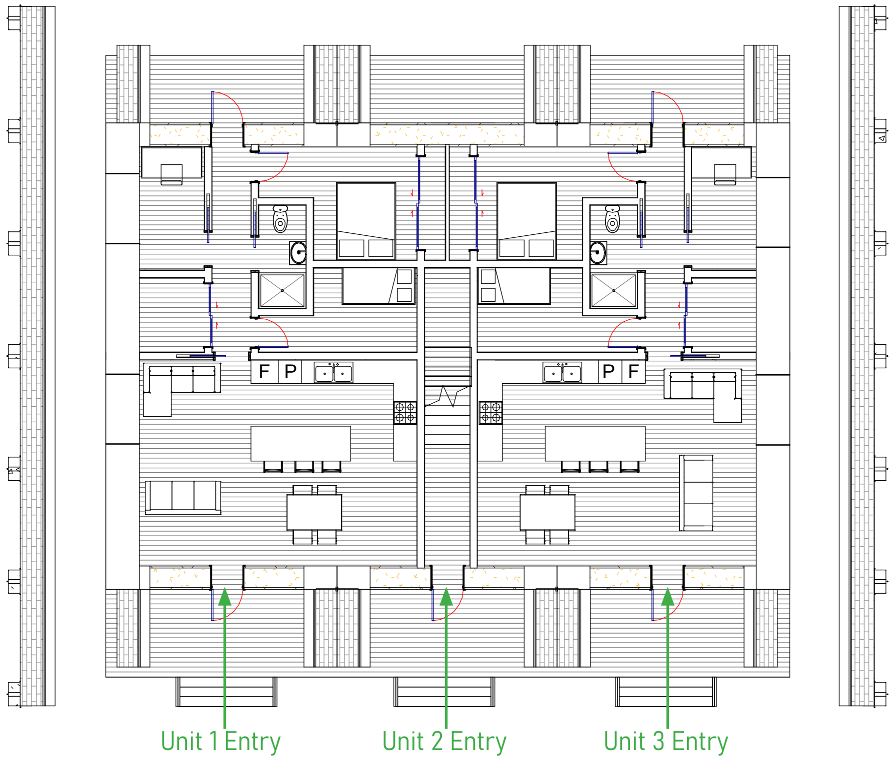
Cross Section 1:200



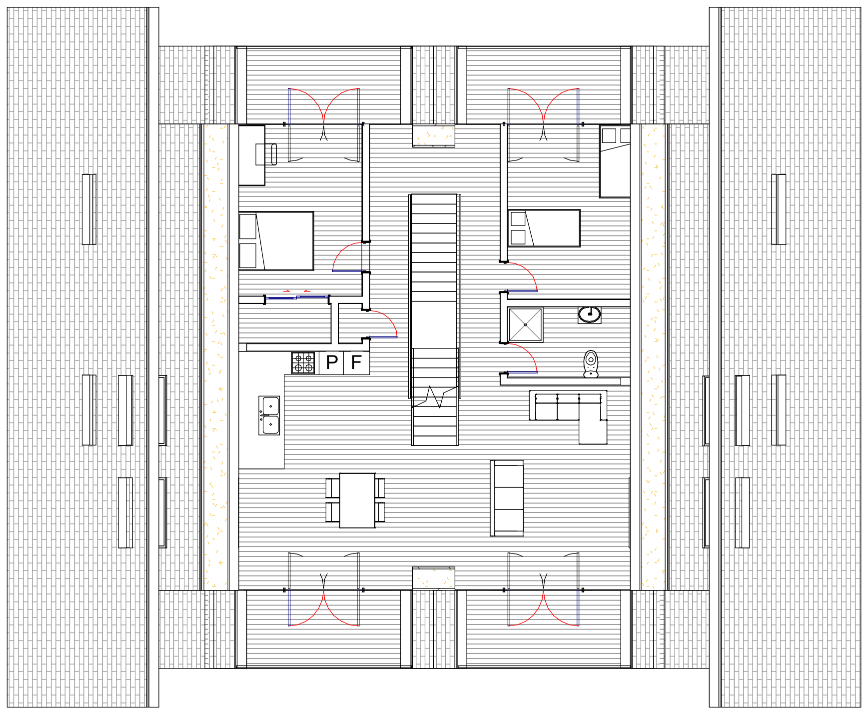


The exterior/roof is double skinned to visually emphasise as an architectural feature the importance of protecting biodegradable materials from moisture. The separation between the two exterior skins and their contrasting thicknesses creates a pleasant negative architectural detail as well as creating a practical service cavity for maintenance on the building's exterior. The offset between the inner and outer exterior layers also reduces the exposure of the windows to direct gravity-driven rain which minimises the chance of leaking around window joins. On the front and rear façade the outer skin extends 3 metres and the gable roofs extend 2 metres.

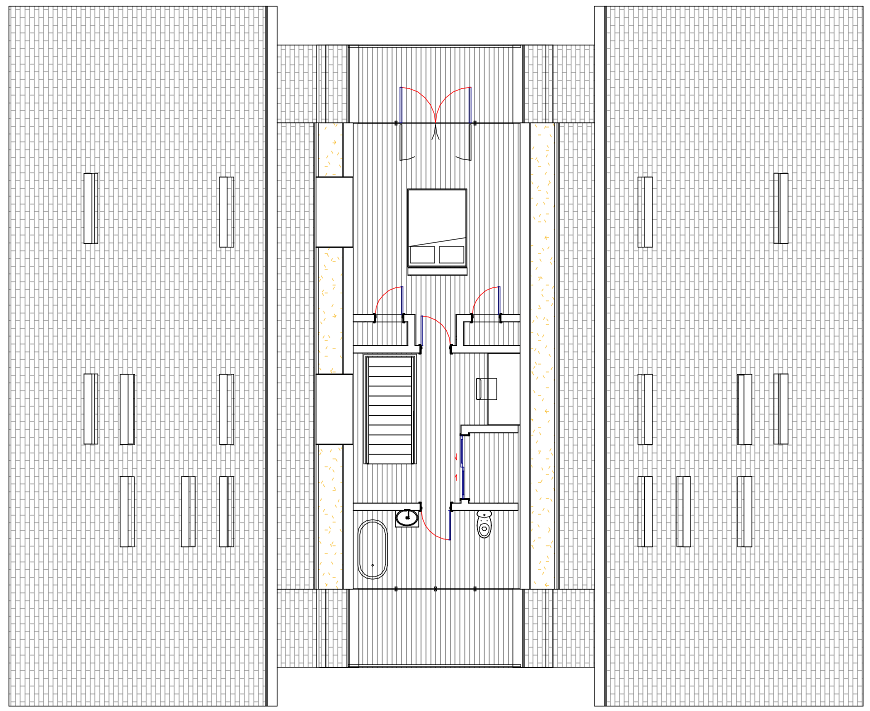
Ground Floor (Unit 1+2) 1:200



First Floor (Unit 3) 1:200



Second Floor (Unit 3) 1:200



The design contains 3 isolated household units. Two units are on the ground floor, each with 2 bedrooms and a bathroom. The third unit occupies both the first and second floors and has 3 bedrooms and 2 bathrooms.

Concept Reflection

It is firstly noted that the slanted exterior walls would be a challenge to construct out of prefabricated panels as would the triangular wall profiles on the front and rear facades. In addition, despite the formal simplicity of the A-frame, the slanted walls reduce the amount of habitable and useable space within the form. The width of the A-frame at the bottom also means that there is a reduction in opportunity for natural light penetration into the centre of the ground floor resulting in bedrooms with no windows..

5.3 Concept 2

Precedent Review

Figure 61

BaleHaus, Bath, England, UK

Note. Constructed with ModCell prefabricated straw bale wall panels. Retrieved from Modcell (https://www.modcell.com/news/balehaus-withstands-hurricanes/) on 18 April 2020.

Figure 62

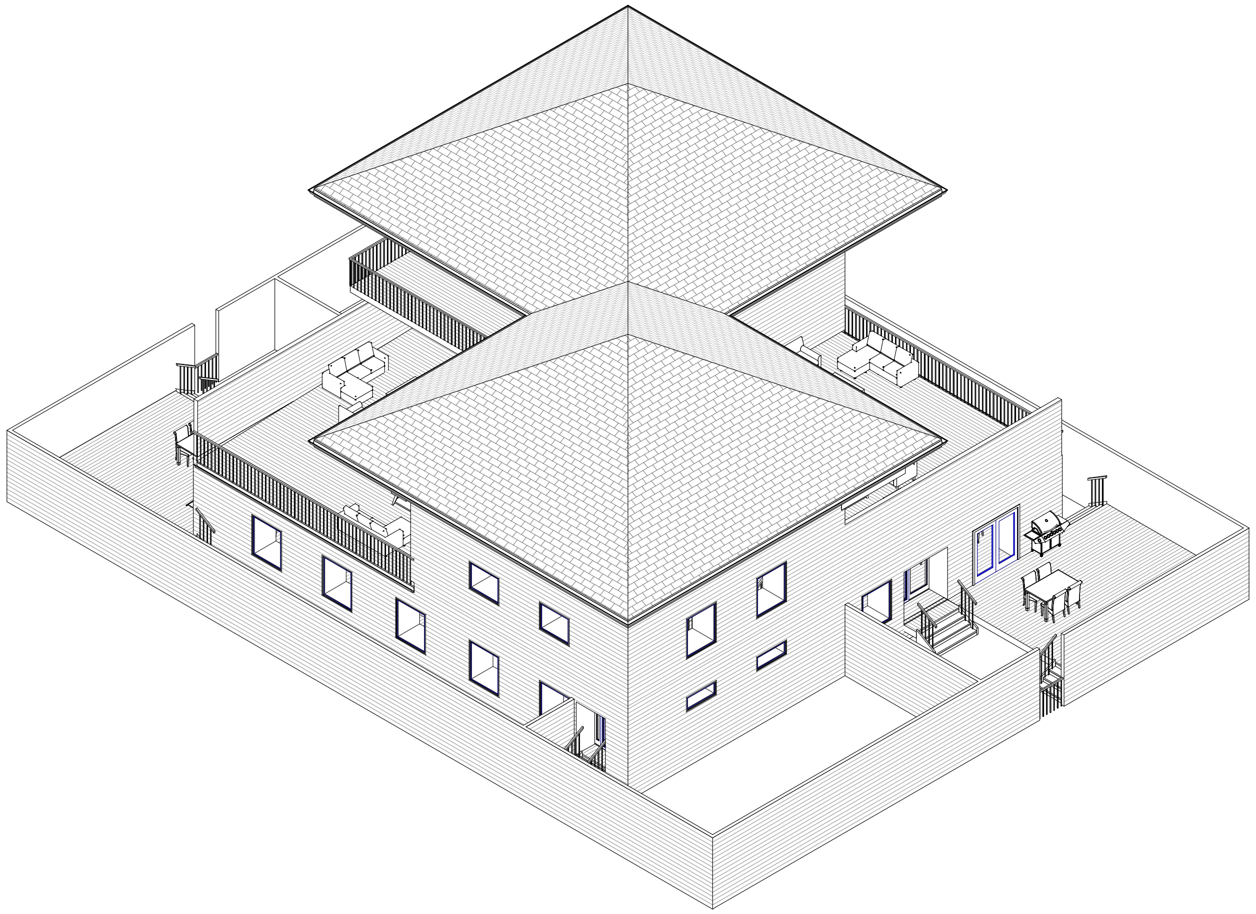
Woodcube, Designed by architekturagentur Hamburg, Germany, 2013

Photographs by Martin Kunze. Retrieved from ArchDaily (https://www.archdaily.com/421676/woodcube-architekturagentur) on 4 June 2020

Given the learnings of concept 1, concept 2 seeks a form with vertical walls that is simple to construct out of prefabricated panels and a form that receives more natural light into its interior.

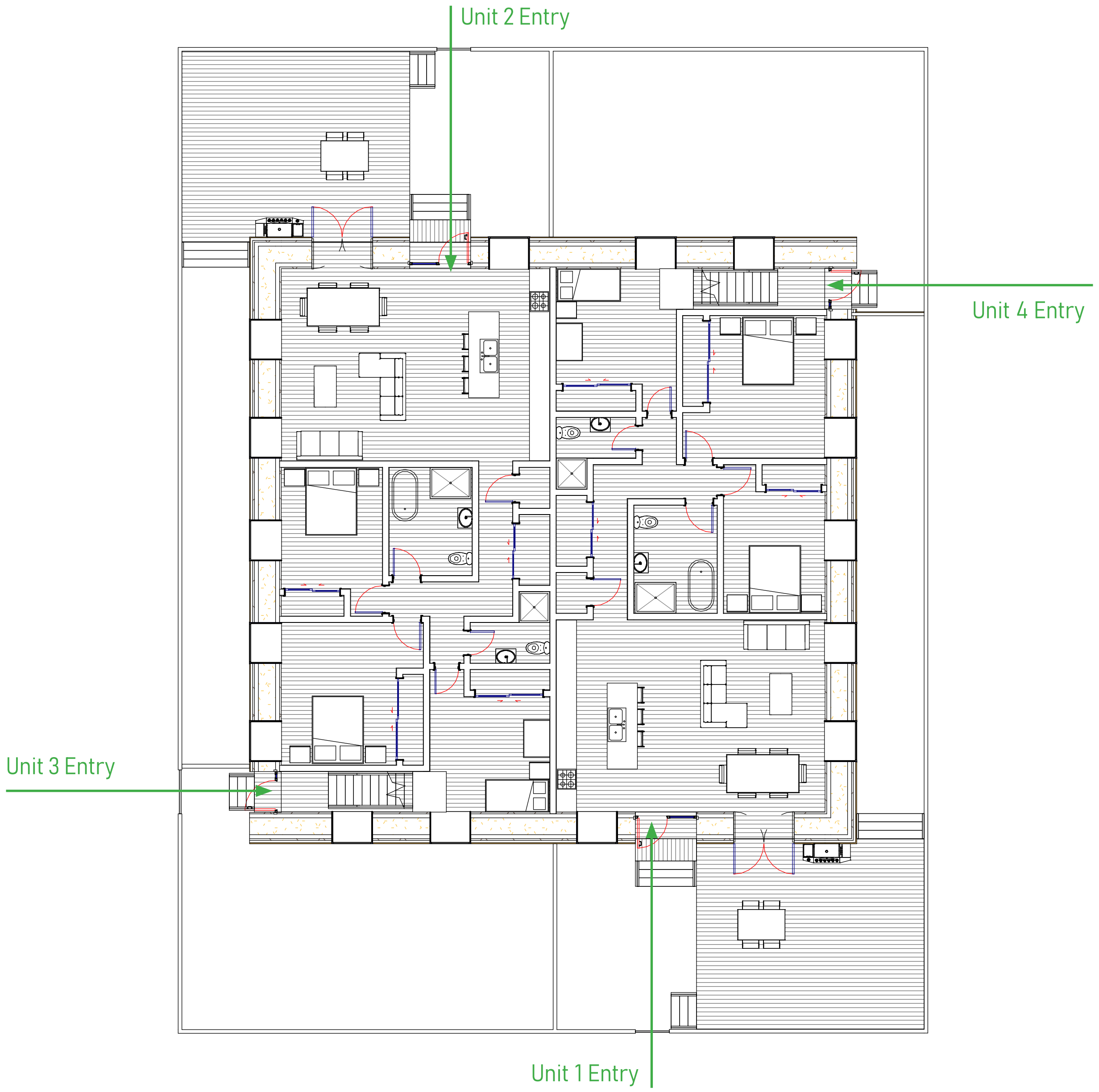
Both the Woodcube (figure 62) and the BaleHaus (figure 61) are constructed out of prefabricated panels. The Woodcube uses an entirely timber prefabricated panel and the Balehaus uses a straw bale insulated panel. Both designs make use of a cuboid form which is easy to construct out of prefabricated panels. However, both designs lack a steep roof with large overhangs which the proposed design will require. In addition, a cuboid form at the scale of the Woodcube results in a similar lack of natural light into the centre of the plan as was the case in concept 1. The proposed design for concept 2, therefore has to be at a smaller scale or the cuboid form has to be altered.

Design Proposal



The proposed design for concept 2 is based on the cuboid form used by the precedents but with volumetric subtractions to increase opportunities for natural light penetration into the core of the building and an added steep hipped roof with large overhangs. A hipped roof is chosen for simplicity as it requires no angled wall profiles from the prefabricated panels. Due to the increased exposed wall area compared to concept one, balconies are used in places to shield the exterior walls from rain. The vertical walls of this concept also mean that the deep-set windows in the exterior walls provide opportunities for window seats.

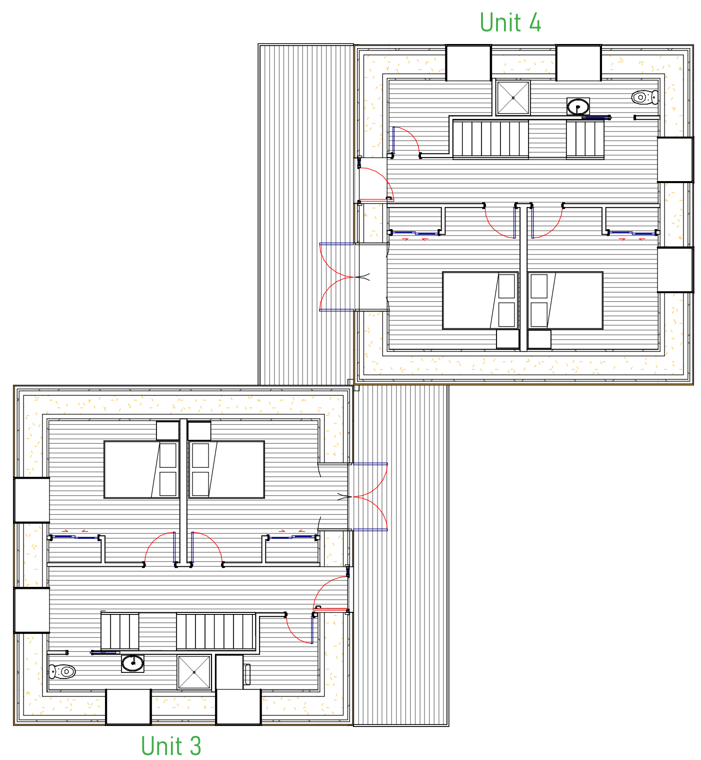
Ground Floor Plan (1:200)



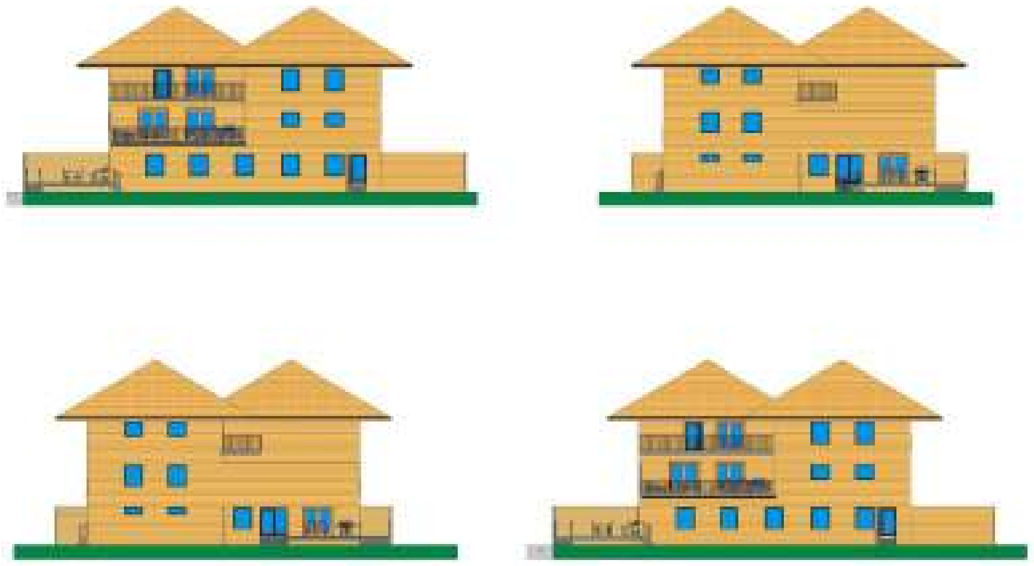
This concept contains 4 isolated accommodation units of identical volume. Units 1 and 2 are on the ground floor each with their own private outdoor deck/garden space. Units 3 and 4 are spread over 2 storeys and are stacked above units 1 and 2. Units 3 and 4 have their own private balcony spaces on two levels. The first-floor balconies are surrounding by a timber screen for privacy. Each of the 4 units has its own private ground-level access. The entries into the units are spread over the 4 facades for privacy.

First Floor Plan (1:200)

Second Floor Plan (1:200)



Elevations (1:500)



Design Review

Whilst subtracting volumes from the cuboid form has allowed more natural light into the interior of this concept it has created more exterior junctions where there are higher chances of leaks occurring. In addition, the first-floor balconies act as a flat roof over the ground floor and are not a wise design strategy for water tightness. There are also instances on the first floor where plumping is required to go through a straw insulated exterior wall which is not ideal.

5.4 **Concept 3**

Precedent Review

Figure 63

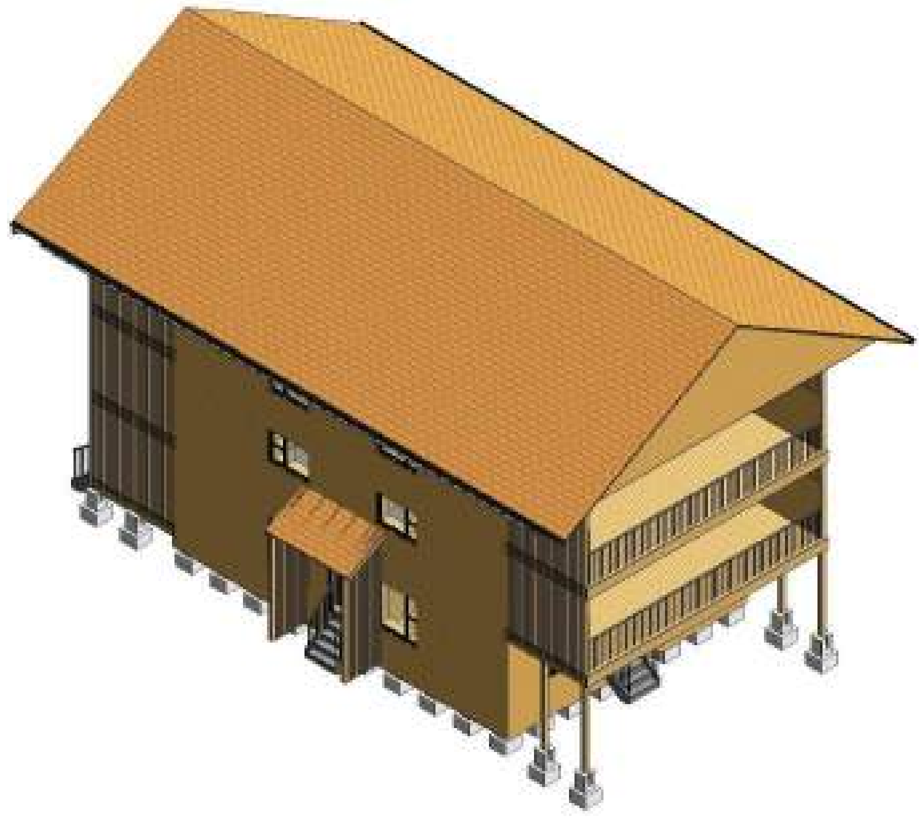
Chalet in Switzerland, by Charles Pictet, 2008

Retrieved from Archdaily (https://www.archdaily.com/324646/chalet-in-les-diablerets-charles-pictet-architecte) on 1 September 2020

Given the learnings from concept 2, concept 3 seeks to minimise the number of external junctions in the building's form whilst maintaining adequate natural light penetration. In addition, concept 3 seeks to add more aesthetic interest, shield a greater external wall area from rain and allow pluming to be piped through internal walls where no straw insulation is present.

The chalet design (figure 63) is an almost entirely timber construction and makes use of large overhangs and balconies which not only shield the exterior walls from the weather but also provide aesthetic interest.

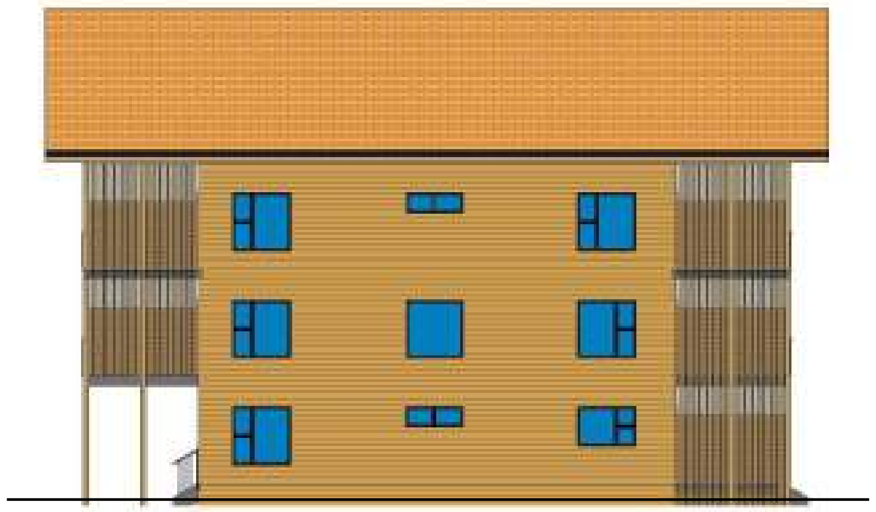
Design Proposal



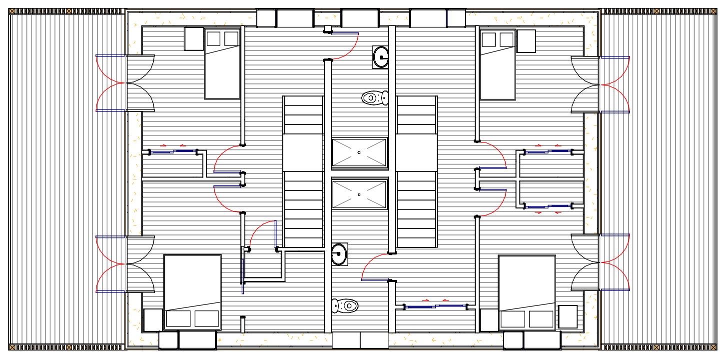
The proposed design for concept 3 is smaller than concept 2 allowing for a simpler form that receives sufficient natural light into the interior. The design also incorporates a gable roof with large overhangs and balconies similar to the chalet precedent. The gable roof adds aesthetic interest compared to the hip roof of the previous concept. In addition, the smaller form allows the roof and balconies to shield more external wall area than concept 2. The interior layout was also designed so that plumbing did not need to be piped through external walls.

Elevations 1:200

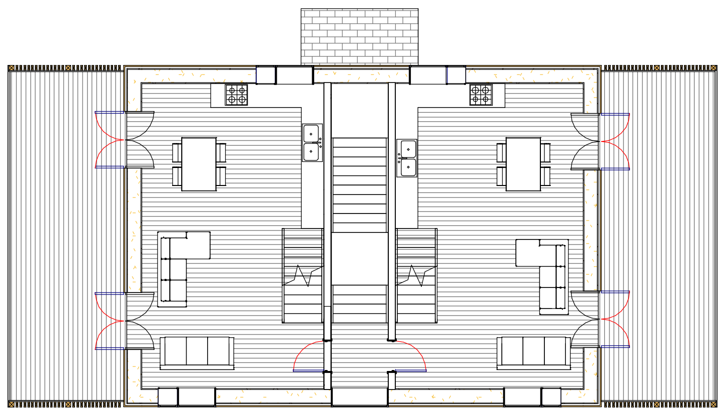
Elevations 1:200



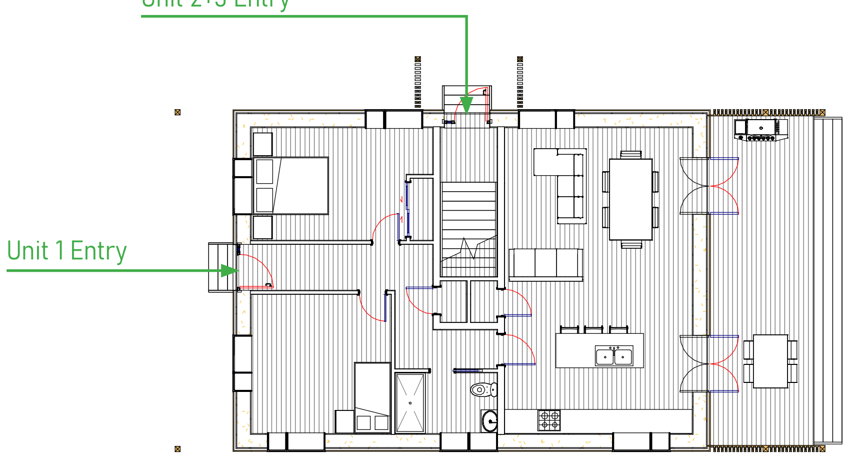
Second Floor Plan 1:200



First Floor Plan 1:200

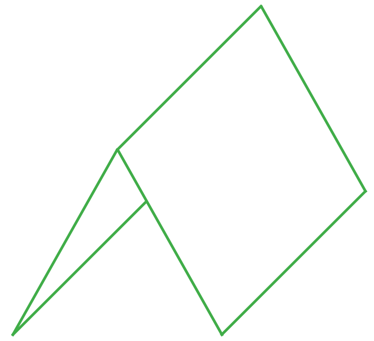


Ground Floor Plan 1:200

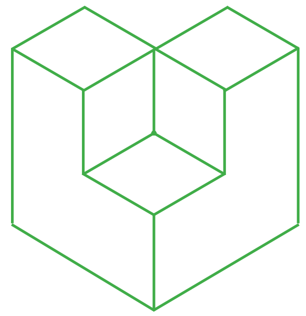


The design has 3 isolated units each with two bedrooms and one bathroom. Unit 1 is on the ground floor and has its own private access and garden area. Units 2 and 3 are both two storeys and are above unit 1. A shared stairway in the centre of the building is used to access units 2 and 3.

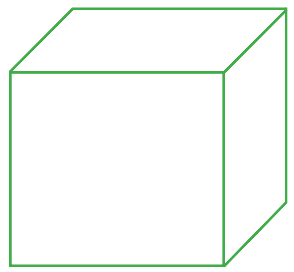
5.5 Review of Concept Designs



Concept 1



Concept 2



Concept 3

Formal Simplicity (minimising complex junctions where leaks are more likely is desirable for biodegradable materials)		**Dwelling Density**		
Concept 1	0.3 exterior junctions/ dwelling	Concept 3	294 bedrooms/hectare	3 points
Concept 3	2.6 exterior junctions/ dwelling	Concept 2	192 bedrooms/hectare	2 points
Concept 2	6.25 exterior junctions/ dwelling	Concept 1	148 bedrooms/hectare	1 point

Most suitable concept design	Total Points
Concept 3	5 points
Concept 1	4 points
Concept 2	3 points

Concept 3 is the result of an iterative design cycle attempting to find a building form that firstly supports the use of biodegradable building materials and secondly a suitable medium density housing design. In addition, it also rates the best in terms of formal simplicity and dwelling density. It may not have the simplest form out of the concepts, but it does have the greatest dwelling density which is desirable. Concept 1 has the simplest form but the lowest dwelling density and concept 2 had the most complex form and had a dwelling density between the other to concepts.

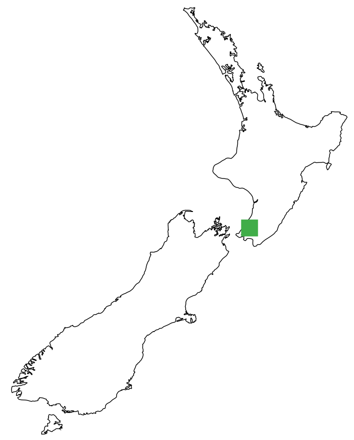
Site Integration

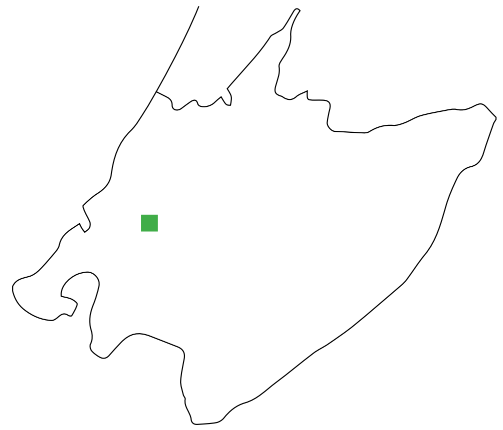
6

Chapter Outline

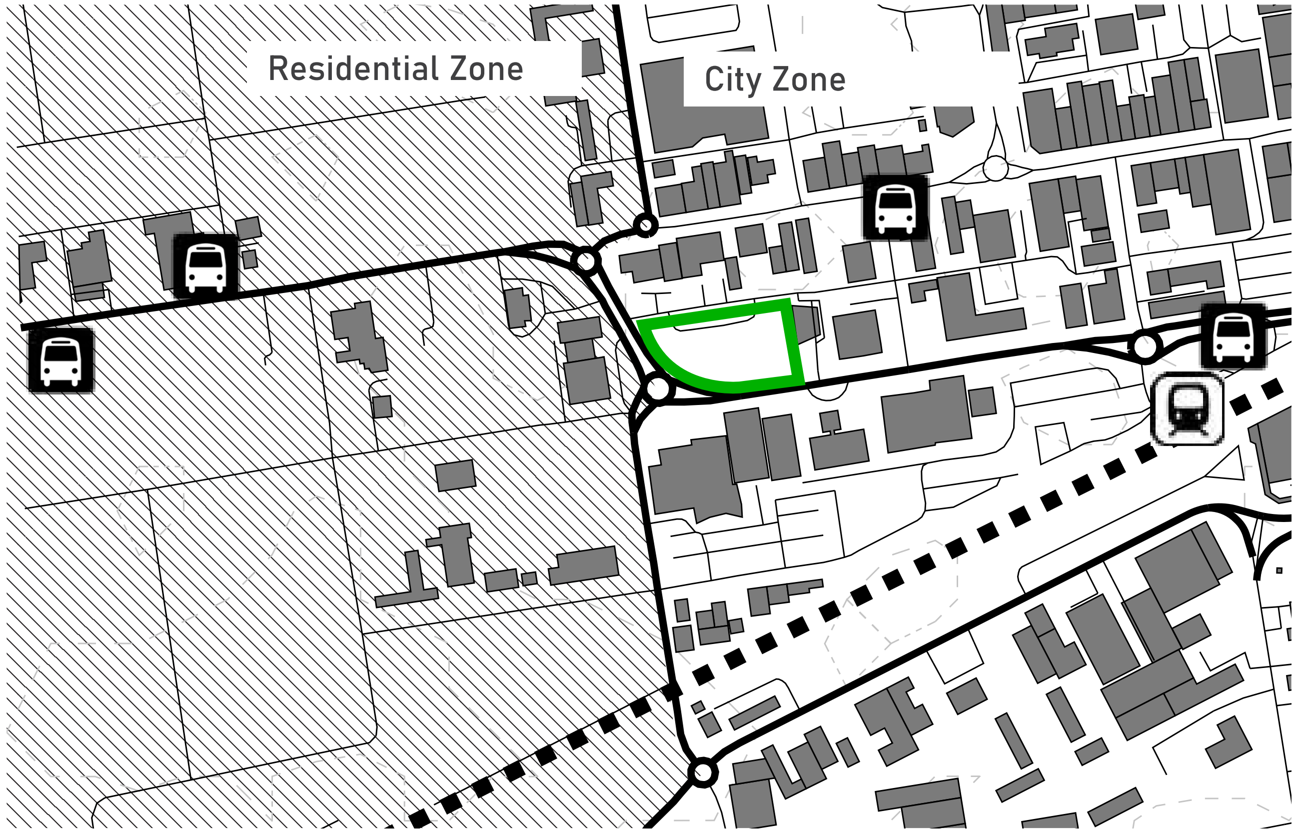
Although a sited is not a primary objective, no architectural design is ever produced in isolation to its site. Therefore, the design needs to be integrated with a site to architecturally test the building design. A sited design is also required to demonstrate the potential of applying biodegradable building materials to an urban site at the scale of a medium density housing development. In addition, the selected architectural typology of medium density housing requires careful consideration of site and inter-unit relationships. However, because a site development design does not contribute towards the thesis objectives it is not pursued beyond the point of architectural sufficiency. It is instead the building design which is used to pursue and assess the thesis objectives. A suitable site is selected before medium density housing precedents are reviewed to inform the layout of the proposed site development.

6.1 Selected Site





Location: Upper Hutt City
Size: approximately 98m x 51m
Area: 4262m^2



Site Selection Reasons:

1. Flat
2. Prime location for MDH on the boundary between residential and city zones
3. "Green field" site means the objective of zero-waste will not be compromised through demolition
4. Sufficient public transport nodes and amenities nearby

6.2 Medium Density Housing Precedents

Figure 64

Earthsong Eco-Neighbourhood, Waitakere, New Zealand

Retrieved from Cohousing New Zealand (https://cohousing.org.nz/communities/earthsong-eco-neighbour-hood) on 25 May 2020

Figure 65

Earthsong Site Plan, Waitakere, New Zealand

Retrieved from Pinterest (https://www.pinterest.nz/pin/669207444418499541/) on 25 May 2020

Figure 66

LILAC Bramley, West Leeds, UK

Retrieved from ModCell (https://www.modcell.com/projects/lilac-affordable-ecological-co-housing/) on 10 March 2020

Figure 67

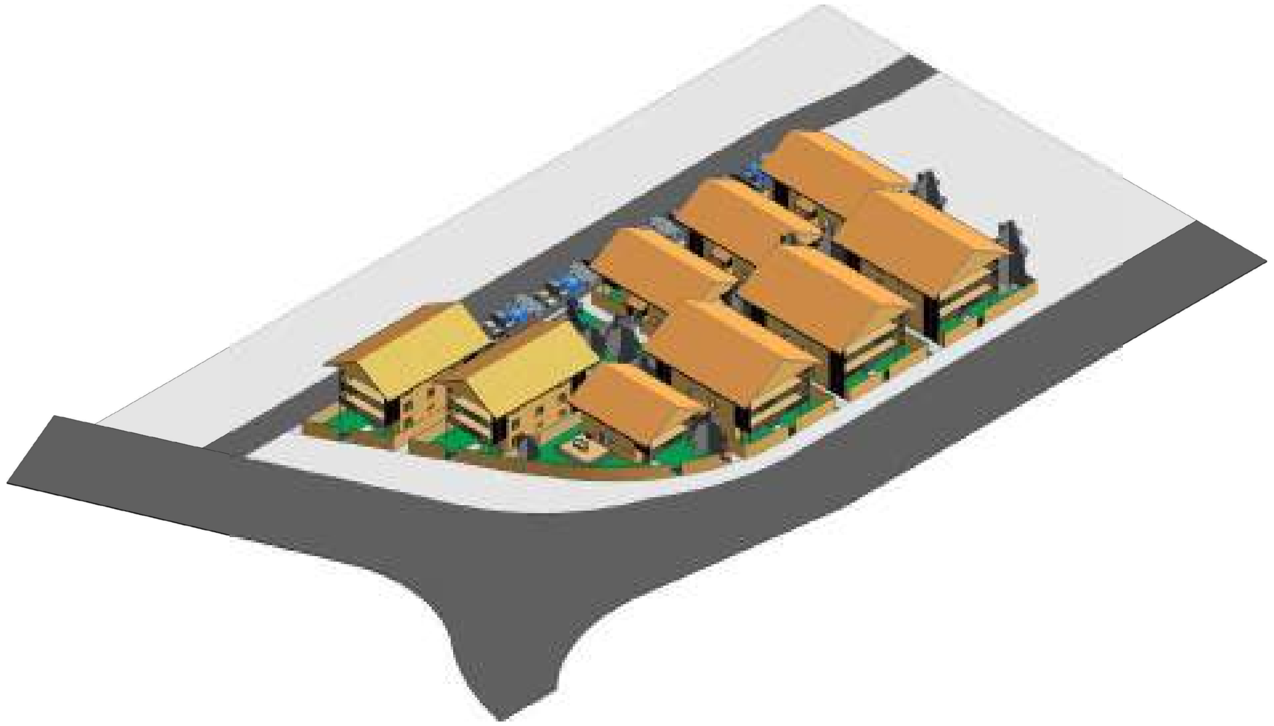
LILAC Ariel Image

Retrieved from Google Images (https://goo.gl/maps/AfAmrAtmGGy7qe9c8) on 10 March 2020

Earthsong (figure 64,65) and LILAC (figure 66,67) are both medium density housing precedents that have a focus on environmental sustainability. Earthsong is in New Zealand and is constructed primarily out of untreated timber and earth. LILAC is in the UK and primarily constructed out of untreated timber and straw bales prefabricated panels from ModCell®. Both developments offer a range of unit sizes and an abundance of green space. Both also have car parks located at the perimeter of the site reducing the need for paved areas within the complex and making the development more pedestrian-friendly.

6.3 Site Development Proposal

Site Axonometric 1:1000

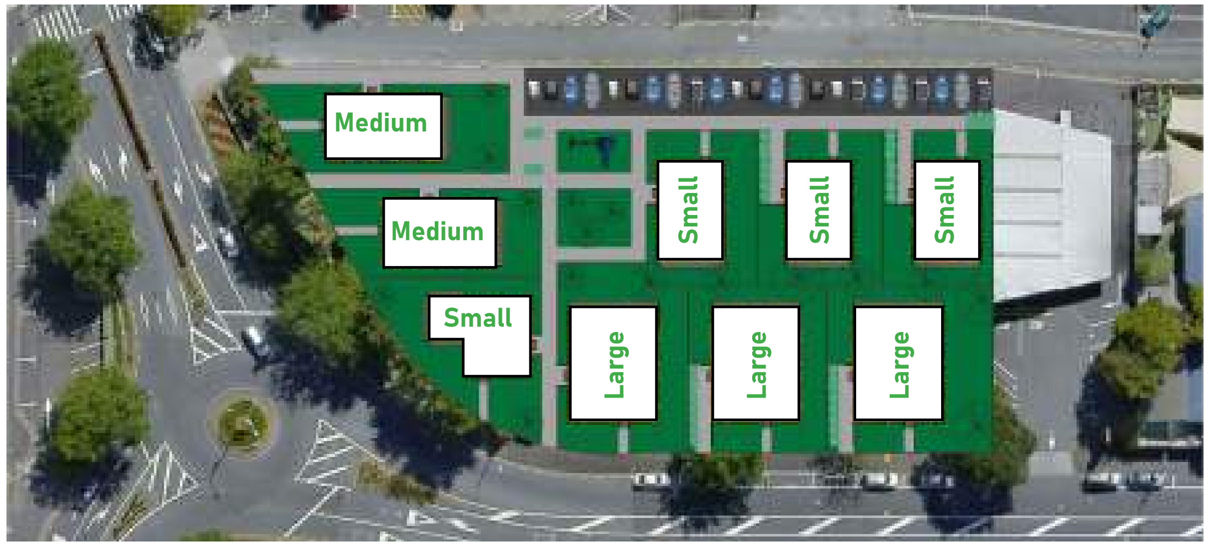


North Elevation 1:1000

South Elevation 1:1000

West Elevation 1:1000

Locality Site Plan 1:1000



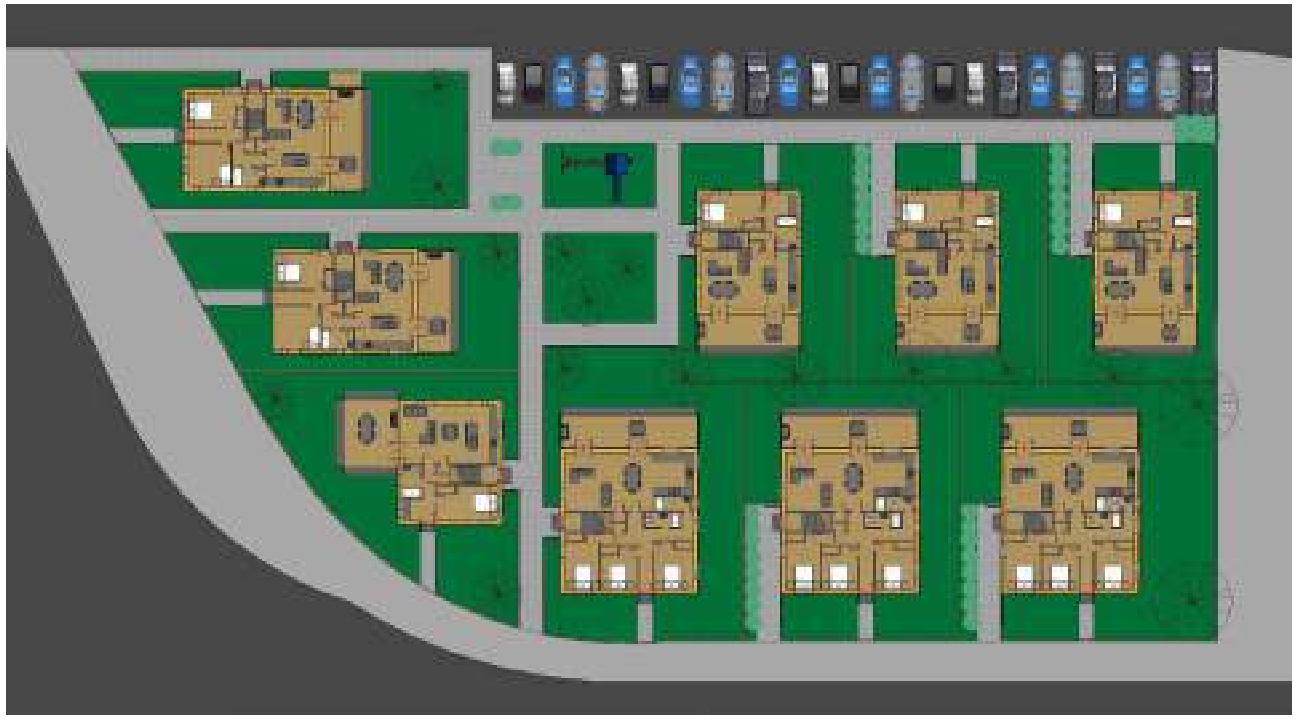
The proposed design incorporates different accommodation sizes and a car park on the edge of the site just as the precedents do. The design has three different apartment building types offering different sizes of accommodation. It was important for the spacing between each dwelling to be carefully considered for this design. If the buildings are too close there is decreased privacy and green space and increased fire spreading risk given the flammable nature of the biodegradable materials. However, if the buildings are too far apart, they lose the additional shelter provided by the eave of the neighbouring building which the biodegradable materials benefit from.

To reduce shading, the smaller buildings were positioned to the north and larger ones to the south. In addition, the large buildings to the south are offset from the smaller buildings to the north to prevent direct lines of visibility into adjacent units. Trees are also planted between the smaller buildings to the north and larger buildings to the south to improve privacy and amenity.

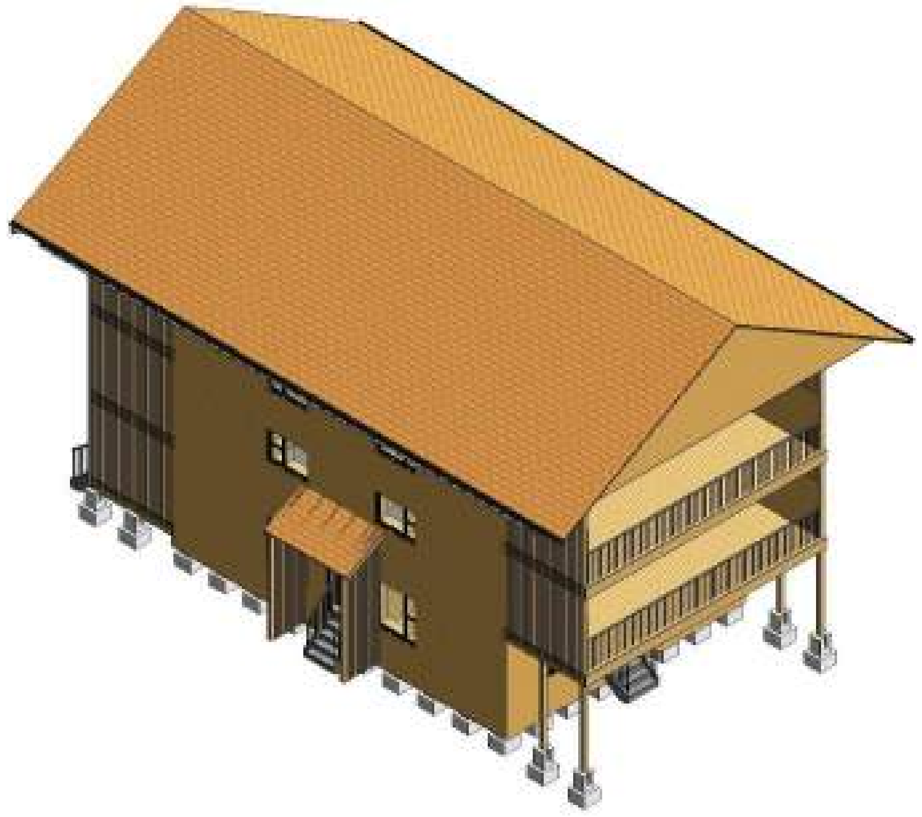
Key:

Small = 2 x (one bedroom + one bathroom units). 2-storey building
Medium = 3 x (two bedrooms + one bathroom units). 3-storey
Large= 3x (three bedrooms + two bathrooms). 3-storey

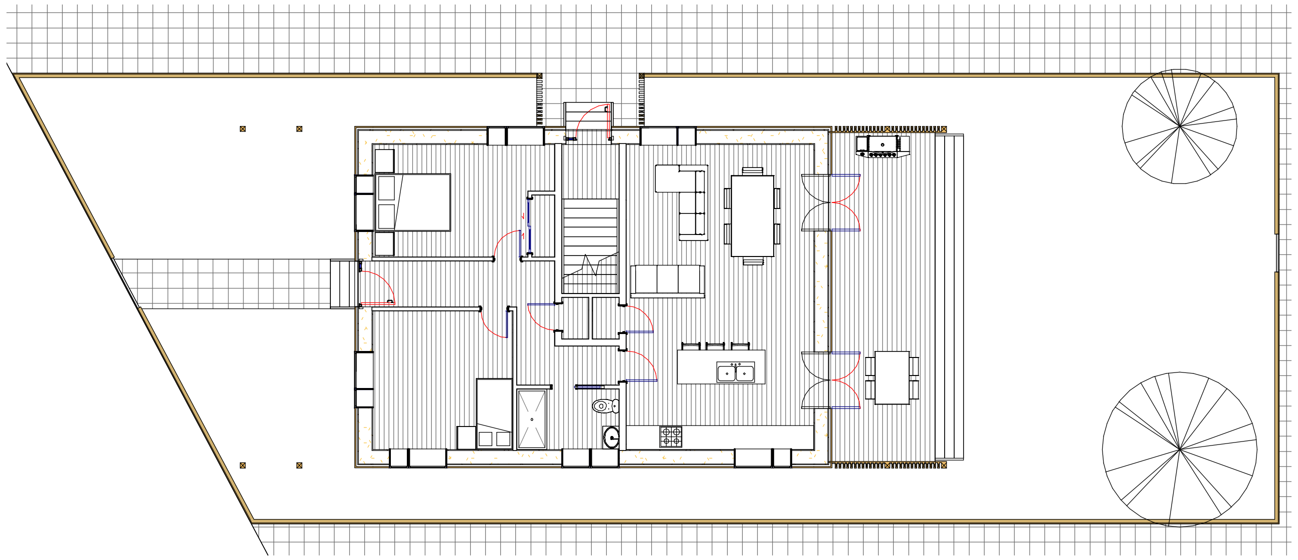
Ground Floor Site Plan



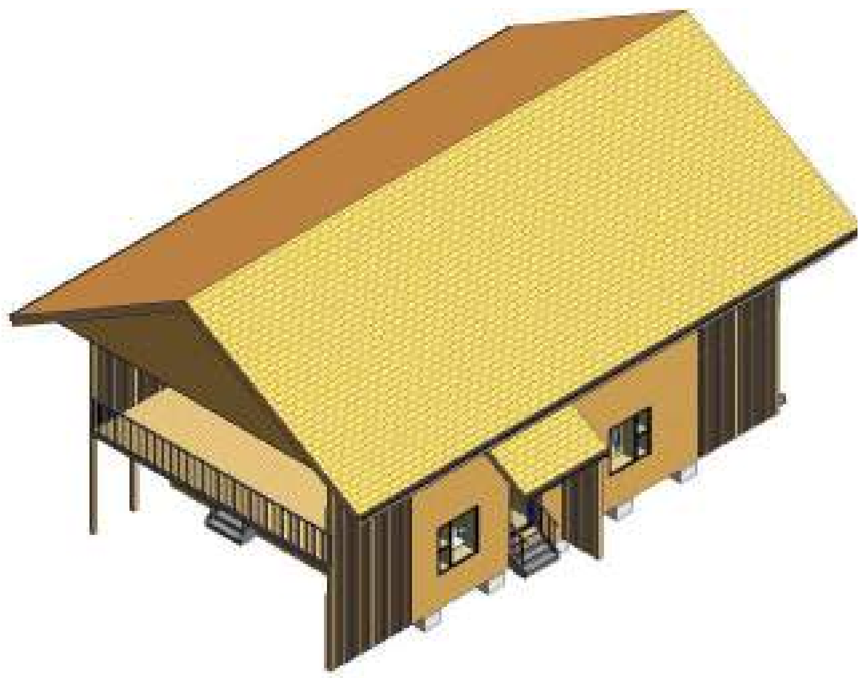
Medium Building (Concept 3) 1:200



Medium Building Sited Ground Floor 1:200

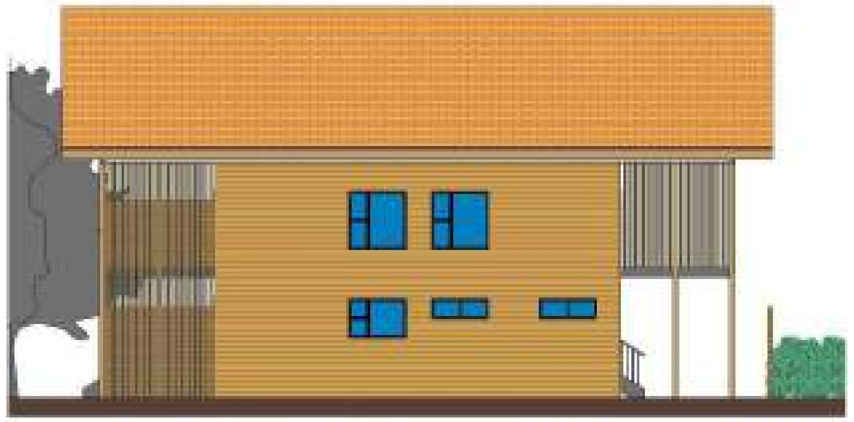


Small Building 1:200



Small Building West Elevation 1:200

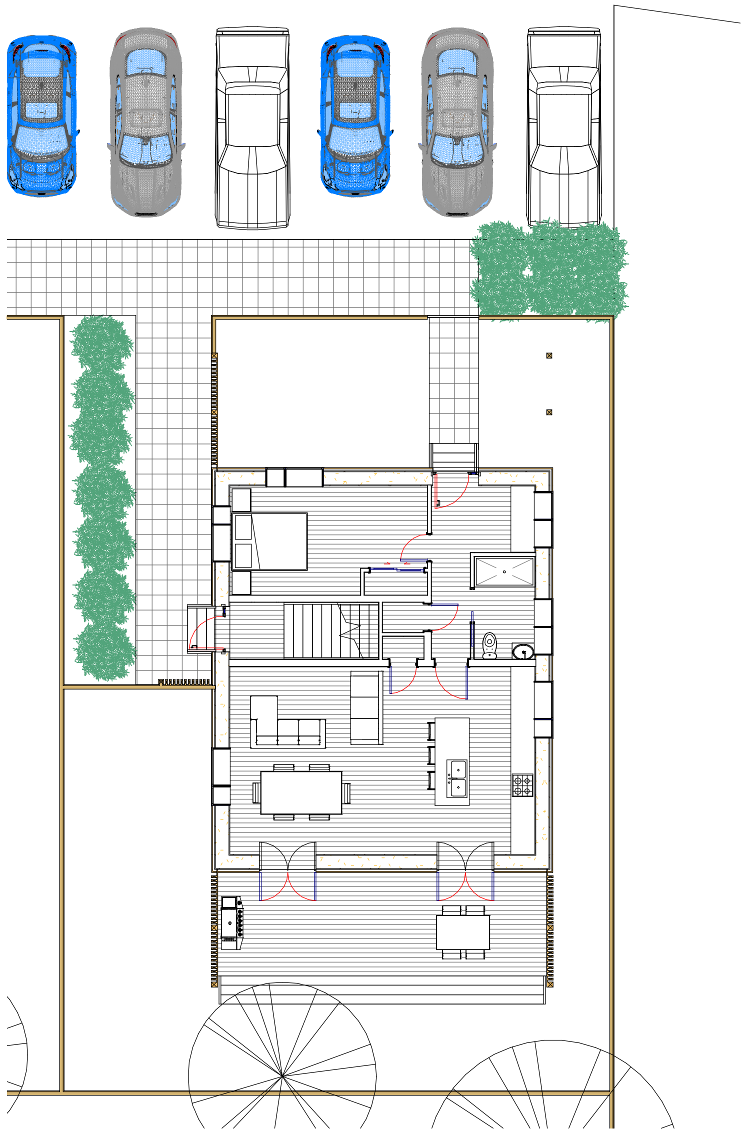
Small Building East Elevation 1:200



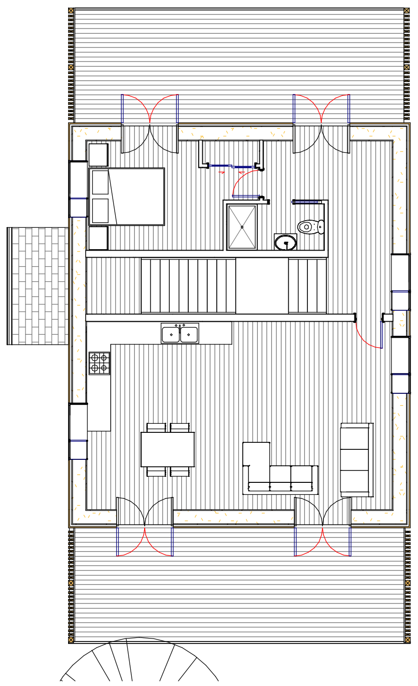
Small Building South Elevation 1:200

Small Building North Elevation 1:200

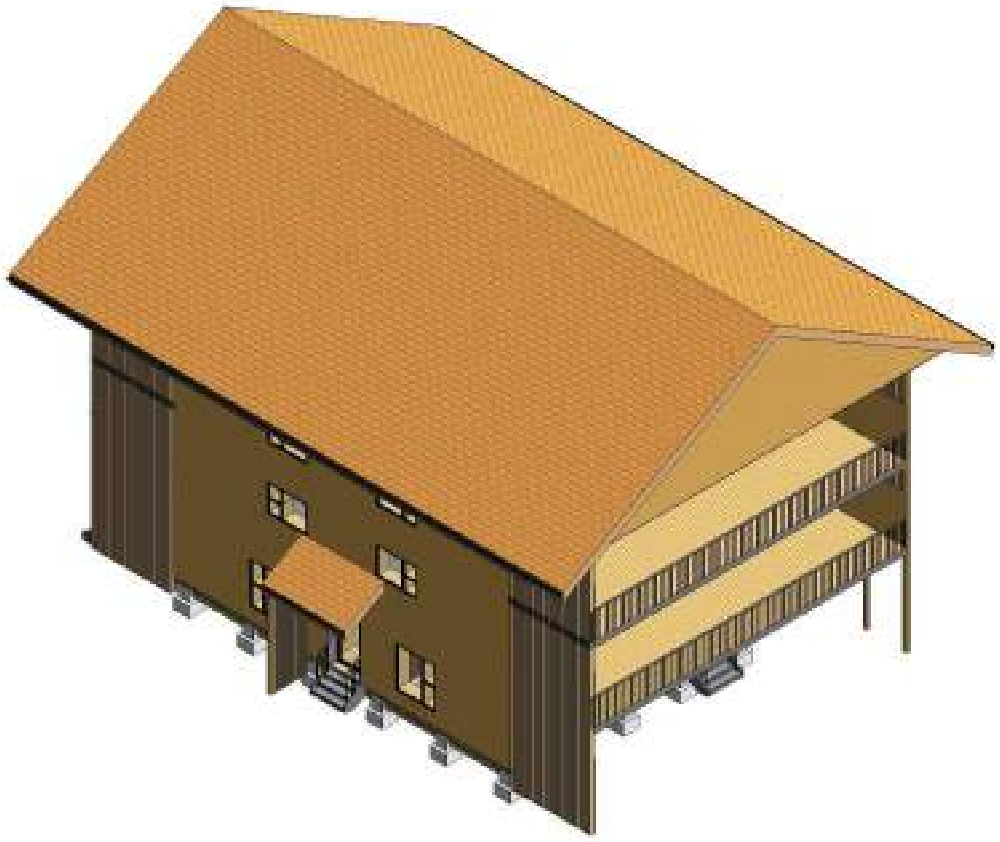
Small Building Ground Floor 1:200



Small Building First Floor Plan 1:200



Large Building 1:200



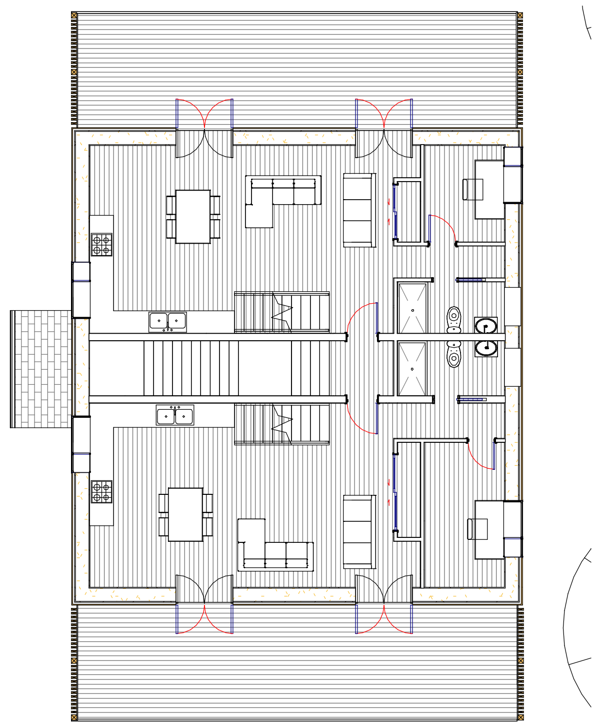
Large Building West Elevation 1:200

Large Building East Elevation 1:200

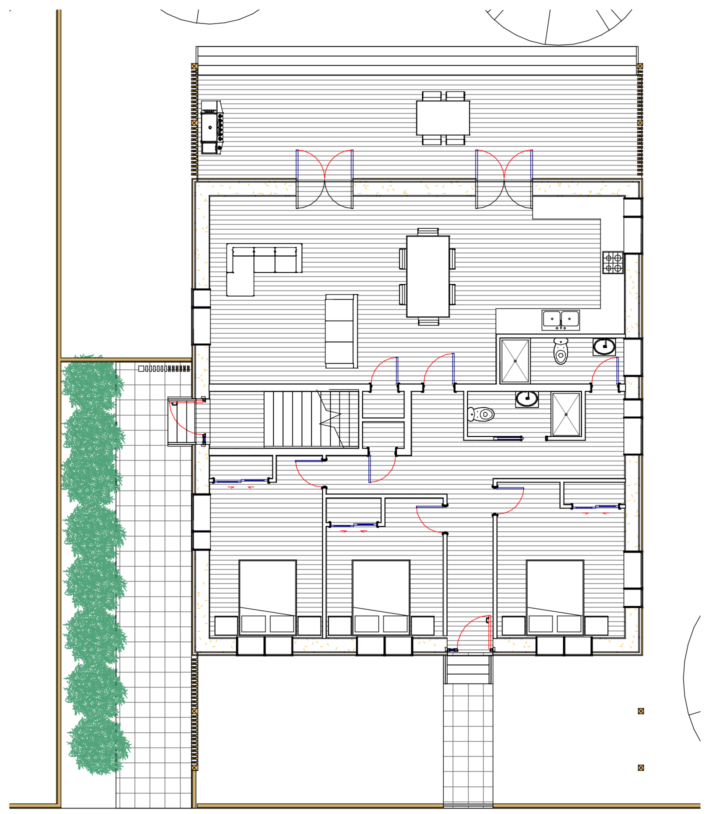
Large Building South Elevation 1:200

Large Building North Elevation 1:200

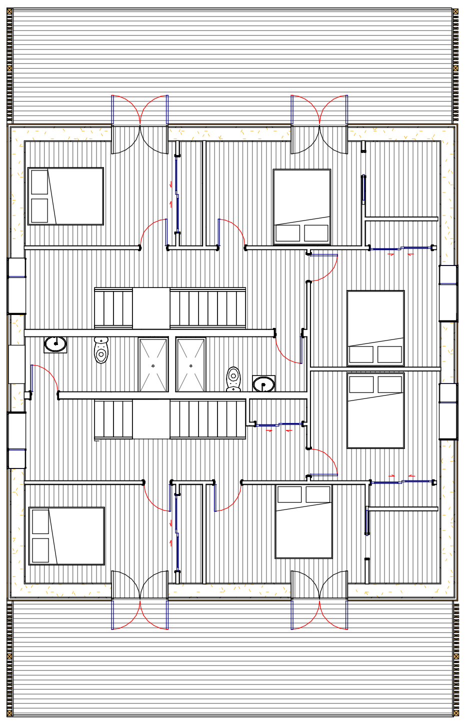
Large Building First Floor Plan 1:200



Large Building Ground Floor Plan 1:200



Large Building Second Floor Plan 1:200



Detailed Design

7

Chapter Outline

In the previous chapter, the building design was integrated on site to ensure the design functioned sufficiently as a medium density housing development. In this chapter, the construction of the medium building (concept 3) is designed in detail. This is done to accurately assess the quantity of waste diverted from landfill and the end of life of the building and the proportion of biodegradable materials in the construction. Precedents and literature are reviewed to inform the development and integration of the prefabricated straw and wool insulated panel from chapter 4 into the design. A detailed BIM model is then produced of the entire building from which volumes can be extracted. The material components are then categorised regarding their biodegradability, reusability or lack thereof to accurately assess the first two thesis objectives. The same assessment is undertaken for an identical design but using conventional New Zealand materials for comparison.

7.1 Prefabricated Panel Development and Integration

Precedent and Literature Review

Figure 68

Diagonal Braces

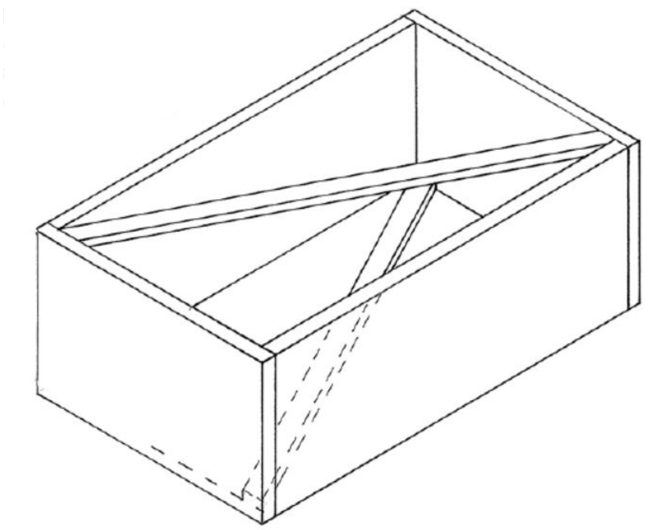
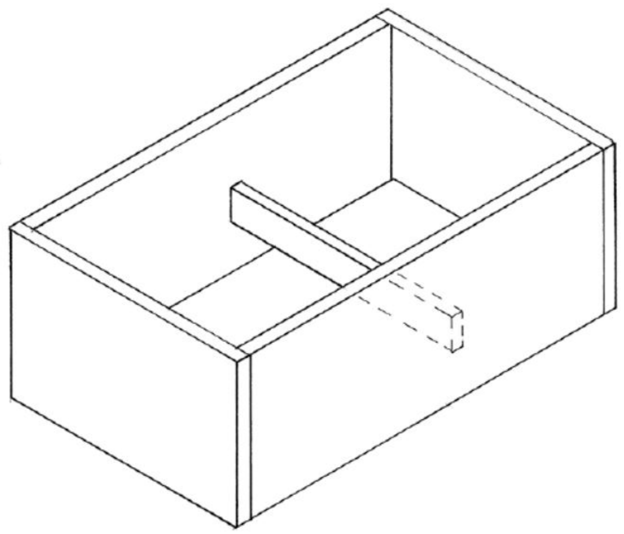


Figure 69

Buried brace



Reprinted From "Essential Prefab Straw Bale Construction: The Complete Step-by-Step Guide" by C. Magwood, 2016, p. 16. Copyright 2019 by Chris Magwood.

Figure 70

Ecococon panel to floor connection

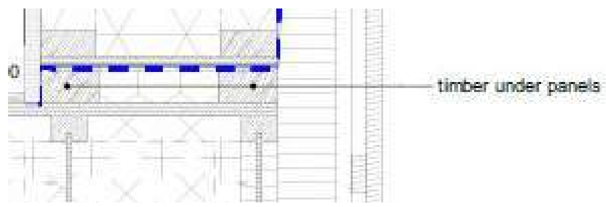


Figure 71

ModCell® panel to floor connection

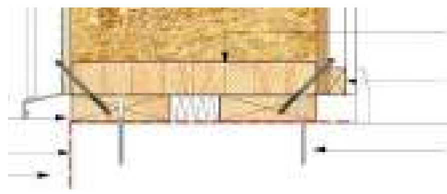


Figure 72

ModCell® panel to panel connection (plan)

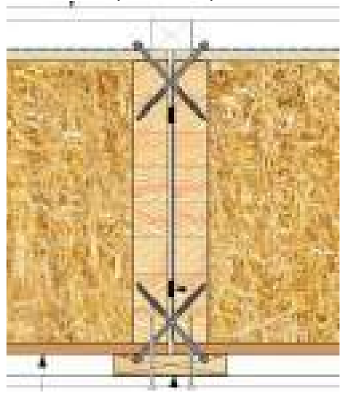
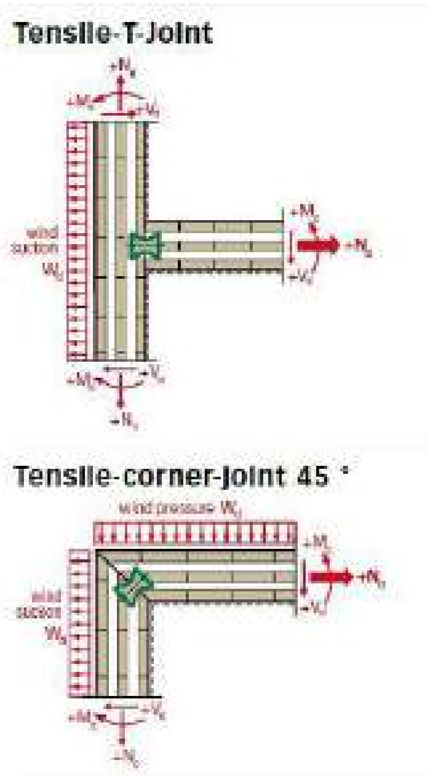


Figure 73

Haslacher timber connector

Figure 74

Haslacher timber connector details



The prefabricated panel design from concept 3 requires further development before it can be integrated into the building design. One area of required development is bracing. Magwood explains that straw insulated prefabricated panels can be braced by diagonal braces (figure 68) or a buried brace (figure 69) (Magwood, 2016). Diagonal braces provide the most effective bracing whilst the buried brace allows the brace to span across the whole panel not just between vertical members of the frame (Magwood, 2016). The buried brace's ability to span the whole panel increases the continuity and strength of the brace.

Another required area of development for the panel is its connection to floors. Both Ecococon and ModCell® panels are connected timber runners which are in turn fixed into the floor (figure 70,71). In both cases, insulation is also used in the cavity.

Finally, how the panels connect to each other needs to be developed. The ModCell® panel (figure 72) and the Ecococon panel both connect to adjacent panels with screws. However, opportunities for biodegradable connectors exist as an alternative to screws such as the timber connector from Haslacher (figure 73,74). These connections are simply hammered into place and can be removed at the end of life as easily as a screw.

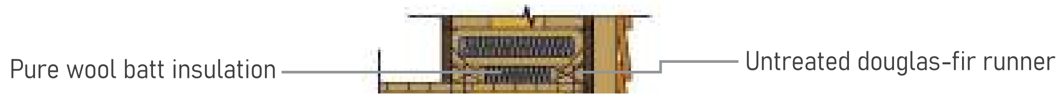
Panel Design Proposal

The proposed panel design utilises a buried diagonal brace that combines the two bracing options explored in the precedents. Timber runners are used as a fixing method to the floor as the precedents demonstrate, and pure wool insulation is used to insulate the cavity. Finally, timber connectors like that from Haslacher are used to connect the panels together.

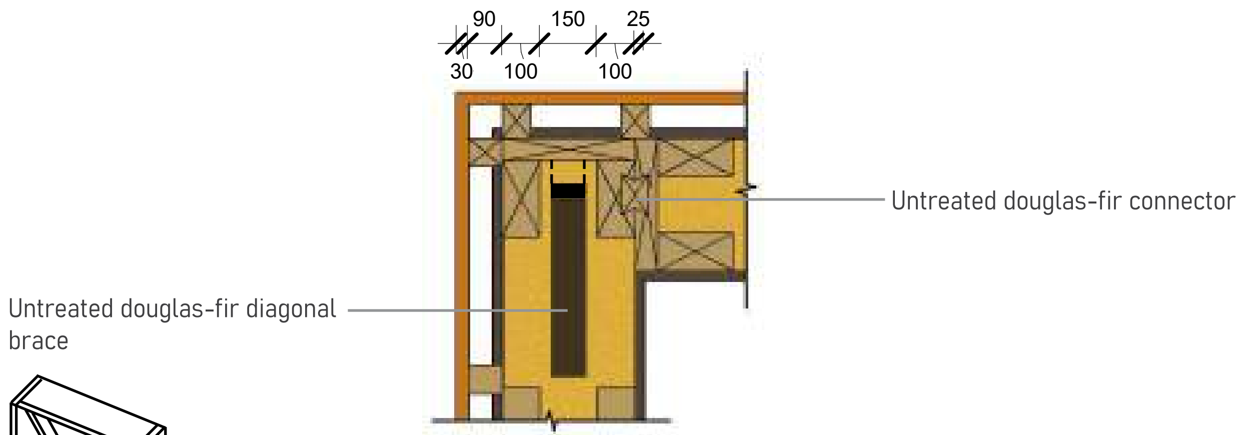
The panels are integrated into the envelope of the building such that the width of the panels are aligned and consistent on each floor. The exterior dimensions of the building were slightly manipulated to achieve panels widths of increments of 600mm (the use of compressed straw in the panels allows dimensional flexibility). 600mm was chosen as it is a dimension of a standard structural grid spacing for residential buildings.

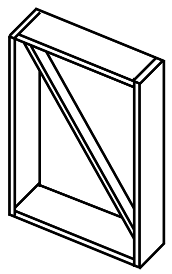
The "Multi-Storey Light Timber-Framed Buildings in New Zealand - Engineering Design" from BRANZ specifies 140x45mm SG8 wall studs at 600mm centres for a worked example of a 4-storey building (Carradine et al., 2019). The proposed design in this thesis is only 3 storeys but has a considerably heavier construction therefore 200x100 stud members were selected to be conservative.

Panel to Floor Detail 1:20



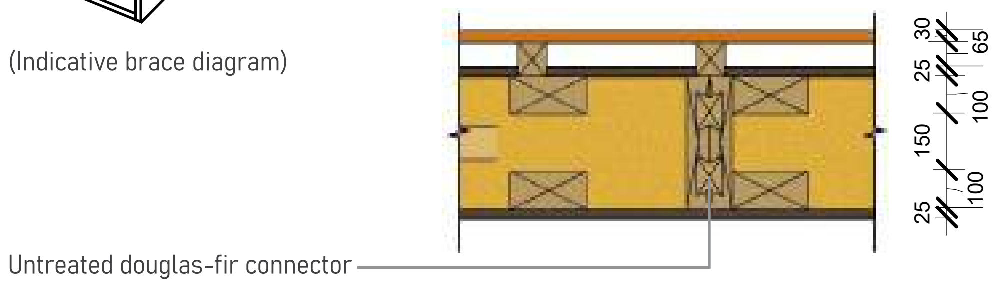
Wall Panel Corner Detail 1:20





(Indicative brace diagram)

Wall Panel Connection Plan Detail 1:20

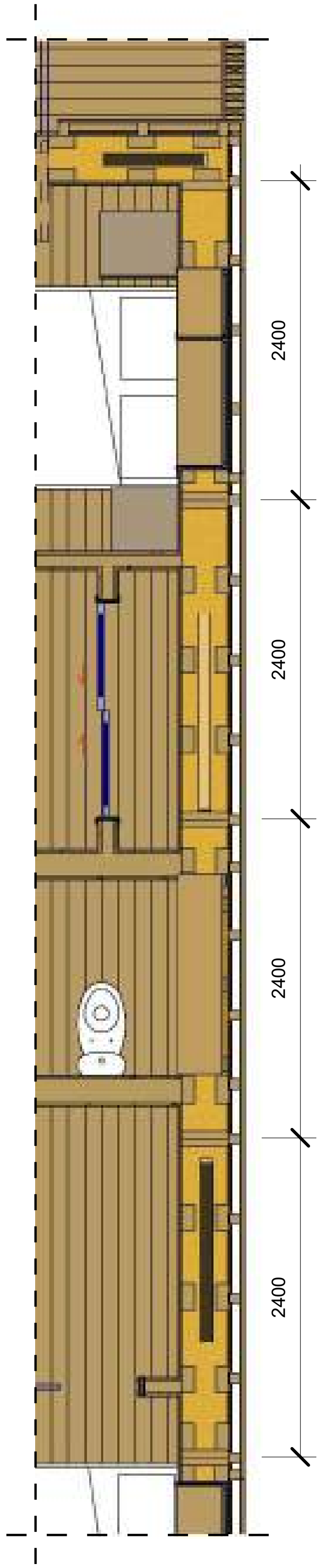


Wall Panel Ground Floor Plan 1:100

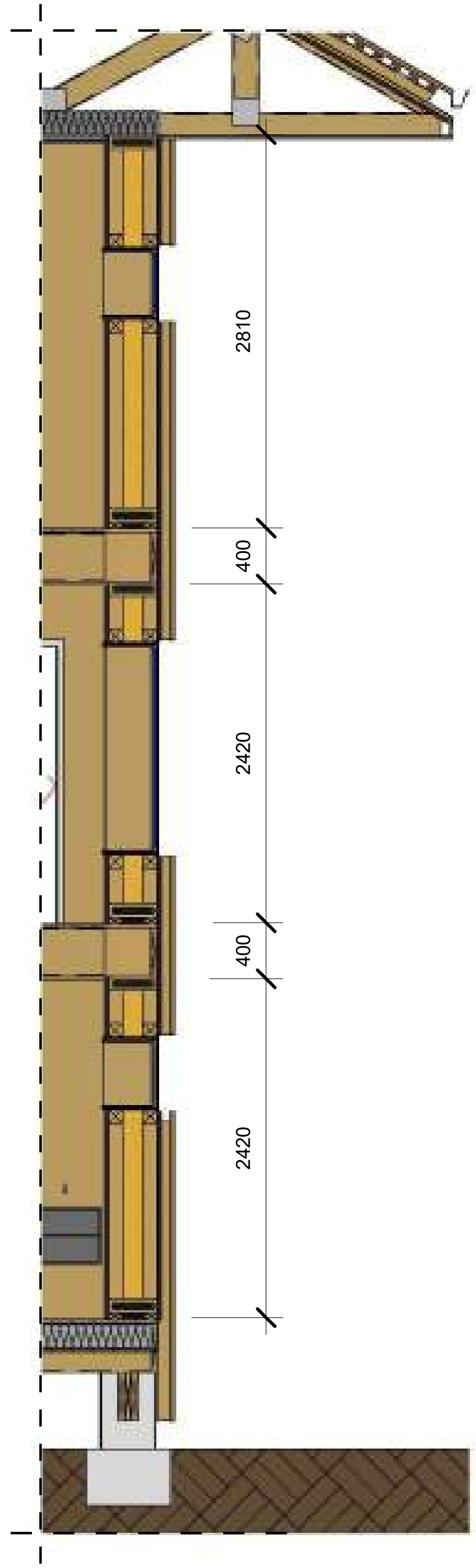
Wall Panel First Floor Plan 1:100

Wall Panel Second Floor Plan 1:100

Ground Floor Plan 1:50



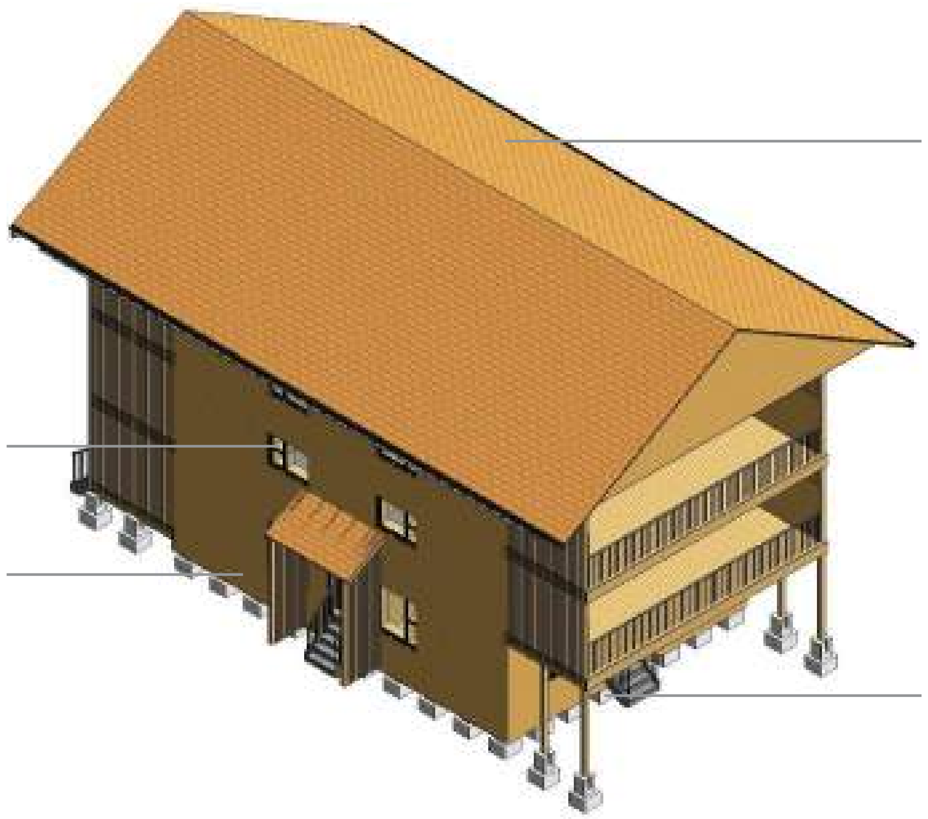
Facade Section 1:50



7.2 Final Design and Conventional Design Comparison

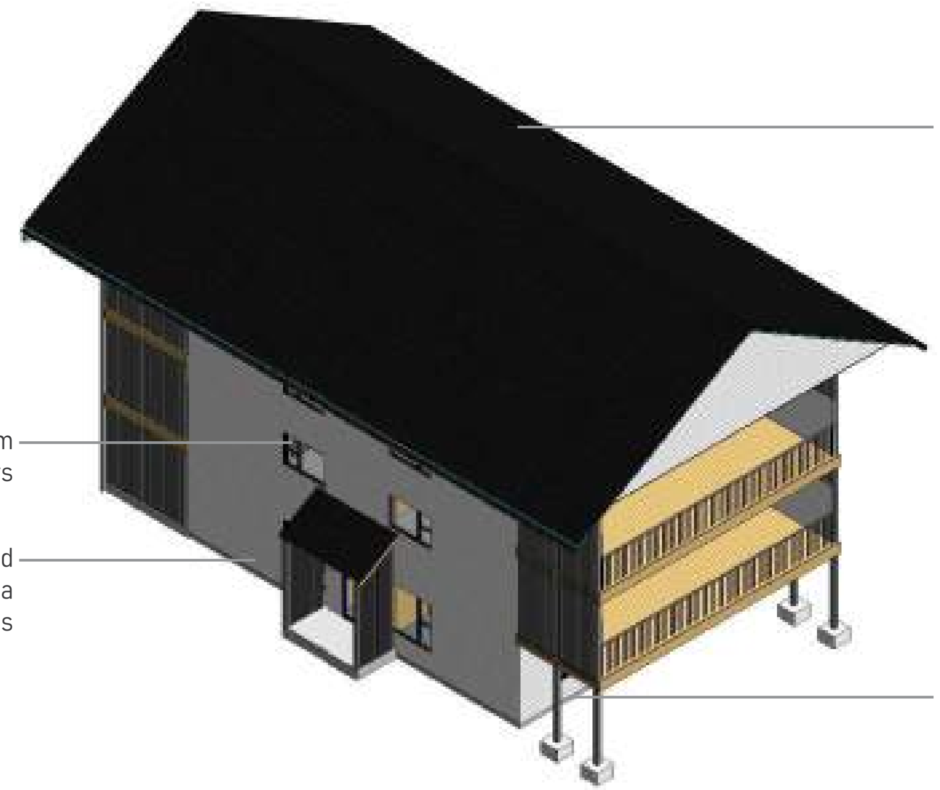
In this section of the chapter the rest of the building's construction is designed and compared with conventional New Zealand residential construction. It is in this section that the most suitable biodegradable or reusable materials for New Zealand that were found in chapter 3 are integrated into the design.

Final Design



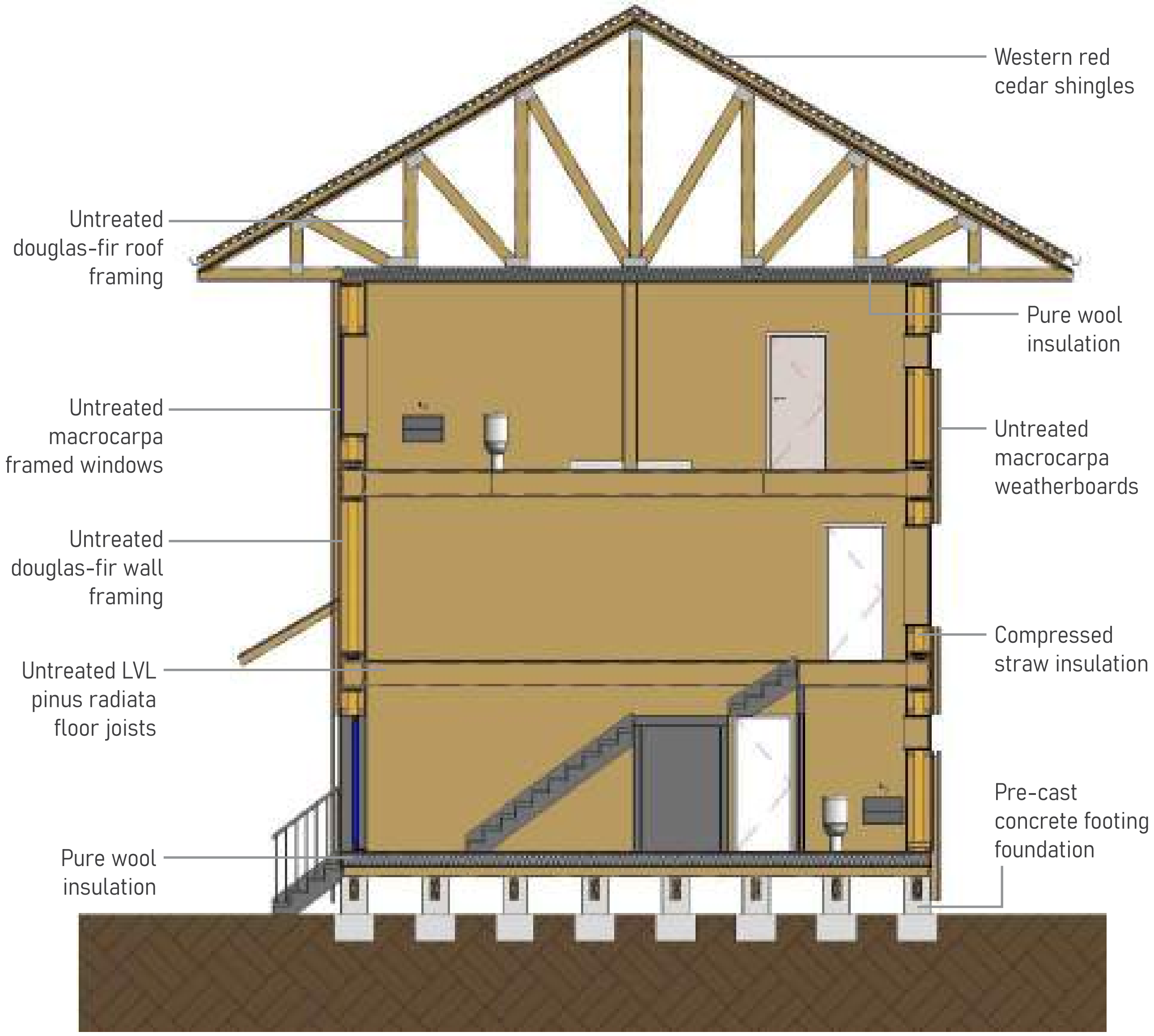
The final design is the building design from this thesis with the objective of eliminating end of life waste and maximising the use of biodegradable building materials.

Final Design with Conventional New Zealand Materials



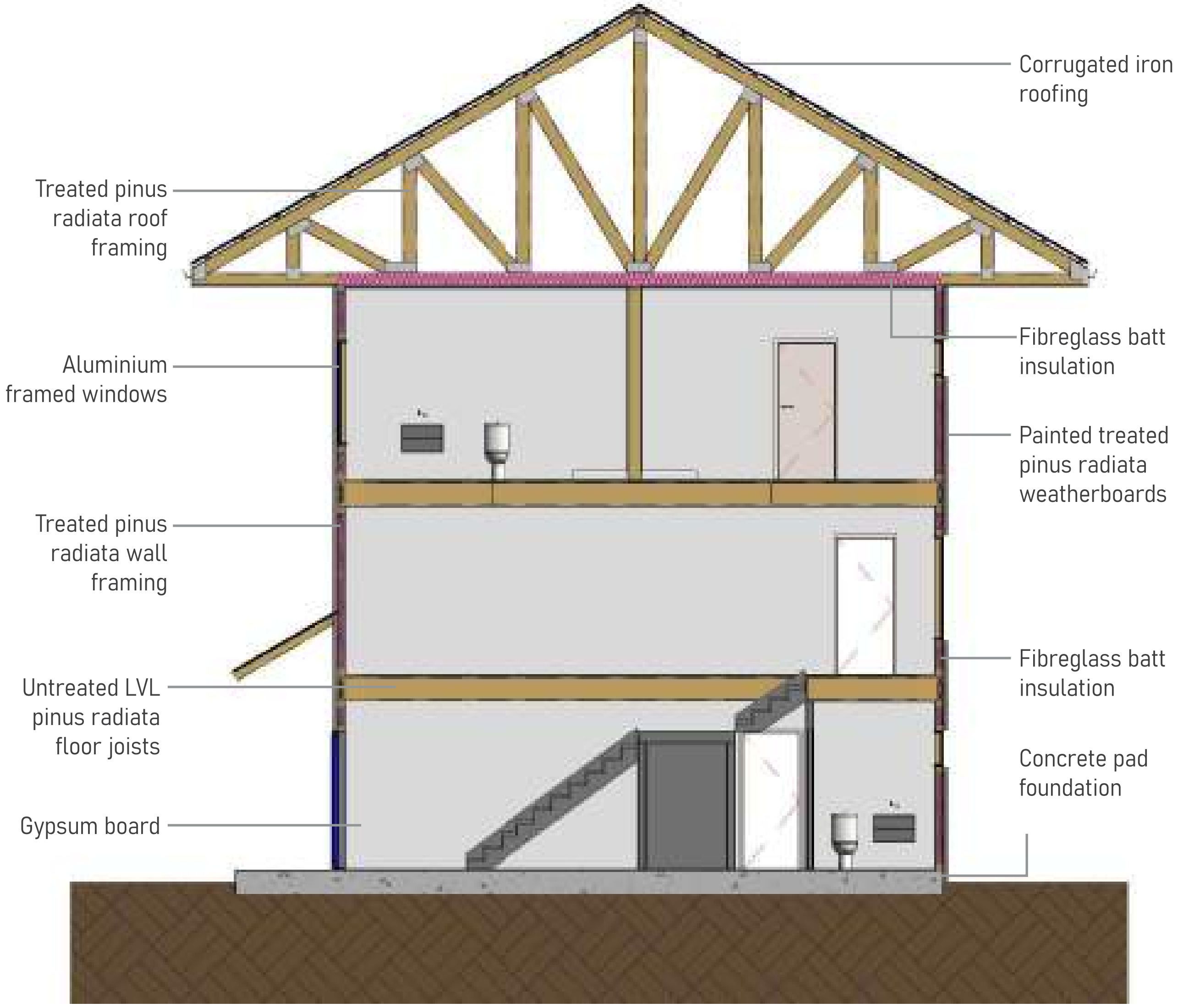
The final design with conventional New Zealand materials is identical in design to the final design but with conventional New Zealand materials and construction techniques. Literature was used to inform which materials were most popular in homes in New Zealand (see page 165 for references).

Final Design



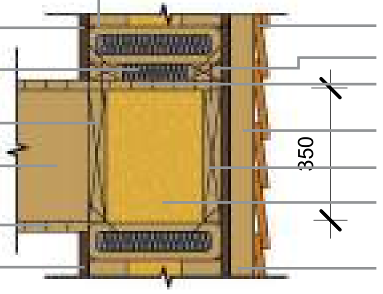
Because wool is less dense than straw it was used to insulate the roof to minimise dead load. Wool was also used for underfloor insulation as it is simpler to place between joists than compressed straw, loose straw or resized bales.

Final Design with Conventional New Zealand Materials

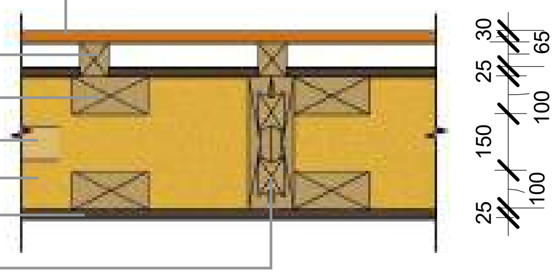


Final Design

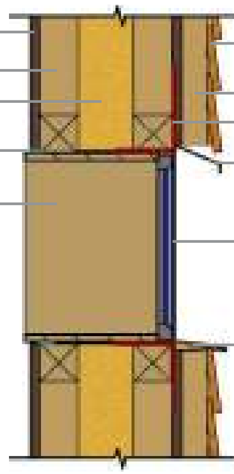
Inter-storey Detail 1:20



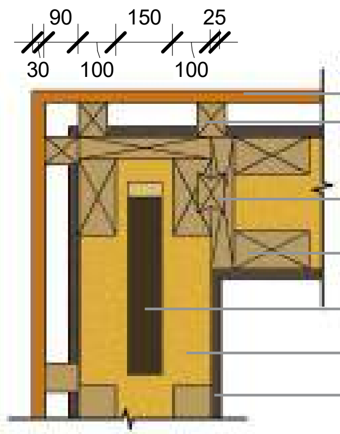
Wall Panel Connection Plan Detail 1:20



Window Detail 1:20



Wall Panel Corner Detail 1:20

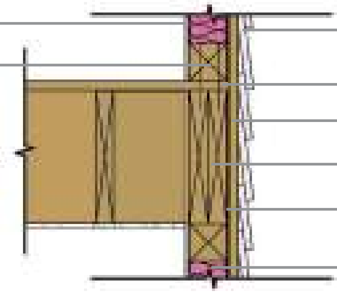


Key

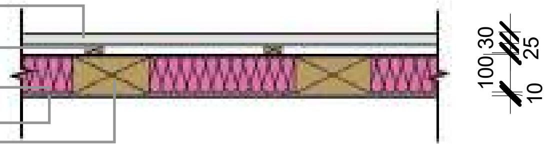
- Untreated douglas-fir
- Compressed straw
- Clay plaster
- Pure wool insulation
- Untreated macrocarpa weatherboards

Final Design with Conventional New Zealand Materials

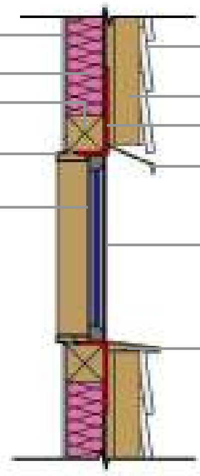
Inter-storey Detail 1:20



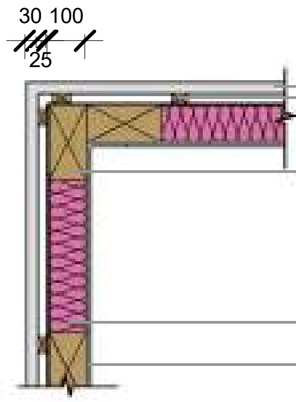
Wall Plan Detail 1:20



Window Detail 1:20



Wall Plan Corner Detail 1:20

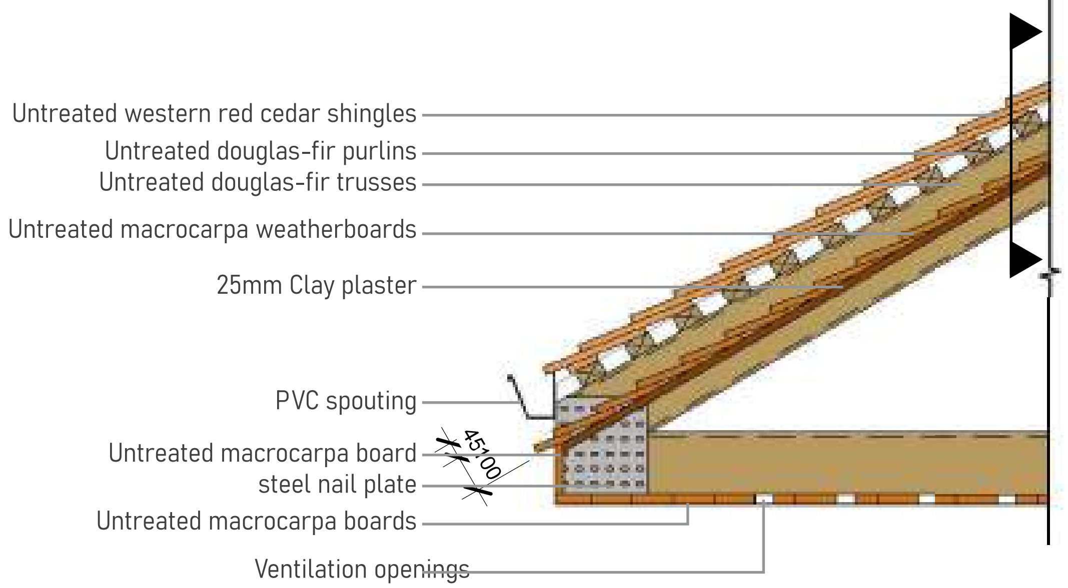


Key

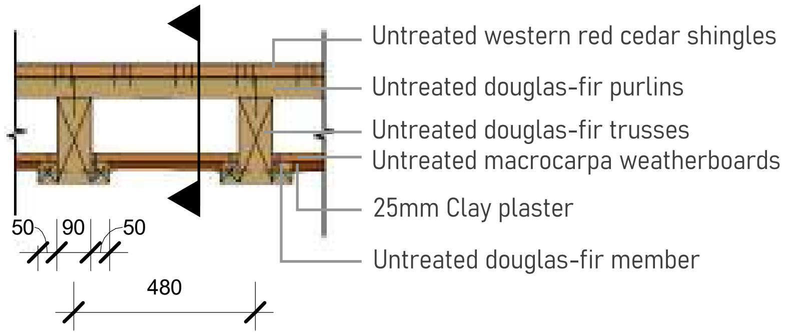
- Treated pinus radiata
- Fibreglass batt insulation

Final Design

Eave Detail 1:20



Rafter Detail 1:20



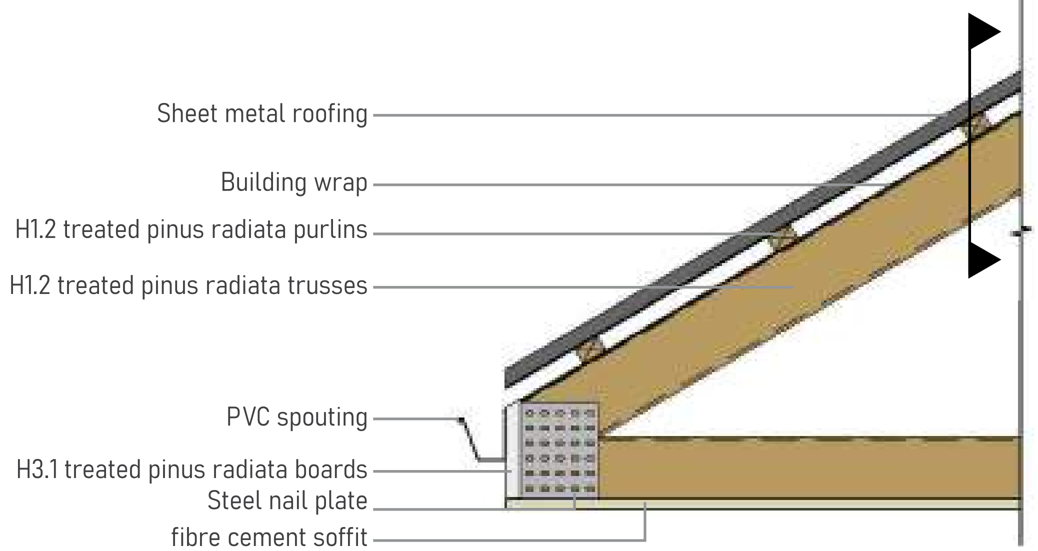
It has been noted that it is difficult to achieve weathertightness for a roof without an inorganic membrane. Given that the roof is also the primary means of deflecting water away from the building it is thoroughly considered here regarding its construction. This roof construction seeks to achieve weathertightness without the use of non-reusable and inorganic materials.

Waterproof membranes operate as the second line of defence against water as good weathertightness design assumes water will find a way through the first layer, which in this case is cedar shingles. A double layer of cedar shingles is proposed with a ventilated drainage cavity in between. Clay-plaster is present on the underside of the lower layer of cedar shingles because its incredible hygroscopic nature would absorb and hold the water that makes it past the lower layer of shingles only to release slowly into the air later. This offers three lines of defence against water infiltration. This strategy would also aid in drying out the cedar in the lower layer. The clay-plaster would not be exposed to direct rain but at worst a steady supply of moisture within its absorption capability, so the risk of erosion is eliminated. This approach relies on a very well-ventilated roof space to carry all the moisture out of the roof space.

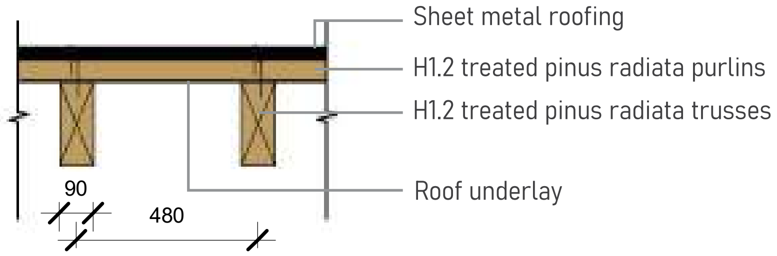
Regarding the structure of the roof, structural members could not be accurately sized as roof trusses are normally designed by the truss manufacturer. Therefore, members were sized conservatively. Each rafter must span 4.435m. The smallest spacing of 480mm was chosen to be conservative. According to the rafter table (table 10.1) in NZS3604:2011 190x90 SG8 rafters can span a maximum of 4.7m (Standards New Zealand, 2011). the rafters are required to be fixed to the top plate by 2 / 90 x 3.15 skew nails + 2 Wire dogs to resist uplift (Standards New Zealand, 2011). According to the purlin table in NZS304:2011 (table 10.10) 70x45 purlins are suitable in any wind zone with a span no more than 900mm (the required span is 450mm) (Standards New Zealand, 2011). The heaviest duty fixing required for an extra high win zone is 1/14g self-driving type 17 screw, 100mm long (Standards New Zealand, 2011). This fixing is used to be conservative.

Final Design with Conventional New Zealand Materials

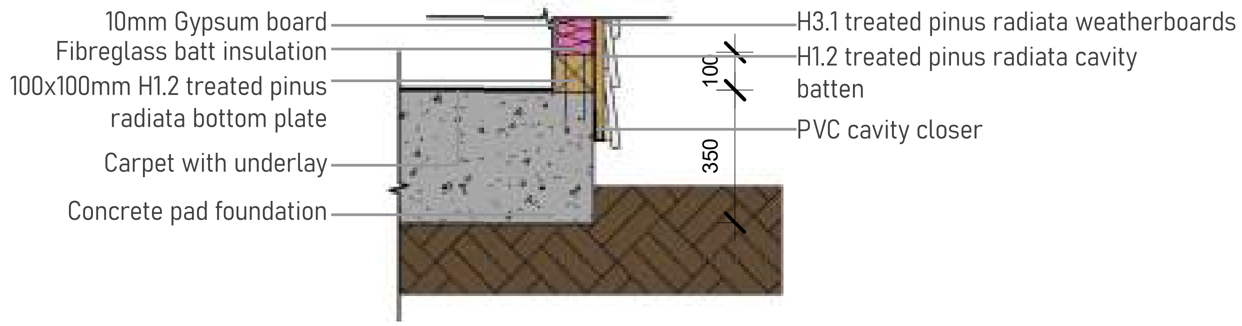
Eave Detail 1:20



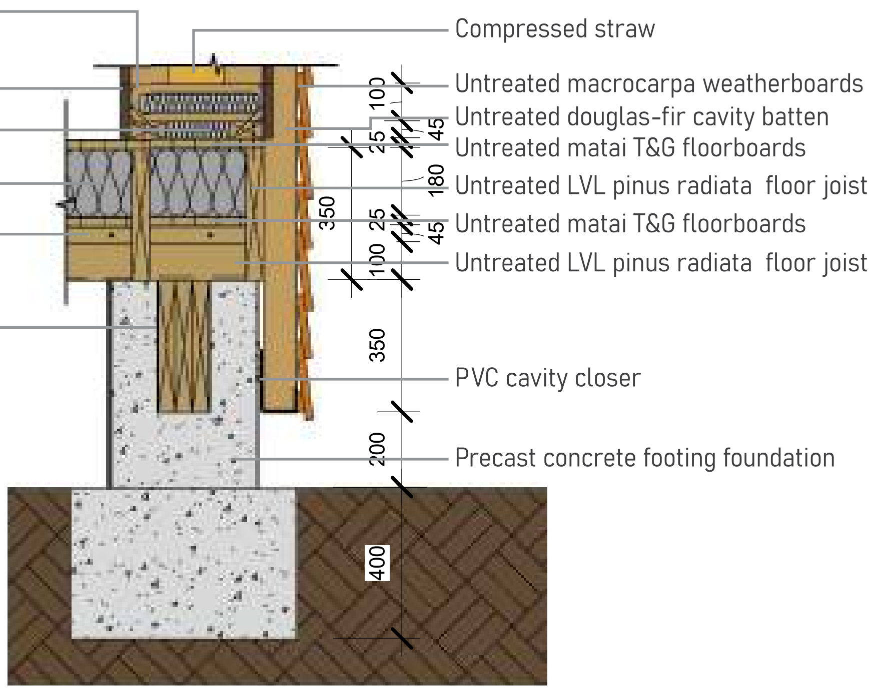
Rafter Detail 1:20



Foundation Detail 1:20



Foundation Detail 1:20



Due to the scale of the building, sizing the floor joists and bearers falls outside the scope of NZS 3604:2011. In addition, the weight of the building and the spans of the floor joists likely exceed the structural capacity of Douglas-fir timber. In place of steel bearers and floor joists, Douglas-fir LVL can be used. The glue in the LVL prolongs the biodegradation process as previously discussed, but not to the same time frame as a steel member. It is therefore a preferable selection. In addition, because the bearers and floor joists could not be sized accurately the members are sized conservatively. Floor joists are 350x45, spaced at 450mm centres. Bearers are 350x135, spanning 1.5m and spaced at 1.2m.

7.4 Biodegradable and Reusable Definitions

In order to obtain an accurate understanding of the waste generated by both designs the definition of a biodegradable or reusable component has to be clear.

Every material will eventually biodegrade; therefore, it is not whether or not a material will biodegradable but how long it will take to do so that needs to be understood. Sassi (2008) believes the European Norm (EN) 13432 standard for composting of packaging can be useful in forming a definition for the building materials (Sassi, 2008). The EN 13432 standard uses the criteria of the rate and efficiency of the biodegrading process and the quality of the resulting compost to determine biodegradability (Sassi, 2008). Regarding rate and efficiency, a material in a watery medium must convert at least 90% of the organic material into carbon dioxide within six months. Research testing of building materials against this criterion has been carried out by the Building Research Establishment and given suitable preparation for composting (e.g. shredding), untreated timber showed adequate results within six months and therefore achieved the criterion (Hobbs et al., 2005). Regarding compost quality, the standard also stipulates that the resulting compost should not present a hazard to humans or plants (Sassi, 2008).

LVL is not biodegradable under these criteria as Love specifies that New Zealand LVL takes 23 years for 50% of its content decompose (Love, 2010).

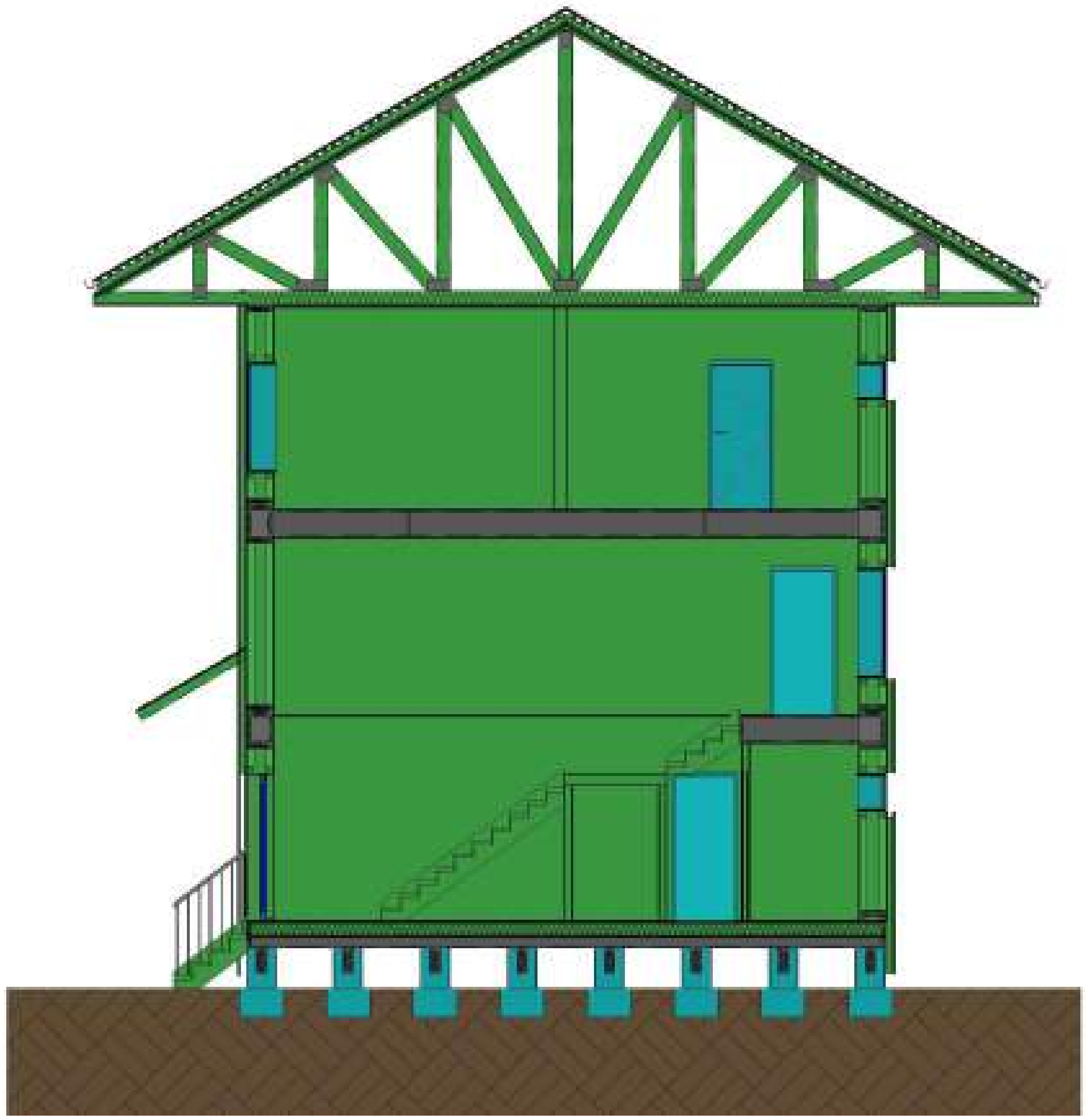
A material is defined as reusable in this thesis if there is certainty of an identical application in another project and the material has sufficient integrity to perform in that new application without the need for alterations or repairs. Therefore, only interior elements were deemed reusable because one can be more certain of their integrity due to the absence of exposure to weather. Building elements such as doors, windows, batt insulation and screw fixings and floorboards were deemed reusable components. The precast concrete footings were also deemed reusable due to the material's durability despite its external application.

Figure 75

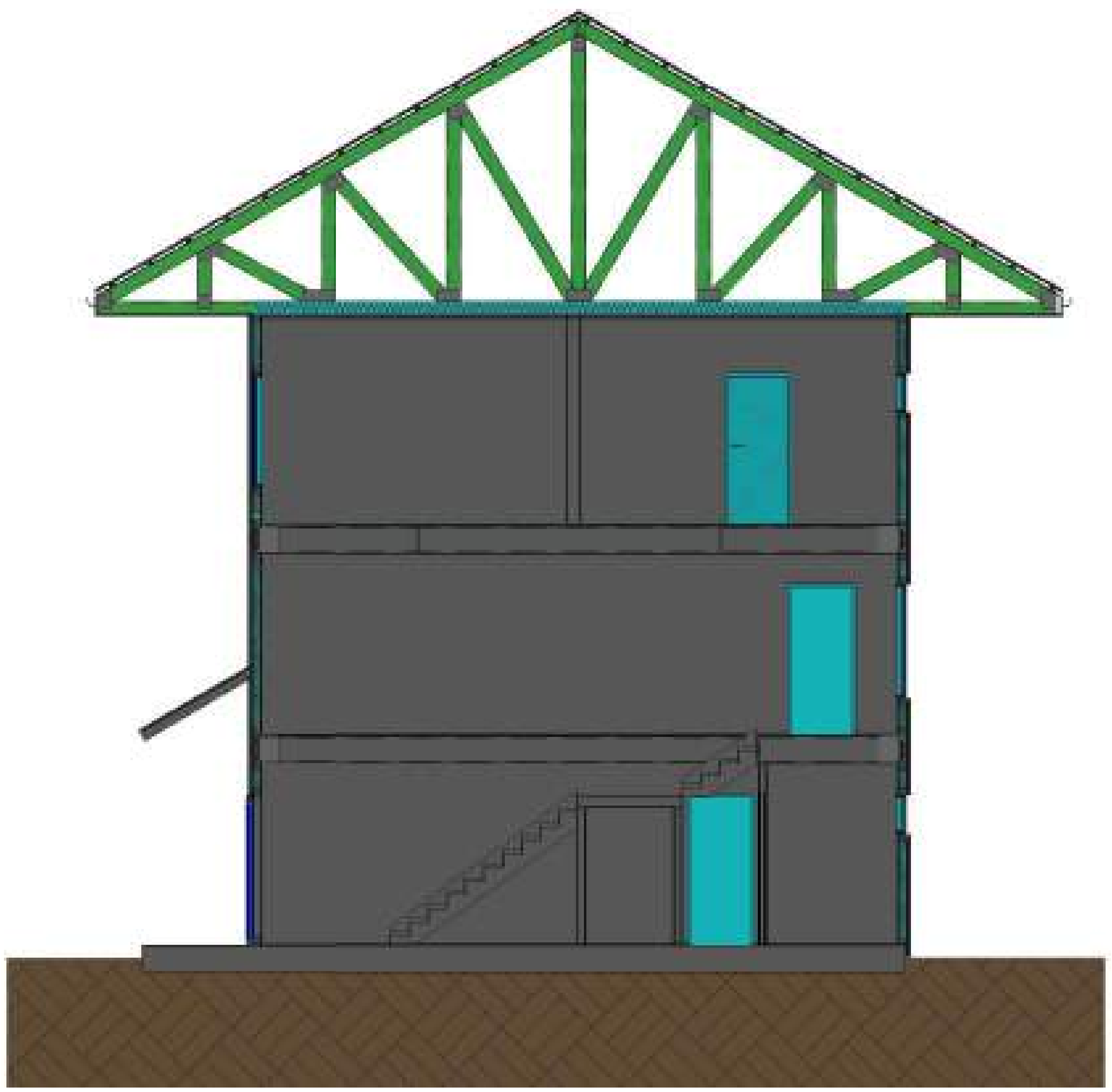
Reprinted from "The re-use atlas : a designer's guide towards the circular economy" by D. Baker-Brown, 2017, RIBA Publishing, p. 13. Copyright 2009 by Duncan Baker-Brown.

7.3 End of Life Analysis

Final Design



Final Design with Conventional New Zealand Materials



Final Design

Biodegradable + Reusable | Biodegradable | Reusable | Waste

Component	Material	Volume (m³)
Flooring Ground Floor	Untreated Matai T&G floor boards	5.530
Flooring First Floor	Untreated Matai T&G floor boards	2.508
Flooring Second Floor	Untreated Matai T&G floor boards	2.546
Ceiling Lining	Untreated Matai T&G boards	2.378
Doors interior 810mm single	Solid wood Untreated Kauri Door	2.085
Doors Cavity Slider	Solid wood Untreated Kauri Door	0.281
Doors Double Sliding Door	Solid wood Untreated Kauri Door	1.687
140mm Interior Wall Lining	Untreated Matia T&G boards	4.5745
230mm Interior Wall Lining	Untreated Matia T&G boards	6.93875
Soffit	Untreated macrocarpa boards	3.292
Full Height Studs	Untreated douglas-fir heartwood	10.56
Sills and Lintels	Untreated douglas-fir heartwood	1.38
Braces	Untreated douglas-fir heartwood	0.45
Bottom Runs	Untreated douglas-fir heartwood	1.176
Partial Height Studs	Untreated douglas-fir heartwood	3.087
Wall Insulation	Compressed straw	69.972
Box Beam Insulation	Pure wool batt insulation	3.798
Wall Base Insulation	Pure wool batt insulation	0.968
Exterior Wall Interior Lining	Clay plaster	7.655
External Wall Vapour/Air control layer	Clay plaster	7.086
Cavity Battens	Untreated macrocarpa heartwood	5.698
Wall Cladding	Untreated macrocarpa weatherboards	9.354
Underfloor Insulation	Pure wool batt insulation	17.416
Ceiling Insulation	Pure wool blown-in insulation	19.910
Balcony Walls	Untreated macrocarpa boards	1.61
Interior Walls (Framing+Lining)	Untreated douglas-fir heartwood framing + Untreated Matia T&G Boards	37.815
Exterior Posts Big	Untreated macrocarpa heartwood	0.695
Exterior Posts Small Long	Untreated macrocarpa heartwood	3.152
Exterior Posts Small Short	Untreated macrocarpa heartwood	2.126
Roof Trusses	Untreated douglas-fir heartwood	36.72
Roof Purlins	Untreated douglas-fir heartwood	6.435
Decking (ground and balconies)	Untreated macrocarpa boards	3.52
Awning Roofing	Untreated western red cedar shingles	0.161
Awning Framing	Untreated douglas-fir heartwood	0.11
Roofing	Untreated western red cedar shingles	9.286
Roof Underlay	Clay plaster	5.694

Table continued on page 164

Final Design with Conventional New Zealand Materials

Biodegradable + Reusable | Biodegradable | Reusable | Waste

Component	Material	Volume (m³)
Mechanical Fixings For Roofing	Steel	0.446
Mechanical Fixings For Purlins	Steel	0.446
Mechanical Fixings For Rafters	Steel	0.036
Mechanical Fixings For Ceiling	Steel	1.125
Mechanical Fixings For Cavity Battens	Steel	0.117
Mechanical Fixings For Cladding	Steel	2.347
Mechanical Fixings For Wall to Floor	Steel	0.095
Mechanical Fixings For Flooring	Steel	2.363
Mechanical Fixings For Floor Framing	Steel	0.078
Plywood Flooring First Floor	Plywood	2.508
Plywood Flooring Second Floor	Plywood	2.571
Balcony Decking	H3.2 treated pinus radiata	2.816
Doors interior 810mm single	Hollow core radiata pine door	2.085
Doors Cavity Slider	Hollow core radiata pine door	0.281
Doors double sliding door	Hollow core radiata pine door	1.687
Wall Insulation	Fibreglass Insulation (BRANZ, 2020a, Brunsdon & Magan, 2017)	18.268
Ceiling Insulation	Fibreglass Insulation (BRANZ, 2020a, Brunsdon & Magan, 2017)	19.910
Balcony Walls	H3.2 treated pinus radiata	1.61
Windows Type 1	Aluminium framed window (Burgess, 2011)	1.238
Windows Type 2	Aluminium framed window (Burgess, 2011)	0.075
Windows Type 3	Aluminium framed window (Burgess, 2011)	0.075
Windows Type 4	Aluminium framed window (Burgess, 2011)	0.075
Window Type 5	Aluminium framed window (Burgess, 2011)	0.113
Door Exterior entrance	Aluminium framed door	0.48
Double door exterior	Aluminium framed door	3
Spouting	PVC	0.621
Down Pipes	PVC	0.017
Carpet Ground Floor	Nylon and polyester	1.033
Carpet First Floor	Nylon and polyester	0.906
Carpet Second Floor	Nylon and polyester	0.945
Awning Roofing	Sheet metal (Brunsdon & Magan, 2017)	0.161
Ceiling Lining	Gypsum board	0.951
Soffit	Fibre Cement	3.292
Full Height Studs	H1.2 treated pinus radiata (Brunsdon & Magan, 2017)	4.576
Sills and Lintels	H1.2 treated pinus radiata (Brunsdon & Magan, 2017)	0.69
Partial Height Studs	H1.2 treated pinus radiata (Brunsdon & Magan, 2017)	1.548

Table continued on page 165

Final Design

Roof Weatherboards	Untreated macrocarpa weatherboards	6.825
Foundations	Concrete	18.656
Windows Type 1	Glass with untreated macrocarpa framing	1.238
Windows Type 2	Glass with untreated macrocarpa framing	0.075
Windows Type 3	Glass with untreated macrocarpa framing	0.075
Windows Type 4	Glass with untreated macrocarpa framing	0.075
Window Type 5	Glass with untreated macrocarpa framing	0.113
Door Exterior entrance	Glazed with untreated macrocarpa framing	0.48
Double door exterior	Glazed with untreated macrocarpa framing	3
Spouting	PVC	0.621
Down Pipes	PVC	0.017
Mechanical Fixings For Roofing	Steel	1.782
Mechanical Fixings For Purlins	Steel	1.782
Mechanical Fixings For Rafters	Steel	0.036
Mechanical Fixings For Ceiling	Steel	1.125
Mechanical Fixings For Cavity Battens	Steel	0.117
Mechanical Fixings For Cladding	Steel	2.347
Mechanical Fixings For Wall to Wall Connections	Steel	0.216
Mechanical Fixings For Wall to Floor	Steel	0.095
Mechanical Fixings For Flooring	Steel	2.363
Mechanical Fixings For Floor Framing	Steel	0.078
Steel Nail Plates For Trusses	Steel	0.047
Floor Framing Ground	Untreated LVL pinus radiata	5.862
Floor Framing First	Untreated LVL pinus radiata	4.205
Floor Framing Second	Untreated LVL pinus radiata	4.614
Bearers	Untreated LVL pinus radiata	4.668
Deck Framing	Untreated LVL pinus radiata	1.914
Cavity Closer	uPVC	0.320
Top and Bottom Box Beams	Untreated LVL pinus radiata	5.808
Panel Sides	Untreated LVL pinus radiata	4.386
DPC	Polyethylene	0.010
Metal Flashings	Aluminium	0.059
Window Opening Tapes	SBS-modified bitumen	0.067
Door Opening Tapes	SBS-modified bitumen	0.025
Sealants	Silicone	0.013

End of life characteristics	Volume
Biodegradable + Reusable	33m³
Biodegradable	276m³
Reusable	34m³
Waste	32m³
Total	375m³

Note: Balustrade and stairs volumes were excluded from the calculations as accurate volumes are not produced by Revit for these components.

Total Volume: 375.27m³

Final Design with Conventional New Zealand Materials

Top And Bottom Plates X Direction	H1.2 treated pinus radiata (Brunsdon & Magan, 2017)	1.428
Top And Bottom Plates Y Direction	H1.2 treated pinus radiata (Brunsdon & Magan, 2017)	1.044
Exterior Wall Interior Lining	Gypsum board	3.062
Building Wrap	Polypropylene	1.13
Cavity Battens	H3.1 treated pinus radiata (Department of Building and Housing, 2006)	0.777
Wall Cladding	H3.1 treated pinus radiata weatherboards (Brunsdon & Magan, 2017)	9.354
140mm Interior Wall Framing	H1.2 treated pinus radiata (Brunsdon & Magan, 2017)	82.341
140mm Interior Wall Lining	Gypsum board	0.9149
230mm Interior Wall Framing	H1.2 treated pinus radiata (Brunsdon & Magan, 2017)	24.9795
230mm Interior Wall Lining	Gypsum board	1.38775
Exterior Posts Big	H3.2 treated pinus radiata	0.695
Exterior Posts Small Long	H3.2 treated pinus radiata	3.152
Exterior Posts Small Short	H3.2 treated pinus radiata	2.126
Roof Trusses	H1.2 treated pinus radiata	36.72
Roof Purlins	H1.2 treated pinus radiata	1.625
Awning Framing	H1.2 treated pinus radiata	0.11
Roofing	Sheet metal (Brunsdon & Magan, 2017)	9.286
Roof Underlay	Synthetic material	1.238
Foundation	Concrete slab (Brunsdon & Magan, 2017)	48.841
Steel Nail Plates For Trusses	Steel	0.047
Floor Framing First	H1.2 treated pinus radiata (Brunsdon & Magan, 2017)	4.205
Floor Framing Second	H1.2 treated pinus radiata (Brunsdon & Magan, 2017)	4.614
Deck Framing	H3.2 treated pinus radiata	1.531
Cavity Closer	uPVC	0.320
DPC	Polyethylene	0.279
Metal Flashings	Aluminuim	0.059
Window Opening Tapes	SBS-modified bitumen	0.067
Door Opening Tapes	SBS-modified bitumen	0.025
Sealants	Silicone	0.013

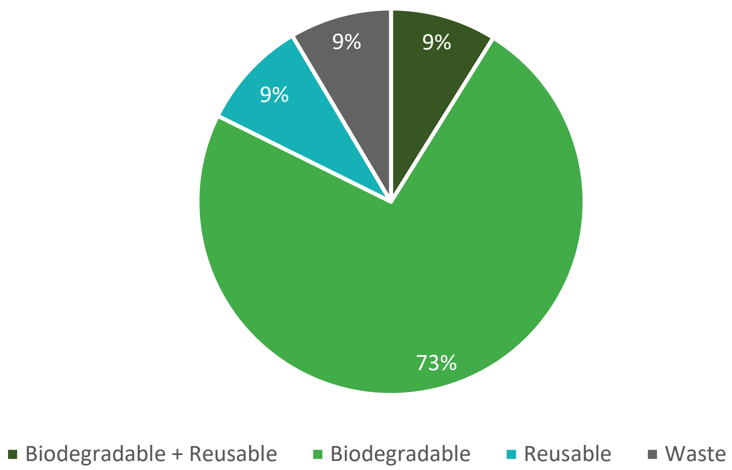
Note: Balustrade and stairs volumes were excluded from the calculations as accurate volumes are not produced by Revit for these components.

Total Volume: 321.85m³

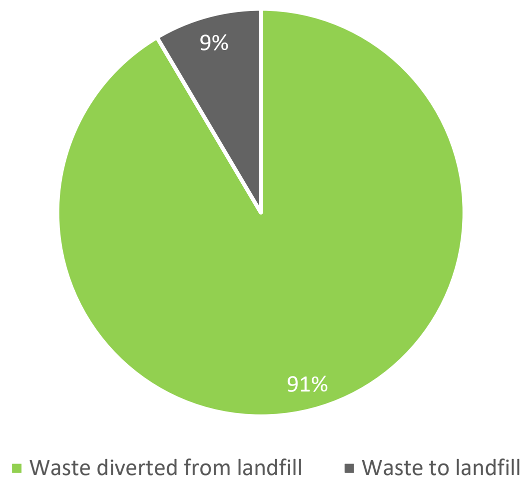
End of life characteristics	Volume
Biodegradable + Reusable	0m³
Biodegradable	0m³
Reusable	64m³
Waste	258m³
Total	322m³

Final Design

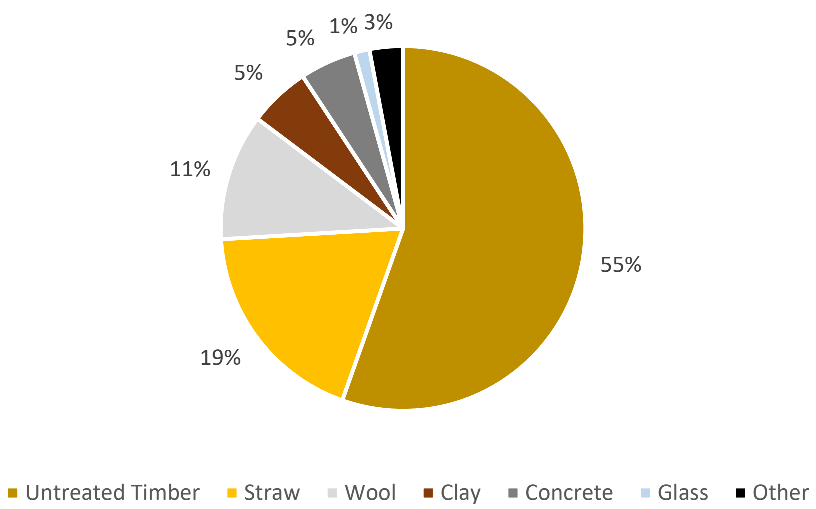
End Of Life Summary



Waste Summary

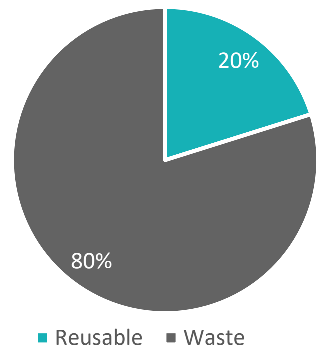


Material Breakdown

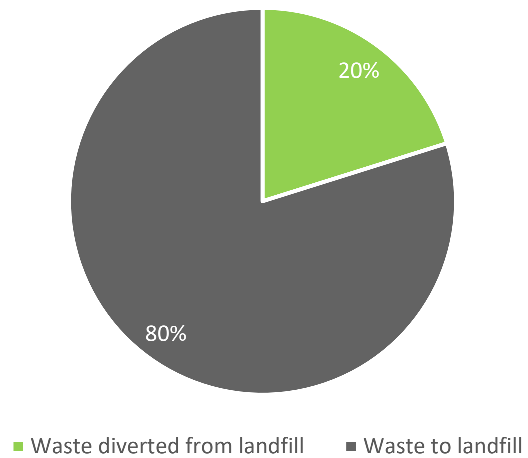


Final Design with Conventional New Zealand Materials

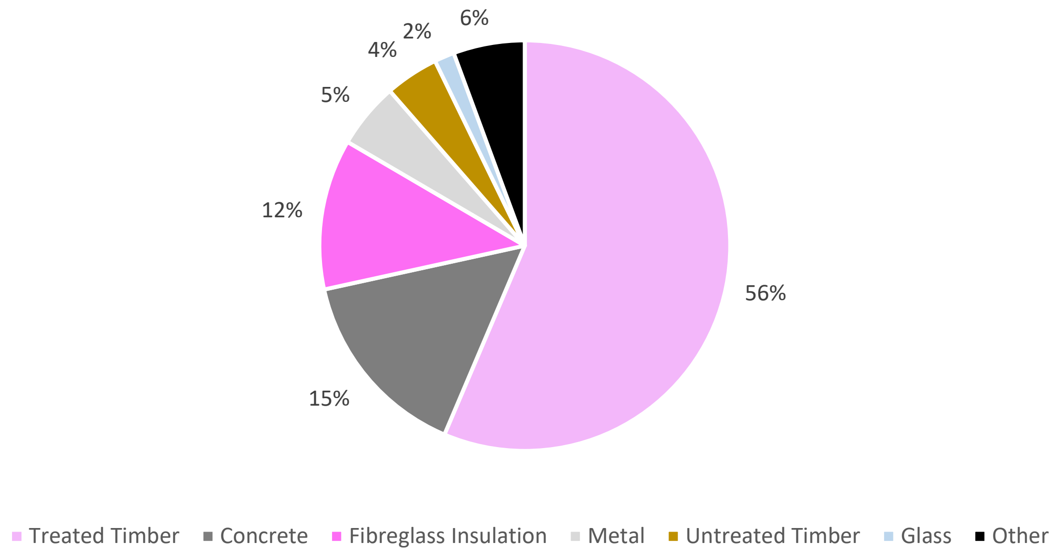
End Of Life Summary

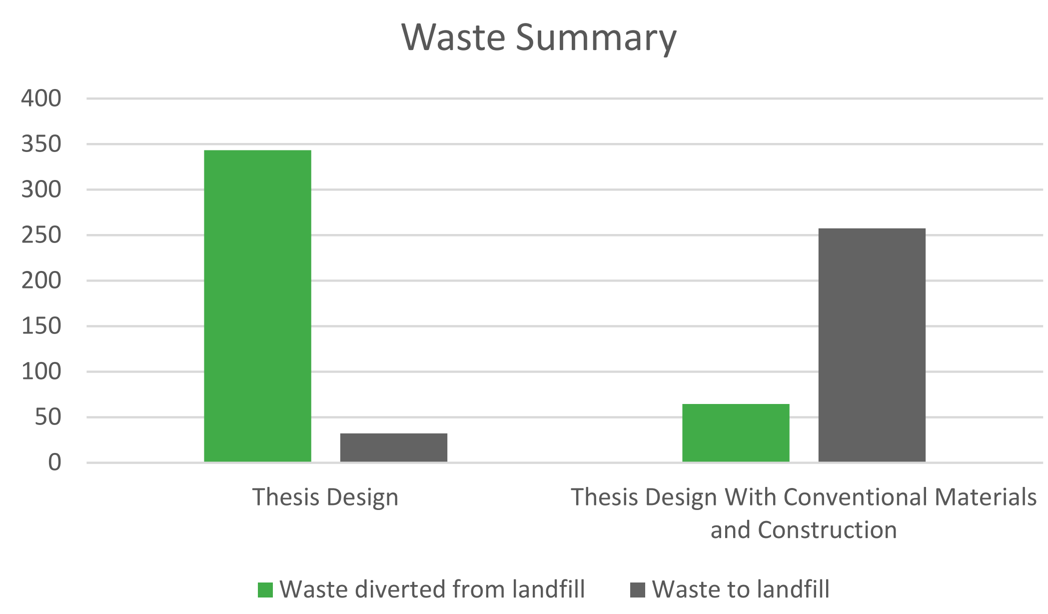


Waste Summary



Material Breakdown





Thesis Design

Thesis Objective	Assessment Criteria	Score
1. Zero Waste	Percentage of waste diverted from land fill by volume	91%
2. Maximise Biodegradable Materials	Percentage of biodegradable materials by volume	82%

Thesis Design with Conventional New Zealand Materials

Thesis Objective	Assessment Criteria	Score
1. Zero Waste	Percentage of waste diverted from land fill by volume	20%
2. Maximise Biodegradable Materials	Percentage of biodegradable materials by volume	0%

7.5 Discussion

The primary objective of this thesis was to produce zero waste at the end of life of the building. However, 100% waste diversion was not achieved. The components that were neither biodegradable nor reusable that produced waste for this project include non-reusable mechanical fixings, engineered LVL timber (which was structurally required in places due to the scale of the building), cavity closers, DPC and flashings, tapes and sealant around windows and doors. In modern construction, these components cannot be done without and no suitable biodegradable or reusable substitutes exist.

However, although zero waste was not achieved a considerable proportion of waste was diverted from landfill of 91%. This an improvement of 71% over the same design using conventional New Zealand materials and construction. This research reveals that as the scale of a building increases so does the demand for stronger more durable materials like concrete and steel which are not biodegradable or reusable (steel is often recycled but no reused). Therefore, these waste reduction findings are only applicable to developments of a similar scale. Indeed, even greater waste reduction would be possible with a smaller dwelling where the use of engineered timber was not necessary.

It is important to note that while all building components categorised as waste in this thesis will end up in a landfill there is still a distinction between inert waste materials and waste materials that will continue to damage the environment in a landfill. Mineral materials such as concrete are inert and do no further damage to the environment once they are produced. Whereas materials such as chemical treated timber can damage the environment while in a landfill.

The secondary objective of this thesis was to maximise the use of biodegradable materials. The final design was comprised of 82% biodegradable materials. This is in stark contrast to the 0% present in the design using conventional New Zealand construction techniques. The final design was comprised of 55% untreated timber, 19% straw and 11% wool. Whereas, the conventional New Zealand construction design was comprised of 56% treated timber, 15% concrete and 12% fibreglass insulation. Only 4% of the conventional design was untreated timber. This highlights the degree to which the chemical treatment of timber is a barrier to waste reduction. These findings also display the opportunity to dramatically increase the proportion of biodegradable material in a dwelling by substituting inorganic insulation with an organic alternative. In addition, this research highlights the amount of waste caused by a concrete pad foundation which is now the most common foundation type in New Zealand (Brunsdon & Magan, 2017).

7.8 Techsphere Barriers

The percentage of waste diverted from landfill of 91% for the final design remains only theoretical potential without the required deconstruction and separation to allow for the organic cycle and technical cycle to occur. This is the area of the construction industry that needs altering for any progress on waste reduction to be made. The main barrier to a circular economy is the building industry's inability to facilitate deconstruction both in design and practice.

Regarding the design, specialist, non-removable and adhesive fixings contribute to the monolithic permanence of buildings. These fixings can be found in most houses, especially new homes as they are demanded by our highly regulated building industry (Finch et al., 2017). These fixings methods inevitably cause serious damage on removal as their ability to adhere and not be removed provides their durability. This often means that a high proportion of reclaimed material or sufficient integrity of the material cannot be ensured for reuse (Sassi, 2008). In addition, the accessibility of building components and fixings is often not considered during the design process (Sassi, 2008). Our buildings are not designed for ease of deconstruction, in fact the opposite seems true.

Regarding the practice of deconstruction, the construction industry is driven by economic efficiency and in this regard, demolition is superior to deconstruction (Coelho, 2013). This is because of the additional processes that deconstruction requires. Deconstruction requires the demounting, storing, testing, certifying and resupplying of building components (Gorgolewski, 2008). Until the construction industry is mature enough to adopt this approach zero waste will be unobtainable as deconstruction is also required for the separation of any biodegradable materials.

In addition to deconstruction, the lack of standard measures for building components means that opportunities for reuse are specialised (Minunno et al., 2018). Reuse is therefore witnessed as a niche activity and not on a mass scale.

Conclusion

This thesis had the objectives of achieving zero waste at the end of the design's life, maximising the use of biodegradable building materials, and finding the optimum biodegradable construction approach for New Zealand. It was hypothesised along with Sassi (2006) that an entirely zero-waste construction could be achieved through a combination of both biodegradable and reusable building components. The project investigated how a MDH house scale design could best be built predominantly out of biodegradable building materials.

It was found that an entirely zero-waste construction could not be achieved as not every necessary building component could be substituted for a biodegradable or reusable alternative. This confutes Sassi's hypothesis that zero waste could be achieved through a combination of biodegradable reusable components (P Sassi, 2006). Engineered timber of LVL which has a significant proportion of inorganic glue was required by structural necessity and moisture managing devices in external openings such as flashings tapes and sealants could not be done without. However, a significant proportion of waste of 91% by volume could be diverted from landfill compared to the 20% of waste by volume that could potentially be diverted from landfill for the design with a New Zealand conventional construction. This suggests that Auckland Council's goal of 60% waste reduction by 2030 is at least theoretically possible in the residential sector but the goal of 'zero waste' by 2040 is unrealistic and perhaps unobtainable.

In addition, a proportion of biodegradable materials of 82% by volume was achieved for the final design in contrast to the 0% present in a conventional New Zealand construction.

The optimum biodegradable construction approach for New Zealand made use of materials that were deemed most suitable for New Zealand based on their availability and performance in New Zealand's climate and seismic context. These materials were untreated western red cedar for roofing, untreated Douglas fir heartwood for structural framing, straw bale and pure wool for insulation, clay or lime-based plasters as well as untreated macrocarpa, redwood or red beech cladding for cladding, untreated matai, macrocarpa or red beech for flooring. Reusable foundations were the most suitable to provide sufficient durability such as precast footing, piles or strip foundations as well as screw piles. The optimum construction approach for the external walls of the building using straw and wool insulation that are susceptible to moisture was prefabricated wall panels. This is because of the benefits of reduced construction waste, the dry interior environment and the potential for improved construction accuracy and quality assurance. The success of existing prefabricated straw wall panels from Ecococon and Modcell also demonstrates the ability of this construction technique to increase the uptake of biodegradable insulation materials in the modern construction industry. A new prefabricated wall panel was proposed informed by literature and the existing prefabricated straw wall panel precedents of Ecococon and Modcell that includes pure wool batt insulation in the panel's timber hollow box beams used as top and bottom plates.

The form of the building design was primarily driven by the needs of the biodegradable materials which is principally the need to keep the straw and wool insulation free from moisture. The design, therefore, had large eave overhangs of 2m and balconies of the upper storeys to protect the walls from rain. The design also had minimal external junctions (2.6 exterior junctions/dwelling) in order to minimise potential areas of construction failure where moisture infiltration could occur. The design had a dwelling density of 294 bedrooms/hectare.

The building design was then integrated on site to architecturally test the building design. A site was also integrated to demonstrate the potential of the biodegradable material construction for application in an urban setting at the MDH scale. The final design was sited in Upper Hutt Wellington, but the construction approaches from the design can be applied to any site and architectural typologies of a similar scale.

Most of the New Zealand population would be unaware of the potential to build their future dwellings from biodegradable building materials and the numerous environmental benefits that flow from doing so. This project increases awareness of the opportunity that exists to utilise the abundance of the biodegradable materials of timber, straw, wool and clay in New Zealand to mitigate the issue of construction and demolition waste in our country.

Limitations

While the proportion of biodegradable materials that one builds with in New Zealand can be significantly increased it will come at a significantly increased cost which will likely be the single largest barrier preventing the uptake of biodegradable materials and by extension waste reduction.

It is also important to note that while the final design produces less waste it is also less resource-efficient. The final design uses more material for the same floor area as the conventional design due to its thicker walls. Resource conservation, despite whether or not the material is renewable, is an important sustainability consideration.

Finally, even though the biodegradable cladding and roofing materials used in the design for this thesis meet the durability requirements of the NZBC they will require more maintenance than conventional alternatives.

Further Research

Further research into the hygrothermal performance and the constructability of the proposed straw and wool prefabricated wall panel is necessary. Hygrothermal simulation of the panel in a program such as Wufi would provide greater confidence in the panel's performance in New Zealand's climate than the simple hand thermal and vapour resistance calculations performed in this thesis. In addition, 1:1 scale built prototypes of the panels would allow a more thorough analysis of the panel's construction and connections.

In addition, only waste and closed loop categories were calculated for this project, but if more time was available a life-cycle assessment as well as an analysis of embodied energy and emitted CO_2 of the final design would further this research.

Finally, this research has revealed that despite the unavailability of cork, mycelium, bamboo, wood fibre insulation and cellulose insulation in New Zealand, they are materials that would perform well in our climate and seismic context. There is an opportunity for these biodegradable building materials to be produced in New Zealand in the future and therefore research into how to integrate these materials into a construction suitable to New Zealand would be beneficial.

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Appendices

Thesis Design Volume Calculations

		Area						
Component	**Number**	**Width**	**Height**	**Depth**	**Volume (m3)**		**Material Type**	**Notes**
Flooring Ground Floor	2	110.609		0.025	5.530		Untreated Timber	
Flooring First Floor	1	100.312		0.025	2.508		Untreated Timber	
Flooring Second Floor	1	101.853		0.025	2.546		Untreated Timber	
Ceiling Lining	3	11.72	8.115	0.025	7.133		Untreated Timber	
Doors interior 810mm single	13	0.81	1.98	0.1	2.085		Untreated Timber	
Doors Cavity Slider	2	0.71	1.98	0.1	0.281		Untreated Timber	
Doors double sliding door	6	1.42	1.98	0.1	1.687		Untreated Timber	
140mm Interior Wall Lining	2	91.49		0.025	4.575		Untreated Timber	
230mm Interior Wall Lining	2	138.775		0.025	6.939		Untreated Timber	
Soffit	1	3.292			3.292		Untreated Timber	
Full Height Studs	240	0.044			10.56		Untreated Timber	
Sills and Lintels	92	0.015			1.38		Untreated Timber	
Braces	30	0.015			0.45		Untreated Timber	
Bottom Runs	24	0.049			1.176		Untreated Timber	
Partial Height Studs	343	0.009			3.087		Untreated Timber	
Wall Insulation					69.972		Straw	
Box Beam Insulation	6	0.3	0.05	42.2	3.798		Wool	
Wall Base Insulation	3	0.045	0.17	42.2	0.968		Wool	
Exterior Wall Interior Lining	1	306.2		0.025	7.655		Clay	
External Wall Vapour/Air control layer					7.086		Clay	
Cavity Battens	259	0.022			5.698		Untreated Timber	
Wall Cladding	1	311.8		0.03	9.354		Untreated Timber	
Underfloor Insulation					17.416		Wool	
Ceiling Insulation	1	12.47	8.87	0.18	19.910		Wool	
Balcony Walls	10	0.161			1.61		Untreated Timber	
230mm Interior Wall Framing	0.35	138.775		0.18	8.743		Untreated Timber	Assumed timber framing is approxiamtely 35% of the wall area
140mm Interior Wall Framing	0.35	91.49		0.9	28.819		Untreated Timber	Assumed timber framing is approxiamtely 35% of the wall area
Exterior Posts Big	4	0.14	0.14	8.86	0.695		Untreated Timber	
Exterior Posts Small Long	52	0.14	0.05	8.66	3.152		Untreated Timber	
Exterior Posts Small Short	52	0.14	0.05	5.84	2.126		Untreated Timber	
Roof Trusses	40	0.918			36.72		Untreated Timber	
Roof Purlins	99	0.065			6.435		Untreated Timber	
Decking (ground and balconies)	5	28.16		0.025	3.52		Untreated Timber	
Awning Roofing	1				0.161		Untreated Timber	
Awning Framing	10	0.011			0.11		Untreated Timber	
Roofing	1	9.286			9.286		Untreated Timber	

Table continued on page 178

		Area					Material Type	
Component	**Number**	**Width**	**Height**	**Depth**	**Volume (m3)**		**T/S/W/CL/GL/CN/O**	**Notes**
Roof Underlay	39	0.146			5.694		Clay	
Roof Weatherboards	39	0.175			6.825		Untreated Timber	
Foundations	88	0.212			18.656		Concrete	
Windows Type 1	11	1.5	1.5	0.05	1.238		Glass	
Windows Type 2	1	1	1.5	0.05	0.075		Glass	
Windows Type 3	1	1.5	1	0.05	0.075		Glass	
Windows Type 4	2	1.5	0.5	0.05	0.075		Glass	
Window Type 5	1	1.5	1.5	0.05	0.113		Glass	
Door Exterior entrance	2	1.2	2	0.1	0.48		Glass	
Double door exterior	10	1.5	2	0.1	3		Glass	
Spouting	2	20.7	0.15	0.1	0.621		Other	
Down Pipes	2	9.22	0.001		0.017		Other	
Mechanical Fixings For Roofing	3960	0.00045			1.782		Other	1 per purlin (fixing assume 0.015x0.015x0.2)
Mechanical Fixings For Purlins	3960	0.00045			1.782		Other	Fixing into each truss
Mechanical Fixings For Rafters	80	0.00045			0.036		Other	Trusses fixed to tops of walls
Mechanical Fixings For Ceiling	2500	0.00045			1.125		Other	1 per truss per 140 board
Mechanical Fixings For Cavity Battens	259	0.00045			0.117		Other	4 per cavity batten
Mechanical Fixings For Cladding	5215	0.00045			2.347		Other	1 per weather board per cavity batten
Mechanical Fixings For Wall to Wall Connections	480	0.00045			0.216		Other	5 fixing from inside and out per wall join
Mechanical Fixings For Wall to Floor	210	0.00045			0.095		Other	Every 600mm on each floor
Mechanical Fixings For Flooring	5250	0.00045			2.363		Other	Every joist for every 140 board for every floor
Mechanical Fixings For Floor Framing	174	0.00045			0.078		Other	Every timber connection (average 29 joists per floor)
Steel Nail Plates For Trusses	1280	0.068	0.18	0.003	0.047		Other	1 plate on both sides per timber connection per truss
Floor Framing Ground					5.862		Untreated Timber	
Floor Framing First					4.205		Untreated Timber	
Floor Framing Second					4.614		Untreated Timber	
Bearers	8	0.35	0.135	12.35	4.668		Untreated Timber	
Deck Framing	5	0.383			1.914		Untreated Timber	
Cavity Closer	3	42.68	0.05	0.05	0.320		Other	
Top and Bottom Box Beams	24	0.242			5.808		Untreated Timber	
Panel Sides	86	0.051			4.386		Untreated Timber	
DPC	88	0.135	0.4	0.002	0.010		Other	Between every bearer and concrete footing
Metal Flashings	28	0.01	0.14	1.5	0.059		Other	1 per head of every exterior opening (approximated dimensions as openings vary slightly)
Window Opeing Tapes	64	0.35	0.002	1.5	0.067		Other	4 per window. 1 per corner of opening (dimensions of tape are approximate)
Door Opening Tapes	24	0.35	0.002	1.5	0.025		Other	2 per door. 1 per corner of opening (dimensions of tape are approximate)
Sealants	28	0.01	0.01	4.5	0.013		Other	Around every opening (dimensions of sealant are approximate)
Total (2dp)					375.27			

Thesis Design with Conventional New Zealand Materials Volume Calculations

		Area						
Component	**Number**	**Width**	**Height**	**Depth**	**Volume (m3)**		**Material Type**	**Notes**
Mechanical Fixings For Roofing	990	0.00045			0.4455		Metal	1 per purlin (fixing assume 0.015x0.015x0.2)
Mechanical Fixings For Purlins	990	0.00045			0.4455		Metal	Fixing into each truss
Mechanical Fixings For Rafters	80	0.00045			0.036		Metal	Trusses fixed to tops of walls
Mechanical Fixings For Ceiling	2500	0.00045			1.125		Metal	1 per truss per 140 board
Mechanical Fixings For Cavity Battens	259	0.00045			0.11655		Metal	4 per cavity batten
Mechanical Fixings For Cladding	5215	0.00045			2.34675		Metal	1 per weather board per cavity batten
Mechanical Fixings For Wall to Floor	210	0.00045			0.0945		Metal	Every 600mm on each floor
Mechanical Fixings For Flooring	5250	0.00045			2.3625		Metal	Every joist for every 140 board for every floor
Mechanical Fixings For Floor Framing	174	0.00045			0.0783		Metal	Every timber connection (average 29 joists per floor)
Plywood Flooring First Floor	1	100.312		0.025	2.5078		Untreated Timber	
Plywood Flooring Second Floor	1	102.853		0.025	2.57133		Untreated Timber	
Balcony Decking	4	28.16		0.025	2.816		Untreated Timber	
Doors interior 810mm single	13	0.81	1.98	0.1	2.08494		Untreated Timber	
Doors Cavity Slider	2	0.71	1.98	0.1	0.28116		Untreated Timber	
Doors double sliding door	6	1.42	1.98	0.1	1.68696		Untreated Timber	
Wall Insulation					18.268		Fibre Glass	Total is 30.616 before framing and lining subtraction
Ceiling Insulation	1	12.47	8.87	0.18	19.90960		Fibre Glass	
Balcony Walls	10	0.161			1.61		Untreated Timber	
Windows Type 1	11	1.5	1.5	0.05	1.2375		Glass	
Windows Type 2	1	1	1.5	0.05	0.075		Glass	
Windows Type 3	1	1.5	1	0.05	0.075		Glass	
Windows Type 4	2	1.5	0.5	0.05	0.075		Glass	
Window Type 5	1	1.5	1.5	0.05	0.1125		Glass	
Door Exterior entrance	2	1.2	2	0.1	0.48		Glass	
Double door exterior	10	1.5	2	0.1	3		Glass	
Spouting	2	20.7	0.15	0.1	0.621		Other	
Down Pipes	2	9.22	0.0009		0.01660		Other	
Carpet Ground Floor	1	103.304		0.01	1.03304		Other	Carpet with underlay. Approximated over total interior area but not under walls
Carpet First Floor	1	90.574		0.01	0.90574		Other	Carpet with underlay. Approximated over total interior area but not under walls
Carpet Second Floor	1	94.504		0.01	0.94504		Other	
Awning Roofing	1				0.161		Metal	
Ceiling Lining	3	11.72	8.115	0.01	2.85323		Other	
Soffit	1	3.292			3.292		Other	
Full Height Studs	104	0.044			4.576		Treated Timber	
Sills and Lintels	46	0.015			0.69		Treated Timber	
Partial Height Studs	172	0.009			1.548		Treated Timber	
Top And Bottom Plates X Direction	12	0.119			1.428		Treated Timber	
Top And Bottom Plates Y Direction	12	0.087			1.044		Treated Timber	

Table continued on page 182

		Area						
Component	**Number**	**Width**	**Height**	**Depth**	**Volume (m3)**		**Material Type**	**Notes**
Exterior Wall Interior Lining	1	306.2		0.01	3.062		Other	
External Wall Vapour/Air control layer					1.13		Other	
Cavity Battens	259	0.003			0.777		Treated Timber	
Wall Cladding	1	311.8		0.03	9.354		Treated Timber	
140mm Interior Wall Framing	0.35	91.49		0.9	82.341		Treated Timber	
140mm Interior Wall Lining	2	91.49		0.01	0.9149		Other	
230mm Interior Wall Framing	0.35	138.775		0.18	24.9795		Treated Timber	
230mm Interior Wall Lining	2	138.775		0.01	1.38775		Other	
Exterior Posts Big	4	0.14	0.14	8.86	0.69462		Treated Timber	
Exterior Posts Small Long	52	0.14	0.05	8.66	3.15224		Treated Timber	
Exterior Posts Small Short	52	0.14	0.05	5.84	2.12576		Treated Timber	
Roof Trusses	40	0.918			36.72		Treated Timber	
Roof Purlins	25	0.065			1.625		Treated Timber	
Awning Framing	10	0.011			0.11		Treated Timber	
Roofing	1	9.286			9.286		Metal	
Roof Underlay	1	1.238			1.238		Other	
Concrete Pad	1	48.841			48.841		Concrete	
Steel Nail Plates For Trusses	1280	0.068	0.18	0.003	0.04700		Metal	1 plate on both sides per timber connection per truss
Floor Framing First					4.205		Treated Timber	
Floor Framing Second					4.614		Treated Timber	
Deck Framing	4	0.3827			1.5308		Treated Timber	
Cavity Closer	3	42.68	0.05	0.05	0.3201		Other	
DPC	1	139.545		0.002	0.27909		Other	under concrete slab
Metal Flashings	28	0.01	0.14	1.5	0.0588		Metal	1 per head of every exterior opening (approximated dimensions as openings vary slightly)
Window Opeing Tapes	64	0.35	0.002	1.5	0.0672		Other	4 per window. 1 per corner of opening (dimensions of tape are approximate)
Door Opening Tapes	24	0.35	0.002	1.5	0.0252		Other	2 per door. 1 per corner of opening (dimensions of tape are approximate)
Sealants	28	0.01	0.01	4.5	0.0126		Other	around every opening (dimensions of sealant are approximate)
Total (2dp)					321.85			