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DEVECI, G., MUSAU, F., CLUBB, M., FOSTER, J., VICTORIA, M., STUART, B. and BUCHANAN, S.

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Design Optimisation and Prototyping for Affordable Rural Housing

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Portfolio Abstract

This project was funded through the *Transforming Construction Network Plus* "(N+)" programme. The project was led by Robert Gordon University, in collaboration with the Glasgow School of Art, Sylvan Stuart Ltd, Pasquill Ltd and the Construction Scotland Innovation Centre. Investigators included the following:

- Professor Gokay Deveci (Robert Gordon University – Principal Investigator)
- Filbert Musau (Glasgow School of Art – Co-Investigator)
- Matt Clubb (Robert Gordon University – Research Assistant)
- Janice Foster (Glasgow School of Art – Co-Investigator)
- Dr. Michele Victoria (Robert Gordon University – Co-Investigator)
- Bryan Stuart (Sylvan Stuart Ltd – Co-Investigator)
- Sarah Buchanan (Construction Scotland Innovation Centre – Co-Investigator)

The current shortage of rural area new-build homes calls for innovation and improved productivity. There is a current need for housing construction to catch up and develop in tandem with social, economic, scientific and technological advancements. This project therefore focused on design optimisation and prototyping for digitally integrated production of affordable rural housing. The project offers potential for transformative, faster and scalable production, and greater potential for attracting the digital generation into housing construction than traditional methods. It involved iterations of CAD, energy and environmental simulation, structural and capital/life cycle cost analysis of truss options of whole and milled timber combinations, compared against existing solutions. Two key elements of prototyping - novelty and performance testing - were met by producing, assembling and evaluating the productivity of digital/robotic versus artisan production and assembly of parts, and full-scale truss options. These helped articulate the cost-effective

optimum, meeting requirements for structural strength, breathable construction and low energy. The main impacts of the project are affordability and access to good quality rural housing, reduction of rural fuel poverty, improvement of health and well-being of occupants, contribution to climate change mitigation via circular economy, and waste and CO2 reductions. This research was undertaken as a follow-up to the original Integra House ("Integra House 1") project, aiming to build on the innovations of the earlier project by firstly lowering environmental impact, using hybrid whole/milled timber, and secondly by moving towards industrial manufacturing using faster, digitally integrated production and robotic/artisan methods of construction.

Material in this portfolio is taken from several sources:

1. A draft research report (pages 5-44):
    - DEVECI, G. et al. 2020. *Integra House N+ Project: research report*.
2. A final research report (pages 45-57):
    - DEVECI, G. et al. 2020. *Transforming Construction Network Plus: Final*.
3. A design proposal (pages 58-70):
    - DEVECI, G. 2020. *A design proposal for a whole timber truss*.

Source 1 has been edited, so that the material presented here represents only the completed sections of that draft. Source 2 has been reproduced in its entirety, though the page numbers have been changed in order to merge it into the overall pagination of this portfolio. Similarly, Source 3 has been reproduced in its entirety, but is missing any form of page numbers as these were not present on the original.

Source 1: Integra House N+ Project: Research Report

1. Introduction

Average house prices in the UK are less affordable for rural dwellers in comparison with urban living, in the context of average earnings. Fuel poverty, a related challenge, is also higher in rural areas than urban areas. Energy inefficiency of rural dwellings is a driver for fuel poverty, and fuel poverty is recognised as a form of social inequality and injustice. Yet most current innovation in the quality of housing is focussed on urban housing. To address these challenges, a previous research project – entitled “Integra House 1” (Figures 1-4) – created a prototype of affordable low-energy housing. It utilised an innovative floor-cum-wall-cum-roof truss model using one of the UK’s most prevalent and traditional materials – milled timber. The innovation delivers a rethinking of the truss, one of the most traditional structural systems, creating an integrated structural and construction system for a cost-effective and thermally efficient envelope. It simplifies construction by reducing operations, construction time and waste. The result is a healthy, low cost, low impact dwelling with an aesthetic that blends well with rural settings.

Figure 1. Integra House 1 (exterior).

Figure 2. Integra House 1 (exterior – alternative view).

Figure 3. Integra House 1 (interior).

Figure 4. Integra House 1 (interior - alternative view).

Beyond the challenges addressed through Integra House 1, two other challenges need urgent attention: low productivity in the construction industry and shortages in construction labour, particularly the challenge of attracting young labour into the construction industry. The aim of this project is to build upon the innovations of Integra House 1 by:

- Lowering the environmental impact (using hybrid whole/milled timber), and;
- Moving towards industrial manufacturing using faster, digitally integrated production and robotic-cum-artisan methods of construction.

The project objectives are as follows:

1. Optimise the design of the floor-cum-wall-cum-roof truss and a slice of Integra House 1 in the context of lower energy, lower CO2, indoor environment, fabric longevity, and automated versus manual production and assembly;
2. Explore the use of mixed milled/whole timber, automation and robotic-cum-artisan techniques to reduce economic and environmental costs further;
3. Evaluate environmental and energy performance of options of components and assemblies;
4. Report and disseminate findings.

This project was funded by Transforming Construction Network Plus and, in the context of their aims, the approach for Integra House 2 focusses on a current need for housing construction to catch up and develop in tandem with social, economic, scientific and technological advancements. Digitally integrated fabrication offers potential for transformative, faster and scalable production and there is little precedent of robotics being applied to whole timber housing construction. The design optimisation will involve iterations of CAD design, energy/environmental simulation, structural and capital/LC costs analysis of truss options, whole/milled timber combinations, and dwelling forms – compared with existing solutions. These will apply the latest software packages to provide digital design information that is easily transferable to automated production. Use of timber for new UK housing is highly encouraged, and design creativity will address questions on durability of timber housing and mortgage market acceptability by 'designing-in' longevity – beyond timber treatment. Design for longevity will integrate opportunities for future 'parts' replacement and fabric 'servicing' of the dwelling. Two key elements of prototyping – novelty and performance testing – were intended to be tested through producing, assembling, and evaluating productivity of digital versus artisan methods; however, nationwide restrictions due to the COVID-19 pandemic meant that this wasn't possible.

2. Background

The premise of using whole timber dates to the very origins of timber construction. Post and beam structures have been typical in timber construction, but as simplified engineering approaches have evolved, timber frames with highly engineered sheet materials have become prevalent. This approach has relied on highly consistent timber properties, which are only possible through mass planting of a limited number of species. The timber industry that has resulted from this homogenous product requirement regularly manage their forests to remove smaller trees, giving the straighter and larger trees more room to grow – an operation called "thinning".

By-products of thinning in the UK are processed into 3 main uses:

1. Cheap timber products, such as fence posts;
2. Timber sheet products e.g. OSB, Plywood, MDF;
3. Burnt for energy as biomass.

In the UK, an increasingly large proportion is used for biomass, which releases the sequestered carbon from the timber. Bukauskas et al. (2019) have shown the possibilities of using whole timber in construction.

2.1 Existing Technology

- **Sheet connections (Figure 5)**
  The connection of sheet materials to the truss structure must also be considered. The work by Robeller et al. shows how modern manufacturing methods can be used to create complex joints with no metal fixings. Most of the work focuses on thin shell structures so is not suitable for the truss connections; however, it may be suitable for the fixing of sheet materials to the trusses and for connections at corners.

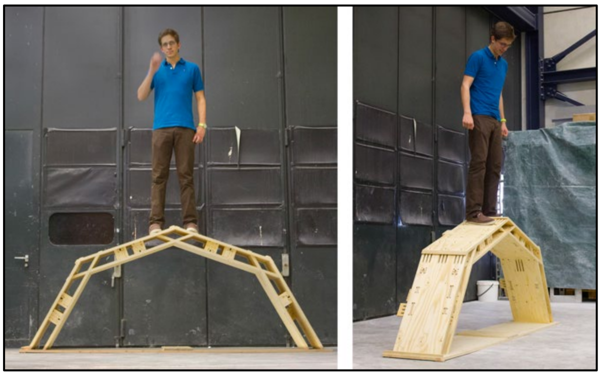


Figure 5. Double-layer arch.

- **Lignoloc (Figure 6)**

  Beck Fasteners have developed a collated wooden nail which can fire from a purpose made nail gun (https://www.beck-lignoloc.com/en). The nails are made of compressed hardwood and are coated in lignin (a natural organic polymer that is found in trees). Each nail is mechanically fixed as well as chemically fixed. The heat generated by the firing of the nail causes the lignin coating to melt and then reharden around the nail and surrounding timber. The Construction Scotland Innovation Centre (CSIC) have conducted trials with these nails. They are most suitable for sheet materials (OSB, MDF, Plywood) and have a propensity to split low grade timber. They are well suited for securing sheet materials to timber structures; however, trials would need to be conducted to test them in this scenario.

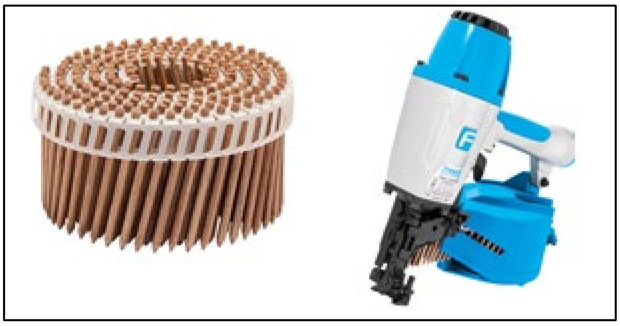


Figure 6. Lignoloc nails and tool.

2.2 Structural Optimisation

There are several ways in which structural capacity can be optimised:

1. **Inherent properties of whole timber**

   When roundwood timbers (>140mm diameter) are cut into milled timbers they lose some of their strength. There are two reasons for this, the discontinuity of fibres that is created around knots and secondly the inherent advantage of a circular profile versus the rectangular profile. (A. Bukauskas et al., 2019) By this method it is therefore possible to substitute similar sizes of whole timber for milled timber when substituting with similar species. Table 1 shows (by simple calculation) how sizes could be substituted.

Table 1. Table showing size-based substitution of whole and milled timber.

TR-26 timber size		Round timber diameter where A and I are greater than TR-26																		
mm	mm	80	85	90	95	100	105	110	115	120	125	130	135	140	145	150	160	170	175	180
38	97	NO	NO	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
38	75	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
47	72	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
47	97	NO	NO	NO	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
47	122	NO	NO	NO	NO	NO	NO	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
47	147	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	OK	OK	OK	OK	OK	OK	OK	OK	OK
47	172	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	OK	OK	OK	OK	OK	OK
47	222	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	OK	OK

When substituting miller timber with whole timber, two other geometric considerations have been made. The strength of an individual element is based on its yield strength, area and second moment of area. Assessing yield strength is rather complex for now, so it is assumed for now that the yield strength of whole timbers is equal to TR-26 grade. Assessing area and second moment of area is a matter of geometry and governs the bending stress in each element. Table 1 compares these two engineering parameters for milled timber with those of whole round timber, for standard milled timber sizes. Where the round timber possesses a greater area and second moment of area, the field is shown OK in green. This gives a guide for substituting timbers in the design.

2. **Air drying (Figure 7)**

   Although the timber industry has adopted a widespread approach of kiln drying, the process reduces the strength of round timbers. ASTM D2899 declares a 10% reduction in strength when kiln drying. Air drying is therefore justifiable in embodied energy and strength terms.

3. **In-depth truss analysis**

   It is quite normal for all truss members to be made from the same grade of timber (TR-26); however, each member of the truss is subject to different stresses, some undergoing bending, others compression and usually shear at the connections. It can therefore be said that not all members of the truss need to be TR-26 grade timber, it is obviously more cost efficient for truss manufacturers to work with one grade of timber for the benefits in material handling, logistics and processing that this brings. If processes can allow then timbers of a lower grade can be used in "secondary members" i.e. those not taking the highest stresses, which can therefore result in the following truss strategies.

Figure 7. Solar kiln and solar-photovoltaic-driven fans.

2.3 What is digital production?

A digital production process integrates all operations of the production into one computerised system. This does not predicate the level of complexity or automation within the manufacturing process; i.e. a factory using manual assembly techniques may just as easily be digitised as a fully automated robotics factory.

The benefits of digital production are:

1. Traceability of components and assemblies;
2. More consistent product;
3. Easier automation;
4. Competitive gain;
5. Defect reduction;
6. Reduction of waste;
7. High levels of product customisation become more viable.

In optimising the design for digital production, the complete lifecycle of the timber is considered. Some of the benefits of this optimisation can benefit the artisan as well.

A Materials Resource Planning (MRP) database system is the commercial system used to describe a digital production planning system. All materials and resources are tracked through a central database that cross-references each finished product with the machines, materials and personnel involved in manufacture.

Effectively a digital twin of each item. MRP systems are necessarily large, complex databases that have spawned their own industry; however, the development of mobile hand-held devices and cloud computing platforms means that such systems are now viable for smaller businesses, with standard data platforms allowing for easier integration of data.

2.4 The Importance of Digital Manufacture

1. **Embodied Carbon**

   To reduce embodied carbon, we need to capture and record what goes into every building, so a digital twin is a great way of doing this. It has already been discussed how the embodied carbon of a specific timber can vary significantly based on where it was planted, the soil type, age etc. The cradle-to-grave approach requires complete traceability of each timber from the point at which it was planted to the point when it no longer forms a useful product. Digital production can help form part of a digital supply chain that captures this.

2. **Off-site manufacture**

   Pre-fabricated elements allow for the adoption of all the benefits of digital manufacture. Looking beyond the truss, building modules can be assembled off-site allowing for rapid construction on-site. This improves delivery times and can increase profit margins. The case of modules, constructed of 5 timber trusses, spaced 600mm apart, forming sub-assemblies that are 2.4m long, are considered as part of this study.

2.5 What is Robotic Assembly?

Robotics are becoming more prevalent throughout factories worldwide. The majority are used for performing repetitive operations that require consistent accuracy over extended periods of time. They are also used in instances where hazardous conditions apply, e.g. welding of vehicle chassis and spray painting.

The predominant image of a robot is that of an arm (Figure 8), with close resemblance to the human form, which holds a tool ("end effector") to perform a specific operation. The dexterity and articulation of such an arm can also perform complex operations that might otherwise require numerous machines to achieve the same result with the same accuracy. This, however, requires a lot of programming – self-learning algorithms have not yet developed to the point where highly customised operations can be realised in an automated fashion.

It is also important to recognise that a robot does not necessarily need to take the form of a multi-nodal arm. Robotics simply describes the automation of a machine.

Figure 8. Kuka robots.

2.6 How can robotics help with the assembly of Integra House?

For this design optimisation, a full spectrum of robotics is considered such that the full spectrum of appropriate business models can be cross-matched. Highly complex robots (such as the robot arm in Figure 8) can be expensive to purchase and maintain. However, less complex Computer Numerical Control (CNC) machines can have much lower overheads. First, a SWOT analysis is conducted:

Table 2. SWOT analysis of robotics versus artisans.

SWOT	Artisan Assembly	Robotic Assembly
Strengths	• Tricks of the trade can save time and overhead costs. • Assembly can begin very rapidly with minimal equipment and overheads.	• Precision and Quality - Highly precise operations can be performed improving the quality of the end product. • Safety - Hazardous operations can be performed without risk to operators. • Occupational Health - Repetitive operations can be performed without risk of fatigue to operators. • Operational Efficiency - 24 hours operations. • Production Monitoring - Robotic systems can perform in-line monitoring which can improve the

SWOT	Artisan Assembly	Robotic Assembly
		final product, e.g. measuring insulation density as it is pumped.
Weaknesses	• Highly skilled carpenters are required, which are not commonly found in rural communities. • Speed of high-volume production can be slow. • Artisan designs are often improvised on the spot, which means they are not captured on a drawing. This is a disadvantage when trying to provide traceability of the part/assembly. • Human operators will always be exposed to risk during the assembly process.	• Robotic systems cannot handle unregularized elements without complex visual recognition systems. • Requires large amounts of pre-programming and operational testing before new programmes can be used. • Expensive capital outlay. • Highly trained operators required to programme for new operations. • Maintenance routines are highly specialised.
Opportunities		• Some simple visual systems are already available for identifying pre-marked weak-points on timbers. Hence simple visual systems could be adopted. • Standardised design of components can reduce the skillset required. • The position of services can be machined accurately during final assembly.
Threats	• Speed of production can limit competitiveness.	• A digital production process is key to deploying robotic assembly. If this is not possible then the time to reprogram robots will challenge their viability.

There are opportunities arising from this analysis. These must be evaluated in the context of manufacturing volume. By analysing the five main strengths of robotics above, we can eliminate those which apply to high-volume manufacture. We are therefore left with precision, quality, safety and occupational health. Most of these benefits, in the context of truss-form-modules, can be achieved with CNC machines and production line methodology (e.g. assembly jigs). The following assembly process has been designed to include CNC machines and other automated methods of manufacture that will improve the precision, quality, safety and occupational health of its construction.

2.7 Design optimisation for digital versus artisan production

There is also a case for on-site manufacture. Consider the embodied carbon content:

Table 3. Comparison of off-site versus on-site manufacture.

Aspect	Off-Site	On-Site
Process	• Materials are transported to a central location (distance dependent on infrastructure). • Modules are made with machines and personnel that remain at the factory location. • Modules are shipped to location and whole dwelling assembled quickly.	• Trees are sourced on or near the site. • Dried on/near the site. • Processed on site. • All other materials are transported to site. • Tooling is brought to site. • Tooling must be lightweight and transportable.
Strengths	• Robust tooling with good accuracy can be used. Quality is high. • Easy to collect embodied carbon data and conduct digital manufacturing.	• Whole timbers travel a very minimal distance. • Site-locale employment higher.
Weaknesses	• Large modules will be unsuitable for transportation to remote locations. • Whole timbers will be subject to double-travel to and from factory.	• Hard to capture digital data for building components. • Chances of design improvisation on-site are much higher.

Aspect	Off-Site	On-Site
		• Shortage of specific materials on-site will lead to unspecified products being used.

The following SWOT analysis considers the strengths and weaknesses of artisan manufacture, versus digital manufacture. This analysis is specifically within the context of truss manufacture and building-module assembly.

SWOT	Artisan Manufacture of Trusses	Digital Manufacture of Trusses
Strengths	• For whole timber trusses, highly customised joints can be made. • For milled timber trusses a relatively low skillset is required. • Knots and weak points in timbers can be avoided. • Tricks of the trade can save time by making design optimisations in-process. • Carpenters can physically articulate unregularized timbers quickly and easily. • Manufacture can be achieved with the lowest technology option, hence low business overheads.	• Data from the timber supply chain could be fed directly into the digital production system. • Integration with BIM systems and creation of a Digital Twin can be achieved with ease. This makes traceability of the product life cycle easily achievable and compatible with 'Design for Deconstruction'. • Lean manufacturing techniques can be easily adopted. • CNC machines can automatically feed information into the digital system, rather than requiring manual operator input.
Weaknesses	• Highly skilled carpenters are required which are not commonly found in rural communities. • Artisan designs are often improvised on the spot which	• A broader skills set is required, e.g. drawings are required, IT skills are required. • Information must be fed into the computer system, which is best done using CNC machinery. (1)

SWOT	Artisan Manufacture of Trusses	Digital Manufacture of Trusses
	means they are not captured on a drawing. This is a disadvantage when trying to provide traceability of the part/assembly. • The truss manufacturing industry oriented around the use of regularised timber without a true trace of the embodied carbon in the timber being used. • The embodied energy contribution will be very difficult to capture.	• More business overheads in computer platforms. • Digital manufacture is potentially less flexible to design changes and manufacturing flaws if not built into the system at the outset. • It is harder to convince an established truss manufacturer to adopt digital systems than it would be for a new start-up business to adopt.
Opportunities	• A simple Human-Machine-Interface could capture the transfer of information, e.g. a simple mobile device app. • The embodied energy contribution could be captured with IoT devices attached to machines to measure their power consumption. (2) • Standardised designs and a manufacturing process can help reduce the skillset required.	• Some simple visual systems are already available for identifying pre-marked weak-points on timbers. Hence simple visual systems could be adopted. • Standardised design of components can reduce the skillset required. • A digital supply chain can provide much better detail on the embodied carbon contribution. This can allow for diversification throughout the supply chain without consequence. (3) • Digital manufacture allows for better integration of parts at the design stage. (4)
Threats	• Culture: Capturing data to the level required is not something	

SWOT	Artisan Manufacture of Trusses	Digital Manufacture of Trusses
	that truss manufacturers are necessarily used to. • As the industry moves towards more detailed embodied carbon recording truss manufacturers may not be able to adapt.	

Notes:

1. Information can be fed into the computer system manually, but this requires a human interface which introduces the possibility of error. Hence where CNC machines are used this information can be easily integrated.

2. However, power consumption in each specific location will need to be assessed first.

3. For example, rather than specific roles being fixed in place, different suppliers in the chain could add value at different points.

4. This refers to the customisation of parts and their fixing to others. For example, if the exact location of a component is known from the outset, then the method of fixing with other components can be determined. This compares with most other building materials, such as timber sheet products, which a homogenous allowing for fixing points to be added at the final stage of assembly.

3. Method

A series of work packages for investigation were as follows:

- WP (A). Preliminaries
- WP (B). Design optimisation
- WP (C). Performance simulation
- WP (D). Digital versus artisan production and testing of components
- WP (E). Digital versus artisan assembly and testing of test slices
- WP (F). Evaluation of environmental and energy performance
- WP (G). Reporting and dissemination

Due to the restrictions imposed by the COVID-19 pandemic during the course of the project, the physical production and assembly trials were not conducted. An extended design optimisation was conducted instead.

3.1 Design Optimisation

In the context of the research review laid out above, this paper takes the position that in the context of climate change and the need to innovate in how we construct buildings, the value of home-grown timber should be realised. It should be realised through vernacular examples and enhanced by the production methods available today. To this end, the objectives for the design optimisation were:

1. Minimising metal components;
2. Minimising processing of material;
3. Maximising use of UK grown whole timber;
4. Structural optimisation;
5. Minimising complex/highly skilled manufacturing techniques.

Detailed cost and structural engineering are not included in the process; rather a proof of concept is considered. Key aspects that were considered included: connection details, structural optimisation (ratio of whole-to-milled timber) and aesthetic considerations. The limitations were that of passive house design, namely: an air-tight envelope is required, transport height limitation, 400mm wall cavity required for adequate insulation.

3.1.1 Minimising Metal Components

Reducing the embodied carbon can be achieved by adopting a risk avoidance strategy of avoid, reduce, transfer, accept:

- **Avoid** the use of fasteners by using joints or connections that require less fasteners;
- **Reduce** the use of fasteners through joint selection;
- **Transfer** the responsibility of metal fasteners to other materials of less embodied carbon;
- **Accept** that certain connections may need metal fasteners where other methods are not viable.

All-timber connections largely avoid the requirement for metal fasteners.

3.1.2 Minimal Processing of Material

When considering a building constructed of whole timbers, one is reminded of the log cabin and large timber frame structures. Log cabins and small timber frame structures rely on very precisely fitting joints made by a carpenter. Conversely the modern timber truss is a very low-skilled assembly of well-engineered components. The aim here is to look at bringing whole timbers into the realm of low-skilled construction with well-engineered connections. Several options were considered:

- **Type 1: Flitch Plate Connection (Figure 9)**

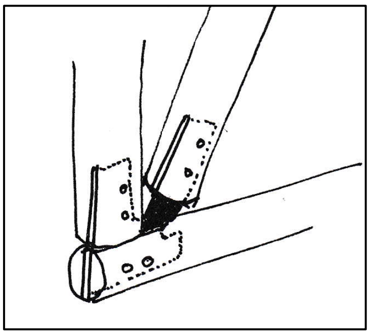


Figure 9. Flitch plate connection.

  - Strengths:
    - A commonly used connection with good structural integrity.
    - Easily modified to accommodate bigger loads.
    - Any combination of angles can be accommodated.
  - Weaknesses:
    - Steel is the most common flitch-plate material – high embodied carbon.
    - Thermal bridging by flitch plates.
  - Opportunities:
    - Universal flitch plate design could allow for standardisation.
    - Flitch plates made from timber sheet products could reduce thermal bridging and weight.
    - Flitch plate fasteners could be designed that eliminate need for metal.
  - Threats:
    - Bolts are required to hold the timber against the plates (generating friction). To eliminate these entirely would be difficult.

- **Type 2: Gang-Nail Plate Connection (Figure 10)**

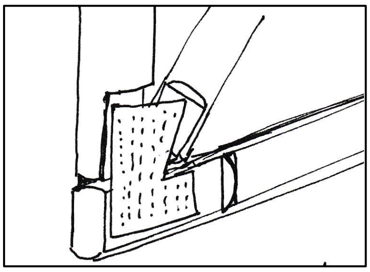


Figure 10. Gang-nail plate connection.

  - Strengths:
    - A highly engineered system already used in mainstream truss manufacture.
    - Less embodied carbon than flitch plates (less steel).
  - Weaknesses:
    - Metal elements cause thermal bridging, albeit less than flitch plates.
    - Additional machining of timbers required to accommodate.
    - A truss press is required to install the gang-nail plates.
  - Opportunities:
    - [None listed]
  - Threats:
    - Typical truss-presses might not be able to accommodate round-timber profiles.

- **Type 3: Whole-Timber Connections (Figure 11)**

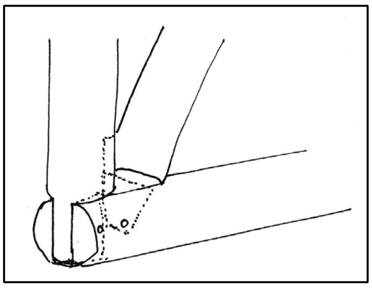


Figure 11. Whole timber connection.

  - Strengths:
    - Thermal bridge free design.
    - Low embodied carbon (no steel).
    - Securing dowels/screws can be non-metal.

- Weaknesses:
  - More reliant on timber grade.
  - Typically time consuming to produce.
  - Typically required high skills levels.

- Opportunities:
  - The precision required by classic timber connections could be recreated by automated machining methods.
  - Finger joints are a well-engineered, easily produced, connection that could be employed.
  - If automated machinery was used then it's possible that snap-fit joints could be employed which would eliminate the need for metal fasteners.

- Threats:
  - Automated machining methods may not be viable option for rural manufacturers.

- **Type 4: Hybrid Connections**
  - Using whole timbers in combination with milled timbers is possible by combining any of the options above (Figure 12).

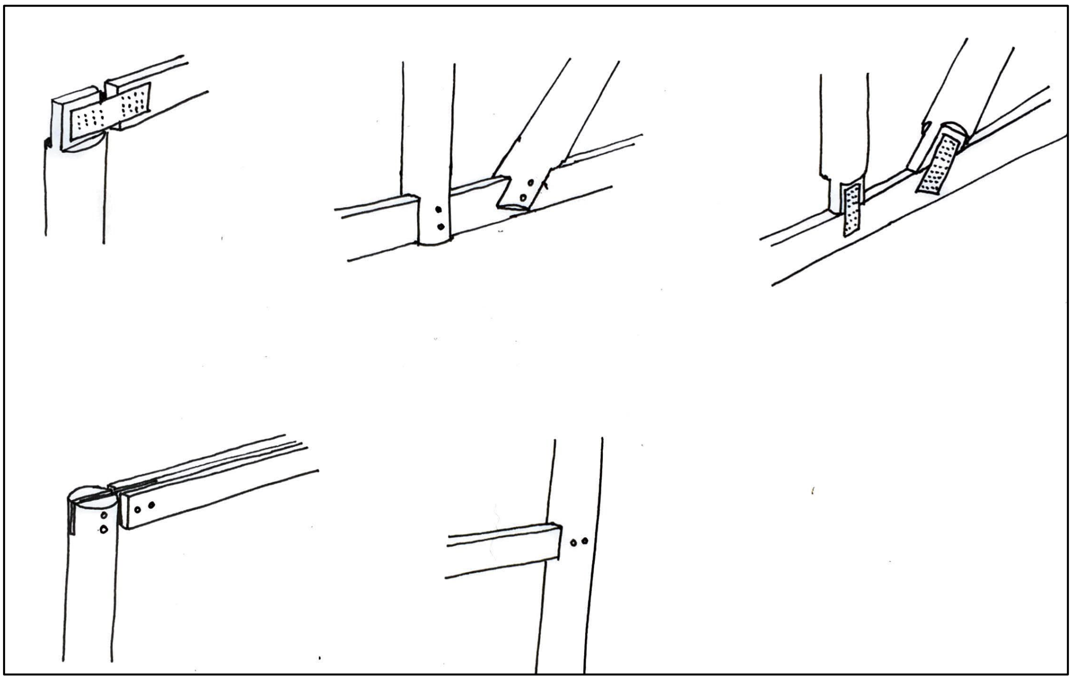


Figure 12. Hybrid connections.

3.1.3 Truss Strategies

The method above results in the following strategies, shown in figure 13 below:

1. Partial whole timber use – secondary members only. Hybrid connections are used to replace secondary elements of the truss with round timber.

2. Partial whole timber use – all vertical elements. Hybrid connections are used to replace all vertical and some secondary elements in the truss.

3. Full whole timber use – metal fixings. All elements of the truss are made from round timber, but retain a method of metal fixing.

4. Full whole timber use – metal free. All elements of the truss are made from round timber and connections are timber only.

Figure 13. Truss options. Red = milled timber; Green = whole timber.

3.2 Tested Designs

The following designs result from the methods described above and should be taken forward for simulation and evaluation:

1. **Hybrid Truss – (whole timber for vertical elements only)**

   The testing of hybrid connections will add value to the knowledge base and could represent a way of transitioning normal truss manufacture to use round-timbers.

   a. Morticed joints in whole timbers that fit over the milled timbers.
   b. Flat sided areas on whole timbers that allow for gang-nail plates.

2. **Full whole timber use – metal fixings**

   This option should be evaluated to quantify the embodied carbon of flitch plates and ease of manufacture. Gang-nail plates are being avoided because of the additional machinery required. Flitch plates represent an opportunity to produce standardised elements that could be manufactured centrally and transported to rural locations with minimal impact.

   a. Metal flitch plates.
   b. Metal gang-nail plates.

3. **Full whole timber use – metal free**

   To fully test the concept of an entirely timber construction and all-timber connections. This design option should include looking at the concept of snap-fit connections.

   a. Glued mortise and tenon connections.
   b. Timber flitch plates with hardwood dowels.
   c. Snap-fit connections.

Each of the above options represents a varying level of manufacturing complexity, which will allow different levels of adoption to be considered. Each of these options will be assessed against further criteria in the following sections. See separate document [**Source 3**] with truss drawings.

3.3 Truss Design Evaluation

- Option 1a: Hybrid Truss – Mortice and Tenon
  - Pros: minimal complexity in its manufacturing, requiring only a few pieces of machinery to adopt.
  - Cons: the continued use of milled timber would still likely require a truss-press.
  - Is this idea ambitious enough if we are only replacing 30% of the timber with whole timber?

- Option 1b: Hybrid Truss – Gang-nail plates
    - Pros: Possibly a good interim step for an existing truss manufacturer to take if they was to try the idea on their press.
    - Cons: Large amounts of material need to be removed from each whole timber to match the 47mm thickness of the milled timber.
    - Again, one has to ask if this idea is ambitious enough?

- Option 2a: Whole timbers – Steel flitch plates
    - Pros: Eliminates the need for a truss press.
    - Cons: Concerns about the use of steel.
    - Does this potentially negate embodied carbon benefits given that these plates would be made by another supplier and shipped to site?
    - Also the thermal bridging effects of using metal flitch plates will have a negative impact on the thermal performance.

- Option 2b: Whole timbers – Steel gang nail plates
    - Pros: Minimal machining required to each whole timber to make this idea work.
    - Cons: A truss press is required.

- Option 3a: Whole timbers – Mortice and Tenon (no metal fixings)
    - Pros: Mortice and tenon joints are possibly the best used carpentry joints.
    - Cons: Accuracy through a good manufacturing set-up will be required. Diagonal braces are tricky to adopt in this design.
    - The innovation in an all timber design is unique.

- Option 3b: Whole timbers – Timber flitch plates (no metal fixings) ***preferred option***
    - Pros: Simple manufacturing process, no need for a truss press. All made with mobile tools except the plates. Flitch plate extensions provide useful lifting points for module handling. Processing of whole timbers could be done on-site, on in the factory. The slot for the flitch plate does not need to be as accurate as a mortice and tenon.
    - Cons: CNC router might be required; however, this could be used in processing other components for the module. An alternative would be to have the plates made elsewhere, but these machines are becoming more common.

- Option 3c: Whole timbers – Timber snap-fit connections
    - Pros: Fast assembly, no glues or secondary fixings required. Some snap-fit geometry algorithms have already been designed by Robeller et al.
    - Cons: Complex joints that require precision and timber before assembly. Technology is not very well proven. Hard to process end connections on site, would really need to be done in a factory.

3.4 Recommendations for Physical Prototyping

Option 3b represents a good level of innovation and combined technologies. Pursuing an all-timber design seems like a good ambition. Option 3b would also involve the training of tradesmen in new machinery (CNC router) that is probably not beyond their financial limits, but also builds digital skills and could integrate with digital production easily. The dowel-splitting by Lignoloc concept would be easy to test with CSIC and the mechanics of this type of connection have been used in carpentry for years. The flitch plates can be made using the CNC router at RGU. The snap-fit joints from option 3c would also be nice to prototype.

- **Flitch plate extensions (Figure 14)**
  The flitch plates in the trusses can provide lift points for the finished module by simply extending them through the external envelope.

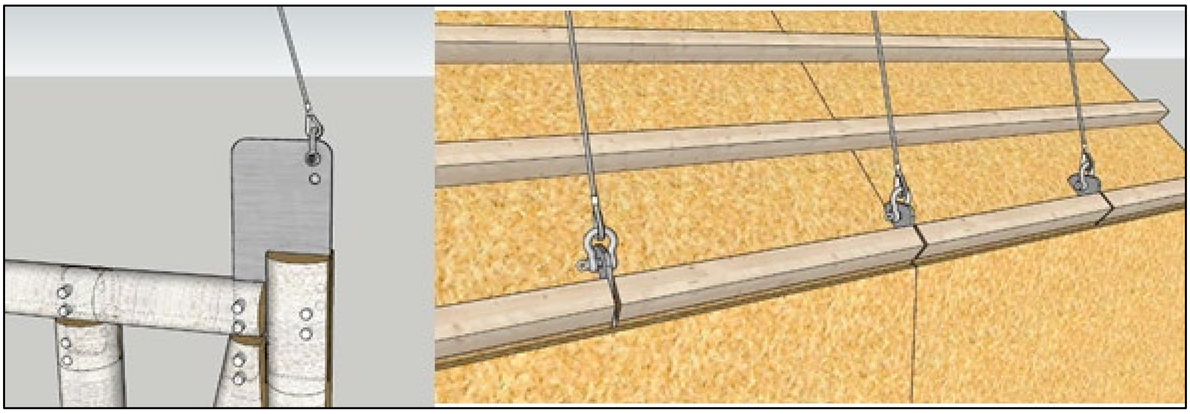


Figure 14. Flitch plate extensions.

- **Dry Elastomer seals for air tightness (Figure 15)**
  Elastomer seals are used extensively in window and door design to seal against wind and rain. The materials and geometry required to make them work are therefore very well defined. Pre-fabrication allows for their use in the building envelope which would eliminate the need for single used adhesives and sealants.

Figure 15. Dry Elastomer seals.

3.5 Digital supply chain proposal

Stage One: Carbon Sequestering (Figure 16)

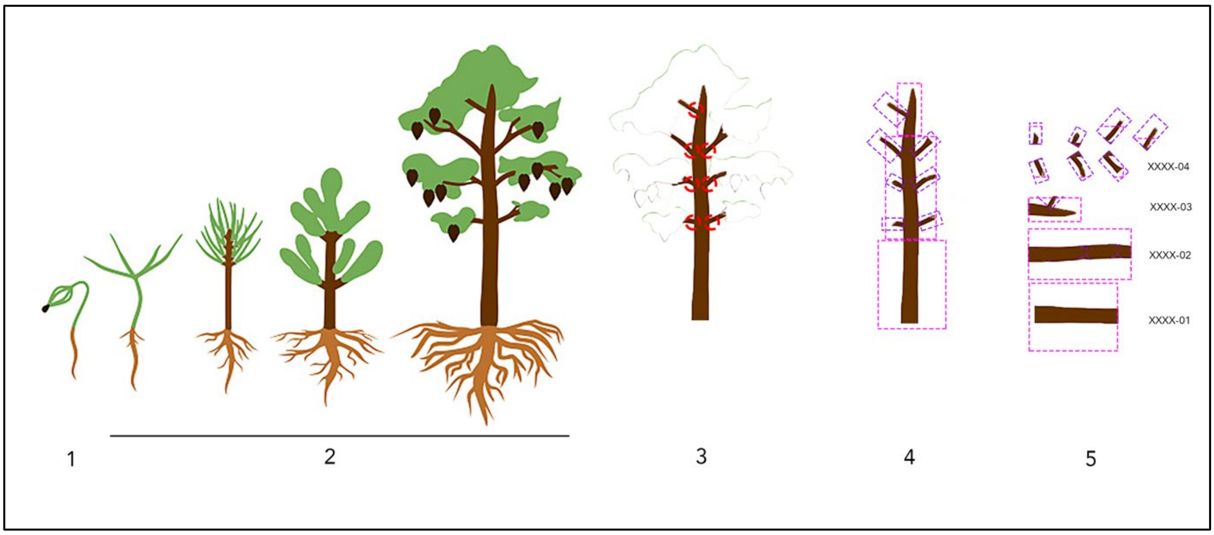


Figure 16. Carbon sequestering sequence.

1. Tree is planted – position recorded, GPS location tagged, ID number assigned.

2. Growth is monitored and recorded.

3. Prior to thinning operations, a photogrammetry survey (see Appendix 2: Katam Forestry Software) is conducted to determine trunk profile and position of knots. Non-destructive testing of tree grade conducted.

4. Tree is felled and branches removed.

5. Trunk sections are digitised and marked with their unique ID and sent for drying – at this stage the first entries are made in the MRP System. A unique ID is given to each timber such that its final

position can be determined. Timbers should also be sorted and grouped at this point. Sorting should be categorised firstly by grade, and then by size.

Stage Two: Product Processing

6. Drying – after drying the trunk sections will undergo shrinkage, cracking, bending and warping. Each timber is re-assessed against its record to ensure no sizeable splits or cracks have occurred that would make the timber unfit for use. A method of statistical monitoring should allow more efficiency in this process over time.

7. Timber allocation – each timber is allocated a position in a truss design. This becomes the point where it's manufacturing profile is assigned. With a standard library of component designs an algorithm can easily be written to carry out a best-fit case.

8. Timber processing – timber undergoes digital manufacture. Embodied carbon contribution is added to digital twin.

9. Truss assembly – timber element is assembled into a truss and status changed accordingly. The digital twin becomes a BIM record.

10. Transportation to factory/site and construction – the timber asset is transported to the factory or site and its digital twin updated with the embodied carbon created in the process of transport and construction.

Stage Three: In-Use and End-of-Life

11. Final product determination – the location of the timber asset within the building is recorded.

12. Build deconstruction – the building is deconstructed and the timber asset is re-used in another building, or disassembled and its elements re-used.

3.6 Truss Design Assessment

The table below shows the least complex machinery required to manufacture each truss design option.

Table 4. Machinery used in truss design.

Machinery	(1a) Mortise + Tenon	(1b) Gang-nail plates	(2a) Flitch Plates	(2b) Gang-nail plates	(3a) Mortise + Tenon	(3b) Timber flitch plates	(3c) Snap-fit connections
Sawmill Bandsaw	●	●					
Kiln drying	●	●					
Air drying /Solar kiln			●	●	●	●	●
Mobile sawmill	●	●	●	●	●	●	
CNC Router*							●
Chain Mortiser			●		●	●	
Truss Press	●			●			
Pillar Drill			●			●	
Prefab. CNC components*			●			●	●

*Native digital machinery – Note, all others will require additional HMI to be part of a digital process.

3.7 Production Line Proposal

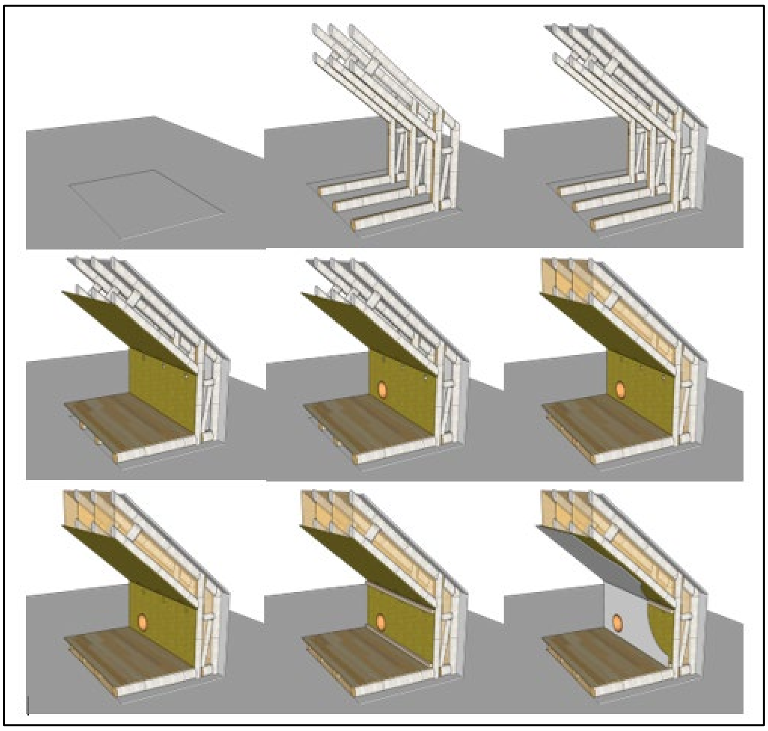


Figure 17. Production line proposal.

The following process is based on that of a moving production line, a conveyor belt, with stages like that of automated vehicle assembly (Figure 17 and Table 5). For a breakdown of the tooling used, see Appendix 3.

Table 5. Production line proposal.

Production Line Stage	Quality	Health & Safety	Digitisation
Stage 1: Sheet materials laid on conveyor bed Sheet materials can represent a potential manual lift hazard as many products exceed the recommended 25kg safe lift for one person. Pneumatic suction cup lifting equipment can eliminate this and reduce the likelihood of damage. Tooling: Suction lifting equipment	•	•	
Stage 2: Pre-made trusses laid onto sheet materials and held in place by production line jig Hybrid and flitch plate trusses (options 1a, 1b, 2a, 3b) will allow for easy location in such a scenario. The milled timbers and flitch plates can act a datum locations on which to location them in the production line jig.		•	
Stage 3a: External sheet materials positioned on trusses and secured In a digital production environment, the sheet materials can be pre-marked and pre-machined with service holes. Simple drills or routers could be used for this process, but a CNC router would be compatible with digital manufacturing and could perform different shapes and size holes with one cutting tool. Tooling: CNC Router	•		•

Production Line Stage	Quality	Health & Safety	Digitisation
Stage 3b: External sheet materials positioned on trusses and secured Positioning of the sheets can be conducted by suction lifters. A robotic arm would be able to position these accurately on the structure, however simple jigs and stoppers on the assembly trestle will allow the same functionality at lower complexity and cost. Tooling: Suction Lifter	•		
Stage 3c: External sheet materials positioned on trusses and secured If the sheet products can be secured using the Lignoloc timber nails then a production line nail-gun can be mounted to the conveyor system to provide accurate locations for the nails. This could be safely achieved using a human operator with location pins in a guide rail to accurately position the nails. Tooling: Lignoloc nail-gun	•	•	•
Stage 4a: Window and door reveals are installed and secured Window and door reveals will be made from sheet materials. These could be cut using a table saw, or band saw, but again a CNC router provides the most flexibility and integration with a digital production environment. Tooling: CNC Router	•		•

Production Line Stage	Quality	Health & Safety	Digitisation
Stage 4b: Window and door reveals are installed and secured If the sheet products can be secured using the Lignoloc timber nails then a production line nail-gun can be mounted to the conveyor system to provide accurate locations for the nails. This could be safely achieved using a human operator with location pins in a guide rail to accurately position the nails. Tooling: Lignoloc nail-gun	•		•
Stage 5: Internal sheet materials are fixed to the trusses As for the external sheet materials, internal sheets can be located by suction lifting equipment and secured with timber nails. The complication is that a larger framework will be required to handle the sheets inside the structure. Tooling: Suction Lifter	•	•	•
Stage 6: Service ducts are installed through wall structure Assuming that the sheet materials were pre-machined with service duct holes will allow this stage to merely be the installation of ducts. This operation will be difficult to achieve robotically given the location and size of services. Installing chimney ducts, soil pipes and cabling through the wall fabric will be easier for a human operator and won’t compromise safety or quality if digital principles are adhered to.			

Production Line Stage	Quality	Health & Safety	Digitisation
Stage 7: Applying air-tight seals To achieve the air-tightness specification tape will need to be applied at internal sheet material junctions and at penetrations. There are two options here: 1. Apply air-tight tape to junctions after assembly. This is the standard practice for achieving airtight envelopes in the industry. However, these tapes will be almost impossible to install around ducts and corner junctions by robotic means. Manual installation by a human operator will be the only viable option. Unfortunately, these tapes are rarely recyclable and do not help the case for DfD. 2. Apply dry-elastomer-seals to sheet materials as they are prepared for the production line. Elastomer seals are widely used in many other industries and are capable of sealing to high pressures where required. Sheet materials are where these seals are required, so if these sheets can be prepared with grooves to accommodate elastomer seals as part of the process then seals can be installed prior to the sheet materials being fixed to the structure. Tooling: Human Operator	•		•

Production Line Stage	Quality	Health & Safety	Digitisation
Stage 8a: Insulation is pumped into module cavities Holes in the sheet materials are required for pumping insulation into the cavity. It is recommended that these holes be placed in the outer sheet materials to reduce the number of penetrations through the internal air-tight barrier. To enable a production line approach these holes should be in standard positions. Ideally these holes could be made on a CNC router to maintain accuracy and position which will also make re-sealing them an easy task. Tooling: CNC Router			•
Stage 8b: Insulation is pumped into module cavities Pumping of the wood fibre insulation at stage 8 can now be easily accommodated by fixed machine with a retractable nozzle that levers towards the module at the correct time. Tooling: Insulation pump	•	•	•
Stage 9: Pumping inlets and outlets are sealed Similar to stage 6, the installation of plugs in the pumping outlets is probably best achieved by a human operator. Tooling: Human operator			

Production Line Stage	Quality	Health & Safety	Digitisation
Stage 10: Breather membranes are applied to the outside of the structure Breather membranes are an essential part of the construction and their installation can be cumbersome with on-site construction. In a digital production line large rolls of membrane could be mounted on an arm and unrolled across the module with ease. Securing the membrane to the envelope can be achieved without metal staples if conducted as the same time as stage 11. The fixings for the cladding battens can help the membrane in place. Tooling: Manipulator arm			
Stage 11: Battens for external cladding are fitted to the external skin Pre-cut battens are brought to stage 11 on the production line. Collated screw guns are used to secure the battens and breather membrane to the outer sheathing. Tooling: Human operator			
Stage 12: Battens are fitted to the internal skin to provide service void Similar to stage 11, pre-cut battens are fitted internally. Collated screws used. Tooling: Human operator			
Stage 13: Internal finishes are applied			

Production Line Stage	Quality	Health & Safety	Digitisation
Stage 14: Completed module transferred to holding bay The flitch plate truss design lends itself well to being able to aid the lifting process. Extensions to the flitch plates can be used as lifting points.		•	

4. Discussion

4.1 Design for Deconstruction

- **Designing out drilling and/or cutting of timber post-treatment**
  This is inherently adopted in the design of the production line methodology above. If a digital production process is followed the drilling and cutting of all timbers can be carried out by CNC router prior to the materials reaching the production line.

  This process will require high levels of precision and a completely digital production process. To enable such methodology by artisan means would be foolhardy. Small variations in the accuracy of components are normally adapted for by the artisan at the final stage of assembly, hence why service penetrations are ordinarily applied on final assembly.

- **Designing in future parts replacements and fabric servicing**
  By following the principles of Design for Deconstruction, through the previous work packages, this requirement has already been met. The principles of using no adhesives, no nails, only screws and other connections which can be reversed without damaging the components, means replacement of parts in the future can easily be accommodated.

  The principle of digital design is also critical to achieving this. By adopting a digital design and production process there will be records of each component within the structure allowing future modifications or replacements to be simulated on the digital twin, before being carried out physically. The larger question to raise here is about occupant behaviour, especially in the case where the house is sold or rented to a third party later. In this scenario it becomes likely that the occupants will employ their own tradesmen to carry out repairs, hence invalidating the digital twin.

- **Other considerations**

  Providing timber only connections on the 'wet' side of the envelope is potentially problematic. Hence metal screws are used to secure the timber battens to the external sheathing.

4.2 Digital Performance

The provision of rural housing does not demand mass production. However digital production offers a lot of benefits:

- Digital production can offer significant benefits to the traceability of products, which is really required for capturing the embodied carbon in construction and the ability to Design for Deconstruction.

- Every factory will require some amount of human data input, so the final production line design must include the provision of applications that can run on cheap handheld devices that can consolidate information from all parts of the production line and supply chain.

- Capturing the lifecycle of a tree from first planting to end-of-life is possible. Commercial tools are now available that can digitise the forest. Passing this information along the supply chain is achievable and arguably necessary.

- There are some technology gaps in making this happen, i.e. a lightweight MRP system does not currently exist for this type of timber cataloguing, however writing such a system would be quite possible.

- When comparing the embodied carbon of off-site manufacture with on-site manufacture the picture is complex. A simple judgement about which is better cannot be made without assessing the local infrastructure and material availability. However, a more digital supply chain would allow this assessment to be made if the entire supply chain was digital from tree planting to final construction.

- If we act in the short-term then we need to evaluate the carbon of both on-site and off-site manufacture. If we act in the medium/long term, we know that the transport network will be decarbonised, so embodied carbon from transport will be reduced, and the factory-based approach becomes the *de facto* choice.

- Achieving digital manufacture with on-site manufacture will always be very difficult.

- The industry has adapted to use TR-26, a grade specifically chosen for its strength and reduced knots. Digitisation could reduce the industry's reliance on this by using timber more efficiently, e.g. digital manufacture could link the position of knots in a tree to its final destination in a truss, optimising where to position the timber to avoid weak points and by matching it's grade to its intended location in the truss. A more granular approach to timber grading.

Some further conclusions specifically around robotic production:

- Processing of the sheet materials prior to assembly can offer a lot of benefits to the production process in safety, efficiency and quality. This also offers the opportunity to conduct all cutting offline, such that the production line becomes a pure assembly line.

- Other simple improvements show how the quality and safety of assembling these modules can be improved by moderately simple pieces of machinery.

- There are several unproven technologies here, the most significant being:

    - Use of elastomer seals between sheet materials;
    - Fixing membranes to the outer envelope by secondary means.

- Processing of the sheet materials prior to assembly can offer a lot of benefits to the production process in safety, efficiency and quality. This also offers the opportunity to conduct all cutting offline, such that the production line becomes a pure assembly line.

- Other simple improvements show how the quality and safety of assembling these modules can be improved by moderately simple pieces of machinery.

- There are several unproven technologies here, the most significant being:

    - Use of elastomer seals between sheet materials;
    - Fixing membranes to the outer envelope by secondary means.

5. Further Work

The following are suggestions for other work that could be carried out in future, or during the analysis phase of the project, if lockdown restrictions prevent the team from building in the workshop.

1. Structural engineering study of these all timber joints.

2. Lightweight MRP system for production, investigating what lightweight apps there are already out there for digitizing the production of these modules.

3. Strength grading of solar-kiln dried timber. Digitising the whole supply chain could be a real innovation here, but it doesn't work if we can't grade the timbers, or at least come up with statistical models for what grades we can expect from Scottish timbers that are processed in the way described and dried in solar kilns.

6. References

Bakauskas, A., 2019. Whole timber construction: a state of the art review. *Construction and Building Materials*, 213, pages 748-769.

Robeller, C., 2015. Integral mechanical attachment for timber folded plate structures. EPFL, DSc thesis. Available from: https://doi.org/10.5075/epfl-thesis-6564

Appendix 1

[Placeholder – table giving the maximum depth of cut permissible when a 30% area limit is enforced.]

Appendix 2: Forestry Data Collection

There are commercially developed tree measuring products now available. Katam (https://www.katam.se/) provide a mobile device application that uses the device's camera to perform photogrammetry and data processing to provide the diameter of a group of trees (Figure 18).

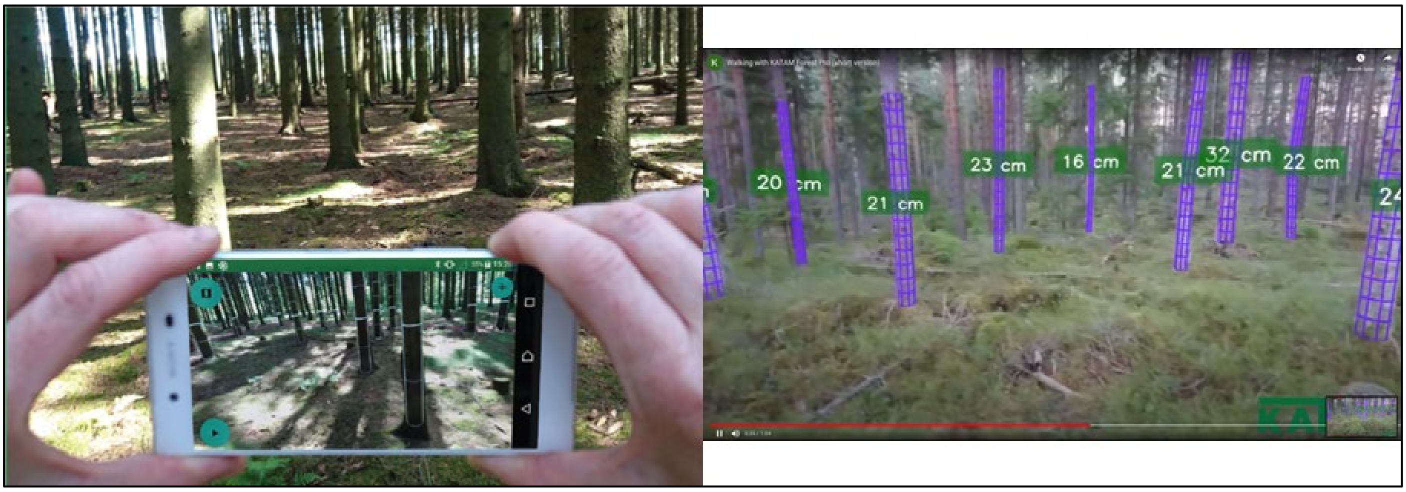


Figure 18. Katam mobile application for tree measurement.

Appendix 3: Machine Glossary

1. Pneumatic compressor (Figure 19)

Figure 19. Pneumatic compressor.

2. Suction Cup Lifting equipment (Figure 20 - also required: Pneumatic Compressor)

Figure 20. Suction cup lifting equipment.

3. CNC router (Figure 21 – also required: Dust Extraction Unit)

Figure 21. CNC router.

4. Dust Extraction Unit (Figure 22)

Figure 22. Dust extractor unit.

5. Lignoloc nail gun (Figure 23)

Figure 23. Lignoloc nail gun.

6. Sawmill Bandsaw (Figure 24)

Figure 24. Sawmill bandsaw.

7. Kiln drying (Figure 25)

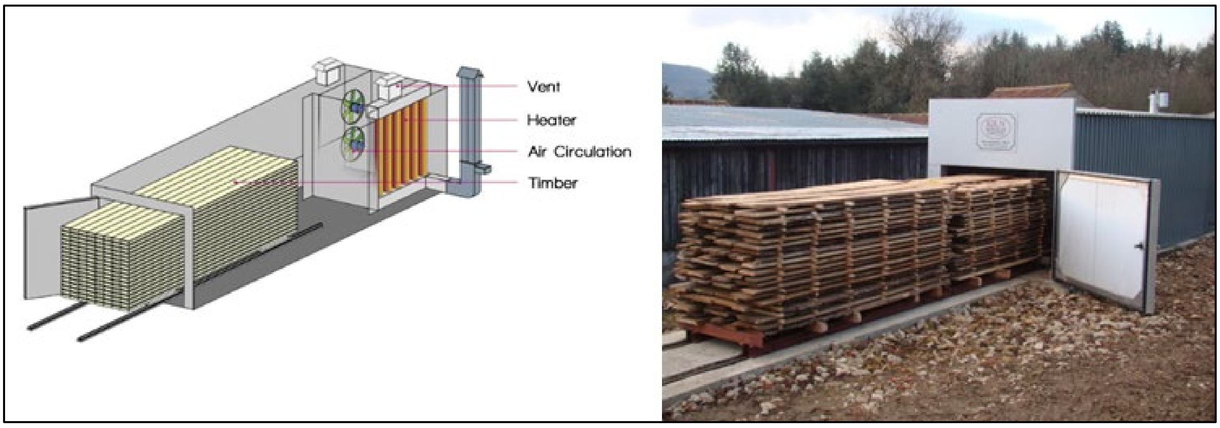


Figure 25. Kiln drying.

8. Air drying / Solar kiln (Figure 26)

Figure 26. Air drying / solar kiln.

9. Mobile sawmill (Figure 27)

Figure 27. Mobile sawmill.

10. Chain mortiser (Figure 28)

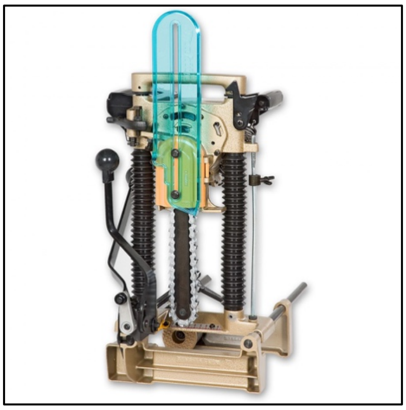


Figure 28. Chain mortiser.

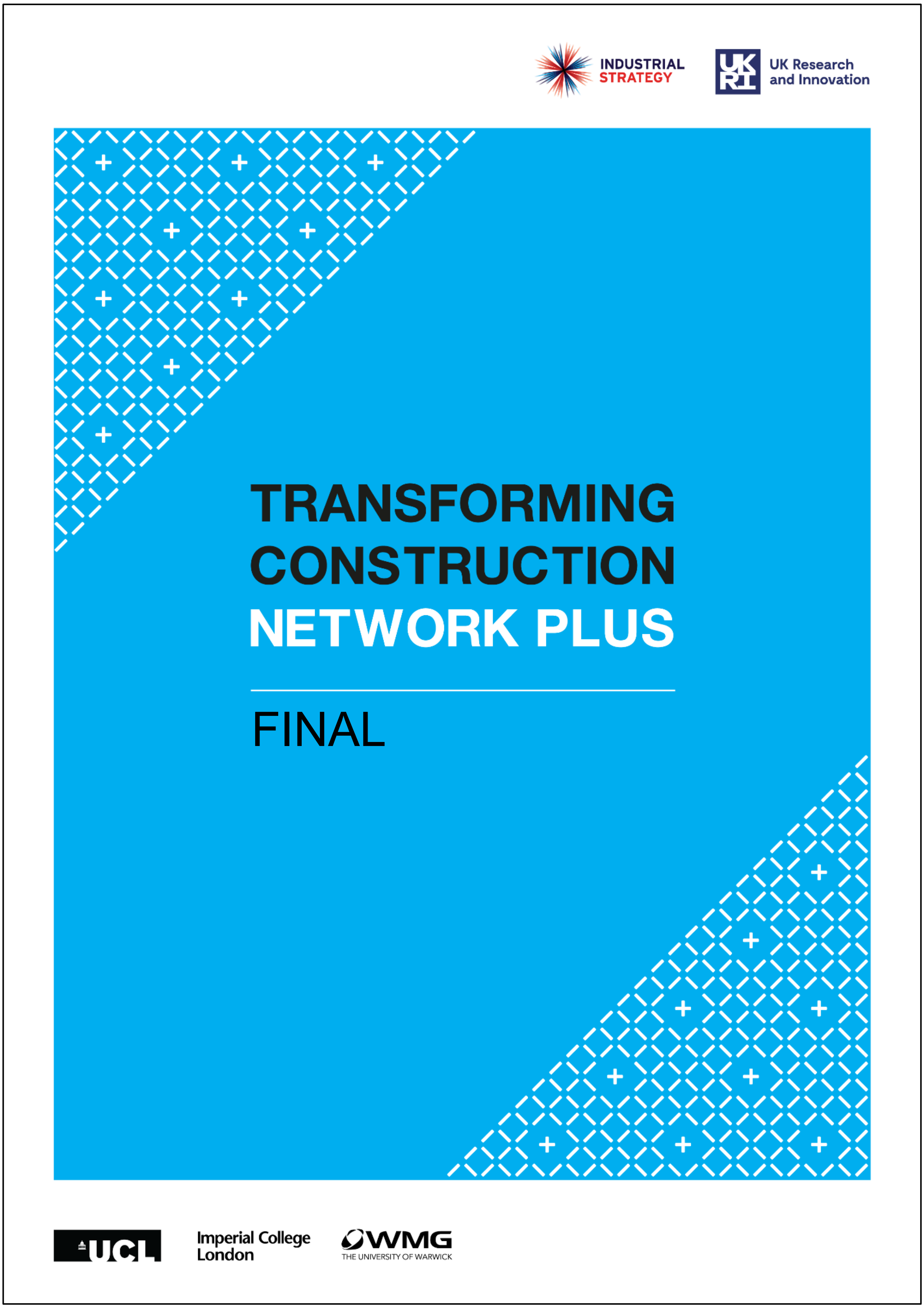
11. Truss press (Figure 29)

Figure 29. Truss press.

12. Pillar drill (Figure 30)

Figure 30. Pillar drill.

Source 2: Transforming Construction Network Plus: Final


INDUSTRIAL STRATEGY

UK Research and Innovation

TRANSFORMING CONSTRUCTION NETWORK PLUS

FINAL

UCL

Imperial College London

WMG THE UNIVERSITY OF WARWICK

TRANSFORMING CONSTRUCTION NETWORK PLUS

REPORTING TEMPLATE

PROJECT DETAILS	
Project Title	**Design Optimisation and Prototyping for Affordable Rural Housing**
Start date	3rd February 2020
End date	31th August 2020
Date of this report	September 2020

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Grade	7
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Departure Date	31st August 2020
Destination type and post	Research Assistant

1. New Collaboration and Partnerships

Note: Due to the government guidelines in place, due to the COVID-19 pandemic, some of our engagement activities have not been able to take place, and changed to telephone interviews.

Engagement activities	
Title	Timber Forestry Research
Type of activities	Phone calls with Forestry Commission Scotland (Andy Leitch)
Audience	None
Number of attendees	2
Geographical reach	UK
Objectives	To get a better understanding of how the forestry industry currently manage the stock of thinnings and to get their thoughts on the type of development we are proposing.
Outputs and Outcomes	The interview provided some useful information on how thinnings are currently used and how forests are managed. Andy was able to connect us with some innovative companies that are providing better digital information of forestry stock. He highlighted the fact that most of the timber we are proposing to use is currently used for biomass and it will continue to increase in that regard.

Engagement activities	
Title	Forestry surveying
Type of activities	Phone calls with Joe O'Carroll of Treemetrics
Audience	None

Number of attendees	2
Geographical reach	
Objectives	To get an understanding of the latest forestry surveying techniques available.
Outputs and Outcomes	Fruitful conversation where Joe explained the capabilities of Treemetrics and to what extent they can digitise a forest. We also gained an understanding of the market which they serve and who generally uses these services.

Engagement activities	
Title	Engagement with Scottish Foresters
Type of activities	Phone calls with two private foresters in north east Scotland.
Audience	None
Number of attendees	2
Geographical reach	None
Objectives	To gain an understanding of their forestry practices in regard to thinnings and to see if they would have stock available for a prototype for our project.
Outputs and Outcomes	Both sources had materials available to support our project activities. Unfortunately, due to the COVID-19 restrictions we were unable to take delivery and make use of these elements. One of the foresters had experience in using whole timbers to construct buildings and was very interested in our methodology. Again, further meetings to discuss our methods and to look at suitable timbers was not possible. However, discussions are ongoing.

Engagement activities	
Title	Engagement with Makar ltd.
Type of activities	Phone call
Audience	None
Number of attendees	2
Geographical reach	None
Objectives	Makar specialise in using Scottish grown timber to build homes using prefabrication methods. The objective was to get their thoughts on using whole timbers and the truss design methodology.

Outputs and Outcomes	Makar experience in using whole timbers to construct buildings and was very interested in our methodology. Again, further meetings to discuss our methods and to look at suitable timbers was not possible. However, mail and telephone discussions are ongoing.

Engagement with TCC Investments and other N+ Projects	
Project Name	
Format of engagement	*Please explain how you engaged (events, projects, emails, etc)*
Objectives	*Please explain if this collaboration or partnership was new and why you decided to collaborate with this organisation for this project*
Outputs and Outcomes	*Please explain how these activities contributed to either increase the number of collaborations, develop new research findings, develop new skills for participants or if they helped to mobilise for follow on funding proposals*

[Copy and repeat as necessary, if multiple items need to be reported]

2. New Findings

Key Findings	
Discoveries	Forests are generally overstocked with trees. Thinning operations continuously remove smaller trees that are used in low value applications. In 2019, 22% of all UK timber was burnt as biomass. These timbers could be processed and employed as structural building elements in the Integra House truss typology home. Digital scanning techniques (such as LIDAR and photogrammetry) have developed to the point where they can be used on a commercial basis to scan forests, with resolution to individual tree level. This creates the starting point for a digital supply chain. Whole timbers exhibit greater strength than milled timbers by virtue of their shape and continuity. Kiln drying reduces timber strength and is a major contributor to embodied carbon of timber buildings. Air drying and solar kilns can improve the strength compared with kiln drying. Applying a minimal processing methodology to the construction of timber-truss buildings can provide cost effective buildings that have significantly less embodied carbon. Automated methods of manufacture and digital production methods can be applied to the truss-type house model and forest digitization technologies are available that could bring digitisation to the supply chain.
Objectives	To research the latest state-of-the-art in whole timber construction and to apply it to a whole-house-truss design which can produce low-cost affordable accommodation in rural locations. To investigate the application of digital technologies to the production of rural buildings, making comparison with existing artisan techniques in the context of SMEs. To investigate automated methods of manufacture that can be applied to the resulting design of whole-house-truss. To build a whole-timber prototype module to demonstrate the principles explored through the research (unfortunately this hasn't been possible due to the COVID-19 epidemic However a design for the prototype module developed and assessed)
Reasons	Greater value could be brought to the British timber industry. Much greater volumes of carbon can be sequestered by using small roundwood timber for structural purposes than by burning it as biomass. Digital supply chains that incorporate SMEs can decentralise production and boost rural and remote economies.
Dissemination Action	Preparation of information for publishing in journals as well as posters and presentations that can be shared online

	Life Cycle Assessment and whole timber truss design prototype; case studies are to be published as a journal paper.
Dissemination Reach	Currently assessing suitable journals in construction (see lists) SMEs, CSIC, construction manufacturers, industry partners and fellow academic professionals.

Narrative Impact	
	Please explain how the findings of the project contribute to addressing the knowledge gaps of the construction sector The findings of this research show that whole timbers can be used in the construction of whole-house-truss type buildings at a lower cost than conventional milled timber buildings and with significantly less embodied carbon. Building on the research by Bukauskas et al (2019) on the possibilities of using whole-timber, the project performed a design optimisation exercise using an innovative whole-house-truss typology. This typology presents a low-cost method of construction that uses off-site construction to enable rapid assembly on site while achieving high levels of insulation and air tightness. Whole timbers exhibit greater strength characteristics than milled timber by virtue of their geometry and continuity. By adopting whole timber in construction, the UK can bring more value to its own timber resources by using home grown timber. The development of digital scanning techniques have made the digitisation of forests a reality. These techniques are adopted in a proposed digital supply chain where timbers are identified at plantation and begin the journey of the digital twin. Adopting automated methods of manufacture into the design allow for full integration of the digital supply chain information. The adaption of digital manufacturing techniques in the construction industry is poor. Many operations can be achieved with mid-scale automation, rather than full robotics. The trend towards airtight envelopes, modular construction and design for deconstruction could be greatly improved by adopting these techniques.

Narrative Impact against N+ Objectives	
	Please explain how the findings of the project contribute to addressing one or more of the following objectives: • *Increased adoption of digital manufacturing approaches and active energy technologies in new construction projects (increase in pre-manufactured value).*

- *Increase in productivity of construction projects (target: 15% over current methods).*
- *Scalable approaches for faster delivery and greater certainty of construction projects (target: 50% inception to completion from 2010 baseline).*
- *Develop active (energy) building components based on the product platforms and reduce cost of delivery of active buildings to be nearer standard market cost.*
- *Reduction in cost of construction and whole-life cost of built assets (target 33% over 2010 baseline).*
- *Improved whole-life value of built assets (user performance), including reduction in carbon intensity (50% target).*

N+ Impact Objectives

To provide an indication of the potential for the project to deliver against key N+ impact objectives, the following assessment was made.

Saves time	
Reduces costs	X
Reduces emissions	X
Increases whole-life value	X
Increases productivity	X
Incorporates active energy	
Potential to impact on the trade gap	X
Positive impact on investment	X
Accelerates uptake	X
Improves the health and safety of construction workers	
Improves the health and safety of the end users of buildings	X
Encourages collaboration in the construction industry and throughout the supply chain	X
Plays a role in 'levelling up'	

Our objectives were:

1. Optimise the design of the floor-cum-wall-cum-roof truss and a slice of Integra House 1 in the context of lower energy, lower CO2, indoor environment, fabric longevity, and automated versus manual production and assembly;

A design optimisation process has presented designs which can provide high levels of insulation and airtightness (suitable for Passive House Standards) using affordable materials and manufacturing techniques. The designs will facilitate digital manufacture and rapid on-site construction. The project team identified one option to move forward to advanced detailed design. The final proposed design (and associated supply chain) reduces the amount of processing (and hence embodied carbon) required to construct timber trusses. This is done by maximising the mechanical properties of whole timber, eliminating metal components and adopting existing connection techniques. As part of the supply chain evaluation, alternative methods of drying timber have been investigated and proposed.

The design is optimised for and accompanied by a digital manufacturing methodology which could provide scale to the project. The premise of the truss design is that it provides an engineered module, hence pushing the engineering further could allow for modules to be stacked or scaled up to create other volumes.
The life cycle cost is still an ongoing part of the project that will provide further definition on the embodied carbon performance.

2. Explore use of mixed milled/whole timber, automation and robotic-cum-artisan techniques to reduce economic and environmental costs further.

Literature review has revealed that whole timbers are a viable option in modern construction. Design optimisation has demonstrated that there are digital and automated methods of production that lend themselves well to the truss-type method of construction and these methods could be easily scaled up.
There are potential cost savings in the proposed use of timber. Historically forest thinnings have been far cheaper than wholesale roundwood, so by using them for construction (rather than burning as biomass) these timbers could be competitive when compared to the imported milled timber grades currently used.

3. Evaluate environmental and energy performance of options of components and assemblies;

Work on calculations of embodied carbon and capital costs of the occupied Integra house 1 versus the proposed Integra House 2 is nearing completion. This is broken down into the lifetimes of the houses: Product stage, Construction Stage, Use Stage, and End of Life Stage.

Product stage
The cradle-to-gate embodied carbon (EC) and capital cost (CC) of Integra House 2 was estimated to be 288kg CO_2/m2 Gross Internal Floor Area (GIFA) and £682/m2 respectively for the structure and shell (trusses, ground floor, walls, roof, doors and windows), and represents a 50% reduction in EC and 28% reduction in cost in comparison to Integra House 1, as a result of opting for a whole timber option). This is before detailed analysis of whole timber weight and structural performance. For affordability, the cost of whole timber appears to be very low, resulting in a significant reduction of cost. The reduction in EC was mainly achieved by use of wood wool insulation. Integra House 2 has made possible reductions in all the elements (except windows and doors which were not changed), which makes this option more attractive than Integra House 1. Transport EC and cost are considered to be the same for Integra Houses 1 and 2 for a given site if the trusses were to be transported from the nearest mill to the site. Further work is assessing the EC impact of the weight of whole timber versus milled timber trusses to achieve the same structural performance.

Construction Stage
Truss erection operation of Integra Houses 1 & 2 can be completed within a day by two labourers. All other operations will be the same except for the wood wool insulation blowing in Integra House 2, which requires power, while the conventional insulation installation does not

	require additional power. However this is insignificant compared to the savings achieved in the cradle-to-gate stage. *Use Stage* We expect similar EC and costs for repairs, maintenance, replacements; and EC and cost of operational energy and water usage, if the two houses were to be used by similar occupants. *End of Life Stage* We expect similar EC and costs for demolition of trusses and other components. However, in terms of waste processing and disposal, we expected lower EC and costs for wood wool insulation in Integra House 2, since it can be decomposed locally in a compost pit or compost bags. Insulation used in Integra House 1 will have to be disposed properly for which fees for transportation and disposal will be incurred. *Benefits and loads beyond the system boundary* Benefits beyond system boundary include, reuse, recovery and recycling potential. Some timber products can be reused or recycled into a new material or product. When reuse/recycle is not possible, timber can still be used to recover energy through direct combustion or through conversion to gaseous or liquid fuel before burning. The ambition for Integra House 2 is to eliminate contamination of the timber through treatment, painting, or use unclean adhesives to optimise end-of-life options. The possible end-of-life options available for Integra House 1 and Integra House 2 are: • Re-use: Timber in trusses in both Integra House 1 and 2 can be re-used in construction or other purposes; • Recycling: Wood wool can be upcycled into timber products such as chipboard and wood fibre board; and • Recovery: Whole timber in Integra House 2 trusses can be used for energy recovery. This work is still ongoing with simulation using TAS (Thermal Analysis Software) is underway to assess the energy and thermal performance of a floor-cum-wall-cum-roof shell slice of the final proposed design. **4.**Report and disseminate findings The reports are being written as the project progresses. We have discussed the potential for developing two articles: (i) The LCA/LCC impacts of using whole timber as an option to traditional housing construction, (ii) The potential for automated whole timber construction to transform housing delivery and affordability in a changing climate.

Publications	
Publication Date	Draft in progress.
Authors	*Deveci, G, Clubb, M; Musau, F; Victoria, M & Foster, M*
Publication Type	Journal paper

	Whole Timber Construction as Part of a Digital Supply Chain; *A prototype design of whole timber truss technology using modern methods of construction.*
Journal/Conference Name	*Journal Papers* 1. Building and Environment - ISSN: 0360-1323 - open access 2. ENQ (Enquiry) - ISSN 2329-9339 - open access, or 3. Architectural Science Review - ISSN: 0003-8628
Target Audience	*Tbc*
Objectives	*Dissemination of outputs of research*
DOI and/or institutional repository URL	*Tbc*

Publications	
Publication Date	Draft in progress
Authors	*Victoria, M; Deveci, G; Musau, F; Clubb, M; & Foster, M*
Publication Type	Journal paper *The Life Cycle Assessment of Integra House; A case Study of Modern methods of Construction Using Truss Technology*
Journal/Conference Name	*Journal Papers* 1. Building and Environment - ISSN: 0360-1323 - open access 2. Energy and building - ISSN: 0378-7788 - open access
Target Audience	*Tbc*
Objectives	*Dissemination of outputs of research*
DOI and/or institutional repository URL	*Tbc*

[Copy and repeat as necessary, if multiple items need to be reported]

IP and commercialisation	
Type of protection	*n/a*
Name of declaration/patent/ discovery	
Date	

Outline description	
Status	

[Copy and repeat as necessary, if multiple items need to be reported]

Awards and Recognition	*Medals, prizes and other accolades*
Award Type	None
Award Name	
Individual	
Award Level	
Award Year	
Award Description	
Award Impact	

[Copy and repeat as necessary, if multiple items need to be reported]

3. Further Funding

Public Funding (Grants)	
Funding Scheme/Programme	n/a
Organisation Name	
Funding Type	
Funding Currency	
Funding Amount	
Start Date	
End Date	
Objectives	
Reasons	*Please explain how the Transforming Construction Network Plus funding helped you prepare the follow on funding*

[Copy and repeat as necessary, if multiple items need to be reported]

Private Funding	
Funding Type	*n/a*

Nature of the funding	
Organisation Name	
Funding Currency	
Funding Amount	
Start Date	
End Date	
Objectives	
Reasons	

[Copy and repeat as necessary, if multiple items need to be reported

Version 3.0
Any queries about this template should be addressed to the N+ Project Manager at UCL (l.hanselmann@ucl.ac.uk).

Source 3: A Design Proposal for a Whole Timber Truss

This source appears without page numbers, having been directly imported into this portfolio from the original PDF. It covers pages 59 through 70 of this document.

INDUSTRIAL STRATEGY

UK Research and Innovation

TRANSFORMING CONSTRUCTION NETWORK PLUS

A design proposal for a whole timber truss

ROBERT GORDON UNIVERSITY ABERDEEN

MACKINTOSH ENVIRONMENTAL ARCHITECTURE RESEARCH UNIT
THE GLASGOW SCHOOL OF ART

CONSTRUCTION SCOTLAND INNOVATION CENTRE

Sylvan Stuart

UCL

Imperial College London

WMG
THE UNIVERSITY OF WARWICK

Prototype designs:

Option 1a: Hybrid Truss – Mortice & tenon connections

Option 1b: Hybrid Truss – Gang-nail plates

Option 2a: 100% Whole timbers – Steel flitch plates

Option 2b: 100% Whole timbers – Steel gang nail plates

Option 3a: 100% Whole timbers – Mortice & Tenon (no metal fixings)

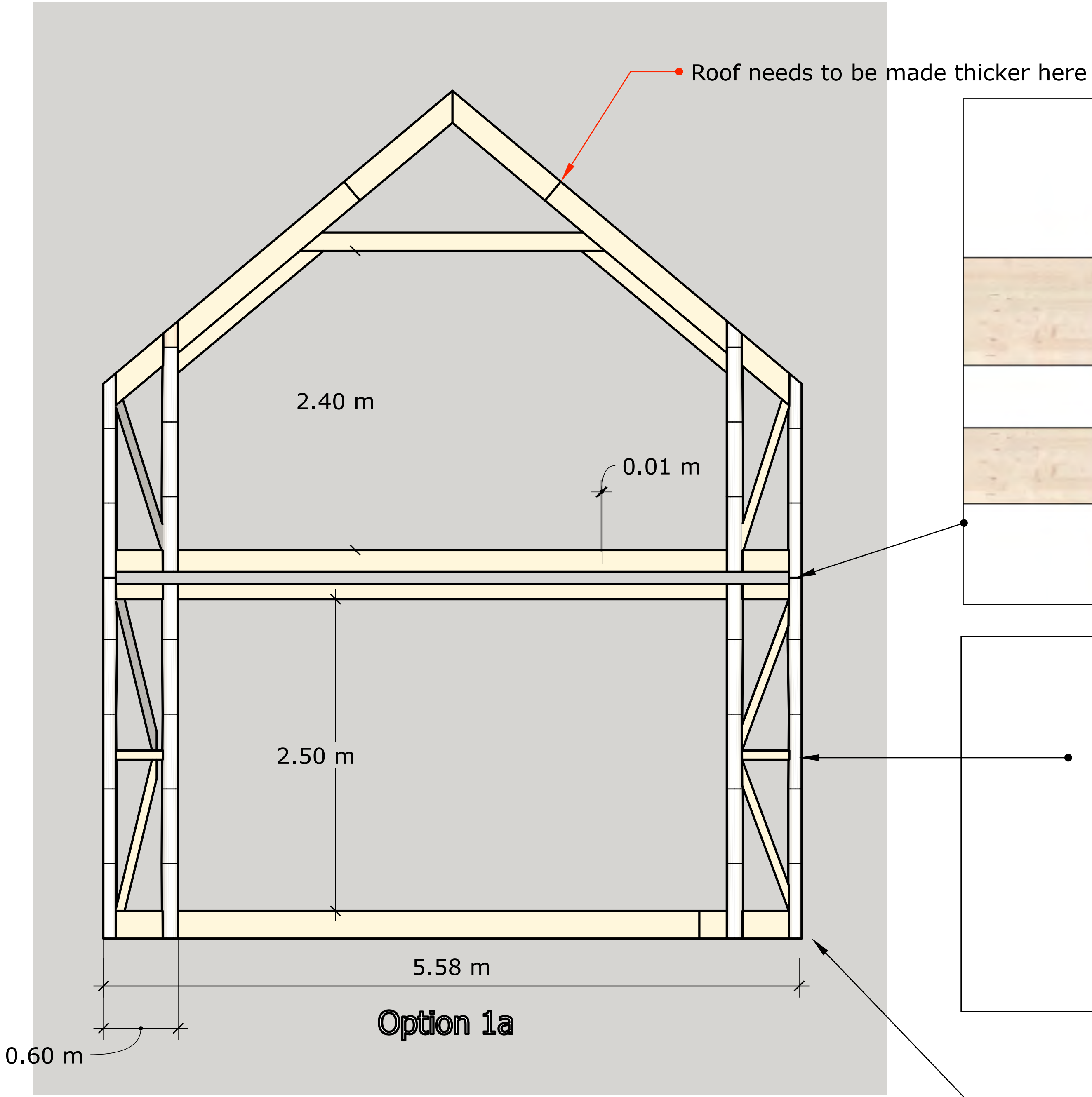
Option 3b: 100% Whole timbers – Timber flitch plates (no metal fixings)

Option 3c: 100% Whole timbers – Timber snap-fit connections (no metal fixings)

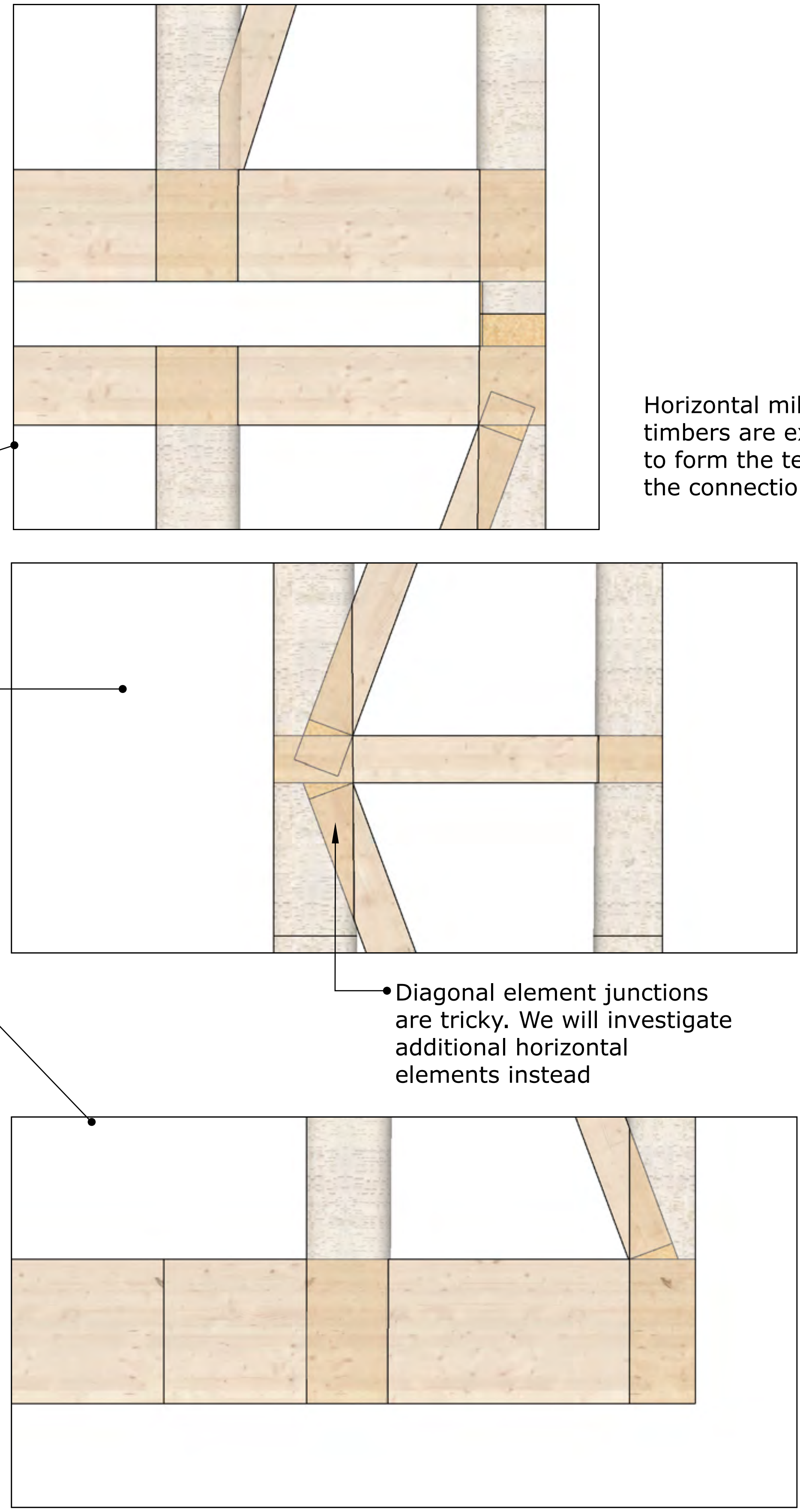
Notes:

All these designs use Integra House 1½ storey design as a base. This has the most connections, so solving the design for this arrangement should mean any connection can be solved.

Truss Assembly



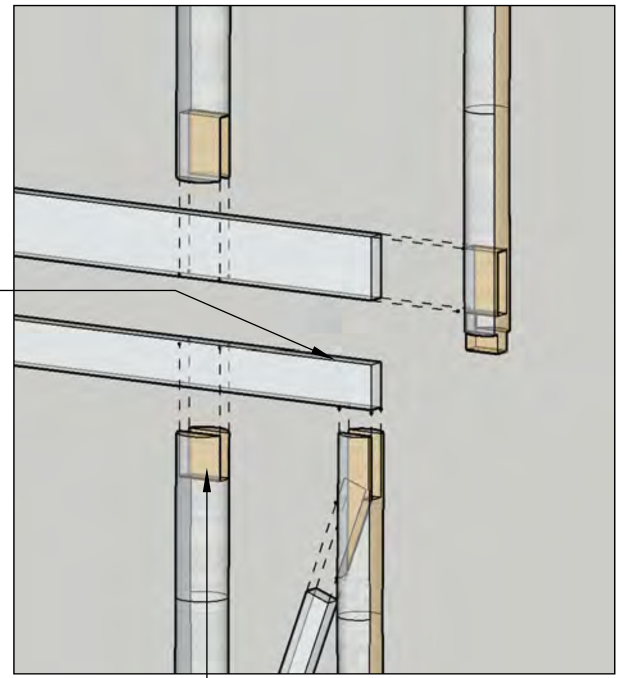
Connection details



<u>Description</u>

<u>Option 1a</u>

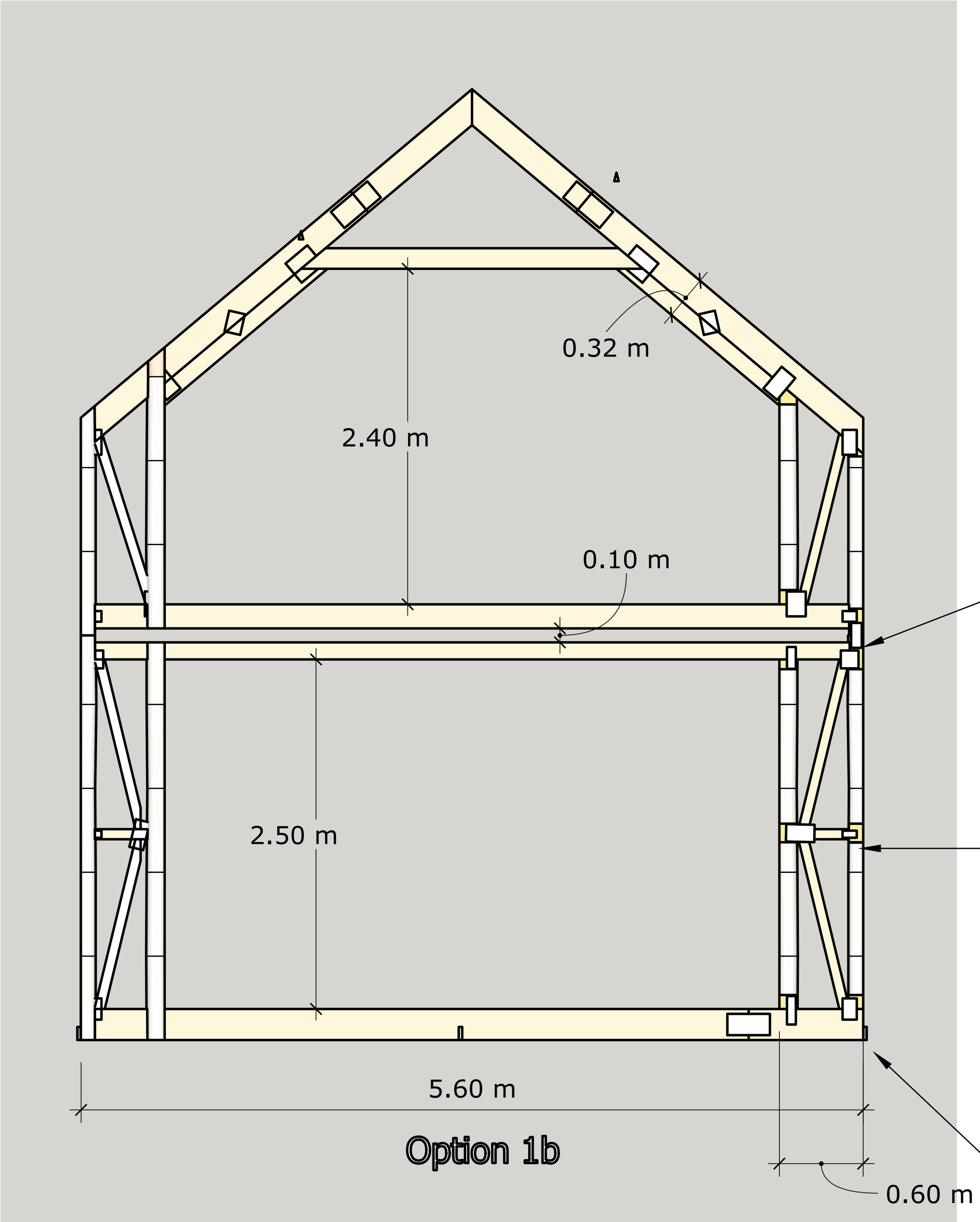
- Hybrid truss design
- Vertical whole timbers only
- Mortise & tenon joints between whole timber and milled timbers
- Gang-nail connections at milled timber connections



Revision Table	
123456789	Drng No
DRAFT	Revision
Option 1a	Title
01/01/2020	Date
A3	Paper
1:100	Scale

Integra House Prototypes

Truss Assembly



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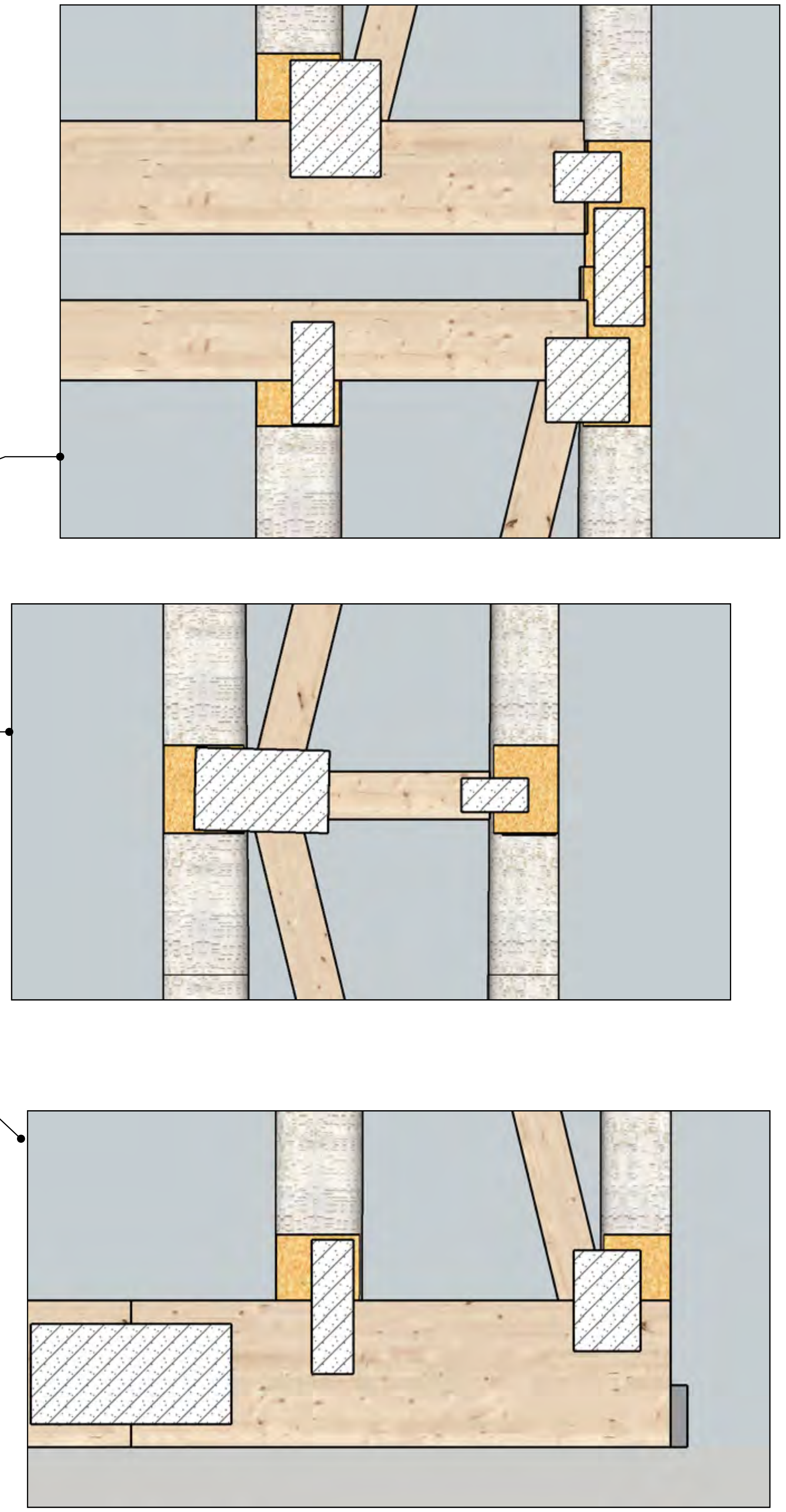
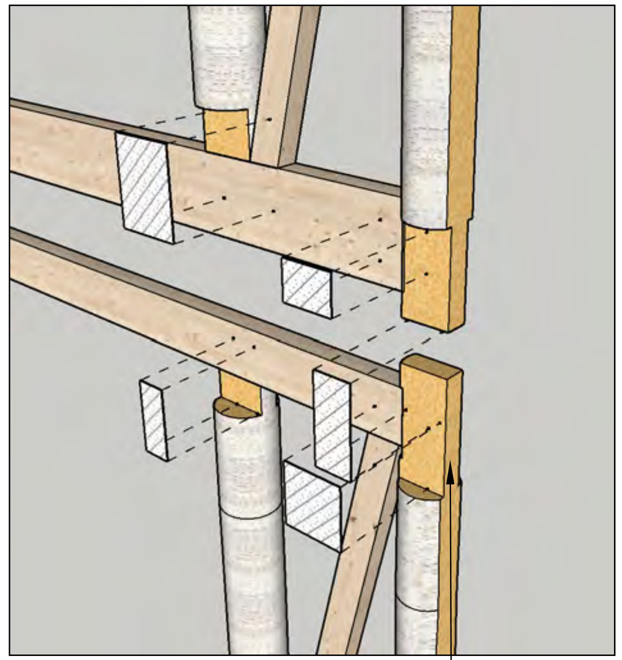


Description

Option 1b

- Hybrid truss design
- Vertical whole timbers only
- Steel gang-nail plates



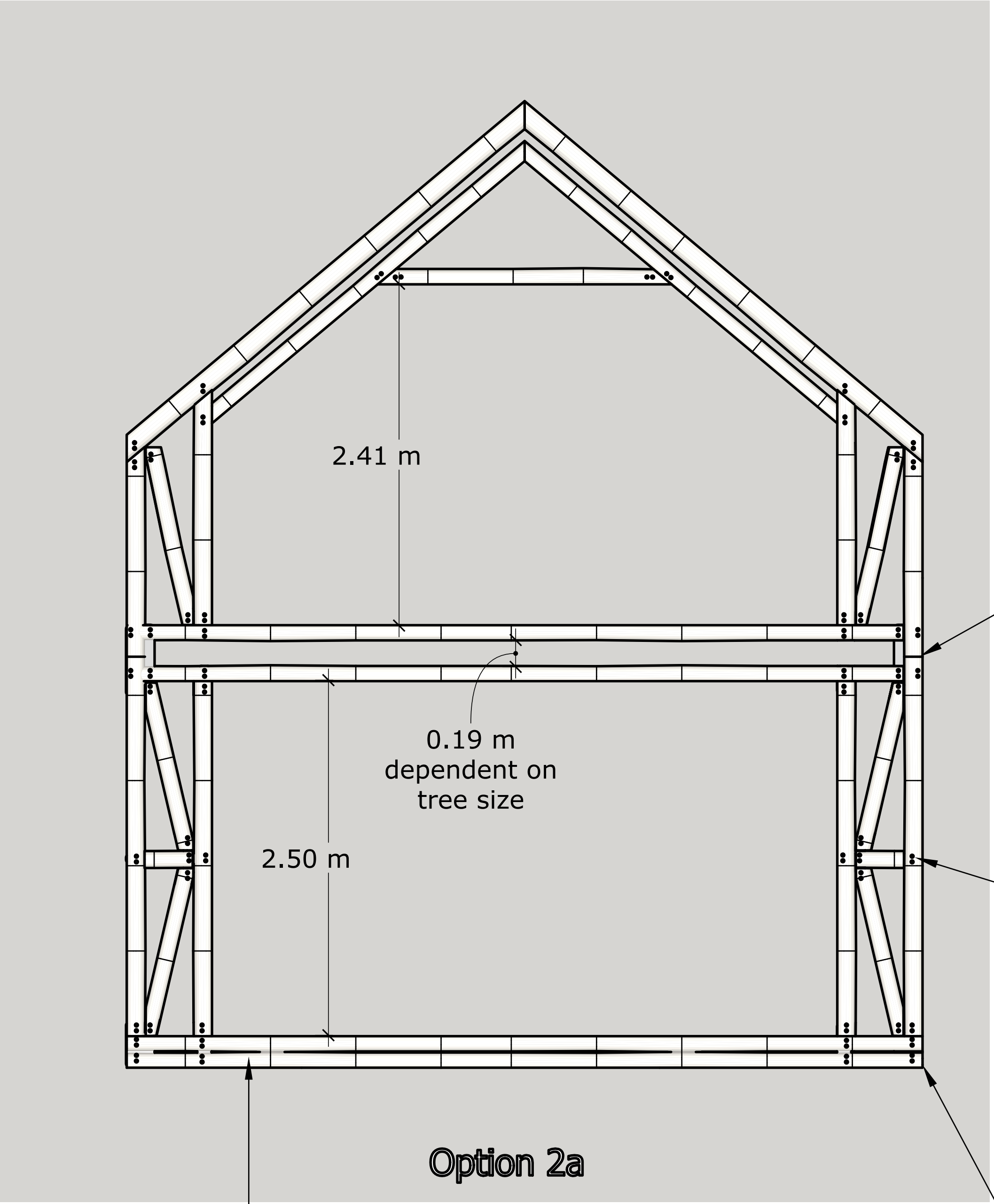
Whole timber thickness reduced to same thickness as milled timber (47mm shown)

Revision Table

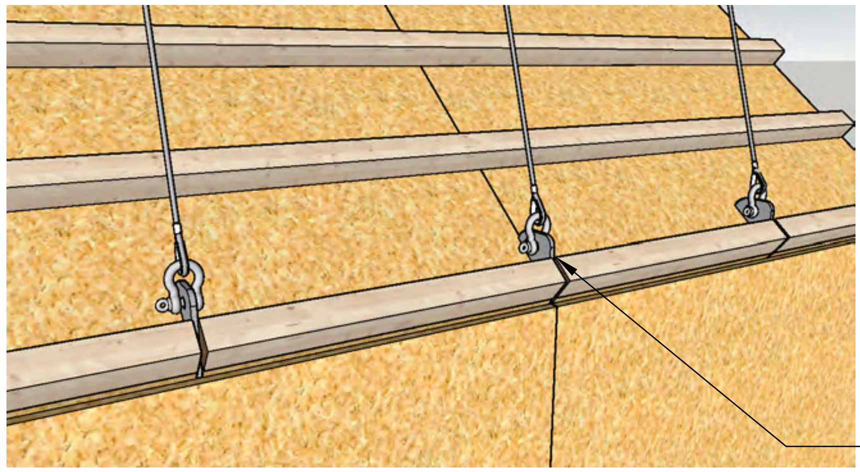
Drng No	123456789
Revision	DRAFT
Title	Option 1b
Date	01/01/2020
Paper	A3
Scale	1:100

Integra House
Prototypes

Truss Assembly

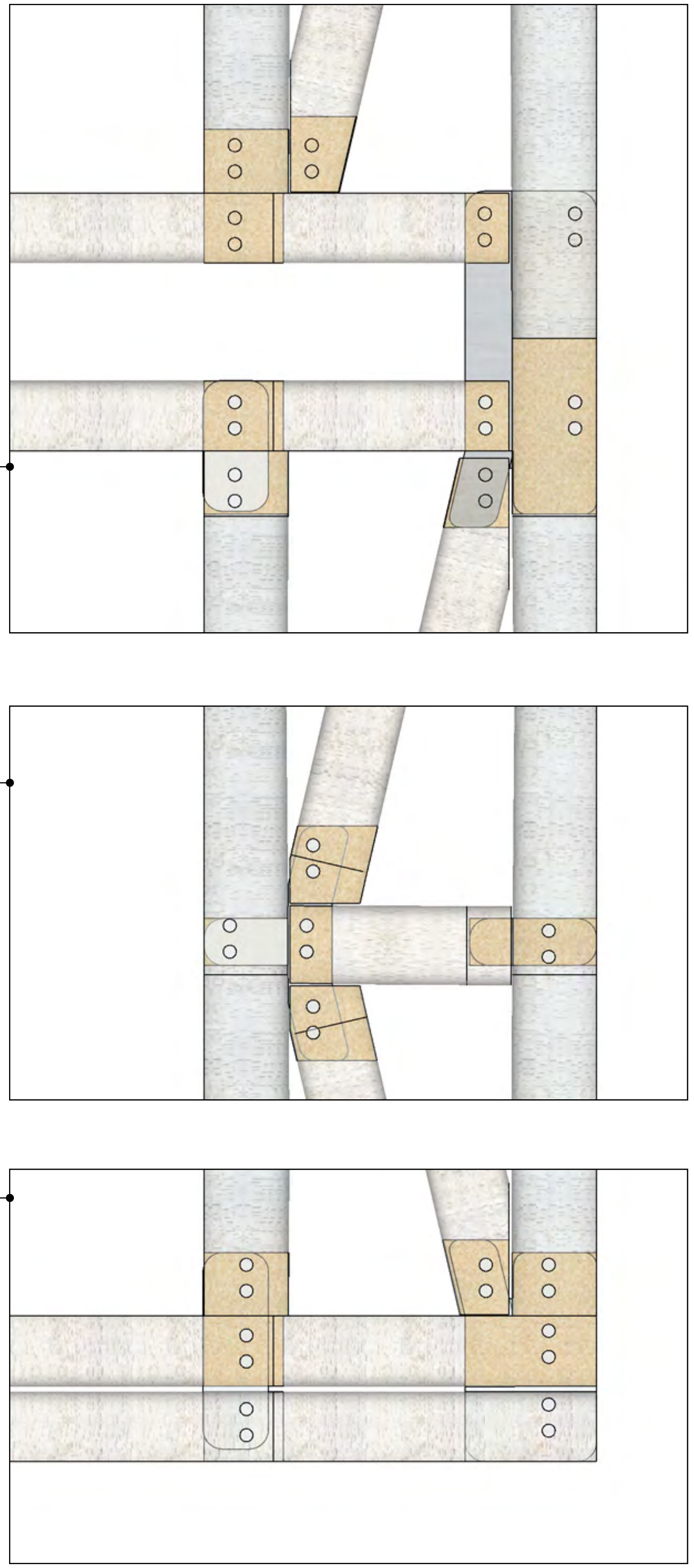


- Double joist depth shown
  If placed on a concrete floor
  thickness can be reduced to
  one timber



- Flitch plates can be extended to provide lift points for the module

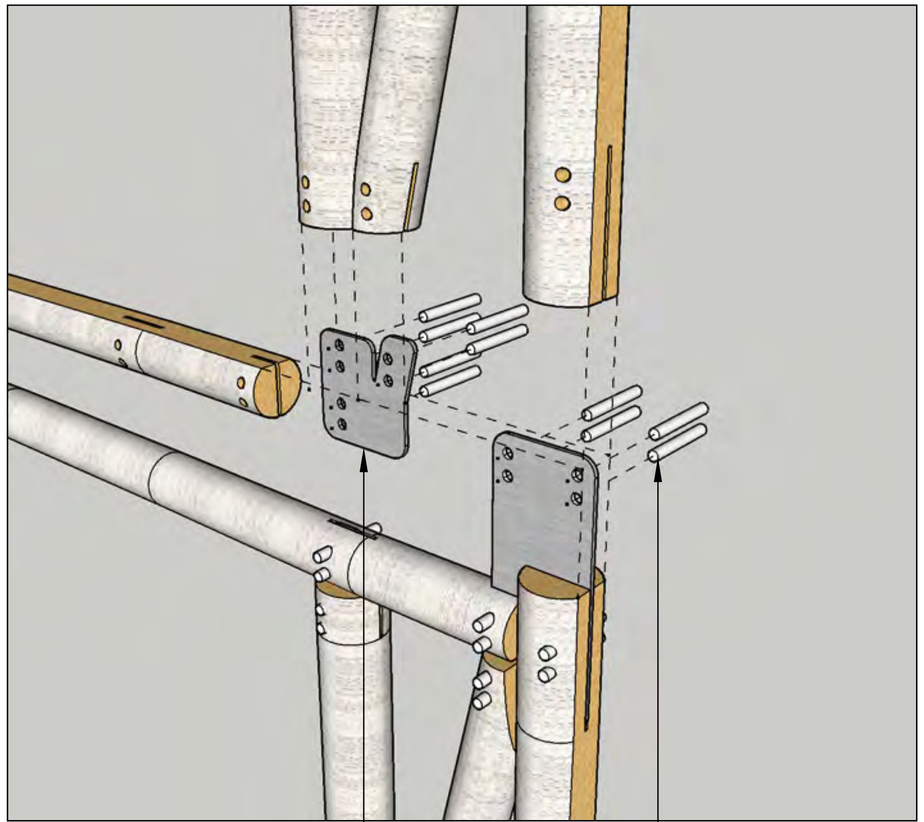
Connection details



Description

Option 2a

- **Whole timber truss design**
- Steel flitch plates to standard designs
- Steel bolts to secure flitch plates



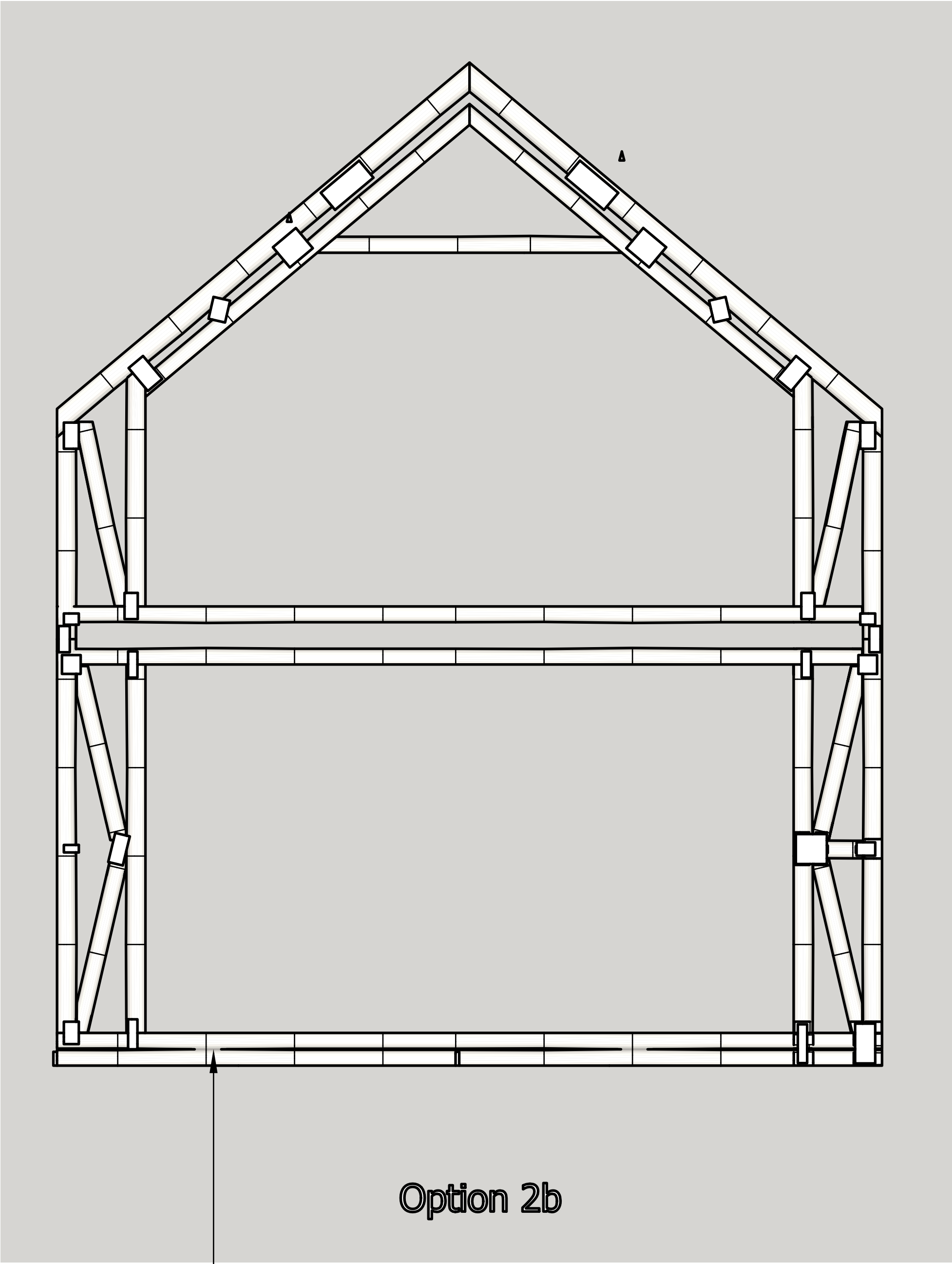
- Steel Flitch plates (8mm shown)
- Securing dowels or bolts

Revision Table

Drng No	123456789
Revision	DRAFT
Title	Option 2a
Date	01/01/2020
Paper	A3
Scale	1:100

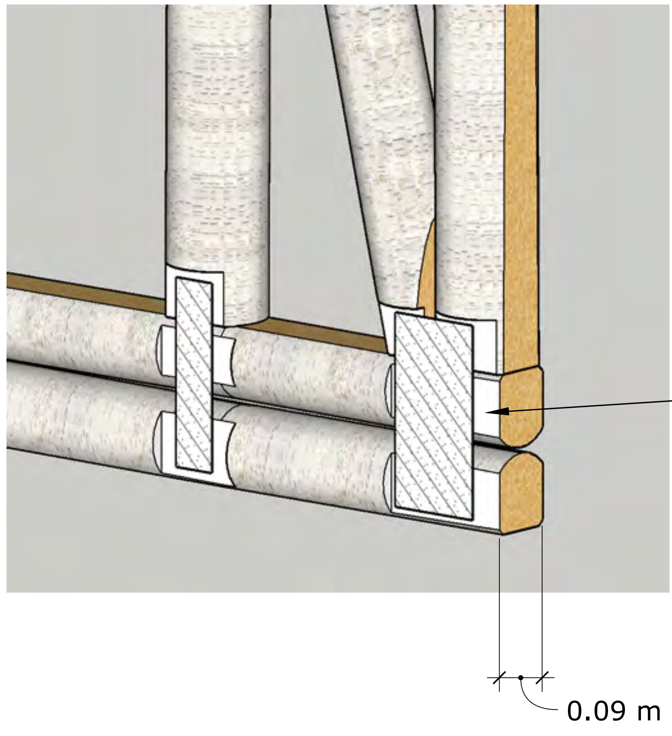
Integra House
Prototypes

Truss Assembly



- Double joist depth shown
If placed on a concrete floor thickness can be reduced to one timber

Connection details



- Nail-plate flats do not need to match any milled timbers, so minimal material can be removed instead (90mm width flats shown)

<u>Description</u>

<u>Option 2b</u>

- Whole timber truss design
- Metal gang-nail plates

Revision Table

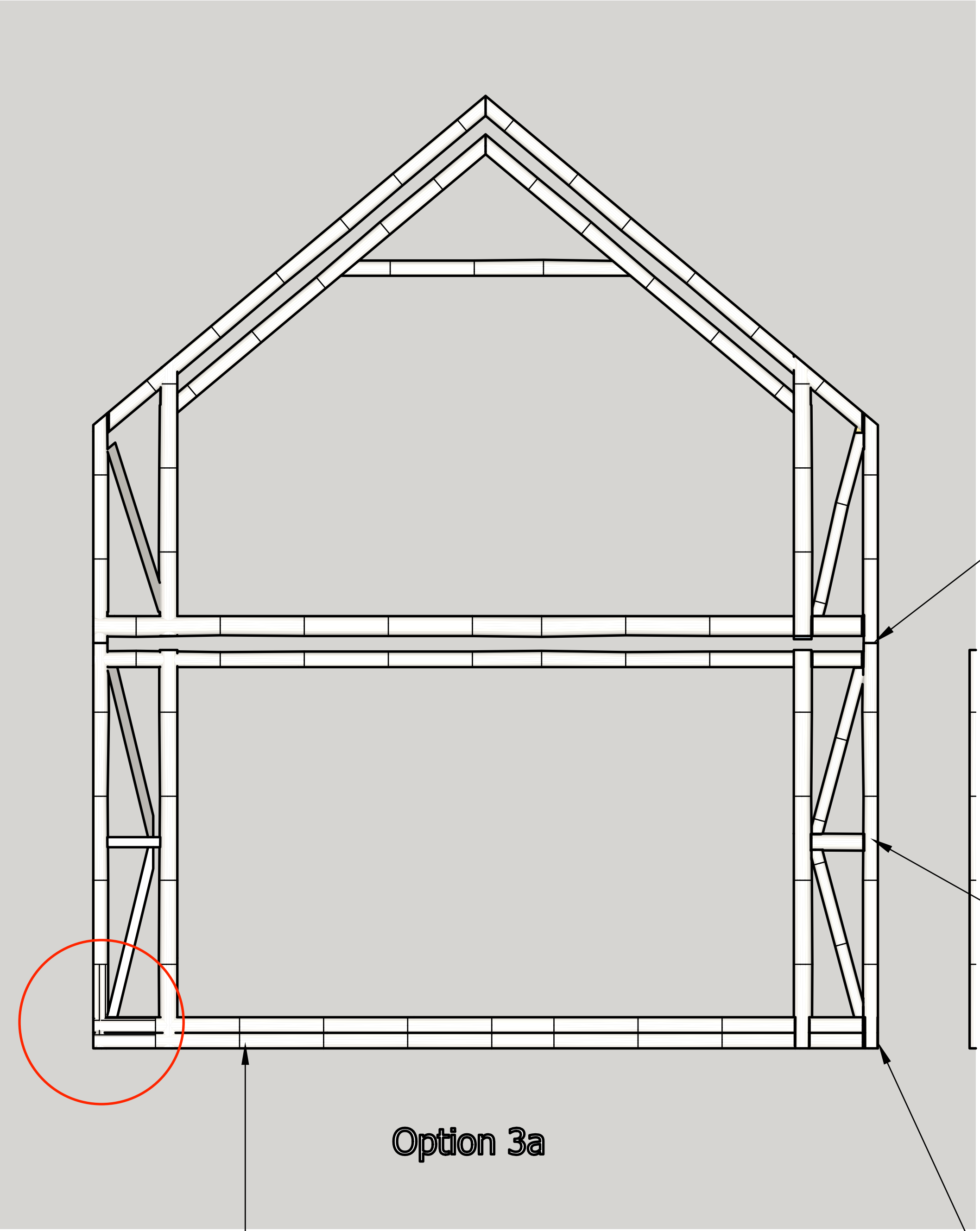
Drng No	123456789
Revision	DRAFT
Title	Option 2b
Date	01/01/2020
Paper	A3
Scale	1:100

Integra House Prototypes

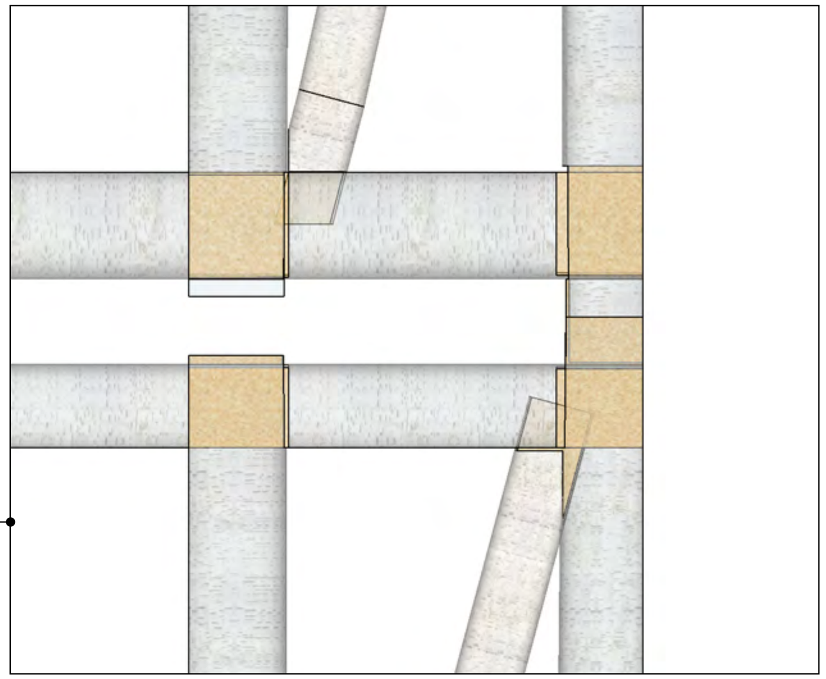
Description

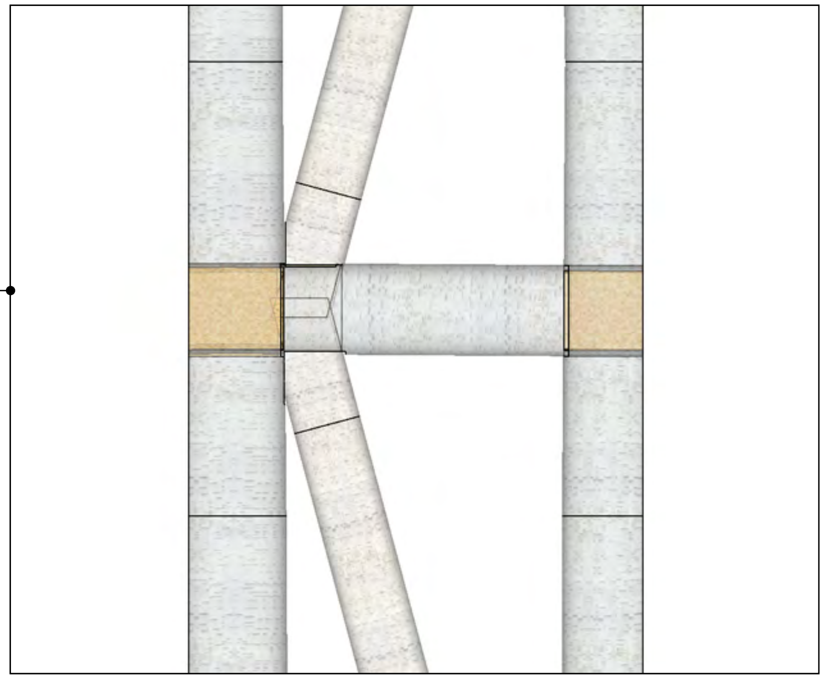
Option 3a

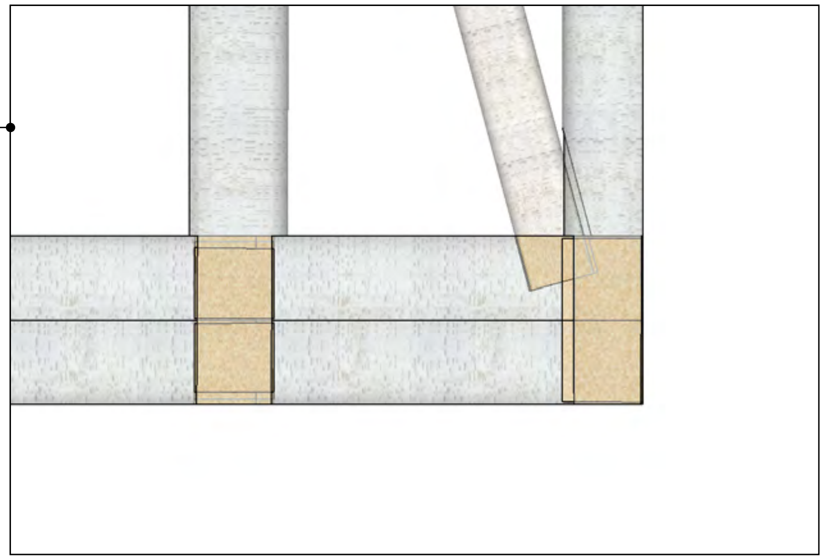
- 100% Whole timber truss design
- No metal fixings
- Mortise & Tenon joints secured with glue or timber dowels

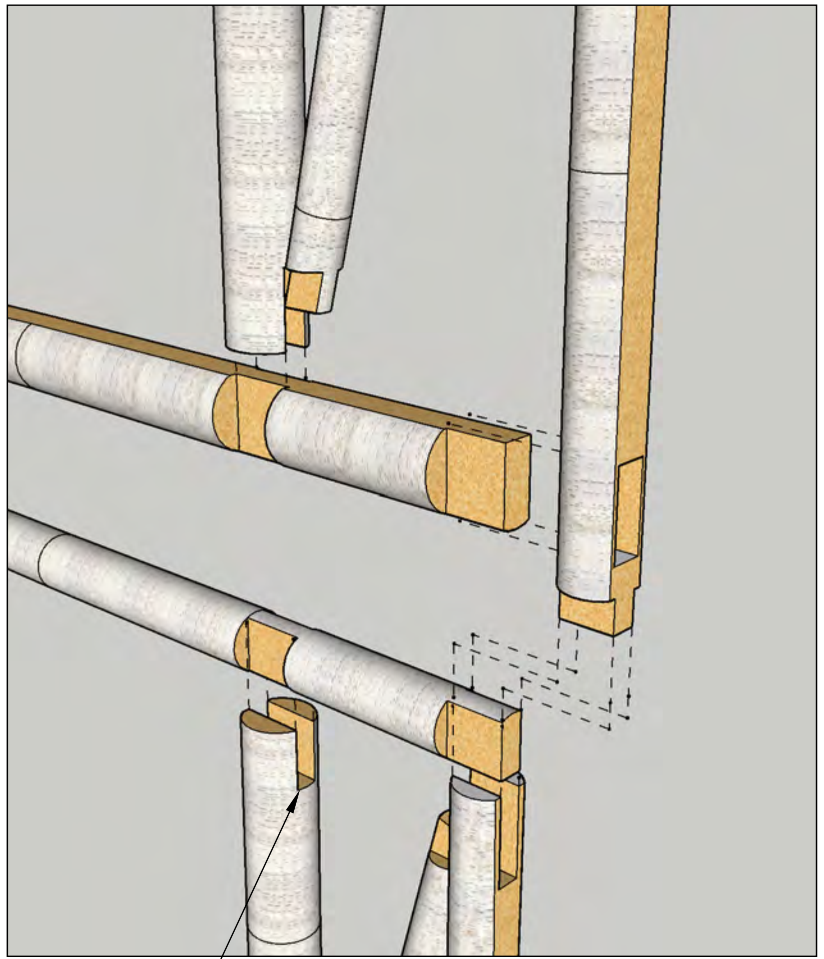


Double joist depth shown
If placed on a concrete floor
thickness can be reduced to
one timber





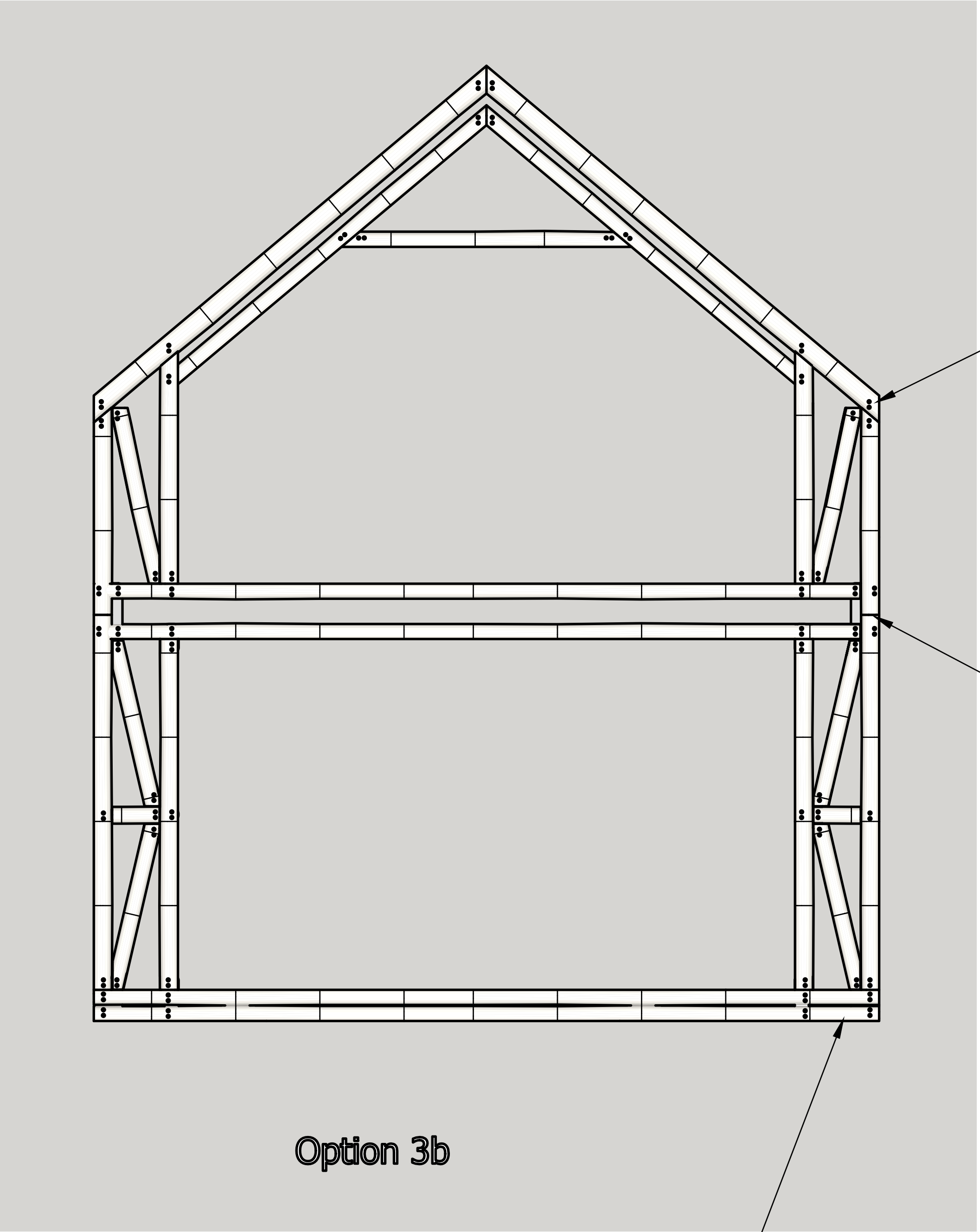


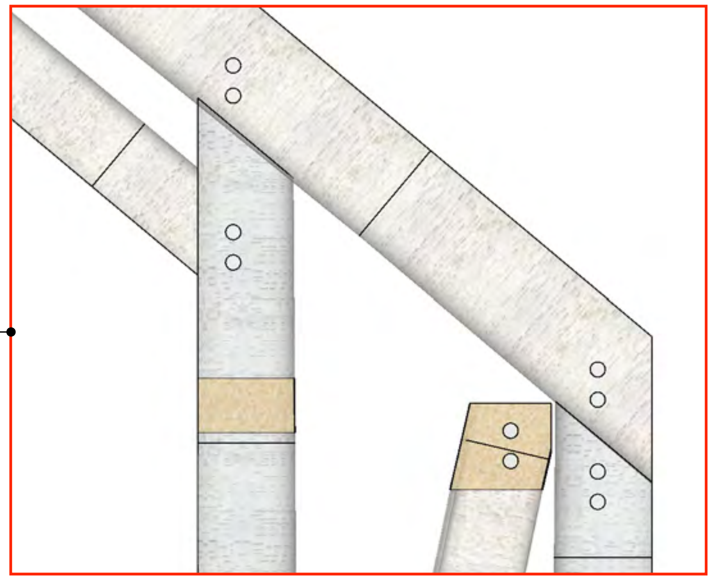


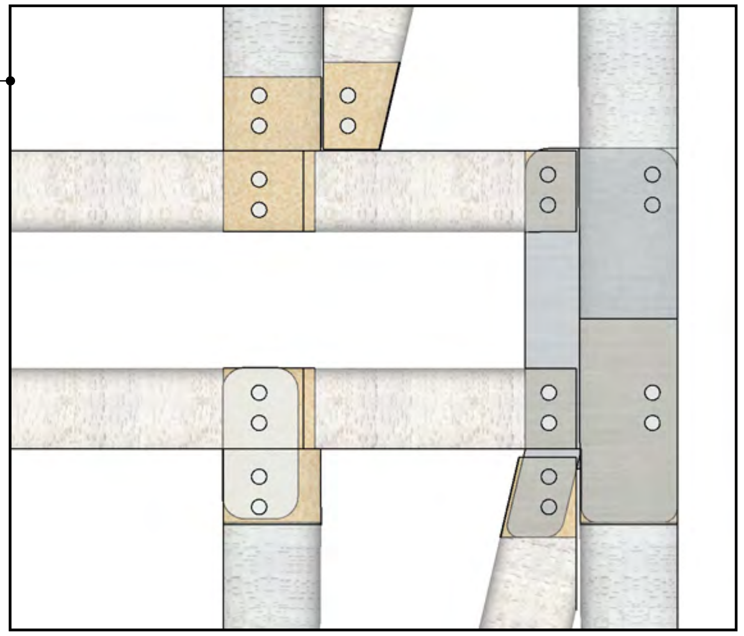
Universal tenon size
Can be used for main
timber junctions.
smaller tenons for
minor connections

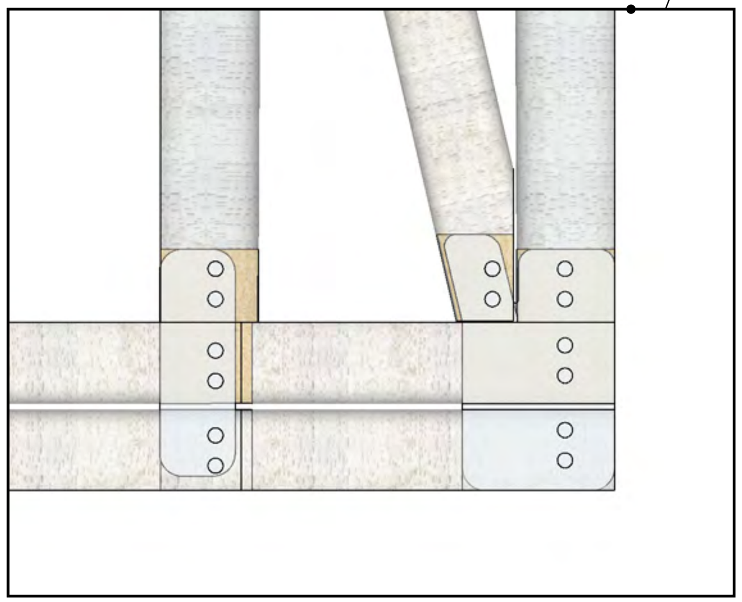
Revision Table	
Drng No	
Revision	
Title	Option 3a
Date	
Paper	
Scale	

Integra House
Prototypes





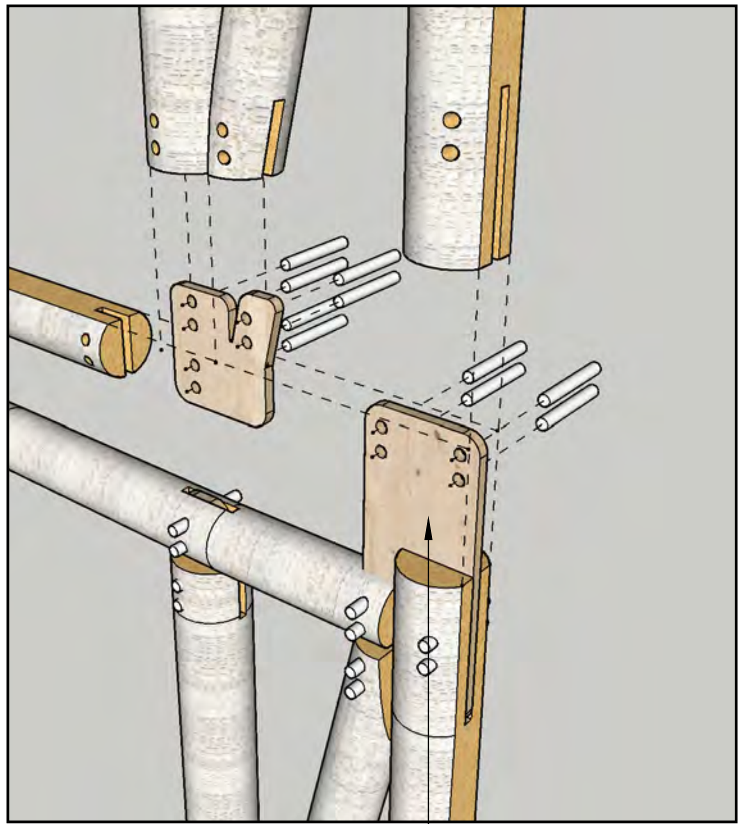




Description

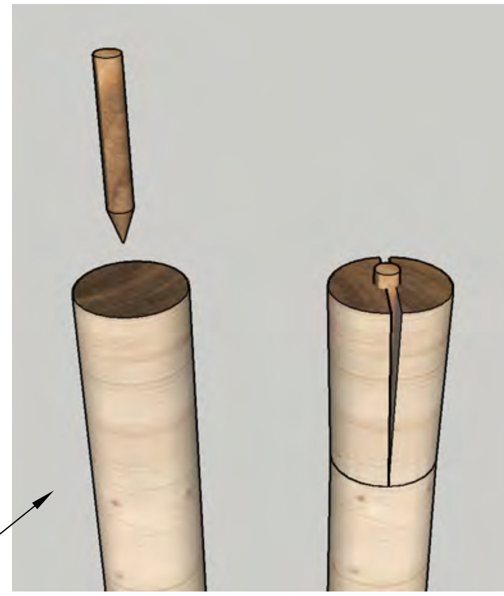
Option 3b

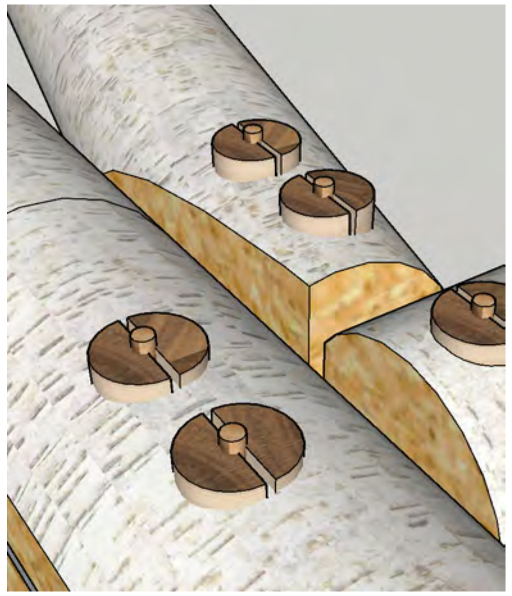
- 100% Whole timber truss design
- No metal fixings
- Timber Flitch Plates secured with glue or timber dowels



Timber flitch plates (18mm shown)

A solution to all-timber fixings. If Lignoloc timber nails are fired into the dowels that go through the flitch plates the will cause them to split and expand, hence securing them in the hole.
This avoids the use of glue and they can be drilled out again in future if they to be dismantled.





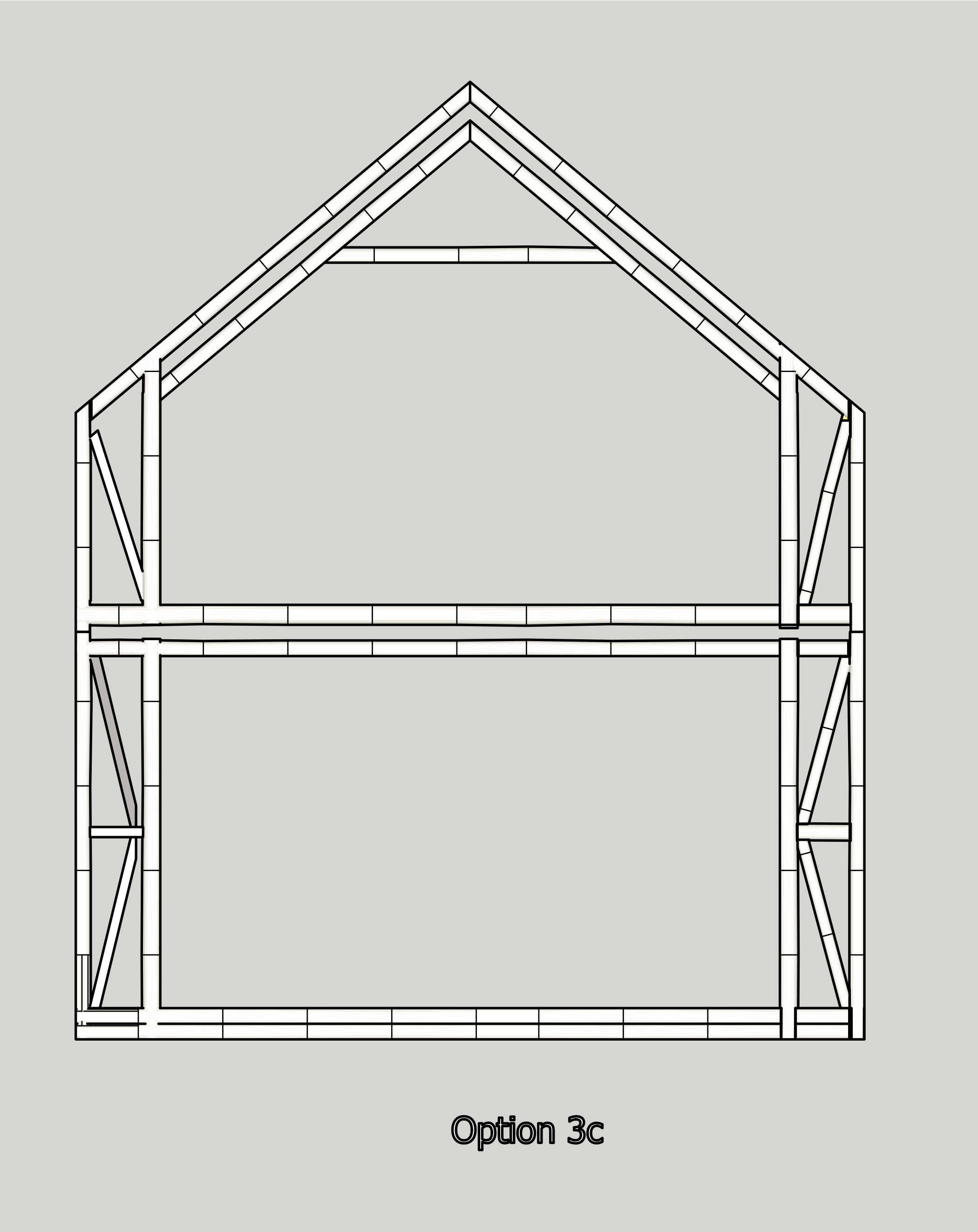
Revision Table	
Drng No	
Revision	
Title	Option 3b
Date	
Paper	
Scale	

Integra House Prototypes

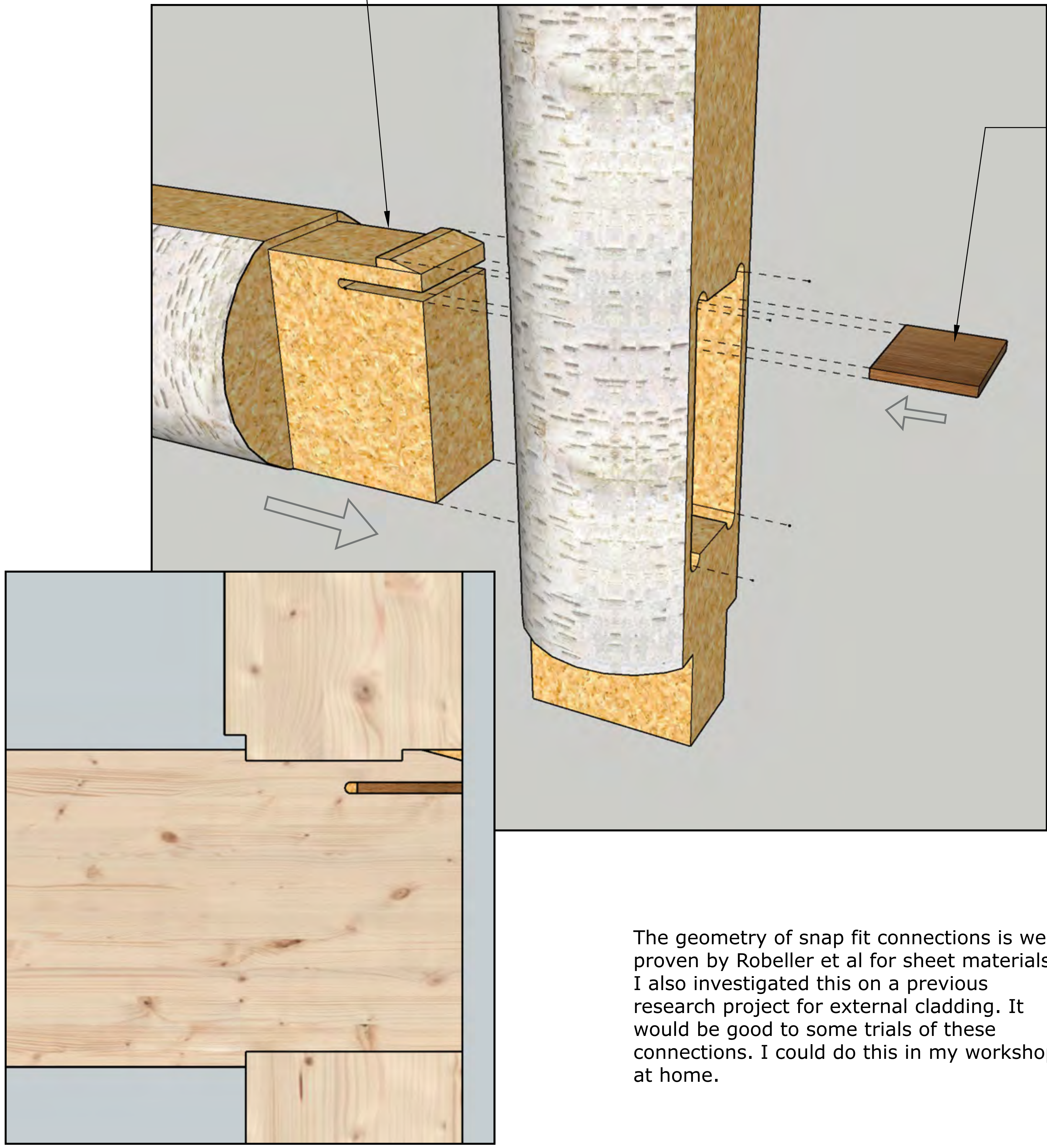
Description

Option 3c

- 100% Whole timber truss design
- No Metal fixings
- Snap-fit connections



Profile could be cut using CNC router



Hardwood Locking Piece is installed into slot after joint is made.
This effectively locks the joint and improves its structural performance

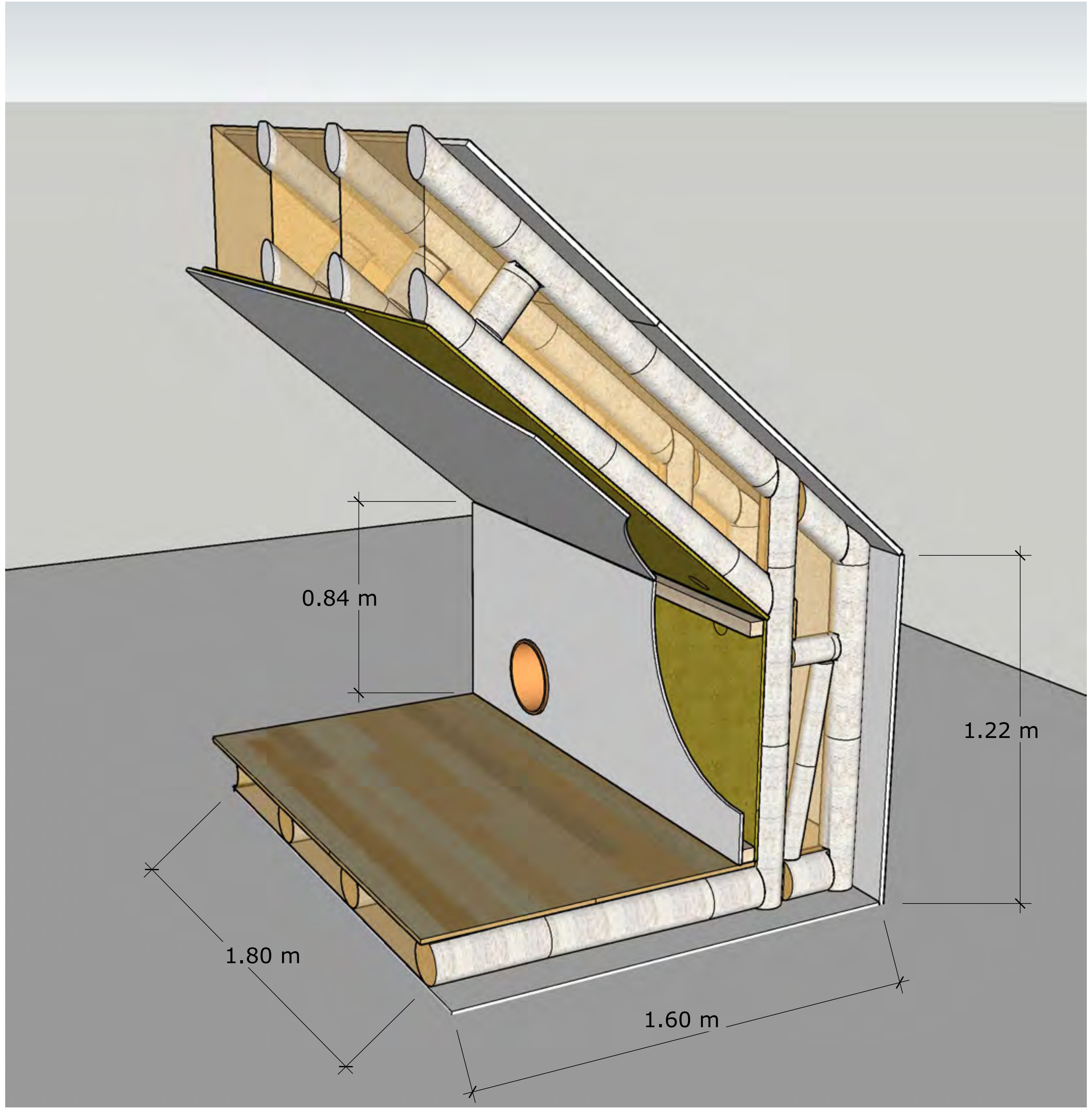
Alternatively the Lignoloc nail idea from 3b may work instead

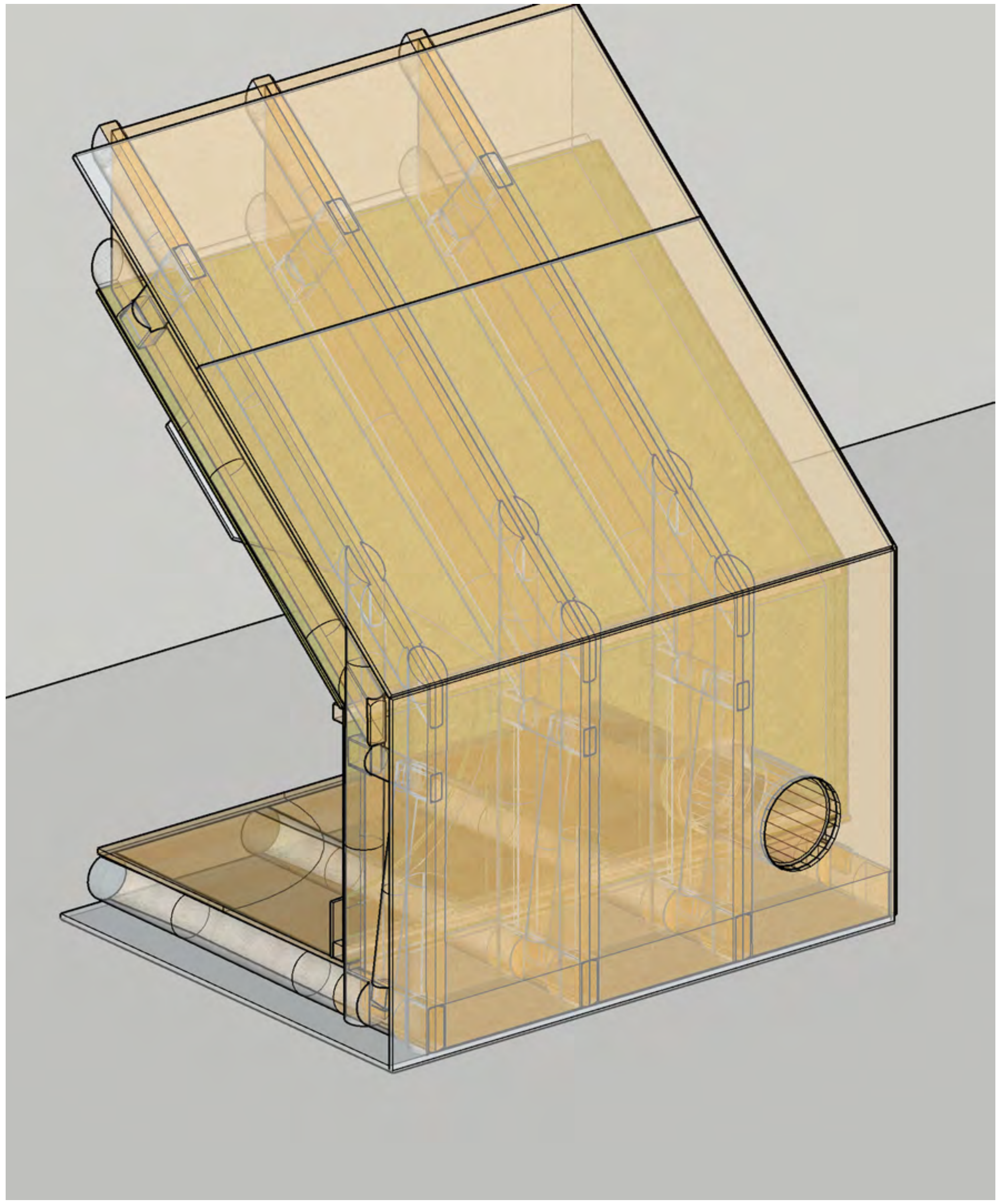
The geometry of snap fit connections is well proven by Robeller et al for sheet materials. I also investigated this on a previous research project for external cladding. It would be good to some trials of these connections. I could do this in my workshop at home.

Revision Table	
Drng No	
Revision	
Title	Option 3c
Date	
Paper	
Scale	

Integra House
Prototypes

A proposed demonstration module





The figures above show two views of a truss demo module.
The exact trusses used in this design are yet to be determined, these figures are for illustration and approximate size only.

Revision Table

Drng No

Revision

Title

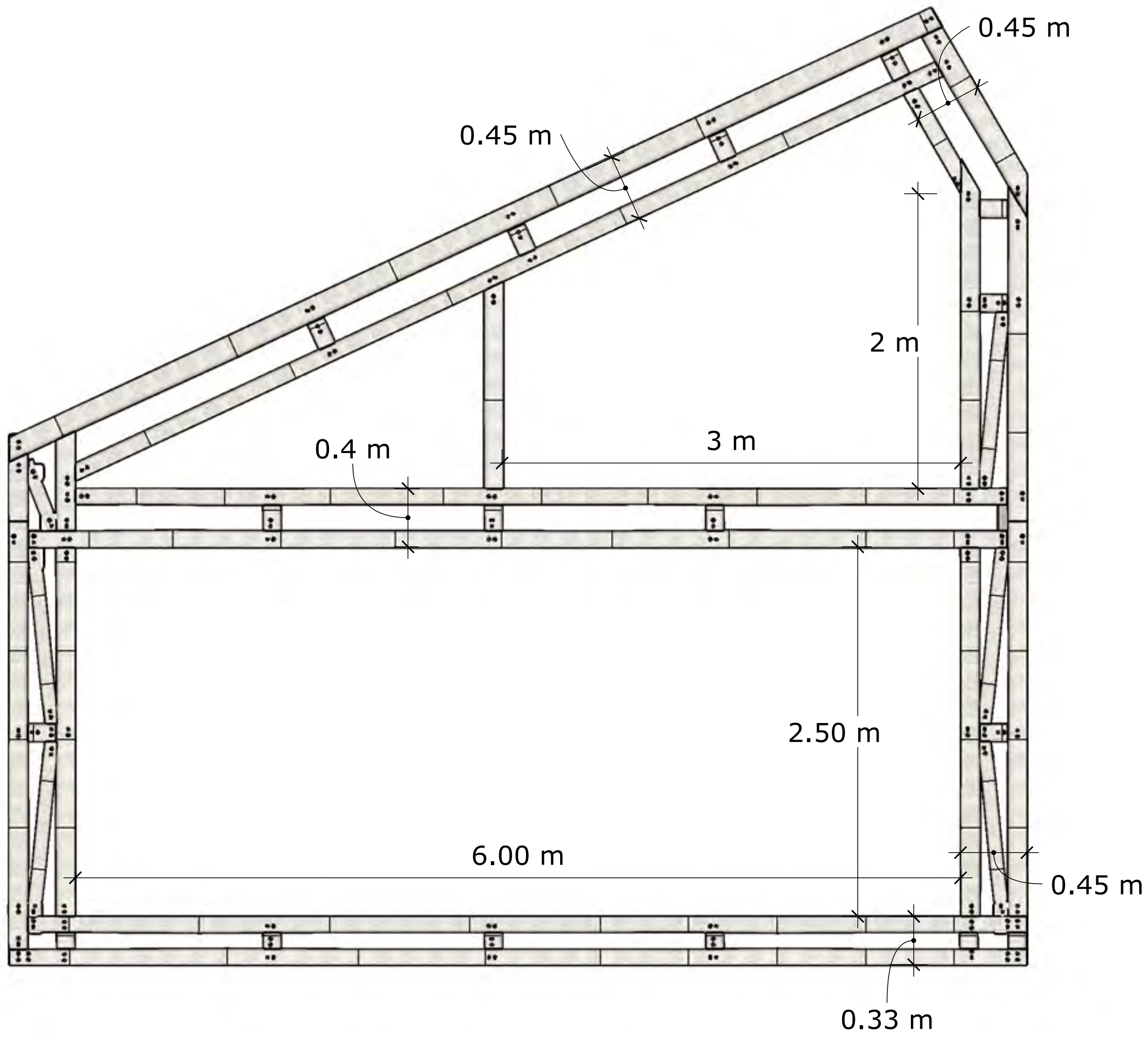
Date

Paper

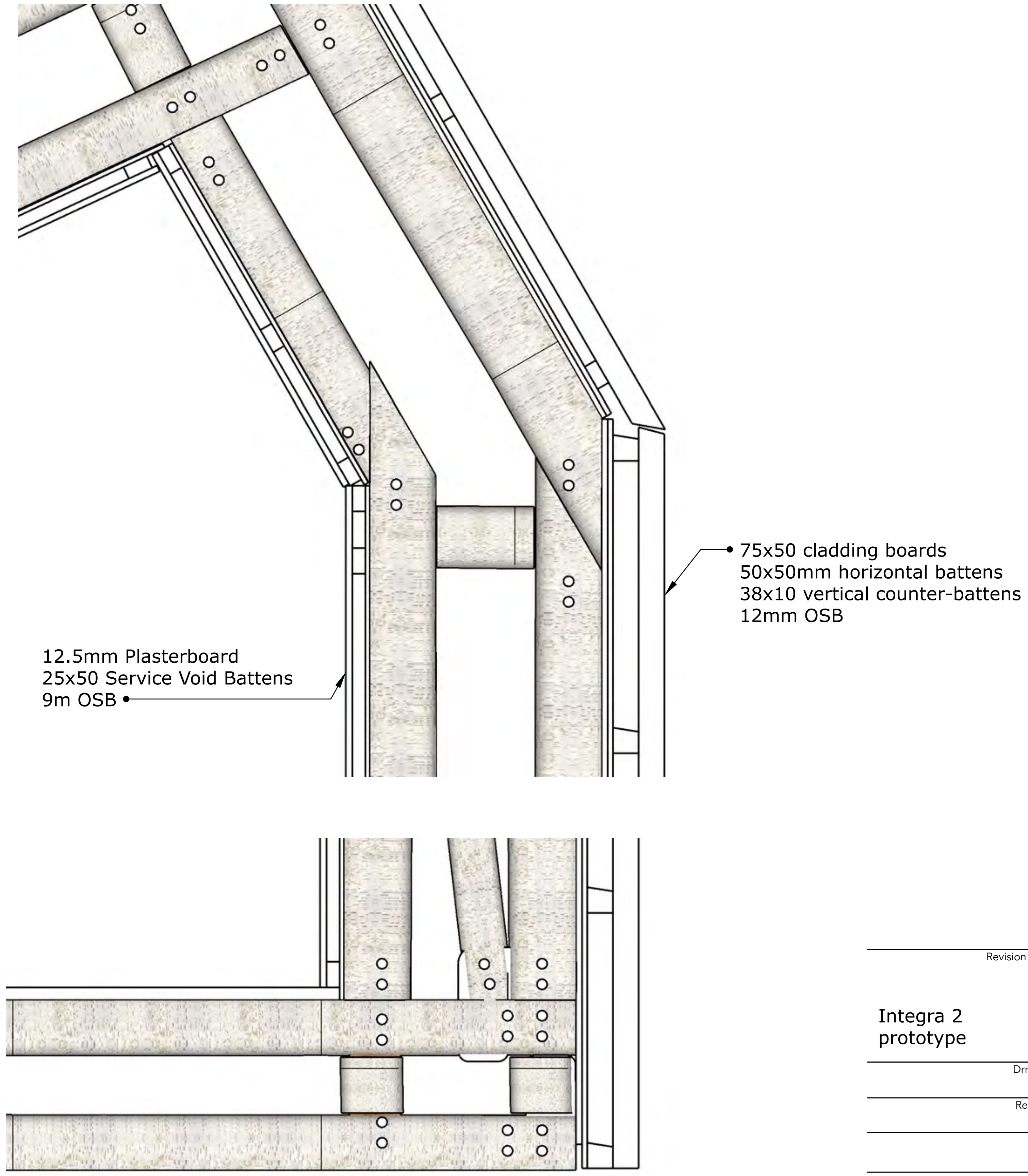
Scale

Integra House
Prototypes

Final proposed truss design



Lining details



<u>Truss Construction</u>

Whole timber trusses with 18mm plywood flitch-plates and timber dowels

<u>U-Values:</u>

Walls: 0.11 W/m²K
Roof: 0.11 W/m²K
Floor: 0.13 W/m²K

Revision Table

Integra 2 prototype

Drng No

Revision

Title

Date

Paper

Scale

Integra House Prototypes