Appendix B

Design for deconstruction and reuse: Case study Everett Grand

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Figure 1 Everett Grand ©Robertson Timber Engineering

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Innovative Design for the **Fu**ture – **U**se and **Re**use of **Wood** Building Components

FOREWORD

This report is one in a series of five case study reports in the InFutUReWood project – Innovative Design for the Future – Use and Reuse of Wood (Building) Components. The first case (Sandin et. al 2021) served as a template, and therefore the report structure as well as some of the general content is common to this report and the first one. All five cases can be found as appendices to Y. Sandin, E. Shotton, M. Cramer, V. González-Alegre, G. Íñiguez-González, S.J. Walsh, C. Cristescu, K. Sandberg (2022): *Design of Timber Buildings for Deconstruction and Reuse: Three methods and five case studies.* RISE Report 2022:52, ISBN 978-91-89561-92-2.

InFutUReWood is supported under the umbrella of ERA-NET and financed by funding agencies from each of the participating countries. The industry partners participate mostly with in-kind.

The research and academia project partners are RISE (Sweden), Edinburgh Napier University (UK), National University of Ireland Galway (Ireland), University College Dublin (Ireland), Polytechnic University of Madrid (Spain), University of Ljubljana (Slovenia), Aalto University Helsinki (Finland), and Technical University Munich (Germany).

The industry partners are Kiruna Municipality Technical Service, Swedish Wood, Derome, Isotimber, Offsite Solutions Scotland, Hegarty Demolition, Robertson Timber Engineering, SIP Energy, Connaught Timber, The Federation of the Finnish Woodworking Industries, Jelovica, The Swedish Federation of Wood and Furniture Industry, Balcas Timber, Stora Enso, Klimark + Nova domus Hábitat, and Brenner Planungsgesellschaft.

InFutUReWood is supported under the umbrella of ERA-NET Cofund ForestValue by Vinnova – Sweden's Innovation Agency, Formas, Swedish Energy Agency, the Forestry Commissioners for the UK, the Department of Agriculture, Food and the Marine for Ireland, the Ministry of the Environment for Finland, the Federal Ministry of Food and Agriculture through the Agency for Renewable Resources for Germany, the Ministry of Science, Innovation and Universities for Spain, the Ministry of Education, Science and Sport for Slovenia. This is supported under the umbrella of ERA-NET Cofund ForestValue, and ForestValue has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 773324

Summary

Background: More than 80% of new built houses in Scotland use timber frame construction. This has been a development of the last twenty years, and before 2000 masonry construction was the predominant building technique for residential houses. Nonetheless, more than 25% of the UK's wood waste comes from demolitions. In the future, when today's buildings come to the end of their life, a considerable amount of wood will become available. Currently, wood waste is mostly chipped and incinerated for energy production, but if timber could be recovered in a good condition, it could be reused in buildings instead. Deconstructing buildings and reusing their parts instead of demolishing them is a circularity strategy that keeps timber in use for longer and has environmental benefits.

Aim and objectives: The case study aims to uncover advantages and disadvantages of contemporary UK timber houses with respect to deconstruction and reuse. We aim to address the disadvantages with new design concepts that can ultimately be generalised to facilitate design for deconstruction and reuse (DfDR) in other designs. It is hoped that this work will encourage the deconstruction of timber buildings instead of demolition and the reuse of timber building components.

Methods: The case study method involved a discussion between researchers and building manufacturers at Robertson Timber Engineering. We imagined how the deconstruction of the case study building would be conducted, which tools would be needed, which damage to the timber structure might occur and how assemblies could be reused in a new building. Advantages of the current design were analysed following the discussion and new design concepts that address the disadvantages were proposed. The amount of wood that is easily recoverable and reusable in both the current and the new design were calculated.

Results: The case study building could be deconstructed and its assemblies reused even with today's design. It is assumed that around 95% of structural timber could be recovered damage free and reused in the same building type. Small design changes would facilitate deconstruction and open more reuse options, however. If nails were to be replaced with screws, deconstruction would be more controlled and safer. Assemblies could also be more standardised to allow for different reuse scenarios. With the different improvements, up to 98% of structural timber can be reused.

In addition, design changes to improve the adaptability of the building are proposed. Adaptable buildings are expected to have a longer lifespan and are hoped to be perceived as more desirable and preservable houses.

In addition to improving the building design, to enable deconstruction and reuse it is important to plan and communicate circularity goals and to adapt business models to circularity. A business model is suggested, in which the manufacturer retains ownership of the building assemblies and incorporates a reuse strategy in its business as usual. As part of this, recommendations for deconstruction instructions and an example deconstruction plan were developed.

Conclusion: Contemporary timber houses can be deconstructed and reused. Small design changes can improve the reuse potential of recovered assemblies, but they need to be part of a holistic design strategy and a circular business model to achieve maximum effects.

Content

1. Introduction

1.1. Background

Around 83% of new houses in Scotland are built as timber frame construction (Structural Timber Association 2017). This has been a development of the last twenty years (besides a short surge of the construction technique in the 1970s and 80s), and before 2002 other construction methods were predominantly used in residential buildings (Palmer, n.d.). Nonetheless, more than 25% of the UK's wood waste comes from demolitions and this resource is mostly chipped and used for energy production (Cramer and Ridley-Ellis 2020a). Buildings in the UK are often being demolished because they are in the wrong place at the wrong time, and not because the materials inside the building are faulty or too old (Cramer and Ridley-Ellis 2020b). One way of keeping wood in use for longer and decreasing the environmental impact of construction is to reuse buildings and building components to a higher degree. In order to facilitate this, buildings would need to be designed with that aspect in mind. Today, significant difficulties can arise in deconstructing already manufactured buildings and reusing their parts. The difficulties have to do with things like joining techniques, use of chemicals etc. There is a lack of published knowledge on how wood-based building frames are best designed for deconstruction and reuse.

InFutUReWood, Innovative Design for the Future - Use and Reuse of Wood (Building) Components, focuses on the structural reuse of timber. Within work package 2 of the project, we aim to optimise primary design to enhance resource efficiency in building deconstruction. In particular, we aim to answer the following research questions:

1. What new design concepts facilitate deconstruction?
2. How can connections be optimised?
3. How can guidelines for disassembly be formulated?

To answer these questions, we conducted five case studies in four of the partner countries. In this report, we describe the case study of an offsite constructed, light timber frame house in the UK.

Offsite Solutions Scotland (OSS) is a network of eight offsite timber manufacturing companies in Scotland. They work together with research institutes and Government to carry out collaborative research to drive forward the offsite industry to improve delivery, increase quality and reduce waste. Robertson Timber Engineering are a member of OSS.

1.2. Aim

This work aims ultimately at producing guidelines for the design of wooden building frames with respect to deconstruction and reuse. A case study has been conducted to examine the problems that can occur for a specific design and to suggest how the problems could be solved by modifying the design.

The case study is the third in a series that will consider different types of wooden frame systems. With a number of completed cases, it should be possible to identify common as well as and case-specific characteristics.

The object of this case study is a design concept from Robertson, the “Everett Grand”, which is a light timber frame construction with prefabricated open panels, Figure 2.

Figure 2 Everett Grand, exterior. ©Robertson Timber Engineering

1.3. Objective

To satisfy the above aim, the objectives of the case study were to identify:

- What strengths and weaknesses the design of the Everett Grand has, with regard to future deconstruction and reuse.
- How the design could be improved with respect to future deconstruction and reuse.
- How much wood could be reused in the future with the current design and how much wood could be reused after further development. By reuse we mean that a part / component is used for basically the same purpose as it was originally intended. (See also 1.5 Terms and Definitions.)

1.4. Delimitations

The study focuses on the design of the *load-bearing structure* i.e. the frame. The design of the frame can depend on how installations are drawn, how the climate shell is designed and so on. Such parts therefore may need to be taken into account in the analysis to some extent.

The case study focuses on solutions that can be considered in the design phase. We are looking for solutions that make building frames as well adapted for reuse as possible, while at the same time having a price and a design that means that the manufacturer has a sustainable business model. The fact that the building is "adapted for reuse" here means that the parts can be disassembled, transported, stored and reassembled without losing [much of] their function and economic value. (For example, by being damaged by disassembly and handling.)

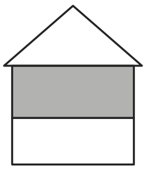
It is assumed here that it is efficient from an environmental and resource point of view to design buildings so that in the future it is possible to deconstruct them and reuse their parts, i.e. to adopt a design philosophy sometimes referred to as Design for Deconstruction and Reuse, DfDR. The environmental impact from construction and real estate industry would perhaps decrease the most if buildings were designed for adaptability. That is, if they were designed so that they could be adapted for new demands when necessary, and kept in the place where they were originally erected. In practice, buildings must in many cases be taken down after a number of years of use, and to minimise the harmful environmental impact of this, we focus here on DfDR. Approaches for design for Adaptability are also discussed in this study, but are not the primary focus.

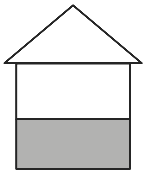
This study investigates *technically possible* design improvements with respect to DfDR. Costs and environmental impacts for different solutions are not examined.

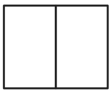
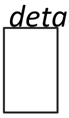
The study is in large parts qualitative rather than quantitative. For example, judgements of which work steps that can be considered difficult or time-consuming in a deconstruction process are based on the judgement of timber frame manufacturers and joiners and their experience with the erection of the structure. The study does not test the feasibility, let alone measure the time or energy it takes to perform different deconstruction actions.

1.5. Terms and definitions

Adaptability	Ability to be changed or modified to make suitable for a particular purpose, with minimal material flows. Within the built environment. The concept of adaptability can be broken down into a number of simple strategies, such as versatility, convertibility and expandability.
Assembly	Set of components, attached to each other to form a functional unit. Can be 2-dimensional (planar), e.g. wall panels, floor cassettes or roof trusses, or 3-dimensional, e.g. modules, pods.

Building Information Modelling **BIM**	Digital models that contain not only the building geometry, but are data-rich in terms of relations, physical attributes, time, costs and quantities. The result is a collaborative tool that can be used by the whole project team, clients and end users. BIM is used to generate and manage data throughout the entire life cycle of the building, from inception, design, through construction to demolition and recycling. Benefits include a significant reduction in risk through improved co-ordination, control and flow of information, improved accuracy of cost and programme planning, increased productivity, efficiency and predictability because of managing teams and data centrally and reduced rework on site.
Deconstruction **Disassembly**	The systematic dismantling and removal of a structure or its parts, in the reverse order of construction, with the intent of repurposing, reusing, recycling, or salvaging as many of the materials, products, components, assemblies, or modules as possible.
Design for Deconstruction **Design for Disassembly**	Design and construction strategy to facilitate future change and the eventual dismantlement (in part or whole) for recovery of systems, components and materials. Includes: 1) how building parts can be repaired or dismantled without breaking them 2) how the remaining lifetime of the dismantled parts can be utilised in new applications. The primary goal is to re-use the dismantled components: either reusing for the original purpose or for other purposes; whereas the secondary goal is to recycle.
First floor	We adhere to traditions large parts of Europe to call the floor on the ground the ground floor and the next floor up the first floor. 
Framed Building	Building that relies wholly or mainly on a frame rather than on loadbearing walls for strength and stability.

Ground floor	We adhere to traditions large parts of Europe to call the floor on the ground the ground floor. 
Modular	Composed of sets of standardised parts or independent units (modules) for easy construction or arrangement and adaptation or disassembly.
Offsite construction	The planning, design, fabrication and assembly of building modules at a location other than their final installed location to support the rapid and efficient construction of a permanent structure. Such building modules may be prefabricated at a different location and transported to the site or prefabricated on the construction site and then transported to their final location. Offsite construction is characterised by an integrated planning and supply chain optimisation strategy. Common alternative spellings for offsite are *off-site* or *off site* or it can be referred to as *industrialised construction*.
Open (Cell) Panel Timber Frame	Structural timber panels forming the inner load-bearing leaf of the cavity wall which are manufactured in factory conditions, brought to the site and fixed together to form a rigid load-bearing superstructure. These consist of timber studs and beams, stiffened on one side with wood-based panels, such as oriented strand board. The lining of the second side of the building component, and the application of insulation and other materials, usually happens onsite. Open cell timber frame is currently the conventional form of timber frame in the UK and is often just referred to as *Timber Frame*.

Reclamation **Reclaiming**	Collection of products, components or materials with the intention of reuse or recycling and avoiding waste. Synonym: *salvage.*
Remanufacturing	A series of industrial processes in a factory environment that return a used product to at least its original performance with a warranty that is equivalent to or better than that of the newly manufactured product. The manufacturing effort involves dismantling the product, the restoration, replacement and recombination of components —with as few as possible new parts, and testing of the individual parts and whole product to ensure that it is within its original design specifications.
Renovation	Modification and improvements to an existing building in order to bring it up to an acceptable condition.
Repurpose	Reclamation of an object or assembly to a productive condition corresponding with a use alternative to the previous use with minimal material intervention.
Reuse	Any operation by which products or components that are not waste are used again, with minimal re-processing, i.e. checking, cleaning and repairing (including surface treatments, such as repainting, recoating etc.). Reuse can include *repurposing*.
Semi-detached house	House sharing one wall with another house. 
Single family house	House not sharing any wall with another house. Synonym: *detached house.* 

2. Method and implementation

2.1. Overview of steps

The method used for the case study has four steps, see Figure 3. The different steps are described in sections 2.2 – 2.5.

Figure 3 The steps of the case study method

Step 1. Existing design

1.1 Description of the building and its assembly

- 1.2 Simulation of deconstruction and reassembly as well as identification of strengths and weaknesses
- 1.3 Identification of areas to improve
- 1.4 Selection of areas to improve
- 1.5 Calculation of the amount of wood that can be reused with today's design

Step 2. Modified design

Step 3. Comparison between existing and modified design

Step 4. Reuse documentation that can be linked to BIM

2.2. Step 1. Analysis of existing design

First (step 1.1 in Figure 3), based on the supplier's drawings, descriptions and oral information, a description was made of the building system and how it is assembled in its original/first phase. The predicted main steps in a deconstruction process were also defined based on the knowledge that existed about the system and its assembly.

Then (step 1.2 in Figure 3), in an online meeting with Robertson’s Managing Director and Technical Manager, the assumed deconstruction process was discussed in more detail, as well as strengths and weaknesses the existing design has with regard to deconstruction and reuse. For the different steps in the process, various aspects were discussed, such as:

- tools needed for deconstruction
- damage that may occur to components and materials during deconstruction

- need for reconditioning, repair and controls
- foreseen waste
- risks with regard to personal safety
- risks to the environment

The discussions were documented with notes (Appendix 1).

After this meeting, the data were examined, the system's weaknesses and strengths were summarised and areas for improvement were highlighted (Figure 3, step 1.3). Based on this, we made a choice on which areas showed the highest potential for improvement to take these areas forward to step 2 (Figure 3, step 1.4). Finally, an estimation was made of the amount of wood that would go to waste if the current design was to be deconstructed and reused (Figure 3, step 1.5).

2.3. Step 2. Modified design

Areas that were selected in step 1.4 were improved according to suggestions made in a meeting with Robertson and representatives from WP2 of the InFutUReWood project. In this meeting, it was concluded that few changes needed to be made to increase the deconstruction potential of the discussed house type. Therefore, the scope of this step was widened to include design for adaptability

2.4. Step 3. Comparison between existing and modified design

In step 3, a comparison is be made of the "easily accessible and reusable amount of wood with current design" and the "easily accessible and reusable amount of wood with improved design".

The amount of wood in an Everett Grand with current design is known. An estimation can be made of the amount of wood that can be reused with the current design, based on the results from step 1 (where possible damages and waste from deconstruction were identified). Equally, an estimation can be made of the amount of wood that can be reused with an improved design, based on the findings from step 2.

Some design changes lead to non-quantifiable improvements. The qualitative reuse and refurbishing options for both designs, as well as potential challenges beyond the scope of this study, will also be discussed.

2.5. Step 4. Recycling documentation that can be linked to BIM

In Step 4, we suggest a way to make “deconstruction and reuse manual” and examine how it can be linked to BIM. Problems such as damage of deconstructed building assemblies and time-consuming disassembly work were identified in step 1. Some of these could be prevented with instructions on how best to deconstruct and reuse the parts of the building.

3. Results from ‘Step 1. Analysis of existing design’

3.1. Description of the object with current design

Figure 4 Everett Grand, the object of the case study. ©Robertson Timber Engineering

The object of the case study is, as mentioned, a house from Robertson, Everett Grand, Figure 4. It is a three-storey, single-family residential building with five bedrooms and five bathrooms. A single-storey room with a pitched roof (referred to as the garden room) is located at the back of the building and a garage with a flat roof extends to the front. The frame consists of prefabricated planar wall panels mounted on a concrete slab. Intermediate floors are made from prefabricated cassettes containing timber I-joists, covered with a 15 mm OSB deck. The roof consists of trussed rafters that open for two pre-assembled dormer windows in the front.

Vertical loads on the roof are carried by roof trusses to the external walls of the long sides via the wall studs. The vertical loads on the intermediate floor are carried by floor cassettes to the external walls of the long sides and to the loadbearing internal walls and then down to the foundation.

Horizontal loads perpendicular to the long side are carried by the external walls to the roof, the intermediate floor and the foundation. The roof and floor carry the load to the gables, which transfer the load to the foundation. Horizontal loads perpendicular to the gables are carried by the external walls to the roof, the intermediate floor and the foundation. Roof and intermediate floors take the loads to the external walls on the long sides and loadbearing internal wall and further down to the foundation.

3.1.1. Parts and joints

Parts of the building

The building is made of planar prefabricated assemblies, including 2D wall panels and floor cassettes. Examples of the prefabricated assemblies can be seen in Figure 5 and Figure 6.

Figure 5 Roof trusses being lifted into position as one piece

Figure 6 Wall panel being lifted into position

The sectional drawings in Figure 7 show the structure of the Everett Grand.

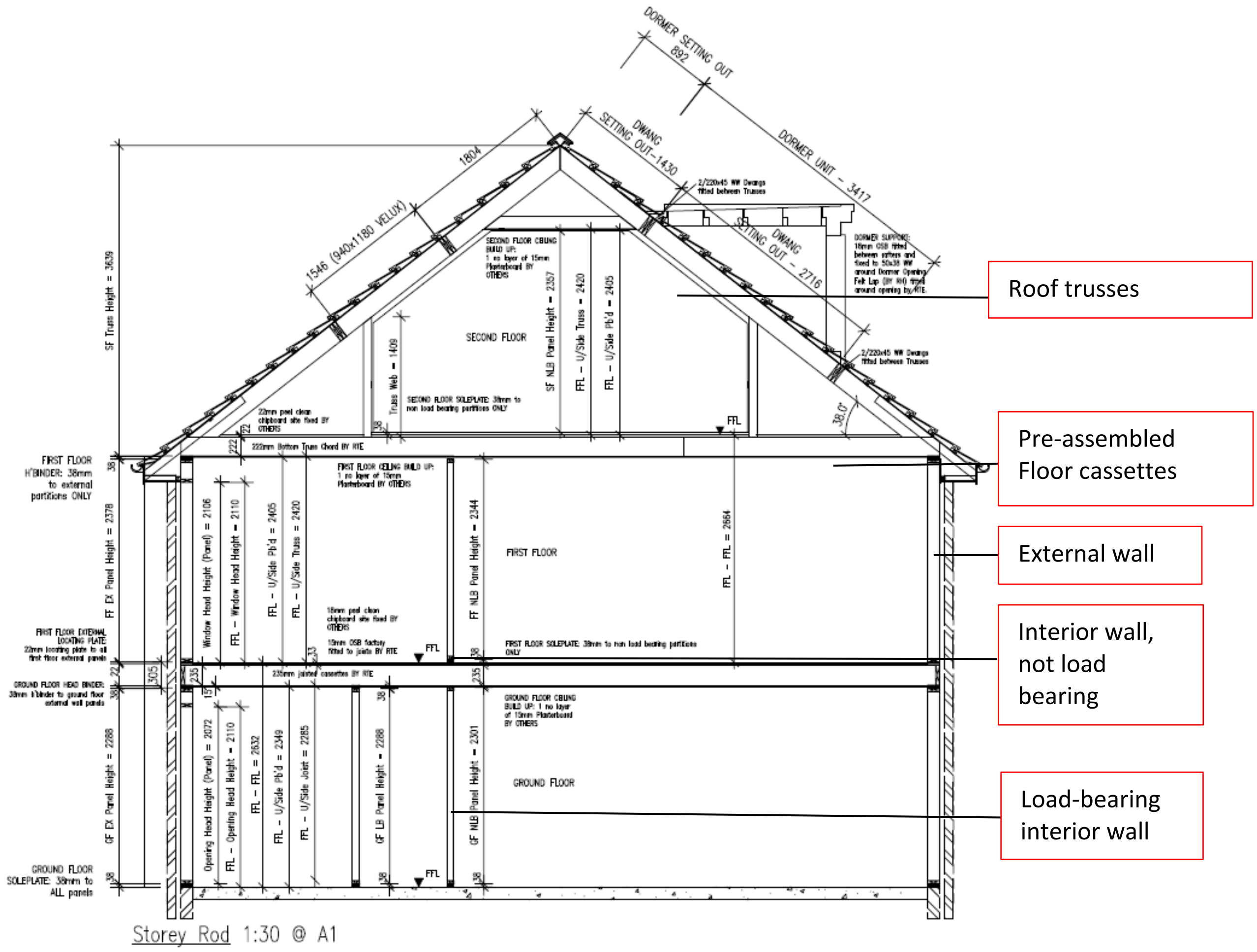


Figure 7 Sectional drawings, Everett Grand. ©Robertson Timber Engineering

The parts that form the building's load bearing structure, from top to bottom, are:

- The **roof**, built up by battens, counter-battens and concrete tiles.
- The **roof trusses** from structural timber and nail plates. The tie beam of the roof truss forms the attic floor together with a suspended ceiling. The attic floor is insulated with mineral wool insulation.
- The **gable** elements (spandrel panels similar to exterior wall panels).
- The **external walls** of first floor: planar elements, studs, noggings, vapour barrier on external OSB. The prefabricated assemblies are finished with insulation, breather membrane and internal plasterboard sheathing over a service zone.
- The **intermediate floor** cassettes are built of I-joists, noggings and OSB sheathing. A breather membrane is wrapped around the cassette where it meets the exterior walls. On the lower side of the cassette plasterboard is attached on site, on the upper side floors are covered with chipboard, which is glued on.
- The external walls of ground floor (equal to the ones of floor level 2).
- The **load-bearing internal wall**, ground floor.

All the above are delivered to the building site as partly prefabricated assemblies and are finished onsite.

In addition, the load-bearing structure of the building includes:

- **Slab on ground**, built on site from concrete.

The building is completed on site with interior walls that are not part of the load bearing structure.

Joints

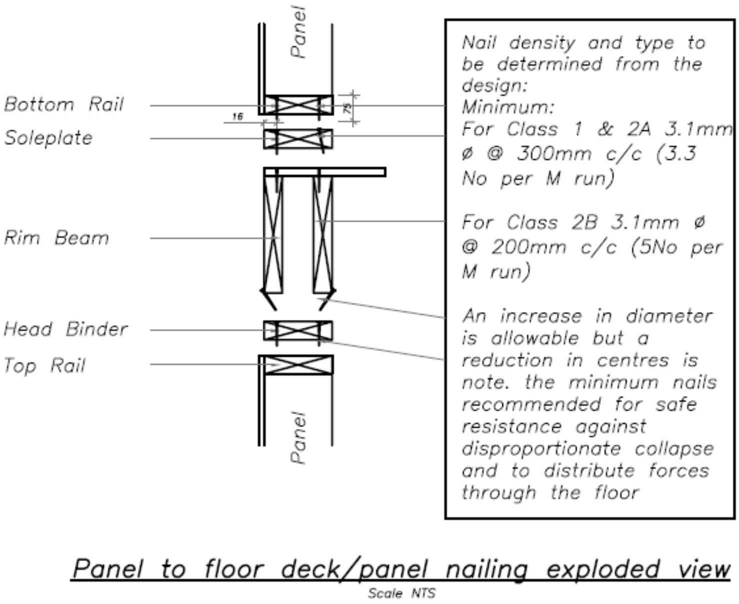
The dominant connection technique are mechanical fasteners in the form of nails. Hangers, which are fixed to the joists using nails, are occasionally used between floor joists. An overview of joints and fastener types is given in Table 1.

Table 1 Overview of joints and joint techniques

Part	Connection (position of)	Technique
ROOF	Counter battens to trusses	Nail connection (2no. every 600mm)
	Tiling Battens to Counter Battens	Face nailed at each truss
ROOF TRUSSES	Truss clip to headbinder (wall panel floor 1)	Twisted nails
	Roof truss to head binder (wall panel)	Nailed connection (2no. skew fixed to every truss end)
GABLES	Spandrel panel to panel	Nail connection (2no. per every 400mm (staggered))
ATTIC FLOOR/ CEILINGS	Floor covering	Glued
	Plasterboard	Screw connection (300mm c/c's (note 150mm c/c's if nails used))
EXTERNAL WALL, FIRST FLOOR	External wall/intermediate floor	Nailed (2 per joist and intersection)
	Vertical joints between wall panels	Nailed (Each stud face @ 600mm c/c's (staggered)
	Vertical corner joints between wall panels	Nailed as above
	Sole plate to wall panel (sole plate to bottom rail)	Nailed (2 every 600 mm)

	OSB sheathing to studs	Nailed, minimum 50mm centres
INTERMEDIATE FLOORS	Supports of cassettes at external walls	Nailed (2 per joist and intersection)
	Longitudinal joints between cassettes	Hangers/ Nailed
EXTERIOR WALL, GROUND FLOOR	See exterior wall first floor	
PLATE ON GROUND INCL. SLEEPER	Sole plate to foundation	100mm hammer fixings or 72mm hilti nails
INTERNAL, LOADBEARING & NON-LOADBEARING WALLS	Between panels and to external walls	Nailed (Each stud face @ 600mm c/c's (staggered))
	To floor joists	Nailed (2no. between each stud face)
	To trusses and ceiling joists	Nailed (2no. between each stud face)
	OSB sheathing to studs	Nailed, minimum 50mm centres

The connection between wall panels and floor cassettes is shown in Figure 8 below. The type of connection is representative for other connections between assemblies.



Nail density and type to be determined from the design:
Minimum:
For Class 1 & 2A 3.1mm ø @ 300mm c/c (3.3 No per M run)

For Class 2B 3.1mm ø @ 200mm c/c (5No per M run)

An increase in diameter is allowable but a reduction in centres is note. the minimum nails recommended for safe resistance against disproportionate collapse and to distribute forces through the floor

Figure 8 Panel to floor deck nailing exploded view. ©Robertson Timber Engineering

3.1.2. Presence of chemicals

Chemicals are found in the form of preservatives and glues. All timber at the risk of moisture contact is treated with preservatives. This includes the timber in soleplates, external wall studs and the roof structure. The chipboard is glued on top of the floor cassettes using non-toxic expansion glue.

3.1.3. Mechanical and electrical services and their connection to the load bearing structure

As found in the interview with Robertson, the mechanical and electrical services are not expected to complicate disassembly. Wall panels include a 50 mm service zone, directly under the plasterboard. In the floor cassettes, services run between the joists and occasionally through holes in the joists. That means that services in walls and ceilings can be easily accessed after removing the plasterboard sheathing from walls and ceilings.

3.1.4. Assembly process for original construction

The assembly process can be described as a conventional process from the bottom up. According to Robertson, it takes one day to mount the assemblies delivered from the factory on the cast slab and get the building under roof. Special weather protection is only used when panels have to be stored onsite during assembly, but normally the wood is not expected to have time to absorb harmful amounts of moisture during the hours it takes to make the building weather tight. Roughly, the load bearing structure with its prefabricated assemblies is assembled in the following steps:

1. The ground slab is cast
2. The roof is pre-assembled on the slab from pre-fabricated trussed rafters, gable ladders, spandrel panels, purlins and temporary bracing
3. The roof is lifted as a whole and set aside
4. Soleplates are mounted on the slab for external and internal walls to mark the positions of wall panels.

   - Soleplates are anchored to concrete with 100mm hammer fixings or 72mm hilti nails

5. Exterior wall panels of the ground floor are installed. Wall assemblies come as planar, open panels from the factory, where they have been fitted with transport protection.

   - Panels are lifted by crane from the truck and mounted against soleplates. Walls are temporarily braced.
   - Bottom rail of the wall panel is nailed to the soleplate from the inside.
   - Wall panels are attached to each other in vertical joints and in corners with nails, nailed through two studs, one from each panel.
   - Headbinders are nailed on top of the panels, so that they form a continuous element over individual panels.

- Holding-down straps are fixed to the outside of wall panels with nails.
- When all external walls are standing, the breather membrane is folded over panel boundaries and stapled to the external sheathing.

6. Internal wall panels (loadbearing and non-loadbearing) are lifted with a crane from the truck and mounted.

    - Erection in the same way as external walls

7. Floor cassettes come fully pre-assembled and are lifted by crane from the truck and placed on outer walls and loadbearing walls.

    - The cassettes are nailed to the headbinders of external walls from the outside, obliquely downwards inwards through the edge beam and the top plate. (Figure 8)
    - Cassettes are connected with nails through the headbinders

8. Soleplates are mounted on floors according to first-floor wall layout.

    - Soleplates are nailed through the floor cover to the floor joists (Figure 8)

9. Exterior wall panels (first floor) are lifted with a crane from the truck and mounted against soleplates. Walls are braced.

    - Erection in the same way as ground-floor walls

10. Internal wall panels (first floor) are lifted with a crane from the truck and mounted against soleplates. Walls are braced.

    - Erection in the same way as ground-floor walls

11. Pre-assembled roof structure is lifted by crane from the ground and mounted on exterior walls.

    - Roof trusses are attached to top rails with clips and nails.
    - Tiling battens are nailed between trusses and spandrel holding-down straps are fixed.
    - Tilting fillets, eaves and ridge sarking boards, eaves soffit framing, fascia board and soffit plywood are nailed on trusses and framing.
    - Roof felt is nailed to trusses.
    - Counter battens and space tile battens are nailed to trusses.
    - OSB is fixed in coombe and between trusses, where dormer windows need additional support.
    - Prefabricated dormer windows are lifted into openings using a crane and screwed to battens and support rafters.
    - Concrete tiles are nailed to battens.
    - Temporary lifting web is removed under trusses.

When the structure is completed, finishes need to be applied, which is referred to as "second fix". Windows and doors are fixed in openings, if they were not included in the prefabricated panel. The external walls are finished with insulation and masonry cladding from the outside. All wall panels are closed up with plasterboard sheathing, after services have been installed. It takes approximately two weeks to finish the construction process with surface layers, installations and finishes.

3.2. Results from simulation of deconstruction and reassembly with identification of strengths and weaknesses (step 1.2)

3.2.1. Deconstruction process

The process of deconstructing the frame for reuse was assumed to be carried out as suggested by Table 2. The scenario the deconstruction steps are based on is outlined as follows: After 50 years in use the house needs to be moved a short distance from its original location due to increased flood risk. It is moved within the same municipality and the same snow- and wind loads apply. The house is then erected on the new site exactly as it was before, perhaps with some aesthetic changes. For the disassembly, this means that the building is deconstructed to a degree so parts can be transported on a lorry. Parts are further taken apart if the structure needs to be inspected for damage or degradation. It is assumed that during the service life the building regulations, including the energy performance of the external structures, remain the same.

Table 2 Assumed deconstruction process

DECONSTRUCTION STEP	**DESCRIPTION, WHAT IS DONE**
1. PREPARATORY WORK	Masonry cladding is removed in the same way it was built (block by block). It will be destroyed in the process. Stairs are removed. Flooring removed. "Second fix" removed. Windows and doors only need to be removed in case they are to be replaced (for aesthetic or energy related reasons), otherwise they can remain in the panels.
2. ROOF Tiles	Heavy concrete tiles are removed and are likely to be damaged in the process. Concrete tiles might also have reached their design life after 50 years and may have degraded to the point they need replacement. Alternatively, if lighter tiling was used, it could stay in place, but tiling choices might also be subject to trends and there might be a need to replace it for aesthetic reasons, nonetheless.

DECONSTRUCTION STEP	**DESCRIPTION, WHAT IS DONE**
3. ROOF	Fixings between the headbinder of the external walls and the roof trusses need to be removed by sawing through the nails. A temporary lifting web needs to be fixed below trusses (as it was during installation). The positions of the support should be known and marked in BIM. Afterwards the roof can be lifted off as a whole. Roof felt and/or internal lining (plasterboard) needs to be removed so trusses and other timber parts can be visually inspected for damage, decay, degradation or changes made by the homeowner. Moisture damage and decay are perceived to be unlikely, if everything was installed and controlled correctly. It is also unlikely that owners or tenants interfere with the structure, since it is hidden behind plaster since the attic is a habitable space. However, should they be needed, repairs can be carried out in the factory without problem. It remains unclear whether the preservative treated timber would need to be re-treated after 50 years of service life. For transport the roof might to be sawn into parts (half or thirds). NOTE: All timber elements need to be wrapped for weather protection during transport.
5. EXTERNAL WALLS, FIRST FLOOR	Disassembly of vertical joints connecting one wall element to another. The vertical joints are covered by plasterboard. Boards must first be removed to uncover the nailed connections. Since they are screwed on this is an easy task. Then nails can then be sawn apart with a sabre saw. NOTE: removing the plasterboard could be avoided but has several advantages. a) The plaster is attached to service battens and its removal would not affect the structure b) after removal the services within the panels are accessible and can be detached or replaced c) the insulation within the panels would be accessible as well and can be replaced or additional insulation

DECONSTRUCTION STEP	DESCRIPTION, WHAT IS DONE
	added d) the breather membrane would be accessible and could be replaced or repaired e) the plasterboard is the most moisture sensitive part of the wall panel and its removal (and exclusion from reuse) makes transport and storage less susceptible to moisture In bathrooms, where tiles are used, they need to be removed before access to the plasterboard is possible. If wetwall is used, it can be removed and reused later. <u>Disassembly of joint between external wall panel and intermediate floor.</u> Nailed connections between the sole plate and the floor cassette need to be sawn apart. The sole plate is likely not reusable afterwards. Exterior walls are removed in the same format as they were installed. Loops are mounted in existing holes and the panels are lifted by crane to transport vehicles. NOTE: The wall panels need to have marks for identification (QR codes?), preferably linked to BIM.
6. INTERMEDIATE FLOOR CASSETTES	<u>Disassembly of longitudinal joints connecting floor panels to each other</u>. The ceiling lining is removed from below and afterwards individual cassettes can be seen. Where they need to be separated (to extract transportable parts) the nailed connections are sawn apart with a sabre saw. The chipboard floor cover is glued on and cannot be removed. It is therefore also sawn apart between transport units and can be glued back together at the new site, using expansion glue. <u>Disassembly of joint connecting floor cassettes to exterior wall ground floor.</u> The nailed connections have to be sawn apart. The headbinder of the wall panels below could be damaged in the process. Loops are attached to floor cassettes (holed for their insertion are visible from below) and they are lifted by crane.
7. EXTERIOR AND LOADBEARING WALLS, GROUND FLOOR	Process similar to that of exterior wall on the first floor. Again, only the soleplates are likely to be damaged in the process.
8. SLAB	An excavator chops the concrete slab to smaller pieces.

3.2.2. Analysis of deconstruction process

As described in section 2.2, different aspects of each step in the deconstruction process of Table 2 were discussed. This included: tools, damage that may occur to assemblies, need for reconditioning, repair and controls, foreseen waste, risks with regard to personal safety and risks to the environment. This way, the participants developed their knowledge and perceptions of the deconstruction process and potential to reuse the parts of the building. See Appendix 1 for notes.

3.2.3. Identifying strengths and weaknesses of existing design

The results of the analysis were restructured under the headings Strengths and Weaknesses for the different parts of the building, see Table 3. In summary, the following strengths and weaknesses can be identified with the current design with respect to deconstruction and reuse.

Strengths

- Industrially produced, large assemblies:
- The structure is built up by large assemblies and can be deconstructed in a reversed process resulting in even more finished/ larger modules. There are thus conditions for a relatively fast and rational deconstruction process with relatively few units.
- Low weight:
- The assemblies are sufficiently light to be transported (a prerequisite for prefabricating them).
- Knowledge and logistics already at hand:
- Knowledge and logistics are already in place for the prefabricated system with its efficient transport and assembly methods; the aspect of deconstruction and reuse, as well as quality control and possible repair works, can be worked into the business model if there are incentives to do so.
- Lifting is planned:
- Wall and floor panels have existing positions for lifting devices and can be lifted in the same way as during the original erection.
- Few, common tools needed:
- Deconstruction can be done with a few common tools, as drill, saw and electric screwdriver. As the assemblies are large, a crane will be needed for lifting.
- Services and membranes accessible:
- After the removal of the plasterboard, services and membranes (VCL and breather membrane) are accessible and can be replaced or repaired.

Weaknesses

- Disassembly of nailed connections:
- It is assumed that nailed connections can be sawn apart with minimal damage to the parts they are connecting. In practice, it could be difficult to remove these

connectors without damaging the wood. The process could be more labour intensive than foreseen, especially if many unprescribed connectors exist.

- Limited flexibility:
- The disassembly and reuse of components in the exact same house appears to be a straightforward task. However, when it comes to reusing the components in a different house type, this might proof to be more challenging. Wall panels and floor cassettes come in many different configurations and sizes and are highly specific to the house type and their position within the building. In addition, room layouts are often not adaptable for different use scenarios.
- Need for weather protection:
- The deconstructed parts are sensitive to moisture. If deconstruction is a slower process than assembly, the risk of damage due to rain is greater in the deconstruction stage. It is assumed, however, that the deconstruction could be carried out in a matter of days, and it would be sufficient to use weather protection in a similar way as during transport of new assemblies.
- Not prescribed connectors:
- There may very well exist connectors (nails) in completed buildings that were not prescribed by the nailing schedule but have been added by the assembly teams. These “extra” nails can be difficult to detect in a deconstruction process and difficult and time consuming to remove.
- Verification according to building regulations of assemblies:
- It is desirable to deconstruct and reuse entire wall and floor assemblies. These parts can be visually assessed and occasionally tested in the factory environment, but it is unclear if this would satisfy insurance providers. Extensive testing of recovered assemblies might be needed before mass-reuse is possible.
- Storing requires controlled climate:
- As the building parts are wood based, temporary storing needs to be done in a controlled climate in order to avoid problems with decay and deformation.
- Social acceptance:
- It is unclear whether people would be willing to buy a house that has been moved from another site and if they would be willing to spend the same amount of money for a used house.

Table 3 Analysis of strengths and weaknesses based on building component

	Strengths (properties to maintain)	**Weaknesses (properties to improve)**
General remarks	Industrial production with prefabricated panels is an efficient process that can be reversed. The company has methods to work with packaging, loading and transport that is safe for people and safe for the products. They are used to thinking about the entire logistics chain. The process can be reversed; the company can include the deconstruction process in their business as usual, including repair, retrofit and control as needed. Connections can be designed differently within the efficient industrial process; many of the connections might be more reversible using fittings. Long technical service life of most components.	Many metal connectors In practice, there can be more connectors than building instructions indicate. Extra nails are driven in during assembly. These can cause problem and even danger in deconstruction. The masonry façade needs to be removed before the timber structure can be deconstructed. Separating the outer leaf of brickwork from the wall ties without damaging the timber could be a complex process.
The different parts		
ROOF	The roof is lifted onto the building as a whole and can be removed in the same way. Only the roof tiles need to be removed before lifting, as they are made from heavy concrete. The tiles can likely not be reused. The fasteners that are removed are the ones between the headbinder of the first-floor walls and the roof trusses, the rest of the roof structure can stay assembled.	The connection between headbinder and roof trusses is nailed and needs to be sawn apart. This deconstruction method bears some uncertainties and potential safety risks.

EXTERIOR WALLS, FIRST FLOOR and GROUND FLOOR INTERNAL LOADBEARING WALLS	It is technically possible to disassemble, remove, transport and reuse wall panels in the same shape as they were inserted, with the surface layers left in place. It might however be an advantage to remove the internal plasterboard layer, for the following reasons: The service zone and breather membrane will be exposed, so that disconnection of services and damage assessment are facilitated The plasterboard is the most moisture sensitive part of the assembly and would need additional protection It is therefore assumed that the internal plasterboard is removed and the rest of the wall panel assembly extracted for reuse.	The assemblies contain vapour barriers. The expected service life of these is shorter than that of the studs. In addition, they depend on taped joints for their air tightness. Repairs to existing membranes can be carried out after extraction of the assemblies, but occasionally one might have to replace vapour barriers after disassembly in order to guarantee their function. For inspection of the studs, the internal breather membrane would need to be removed, but this only needs to be done in the following cases: Damage to the timber structure is suspected due to moisture or other indicators Insulation needs to be exchanged or additional insulation needs to be inserted The wall panels are mounted on sole plates that are nailed to the floor cover. The connection between wall panels and soleplates can be sawn apart, but the soleplates themselves are not likely to be recovered damage free.
INTERMEDIATE FLOORS	The cassettes can be removed and transported in the same format as they were mounted and with the chipboard left on top.	The chipboard cover needs to be sawn apart between cassettes, which would leave a small gap of 3 mm between floor covers after re-assembly. This can be repaired with expansion glue that is usually used for fixing the chipboard to the floor cassette. If the chipboard needs to be replaced for any reason, the glued connection between chipboard and floor cassettes is irreversible and a removal attempt would likely leave the floor cassettes damaged.

3.3. Identification of areas to improve

The identified weaknesses highlight features that can be improved with respect to disassembly and reuse, as well as adaptability, while the identified strengths highlight features that should be retained. From identified weaknesses and strengths, the following possible areas for improvement of the construction system can be formulated.

3.3.1. General

Prevent using extra connectors

Study how extra connectors could be made unnecessary. For unknown reasons, it happens that the assembly teams add nails that are not prescribed. Interviews should be conducted with assembly teams to find out why. Joint details may need to be improved and tested so as not to require extra attachments with nails. Clearer installation instructions may need to be developed.

The potential for improvement is that the time and energy consumption for disassembly is reduced and that personal risks are reduced.

3.3.2. Areas of improvement for deconstruction

Deconstruction instructions

Deconstruction instructions should be produced, similar to construction instructions of today, but in reverse order. The deconstruction plan should specify:

- Length, height and weight of assemblies
- Order of assemblies to remove
- How to remove assemblies and which tools are needed to loosen connections
- Which layers of assemblies need to be removed before lifting, and what happens to these layers afterwards
- Where to apply bracing and lifting loops or hooks
- Which controls to carry out before deconstruction and before reuse
- How to check that there are no extra connectors connecting assemblies before lifting
- How to protect deconstructed assemblies from weather and how to transport and store them

Prepared disassembly process

The position of the holes intended for lifting loops can be standardised, so that a future deconstruction team can easily find them. Lifting loops could also be left in place after installation. The lifting positions should also be specified in deconstruction instructions.

Carry out a study on deconstruction and reassembly of assemblies

It has been assumed here that it is technically possible to deconstruct and reassemble planar wall panels and floor cassettes complete with all their layers and materials as sheathing, studs or joists, insulation and vapour- and wind barriers, by sawing apart nailed connections. However, questions have arisen whether you can dismount a building reliably and safely with a sabre saw, or if unforeseen problems would arise.

Even if nails were to be replaced with screws, practical experience for disassembly is invaluable. It has not been confirmed whether screws can be removed after years of service and whether all (or most) layers of planar assemblies can be kept intact and reused after disassembly. Plastic membranes could become degraded or damaged, and it is unclear whether membranes would need to be replaced routinely after the assemblie's first service life. In addition, removing the masonry cladding could be more difficult than anticipated and the wall ties between the timber and the cladding could cause damage upon removal. It would take practical experiments in deconstruction and reassembly to answer these questions.

Develop assessment and reconditioning methods for assemblies

It is assumed that plasterboard is removed from walls and ceilings, so that timber elements can be visually inspected, services can be disconnected, and insulation can be retrofit if needed. It is, however, unclear how to assess whether timber elements are still fit for purpose after their first life. It is likely that an initial test period of recovered assemblies would be needed to develop reliable assessment strategies. The strategies should include a visual assessment guide to use before and after deconstruction, that allows to discern unsafe assemblies that need to be removed with additional care, as well as potentially unsafe assemblies that need to be further assessed and/ or retrofit in a factory environment. Besides visual assessment, mainly for fungal, insect and other visible damage, the inspection of recovered elements in assemblies could include measuring the moisture content and acoustic velocity, which is used to estimate the modulus of elasticity. Destructive testing of a percentage of recovered elements or assemblies would assess their compatibility with the design values.

Most of the timber in the external walls, roof structure and sole plates are treated with preservatives. It is unclear whether the treatment is still effective after the first life of the elements and whether re-treatment would be feasible. The treatment is currently required by insurance providers, even though timber elements in modern buildings should be sufficiently protected from moisture to be protected from insect and fungal attacks and preservative treatment is not required in other countries, like Sweden. Before deconstruction and reuse can become a widespread business practice for house builders, it would either need to be tested to determine if preservative treatment is still effective after years of service; a method for retreating whole assemblies needs to be developed; or a new agreement with insurance providers needs to be negotiated in which moisture protection serves as sufficient protection against biological degradation. The last option is arguably the most environmentally friendly and the cheapest solution.

Increase readability

Screw heads can be marked with spray paint in order to make it easier to find them during a deconstruction process and reduce time spent. Assemblies should be marked in alignment with the deconstruction plan (and BIM model) to assure all information relating to an assembly is available and the assembly can be reused efficiently.

Nailed connections between assemblies

Assemblies are connected with nails onsite. While these connections can likely be sawn apart, there might be connection methods that are safer and less uncertain in their disassembly. On-site nails could be replaced with screws, but these might require different lengths, diameters and spacing, which might not be compatible with the timber cross sections or design. The strength and failure behaviour of screws differ from nails, and it needs to be confirmed that screws are suitable as onsite fixings. Fixing screws on-site might also require more time or could meet lower approval by construction workers, who are used to using high-speed nail guns. All of these factors need investigation.

Floor cassette to chipboard connection (glued)

The chipboard cover is glued to the floor joists, which is necessary to avoid creaking. The floor cover can be sawn-apart and re-joint upon reassembly, but this deconstruction method bears safety-risks and uncertainties. Floor cassettes are sometimes connected with hangers (which are nailed to the joists) and sometimes nailed together in the current design. A method of connecting floor cassettes in a reversible manner could be used instead, to avoid the use of saws in the deconstruction process.

3.3.3. Areas of improvement for adaptability

Wall panel layouts

Wall panel lengths and wall panel configurations are not uniform, so much so that 75 different panels are used in the building. If wall lengths were designed to be multiples of 300 or 600 cm, wall panels could have more uniform dimensions. In addition, if different sections within wall panels could have lengths that are multiples of 300 or 600 cm and if these sections were detachable, the wall panels could be reconfigured to be reusable in various constellations.

Room layouts

The room layouts are relatively restricting and do not necessarily accommodate different aspects of modern living. It could be explored how rooms could be adapted for different uses and how the whole building could be redesigned to accommodate for different user scenarios, such as single-family, multiple-family (in two dwellings within the building) of multiple-tenant occupation.

Services

Services run in an easily accessible service zone under the plasterboard, which is an advantage. They could however be bundled in a central service cavity in the building which runs over all floors, which would make the installation of new services or the alteration of existing services even easier.

3.4. Selection of areas to improve

One design change that has the potential to significantly increase the deconstruction potential of the discussed design would be to replace nail fasteners with screws. As screws are in theory a reversible connection type, this means they can be removed with a limited level of damage therefore salvaging the majority of timber within the building. This option will also make the deconstruction process more controlled and safer, as it avoids the use of a sabre saw for deconstruction.

Improving the reuse potential of assemblies by making them uniform and therefore more flexible for different reuse scenarios is the second most impactful improvement. If assemblies can be recovered damage-free but are too specific to be reused in any other house type, their recovery might not be worth the effort. Trends and tastes in houses are likely to change within 50 years and recovered assemblies need to fit into new designs. It has therefore been attempted to make wall panels uniform, by dividing them into functional areas that can be joined with reversible connections in the factory and disassembled after recovery. At the same time, room layouts have been adapted to more uniform sizes and to serving variable needs. Specifically, the option to divide the house into two separate dwellings (ground floor and first plus second floor) has been introduced into the layout. Rooms have generally been made slightly bigger to allow for modern living needs, like working from home. Some bathrooms have been omitted in the layout plan, which leaves prospective buyers with the option to reduce the number of bathrooms by up to two.

3.5. Calculation of the amount of wood that can be recycled with today's design

In the simulation of deconstruction and reuse, waste due to damage with the current design was discussed. The loss during disassembly for the various components was estimated to be negligible for most parts, while soleplates are not assumed to be recoverable. The assumptions made for the different elements are shown in Table 4.

Table 4 Assumed wastage for different assemblies and components.

Part	**Waste percentage**	**Notes**
Roof boarding	0-100%	The concrete roof tiles cannot be salvaged, but after their removal the rest of the roof structure stays intact and can be reused. If roofing felt needs to be replaced, the tiling battens would need to be removed and would become waste. Since it is

Part	Waste percentage	Notes
		unclear whether the roofing felt has a life expectancy over 50 years, the waste percentage is taken as 50% for tiling battens. The exact tiling batten number cannot be seen in the design drawings and has been estimated.
Roof trusses	0%	The roof structure is judged to be reusable as a whole.
Gables	0%	
Exterior walls, first and ground floor	0%	Exterior walls are judged to be reusable in their entirety.
Soleplates first floor and ground floor	100%	Wasted when sawing through nail connection.
Intermediate floor	0%	The floor cassettes are judged to be reusable in their entirety. They will suffer minor local damage when the chipboard is sawn apart between cassettes. These are judged to be repairable when the cassettes are reassembled in a new building.
Slab	100%	This does not contain timber

It follows from the estimate, that 16.56 out of 17.52 cubic metres of solid wood, along with potentially all OSB (3.51 m^3), glulam (0.19 m^3) and I-beams (81.57 running metres) in the building could be reused with the current design.

4. Results 'Step 2. Modified design'

Nailed connections between assemblies

The replacement of nailed connections with screwed connections on site would lead to improved deconstructability, as connections can be reversed in a more predictable and safe way. This change in connections leads to several questions, which are answered below.

Would the replacement of nails with screws in connections that are fixed on-site change the assembly process in terms of speed, safety, costs and acceptance among the workforce?

Gregor Adam, Contracts Manager at Robertson Homes, thinks that modern, battery-powered tools for fixing screws are similar enough to the ones used for nails, so that the difference in the assembly (time and handling) would be minimal. He mentions that additional procurement costs for these tools could be an obstacle, however. It is also unclear whether the fasteners themselves have a significant difference in cost.

How does the spacing and size of screws relate to the one of nails?

When reassembling pre-used assemblies, can screws be used in or near old screw holes? How would this affect the strength of the connection?

Eurocode 5 (BS EN 1995-1-1:2004+A2:2014 2004) was used to calculate the size of screws that is required to replace nails (paslode) of 3.1 mm diameter and 75 mm length. The calculation is shown in Appendix 2. Firstly, the connection between two vertical timber members in single shear, as seen for example between studs of two wall panels, was examined (Figure 9). Secondly, the connection between two horizontal members in single shear, as for example between top rail and headbinder of wall panels, was examined (Figure 10).

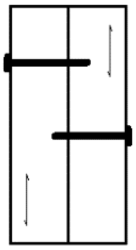


Figure 9 Connection between two vertical timber members

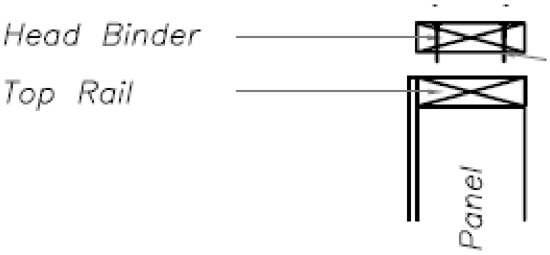


Figure 10 Connection between two horizontal timber members

In the two connections above, nails can be replaced with screws of roughly the same diameter and length (d_i=3 to 3.45 mm, l=70 mm). It could be possible to reduce the screw diameter further, but, for simplicity, this screw choice is retained.

For assessing whether screws have to be placed in or near old screw holes when reassembling recovered assemblies, the minimum spacing for screws according to Eurocode 5 is analysed. No complications should arise when placing screws with minimum spacing to old screws or holes.

Wall panel studs of the smallest cross section (75 by 38 mm) have the least flexibility for re-spacing fasteners, but even these studs could be reused three times before reusing old holes is necessary. Assuming that one use cycle has 50 years, this would limit the life of these timber members to 200 years, an optimistic life span that might not be reached by typical building timber for other reasons.

It might sometimes be necessary to remove OSB panels, either to replace them, or, in the new design, when reconfigurating panels. The OSB to stud connection is therefore analysed as well.

Nails in this connection can be replaced with the same screws as above to meet the structural requirements. Attaching OSB requires more fasteners, however, and OSB could not de detached and reattached without using screws in or close to old screw holes.

Not all OSB will need to be removed from wall panels before reuse, and it might be a sensible approach to discard the OSB panels that have to be detached. Another option would be to cut off the edges of the detached OSB to reuse it for covering smaller wall panels (spandrel panels or windowsills). On the other hand, the number of screws could be reduced in OSB panels, which do not contribute to the racking resistance of the building. This way some of the OSB panels would come with more re-spacing options for screws. Lastly, it might not be a problem to reuse the old screw holes and therefore the OSB. It would be useful to study the effect of reusing old screw holes on the connection strength and panel behaviour, also for other reuse scenarios and for solid wood and panel products.

Overall, replacing nails with screws poses no problems in theory, but contributes to facilitating deconstruction.

Wall panel layouts

Wall panels are divided into different functional units, which are 300 or multiples of 600 mm long. In the simplest case, wall panels could comprise of studs at 600 mm centres plus top- and bottom rail, and simple functional units of 600, 1200 and 1800 mm length are available. Additional functional unites are needed, as additional studs and nogging are needed for several reasons: As movement joists, to support perpendicular wall panels, to support floor cassettes above or as additional support near openings. The introduction of additional studs makes the required functional units more complicated and versatile.

In addition, timber elements in wall panels have a thickness of either 140mm (external walls), 89 mm (internal loadbearing walls) or 75mm (internal, non-loadbearing walls) and therefore some functional areas need to be manufactured in different thicknesses. Internal non-loadbearing walls also have nogging in all panels. In the current design, wall panels have slightly different heights depending on which floor they are located on, and whether they are internal or external panels, which is shown in Table 5. It is confirmed with the manufacturer, however, that wall panels in all floors can be of the same height.

Table 5 Height of different wall panels

Wall height in mm	**Ground floor**	**First Floor**	**Second Floor**
External wall	2288	2378	Varies
Internal, loadbearing wall	2288	-	-
Internal, non-loadbearing wall	2301	2344	2357

An additional unit, referred to as Ecor, is introduced, which is 140 mm wide and 140 mm thick, matching the thickness of external wall panels. This unit can be added to external wall panels in corners of the building where two wall panels meet in a right angle. This assures that the internal walls, if they span the entire floor, can still be multiples of 600 mm in length (see Figure 11).

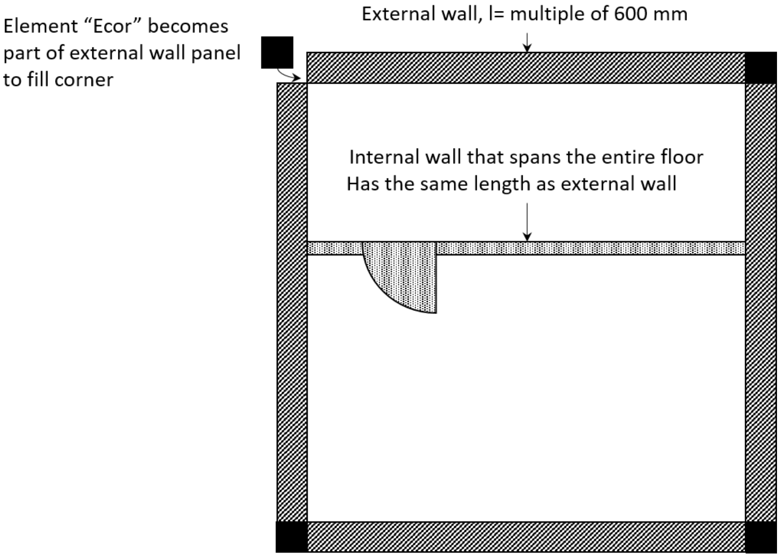


Figure 11 Function of unit "Ecor"

In total, 35 different functional units are needed, which are shown in Figure 12. An explanation of all functional units can be found in Appendix 3. Panels come in different widths and some units need to be repeated with 140, 89 and 75 mm thickness. Second floor external wall panels are spandrel panels, which are not considered in the improvements, as they cannot be manufactured from the same standard units due to their triangular shape. Panels with a special shape for the cathedral window (EX16GF and EX17GF) are disregarded as well.

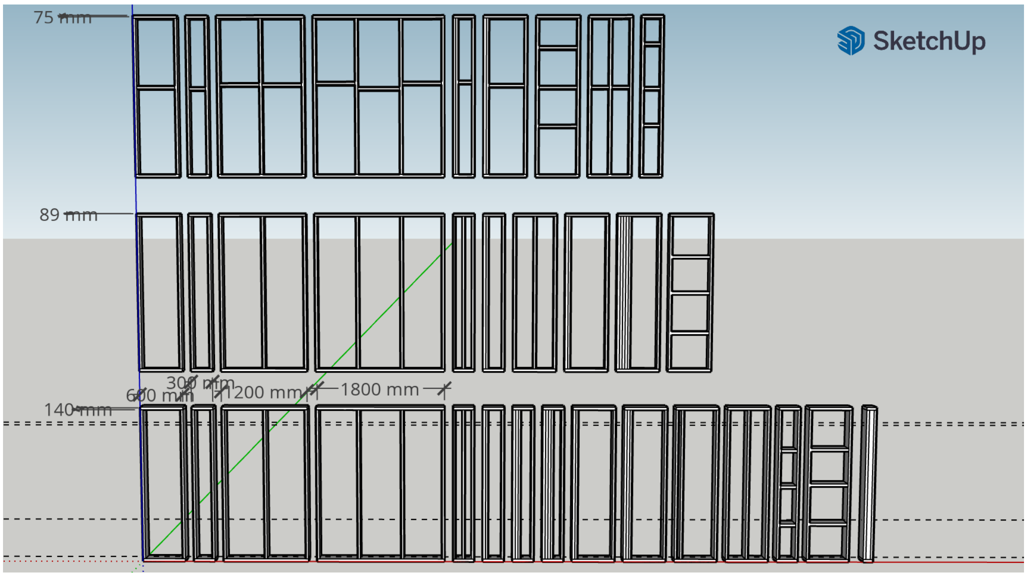


Figure 12 All standard functional areas

Standard opening units can be doors or windows, and some might even be used as either. They come as 900 mm, 1648 mm or 2400 mm openings, so that units have a total width of 1200, 1800 and 3000 mm respectively. In some cases, glulam lintels support openings. At least two studs on either side support all openings and while the lintel and any additional areas on the side of openings come with pre-fitted OSB, the 2-stud wide area at the edge of an opening unit is not covered. OSB from adjacent units will overlap these studs instead.

Again, panels come in different widths and some units need to be repeated with 140, 89 and 75 mm thickness.

Sills in different heights can be fitted in any of the openings to form windows. This way, doors can be easily transformed into windows and vice versa. Sills come with pre-fitted OSB. All standard openings and sills are shown in Figure 13.

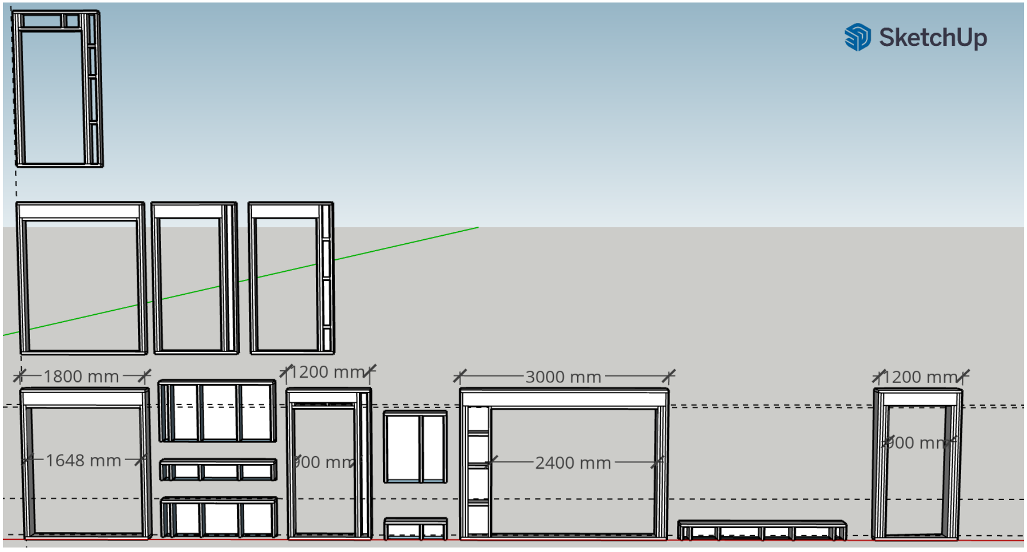


Figure 13 All standard openings and windowsills. OSB is only shown on backside.

OSB comes as 300, 600 and 1200 mm cover, but, on occasion, needs a 2-stud-wide overlap area next to openings. A 4-stud-wide OSB panel is needed to cover the area where two openings meet. All standard OSB units are shown in Figure 14.

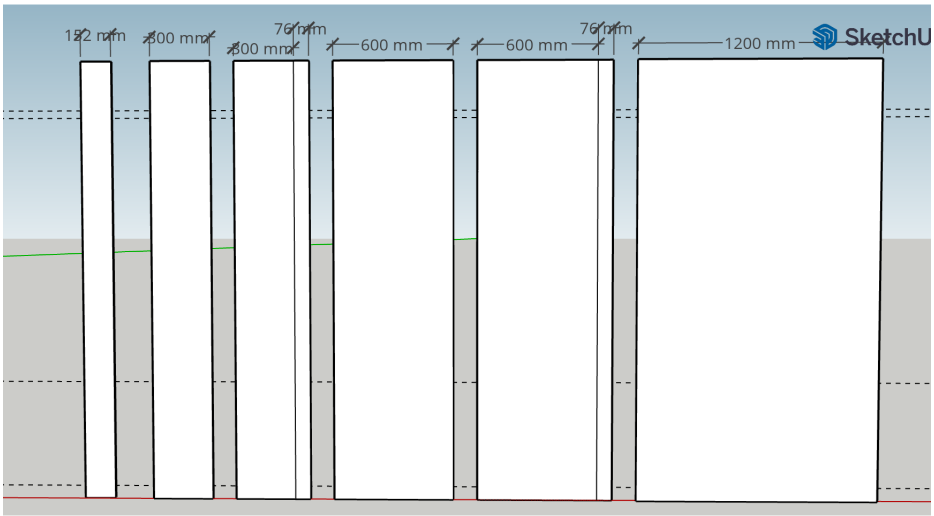


Figure 14 All standard OSB units

The functional units (studs, top and bottom rail, lintels) are manufactured in the factory as usual and can be nailed. They are then joint in the factory into wall panels. This is done by connecting studs of different units with screws, so that they could be disassembled, should it be needed. OSB sheathing is attached in the factory too, sometimes overlapping more than one functional area, so that it would be beneficial to use screws in this connection too. The factory assembly is shown in Figure 15.

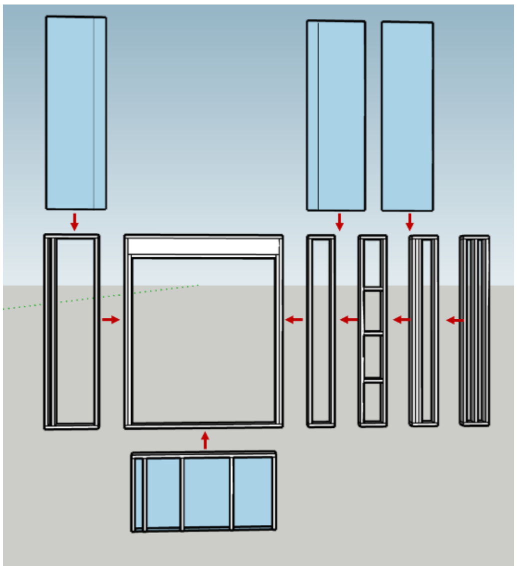


Figure 15 Panel assembly (example of EX1FF). Functional sections are screwed together as shown by red arrows. Note 2-stud-wide overlap of OSB next to window opening.

The finished wall panels resemble the original ones (Figure 16). To improve the standardisation further, it would be possible to adjust the length of individual panels as well to achieve the smallest possible number of different panel lengths. If the external walls were arranged symmetrically, it would be possible to remove or add sections to the house easily, which would further increase its adaptability. The composition of all wall panels from standard units and potential optimisations to wall panel configurations are shown in Appendix 4.

It would also be possible to limit the number of different wall thicknesses needed, by specifying loadbearing wall panels with 140 mm thickness to match external wall panels. This requires more material input, however, and it is out of the scope of this study to assess the environmental and financial impact of this option.

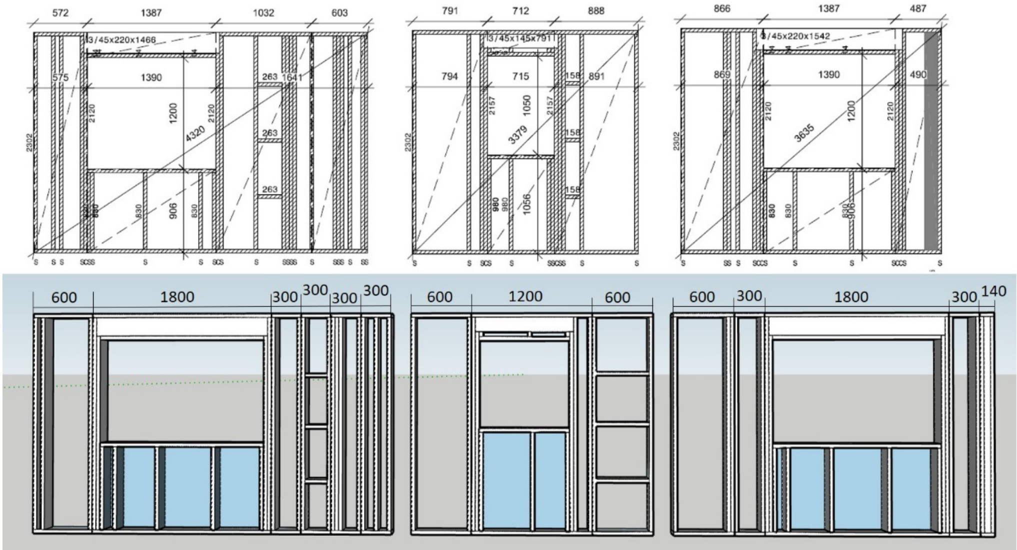


Figure 16 Original vs. improved wall panels (EX1FF, EX2FF and EX3FF) (OSB omitted in improved drawing outside openings)

On site, the wall panels are mounted on sole plates and connected with screws through studs from both sides. Headbinders, overlapping individual panels, are fixed on top (Figure 17). After fitting insulation and services, internal lining is fixed. Where non-standard OSB panels are needed around openings, these sections of the panels could entirely be finished in the factory. Figure 18 shows how the wall made up from the above panels would look inside the building.

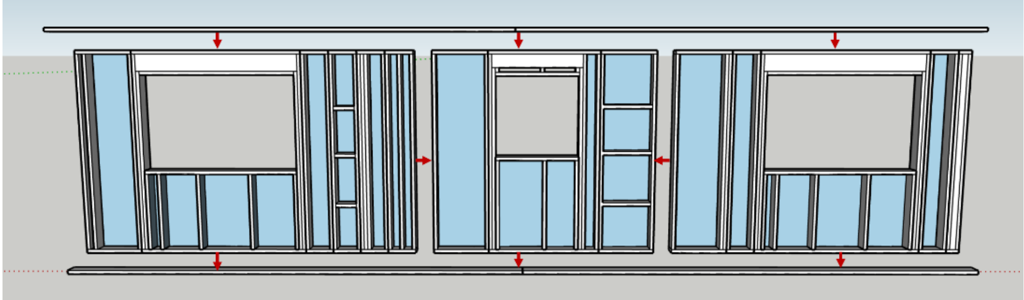


Figure 17 Onsite assembly. Panels are screwed together and on soleplates and connected with headbinders as shown by red arrows. OSB in the back is fixed in the factory and internal lining could also be fixed in the front, where non-standard units are needed (windowsills, next to openings). Onsite, services and insulation as well as remaining internal lining are fitted.

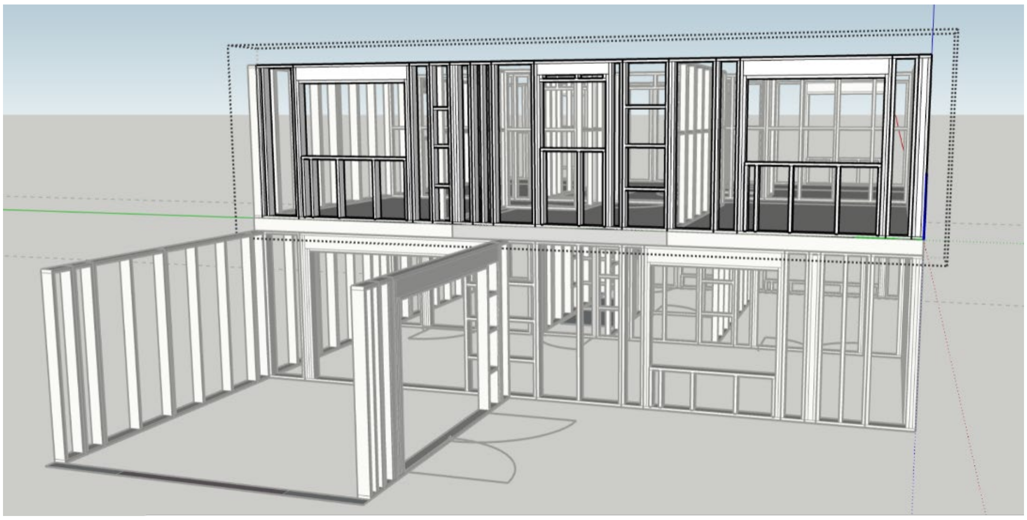


Figure 18 Wall panels inside the building. (Soleplates and headbinders, second floor, roof and cathedral window of garden room not shown.)

The wall panels resemble the current design closely. If a standard stud length (governing the panel height) of 2212 mm is assumed, which is currently found in ground floor external and internal loadbearing panels, the following changes in the amount of wood in the house are calculated (Table 6).

Table 6 Amount of wood in wall panels in the current and new design

Amount of wood in m^3	Solid timber	OSB	Glulam
Current design	8.6	2.0	0.2
New design	8.1	2.0	0.6

The amount of solid wood is slightly lower in the new design, which is due to omitting several wall panels. The amount of glulam increases, as most openings are expected to have a glulam lintel. Detailed design calculations could prove that this is not always necessary, but even if it was, the amount of glulam with 0.6 m^3 is reasonable.

Room layouts

The layout of the house is simplified to be rectangular (with an addition of the garden room on the ground floor), which makes the wall panels EX6GF, EX8GF, EX10GF, EX9FF and EX4SP as well as Floor cassette 1 redundant (see Figure 19 for example of the ground floor). The room layouts are changing with the new wall panel configurations, so that the walls come in standard lengths. The new room sizes are not always multiples of 600 mm, but are also governed by wall thickness and the position of the stairs, which was not changed (Figure 20).

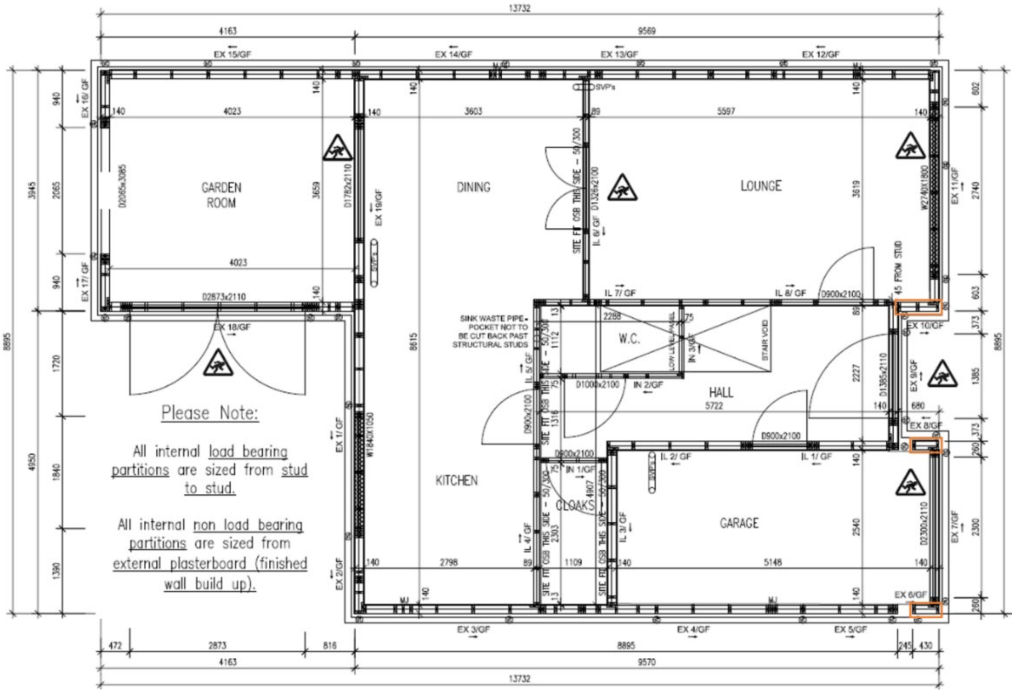


Figure 19 original ground floor layout. Wall panels in orange rectangles are omitted thanks to new layout.

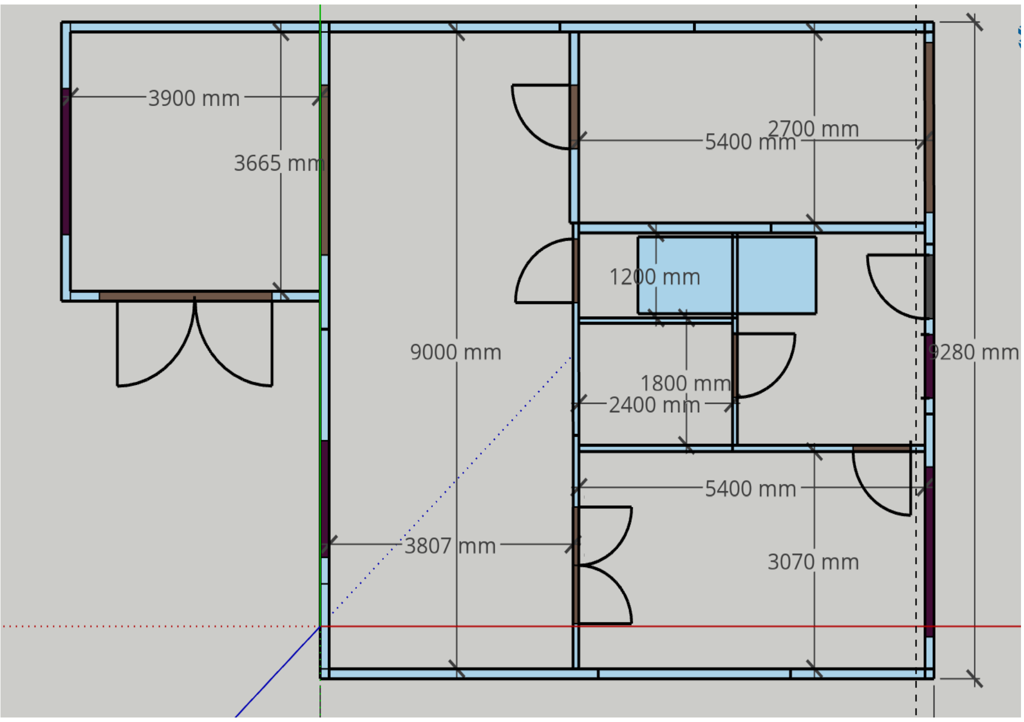


Figure 20 improved ground floor layout

The rooms are also adapted so that the dwelling could be split into two, for example if after years of occupation by a family the original owners want to only occupy the ground floor and another family can occupy the first and second floor. For this scenario, the bathroom on the ground floor is enlarged to offer room for a bath or shower. It could further be merged with the utility room, should more space be required. The hallway is designed so that it would require only the addition of one wall, and the replacement of the window with a door, to become two hallways, one for each dwelling (Figure 21). The garage could be modified to become an additional room, when the door is transformed into a window. Additional considerations should be made, such as specifying wall panel IN3GF under the stairs and floor cassettes so that they meet criteria for party walls, alternatively, they could be retrofitted to meet these requirements. The existing garage wall (IL1GF and IL2GF), which would be between dwellings, is made from external wall panels and would not need retrofit.

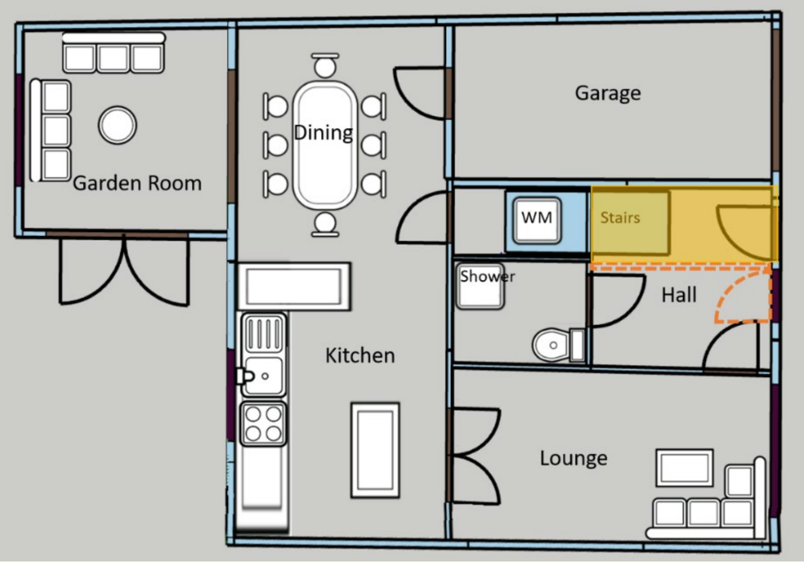


Figure 21 Ground floor modification. A new party wall is built and a window is transformed into an entrance door. The hallway of the upstairs dwelling is marked in yellow and the rest of the ground floor would be one dwelling.

Alternatively, the ground floor could be modified as below (Figure 22), so that the whole hallway becomes part of the upper dwelling. The doors to the bathroom and lounge would need to be closed up and the two wall panels that become party walls (IN1GF and IL8GF) might also need retrofit to meet the changed requirements. The wall between the utility room and the bathroom would need to be removed and the position of the shower changed. The new entrance could be fitted into the garage door and the rest of the opening could become a window.

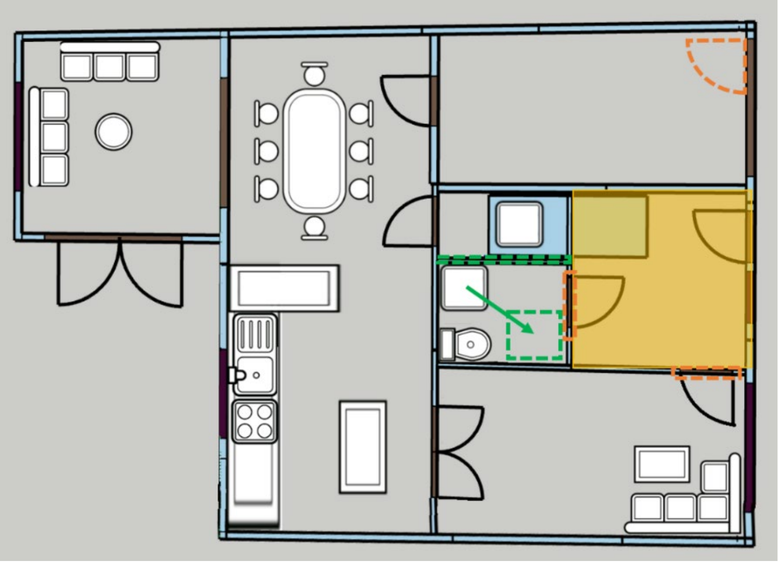


Figure 22 Alternative ground floor modification. Two doors are closed, a new entrance door is fitted instead of the garage door, an internal wall is removed and the shower is relocated. The hallway of the upstairs dwelling is marked in yellow.

The first floor layout sees changes towards standardised wall dimensions as well (compare Figure 23 and Figure 24). In addition, two bathrooms are omitted to allow more space in two bedrooms, for example for a home-working area in case of multiple occupation, when not all tenants can have a bedroom and separate office. The option of re-including one or both of the omitted bathrooms into the room layout could, however, be presented to prospective buyers.

In the scenario where the house is split into two dwellings, the two larger bedrooms would become kitchen and living room respectively, and since their doors are facing each other over the hallway, the living space could be easily linked by removing the doors from the frames (see Figure 24). Additional windows are introduced into the larger rooms, which would be needed in both these scenarios for additional light and ventilation. If the position of the stairs was adapted to suit standard wall lengths, room layouts could be even more flexible.

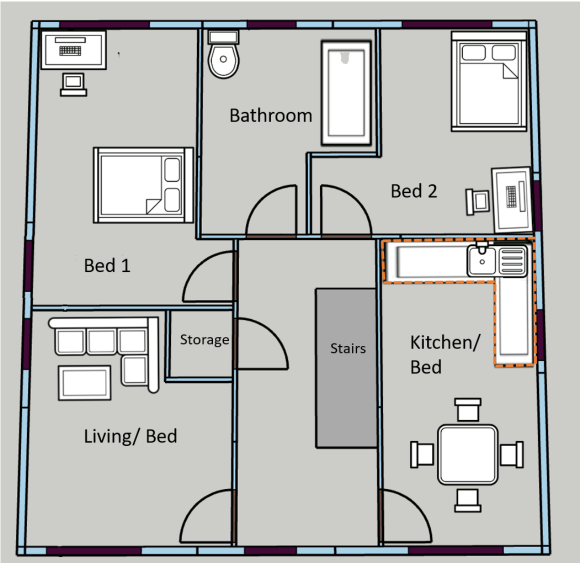


Figure 23 Original first floor layout. ©Robertson Timber Engineering

Figure 24 Improved first floor layout

The second floor layout (Figure 25) is relatively unchanged, with the exception of the removal of one external wall panel. Triangular spandrel panels are not considered in the panel improvement, and their length, height and stud spacing would need to be adjusted in the final design.

Figure 25 Second floor layout (unchanged) ©Robertson Timber Engineering

The floor cassettes, with the simplified rectangular layout of the house, become simpler as well. Floor cassette 1, seen in Figure 26, is omitted and a new floor cassette layout could look like in Figure 27. The length of all floor cassettes is governed by the position of the stair opening. The width of FC5b and FC3a as well as FC2a is not a multiple of 300, because floor cassettes also need to cover the extra 140 mm external wall width on each side, which adds 280 mm total. Floor cassette 5 comes in three pieces in the current layout, so it was decided to keep it that way. Floor cassette 2 and 3 were divided into two pieces, so that floor cassettes are aligned and the layout can be easily modified.

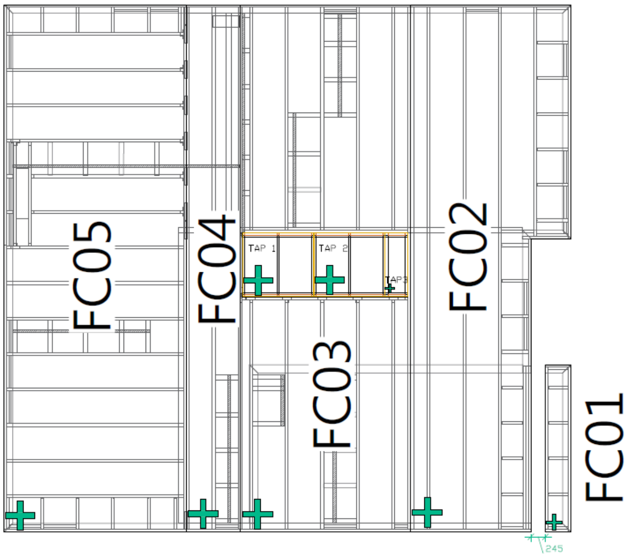


Figure 26 Current floor cassette layout ©Robertson Timber Engineering

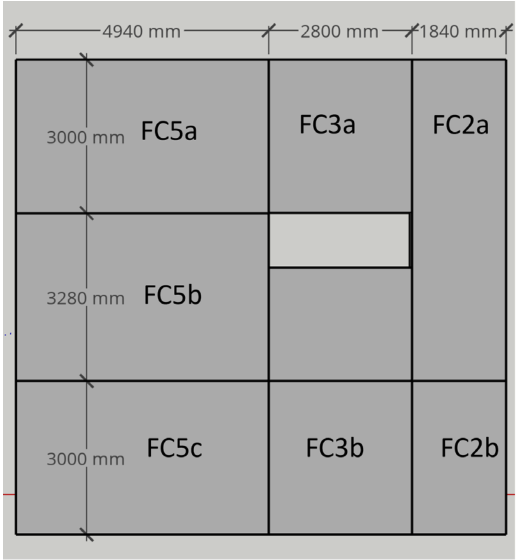


Figure 27 New floor cassette layout

Additional potential for adaptability

The house could be designed in an even more adaptable way, which would allow to reduce its size by removing rooms or floors. The company could take back the assemblies that were no longer needed. The reverse case would be possible as well. Customers could buy a smaller house that is extendable with rooms or floors being added, should they be needed. This more advanced design for adaptability requires more thought on wall lengths, floor cassette sizes and room layouts, so that several options for adding or removing walls could be included in the design. These options could be presented to the customer before sale and work as an additional sales argument and unique selling point.

One example of a possible modification to make the whole building adaptable is given below.

The size of the house could be reduced by about one third, by moving one side-wall inwards on all floors. The side-wall without the garden room has been chosen, since the garden room is the character-defining element of the house and should not be removed. Looking from the front of the house, the wall in question is the left side wall so we will refer to it as “left”. Figure 28 to Figure 30 show the modified house in comparison to the original floor layouts.

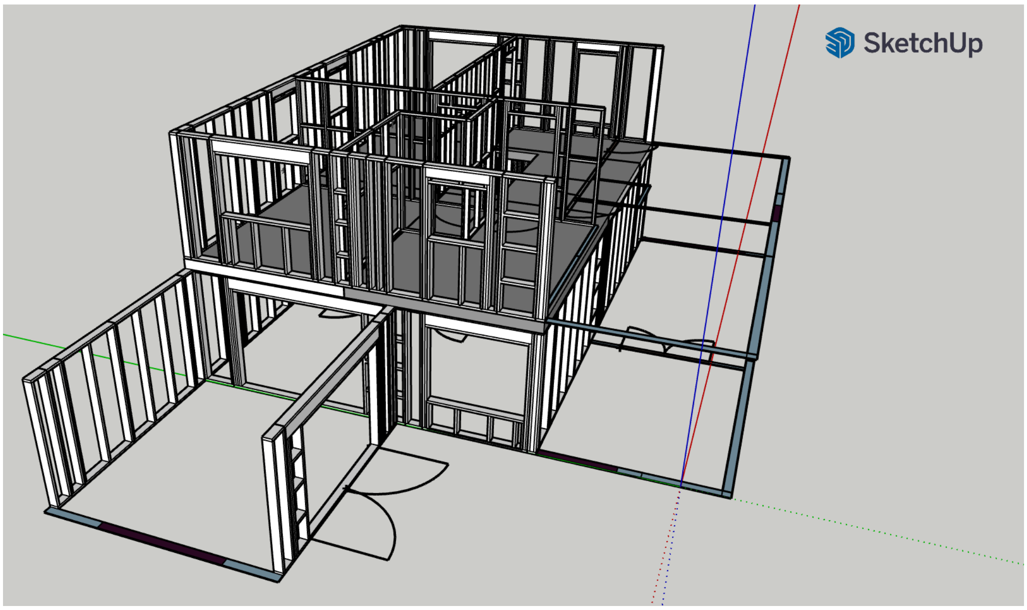


Figure 28 Whole house as smaller version vs. original size seen from the back. Floor layout shows original size. (Cathedral window of garden room and first floor "left" replacement wall not shown.)

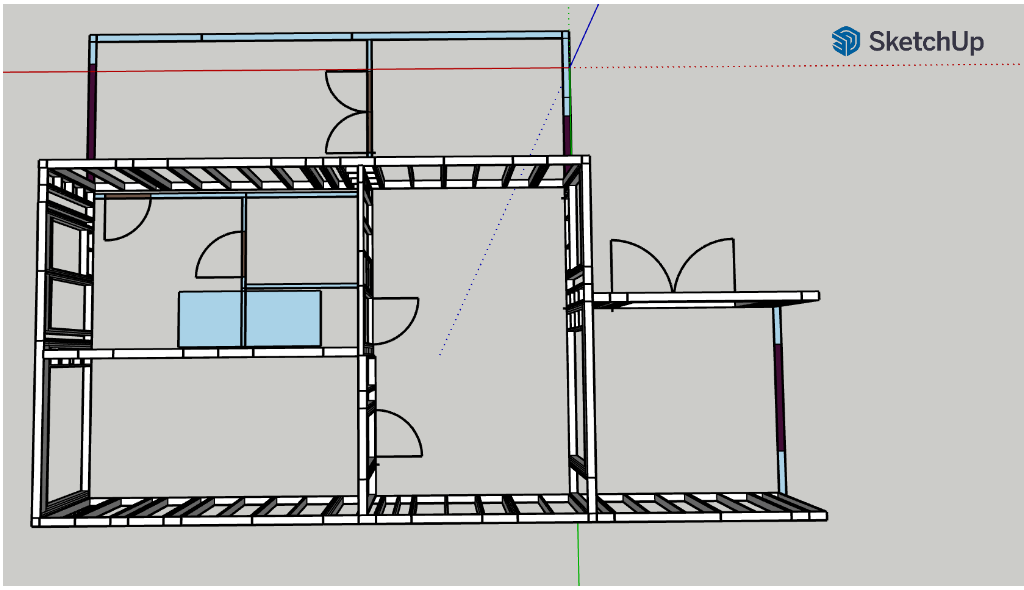


Figure 29 Ground floor layout in smaller version. Floor layout shows original size. "Left" wall is moved inwards and some internal walls removed. (IL3GF under the stairs and cathedral window of garden room not shown.)

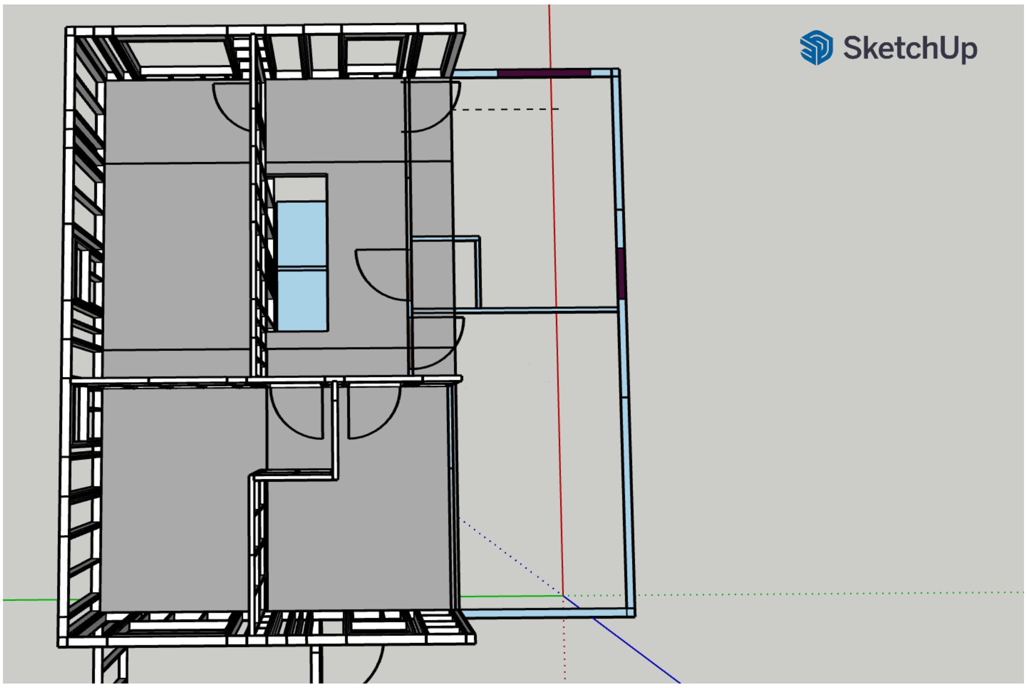


Figure 30 First Floor wall layout in smaller version vs original size. Some internal walls are removed. Ecor is added to the leftmost wall panels but the rest of the “left” replacement wall is not shown.

In this example, the floor cassettes FC5c, FC3b and FC2c, as well as the external wall panels EX2GF and EX11GF (on the ground floor) and EX3FF and EX7 FF (on the first floor) are removed. A new “left” wall is then added. The original “left” wall could be used, but this might need some changes to fulfil the new requirements. Some internal walls on both floors need to be removed as seen in Figure 29 and Figure 30 (IL6GF, IN1GF, IN2GF, IN7GF, IN8GF, both IN2FF, IN5FF, IN6FF, IN8FF (left), IN9FF (left) and IN10FF). This would also mean that the bathroom on the ground floor would be omitted. All removed assemblies could be reused, in case of the “left” external walls directly on site, or otherwise in other constructions. The company could include a modification and take-back scheme into their business model.

To enable these modifications some changes in the wall panel configurations are necessary, so that the leftmost wall panels of the “front” and “back” wall, as well as parallel internal walls, have a length of 3000 mm, so that they end in 140 mm distance to the edge of the floor cassettes FC5b, FC3a and FC2a (Figure 27). The 140 mm gap will then be filled with the unit Ecor of the replacement “left” wall. Panels in the “front”, “back”, and parallel walls need to be changed not only in length, but also in the position of openings. The specific changes required in this example are shown Figure 31.

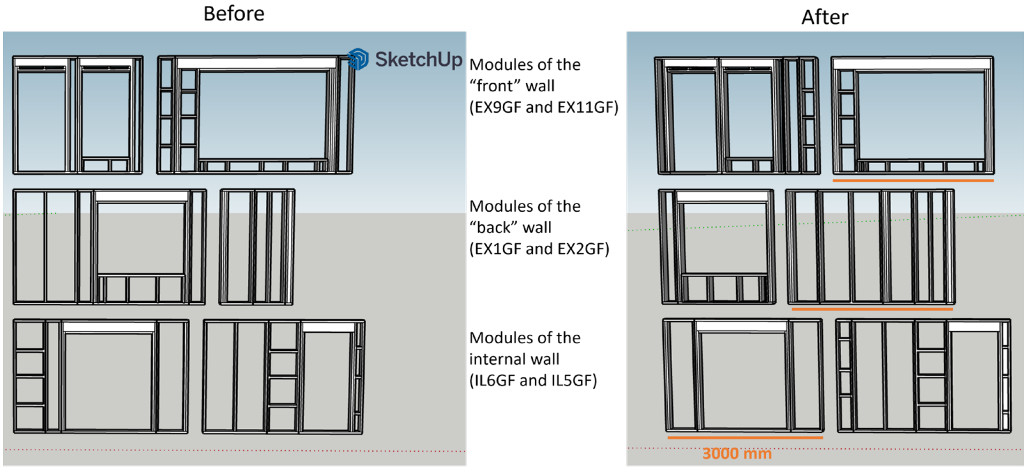


Figure 31 Changes in wall panels. Front, back and internal wall change in length and position of openings.

On the first floor, the length of the leftmost external wall panels in the “front” and “back” wall is already 3000 mm, so that the change can be easily accommodated.

On the second floor the spandrel panels of the “left” wall need to be moved inwards, which can only be done after part of the roof structure (six trusses) is removed. It is assumed that the roof can be sawn apart where needed. One of the dormer windows needs to be taken out before the roof is cut apart and can be reused in another building. Gable ladders will need to be fitted on the new roof edge and trusses and purlins may need to be added for additional support. The roof truss layout is not covered in this report, but it would be helpful to line up one of the trusses with the end of the middle floor cassettes on the left side. Currently the roof truss in question is in 96mm distance to the cassette edge.

One wall on the second floor would likely need to be removed after downsizing the house, to keep the second-floor bedroom in a useful size. The wall in question (IN3SF and IN4SF) is shown in Figure 32.

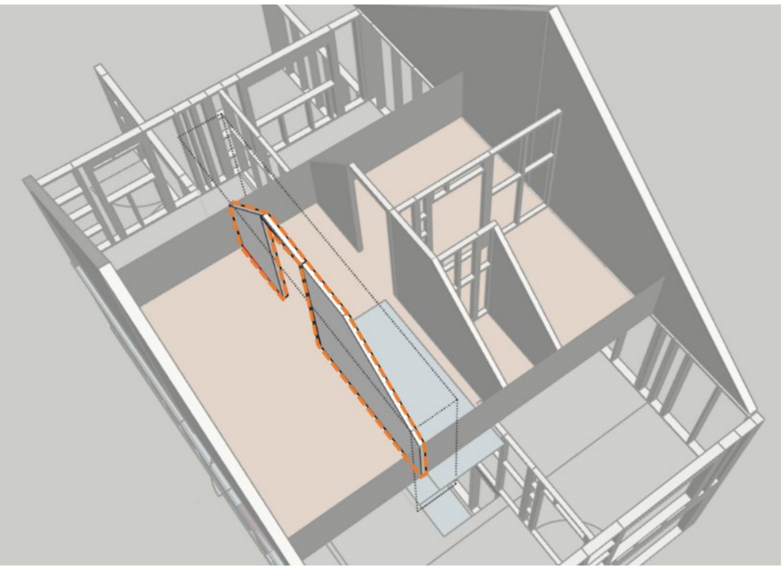


Figure 32 Internal walls on second floor after downsizing. Wall panels marked with orange line will likely be removed.

Services

Services in the horizontal direction run in a service zone under the plasterboard of wall panels. This is easily accessible and can be altered after removing the internal lining. In the vertical direction, all services can run in two service zones. Service zone 1 is located in the wall right next to the stairs (panel IL2GF, IN15FF and IN4SF) and runs over all floors as seen in Figure 33 and Figure 34. Bathrooms on the ground floor and second floor as well as the utility room are conveniently located closely to this wall, which is in the same position on all floors. Should the first floor bedroom be converted into a kitchen, as suggested above, this service zone could supply the appliances there. In addition, services needed in the garage could be supplied from this zone.

On the ground floor, the kitchen appliances require an additional service zone in the external wall to the back (EX1FF), which is shown as service zone 2 in Figure 33 and Figure 34. This service zone could be extended to the first floor (EX2FF) and contain the services needed in the bathroom. In addition, a water tap in the garden can be supplied from this zone.

Figure 33 Service zones shown in the floor layouts of all floors. From left to right: Ground floor, first floor, second floor.

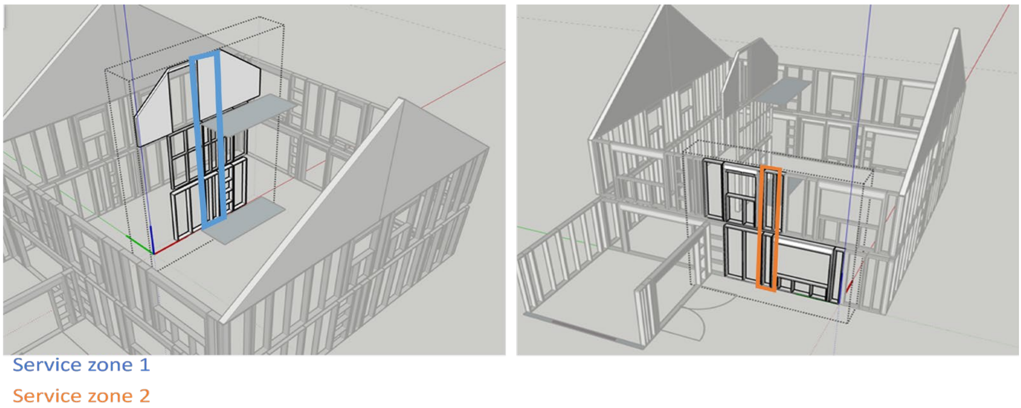


Figure 34 Vertical service zones shown in the building. (All other internal walls and floor cassettes are not shown.)

5. Results 'Step 3. Comparison existing design - modified design

In the original design, around 94.5% of timber could be reused after deconstruction. In the improved design, this can be increased to 98.4% since the soleplates can be recovered damage-free, when they are screwed instead of nailed to the floor. The design was well suited for deconstruction even before the design changes, and the quantitative reuse improvement is not large.

Nonetheless, the design changes made are important, as they improve reuse options qualitatively. Firstly, the more flexible and adaptable layout allows a more versatile and therefore potentially longer initial use of the house. Secondly, the standardised units can be reused in various design and different house types, while the original assemblies are highly specific and their reuse inflexible.

The amount of wood and wood products is nearly identical in both designs. The construction and deconstruction time should be nearly identical as well. Therefore, the costs for both designs should be very similar, but the improved design offers additional incentives:

- The panel heights on all floors have been adjusted to be identical, which facilitates production and procurement, as well as reuse. The manufacturer is planning on incorporating this change in their design.
- The improved design is adaptable during its lifetime, which can be an important feature and sales argument. This is also expected to extend the life span of the building.
- The flexible reuse of the improved assemblies guarantees the value of the recovered assemblies to the company.

6. Results 'Step 4. Reuse documentation that can be linked to BIM'

A sample deconstruction plan has been developed and is shown in Appendix 5. It is assumed that the deconstruction is carried out by the building manufacturer, who has access to additional information and documents, which accompany the deconstruction plan. The documents linked to the deconstruction plan are:

- Original nailing schedule
- Design drawings of building and individual assemblies
- Guideline for pre-deconstruction inspection and survey (This document needs to be written. It should include a survey to check the expected build with the existing build, instructions on how to check for extra connectors, instructions on how to assess the integrity of the timber structure in-situ)
- Guideline for post-deconstruction inspection (This document needs to be written. It should include a survey to check the expected assembly configuration with the actual configuration, instructions on how to check for damage or decay, instructions on repairs that can be carried out on-site, instructions on when to send assemblies to the factory for repair, guidance on how much remaining life expectancy assemblies and components need to have in order to be reused, instructions on how to deconstruct assemblies to recycle components on-site)
- Guideline for factory assessment and repair (This document needs to be written. It should include a survey to check the expected module configuration with the actual configuration, instructions on how to check for damage or decay in the factory, instructions on repairs that can be carried out in the factory, instructions on when to discard modules, instructions on how to deconstruct modules to recycle or reuse components)

The assemblie's BIM models are also linked to the deconstruction plan and contain additional information about the dimensions and weight of the assemblies, the assemblie's position within the building, the age of the assembly and components, the connections between assemblies and deconstruction instructions. The different functional units within wall panels could be explained here as well. The reasoning behind the use of additional studs, for example in movement joints, could be included, to facilitate understanding of panel configurations in the future.

Assemblies need to be marked so they can be identified, for example using QR codes or RFID tagging. Similarly, units within wall panels should be marked.

It might be worthwhile to create a collection of simplified design drawings, connection details and assembly descriptions (Assembly ID, components, dimensions, weight). In case the deconstruction operations are carried out by a contractor or by anyone besides the manufacturer, the design drawings and other documents might be hard to understand and it would take time to gather all relevant information from the different files. A summary document could also serve as an inventory.

The deconstruction instructions need to be updated, should changes to the structure be made. This includes adaptations as proposed in Chapter 4 under *Additional potential for adaptability,* as well as other alterations and renovations. It is assumed that the manufacturer retains ownership over the components and that a contract with the homeowners requires them to report any changes made. The contract could also restrict alterations to the structure. The initial inspection and survey would still be able to detect unreported changes.

To facilitate deconstruction, the as built drawings and any renovations/alterations to the building should be documented over the course of the buildings use. All relevant documents should reflect the intention to deconstruct the building at the end of its life and to reuse assemblies. Everyone involved in manufacturing of assemblies and construction of houses should be aware that assemblies are expected to have a life beyond their immediate application. New warranty agreements might need to be negotiated with external suppliers.

In addition, the construction guidelines should address the problem of unprescribed connectors. Gregor Adam, Contracts Manager at Robertson Homes, thinks that a protocol for the use of additional fasteners during erection needs to be in place in order to be able to manage their deconstruction. This protocol should include a) the notion that additional fasteners are not to be used without a valid reason and b) that fasteners outside of the nailing schedule need to be marked and protocoled. If the protocol is briefed to the workforce before erection and monitored on site, unprescribed fasteners would not pose a problem during deconstruction.

7. Discussion and conclusions

The existing design is relatively well prepared for deconstruction and reuse already. Even without design changes, up to 94.5% of the structure can be recovered for reuse. The main advantages of the building system are its offsite manufacturing, which makes assemblies highly precise and controlled, for example in the position of fasteners and lifting positions. The existing knowledge and infrastructure of the manufacturing company can easily be transferred to the deconstruction process, as it is very similar to the construction process.

Disadvantages of the existing design that were addressed in this study are the nailed connections and the high complexity of panels. In addition, the adaptability of the building to different functions was improved. With the design changes, a slightly higher percentage of wood can be recovered after deconstruction (98.4%), but more importantly the reuse options for assemblies become more flexible and the lifespan of the whole building might increase.

However, the problem of deconstruction and reuse is not only linked to the design of buildings and some additional questions came up during the study:

Who takes responsibility for the load-bearing capacity of composite disassembled components such as wall panels and floor cassettes and how? That is, how do you verify the building regulations' requirements for stability and durability of used assemblies?

If the same company who manufacturers the original parts is responsible for disassembly and reassembly of the new building, there is no question about the responsibility for the component’s function. The business model of the company could be extended, so that deconstruction is planned from the beginning and a take-back scheme for their products could be implemented. Over the use period of the building, the company could either retain ownership of the building parts and lease them to the occupants, or the company could agree on a “right of first refusal” (RoFR) contract. Such a contract would give the company the first right to entering a business transaction relating to the building, before the owner could offer the same transaction to a third party. This model could be used in different ways:

- The company could get the first right to buy the house, should the owner decide to sell it
- The owner could be required to offer renovation or alteration contracts to the company first, before looking for other contractors
- The council could give the company the first right to remove the building, should demolition be required.

Before reusing the recovered assemblies and components, the company would need to carry out an initial testing phase, to test their mechanical properties and assure their functionality. After this evaluation phase, an agreement with insurance providers for the reuse of assemblies can be reached. This business model would have several advantages:

- There is no question about who has the responsibility for the functionality of the assemblies, since only one party is involved from manufacturing to recovery, reuse and eventually end of life.
- The infrastructure and knowledge from manufacturing and assembly can be transferred easily to disassembly and reuse steps. If assemblies need to be inspected, repaired, or retrofitted, existing facilities can be used. BIM models do not need to be shared between parties and the knowledge about parts, connections and assembly history can be stored in the same place over the whole lifecycle.
- With the implementation of a take-back scheme or RoFR contract, there will be less uncertainty about the end of life of a building. The company will receive information about deconstruction projects, will have certainty about the costs for the take-back and there will be no competition with other deconstruction or demolition companies.
- The existing relationship between the company and the insurance providers will pose an advantage for the negotiation around the reuse of components.

Can tasks such as disassembling with a sabre saw be safe and controllable?

The deconstruction process and the waste that arises as a result are based on assumptions only. Practical tests need to be carried out to verify that the deconstruction can be carried out as planned and improvements to the deconstruction plan need to be made following the findings of practical deconstructions.

Which houses are attractive enough / have qualities that make them likely to be moved? Do modern houses evoke such feelings that you take the trouble to move or preserve them?

Houses are often demolished not because they are faulty, but because they are in the wrong place at the wrong time. But older houses, over 100 years, are not being demolished, since they are deemed preservable (Cramer and Ridley-Ellis 2020b). Modern UK houses on the other hand are seen as “too uniform and samey” by 36% of new home buyers (ZPG 2018) and only 12.5% of Londoners think they are “built with good design and modern living requirements in mind” (Airey, Scruton, and Wales 2018). The latter study highlights that there is a soft consensus of what makes a building beautiful, and that it is not at all impossible to build in this way. Biophilic design might also play a role in making new houses valued by their inhabitants, as this design concept involves improving the mental and physical health and mood of inhabitants by using natural materials and shapes, and creating a visual and sensory connection with nature (Ryan and Browning 2018). Many new houses lack the ability to provoke positive feelings in people and the design of new houses has to improve to create homes that will be valued and preserved by their occupants and neighbours. But the Everett Grand is built and equipped to high standards and has several features that are, according to a 2012 report by the Royal Institute of British Architects (Finlay et al. 2012), commonly valued by homeowners. This includes large windows and light rooms, spacious rooms (especially in the improved design) and a private garden.

The improved design ensures a longer life span of the building by being adaptable to different tenancy situations or changing requirements of the owners.

The user experience and experienced value of the building could be further improved by incorporating biophilic design. The design could for example use more natural and diverse materials as well as biomorphic forms and patterns in floors, walls, windows and/ or finishes; incorporate layered or dynamic lighting; and ensure comfortable room climate with slight variabilities in airflow and temperature (Ryan and Browning 2018). The façade should be designed to the same principles of "beauty" and biophilic design, as it affects the perception of everyone who sees the building. It should be of high quality and durability but also adaptable and customizable, as it reflects the personality of the owner to their neighbours. Of course, people's living experience is not confined to the inside of their own house either, but largely impacted by their neighbourhood. The impression and perceived value of new-built homes therefore also needs to diagnose problems in housing developments.

Can developments, alongside houses, be improved to be more adaptable and preservable?

The case study building is part of a new housing development in the South of Glasgow with 70 plots. Sixteen different house types, all built by Robertson Timber Engineering, make up the development, which will be completed in 2022. The new homes are all single-family, 4- to 6-bedroom houses and cost between £365,000 and £465,000. This development is tailored to large, high-income families and unlikely to attract other demographics, such as young people, families without children, low-income families or elderly people. Furthermore, there is little communal space within the development. A green area and a play area serve as communal meeting spaces, but there is no room for commercial areas like shops and cafes. Of course, not every housing development can include a restaurant, hairdresser and grocery shop, but this is not the only development in the area that is missing such amenities and the closest shop and café is found in 1.4 km walking distance, outside the new housing developments. The concept of 20-minute neighbourhoods is highlighted as a development goal in Scotland's Housing to 2040 roadmap (Scottish Government 2021a), which would address the problem that only 10-15% of new house buyers in the UK rate new-built houses to "have good facilities nearby" (ZPG 2018). The absence of commercial and communal spaces in new housing developments does not only make it harder for people to rely on climate-friendly methods for transport like walking and cycling, but also separates people's homes from the rest of their life. If people have to leave their neighbourhood for everything from working over shopping to eating in a restaurant, they are unlikely to develop a sense of community, a connection with their neighbours or appreciation for their houses. It is also unlikely that someone would live in their neighbourhood for the rest of their life, as there is no opportunity to move into a smaller home in the same area (a problem that is addressed with the new adaptable design).

The abovementioned factors are likely a part of the negative bias against modern houses in the UK. People who have an emotional connection to the houses in their neighbourhood (which might be provoked by a beautiful design, but equally by positive memories and the experience of community) are probably more likely to preserve their houses and houses that surround them, and favour renovation over demolition.

Spaces that people want to live in are located close to amenities, are easily reached by a variety of transport modes, foster a community with mixed tenancy options and communal spaces, provokes positive feeling through design, incorporate natural green spaces, and are designed to be sustainable and lasting (Carmichael and Stern 2018). The Scottish Government highlights the importance of these aspects in the design of new housing developments in their Housing to 2040 vision (Scottish Government 2021b). Robertson is also involved in a positive example of a new neighbourhood being built. In the South of Inverness, Robertson and other building companies are building 67 new homes, a mix of houses and flats, as well as commercial spaces, including a restaurant, and a community square. In addition, the community has been involved to some degree in the planning and design of the space. Local high school pupils designed the art for the community space and had the chance to visit the construction site. An impression of the new development can be seen Figure 35. Building neighbourhoods with and for communities is a crucial aspect of building long-lasting, preservable houses and a challenge for the UK house-building industry.

View looking from arrival space towards the multi-use community square

Figure 35 New mixed housing development. ©Robertson

In summary, contemporary timber houses can be deconstructed and reused. Small design changes can improve the reuse potential of recovered assemblies. To achieve maximum effect, however, DfDR design changes need to be part of a holistic design strategy that focuses on the community's need, which is embedded in the manufacturer's circular business model.

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List of appendices

Appendix 1 Meeting Notes - Deconstruction Analysis

Appendix 1 Meeting Notes - Deconstruction Analysis

DECONSTRUCTION STEP	DESCRIPTION, WHAT IS DONE DURING THIS STEP	Tools that come into use	Damage that may occur to components and materials during disassembly and handling	Reuse potential	Foreseen need for reconditioning, repair and controls	Suitability of disassembled components for intermediate storage	Foreseeable wastage (timber elements)	Risks with regard to personal safety. (There may be a risk of inhaling particles, risk of exposure to chemicals, risk of falling or lifting too heavy, etc.).	Risks of chemicals contaminating soil or air
PREPARATORY WORK	Remove flooring, staircase, external cladding	All steps: Scaffolding, lorry for transport	Components damaged and not reused	none		All parts: weather protection wrappig for transport and storage			
	Windows and doors only need to be removed if they are not to be reused, else they remain in the panel		No damage	high		For deconstruction, additional protection is not needed, as it will be a matter of days that the structure is exposed			
ROOF	Tiles need to be removed if they are heavy/ their weight is not planned for. Concrete tiles might have a low life expectancy. Roof cladding might be subject to trend changes and might need to be changed anyway.		Degradation	Concrete tiles: none; Slate: high; lightweight tiles: high					
	Dormer windows to be taken out as a whole		none	high					
	Roof (headbinders+trusses+gable laders+bracing+battens+ sarking+felt+ insulation+ceiling covers, can be lifted as a whole and transported in big pieces (depending on distance, bridges etc.)	Saw: sawing through nails in headbinder, sawing in half/ thirds (transport of parts up to 4.5m possible) Crane: Lift after lifting web has been reinstalled	none	high	Visual inspection: rot, (moisture) damage, unexpected alterations; repair acordingly Timber might need to be retreated		none	safety inspection before lifting, risk manageable Lifting points should be known/included in BIM	Treated timber: no risk to environment
EXTERNAL WALLS, FLOOR 2	Remove internal plasterboard	Electric screwdriver	Plaster is fixed to service battens and its replacement would not affect structure	no reuse					
Panels 5-194 kg	Dissassembly of joint between wall element and intermediate floor: sawing through nails	saw	none	high	visual inspection of studs (repair as needed), replacement or addition of insulation material, replacement or patching of vcl and breather membrane		none	risks manageable, time consuming labour	Treated timber: no risk to environment
	Lifting holes exist, a new loop or hook would need to be fixed there	temporary lifting device, crane			Timber might need to be retreated				
Repair of Breather membrane?	Replacement or patching				Marking of panels needed to determine order of removal/ reinstallation: include in BIM				
Serice installations?	Are accessible after plaster is removed, could be replaced if needed; same for insulation								
INTERNAL WALLS, Loadbearing	Same procedure as for external walls								
INTERMEDIATE FLOOR CASSETTE	Remove ceiling lining plasterboard	Electric screwdriver		none					
40-600 kg	Floor cover - chipboard: saw through where cassettes need to be separated, glue together at new site	saber saw	minor damage (3mm cut)		glued with expansion glue on new site		none	risks manageable, time consuming labour	glue: no known risks
	Cassettes/ cassette groups can be lifted off, holes for loops exist, loops need to be temporarily fitted	temporary lifting device, crane	none		visual inspection (repair as needed)	stack cassettes correctly to avoid damage			
SLAB ON THE GROUND	sole plates concrete		damaged crushed	cannot be reused cannot be reused, but recycled			100%		
NON LOAD BEARING INNER WALLS	Same as loadbearing walls								
BATHROOM	Tiles can be removed but will be damaged Wetwall could be removed and reused								
INSTALLATIONS	Can be accessed after plasterboard is removed, alterations possible								

Appendix 2 EC5 Calculations

General assumptions

- C16 timber with characteristic 5th percentile density ρk of 310 kg/m^3
- Holes are not predrilled
- Paslode tensile strength minimum 700 N/mm^2
- Paslode head pull-through strength $f_{head,k}$=20.72 N/mm^2 for average wood density 350 kg/m^3
- Paslode withdrawal strength $f_{ax,k}$=10.33 N/mm^2 for average wood density 350 kg/m^3
- Paslode pointside penetration length t_{pen}=75 mm – 4.7 mm = 70.3 mm
- Paslode head diameter d_h=6.5 mm
- Paslode diameter d=3.1 mm

Connection between two vertical timber members, single-shear (e.g. wall panel to wall panel connection, Figure 36)

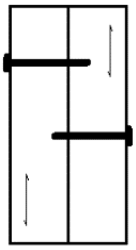


Figure 36 Connection between two vertical timber members

Nails perpendicular to grain
Member1= stud of wall panel
Member2= stud of wall panel
Row parallel to grain, but staggered n_{ef}=n
2 every 600 mm (2 every 400 mm in spandrel panels)
t_1=38mm
t_2=75 mm – 38 mm = 37 mm
f_{h1k}= f_{h2k}= 0,082 ρ_k $d^{-0,3}$ = 18.1 N/mm2 (characteristic embedment strength for both timber members)
f_u=700 N/mm^2
$M_{y,Rk}$= 0.3 f_u $d^{2.6}$= 3978.87 Nmm
$F_{ax,Rk}$= unknown = 0
$\beta = \frac{f_{h2k}}{f_{h1k}} = 1$
Which leads to screws with the following characteristics:
n=1
d_{efmin}=3.1 mm (to match nail diameter)
d_{imin}=3.1/1.1 = 2.82 mm
d_i= 3 – 3.45 mm = 3.23 mm (assumption from (ETA Danmark 2021))
d_{ef}=3.55 mm
d=5 mm (assumption from (ETA Danmark 2021))
l=70 mm (assumption from (ETA Danmark 2021))

t_2=70 mm – 38 mm = 32 mm

$M_{y,Rk}$= 0,15 · 600 · $d^{2.6}$= 5909.69 Nmm (Equation from from (ETA Danmark 2021))

f_{h1k}= f_{h2k}=$\frac{0{,}082\,\rho k d^{-0.3}}{2.5\,cos^2\alpha+sin^2\alpha}$= 15.69 N/mm^2 (Equation from from (ETA Danmark 2021))

fix$F_{ax,Rk}$= unknown = 0

Table 7 Parameters of nails and screws to replace nails in the same connection

Parameter	**Nail**	**Screw**
t_1	38 mm	
t_2	37 mm	32 mm
f_{h1k}= f_{h2k}	18.1 N/mm^2	15.69 N/mm^2
β	1	
$M_{y,Rk}$	3978.87 Nmm	5909.69 Nmm
$F_{ax,Rk}$	0	

$$F_{v,Rk} = \min \begin{cases} f_{h,1,k}\,t_1 d & \text{(a)} \\ f_{h,2,k}\,t_2 d & \text{(b)} \\ \dfrac{f_{h,1,k}\,t_1 d}{1+\beta}\left[\sqrt{\beta+2\beta^2\left[1+\dfrac{t_2}{t_1}+\left(\dfrac{t_2}{t_1}\right)^2\right]+\beta^3\left(\dfrac{t_2}{t_1}\right)^2}-\beta\left(1+\dfrac{t_2}{t_1}\right)\right]+\dfrac{F_{ax,Rk}}{4} & \text{(c)} \\ 1{,}05\,\dfrac{f_{h,1,k}\,t_1 d}{2+\beta}\left[\sqrt{2\beta(1+\beta)+\dfrac{4\beta(2+\beta)M_{y,Rk}}{f_{h,1,k}\,d\,t_1^2}}-\beta\right]+\dfrac{F_{ax,Rk}}{4} & \text{(d)} \\ 1{,}05\,\dfrac{f_{h,1,k}\,t_2 d}{1+2\beta}\left[\sqrt{2\beta^2(1+\beta)+\dfrac{4\beta(1+2\beta)M_{y,Rk}}{f_{h,1,k}\,d\,t_2^2}}-\beta\right]+\dfrac{F_{ax,Rk}}{4} & \text{(e)} \\ 1{,}15\sqrt{\dfrac{2\beta}{1+\beta}}\sqrt{2M_{y,Rk}\,f_{h,1,k}\,d}+\dfrac{F_{ax,Rk}}{4} & \text{(f)} \end{cases} \tag{8.6}$$

Figure 37 Equation 8.6 from Eurocode 5 for the calculation of the characteristic load-carrying capacity per shear plane per fastener

Table 8 $F_{v,RK}$ for nails and screws, calculated using equation 8.6 from Eurocode 5 (Figure 37) and the parameters in Table 7, minimum highlighted in bold

In N/mm^2	Nail	Screw
(a)	2132.61	2290.39
(b)	2076.49	1928.75
(c)	871.86	879.29
(d)	852.58	957.37
(e)	835.61	856.75
(f)	768.52	970.64

The characteristic load-carrying capacity per shear plane per fastener is bigger for the screw than for the nail (Table 8) and therefore the screw is adequate for replacement.

Connection between two horizontal timber members, single-shear (e.g. headbinder to top rail of panel, Figure 38)

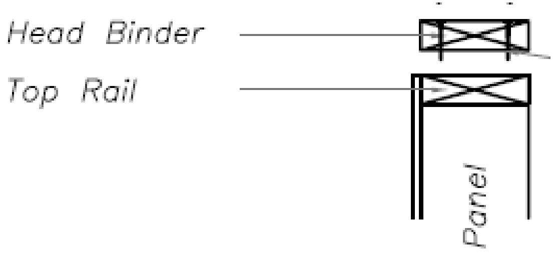


Figure 38 Connection between two horizontal timber members ©Robertson Timber Engineering

Member 1= headbinder or bottom rail
Member 2= top rail or soleplate
Nails perpendicular to grain
Row perpendicular to grain
2 every 600 mm
t_1, t_2, f_{h1k}, f_{h2k}, f_u, $M_{y,Rk}$, $F_{ax,Rk}$, β are the same as above and therefore the screw specifications are as above.

Connection between a panel product (OSB) and a timber member, single-shear

Member 1= OSB sheathing, 9 mm thickness
Member 2= stud, headbinder, bottom rail of panel
t= 9 mm
t2= 75-9 mm = 66 mm
Minimum spacing 50 m
fhk = fh1k = (characteristic embedment strength since dh>2d) = 65 d -0,7 t0.1 = 36.38 N/mm2
fh2k= 0,082ρk d -0,3 = 18.1 N/mm2
= 0.50
fu=700 N/mm2
My,Rk= 0.3 fu d2.6= 3978.87 Nmm
Fax,Rk= unknown = 0
Which leads to screws with the following characteristics:
n=1
defmin=3.1 mm
dimin=3.1/1.1 = 2.82 mm
di= 3 – 3.45 mm = 3.23 mm (assumption from (ETA Danmark 2021))
def=3.55 mm
d=5 mm (assumption from (ETA Danmark 2021))
l=70 mm (assumption from (ETA Danmark 2021))
t2=70 mm – 9 mm = 61 mm
dhmin=11.5mm >2def
fh1k =65 def-0,7 t0.1 = 33.36 N/mm2
My,Rk= 0,15 · 600 · d2.6= 5909.69 Nmm (assumption from (ETA Danmark 2021))
fh2k= = 15.69 N/mm2 (assumption from ETA Danmark 2021)

Fax,Rk= unknown = 0

Parameter	Nail	Screw
t1	9 mm	
t2	66 mm	61 mm
fh1k	36.38 N/mm2	33.36 N/mm2
fh2k	18.1 N/mm2	15.69 N/mm2
β	0.5	0.47
My,Rk	3978.87 Nmm	5909.69 Nmm
Fax,Rk	0	

In N/mm2	Nail	Screw
(a)	1015.00	1501.20
(b)	3704.01	3676.68
(c)	1361.09	1387.78
(d)	603.54	809.32
(e)	1496.64	1578.07
(f)	888.12	1176.49

For assessing whether screws have to be placed in or near old screw holes when reassembling recovered assemblies, the minimum spacing for screws according to Eurocode 5 is analysed (Figure 39). No complications should arise when placing screws with minimum spacing to old screws and holes.

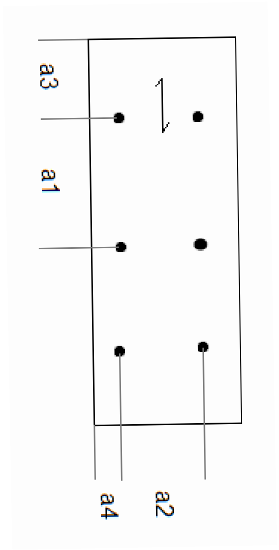
Connection between two vertical timber members, e.g. studs in wall panels α= 0° a_1= (5+7|cos α|) d = 60 mm a_2= 5d = 25 mm a_{3t}= (10+ 5 cos α) d = 75 mm a_{3c}= 10d = 50 mm a_{4t}= (5+5 sin α)d = 25 mm a_{4c}= 5d = 25 mm	

Figure 39 Minimum spacing for screws in connection 1, following the parameters in Table 7

Studs of a 38 by 75 mm^2 cross section (in non-loadbearing internal walls) could only have one screw at the same height, but studs with a 38 by 140 mm^2 cross section (in external walls) could have a maximum of three.

Studs of 2212 mm length contain a maximum of 4 connections with 600 mm spacing (3.69). With a minimum distance to the edge a_3 of 50mm and 75 mm on both sides respectively, screws can be placed on 2087 mm length, with 60 mm lengthwise distance between a pair of screws, meaning that the first assembly requires 60 mm space per screw pair and every following re-assembly requires 120 mm of space.

This means that we can reuse the same stud, without reusing screw holes $(2087\ mm - 4 \cdot 60\ mm) \div (4 \cdot 120\ mm) = 3.85$ times, which in reality means a maximum of 3 times. It is likely that studs are not reused more than three times and thus holes will not need to be reused.

A special case are spandrel panels, that can be much shorter and have a lengthwise nail spacing of 400 mm. The worst cases in terms of spacing flexibility is the stud lengths of 718 mm in panel EX5SP (after panel EX4SP is made redundant due to new wall layout). This would allow lengthwise re-spacing of 1.97 times (1 time in reality). Spandrel panels, as external panels, have a stud width of 140 mm, so that a screw can be placed at the same height in 25 mm distance to the old hole and the edge twice (Figure 40). In total, 5 reuse cycles are possible without reusing screw holes.

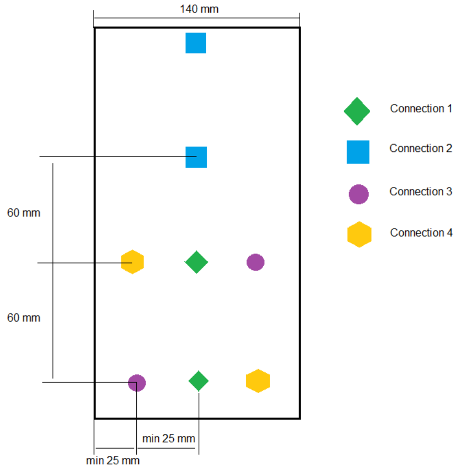


Figure 40 re-spacing of screwed connections in external wall panels of 38 by 140 mm² cross section, schematic

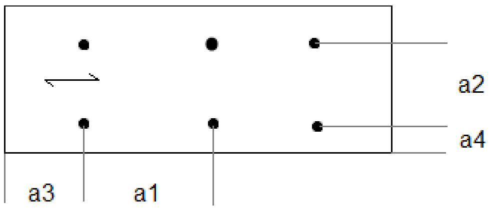
Connection between two horizontal timber members e.g. headbinder to top rail of panel α= 90° a_1= (5+7|cos α|) d = 25 mm a_2= 5d = 25 mm a_{3t}= (10+ 5 cos α) d = 50 mm a_{3c}= 10d = 50 mm a_{4t}= (5+5 sin α)d = 50 mm a_{4c}= 5d = 25 mm	

Figure 41 Minimum spacing for screws in connection 2, following the parameters in Table 7

Soleplates and headbinders have minimum sections of 800*75 mm² with two connections and 1201*75 mm² with three connections. This leaves us with only lengthwise respacing options for both scenarios, but 6.5 and 13.68 possibilities for respacing respectively (calculated as above, Figure 41).

Connection between a panel product (OSB) and a timber member, single-shear

$\alpha = 90°$

$a1 = 0.85\,(5+7|\cos\alpha|)\,d = 21.25$ mm

$a2 = 0.85\ 5d = 21.25$ mm

$a3t = (10+5\cos\alpha)\,d = 50$ mm

$a3c = 10d = 50$ mm

$a4t = (5+5\sin\alpha)\,d = 50$ mm

$a4c = 5d = 25$ mm

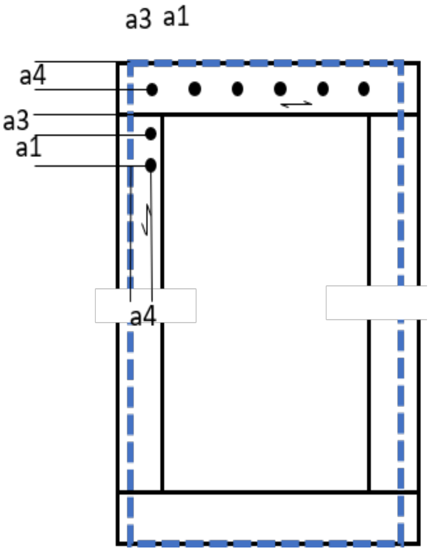


Figure 42 Minimum spacing for screws in connection of OSB, following the parameters in Table 8.

OSB panels require connectors around the edge with a minimum spacing of 50 mm (Figure 42). A standard OSB panel of 597 by 2288 mm^2 requires 12 fasteners on the short side (11.94) and 46 fasteners on the long side (45.76). Only one fastener can be used at the same height in studs and at the same width in top or bottom rail. Using the same approach as above, we get replacement options of 0.47 and 0.62 times respectively. This leads to the conclusion that neither on the short nor on the long side OSB could be detached from the panel and reattached without using screws in or close to old screw holes.

Appendix 3 List of all functional units and unit width in cores (one core = 600 mm)

Unit No.	Unit	Unit width in cores
E1	External wall, 1 core	1
E1a	External wall, 1 core plus 1 stud	1
E2	External wall, 1 core plus 2 studs	1
E2a	External wall, 1 core plus movement joist	1
E2b	External wall, 1 core plus middle stud	1
E3	External wall, 1 core plus nogging	1
E4	External wall, half core	0.5
E5	External wall, half core plus middle stud	0.5
E6	External wall, half core plus 1 stud	0.5
E7	External wall, half core plus 2 studs	0.5
E7a	External wall, half core plus 3 studs	0.5
E8	External wall, half core plus nogging	0.5
E9	External wall, 2 cores	2
E10	External wall, 3 cores	3
E11	Internal loadbearing wall, 1 core	1
E12	Internal loadbearing wall, 1 core plus middle stud	1
E13	Internal loadbearing wall, 1 core plus 1 stud	1
E14	Internal loadbearing wall, 1 core plus 2 studs	1
E15	Internal loadbearing wall, 1 core plus 4 studs	1
E16	Internal loadbearing wall, 1 core plus nogging	1
E17	Internal loadbearing wall, half core	0.5
E18	Internal loadbearing wall, half core plus nogging	0.5
E19	Internal loadbearing wall, half core plus 1 stud	0.5
E20	Internal loadbearing wall, 2 cores	2
E21	Internal loadbearing wall, 3 cores	3
E22	Internal non-loadbearing wall, 1 core	1
E23	Internal non-loadbearing wall, 1 core plus 1 stud	1
E24	Internal non-loadbearing wall, half core	0.5
E25	Internal non-loadbearing wall, half core plus 1 stud	0.5
E26	Internal non-loadbearing wall, 2 cores	2
E27	Internal non-loadbearing wall, 3 cores	3

Unit No.	Unit	Unit width in cores
E27a	Internal non-loadbearing wall, 1 core plus nogging	1
E27b	Internal non-loadbearing wall, 1 core plus middle stud	1
E27c	Internal non-loadbearing wall, half core plus nogging	0.5
E28	Window	3
E29	Small window	2
E30	Large window	5
E31	Internal loadbearing door, 140 mm width	2
E31a	Internal loadbearing large door	3
E31b	Internal loadbearing door, 89 mm width	2
E31c	Internal loadbearing door plus nogging	2
E32	Internal non-loadbearing door	2
E33	Window sill	-
E34	Window sill high	-
E35	Window sill low	-
E36	Small window sill	1.5
E37	Small window sill high	1.5
E38	Small window sill low	1.5
E39	Large window sill	4
E40	OSB, half core	0.5
E40a	OSB, half core plus 2 stud widths	0.5
E41	OSB, 1 core	1
E43	OSB, 1 core plus 2 stud widths	1
E45	OSB, 2 cores	2
E47	OSB, 4 stud widths	-
Ecor	Corner, 140 mm width and thickness	-

Appendix 4 Composition of wall panels from standard units, including new length of panels and optimisation suggestions for increased adaptability

Panel number	Units						Sill	OSB					new length	Optimisation
EX1GF	E9	E4	E28	E4			E33	E41	E43	E40a			3600 (1800)	Add E3 from EX 19GF and move E4, E28, E4 to EX2GF
EX2GF	E2	E2b						E45					1340 (3600)	Add E4,E28,E4 from EX1GF
EX3GF	Ecor	E1	E2a	E9	E9	E3		E45	E41	E45	E45		4200 (3740)	Move E3 from EX3GF to EX4GF
EX4GF	E6	E6	E2a	E10				E45	E41	E45			3000 (3600)	
EX5GF	E4	E2	E9					E45	E40	E41			2100	
EX6GF	Deleted													
EX7GF	E30	Ecor											3140	
EX8GF	Deleted													
EX9GF	E29	E29					E38	E47					2400	
EX10GF	Deleted													
EX11GF	Ecor	E4	E30	E8			E39	E40a	E40a				3600	
EX12GF	E2a	E1	E2	E10				E45	E45	E45			3600 (2100)	Move E9 and E6 from EX12GF to EX13GF
EX13GF	E6	E2	E9					E45	E41	E40			2100 (3600)	
EX14GF	E9	E2a	E9	E2b				E45	E41	E45	E41		3740	
EX15GF	E4	E4	E10	E9	E4	Ecor		E45	E41	E45	E41	E40	3900	
EX16GF	Unchanged													
EX17GF	Unchanged													
EX18GF	E4	E30	E7	E5				E40a	E43				3900	
EX19GF	E3	E30	E1					E43	E43	E45			4200 (3600)	Move E3 to EX1GF
IL1GF	E9	E2	E1					E45	E45				2400 (3000)	Move E1 from IL2GF to IL1GF
IL2GF	E1	E3	E9	E2b				E45	E45	E41			3000 (2400)	
IL3GF	E1	E31	E4	E1				E43	E40a	E41			2700	
IL4GF	Deleted													
IL5GF	E20	E16	E31c					E45	E43				3000	
IL6GF	E13	E31a	E17	E16				E41	E40a	E40a	E41		3300	
IL7GF	E20	E11	E13					E45	E45				2400	
IL8GF	E31b	E20	E13					E43	E41	E40			3000	
IN1GF	E32	E22											1800	
IN2GF	E26	E22	E23										2400	
IN3GF	Special													
EX1FF	E2a	E28	E4	E8	E7	E5	E34	E43	E43	E41			3600	

Panel number	Units						Sill	OSB				new length	Optimisation
EX2FF	E1	E29	E2b				E37	E43	E43			2400 (1800)	Move E3 from EX2FF to EX3FF
EX3FF	E1a	E4	E28	E4			E34	E41	E40a	E40a		3000 (3600)	
EX4FF	Ecor	E1	E2a	E9	E9			E45	E45	E45		3740	
EX5FF	E1	E29	E4	E29			E37	E41	E40a			3300	
EX6FF	E2a	E9	E1	Ecor				E45	E41	E40		2540	
EX7FF	E4	E28	E1	E4			E33	E40b	E40b			3000	
EX8FF	E1a	E29	E1a				E38	E41	E43	E40a		2400	
EX9FF	Deleted												
EX10FF	E1a	E3	E28	E6	E4	Ecor	E35	E40	E43	E43	E40	3740	
EX11FF	E9	E6	E4	E9				E45	E41	E45		3000	
EX12FF	E29	E2b	E1	E29			E37	E43	E43			3600	
EX13FF	E1	E2a	E9	E4	Ecor			E45	E45	E40		2840	
IN1FF	E26	E26										2400	
IN2FF	Deleted												
IN3FF	E26											1200	
IN4FF	E26											1200	
IN5FF	E32	E22										1800	
IN6FF	E32	E32	E27a	E22								3600	
IN7FF	E22	E32	E24	E32	E24							3600	
IN8FF	E26	E25										1500	
IN9FF	E26	E26										2400	
IN10FF	E26	E26	E26									3600	
IN11FF	Deleted												
IN12FF	Deleted												
IN13FF	Deleted												
IN14FF	Deleted												
IN15FF	E26	E23	E23	E22								3000	
IN16FF	E32	E23	E22									2400	
IN1SF	E26	E32										2400	
IN2SF	E27b	E24	E27c									1200	
IN5SF	E25	E27b										900	
All other SF	Unchanged												

Appendix 5 Deconstruction Plan

Deconstruction Plan

ROBERTSON

Contract name	**Everett Grand**	**Building type**	**Detached timber-frame house**	**Updated**	**10.9.21**

Step	Component	Deconstruction details	Weight range of elements	Proposed equipment required	Risks to reuse	Resource recovered	Intended re-use	Value after recovery	Recycling
1	Second fix	Remove furnishing, wall attachments, bathroom installations, visible services like fire alarms etc., stairs				Stair, furniture	Stairs could be reused in another building. Furniture could be reused.	Medium	Timber, small electronic devices, cables, tiles
2	Internal finishes	Remove plasterboard on walls and ceilings (unscrew screws). Detach services inside panels. Remove floor finishes (depending on type).	16.5 to 22 kg (plasterboard)	Electric screwdriver, crowbar, claw hammer, sabre saw	Damage to floor finish	Floor finish (timber)	Floor finish in another building	Medium	Plasterboard, possibly carpet, tiles, chipboard or linoleum flooring
3	Inspection	Inspect structure. Ensure that structure is safe and built as expected. Note and mark any damage or decay. Note and mark any unreported connectors. Update deconstruction information should the structure differ from design drawings. NOTE: Refer to inspection guidance.		Torch, screwdriver, measuring tape, portable moisture meter, portable computer, spray paint, calculator, metal detector?				n/a	
4	Internal non-load bearing walls	Use sabre saw at nailed connections. Use electric screwdriver at screwed connections. Locate lifting points, insert lifting straps. Secure doors before lifting. NOTE: For position, number and type of connections, refer to nailing schedule. For position of lifting points, refer to design drawings and BIM model.	7.8 to 145.2 kg plus doors	Sabre saw, electric screwdriver	Incorrect BIM data or access to information.	Timber framed panels	Rebuild house in new location / reconfigure layout	Medium	
5	External facade	Remove brickwork. Ensure that timber kit is not damaged in the process.		Scaffolding, hydraulic breaker				Low	Brick fragments
6	Roof finish	Remove eaves soffit framing, fascia board, soffit ventilators, soffit plywood and bootends. Remove tilting fillets, eaves and ridge sarking boards (where applicable) and sheet with roof sarking. Remove roof tiles.		Crowbar, Claw hammer, screwdriver, pliers			Possibly reuse, if life-span is not reached	Low	Concrete tiles, uPVC boards
7	Dormer windows	Unscrew screws . Secure windows before lifting. NOTE: Refer to manufacturer's instructions for type and position of connections and lifting points.		Electric screwdriver, Crane		Dormer windows	Rebuild house in new location	High	
8	Roof structure	Fix temporary bracing. Remove holding down straps. Saw apart trusses and panel headbinder. Secure windows before lifting. NOTE: For position, number and type of connections, refer to nailing schedule. For position of temporary bracing, lifting points and holding down straps, refer to design drawings and BIM model.	Around 2990 kg	Torch, Crowbar, Screwdriver, Sabre saw, Pliers, Crane	Moisture damage. Incorrect BIM data or access to information.	Roof	Rebuild house in new location	High	Possibly roofing felt, timber
9	First floor internal load-bearing wall panels	Fix temporary bracing. Use sabre saw at nailed connections. Use electric screwdriver at screwed connections. Locate lifting points, insert lifting straps. Secure doors before lifting. NOTE: For position, number and type of connections, refer to nailing schedule. For position of temporary bracing and lifting points, refer to design drawings and BIM model.	143.0 to 278.8 kg plus doors	Crane - sized to loads, max lifting radius and environment, sabre saw, Electric screwdriver	Headbinder could suffer deconstruction damage. Moisture damage. Incorrect BIM data or access to information.	Timber framed panels	Rebuild house in new location	High	Possibly insulation, timber
10	First floor external wall panels	Fix temporary bracing. Remove holding down straps. Use sabre saw at nailed connections. Use electric screwdriver at screwed connections. Locate lifting points, insert lifting straps. Secure windows before lifting. NOTE: For position, number and type of connections, refer to nailing schedule. For position of temporary bracing, lifting points and holding down straps, refer to design drawings and BIM model.	122.0 to 425.7 kg plus windows				Rebuild house in new location	High	Possibly insulation, timber, OSB, Membranes, Windows

DRAFT PLAN ONLY - NOT FOR USE ON SITE

11	First floor cassettes	Locate individual cassettes from below. Saw apart individual cassettes. Locate lifting points, insert lifting straps. NOTE: For position, number and type of connections, refer to nailing schedule. For cassette layout and position of lifting points, refer to design drawings and BIM model.	individual cassettes: Around 106 to 310 kg	Sabre saw, Crane	Moisture damage. Incorrect BIM data or access to information.	Floor cassettes	Rebuild house in new location	High	Possibly insulation, timber, OSB, Membranes
12	Garden room roof	Fix temporary bracing. Remove holding down straps. Saw apart trusses and panel headbinder. NOTE: For position, number and type of connections, refer to nailing schedule. For position of temporary bracing, lifting points and holding down straps, refer to design drawings and BIM model.	Around 310 kg	Crowbar, screwdriver, Sabre saw, crane	Moisture damage. Incorrect BIM data or access to information.	Roof	Rebuild house in new location	High	Possibly roofing felt, timber
13	Ground floor load-bearing internal wall panels	Fix temporary bracing. Use sabre saw at nailed connections. Use electric screwdriver at screwed connections. Locate lifting points, insert lifting straps. Secure doors before lifting. NOTE: For position, number and type of connections, refer to nailing schedule. For position of temporary bracing and lifting points, refer to design drawings and BIM model.	143.0 to 278.8 kg plus doors	Sabre saw, Electric screwdriver, Crane	Headbinder could suffer deconstruction damage. Moisture damage. Incorrect BIM data or access to information.	Timber framed panels	Rebuild house in new location	High	Possibly insulation, timber, OSB
14	Ground floor external wall panels	Fix temporary bracing. Remove holding down straps. Use sabre saw at nailed connections. Use electric screwdriver at screwed connections. Locate lifting points, insert lifting straps. Secure windows and doors before lifting. NOTE: For position, number and type of connections, refer to nailing schedule. For position of temporary bracing, lifting points and holding down straps, refer to design drawings and BIM model.	122.0 to 425.7 kg plus doors and windows					High	Possibly insulation, timber, OSB, Membranes, Windows, Doors
15	Soleplates	If screwed, unscrew. If nailed, remove using crowbar.	1 to 8.5 kg	Electric screwdriver, Crowbar	Deconstruction damage	Soleplates (timber)	Solplates could be reused if they are recovered damage-free	Medium	Timber
16	Concrete slab	Demolish foundation		Excavator, Skid steer		Concrete rubble		Low	Concrete
17	Inspection	Check components against inventory. Inspect all deconstructed elements for damage. Check if the intended lifespan is reached or close to being reached. NOTE: Refer to inventory. For intended life-span and age, refer to BIM model. For inspection instructions refer to post-deconstruction instructions.		Calculator, Portable Computer					
		a) For intact modules: Stack modules and wrap for protection during transport/storage. Update BIM model. Reuse in new location.		Stapler, Screwdriver, Portable computer, Lorry					
		Special case: Roof. Inspect roofing felt for damage or aging defects. Remove tiling battens and felt as necessary. Update BIM model. Saw apart roof structure as needed for transport. Wrap for protection during transport and storage.		Stapler, Screwdriver, Sabre saw, Portable computer, Lorry					
		b) For slightly damaged modules: Repair on site or note and mark for repair on new site. Order materials to new site as required. Divert damaged components to recycling. Stack modules and wrap for protection during transport/storage. Update BIM model.		Stapler, Screwdriver, Electric screwdriver, Nail gun, Portable computer, Lorry					
		c) For damaged elements: Divert modules for factory control. Not whether modules should be repaired, components exchanged or modules disassembled for recycling. Update BIM model.		Screwdriver, portable computer, lorry					