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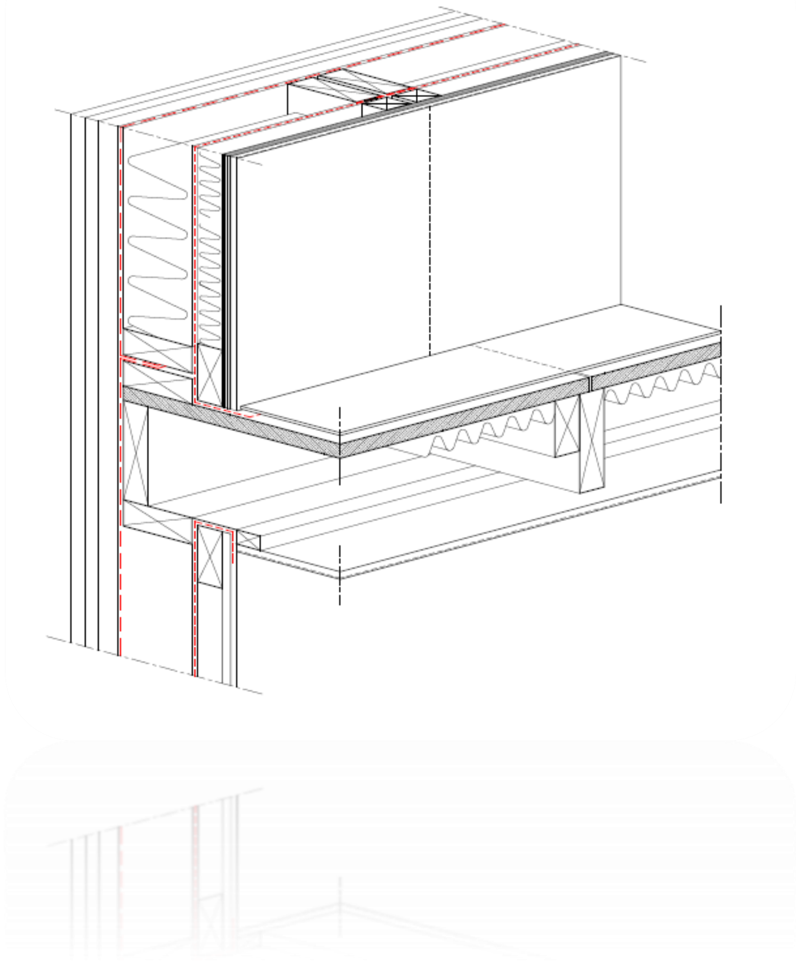

Innovative Design for the **Fut**ure – **U**se and **Re**use of **Wood** (**InFutUReWood**)

Deliverable Report *D3.3* of WP3

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Design concepts for building products optimised for deconstruction

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Innovative **D**esign for the **Fut**ure – **U**se and **R**euse of **W**ood (**InFutUReWood**)
Deliverable No. D3.3
Date: February 2022

Foreword

This report is published under the InFutURe Wood project - Innovative Design for the Future – Use and Reuse of Wood (Building) Components. Work Package 3 (WP3).

The InfutUReWood project has seven work packages:

- WP 1 Coordination and management led by Karin Sandberg, RISE, Sweden
- WP 2 Design of timber structures for the future, led by Ylva Sandin, RISE, Sweden
- WP 3 Product design using recovered timber, led by Annette Harte, NUI Galway, Ireland
- WP 4 Inventory, deconstruction and quality of recovered wood, led by Mark Hughes, Aalto University, Finland
- WP 5 Properties of recovered wood, led by Daniel Ridley-Ellis, Edinburgh Napier University, UK
- WP 6 Environmental and economic assessment of design for recycling in building construction, led by Michael Risse, TUM, Germany
- WP 7 Dissemination and engagement, led by Carmen Cristescu, RISE, Sweden

ForestValue

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The research and academia project partners are RISE (Sweden), Edinburgh Napier University (UK), National University of Ireland Galway (Ireland), University College Dublin (Ireland), Universidad Politécnica de 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, 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.

Summary

The **In**novative Design for the **Fut**ure **U**se and **Re**use of **Wood**en building components (InFutUReWood) project aims to answer two main questions:

- How easy is it to reuse timber from the current building stock, especially as a structural material?
- How can a review of current building practices help in future timber reuse?

To address these questions the project identifies key opportunities and challenges, proposing technical solutions that aim to exploit the opportunities and reduce the challenges identified that may lessen the reuse potential of construction timber.

This report is the result of the work carried out within Task 3.3 *Design new products optimised for improved deconstruction potential.* The aim of this task is to develop construction systems from new timber that are suitable for deconstruction at the end of first use. More precisely, it aims to improve the design and assembly approach used currently by timber product manufacturers and builders such that the reuse and cascade use viability of the timber content is increased. To achieve this, objectives are set out in the following steps:

i. Initially, to identify the current manufacturing and building practices that complicate timber-salvage at building disassembly,
ii. To examine alternative timber construction systems that would optimize the reuse of timber-salvage in the future

The report gathers and presents design examples of low-rise residential timber construction in Sweden, the UK and Ireland. Two different timber construction approaches for residential buildings are reported here, namely, light timber-frame construction and mass-timber construction. Both building systems are manufactured offsite in element format and are assembled and finished onsite.

Working closely with WP2, for each building the issues that currently complicate deconstruction and reuse were identified and alternative designs were proposed to optimise the recovery and reuse of the timber elements. While there are differences in building design within and between companies, many of the issues that complicate deconstruction and reuse are common to all.

The main issues that arose for light timber frame houses were detailing of panel components at connections between elements, use of glued and screws connections between floor elements, use of unprescribed nails by carpenters on site, lack of standardisation in element sizes. Revised designs were presented for the connections and recommendations were made on the inclusion of specific temporary supports to timber components during construction and the standardisation of component sizes. The changes needed to enhance the deconstruction and reuse potential are not significant or costly to implement.

Mass timber buildings were deemed to be well suited to deconstruction and reuse. The elements themselves are robust and stable. The connections are relatively straightforward and generally use high-performance screws to connect the elements. The disassembly process is simply the reverse of the assembly process. The main issues that can arise are access to the screws on the inside where linings are present or possible deterioration of connectors of timber elements exposed to external environments or accidental water leakage internally. Research is required to determine the durability of fasteners in these situations. Regular inspection and maintenance should help prevent major damage.

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1. Introduction

1.1. Background

This report is part of the InFutUReWood - Innovative Design for the Future – Use and Reuse of Wood (Building) Components – project which aims to answer two main questions:

- How easy is it to reuse timber from the current building stock, especially as a structural material?
- How can a review of current building practices help in future timber reuse?

To address these questions the project identifies key opportunities and challenges, proposing technical solutions that aim to exploit the opportunities and reduce the challenges identified that may lessen the reuse potential of construction timber.

Work Package (WP) 3 *Product design using recovered timber* is divided into four tasks. Task 3.1 focuses on the specification requirements for timber products and identifies the current range of timber material that is potentially available from demolition. Task 3.2 examines the recycling potential of wood in engineered-timber manufacture generally. Task 3.3 examines how to improve the design of new products to optimise their deconstruction to optimise the reuse potential of timber. Task 3.4 investigates traceability protocols of wood products.

This report is the result of the work carried out within Task 3.3 *Design new products optimised for improved deconstruction potential.*

1.2. Aims and Objectives

The aim of this task is to develop construction systems from new timber that are suitable for deconstruction at the end of first use. More precisely, it aims to improve the design and assembly approach used currently by timber product manufacturers and builders such that the reuse and cascade use viability of the timber content is increased. To achieve this, objectives are set out in the following steps:

- Initially, to identify the current manufacturing and building practices that complicate timber-salvage at building disassembly,
- To examine alternative timber construction systems that would optimize the reuse of timber-salvage in the future, and
- To undertake an environmental and economical evaluation of the proposed alternatives with respect to the current practices.

The main objective of the study is to improve the efficiency of assembly and disassembly with respect to time, to minimise material waste, and to reduce the need for remedial works at reassembly.

1.3. Method

The report gathers and presents design examples of low-rise residential timber construction and deconstruction in:

- Ireland,

- Sweden, and
- The UK.

The different building methods for residential accommodation reported here are:

- Light timber-frame construction, and
- Mass-timber construction

For each building, the current manufacturing and building practices that complicate timber-salvage at building disassembly are identified and alternative timber construction systems that would optimize the reuse of timber-salvage in the future are examined. i.e objectives (i) and (ii) of Task 3.3. The final objective of the task is reported in the WP6 final report (Ivanica el al 2022).

The task involves close collaboration with the building manufacturing, construction and demolition companies regarding their current assembly and deconstruction practices. It is intended to apply the practical insight gained from this dialogue with industry on their current practices to specific projects, but also to build on the knowledge gained from Task 3.1 and Task 3.2 to propose alternative building systems that have improved circularity potential. The fundamental principle of cascade use with respect to the material hierarchy will be applied. Therefore, the size of elements is kept as close to their original dimension as is practical for the next application.

1.4. Target group

Primarily, this report is targeted towards the research team of the InFutUReWood project. The findings are aimed at architects, engineers, manufacturers, and national code and regulation authorities, to highlight building procedures that may improve the circular use potential of timber from construction and demolition.

1.5. Short glossary of terms

The most used terms in the report are defined as follows:

Recycling is any recovery operation by which waste materials are reprocessed into products, materials, or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations. (EC 2008).

Reuse is any operation by which products or components that are not waste are used again for the same purpose for which they were conceived, with minimal pre-processing, i.e., checking, cleaning, and repairing. (Adapted from EC 2008).

Timber is used here to refer to any wood-based building material, whether structural or non-structural. Depending on the context, the word is used to refer to sawn wood in a prepared state for use in building (or wood intended for that purpose), but it can also be used in a general sense to include laminated elements and other engineered wood products. Wood based panel products are not, themselves, referred to as timber, but they do fall under the general heading of timber construction. In some countries, timber refers to specific end-uses and/or cross-section sizes, but that distinction is not made here

Assembly design is used here to refer to the assembly method used at timber product manufacturing and on site.

Dwelling is used here to refer to a single-family home.

Domestic construction is used here to refer to the low-rise dwelling design.

Planar element is used here to refer to 2-D planar prefabricated roof, wall, or floor elements.

Modular is used here to refer to prefabricated building 3-D units, i.e., comprising rooms rather than individual planar wall and floor elements.

Making good is used here to refer to the process of repairing the building structure and/or finishes to its previous condition, or the condition of adjacent finishes.

2. Light timber frame house construction

2.1. Introduction

An investigation was made of three proprietary house designs:

- the "*Villa-Anneberg"* house design by Derome in Sweden, and
- the "*Everett Grand*" house design by Robertson Homes and manufactured by Robertson Timber Engineering in the UK. Robertson Timber Engineering is a member of Offsite Solutions Scotland (OSS).
- the *"Reflect 140"* house-type by Cygnum in Ireland

The main structure of the Derome and Robertson house types comprises structural timber components. The multi-layer timber-framed planar wall elements, intermediate timber-floor cassettes, and timber roof truss structure are prefabricated, then transported for assembly on-site onto an in-situ concrete ground floor slab. The roof cladding, internal partition walls and all internal finishes, along with the second fix of mechanical, electrical, and sanitary services, is completed at the building assembly stage. The external walls of the Derome house are clad externally in timber. This cladding is fitted at the manufacturing facility. In the case of the Robertson design, the external façade is in-situ brick or masonry. Both buildings are assumed to have a first lifespan of circa 50 years, or two generations.

There were detailed discussions with the manufacturers' representatives on specific junctions with respect to minimising waste or remedial works at a deconstruction and reassembly stage of the buildings. The discussion mainly focused on facilitating the reconstruction of the whole building unmodified. However, the potential to extend or reduce a dwelling in-situ or at a reconstruction stage using prefabricated timber elements was also discussed for the Robertson design. In the case of the Derome "*Villa-Anneberg"* design, it was possible to refer to an example of a previous disassembly and reassembly of a similar Derome one-storey house.

The Cygnum house type is a suburban semi-detached three-bedroom house and chosen for review as it reflects modern light timber-frame construction in an Irish context as well as being a common housing typology. The house has a floor area of 120 m^2 and is constructed with timber-frame internal main structure and non-load bearing masonry external leaf on concrete ground floor slab. A different approach to disassembly was chosen whereby deconstruction to the individual timber board level was considered.

2.2. Derome "*Villa-Anneberg"* house-type

This study addresses the practices that complicate deconstruction and proposes alternative approaches that enhance the reuse potential of the main structural elements of the building. An extended version of the study is presented in Sandin *et al.* (2021). Details of the existing and revised designs were then used as the basis for the comparative life-cycle-assessment (LCA) and life-cycle-costing (LCC) in WP 6 and reported in Ivanica *et al.* (2022) .

The observations and recommendations made here follow discussions between NUIG, RISE, and Derome to examine the current assembly practices used in the manufacture and on-site assembly of a two-storey house type. An image of the house is shown in Figure 2-1. A previous disassembly and reassembly project of a similar Derome one-storey house was used as a reference on the implications to deconstruction and reassembly. In the reference case the owner chose to remove elements of the structural planar walls to enable the building disassembly. Remedial work at the manufacturing facility was required to reconstruct the structural panels before they were suitable for reuse. Much of the material removed was discarded.

Figure 2-1 : Derome "Villa-Anneberg" house-type *(image courtesy of Derome).*

2.2.1. Scope of the work

The discussions on the *Villa Anneberg* two-storey house type focused on improving the efficiency of the initial assembly design and the reduction of material waste at a reconstruction stage. By optimizing the planar element manufacture, and the connection design it is intended that whole panels may be disconnected, transported, and reconnected at a secondary location, without diversion to the manufacturing facility for corrective work before reassembly, thus minimising repairs pre and post reassembly.

The discussions identified four structural junctions to be potentially problematic with respect to the efficient reassembly of the building elements. They are 1) the vertical connection of the external wall panels, 2) the connection between the external wall and the intermediate floor, 3) the connection between the upper floor cassettes and, 4) the disconnection of the roof structure from the supporting wall elements. Figure 2-2 illustrates the first three junctions that were identified.

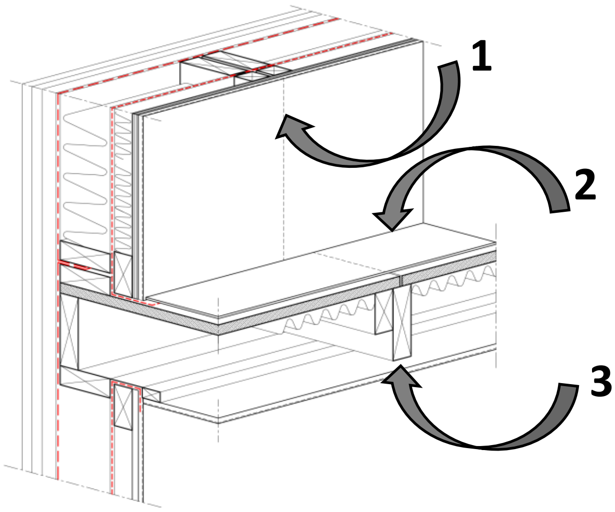


Figure 2-2: Derome Villa Anneberg connections for review

2.2.2. Current building practices that complicate timber-reuse

Here follows a brief description of the connection details currently in use and the challenges they present with respect to deconstruction and reassembly. The proposed alternative connection details that were agreed to circumvent these challenges are outlined in Section 2.2.3.

Detail 1: Existing vertical junction of external wall panels

The existing wall panel build-up from external to internal face is comprised of:

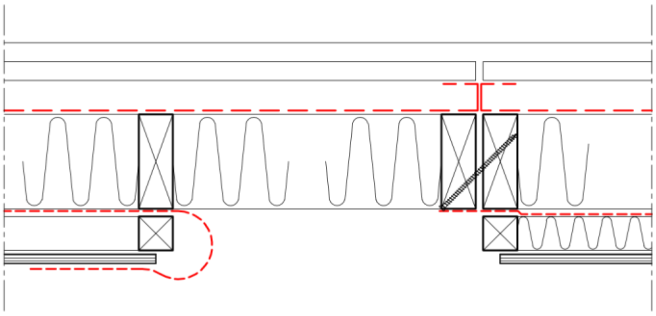
- External timber cladding fixed to horizontal and vertical battens,
- Wind sheet membrane,
- Structural timber frame,
- Quilt insulation between vertical timber studs,
- Air-tightness plastic foil membrane sealed using a synthetic isobutylene with an isoprene sealant,
- Vertical internal battens with an additional insulation layer between the battens,
- OSB layer, and
- Gypsum internal plaster finish taped and skimmed.

Figure 2-3 shows the wall element loaded for transport at the manufacturing facility.

Figure 2-3: Derome Villa Anneberg wall panel loaded for transport at the manufacturing facility *(image courtesy of Ylva Sandin).*

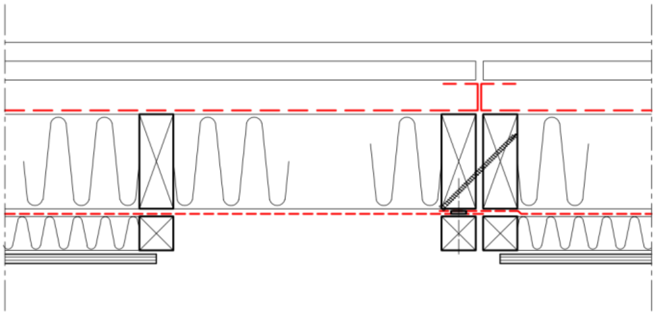
The current Derome practice is to transport the panels incomplete. A section of the internal OSB layer and internal batten and secondary insulation layer is omitted to expose the structural posts for screw-fixing on-site. The air-tightness plastic membrane is oversized and dressed back onto the internal OSB layer during transport. During the building assembly, the wall-panels are made airtight by overlapping and sealing the plastic membrane with an isoprene sealant and the omitted internal battens, additional internal insulation, and OSB are then fitted. The building is finished internally with a gypsum layer which is applied in-situ. Figure 2-4 to Figure 2-7 illustrate the current assembly steps of the semi-prefabricated wall panel. The diagrams are orientated top-down from outside to inside.

An assessment of the current assembly design, referencing the disassembly and reassembly of a similar Derome one-storey house, found that the dismantlement of the building would expose the air-tightness membrane in the wall panels to damage. Its repair would necessitate the removal of the gypsum layer, the OSB layer, vertical battens, and internal insulation layer to expose the air-tightness membrane for replacement. It was necessary to divert the wall panels to the manufacturing facility to restore the wall elements before reassembly. Most of the removed material was discarded and replaced during this transition stage. Additionally, while the structural supports are screwed, sotheoretically can be unscrewed, it was found to be more efficient to cut through the internal wall finishes and the structural screw connections.



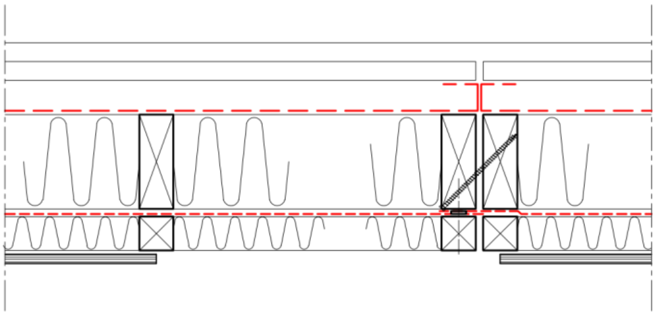
- *A section of the internal wall panel finish is omitted during transport.*
- *The airtightness membrane is dressed back on the internal face of the panel to allow access to main structure.*
- *The structural posts are screw fixed.*

Figure 2-4: Existing Derome Villa Anneberg: Wall panel assembly: Step 1



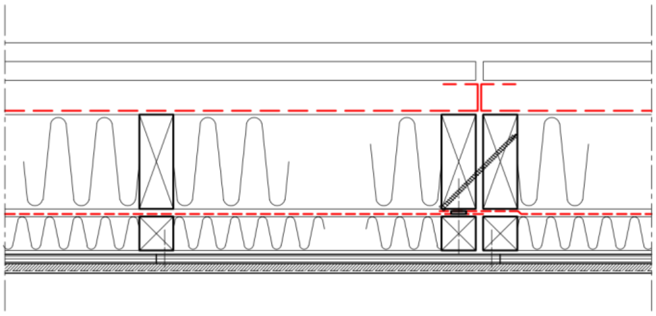
- *The airtightness membrane is overlapped and sealed with a synthetic isobutylene with isoprene sealant.*
- *This sealant (butylband) is not biodegradable.*
- *A vertical internal batten fixes the seal.*

Figure 2-5: Existing wall panel assembly: Step 2



- *The breach to the internal insulation layer can now be bridged.*

Figure 2-6: Existing wall panel assembly: Step 3

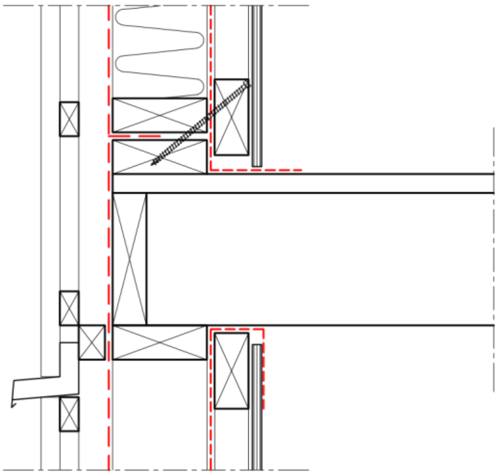


- *The OSB layer is completed.*
- *A gypsum finish is applied to the whole room.*

Figure 2-7: Existing wall panel assembly: Step 4

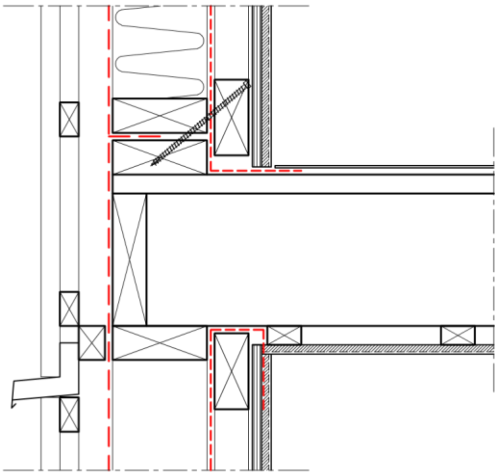
Detail 2: Existing junction of external wall panel to intermediate floor

Figure 2-8 and Figure 2-9 illustrate the current connection detail of the external wall panel with intermediate timber cassettes floors. The diagrams are orientated left-right from outside to inside.



- *The gypsum layer is omitted to allow structural assembly.*
- *The airtightness layer is dressed under the horizontal floor batten.*
- *No sealant is used.*
- *The panels are structurally connected to the base post*

Figure 2-8: Existing Derome Villa Anneberg: Wall to floor assembly: Step 1



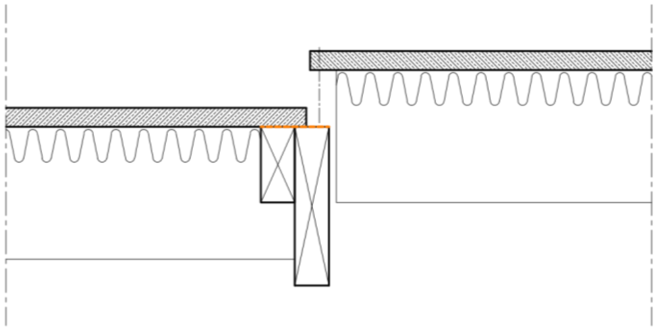
- *A gypsum finish is applied to the whole room.*
- *The finished floating floor is then fitted.*
- *NOTE:*
- *A section of the internal layer of the wall panel is also omitted during transport, (as per detail 1) which is also completed before applying the wall finishes.*

Figure 2-9 Existing wall to floor assembly: Step 2

Access to the main support structure again complicates the reuse of the whole wall panel following its disconnection from the floor. The inevitable damage to the gypsum and OSB layer and subsequent disposal of material cannot be avoided using this assembly detail (in tandem with the assembly sequence outlined in Figure 2-4 to Figure 2-7.

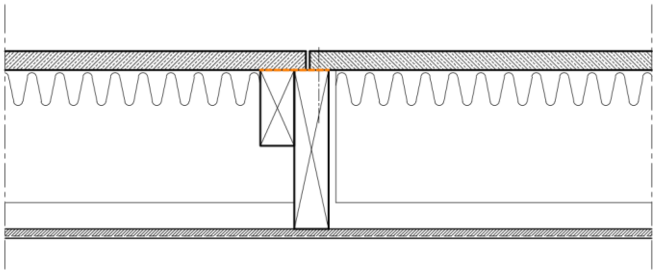
Detail 3: Existing junction of intermediate floor cassettes

Currently the floor cassettes comprise a chipboard floor deck onto a timber joisted frame. An overlap of the deck is glued and screwed onto the adjacent deck, with a batten support parallel with the main joist providing additional support to the deck. Figure 2-10 and Figure 2-11 illustrate the current connection assembly of the intermediate floor cassettes.



- *Chipboard floor deck*
- *Glued (orange line) and nailed to*
- *Structural edge joist, with*
- *Additional 45 mm support to the deck*

Figure 2-10: Existing Derome Villa Anneberg: Floor to floor assembly: Step 1



- *Gypsum ceiling fixed to battens.*

Figure 2-11: Existing floor to floor assembly: Step 2

The cassettes are glued to comply with Swedish design standards to mitigate movement in the lightweight floor. Due to the glued connection, the floor cassettes are significantly damaged at disassembly and therefore discarded completely. A reassembly of the building using this design detail would necessitate a replacement or substantial repair of the intermediate floors.

Detail 4: Existing roof truss connection

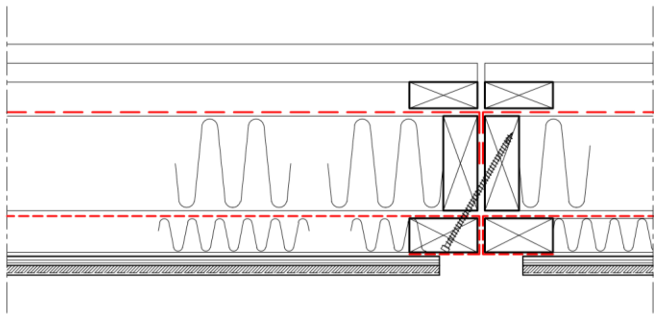
The roof trusses are lifted into place and screwed to the wall plate using angle-brackets and screws (Figure 2-12). During the disassembly of the reference Derome house additional fixings were found other than the prescribed angle-brackets connecting the roof to the walls. These connections were not included in the design/assembly drawings. The partial connection of the roof structure to the walls at unknown positions posed a hazard during the lifting of the roof at deconstruction. This practice also posed a risk of damage to both the roof and walls.

Figure 2-12: Derome roof truss lifted into position on site *(image courtesy of Derome)*

2.2.3. Alternative timber construction systems to optimise the reuse of timber

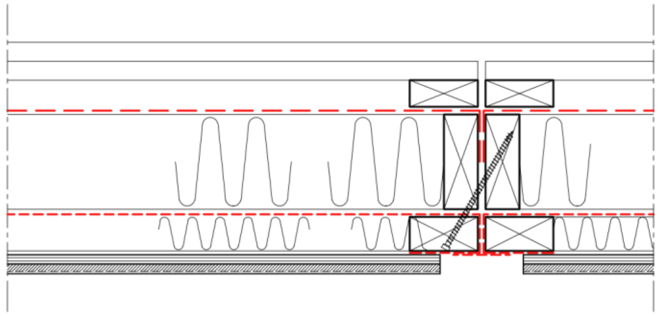
Detail 1: Revised vertical junction of external wall panels

The study aimed to revise the vertical wall-to-wall detail in order that the wall-panels could be more substantially completed initially at the manufacturing facility so that they could be disconnected and transported directly to a secondary site, for reassembly without any diversion for substantial repair. Figure 2-13, Figure 2-14 and Figure 2-15 show the sequence of assembly of the agreed alternative connection detail. The diagrams are orientated top-down from outside to inside.



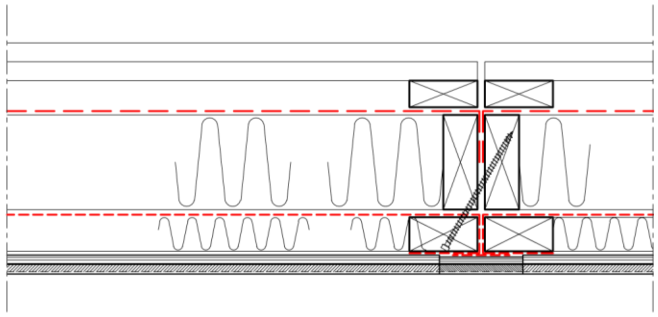
- *The panel is transported from the manufacturing facility complete with internal insulation, OSB and gypsum layers.*
- *The OSB and gypsum layers are finished short of the panel edge to allow access to the vertical structural members.*

Figure 2-13 : Revised Derome Villa Anneberg: Wall panel assembly: Step 1



- *The airtightness membrane is dressed in around the vertical batten.*
- *The batten size is increased to facilitate the structural fixing through to the main supports.*
- *The airtightness layers are sealed with a proprietary tape. (Butylband is not required).*

Figure 2-14: Revised wall panel assembly: Step 2



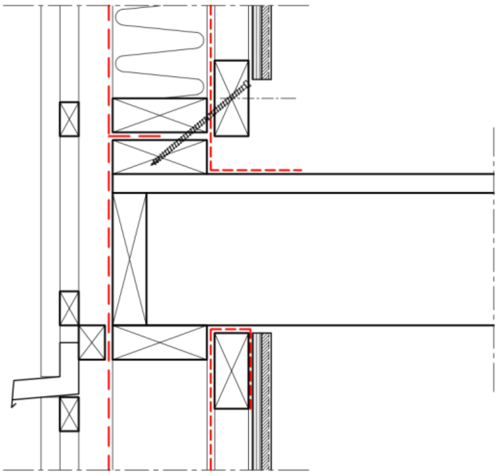
- *The small gap in the OSB and gypsum layers is made good on-site.*

Figure 2-15: Revised wall panel assembly: Step 3

While screwed fixings can theoretically be unscrewed, it was accepted in discussions with the manufacturer that it is most likely that the deconstruction contractor will cut through the internal wall finishes and any structural screw connections in the interest of time. The proposed disassembly of the revised wall-to-wall panel detail incurs cutting the panels apart at the structural junction. Some local trimming of the OSB and gypsum layers to the vertical batten is required at the reassembly stage. Therefore, the reused panel will resemble its initial factory form. The gypsum layer is substantially maintained for secondary use. Any damage to the airtight membrane can be simply repaired with tape on site at reassembly. The wall is repaired locally at the junctions as per the initial building assembly procedure. While there are some minor on-site works required in both the initial and secondary assemblies of the building, this is deemed to be within the expected '*making good*' required in the building assembly. Minor on-site works would also include repair of common marks, dents, and scratches incurred during transport and assembly of the building elements. Additionally, there is an amendment made to the position of the wind sheet membrane in the external build-up of the wall panel. This includes dressing the wind sheet membrane in along the structural posts and providing vertical battens at the connection. This again makes the panel-to-panel disassembly and reassembly more suited to on-site remedial work. The need to substantially repair the panels or divert to an offsite manufacturing facility is avoided with the revised detail. The current design uses Butylband (as per the assembly sequence outlined in Figure 2-4 to Figure 2-7), a material which is not biodegradable. The revised detail (Figure 2-13 to Figure 2-15) negates the use of this product.

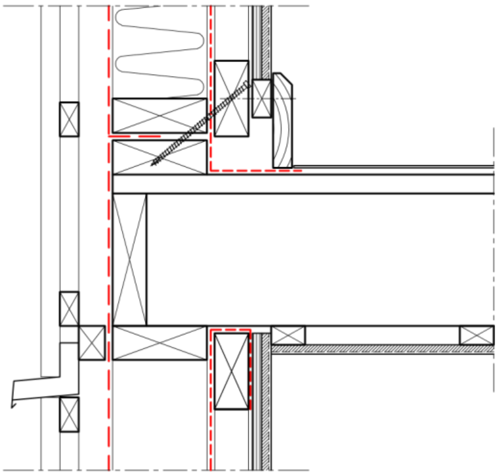
Detail 2: Revised junction of external wall panel to intermediate floor

Figure 2-16 and Figure 2-17 show the proposed alternative assembly sequence to connect the external wall panel with intermediate floors. The diagrams are orientated left-right from outside to inside.



- *The OSB and gypsum layers are now finished short of the floor to allow access for structural fixing.*
- *The airtightness layer is dressed under the horizontal floor batten, as before.*
- *Any breach of the airtightness membrane due to the unscrewing of the bottom structural fixing is deemed insignificant due to its location at several timber supports.*

Figure 2-16: Revised Derome Villa Anneberg: Wall to floor assembly: Step 1



- *The finished floating floor is fitted.*
- *A timber skirting board, fixed to timber grounds, finishes the wall at the floor.*
- *The skirting board can be removed and reused.*
- *The main bottom fixing is accessible for disassembly and reassembly without any significant damage to the wall.*

Figure 2-17: Revised wall to floor assembly: Step 2

The existing inevitable damage and subsequent disposal of the gypsum wall finish and OSB layer is avoided by stopping the wall finishes short of the floor and introducing a timber skirting board. This timber board can be removed and reused. Alternatively, an additional 6 mm plaster finish to the internal walls at the subsequent reassembly of the building will negate the need for a skirting board.

Detail 3: Revised junction of intermediate floor cassettes

The current assembly detail involves the gluing and screwing of the floor cassettes to comply with Swedish design standards to mitigate movement in the lightweight floor. As a result of the glued connection, the floors are significantly damaged at disassembly. A reassembly of the building would necessitate substantial repair. An alternative assembly detail enables the disassembly, transport, and reassembly without substantial damage or repair to the floors.

Figure 2-18 and Figure 2-19 illustrate the alternative connection detail, disassembly/reassembly proposed to connect the floor cassettes.

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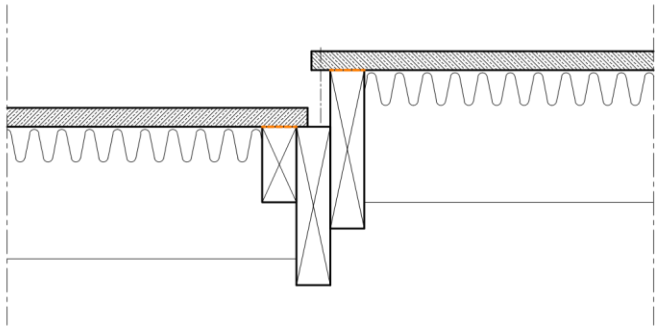
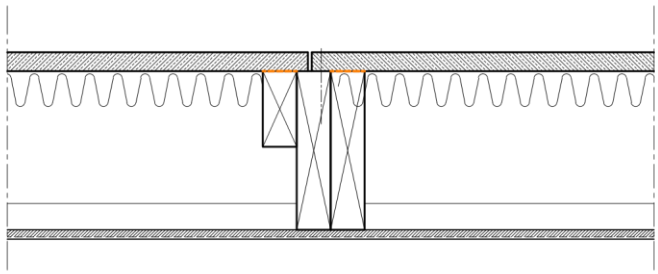


- *Chipboard floor deck*
- *Glued (orange line) and nailed to*
- *Structural edge joist, with*
- *Additional 45 mm support*
- *Additional edge joist glued to the deck of the connecting cassette.*
- *Connection between cassettes screwed only*

Figure 2-18: Revised Derome Villa Anneberg: Floor to floor assembly: Step 1



- *Gypsum ceiling fixed to battens with screws.*

Figure 2-19: Revised floor to floor assembly: Step 2

This revised assembly design adds an additional edge joist for each cassette. The edge joists are glued to the floor decks. The cassettes can therefore be screwed/unscrewed without damaging the floor. Testing of this junction with respect to floor deflection and vibration may be necessary to ensure compliance with serviceability standards in Sweden.

Detail 4: Revised roof truss connection

The disassembly of a similar one-storey Derome house was complicated by additional fixings encountered, that were not outlined in the design/assembly drawings. It was assumed that these fixings were a temporary tie used by carpenters before fitting the design brackets. It is suggested that allocating specific temporary supports in the design for this particular purpose may negate the use of unprescribed connectors. Thus, reducing this unnecessary hazard at disassembly. Alternatively, the assembly of the roof structure on the ground before lifting into position as illustrated in Figure 2-20 would eliminate the need for temporary supports.

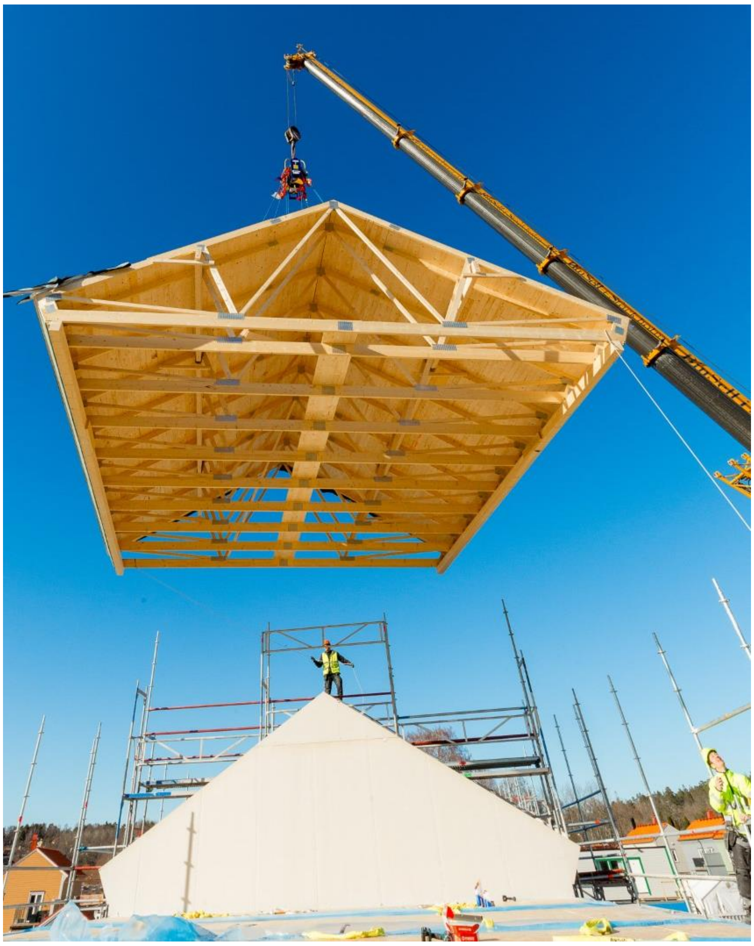


Figure 2-20: Derome roof structure lifted into position on site *(image courtesy of Derome).*

2.2.4. **Conclusions**

The current assembly design of the Derome *Villa Anneberg* two-storey house type was assessed to improve the reuse potential of the timber material. Four key junctions were chosen for review. They are 1) the vertical connection of the external wall panels, 2) the connection between the external wall and the intermediate floor, 3) the connection of the upper floor cassettes, along with 4) an observation on the roof assembly design. A previous reassembly project of a similar Derome one-storey house was used as a reference.

The following improvements to the current manufacturing and assembly design are achieved:

- Improved time and cost:
    a. The time efficiency at the initial assembly stage is improved,
    b. The need for remedial works at reassembly is reduced,
    c. The need to divert planar elements to the manufacturing facility for repair before reassembly is negated.

- Reduced material waste:
    a. The robustness of the planar elements during transport is improved,
    b. The potential for damage during disassembly in reduced,
    c. The volume of material disposal is reduced at the reassembly stage.
- Improved biodegradability at end-of-life:
    a. The non-decomposable material, Butylband, is omitted from the wall panel.
- Health and safety:
    a. The potential hazard caused by un-documented metal fixings in the roof is averted,
    b. Maintaining the integrity of large structural elements during disassembly, transport, and reconstruction, reduced the scope for harm from broken, sharp elements, or falling debris.

During the discussions with NUIG and RISE on these potential revisions to the manufacture and on-site assembly of the Derome *Villa Anneberg* two-storey house type, Derome indicated that the revisions proposed were practical. They estimate that these changes would incur minimal extra cost but could improve assembly efficiency significantly resulting in a potential saving overall. Hence Derome intend to explore further the implementation of the revised details in standard building practice. The suitability to reuse of the components and the efficient disassembly and reassembly potential of the building is regarded as an additional bonus by the manufacturers.

2.3. OSS *"Everett Grand*" house-type

This study investigates the issues that complicate the deconstruction and reuse of the "Grand Everett" house and proposes alternative approaches to enhance the reuse potential. The "Grand Everett" is a five-bedroom, three-storey house design comprising prefabricated structural timber planar elements for the walls and floors and a timber trussed roof (Figure 2-21). Further information on this case study can be found in Appendix B of the WP 2 Report (Sandin *et al*. 2022).

2.3.1. **Scope of the work**

The existing assembly design of the building was analysed by Napier, NUIG, RISE and Robertson Timber Engineering (OSS) with the aim of reducing waste and minimising repair in the context of disassembly for reconstruction. For this purpose, it was assumed that the building is relocated after 50 years of service within a short distance of the original location. The current prefabrication and assembly of the external walls, roof, and the intermediate floor, as well as the potential deconstruction of the building were discussed. The conversion of the building to a larger or smaller dwelling, in-situ, was discussed as well. The advantages of reducing the variability in the prefabricated panels and how resizing layouts may accommodate alternative room functions was also considered.

Figure 2-21: Robertson Homes "Everett Grand" house type

2.3.2. **Current building practices that complicate timber-reuse**

Walls:

The current building design comprises an internal structural timber-stud wall (Figure 2-22) with a cavity and brick or block-render external cladding. The internal timber-stud leaf is clad on the cavity-side with 9 mm OSB sheathing and breather membrane. The external masonry leaf is connected to the timber structure with galvanised wall-ties. Internally the timber-stud wall is lined with a vapour control layer (VCL) air-tightness membrane, 38 mm internal battens, and plasterboard. The skirting board is painted MDF.

All walls are mounted onto base plates, which are nailed to the ground floor concrete slab and to the floor cassettes on the first floor. The wall plates are deconstructed by sawing through the nailed connection between wall plate and wall panel, and it is expected that the wall plates are damaged in this process or during subsequent disassembly of the wall plate to floor connection.

Externally: The current assembly design would necessitate the demolition and disposal of the external masonry layer at disassembly. This would include the removal of the wall ties that accommodate the masonry outer leaf which was identified as a potential source of damage to the OSB sheathing layer and breather membrane on the main timber structural wall. A new masonry external leaf would need to be constructed at a reassembly stage.

***Figure 2-22*: Panel assembly in Robertson Timber Engineering factory**

Internally: The current assembly design would involve the removal of all internal plasterboard for disposal at the disassembly stage. The reasons given for this are:

- To access the services and timber structure for deconstruction

Elements without plasterboard are less sensitive to moisture damage during transport, storage, and reconstruction

It is assumed that the process of removing the plasterboard may damage the VCL and compromise the airtightness of the structure, however, the internal battens may provide some protection to the VCL. Remedial works would be necessary at reassembly, but this is in line with usual repairs of the VCL carried out on-site. It is anticipated that the MDF skirting boards must be removed for disposal and replaced at reassembly.

Standardisation: The potential to standardise the wall panel dimensions is also examined as part of WP 2. During this study a minor variance between the ground floor, first floor, and second floor wall panel height was identified. This difference, due to an alternative wall plate size, currently necessities the use of different timber lengths at the manufacturing stage and makes wall panels of different floors non-interchangeable at the reuse stage.

Roof:

The timber truss roof structure is assembled at ground level and lifted into position (Figure 2-23). The roof build-up comprises concrete tiles on battens onto breathable felt onto roof trusses that comprise the main timber structure, which is fixed to the inner timber-stud leaf of the external structural wall with truss-clips. The truss-clips are fixed with nails. They are accessed internally. The ceiling is plasterboard and fitted on-site. The fascia and soffit boards are uPVC.

It is expected that the timber roof structure can be moved and reused as one component. However, it may need to be divided to suit transportation load limits. It is expected that any damaged truss-clips can remain without causing any negative effect on the building. Replacement truss-clips can be provided adjacent to the original fixings.

The removal of the concrete tiles at disassembly was considered inevitable. The reasons given for this are:

i. Potential damage during transport,
ii. Potential hazard during transport due to falling tiles,
iii. Excessive load on crane and transport vehicle,
iv. To facilitate access to the main timber structure, if it must be divided,
v. Degradation of the tiles, necessitating their replacement,
vi. Access to the roof felt for repair or replacement to accommodate new building standards.

Where the roof felt needs to be replaced, the tiling battens must be removed and are expected to be damaged in the process. Battens will then need to be discarded and replaced with new ones upon reconstruction.

Figure 2-23: House roof structure lifted into position on Robertson site

The uPVC is not designed to provide a 50-year lifespan. It is expected, therefore, that the uPVC fascia and soffit boards will be replaced during the first lifespan of the building and will be removed for disposal at a disassembly stage.

The ceiling plasterboard is removed and discarded to allow access for deconstructing the roof structure and with the acknowledgement that it will likely be damaged during the deconstruction process.

Floors:

The ground floor is concrete. The timber-stud walls are supported via a base plate. The first floor comprises timber cassettes, screw-fixed or spanning wall-to-wall. It is anticipated by the building manufacturers that the floor cassettes can be removed substantially undamaged and reused. The glued joint used in the Derome case study house, which is required in Sweden, is not regulation in the UK. The chipboard floor cover is glued onto the floor cassettes and cannot be removed. Should a new cover be required, it will be glued onto the existing chipboard.

2.3.3. **Alternative timber construction systems to optimize the reuse of timber**

Walls:

Walls are currently deconstructed by sawing through connections between wall panels and between wall plates and wall panels. A more controlled deconstruction would be possible if these connections were screwed instead of nailed. This would also allow the non-destructive removal of the wall plates and thus their reuse.

Externally: Substituting timber cladding or a brick/rendered factory finish cladding panel in place of the currently used masonry wall would allow the disassembly, transport, and reuse of whole external wall panels. This would have several advantages:

i. This would negate the disposal of the external masonry leaf.
ii. The potential damage to the OSB sheathing layer and breather membrane on the main timber structural wall due to the removal of wall-ties would be avoided.
iii. A horizontal external drip detail at the first-floor level would facilitate modular deconstruction, which could allow for phased deconstruction and factory supplied planar elements to modify the property in-situ.
iv. The protection to the wall panel during transport/storage is also improved in this case, thus further reducing potential damage or waste.
v. Standard wall panels integrating internal and external layers would also facilitate pre-manufactured elements in modifications of the property in-situ, thus, extending the use of the building which is identified as the optimum scenario in sustainable design.

Vertical timber cladding best facilitates a homogenised disassembly but is not widely accepted by consumers in the UK. Prefabricated claddings that maintain the impression of a traditional masonry or brick exterior are the preferred solution.

Internally: In the interest of aesthetics, the building manufacturers intend to remove internal finishes at the deconstruction phase. Any damage to the wall panel will be then assessed with a re-route via a factory for repair if necessary. An alternative to removing the internal plasterboard was not considered viable, but standardised junctions of the wall-panels would reduce the overall damage and necessary repair to VCL and the overall airtightness of the structure. This could avoid any diversion to the manufacturing facility, with *"making good"* done on-site. The use of a softwood painted skirting board in place of MDF would improve its potential for reuse or for repurposing, thus, improving the circularity of the material.

Standardisation: Manufacturing all wall panels at the same height would optimise timber use at assembly and reassembly. Standardising room sizes and planar elements generally would make for more efficient manufacturing. It is anticipated that this would facilitate a greater potential also for the mixed reuse of panels in alternative house designs, thus improving their reuse potential generally.

Roof:

It is expected that the timber roof structure can be moved and reused as designed. Any replacements to damaged truss-clips may be fitted adjacent to the original fixings. The removal of the concrete tiles at disassembly was considered inevitable. However, it is possible to reuse the tiles if they are not degraded. The roof felt and battens can remain in place, repaired as necessary, if in accordance with building standards at the time of reconstruction. The use of a treated timber fascia and soffit in place of uPVC would improve their potential for reuse or for repurposing, thus, improving the circularity of the material.

Floors:

It is expected that the floor cassettes are suitable for disassembly, transport, and reuse if undamaged during their first lifespan. Standardising floor cassettes has the same benefits as standardising wall panels.

2.3.4. **Conclusions**

In general, it was agreed that the reuse of timber members in their initial assembly form, such as the roof truss structure or the complete wall panel best avoided any issues that occur when reusing timber. Metal content from unprescribed or irremovable fasteners, including, staples, nails, or screws is a significant deterrent to reusing building timber. By keeping the modular and planar elements intact for reuse as initially intended, the new fixings may be fitted adjacent to the previous fixtures without any adverse effect on the stability of the product.

The standardisation of wall panels, especially with respect to panel height, would minimize timber waste at assembly and reassembly. This also improves the potential of mixed reuse of planar elements in alternative house designs.

It is recommended to substitute a factory finished brick/rendered (or timber) external cladding panel in place of the current in-situ external masonry wall. This would negate the removal of the external cladding, thus avoid damage to the timber structure and minimising the disposal of the external cladding.

The use of timber in place of MDF skirting board and a treated timber fascia and soffit in place of uPVC would improve the potential for recovery, reuse, or repurposing of these elements.

2.4. Cygnum *"Reflect 140"* suburban semi-detached house design

This suburban semi-detached three-bedroom house was chosen for review as it reflects modern light timber-frame construction in an Irish context as well as a common housing typology. The house has a floor area of 120 m^2 and is constructed with timber-frame internal main structure and non-load bearing masonry external leaf on concrete ground floor slab. A BIM model of the existing framing for this house is given in Figure 2-24.

This study, taken from a wider study outlined in WP 2 (Walsh & Shotton 2021), identifies current building practices that complicate timber reuse and proposes alternatives to enhance the reuse potential.

The wider study takes a holistic view of a typical semi-detached dwelling house.

- To address the need for both design for adaptability & flexibility, and design for disassembly and reuse, the existing design was reviewed both spatially and technically.
- Standard domestic construction from the roof ridge down to the rising walls was discussed.
- A proposed disassembly plan (called a Disassembly Information Report (DIR)) was prepared for the project following a study of potential disassembly plan approaches.
- A BIM model was developed to compare the existing and proposed designs as regards the quantity and type of material which could be extracted. The BIM model also produced an inventory of material which formed part of the Disassembly Plan (DIR).

This is the only case study in this project where the reuse potential of individual timber members is examined; however, it is intended that this approach is seen as complimentary to the other component reuse proposals and none of the solutions proposed are exclusive.

2.4.1. **Scope of the work**

The wider *"Reflect 140"* case study addresses the overall design of the building in the context of variable use and on maximising the reuse potential of individual timber members in alternative building designs at a deconstruction stage. The discussion here is aimed at facilitating the reconstruction of the whole building unmodified and on what particular construction approaches specifically hinder the reuse of the timber products as initially intended after a first lifespan of circa 50 years, or two generations.

The discussions identified the following structural junctions to be potentially problematic with respect to the efficient relocation of the building: 1) the roof structure, 2) the intermediate timber floors, 3) the service routes, 4) the wall-to-wall connections, and 5) an observation on the room layout design.

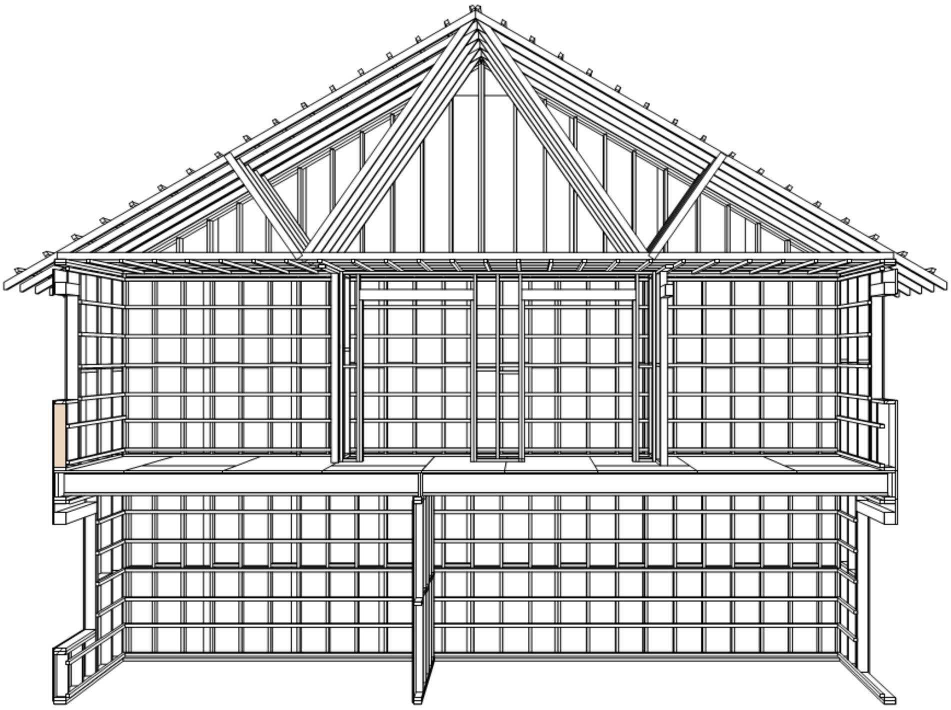


Figure 2-24: BIM model of existing Cygnum semi-detached house timber framing (Walsh 2022)

2.4.2. **Current building practices that complicate timber-reuse**

Here follows a brief description of the connection details currently in use and the challenges they present with respect to deconstruction and reassembly. The proposed alternative connection details to circumvent these challenges are outlined in Section 2.4.3.

Roof structure: The current roof design involves timber engineered roof trusses.

- The timber trusses are suitable for reuse provided the truss clip is located at a convenient position.

In the case of renovating or extending the building:

- The highly engineered layout results in limited scope of potential uses. For example, the roof structure is difficult to adapt for attic conversion and difficult to expand.

Intermediate floors: The current floor assembly comprises a tongued and grooved (T&G) floor boarded deck which is glued to an OSB I-joist structure.

- Due to the glued connection of the deck to the floor structure, both deck and structure will be significantly damaged at a disassembly stage.
- Floor members are nailed very frequently making disassembly without damage difficult.
- The manufacturer advises against reusing OSB I-joists for a second use due to potential degradation of the material quality of the joists over the expected lifespan of the building.

A reassembly of the building using this design detail would necessitate a replacement or substantial repair of the intermediate floors throughout.

Services routes: The service runs are not organised to facilitate maintenance without damage to the building fabric.

- Floor and ceiling joists may be either notched or cored to allow for passage of services. The separation of the integrated service routes and structural timber may be prohibitive with respect to time. Thus, causing unnecessary damage to the timber structure at a disassembly stage.

Wall structure: The current design utilises materials efficiently, with a large composite panel system that is very appropriate to reuse exactly as intended. The panels are connected using 3.1 mm dia. X 90 mm nails, three per 140 mm external timber stud and two nails per internal 89 mm member.

- Locating nail joints between wall panels for removal may be cost- and time-prohibitive. The alternative of saw cutting the joints could damage the structural studs.

Room layout: In addition to the obstacles to deconstruction and reuse, the configuration of spaces in the current design makes adaptive use during the service-life of the building difficult. This issue is addressed in the wider WP 2 study. However, the following is observed with respect to a building practice that complicates timber-salvage:

- The current general layout plan leads to high variability of unit lengths of structural members. Highly specific unit lengths may hinder a future design decision to reuse the elements where a) some units are potentially to be discarded due to damage, or b) where several housing units are relocated at the one time. The standardisation of the building elements simplifies their reuse potential.

2.4.3. Alternative timber construction systems to optimize the reuse of timber

Here follows the proposed alternative connection details to circumvent the challenges presented with respect to deconstruction and reassembly.

Roof structure: The current roof comprises a highly engineered layout. Replacing the current trussed structure with an in-situ cut-roof (Figure 2-25) would improve the use and reuse of the roof structure. A cut-roof structure would also improve the CU potential of the timber members. However, the current truss roof design is more suited to efficient relocation provided that the truss clip is positioned at a convenient location for the disassembly contractors.

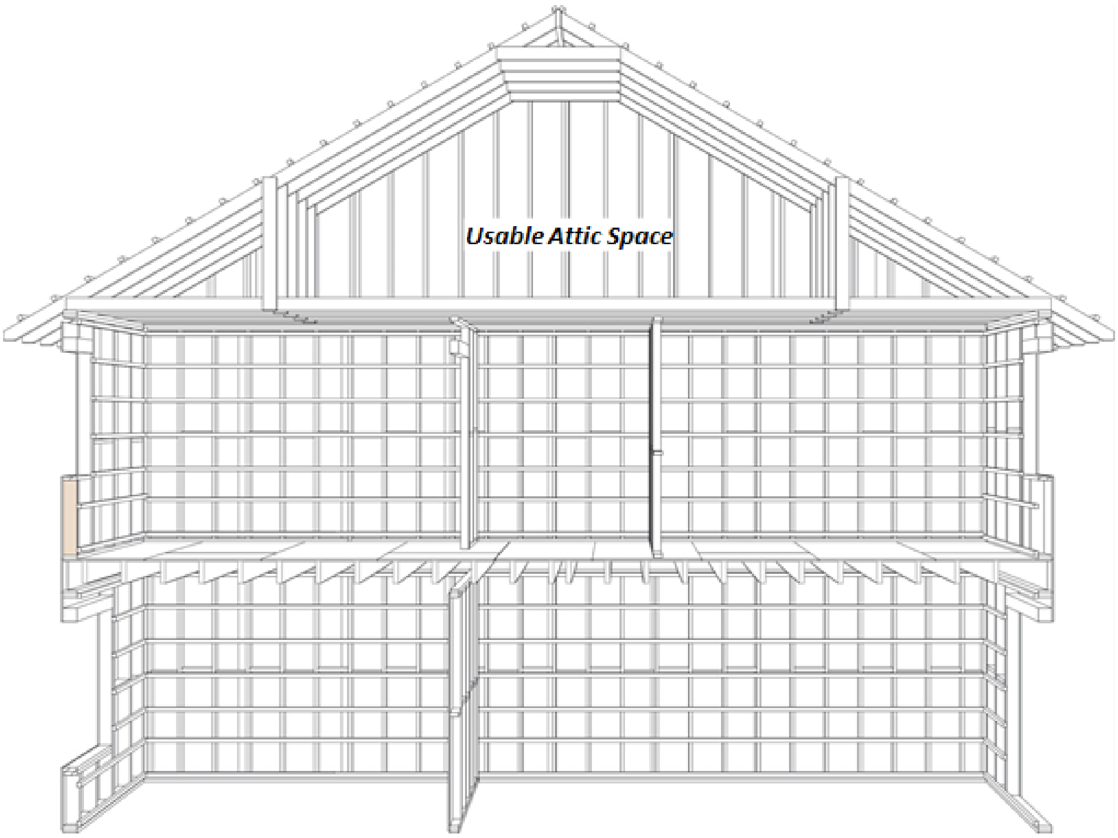


***Figure 2-25: Revised section with cut-roof structure to facilitate the use of the attic space** (Walsh 2021)*

Intermediate floors: The floor deck and structure will be significantly damaged at a disassembly stage using the current assembly design. It is proposed to use more robust materials with greater longevity and retractable connections to increase the potential for reuse of the floor materials.

- To replace OSB I-joist with solid timber joisting,
- To omit glue between deck and floor joists,
- To use screws to allow for ease of removal,
- To adjust the span of the floor joists in order to avoid intermediate supports to the floor and more standardised timber elements which is expected to improve the reuse potential of the timber components at reassembly and the future cascade use of the wood.

Services routes: A defined route of mechanical and electrical services was proposed to avoid surplus and residual metal content in the timber structure at disassembly. The new route may incorporate conduits but should not increase service zones. It is proposed to:

- Centralise the services, and
- Provide hinged or removable internal room linings to access the services without damage to the building fabric. A drawing of the hinged room lining is shown in Figure 2-26.
- It is suggested to locate the services routes so that floor and ceiling joists need not be notched or cored. Thus, avoiding the potential to moisture damage to the timber structure due to the disconnection of sanitary services or unnecessary difficulty in separating the mechanical and electrical services from the building structure at a disassembly stage.

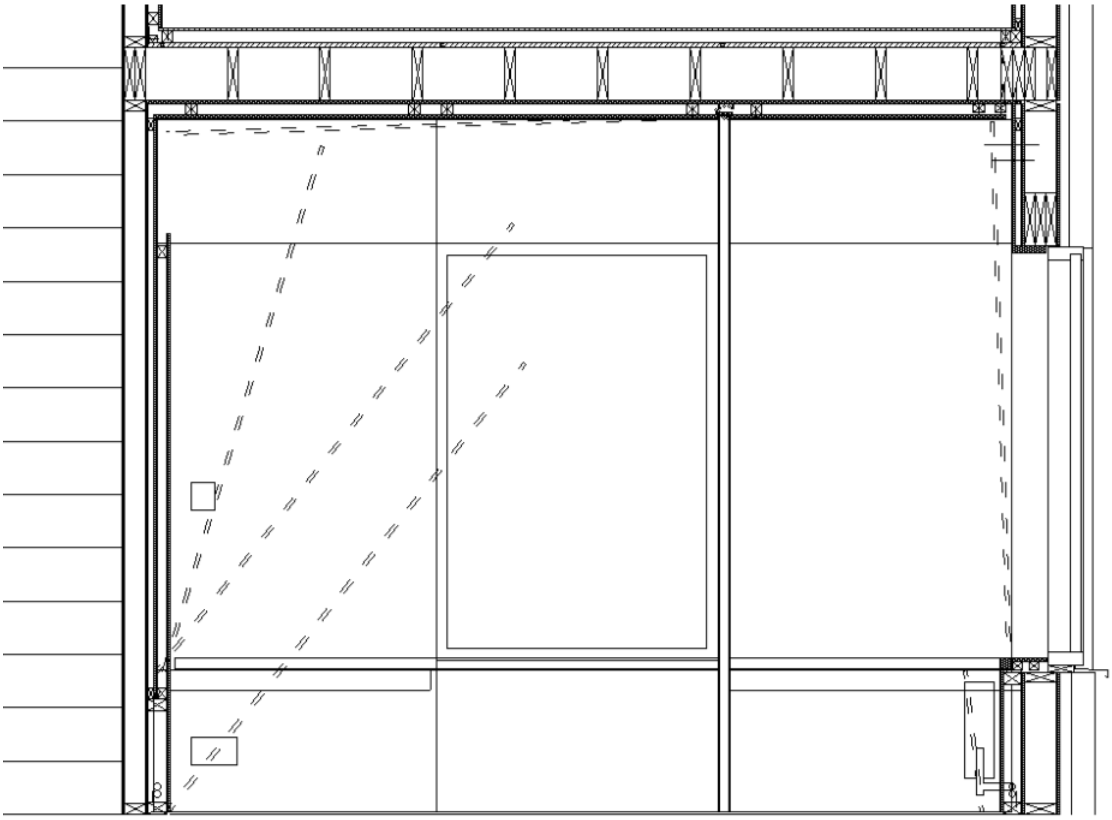


Figure 2-26: Revised section with hinged wall panels to facilitate service maintenance *(Walsh 2021)*

Wall structure: The current design utilises materials efficiently, with a large composite panel system that is appropriate to reuse. The panels are currently connected using metal nails and it is necessary to cut the junction at the disassembly stage. The implications of using metal screws or wood nails were reviewed as part of WP2.

- While the use of screws would allow the disconnection of the panels, without cutting through the wall-to-wall junction, it was assumed that a) new fixings must be placed in an alternative location on the timber frame or b) a larger diameter screw must be used.
    - a) To comply with the European Timber Engineering Design Standard EN 1995-1-1 (2014) guidance on screw spacing, the panels may be fitted twice.
    - b) The timber cross-section must increase for each increase in screw diameter to comply with (EN 1995-1-1 2014).
- Alternatively, the use of wood nails was proposed to reduce the metal content in the timber. However, testing on the embedment and withdrawal strength is needed.

Room layout: The current general layout plan leads to high variability of unit lengths of structural members.

- It is proposed to review the room layouts and structural support locations so to standardise the building elements, thus, simplifying their reuse potential. The wider *"Reflect 140"* WP 2 case study investigates using standard timber lengths (4.8 m) and standardising room dimensions to facilitate alternative room-use over the lifespan of the building, thus extending the lifespan of the building in general.

2.4.4. Conclusions

The current assembly design of the *"Reflect 140"* two-storey suburban semi-detached three-bedroom house by Cygnum was assessed. The discussions focused on facilitating the reconstruction of the building and on what particular construction approaches specifically hinder the reuse of the timber products as initially intended after a first lifespan of the building.

The following structural junctions were identified to be potentially problematic with respect to the efficient relocation of the building: 1) the roof structure, 2) the intermediate timber floors, 3) the service routes, 4) the wall-to-wall connections, and 5) an observation on the room layout design. The proposed amendments to the current design are:

- Roof: Positioning the truss clip at a convenient location to facilitate disassembly for reuse of the roof trusses.
- Floor: Replacing the existing glued and nailed OSB I-joist floor assembly with solid timber joisting, at an alternative span, using screws to allow for ease of removal, and omitting the use of glue between deck and floor joists.
- Services: To centralise the service routes to avoid damage at the disassembly stage due to integration of services runs and the to the timber structure. A hinged or removable internal room lining was also proposed.
- Walls: The use of screws and wood-nails were explored, but the advantages to the efficient assembly and disassembly design are inconclusive.
- Room layouts: The use of more standardised timber lengths is proposed to improve manufacturing efficiency and accommodate better flexibility of panel use that will improve efficiency at the reassembly stage.

3. Mass-timber panelised construction

A review of the implications to relocating a modern mass-timber dwelling house was discussed with the building manufacturer, IsoTimber. The sample building assessed is a rural one-off two-storey house. The relocation of a small pavilion for reuse as a music studio by the same manufacturers was used as a reference when considering the implications of deconstruction and reassembly of the dwelling house. The two buildings are:

- The *"Villa Forshälla Sund"* by IsoTimber in Sweden
- The "*Magnolia Pavilion*" by IsoTimber in Sweden

Further details of these two buildings are available in the Appendix C of the WP 2 report (Sandin *et al.* 2022).

3.1. IsoTimber *"Villa Forshälla Sund"*

The *"Villa Forshälla Sund"* is a once-off, modern two-storey detached dwelling house (***Figure 3-1***). Only the deconstruction of the structural components of this building are considered in the study and these are now summarised.

Due to the sloping site, a glulam frame is used to provide a level platform on which the house is built. For the ground floor, solid timber joists span between the glulam beams. The external walls comprise cross laminated timber (CLT) elements together with proprietary IsoTimber wood-panels, which provide insulation and additional load bearing capacity (***Figure 3-2***). The internal walls and intermediate floor are also made from CLT elements. Connections between all mass timber elements are screwed. Finally, the roof structure comprises I-joists spanning between the external walls and secured with angle brackets (***Figure 3-2***). A breather membrane was placed on top of the I-joists, followed by timber battens and roofing boards, which were secured by nailing, and finally roofing felt. Underneath the I-joists, a vapour control layer is attached followed by timber battens to which plasterboard is attached to form the ceiling. The dwelling house is presently being erected and, in this study, it is assumed to be demounted after 50 years, or two generations.

***Figure 3-1: The "Villa Forshälla Sund" under construction, in Uddevalla, Sweden** (image courtesy of IsoTimber). Designed by Erik Persson and Matilda Lindblom.*

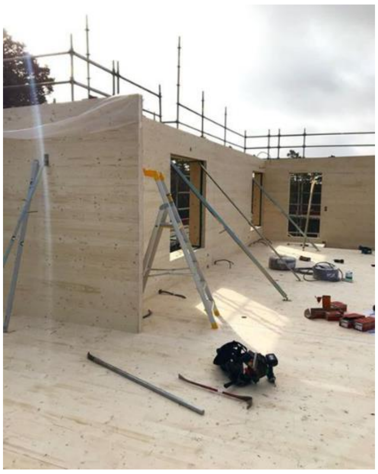


Figure 3-2: Mass timber panels for walls and intermediate floor(left); I-joist roof structure (right).

3.2. IsoTimber *"Magnolia Pavilion"*

The *"Magnolia Pavilion"* is a single-storey building constructed with IsoTimber wall panels, that provide the loadbearing structure and the external wall insulation. The roof and floor are timber cassettes. All sanitary services are contained in a prefabricated bathroom pod. ***Figure 3-3*** shows the pavilion under construction with the bathroom pod being crane-lifted into place.

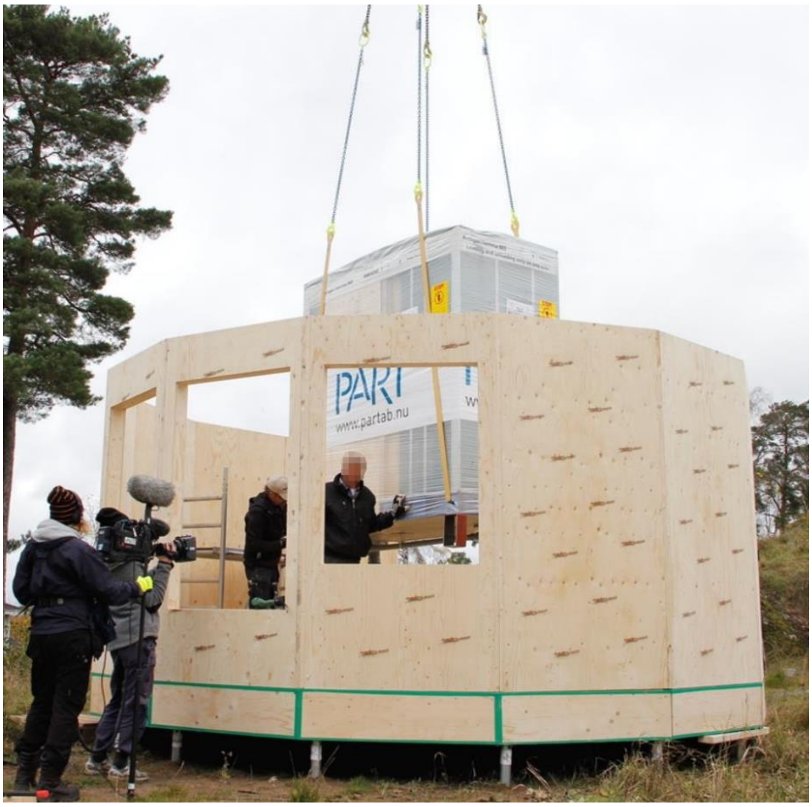


***Figure 3-3: The Magnolia Pavilion under construction, in Tyresö, Sweden** (image courtesy of IsoTimber). Architect is Pål Ross*

The building was successfully deconstructed and reassembled in Segeltorp, Sweden without any significant waste. Figure 3-4 and Figure 3-5 show the roof cassettes demounted and crane-lifted into place after transport.

***Figure 3-4: Magnolia Pavilion roof cassette demounted for transport in Tyresö, Sweden** (image courtesy of IsoTimber).*

***Figure 3-5: Magnolia Pavilion roof reassembled in Segeltorp, Sweden** (image courtesy of IsoTimber).*

3.3. Current building practices that complicate timber-reuse

The *Villa Forshälla Sund* two-storey house by IsoTimber was assessed by a multi-disciplinary team as part of WP2 to determine what wood components could be salvaged for reuse using the current assembly method, and what additional timber-salvage could be achieved by substituting alternative building practices (Appendix C of the WP 2 report (Sandin *et al.* 2022)). It was assumed that design loading for the reassembled building is the same as the original building. The timber-based elements of the building considered for reuse include the roof, the glulam frame, the external CLT and IsoTimber panel walls, the internal CLT walls, and the intermediate CLT floor. The successful disassembly and reassembly of the *Magnolia Pavilion* are referenced where relevant.

Existing roof design:

The current construction of the roof of the *Villa Forshälla Sund* is not demountable or suited to reassembly. The roofing boards and battens are nailed to the I-joists and cannot be separated in a time-efficient way without significant damage to each component and, therefore, the roof material is likely to be downcycled at a reassembly stage. In comparison, the pavilion roof was made using timber cassettes. These were demounted and reused without any significant waste as seen in Figure 3-4 and Figure 3-5.

Existing glulam main frame, CLT wall and floor panel assembly design:

The junctions are screw fixed; therefore, it is assumed that they may be unscrewed at deconstruction.

The external and internal wall structure comprises CLT elements. The lifting eyes are well defined and located on the building assembly drawings. The junctions are screw fixed, therefore may be unscrewed at deconstruction if not damaged. For this building method, no plastic foil is required to provide the recommended airtightness. It is achieved by taping junctions on the outer and inner faces of the external walls. After reassembly, the junctions can easily be taped to ensure airtightness of the new structure.

The intermediate floors are CLT. The lifting eyes are well defined and located on the building assembly drawings. The junctions are screw fixed, therefore may be unscrewed at deconstruction if not damaged. The mass of the CLT floor elements negates the need for glue at floor-to-floor junctions to comply with the Swedish design standards on the deflection and vibration of floors as was the case with the cassette floor system in the "Villa-Anneberg" discussed in Section 2.2.

Overall, the mass timber elements are well suited to deconstruction intact. The potential complications to disassembly for reuse of the main glulam frame and CLT wall and floor panels are:

- Locating the member and panel junctions at the disassembly stage: the first lifespan of the building is expected to last up to two generations, therefore internal finishes by the occupants may be changed many times. Each redecoration could disguise junctions or adhere to the fixing heads, inhibiting an efficient withdrawal of the screws at the disassembly stage. This is also a potential problem with light-frame construction.
- Potential for corrosion of the screw heads: the likelihood of this is small for connections screwed from the inside of the structure as screws are manufactured from hardened steel.

Research is required to determine the corrosion resistance of screws subjected to high moisture fluctuations e.g. external connections, or from accidental temporary leaks or poor ventilation.
- Degradation of the mass timber elements due to moisture, rot, or insect attack, particularly for external elements: The extent of this, if any, must be assessed at the time of deconstruction. This also applies to light-frame timber.

Existing IsoTimber wall panel design:

Proprietary IsoTimber wood-panels provide insulation and some additional load bearing to the external walls. The units are rigid and should be easy to remove, transport and reassemble without damage. The panels are screw fixed, therefore may be unscrewed at deconstruction. As these panels do not bear the main structural loading, deformation of the screw fixings due to loading can be expected to be minimal allowing the screws to be removed efficiently.

Potential complications to disassembly for reuse of the IsoTimber wall-panels are:

- The potential for corrosion of the screw heads on the external face of the building: This may not be an issue as the screws used are made from hardened steel. However, research is required to determine the corrosion resistance of these screws subjected to high moisture fluctuations.

- Degradation of the panels due to moisture, rot or insect attack: The extent of this, if any, must be assessed at the time of deconstruction. This also applies to light-frame timber.

3.4. Alternative timber construction systems to optimize the reuse of timber

Revised roof design:

The use of roof cassettes with an integrated wood fibre insulation in place of the current I-joist and roofing board build-up would significantly improve the reuse potential of the roof structure. This is clearly illustrated in the pavilion-to-music studio reference case (Figure 3-4 and Figure 3-5).

Revised glulam main frame, CLT and IsoTimber walls, and CLT floor design:

The main complications observed with respect to a disassembly of the mass timber components with respect to disassembly and reassembly are:

i. Locating the fixings in-situ at the disassembly stage,
ii. Potential damage to the fixings that may inhibit efficient withdrawal,
iii. Potential degradation of the timber elements,

As constructed drawings showing the location of the fixings should form part of the disassembly documentation for new buildings. As long as this documentation stays with the building over its life, the location of the fixings that need to be accessed for disassembly will be known.

The screws used in mass timber assembly are designed to be corrosion resistant. Nevertheless, their durability in exposed settings, such as in the glulam framing in the *"Villa Forshälla Sund"* building, needs careful monitoring. Screw heads should be protected insofar as possible. Routine inspection and maintenance of the exposed structure will help circumvent any issues that may arise under (ii).

The provision of adequate ventilation in the form of passive (wall vents), rapid (window openings), and mechanical ventilation (in kitchens and bathrooms) and careful detailing that includes vapour layers will reduce the likelihood of degradation of the timber elements (iii) from moisture damage. With respect to damage from sanitary fittings and service pipes, the use of bathroom pods could significantly reduce the risk from wastewater on the timber structure, as used in the "*Magnolia Holiday Cottage*".

3.5. Advantages of using mass timber to DfDR

In the analysis of the reuse potential of the mass timber dwellings, the *"Villa Forshälla Sund"* and the "*Magnolia Pavilion*" by IsoTimber, some advantages to building with mass timber over light timber-framed construction were observed in the context of design for DfD and the reuse potential. They include:

- Mass timber elements are strong, stiff and have good dimensional stability. This reduces the risk of damage during disassembly, transportation and reassembly.
- No plastic foil or non-biodegradability sealants, such as Butylband is required to achieve airtightness in mass timber construction. It is sufficient to tape the junctions on the outer and inner faces of the external walls. Therefore, waste of material is reduced, and reassembly is very straightforward.
- The mass of the CLT floor elements negates the need for glue at floor-to-floor junctions to comply with serviceability design standards. Therefore, assuming there is no damage to the panels and fixings from use or adhesion of finishes, the floors can potentially be reused many times without the need for remedial works or repair.
- The provision of temporary supports and propping of planar elements is included in mass-timber assembly schedules. This reduces the tendency for the on-site construction team to use surplus and undocumented temporary metal fixings which are an unnecessary hazard at disassembly.
- A rigid insulation board is more robust than fibre insulation materials and so is more suited to disassembly, transport, and reuse. The IsoTimber timber insulation panel is a rigid insulation panel made with biodegradable (wood) material.

3.6. Disadvantages of using mass timber to DfDR

Some disadvantages that may arise with mass timber construction that are also possible with light timber-frame design are:

- The main disadvantage to mass timber deconstruction is also a key advantage; the elements are usually connected with large diameter screws. If it is intended to unscrew the junctions, the integrity of the screw fixings and fixing heads is especially significant at the disassembly stage. Particular attention to protecting the metal fixings is needed with mass-timber construction.
- While proper detailing and maintenance should minimise the risk of moisture damage to the timber elements, hidden damage may occur that is not detected until disassembly is underway. Careful assessment of the component to determine the residual capacity and the need for repair or replacement is important for load-bearing components.

3.7. Conclusions

The current assembly design of the *"Villa Forshälla Sund"* two-storey house by IsoTimber has been assessed to improve the reuse potential of its timber structure. It considered the case where the entire dwelling is rebuilt in the same region. The timber-based elements of the building discussed with respect to reuse included the roof, the glulam frame, the external CLT and IsoTimber panel walls, the internal CLT walls, and the intermediate CLT floor. The "*Magnolia Pavilion*" was used as a reference on mass timber disassembly and reassembly.

The following proposed amendments to the current manufacturing and assembly design are:

i. Replacing the existing roof build-up with a timber cassette structure to improve the reuse or cascade use potential of the roof timber and to reduce the volume of material disposal at a reassembly stage.
ii. Provision of protection to screw heads in external conditions to avoid potential damage to the fixing heads that may inhibit efficient withdrawal. Research on durability of screws in fluctuating moisture environments.

Additionally, some advantages to building with mass timber over timber-framed construction were observed in context of design for deconstruction, timber reuse, and its cascade use potential. They are:

iii. Due to the airtightness of the walls in mass timber construction, less material and manpower is required compared to the system commonly adopted in light timber-framed construction.
iv. Compliance with the serviceability design standards in CLT floors does not require the use of glued connections between floor panels. Thus, the potential for reuse of the floor panels is enhanced.
v. The provision of temporary supports and propping of planar elements that is included in mass-timber assembly schedules reduces any need for the on-site construction team to add surplus temporary fixings that may incur additional hazard at the disassembly stage.
vi. A rigid insulation board is preferable with respect to design for deconstruction and reuse compared to pliable fibre insulation which is more commonly used in timber-frame assembly. A rigid panel is less susceptible to damage when exposed between building assemblies.

4. Conclusions

This report has investigated the issues that complicate the recovery for reuse of timber from residential buildings. Both light timber-frame and mass-timber house construction were examined using case study buildings from Sweden, the UK and Ireland. Alternative products and construction methods were proposed in co-ordination with WP 2 to address these issues and enhance the reusability of the timber building elements.

4.1. Light timber frame construction

Three proprietary, light timber frame house designs were investigated. Two deconstruction scenarios were considered, namely, reconstruction to the system level (e.g. wall elements, floor cassettes) and complete deconstruction to the timber board level.

For the case of deconstruction to the system level, the main issues identified and new designs proposed were:

- Connections between built-up external wall elements:

  Issue
  - External wall elements comprise many layers with different functions added at the factory in addition to the structural timber framing. These include OSB sheet, gypsum layer, insulation and air-tightness layer. With the existing connection design and layer build-up in the connection area, the integrity of some of these would be compromised during deconstruction necessitating replacement at the factory prior to reuse.

  Solution
  - Redesign of the wall elements to include additional battens at the edges and rearrangement of the air-tightness membrane and trimming of the OSB and gypsum layers in the connection area allow the elements to be readily deconstructed intact.
- Connections between external walls and intermediate floors:

  Issue
  - The existing connection arrangement would lead to damage to the OSB and gypsum layers during deconstruction requiring partial or complete replacement.

  Solution
  - The OSB and gypsum board were cut short at floor level to allow access to the connectors.
- Connections between floor cassettes:

  Issue
  - Existing connection is glued and screwed. Disassembly will result in significant damage due to the glued connection.

  Solution
  - An additional edge joist is added to one side of each cassette and the floor deck is screwed to this joist.
- Connection between roof truss and walls

  Issue
  - The study highlighted a risk presented by additional nails, which are not part of the connection design but are used by the carpenters during construction. These may cause damage to the roof and walls during deconstruction in addition to posing a safety risk.

Solution

- To prevent the need for unprescribed fasteners, the installation of L-shaped brackets in the factory or the use specific temporary supports could be used to facilitate erection of the trusses. Alternatively, the full trussed structure could be assembled prior to lifting in place by crane.

- Masonry-clad external walls

  Issue
  - In current design, external masonry demolished and disposed of.

  Solution
  - Replace with brick/rendered factory finished panel that can be demounted.
- Timber frame elements

  Issue
  - Proliferation of wall element sizes leads to waste at assembly and disassembly
- *Solution*
  - Standardisation of wall elements, especially with respect to height.

For the case of disassembly of the timber frame house back to the timber board level, the following main issues were identified and solutions proposed:

- Intermediate floors

  Issue
  - The current design comprises tongued and grooved flooring glued and nailed to I-joists. This cannot be disassembled without damage to the components.

  Solution
  - Change floor design to solid joists connected with screws only.
- Room layout

  Issue
  - Current layout leads to profileration of lengths of timber boards recovered.

  Solution
  - Revise room layouts and structural support locations to standardise the building elements and simplify their potential reuse.

4.2. Mass timber construction

Two mass timber buildings using Isotimber elements and CLT elements were investigated. One was a large, single-family dwelling and the other was a small two-roomed structure that had already been successfully deconstructed and re-erected in another location.

Overall, mass timber structures were found to be well suited to deconstruction and reuse. For the studied buildings, the main issues identified and proposed solutions were:

- Roof of large family house

  Issue
  - The roof was not demountable or suitable for reassembly. It was not manufactured from mass timber but from I-joists with battens and roofing boards.

  Solution
  - Change of roof structure to timber cassettes
- Fasteners and mass timber structure

  Issue
  - Possible deterioration of fasteners and timber elements due to moisture effects.

Solution

- Protection of fasteners in exterior structure and consideration given to use of bathroom pods to help protect structure from possible wastewater damage. Regular inspection and maintenance of exposed glulam structure.

4.3. Closing remarks

For the timber buildings examined, the solutions proposed for the different building systems to enhance their deconstruction and reuse do not, in general, require major design changes or additional cost. For light timber frame construction, by careful consideration of the connections between the different building elements, small adjustments to existing designs that make a big difference can be identified similar to those proposed in this report. Overall, avoidance of glued connections and use of screws are recommended. Also, standardisation of building element sizes greatly enhances their reuse potential. For mass timber construction, the building elements are robust and dimensionally stable making them well suited to deconstruction and reuse.

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