Design for Deconstruction and Reuse: Case study Villa Anneberg

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FOREWORD

This report is the first in a series of case study reports in the InFutURe Wood project (Innovative Design for the Future – Use and Reuse of Wood (Building) Components), Work Package 2.

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 the recovered wood, led by Daniel Ridley-Ellis, 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

This study was carried out by Ylva Sandin (developed the method, led the work on the case study and coordinated it with succeeding cases, wrote the report), Anders Carlsson (contributed with all information on the studied building, provided data on design, actively participated in meetings and interviews and secured resources from Derome), Caitríona Uí Chúláin (made design work on new connections, made the drawings of new connections and reviewed the report) Karin Sandberg (participated in meetings, reviewed the report and coordinated and led the InFutUReWood project). Design work in this study was also part of the work within WP 3. Drawings in this report are made by Caitríona Uí Chúlain and photos taken by Ylva Sandin, if not otherwise specified. This first case study has served as a template to the ones that follow which will all have similar outline and headlines.

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

The industry partners participate mostly with in-kind. The research and academia project partners are RISE Research Institutes of Sweden (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, Robertson Timber Engineering, 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.

Special thanks to Mikael Öqvist, Jimi Leo and other staff at Derome who participated in the study and helped producing the underlying information.

SUMMARY

The building sector accounts for a large raw material consumption and waste production. One way of diminishing these would be to reuse buildings and building components to a higher degree. To facilitate that, buildings would need to be designed with that aspect in mind.

Work Package 2 of the InFutUReWood project investigates new ways to design timber-based structures. This study investigates how new design concepts can be developed to make Villa Anneberg, a two-storey light timber house from the Swedish manufacturer Derome, adapted for deconstruction and reuse. The objectives are:

- To identify the inherent strengths and weaknesses of the current design of Villa Anneberg regarding deconstruction, rebuilding and reuse.
- To show how the design could be improved with respect to future deconstruction and reuse and to estimate the amount of wood that could be reused in the future with the current and the improved designs.
- To suggest guidelines for deconstruction and reuse.
- To test and develop a method for carrying out case studies, as the study is the first in a series of case studies treating different structural systems.

The study is limited to the load bearing structure of the building. Focus is on reuse rather than recycling.

Methods used involve interviews, structured meetings, analyses of drawings and documents, photo documentation and design work.

A reuse scenario was assumed where the building will be deconstructed after a few decades into its separate parts. It will then be transported and reassembled to an identical building in the same geographical region.

It was found that the current design of Villa Anneberg is relatively well prepared for this scenario already. The building is designed for efficient transport and assembly and the process is judged to be reversible to a high degree. Many connectors are screwed, and the building can be deconstructed with common and simple tools. Several weaknesses were also identified.

Among these were joining techniques that are not reversible. Modified versions were developed for three joints. The new solutions were achieved with relatively small adjustments in design and within existing technology. One of the new connections was found so economically valuable to the manufacturer Derome, that it is likely to be taken into production soon. We estimated that the proportion of wood that is reusable would be higher for the modified Villa Anneberg than for the current. The proportion wood that is reusable in the load bearing structure with current design is estimated to 82,7 %. The proportion of wood that is reusable with the modified design is estimated to 86,4 %. These figures apply to the studied scenario.

Guidelines for deconstruction and reuse were suggested. The case study method was found efficient and ready to be used in further case studies.

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1. Introduction

1.1. Background

The building sector accounts for a large contribution of the world's' Green House Gas emissions, raw material consumption and waste production (EC 2020). One way of diminishing material consumption and waste production would be to reuse buildings and building components to a higher degree. To facilitate that, buildings would need to be designed with that aspect in mind. Today, difficulties can arise in deconstructing already manufactured buildings and reusing their parts. The difficulties have to do with things like joining techniques, sensitivity to damage and use of chemicals. Accounting for this is not standard design practice, in fact there are barriers to the application of design for deconstruction strategies (Cruz Rios, F., & Grau, D. 2020).

The InFutUReWood project is studying how to establish circularity for timber buildings. In Work Package 2, "Design of timber structures for the future", new ways to design timber-based structures are investigated. New design concepts are developed as well as a method to plan primary design to facilitate deconstruction rather than demolition. In Work Package 3, "Product design using recovered timber", practical industry methods for design, construction, and deconstruction that will facilitate the reuse of timber building products are developed and potential new construction products using recovered timber are identified. The work reported on here was carried out mainly within these work packages.

A state-of-the-art study carried out within InFutUReWood showed a knowledge gap in the published literature (Cristescu et. al. 2020). There is a lack of published knowledge on how wood-based building frames are best designed for deconstruction and reuse. We found few practical examples illustrating advantages and obstacles to design for deconstruction and reuse of different types of existing timber buildings, possible design improvements, guidelines for deconstruction and reuse and general descriptions of methods to find new designs.

1.2. Aim

This case study is the first in a series that consider different types of wooden frame systems. The aim of the collected series is to:

- Develop new design concepts adapted to design for deconstruction.
- Study how guidelines for deconstruction and reuse can be formulated.
- Develop a method to optimise a primary design for deconstruction and reuse.

In the case studies we examine the problems that can occur for a specific design and suggest how problems could be solved by modifying the design.

This first case study concerns a building design from the Swedish manufacturer Derome, the "Villa Anneberg", which has a light timber frame, Figure 1.

Figure 1 Villa Anneberg, exterior. Image: Derome

1.3. Objective

The objective of the case study is to identify:

- The inherent strengths of the current design of Villa Anneberg regarding deconstruction to facilitate rebuilding and reuse.
- What weaknesses it has in the same respect.
- How the design could be improved with respect to future deconstruction and reuse.
- How much wood that could be reused in the future with the current design and how much wood that 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 Terminology.)
- How guidelines for deconstruction and reuse could be formulated for this object.

Another objective of the study is to test and develop a method for carrying out case studies.

1.4. Delimitations and assumptions

The focus here is on the design of the *load-bearing structure,* 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 may therefore also (to some extent) need to be considered in the analysis.

The study also 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 (too much of) their function and economic value. (For example, by being damaged by disassembly and handling.) Much could probably also be said about other stages in a building's life cycle that are not treated here, not least on the topic of demolition and deconstruction practices and methods.

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, 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 minimize the harmful environmental impact of this, we focus here on DfDR. Although important, design for adaptability is outside the scope of this work.

This study investigates *technically possible* design improvements with respect to DfDR. Costs and environmental impacts for different solutions are not examined. A separate study will be carried out, comparing the environmental impacts from different designs with life cycle assessments.

The study is in large parts quantitative rather than qualitative. For example, judgements of which work steps that can be considered difficult or time-consuming in a deconstruction process are based on the participants own experiences. The study does not measure the time or energy it takes to perform different deconstruction actions.

1.5. Target group

The target group considered for this report is manufacturers of timber-based building structures, architects and engineers designing such structures and researchers.

1.6. Terms and definitions

1.6.1. Terms

Deconstruction

The process of taking a building or structure, or portion thereof, apart with the intent of repurposing, reusing, recycling, or salvaging as many of the materials, products, components, assemblies, or modules as possible. (Off-Site Construction Council, (n.d.)

The systematic dismantling and removal of a structure or its parts, in the reverse order of construction, for maximum value through the salvage and harvest of components, primarily for reuse in their original purpose and secondarily for recycling. (Sparandara et. al., n.d.)

Disassembly

Taking apart of an assembled product into constituent materials and/or components

Reuse

Any operation by which products or components that are not waste are used again for the same purpose for which they were initially designed. EC (2008)

Recycling

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)

1.6.2. Definitions

Ground floor and first floor

We adhere to traditions in large parts of Europe to call the floor on the ground the *ground floor* and the next floor up the *first floor*.

Improvement, improved solution

By improvement is understood a measure that leads to components retaining their functions and economic value to a greater degree in a future deconstruction process, or leads to a less time-consuming or safer deconstruction process than can be reached with the current design. With improvements fewer damages will occur, less repair/ reconditioning will be required for the next use cycle, a larger proportion of the material can be reused, less time will be needed for deconstruction.

2. Method and implementation

This chapter presents the case study method. After an overview of the different steps, the separate steps and their implementation are explained.

2.1. Overview of steps

The method developed for this study has five steps, see Figure 2. The different steps are described in sections 2.2 – 2.6.

Step 0. Defining a scenario to design for

Step 1. Analysis of existing design

- 1.1 Description of the building and how it is assembled
- 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 existing - modified design

Step 4. Guidelines for deconstruction and reuse

Figure 2 The steps of the case study method

2.2. Step 0. Definition of scenario to design for

The future scenario that the design was evaluated and adapted for was defined as follows: After one service life (about fifty years), the building will be deconstructed into its original (planar) elements, transported to another site in an area with the same wind and snow loads, and reassembled to an identical building.

2.3. Step 1. Analysis of existing design

First (step 1.1 in Figure 2), 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 main steps in an assumed deconstruction process were also defined based on the knowledge that existed about the system and how it is assembled.

Then (step 1.2 in Figure 2), in a meeting with Derome's research and development manager, quality manager, structural engineer, marketing department and researcher Y. Sandin, the assumed deconstruction process was discussed in more detail as well as the strengths and weaknesses that the existing design has with regard to deconstruction and reuse. For the different steps in the process, aspects such as:

- tools needed for deconstruction
- damage that may occur to components and materials during deconstruction
- need for reconditioning, repair, and controls
- foreseen problems with transport or intermediate storage
- foreseen waste
- risks with regards to personal safety
- risks to the environment

were discussed.

The discussions were documented with notes (Appendix 1). Appendix 1 contains a shortened, translated version, of the original notes that were taken in Swedish.

After this meeting, the recorded data were examined, and the system's weaknesses and strengths were summarized. Areas for improvement were highlighted (step 1.3 in Figure 2.).

Based on the possible areas for improvement, a choice of most promising improvement was made (step 1.4 in Figure 2). The choice was made based on meetings with researchers and Derome. One criterion in the selection process came from the fact that we decided to search for improvements *within* the existing light timber technique (and to not study how to build a Villa Anneberg with CLT for example). Another criterion followed from the fact that studies had to be limited to areas that can be examined without resource-intensive studies such as large-scale testing of whole elements.

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 (step 1.5 in Figure 2). The amount of wood in the load bearing structure of Villa Anneberg with its current design is known. The amount of wood that that can be reused with the current design is not known but can be estimated, based on the results from the discussions described above, where possible damages and waste from deconstruction were identified.

Including personal experiences on deconstruction and reuse

Mikael Öqvist, Derome's quality manager, who participated in the discussions had especially valuable personal and practical experiences of deconstruction and reuse, as he has deconstructed and rebuilt and now lives in a Derome showhouse. He will be referred to as MÖ. The deconstructed building was not a Villa Anneberg design, but another Derome house design, with one storey. The building had been a showhouse for six years when it was deconstructed. The disassembled building was stored in an empty workshop for one year before the house was reassembled. MÖ refurbished the external walls, for two reasons. Firstly, he wanted to change the façade material from plaster to wood panel. It was assumed that the façade type had allowed water ingress or condensation, but it turned out that there was no moisture damage in the walls. Secondly, he wanted to improve the energy efficiency of the walls by adding insulation. Building regulations had changed and were more onerous since the building was first erected.

2.4. Step 2. Modified design

Modifications were discussed in meetings with Derome and researchers. Design studies were carried out to propose new design concepts and the results were presented in drawings and descriptions.

The amount of wood that can be reused with the modified design was then estimated.

Modifications were aiming to improve the design, in the sense suggested in section 1.6. Another criterion for modifications was that they should be applicable to the present production process. The smallest possible changes that still solves the problem of improving the design were studied here. A range of alternative, more dramatically different solutions might be added if the current production process was to be discarded. Here, the production process and the knowledge that Derome employees possess of that are considered as valuable resources.

2.5. Step 3. Comparison existing - modified design

A comparison was made of the amount of easily accessible and reusable wood in current design and the corresponding amount in improved design.

(In parallel with this work and outside this study, a life cycle assessment and a life cycle cost assessment are carried out for the current and improved versions of Villa Anneberg. Results will be reported on in a separate study within the InFutUReWood project.)

2.6. Step 4. Guidelines for deconstruction and reuse

In Step 4, a structure for a deconstruction and reuse documentation for the improved Villa Anneberg was suggested, based on Morgan & Stevenson (2005).

2.7. General methods

The general methods used were interviews, structured meetings, analyses of drawings and documents, study trip to factory, photo documentation and design work (finding solutions in discussions, estimating dimensions, making drawings).

3. Results

In this chapter, we present the results. First, the current Villa Anneberg design is described and the assumed deconstruction process is explained (sections 3.1 and 3.2). Then, the strengths and weaknesses of the current design with respect to deconstruction and reuse are presented (section 3.3) and the potential for improvement is discussed (section 3.4). A selection of details to improve within this study is made (section 3.5) and the proportion of wood estimated to be reusable with current design is calculated (section 3.6). New solutions for the selected details are presented (section 3.7) and the current and modified designs are compared with respect to the proportion of wood estimated to be reusable (section 3.8). Finally, a suggestion is made for guidelines for deconstruction and reuse for the modified design (section 3.9).

3.1. Villa Anneberg: current design

Figure 3 Villa Anneberg. Image: Derome

The object of the case study is, as mentioned earlier, a concept house from Derome: Villa Anneberg (Figure 3). It is a two-storey, single family residential building. The frame consists of prefabricated, insulated planar stick frame elements mounted on a concrete slab.

Vertical and horizontal loads are taken through the building as follows. Vertical loads on the roof are carried by roof trusses to the external front and rear elevation walls and further down to the foundation. Vertical loads on the intermediate floor are carried by floor cassettes to the front and rear external walls and to the core wall and further down to the foundation.

Horizontal loads perpendicular to the front and rear elevations are carried by the facade to the roof, the intermediate floor, and the foundation. The roof and floor carry the load to the gable side walls that takes it down to the foundation. Horizontal loads perpendicular to the gable walls are carried by the facade to the roof, the intermediate floor, and the foundation. Roof and intermediate floors take the loads to the front and rear external walls and core wall and further down to the foundation.

3.1.1. Parts and joints

Elements in load bearing structure

The building is made of planar prefabricated elements. The parts that form the building's load bearing structure are, from top to bottom:

- **Roof** built up by roof-boarding, battens and concrete tiles.
- **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 loose wool insulation.
- **Gable elements**: stick frame elements with wood panel, studs, and insulation.
- **Exterior walls on first floor:** stick frame elements with wood panel, studs, insulation, vapour barrier (a plastic foil), OSB and plaster board.
- The **intermediate floor cassettes** built of structural timber, insulation, and chipboard. (On the lower/under side of the cassette, sparse panel and plaster board are attached on site.)
- The **exterior walls on ground floor**: as for first floor.
- The **core wall (load-bearing inner wall)**.

All the above are delivered to the building site as prefabricated elements. In addition, the load-bearing structure of the building includes:

- **Ground floor slab** of in-situ reinforced concrete.

The building is completed on site with non-loadbearing internal partition walls. A key section of the building with the loadbearing envelope is shown in Figure 4 and examples of elements are shown in Figures 5 and 6.

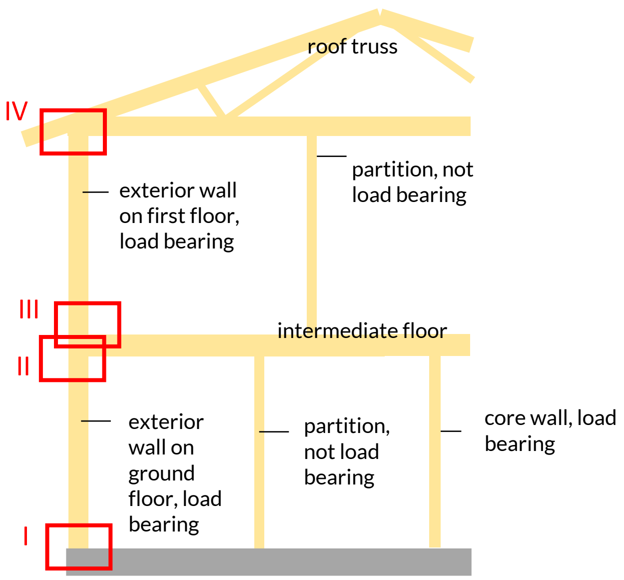


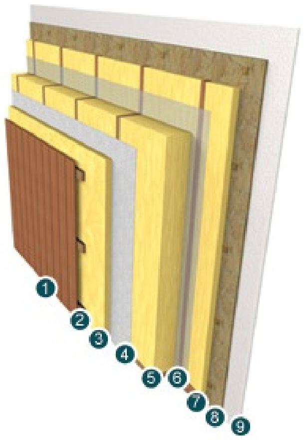
Figure 4 Key section with loadbearing and not load-bearing walls marked out. Rectangles and Roman numbers refer to joints.

Figure 5 Exterior wall elements. Image: Derome

Figure 6 Floor elements (cassettes).

Currently, for Villa Anneberg as for other buildings, the potential to deconstruct and reuse is not a design criterion. The design of the exterior wall panels aims to achieve energy efficiency, avoid thermal bridges, achieve moisture safety, and achieve sound-absorption (Figure 7). To that end the wall is designed with:

- A three-layer construction (having three layers of insulation).
- The vapour barrier (plastic foil) placed inside the internal finishes of the wall. This is to ensure that it will be continuous/unbroken and provide for maximum airtightness. Electric services can be installed without breaking the barrier.
- Continuous/unbroken outer insulation layer, to minimize thermal bridging. A weather/wind sheet membrane placed externally to the insulation insures moisture-protection to the structural frame.
- An external facade primarily weatherproofs the wall, but also provides some insulation to reduce any linear thermal bridging.



The wall panel is comprised of:
1 & 2. External timber cladding fixed to horizontal and vertical battens
3. Quilt insulation
4. Wind sheet membrane
5. Structural timber frame, quilt insulation between structural posts
6. Air-tightness membrane (plastic foil) sealed using a synthetic isobutylene with isoprene sealant
7. Vertical internal battens with an additional insulation layer between the battens
8. OSB layer
9. Gypsum internal plaster finish taped and skimmed.

Figure 7 Wall design. Image: Derome

Joints

The dominant connection technique is screw connections. Some nail joints also occur. An overview of joints and joint techniques is given in Table 1.

Table 1 Overview of joints and joint techniques

Part	***Connection (position of)***	***Technique***
Roof	Battens/roof-boarding	Nail connection
	Roof-boarding/roof truss	Nail connection
Roof trusses	Roof truss/exterior wall, first floor	Screw connection with angle bracket
Gables	Exterior wall first floor/intermediate floor	Screw connection
	Vertical corner joint	Screw connection
Attic floor/ ceilings	Secondary spaced boarding /roof truss	Nail connection
	Gypsum plasterboard/ secondary spaced boarding	Screw connection
Exterior wall, first floor	Exterior wall/intermediate floor	Screw connection
	Wall/wall	Screw connection
	Wall/wall, corner	Screw connection
Intermediate floors	Floor/exterior wall	Screw connection
	Floor/floor	Screw glued connection
	Exterior wall/	Screw connection
Exterior wall, ground floor	Exterior wall/baseplate on ground slab	Screw connection
	Wall/wall	Screw connection
	Wall/wall, corner	Screw connection
Plate on ground incl. Sleeper	Baseplate/slab	Expander nail

The screw connections wall-to-floor are of the basic type shown in Figure 8 (I & III). Exterior wall elements on the first floor are screwed to a baseplate placed on the cassettes forming the intermediate floor. Likewise, the exterior wall elements on the ground floor are screwed to a baseplate on the ground slab.

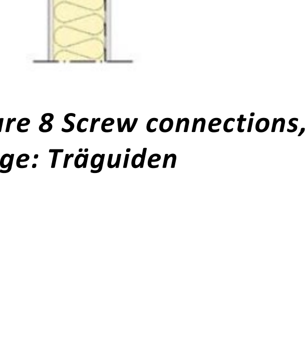


Figure 8 Screw connections, principle. Roman figures refer to joint numbers in Figure 4. Image: Träguiden

Floor cassettes are screwed to exterior wall elements on the ground floor from the outside similarly to the principle shown in Figure 8 (II). The screw heads are covered by the wall element on the second floor when that is mounted on top.

Roof trusses are connected to the top plates of the exterior walls with screws and angle brackets (Figure 9).

Figure 9 Angle brackets connect roof trusses to walls. The photos show roof trusses being installed. In this specific case, the assembly team has mounted the angle brackets before mounting the roof truss. Images: Derome

The vertical joints where exterior wall elements meet are screwed together (Figure 10).

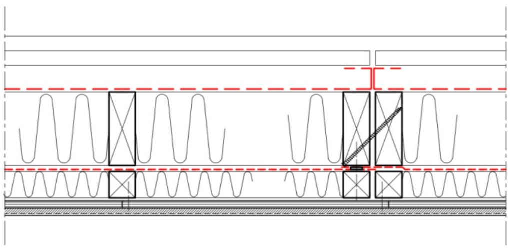


Figure 10 Section showing a wall-to-wall connection. Studs are screwed together.

To that end, part of the panels are left open during assembly (Figure 11).

Figure 11 Exterior wall panel lifted in place during assembly, ends are left open to allow for screwing. Image: Derome

The longitudinal joints between floor cassettes are screw-glued (Figure 12).

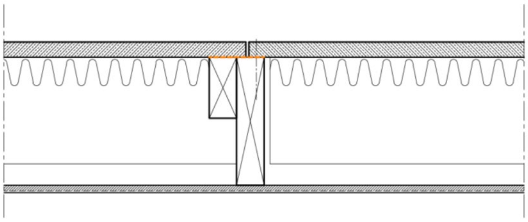


Figure 12 Section showing a connection between two floor cassettes. The particle board on top of the left cassette is glued and screwed to the right cassette.

3.1.2. Presence of chemicals

The building is qualified according to the environmental assessment system "Svanen" ("Nordic Swan Ecolabel"), (Svanen 2021). There is one exception: the joint wall-to-wall does not qualify, as a tape containing butyl is used to make the connection airtight.

No wood is impregnated (neither pressure impregnated nor otherwise). The chipboard on top of the floor cassettes is of a moisture-proof type (V313) but is not considered environmentally unfriendly – it passes the Nordic Swan Ecolabel.

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

Installations for electricity, water and sanitation pass vertically primarily through non-load-bearing partition walls built on-site and occasionally in exterior walls. In the horizontal direction, installations run along the beams in the cassettes. Water pipes that are narrow can also go across beams. Sometimes drainpipes can also be drawn across beams (unless too large holes would be needed). Exhaust air is the most used ventilation system for this building concept. The plant is located in shafts or in thick partitions. Ventilation shafts never go across beams due to their potentially large dimensions. Sometimes heat-recovery systems are fitted to Derome houses with controlled exhaust ventilation and supply air. This requires a dual-channel shaft system.

3.1.4. Assembly process for current design

The assembly process can be described as a conventional process from the bottom up (Figure 13), (compare Hemming 2012). A concrete slab is cast onto insulation on the ground level. On this, prefabricated elements are mounted by special assembly teams. The parts come as planar elements from the factory where they have been fitted with transport protection and packed and braced for safe transport. The components are weather protected while waiting for transport. At the construction site, the prefabricated parts are lifted from the transport vehicles with a crane for assembly on site. According to Derome, it takes one day to mount what is delivered from the factory on the cast slab and get the building to finished roof level. Usually, due to the short erection time, no special weather protection is used during assembly. The wood is not expected to have time to absorb harmful amounts of moisture during the hours it takes to have the roof in place.

After this first day of assembly it takes a week to get the building airtight. It takes in total 16-20 weeks before the customer can move in, largely because of the process needed to dry out the concrete slab.

Roughly, the load bearing structure with its prefabricated elements is assembled in the following steps:

- The ground floor slab is cast.
- Baseplates are mounted at the perimeter of the floor slab and core wall.
    - Baseplates are anchored to concrete with expander nails.
- Exterior wall elements are lifted by crane from the truck and mounted to baseplates. Walls are braced.
    - Walls are attached to the baseplates from the inside with a screw through a scantling in the bottom edge and baseplate. (Compare principle in Figure 8.)
    - Wall elements are attached to each other in vertical joints with structural screws through two studs, one from each element. The connection is made airtight.
    - Parts of elements that were left open to allow for screwing are closed (insulation, studs and OSB are added).
- Core wall elements are lifted with a crane from the truck and mounted.
    - Wall elements are attached to the base plate with screws.
- Floor cassettes are lifted by crane from the truck and placed on outer walls and core walls.
    - The cassettes are screwed to external walls from the outside; obliquely downwards-inwards through the edge beam and the top plate. (Figure 8.)
    - The cassettes are screwed to the core wall elements from the bottom up through top plates and edge beams.
- Baseplates are mounted on floors all around.
    - Baseplates are screwed with one construction screw in the edge beam and one construction screw in one of the load-carrying beams.
- Exterior walls elements on first floor are assembled similarly to wall elements on ground floor.
- Gable elements are lifted by crane from the truck and mounted on exterior walls.
    - Gable elements are attached from the inside with construction screws through scantling and baseplate.
- Roof trusses are lifted by crane from the truck and mounted on exterior walls.
    - Roof trusses are attached to top plates with angle brackets and screws.
    - Scaffold boards (ramps) are placed on ceiling joists.

- The roof-boarding comes in units consisting of several boards. Boards are nailed to the roof trusses. Two nails connect each board to a truss.
- Battens and counter battens are nailed to the roof-boarding.
- Concrete tiles are nailed to battens.

Figure 13 Assembly of a Villa Anneberg. Image: Christin Ljungqvist and Derome (bottom left)

3.2. Deconstruction process

A deconstruction process was formulated and assumed to be carried out in eight phases, Table 2. The note "Comment MÖ" below refers to personal reflections from Mikael Öqvist who has deconstructed and reassembled a Derome produced detached house and who took part in the discussions, as mentioned in section 2.3.

Table 2 Assumed deconstruction process for Villa Anneberg

Deconstruction step	*Description, what is done*
1. Preparatory work	Water and drainpipes are cut off at the bottom slab. Surface layers and internal partition walls are removed so that the structural frame is exposed. Comment MÖ: even surface layers can be reused, as parquet floors were reused in his case. The disassembly should therefore be done with appropriate caution. We discussed back and forth whether gypsum plasterboards must be separated from the load bearing walls. We concluded that it should be technically possible to keep them during deconstruction and reuse the whole assembled wall element with all its layers if plasterboards are protected during transport. The bathroom is demolished which is a big challenge. Comment MÖ: this was difficult. The tiles were heavy, and it was expensive to send material to landfill. Scaffolding is erected. Load bearing walls are braced.
2. Roof	Roof trusses and gable ends are temporarily braced. Concrete roof tiles are removed. The roof trusses are stripped back of battens, felt, and roof boarding. This is probably done with a crowbar and the material is removed for disposal as it will be damaged. Alternatively, the roof-boarding could be sawn up into panels which could be reused or recycled. In that case, the short pieces left on the roof trusses are removed on site. Exterior walls are braced.
3. Roof trusses	The loose wool insulation in the attic is removed using a sludge suction truck. Installations/services in the attic are taken out. The suspended ceiling attached to the roof truss subframe is removed. The joint with screws and brackets connecting trusses to load-bearing walls are disassembled or sawn apart. Loops are fastened to trusses. The trusses are lifted one by one with a crane. Comment MÖ: it should be possible to lift several roof trusses at the same time and possibly with their roof-boarding left on, instead of lifting them one by one. That would be more efficient and risks with persons standing next to roof trusses would be lower, as would waste of roof-boarding.
4. Gables	Temporary braces are attached to the gables to create firmaments for lifting loops. The gables are lifted with a crane.

5. External walls, first floor	Disassembly of the vertical wall-to-wall connection is carried out in two steps. First, panel boards are removed to uncover the structural screw connections. Then, screws are unscrewed. Note: at the meeting, we did not discuss how to find the joints and how to identify the right panel boards to lift to expose screws. This information needs to be stated in a deconstruction documentation. Disassembly of the wall-to-floor junction is also carried out in two steps. 1) Screws must first be uncovered as they are not exposed but covered by gypsum plasterboards and OSB boards. Uncovering can be done by a) removing plasterboards and OSB boards entirely or b) by sawing a horizontal section 100-200 mm above the floor level, removing plasterboard and OSB. This is possible at least in theory. 2) The screws that connect scantlings in the wall with the baseplates on the intermediate floor are unscrewed or cut off with a saw. Note: not prescribed connectors (nails) may occur. Exterior walls are then removed in the same format as they were installed. Loops are mounted and the elements are lifted by crane to transport vehicles. Comment MÖ: MÖ used the same loops that had originally been used for mounting the elements, as they were left in the walls. The building was 6 years old and the loops were in a good condition.
6. Intermediate floor cassettes	Any flooring (parquet/tiles/wood) or sound-insulating layers that remains is removed for disposal. Disassembly of floor-to-floor cassette connection: The joints are located. Screws are unscrewed. The glued connection is disassembled by breaking the chipboard with a crowbar. Disassembly of floor-to-wall joint: The screws are now exposed and visible as the exterior wall on the first floor has been removed. Screws are unscrewed from the outside or sawn off. Loops are attached to floor cassettes and they are lifted by crane.
7. Exterior walls, ground floor	Process like that of first floor.
8. Slab	An excavator chops the concrete slab to smaller pieces.

3.3. Strengths and weaknesses regarding deconstruction and reuse

The recorded knowledge and perceptions of the deconstruction process and reuse potential are presented in Appendix 1 (a slightly shortened, cleaned and translated version of the original Swedish version) and Appendix 2 (interpreted results restructured under the headings Strengths and Weaknesses for the different parts of the building).

In summary, the following strengths and weaknesses can be identified the current Villa Anneberg design with respect to deconstruction and reuse.

3.3.1. Strengths

- Industrially produced, large elements with low weight developed for efficient assembly
  The structure is built up to optimize efficient production, transport, and assembly. The fact that elements are large and have low weight is beneficial for a rational deconstruction process.

  As a general comment, MÖ stated that from his personal experience, deconstructing and reusing floor cassettes, load bearing wall elements and roof trusses poses no problems if you make an effort. (Contrarily, removing bathrooms required a lot of work in his case and lead to heavy waste that was expensive to dispose of. Solutions are not discussed further here as focus is on the load-bearing wood-based structure.)

- Knowledge and logistics already at hand
  Knowledge and logistics are already in place for efficient and safe transport and assembly. The aspects of deconstruction and reuse can be worked into the business model if there are incentives to do so.

- Detachable joints
  Screw connections are used and are assumed to be demountable.

- It might be possible to leave lifting loops in the assembled building. In the case of the deconstruction carried out by MÖ mentioned in section 2.3, wall elements were lifted in the same lifting loops that were used for the original erection, as they were left within the walls. This contributed to a fast and efficient process.

- Few and common tools needed
  Deconstruction can be done with a few common tools, as drill, saw and crowbar. As the elements are large, a crane will be needed for lifting. A potential for improvement exists, as it might be a good idea to develop a special tool for lifting wall elements – a tool that could be inserted to already existing holes intended for lifting loops.

- Mechanical and electrical services are placed so that they are not expected to complicate disassembly.

3.3.2. Weaknesses

- Damages lead to material waste and time-consuming restoration measures.
  The deconstruction of the exterior wall-to wall-joints and floor-to-floor joints will cause damage to the elements so that wall and floor elements will have to be repaired in a factory before reuse. Gypsum plaster boards and particleboards will be wasted in the process and will have to be replaced with new material. For the wall-to-wall connection, the problem is due to the fact that deconstruction will damage the vapour barrier (a plastic foil) so that it will have to be removed and replaced. The floor-to-floor cassette connections are glued and screwed. Disassembling the connection with a crowbar will damage the chipboard on top.

- Hidden, sequentially constructed joints

The disassembly of screw connections in Villa Anneberg is made more difficult by the fact that several connections are hidden by boards (OSB, plasterboards or panel boards). This applies to the wall-to-floor joints for example, where you need to remove gypsum plasterboards to be able to disassemble the structural screw joint.

- Unknown service life of vapour barrier
  The wall elements contain plastic vapour barriers. Their guaranteed service life is 50 years, which is shorter than the envisaged practical service life of the wooden frame. In practice, as the membrane is positioned between insulation layers in an environment protected from daylight and extreme temperatures, it is assumed here that the service life can exceed 50 years. In the following, we assume that a wall element can be reused after 50 years, with its original vapour barrier. This assumption will have to be verified.

- Plaster boards are sensitive
  Gypsum plasterboards are sensitive to damage. Lifting and transporting a wall element with plasterboards can lead to aesthetic problems (the paper layer may be wrinkled). This sensitivity is the reason why wall elements are originally mounted without the gypsum, which is added on-site. Also, after decades of use, there will be holes in the walls caused by hanging of paintings et cetera.

  In this case study, we assume that wall elements will be deconstructed and reused with their original plasterboards left in place. After transport and reassembly on the new location, a new 6 mm thick plasterboard is assumed to be added to cover any superficial damage.

- Disassembly of screw connections – feasible in practice?
  Screw connections are reversible in theory, but it would be good to have this assumption confirmed in practice. Studies should include or simulate screws that have been in use for several years and have been subjected to loads. Such investigations are out of the scope of this case study.

- Not prescribed connectors complicate recovery and introduce risks
  There may exist connectors (nails) in completed buildings that were not prescribed by Derome but have been added by the assembly teams. This was confirmed by MÖ, who has dismantled and rebuilt a Derome dwelling house. Such nails can be difficult to detect in a deconstruction process. It can also be difficult and time consuming to remove them. But more importantly, unprescribed nails could involve risks to workers in deconstruction. MÖ found that, when roof trusses were lifted with a crane, some trusses were stuck even though the structural screws connecting trusses to walls had been removed. Lifting the trusses until the nails gave way could potentially have been dangerous.
  Reasons for adding not prescribed nails could be (for example) a perceived need to keep an element in place while screwing the prescribed screws, or a need to tighten a joint.

- Waste from roofs
  The roof boarding will probably be damaged and all of it go to waste when boards are torn off with a crowbar. However, it might be possible to cut the boards off with a saw and reuse them in shorter lengths.

- Verification of complex elements according to building regulations

The scenario envisaged includes reuse of whole elements. Large parts of the structure will not be visible for inspection after disassembly, as studs, insulation and vapour barrier are hidden behind boards.

- Storing requires controlled climate
  As the building parts are wood based, temporary storing needs to be done in a controlled climate to avoid problems with biological growth. Protecting modular elements between constructs is a significant issue as covering/wrapping the units may cause condensation.

- Need for weather protection
  The deconstructed parts are sensitive to moisture. If deconstruction turns out to be a slower process than assembly, the risk of damage due to rain is greater. The possible need for weather protection during deconstruction as well as appropriate methods are yet to be explored.

3.3.3. Several other questions followed from the analysis

Several questions that do not go under the categories strengths and weaknesses but still were considered as important if timber buildings are to be designed for reuse were noted during the discussions. Some of them will be mentioned here:

• How does the construction industry view future jobs in deconstruction, regarding safety and health? Can tasks such as disassembling with a jigsaw be solved in a good way or is there a risk of vibrations and "white fingers"? Can such work be attractive?

• 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 the house? Or is a competitive cost for a reconditioned house enough to incentivise a buyer?

• What quality do the parts of the building need to have? Should gypsum plasterboards be replaced with plywood, for example?

• What future material costs can be assumed? Today, labor costs of say SEK 500 / h are set against material costs x. But in the future, there will perhaps be a different relationship and a shortage of raw materials. What ratio is required for it to be profitable to reuse?

• Which standard dimensions should apply to wall and floor elements if standard dimensions are desired? The weather protection of the units during transport and storage could be a limiting factor but other considerations will also come into play.

• Who takes responsibility for the load-bearing capacity of composite disassembled components such as wall elements and floor elements and how? That is, how do you verify the building regulations' requirements for stability, strength, and durability of used elements? Will we need updated building codes, that take reuse scenarios into account?

• Are light stick frame elements to be regarded as reusable in their composite form (as we have done here)? Or is it a problem that: 1) studs and their joints cannot be inspected visually 2) the plastic foil risks aging so that you want to replace it before reuse and installation in a building that will stand 50 - 100 years?

3.4. Potential for improvement

Having focused mainly on the load bearing structure, and having aimed at changing weaknesses but retaining strengths, we identified the following potential areas for improvement of Villa Anneberg.

3.4.1. General

Measures to avoid not prescribed connectors

Measures to avoid not prescribed connectors could be worked out. This could potentially reduce time and energy consumption during disassembly and reduce personal risks.[1] Joint details may need to be improved. Alternatively, clearer installation instructions for assembly teams might eliminate risks. This kind of improvement should be worked out together with assembly teams and be based on their experiences.

Taking the roof as an example, MÖ experienced a risk for workers while deconstructing roof trusses. When trusses were lifted with the crane after deconstruction of screw connections, trusses were held back by nails that were unknown to the deconstruction team. When nails suddenly yielded, trusses moved in an unexpected way. That could have been dangerous to the person standing next to the truss.

To minimize the risk that assembly teams add nails that are not prescribed, the screw connection roof truss to-wall could be further developed: angle brackets could be pre-assembled in the factory or an alternative design could be worked out for the screw connection. Alternatively, it might be sufficient to state clearly in assembly instructions that angle brackets must be mounted *before* the roof trusses are placed on the walls (as was the case in Figure 9). This should eliminate the need for extra nails, as roof trusses won't need to be fixed while the brackets are mounted. Deconstruction instructions could be worked out and include information on how to check for extra nails connecting roof truss and wall before lifting. Instructions could also show alternative methods for deconstructing the roof, as lifting several or all roof trusses (with boarding in place) simultaneously instead of lifting one roof truss at a time. Similar processes are used in construction today and should be applicable in deconstruction. This would lead to less waste of roof-boarding would reduce time spent on deconstruction as well as risks to workers.

Increase readability

Screw heads can be marked with spray paint to make it easier to find them during a deconstruction process. Painted screws then provide a lesser health and safety hazard.

[1]A similar problem was identified in a case study by Chisholm (2012). She stated that due to the two-stage construction of the Sigma Home - factory fix and site-installation, the crossover between the two becomes important. In that case, the absence of fixing information on drawings resulted in confusion on site during construction and a lack of transparency regarding deconstruction. She suggested that measures should be taken to minimise fixings and reach a strategy for disassembly.

Verify reusability in practical study

It has been assumed here that it is technically possible to deconstruct and reassemble planar elements, complete with all their layers and materials (as boards, studs, insulation, vapour barriers and wind barriers). However, questions have arisen:

- Whether you can rely on old vapor barriers and if they can be kept intact during a deconstruction process.
- Whether screw connections are reversible in practice or if screws break, work will include poor ergonomics or screwing a second time will be prevented by the presence of old holes or old left-in screws.

Practical studies, where elements are deconstructed and reassembled, are needed out to verify the reusability assumed.

Instructions for weather protection

Methods and instructions for weather protection during deconstruction (example, Figure 14) could be developed to make sure that there is no risk for moisture damage.

Figure 14 Weather protection. Methods and instructions for weatherproof deconstruction needs to be developed. Image: Andreas Videll, Derome

3.4.2. Roof and roof trusses

The building could be designed with roof cassettes; members that are both loadbearing and insulating (Figure 15). Roof cassettes, unlike roof trusses, do not need temporary bracing during erection and deconstruction. The risk that assembly teams add superfluous connectors is probably smaller for this type of structure than for roof trusses. After deconstruction, the entire cassette can be reused, and no boarding will go to waste. The cassettes are robust and easy to handle in deconstruction and transport, which should reduce time and energy consumption compared to handling roof boarding and roof trusses. In summary, time, waste, and risks should be reduced by building with roof cassettes.

Figure 15 Roof cassette, example. Image: Lättelement AB

3.4.3. Walls

Elements prepared for disassembly process

The time spent on disassembly would decrease if wall elements were more prepared for lifting in the deconstruction stage. Measures could be taken to make it easier for disassembly teams to know where to go and with which tool to lift.

The position of the holes intended for lifting loops should be the same for each element type and should also be specified in a deconstruction instruction, so that a future deconstruction team can easily find them. This is true today for rectangular wall elements, but holes in gable elements are drilled manually and their positions vary from one element to another. Also, lifting the gables would be easier and faster if special tool was manufactured, intended for lifting the gable in the holes of the original lifting loops. Alternatively, an existing, common tool might possibly be used and be specified in a deconstruction manual. This would have to be studied further.

It could be studied further if lifting loops used in primary construction (Figure 16) could systematically be left within in the walls, without causing problems such as gaps between wall and floor. The loops could be reused if deconstruction took place in a few years. If the loops have reached an age of several decades, it might be necessary to replace them but having the original ones in place should simplify the replacement.

Figure 16 Lifting loops like this might possibly be left in the mounted structure, but this would have to be studied.

Methods for reconditioning

Provided that wall elements can be reused with their original plasterboards left in place, methods to refurbish walls where the plasterboard has been wrinkled during deconstruction and transport could be developed. An existing technique for renovation projects, is to add a thin gypsum plasterboard to cover imperfections. Plasterboard finishes are routinely tapped and skimmed. Other techniques could be explored or developed. Maybe historic techniques using materials like linen textiles or paperboard could be taken as inspiration and starting point for such a development.

Methods for assessment of light timber elements

Strategies for verifying the demands of building regulations (as mechanical resistance and stability, safety in case of fire and hygiene, health, and the environment) for reused stick frame elements need to be developed.

Alternative frame principle

Alternatively, an entirely different type of wall construction could be used, that does not require a vapour barrier and/or does not make use of gypsum plasterboards. OSB boards that act as vapour barriers are available on the market and CLT elements could be used. To find the solution that would give the least environmental impact and best economical sustainability special studies would be needed.

3.4.4. Floors

Use floor cassettes

The concrete slab could be replaced with wood- based floor cassettes. The solution should be made moisture-safe with devices for monitoring the climate in the ground and (possibly) controlled ventilation.

3.4.5. Connections

Connection roof truss-to-wall

This design of this connection and/or its assembly instructions could, as mentioned earlier, be further developed to minimize the risk that assembly teams put in nails during the primary assembly.

Connections wall-to-floor and wall-to-wall panel

The junctions “exterior wall-to-intermediate floor”, “exterior wall-to-ground slab” and “wall-to-wall panel” could all be developed to be more reversible. It would be preferable if they could be disassembled in one single step, using a minimum of time and energy. Today, deconstruction would have to be done in several steps as gypsum plaster boards need to be removed to expose the structural screws hidden behind.

Connection floor-to-floor cassette

This screw-glued connection could be developed so that it can be dismantled without causing damage to chipboard or beams.

3.4.6. Other

The building could be built with bathroom modules. This is not an issue specific for the load bearing structure in focus here but worth mentioning as the bathrooms give a lot of waste today. Materials cannot be reused and getting rid of the waste is time consuming and expensive. Also, if the bathroom pods had a facility to close off inlets and outlets, this might reduce damage to the timber structure from wastewater after decommissioning of the building, as often there is a delay between occupancy and deconstruction.

Insulation boards could be used to replace loose wool insulation to isolate the attic. Getting rid of loose wool in a deconstruction situation would require a lot of transport as the loose wool is not compressed when taken out. However, this alternative solution is not only positive and the change in design is not obvious as using loose wool insulation is better from a health and safety aspect in the primary construction process. Blowing the loose wool out when erecting the building is done in 2-3 hours and in a comfortable position for the worker. Working with boards means crawling on knees, is difficult and would take almost a week. Also, as boards have higher density, use of boards will probably lead to a higher amount of green-house gases being produced in the primary construction.

3.5. Selection of details to improve

Based on what researchers and industry considered most promising and still feasible to study within the time and resource limits of the InFutUReWood project, three areas of improvements (three connections) were selected for further study: connection wall-to floor, wall-to-wall panel junction and floor-to-floor cassette connection.

Beside what has previously been mentioned about the disadvantages of these details, a few more words will be said here on current designs and the motives for modifying them.

3.5.1. Connection wall-to-floor

The current connection exterior wall-to floor is of the same type for both first and ground floor. Figure 17 illustrates the detail for the case exterior wall-to intermediate floor. In discussions, we have assumed the current connection to be disengaged by unscrewing the structural screws after removal of gypsum plaster boards. Two methods to remove the gypsum to expose the screws were considered possible: 1) Either a horizontal cut is made in the plasterboard about a 100 mm above floor level, and the strip of plasterboard thus created is removed. The connection is then unscrewed. In reuse, reassembly includes patching up with a new strip of plasterboard and covering the wall on the inside with 6 mm gypsum plasterboard to cover damages. 2) Or the complete gypsum plasterboard is removed. In reuse, this is replaced with a new one.

Regardless of method chosen, having to remove the plasterboard is an important disadvantage as it will be time and energy consuming. Also, getting rid of the waste will be associated with costs.

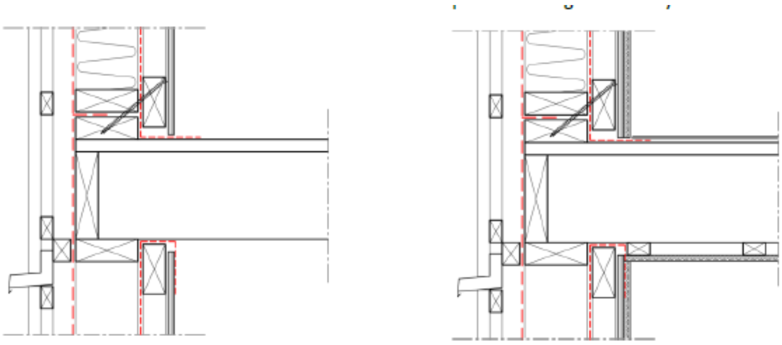


Figure 17 Current wall-to-floor assembly.
Left: Step 1. The gypsum layer is omitted to allow structural assembly. The airtightness layer is dressed under the horizontal floor batten. No sealant is used.
Right: Step 2. When the panels are structurally connected to the base post, a gypsum finish is applied to the whole room. The finished floating floor is then fitted. NOTE: A section of the internal wall panel finish is also omitted during transport, which is also completed before applying the wall finishes. The diagrams are orientated left-right from outside to inside.

3.5.2. Wall-to-wall panel junction

The motive for improving this connection is partly the same as for the one just mentioned: deconstruction must be done in sequences and waste will be produced. A problem that is specific for this connection is related to the scenario. The scenario we assess the design for includes reuse of entire wall elements and requires that the plastic vapour barriers in the panels are still intact after deconstruction. With current design, deconstruction will damage the vapour barriers. Figure 18 shows the connection with current assembly steps of the wall panel in-situ. Studying the detail, discussions led to the assumption that future deconstruction of the joint might be done in two different ways: by unscrewing the structural screw connections or by cutting them off with a saw.[2] In the first case, removal of gypsum, OSB, vertical battens, and internal insulation layer is necessary in

2 It was found during the previous disassembly and reassembly of the similar MÖ one-story house, that it was more efficient to cut through the internal wall finishes and the structural screw connections than unscrewing the screws. All panels were diverted to the manufacturing facility where the gypsum, OSB, vertical battens, and internal insulation layer were removed to expose the air-tightness membrane for replacement. Additionally, the original gypsum layer was discarded and replaced entirely at reconstruction of the building.

order to expose the screws. In the other case, gypsum and OSB will have to be removed before cutting.

Both methods will expose the air-tightness membrane in the wall panels to damage. Also, the original gypsum layer will be destroyed. It will be necessary to divert the wall panels to a manufacturing facility to disassemble them and complete them with a new vapour barrier, internal insulation layer, battens and OSB. The gypsum plasterboard will be replaced entirely at reconstruction of the building.

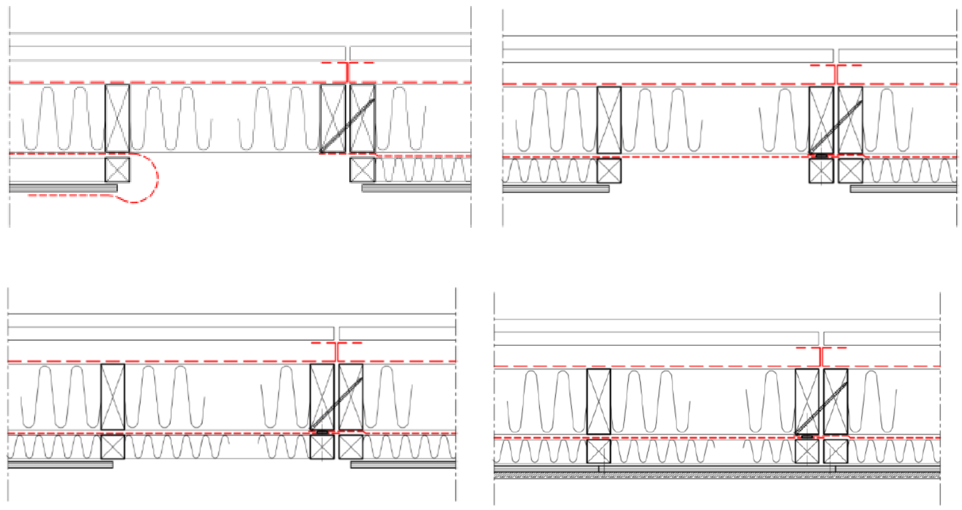


Figure 18 Current wall panel assembly.
Top left, step 1: For the assembly, the exterior wall panels are left incomplete during transport. A section of the internal OSB layer and internal batten and secondary insulation layer is omitted, to expose the structural posts for assembly on-site. The airtightness membrane is dressed back on the internal face of the panel to allow access to main structure. The standard assembly practice consists of screwing the structural posts.
Top right, step 2: The airtightness membrane is overlapped and sealed with a synthetic isobutylene with isoprene sealant. This sealant is not biodegradable. A vertical internal batten fixes the seal.
Bottom left, step 3: The breach to the internal insulation layer can now be bridged.
Bottom right, step 4: The OSB layer is completed. A gypsum finish is applied to whole room.

3.5.3. Floor-to-floor cassette connection

Figure 19 illustrates the connection assembly of the internal intermediate floor cassettes. Currently, the floor cassettes comprise a chipboard floor deck onto a joisted floor frame. An overlap of the deck is screwed and glued onto the adjacent deck, with a batten parallel with the main joist providing additional support to the deck. The cassettes are glued to comply with Swedish design standards to mitigate movement in the lightweight floor. Also, cassettes need to work together as a whole (to provide diaphragm action in the floor when carrying horizontal wind loads).

As a result of the glued connection, deconstruction will be difficult and disengaging the connection will damage both chipboard and joists significantly.

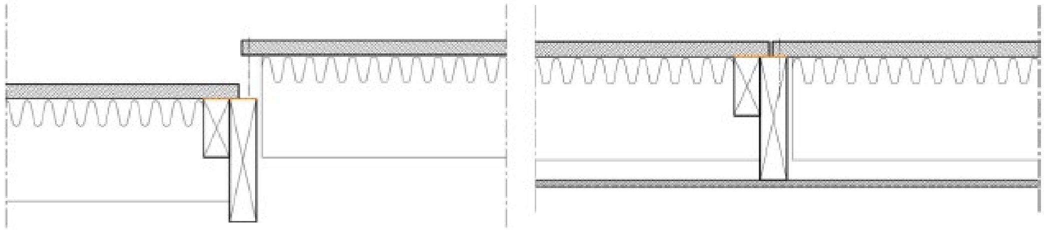


Figure 19 Currrent floor to floor assembly. Left, step 1: Chipboard floor deck glued and nailed to structural edge joist, with additional 45 mm support to the deck. Right, step 2: Gypsum ceiling to battens.

3.6. Calculation of the amount of wood that can be reused with today's design

In the simulation of deconstruction and reuse, waste due to damage was discussed and estimated. The loss during disassembly for load-bearing components was estimated as follows.

- Roof boarding and roof battens: 100 % waste. The boards will be damaged when removed from the trusses. NOTE: these parts could be *recycled*. They might be used for producing chipboards for example. As it is out of the scope of this case study to examine possible recycling scenarios, the parts are here considered as waste, which a pessimistic assumption.
- Roof trusses: 0% waste. The trusses are judged to be reusable in their entirety.
- Gables: 0% waste; they are judged reusable in their entirety.
- Exterior walls are judged to be reusable almost in their entirety. To account for some damage in handling, 0,15 m^3 wood is assumed to go to waste.
- Intermediate floor: 20 – 25 % of each floor cassette is judged to be wasted as joists and chipboard will suffer local damage when the chipboard is torn loose.
- Baseplates: 100% waste.

It follows from the estimate, that 11 580 of the 14 000 kg wood in the load bearing structure could be reused with the current design.[3] That is, 82,7 % (details, see Table 3).

[3]This study focuses on the load-bearing structure of Villa Anneberg and does not account for reuse of other parts of the building. Still, it can be worth mentioning here that the interior non-load-bearing walls were judged to go to waste entirely in a future deconstruction. That is because surface layers/boards will be damaged and because studs are supposed have too low an economical value for it to be worthwhile to take them apart and sell them.

Table 3 Calculation of amount of wood that can be reused with current design

	Mass [kg]
Estimated waste, roof boarding	1320
Estimated waste, roof battens	308
Estimated waste, floor cassettes, solid timber	176
Estimated waste, floor cassettes, chipboard	250
Estimated waste, wall studs	66
Estimated waste, baseplates	300
Total waste	2 420
Wood in the whole load bearing structure	14 000
Estimated mass of wood that can be reused:	14 000 – 2 420 = 11 580
Amount that can be reused: 11 580/14 000 = 0,827	

3.7. Modified design

Designs were developed to meet our criteria for an improved solution. Improvements within the current production principles were sought. A solution like "replacing the light timber structure with a CLT structure" was not considered, neither replacing screws with bolts.

3.7.1. Modified connection wall-to-floor

Figure 20 illustrates the alternative assembly sequence that resulted from discussions between researchers and Derome. The inevitable damage and subsequent disposal of the gypsum wall finish, currently, 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 for the secondary building will negate the need for a skirting board.

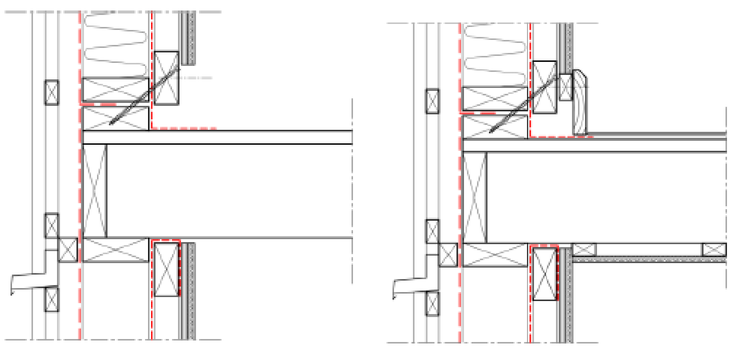


Figure 20 Revised wall to floor assembly. The diagrams are orientated left-right from outside to inside.
Left, step 1: The OSB and gypsum layers are now finished short of the floor to allow access for structural fixing. The airtightness layer is dressed under the horizontal floor batten, as before. Any 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.
Right, step 2: 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.

3.7.2. Modified wall-to-wall panel junction

The next modification is judged by Derome to be such an improvement in several aspects, that it is likely to be integrated in production soon (within the coming months).

This study aimed to revise the vertical wall-to-wall detail to allow for reuse of whole, intact wall elements. With the modified design, the wall-panels can be more substantially completed initially at the factory. They can be deconstructed and transported directly to the secondary site, for reassembly without any diversion for substantial repair. Figure 21 shows the sequence of assembly of the alternative connection. With the revised design, vapour barriers are not overlapping at the connection. Air tightness is achieved with an ordinary type of tape (does not require the use of butyl). The gypsum plasterboards are stopped short of the connection and are intended to be kept in the future deconstruction and reuse.

Deconstruction is assumed to be made by 1) finding the connection (can be seen from above) 2) taking off the strips of plasterboard and OSB 3) unscrewing the structural screws.

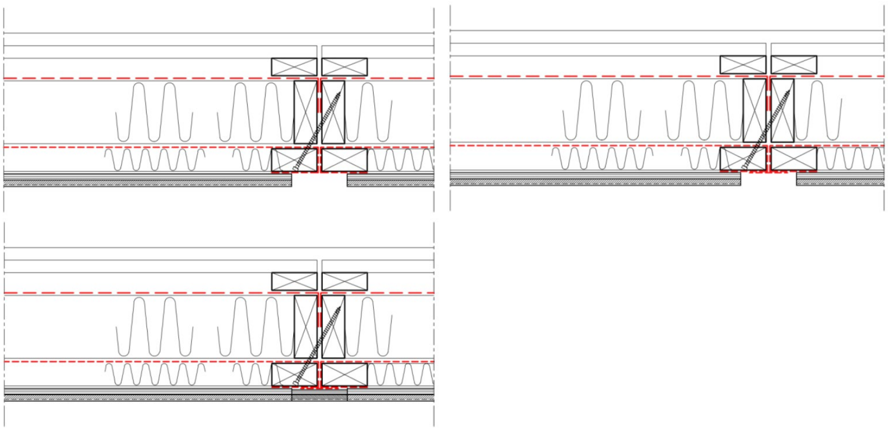


Figure 21 Revised Derome Villa Anneberg wall panel assembly. The diagrams are orientated top-down from outside to inside.
Top left, step 1: The panel is transported from the manufacturing facility complete with internal insulation, OSB and gypsum layers. The airtightness membrane is dressed in around the vertical batten. The batten size is increased to facilitate the structural fixing through to the main supports.
Top right, step 2: The airtightness layers are sealed with a proprietary tape. (Butylband is not required). The OSB and gypsum layers are finished short of the junction locally to allow access for structural fixing and sealing of membranes.
Bottom left, step 3: The small gap in the OSB and gypsum layers is repaired on-site to a condition that matches the adjacent finishes.

3.7.3. Modified floor-to-floor cassette connection

The revised assembly design adds an additional edge joist for each cassette (Figure 22). Chipboards are glued to the joists, but the overlapping part of the chipboard is screwed without glue. It is anticipated that the short span of unglued chipboard and close spacing of the screws will mitigate movement along the junction. This assumption will need to be verified with testing.

Deconstruction can be done by unscrewing screws and does not include damaging the glued members. While there is again some minor on-site works required to 'make good' the secondary assembly of the building, this is deemed to be within the minor works expected that would also include repair of marks, dents, and scratches commonly incurred during transport and assembly of the building elements.

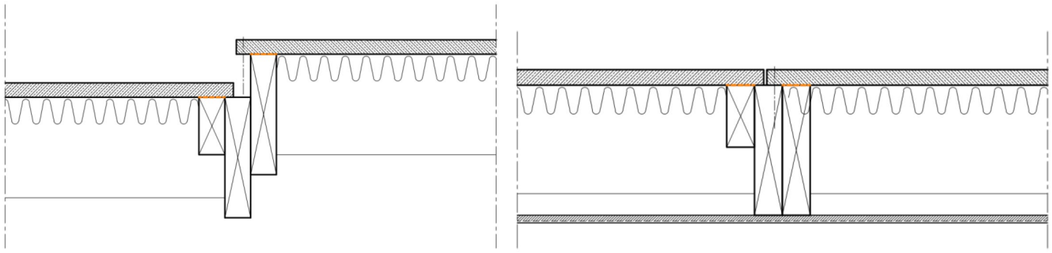


Figure 22 Revised floor to floor assembly. Left, step 1: Chipboard floor deck glued and nailed to structural edge joist, with additional 45 mm support. Additional edge joist glued to the deck of the connecting cassette. Connection between cassettes screwed only. Right, step 2: Gypsum ceiling to battens.

3.7.4. Amount of wood that can be reused with modified design

For the modified version of Villa Anneberg with revised details shown above, an estimation of the amount of reusable wood was carried out, like the one made for the original version. Foreseen (estimated) waste for this version is:

- Roof boarding and roof battens: 100 % waste. Everything goes to waste as the boards are damaged when ripped off from the trusses. Note that these parts could be recycled. They might be used for producing chipboards for example. As it is out of the scope of this case study to examine possible recycling scenarios, the parts are here considered as waste.
- Baseplates: 100% waste.

Floor cassettes will contain more wood with the new solution than the current: the mass of wood in the load bearing structure will increase by 200 kg. It follows from the estimate, that 12 727 kg of the 14 200 kg wood in the load bearing structure could be reused with the revised design.[4] That is, 86,4 % (details, see Table 4).

[4] This study focuses on the load-bearing structure of Villa Anneberg and does not account for reuse of other parts of the building. Still, it can be worth mentioning here that the interior non-load-bearing walls were judged to go to waste entirely in a future deconstruction. That is because surface layers/boards will be damaged and because studs are supposed have too low an economical value for it to be worthwhile to take them apart and sell them.

Table 4 Calculation of amount of wood that can be reused with modified design

	Mass [kg]
Estimated waste, roof boarding	1320
Estimated waste, roof battens	308
Estimated waste, baseplates	300
Total waste	1 928
Wood in the whole load bearing structure	14 200
Estimated mass of wood that can be reused:	14 200 – 1 928 = 12 272
Amount that can be reused: 12 272/14 200 = 0,864	

3.8. Comparison current design - modified design

The modified design leads to an increase in the amount of wood estimated to be accessible and reusable, compared to the current design. Note that the figures are based on estimations. Note also that the figures are based on the assumed reuse scenario.

The load bearing structure of the current design contains 14 000 kg wood, and the estimated reusable quantity is 11 580 kg. Thus 82,7 % of the wood can be reused today. The load bearing structure of the design with new connections contains 14 200 kg wood and the estimated recyclable quantity is 12 272 kg. Thus 86,4 % of the wood could be reused with the new design.

The figures show, that for each building another 692 kg of wood could be made available for reuse with a modified design. Let us see what this could mean on a larger scale.[5]

Derome could make up to 277 more tonnes of wood reusable per year. Derome today builds around 170 of Villa Anneberg buildings per year. With their other two-storey models they build in total around 400 similar houses a year. Assuming all models use the same amount of wood (which is reasonable according to Derome), current Derome two-storey designs use 5 600 tonnes of wood per year and 4 632 tonnes can be estimated to be reusable. New designs would use 5 680 tonnes of wood per year and 4 909 tonnes would be made reusable. The difference would be that 277 more tonnes of wood would be available for reuse per year if new design concepts were adopted.

Expanding the thought experiment to all buildings of this type in Sweden, up to 4 360 tonnes more wood could be available for reuse with modified designs. This estimation comes from the assumption (made by Anders Carlsson, Derome) that the Villa Anneberg production corresponds to 6% of the private market, which means that about 2 800 such buildings are erected per year in Sweden. In addition to these, similar houses are built in areas, about 3 500 per year. Other concepts than Villa Anneberg were not studied within this study, but if we play with the thought that all the around 6 300 buildings contain the same amount of wood and could augment the reuse potential in the same way, that would mean that 4 360 more tonnes of wood were made reusable (692 kg x 6 300 buildings).

Apart from the increased potential to reuse building elements, the modified Villa Anneberg design is most likely advantageous economically. The time needed for production in factory is estimated to be

[5] Note that the scope of the study is narrow as only the load bearing structure is studied. Large quantities of materials are used in construction for less long-lived parts as windows, doors and surface layers. The figures presented here could be related to (for example) the amount of surface materials replaced in refurbishments each year. Such analyses are beyond the limits of this work.

the same as for the current design, but a reduction of time at building site can be foreseen and is estimated to 5 minutes/ joint. The assembly on site is estimated to require less energy (50 W/joint).

Environmental and economic aspects of the original and modified designs are examined in a separate study within the InFutUReWood project (WP 6).

3.9. Guidelines for deconstruction and reuse, Villa Anneberg

In this chapter, we show what guidelines regarding deconstruction and reuse could look like for the revised Villa Anneberg design. This draft for guidelines is based on SEDA Design Guides for Scotland (Morgan & Stevenson 2005).

Statement of strategy for DfDR

Villa Anneberg is designed and assembled to enable a high degree of reuse of load-bearing parts and climate shell. The design is adapted to allow for deconstruction of the building into its original planar elements and reconstruction of the building on a site with the same wind- and snow loads as the original building. For that scenario (where all building elements being are reused for their original purposes) approximately 85% of the weight of the timber in the load bearing structure can be reused.

Reusable parts are:

- Roof tiles
- Roof trusses
- Exterior walls on ground floor and second floor
- Intermediate floor
- Core wall on ground floor

The parts may need to pass through the factory for reconditioning before reassembly.

Components that cannot easily be reused but can be recycled are:

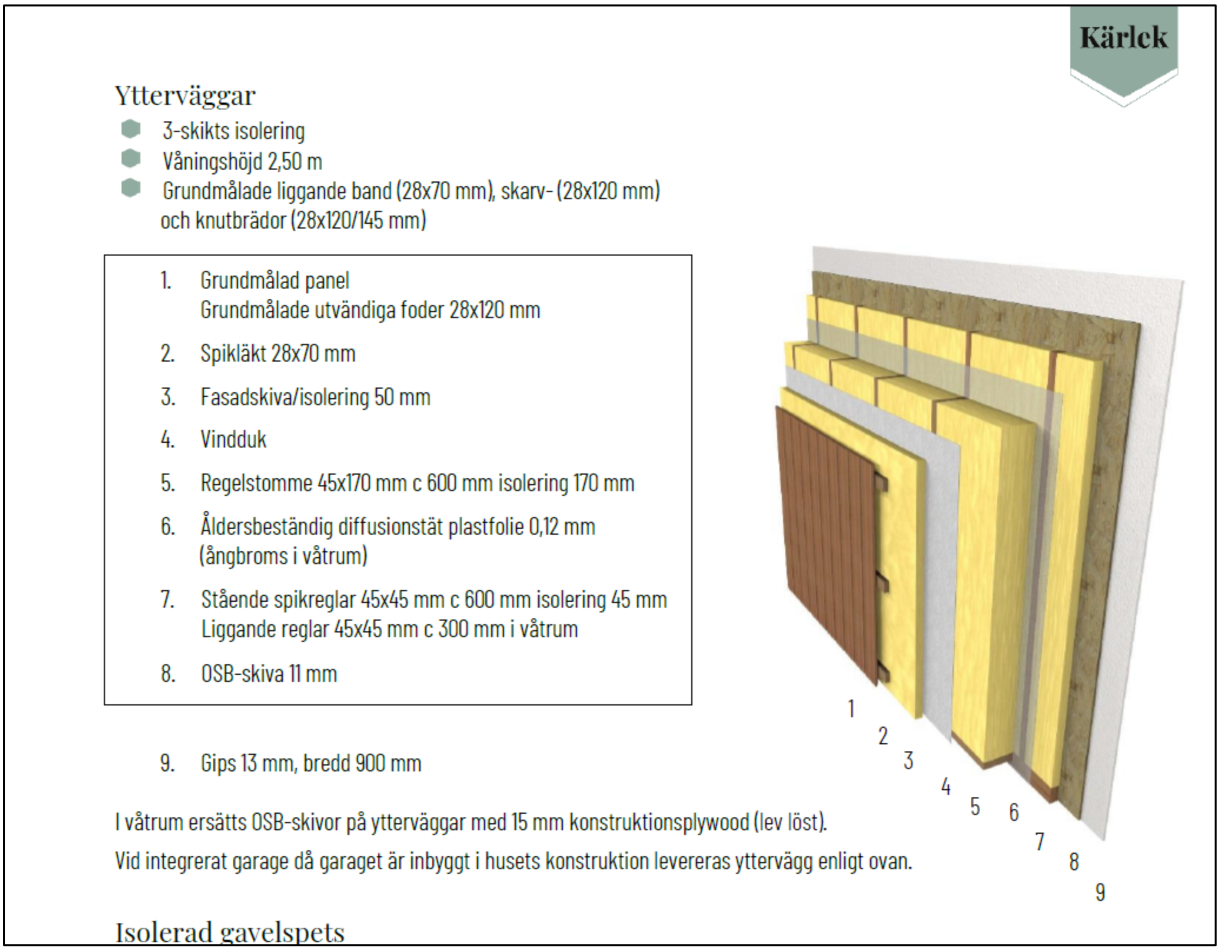
- Roof boarding
- Roof battens
- Roofing felt
- Ceilings (battens + plaster)
- Partitions (studs + plaster)
- Exterior supplementary boards

These should be sorted and divided into material-unique fractions to enable either recycling of the material or incineration.

Elements in the load bearing structure

Delivery declaration

Information on the delivered building is provided in the *Delivery declaration*. This document describes each building component in writing (and with some illustrations). Materials and dimensions are reported, and the document explains which components that are held together as one element. An extract from the document is presented in Figure 23 and shows some of the data given on exterior walls.



Kärlek

Ytterväggar

- 3-skikts isolering
- Våningshöjd 2,50 m
- Grundmålade liggande band (28x70 mm), skarv- (28x120 mm) och knutbrädor (28x120/145 mm)

1. Grundmålad panel
   Grundmålade utvändiga foder 28x120 mm
2. Spikläkt 28x70 mm
3. Fasadskiva/isolering 50 mm
4. Vindduk
5. Regelstomme 45x170 mm c 600 mm isolering 170 mm
6. Åldersbeständig diffusionstät plastfolie 0,12 mm (ångbroms i våtrum)
7. Stående spikreglar 45x45 mm c 600 mm isolering 45 mm
   Liggande reglar 45x45 mm c 300 mm i våtrum
8. OSB-skiva 11 mm

9. Gips 13 mm, bredd 900 mm

I våtrum ersätts OSB-skivor på ytterväggar med 15 mm konstruktionsplywood (lev löst).

Vid integrerat garage då garaget är inbyggt i husets konstruktion levereras yttervägg enligt ovan.

Isolerad gavelspets

Figure 23 Example of data that can be found in the Delivery declaration (in Swedish). The extracted example concerns exterior walls. The rectangle shows components that are held together as an element.

The Delivery declaration is delivered to the buyer. A copy is stored with the manufacturer, Derome (contact information, see last section in these guidelines).

Drawings and other files and documents

A full set of drawings is stored at manufacturer Derome (contact information, see last section in these guidelines). The drawings are created with commercial software AutoCAD and DDS-CAD (AutoCAD 2021, DDS-CAD 2021).

Building permit drawings are stored at the local municipality where the original building is erected.

Apart from drawings, the following files and documents describes the building and forms a BIM model (Building Information Model):

- Purchase information and final quantity lists.
- Digital control files and files for managing cutting machines.
- Bill of quantity.
- Load planning document (showing how elements are fitted into trucks) for the original assembly.

The files are created with DDS -CAD and Monitor (business system) commercial software.

All documents and files are stored at Derome at least ten years from the time of delivery to site (the warranty period).

Prior to deconstruction a desk study of the original design file and as-built documentation should be carried out by a suitably qualified agent. Any variation from the design load or the as-built drawings and health and safety and maintenance files should be noted.

Some elevations and layout plans are presented in Figures 24 and 25.

Figure 24 Elevations

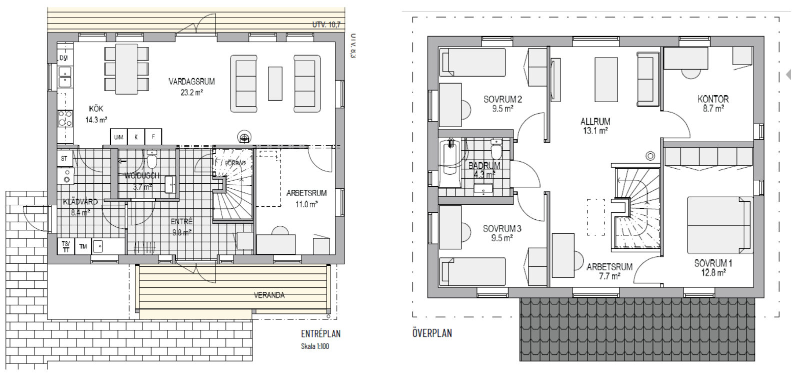


Figure 25 Layout, ground floor (left) and first floor (right).

Definition of elements

The building frame consists of twelve exterior wall elements, five floor cassettes and core wall elements (Figure 26-28). Quantities and performance of elements are given in Table 5.

The different elements are labeled to facilitate reassembly after deconstruction.

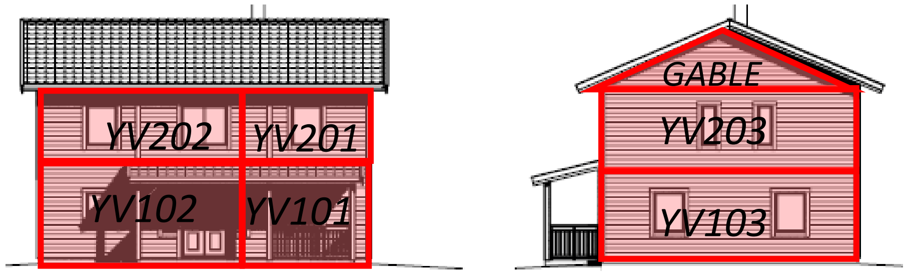


Figure 26 Exterior wall elements.

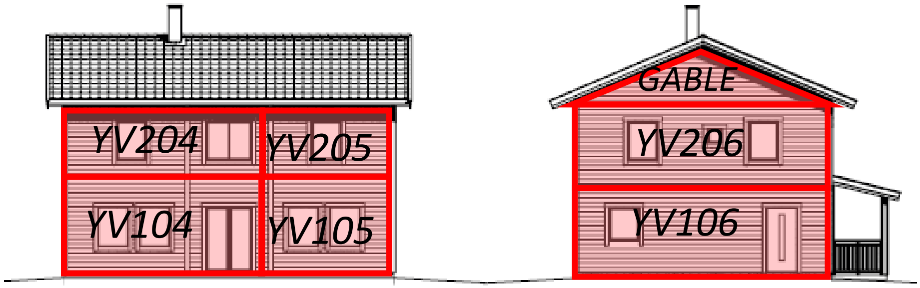


Figure 27 Exterior wall elements.

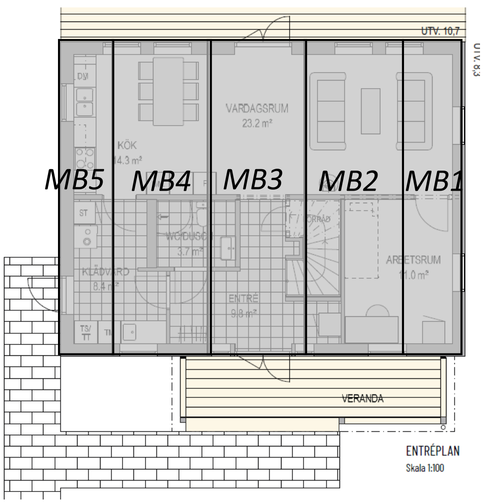


Figure 28 Floor cassettes.

Table 5 Quantities and performance of elements

Element type	*Label/Type number*	*Number of similar elements in building*	*Length [mm]*	*Depth (height) [mm]*	*Weight, one element [kg]*	*Performance declarations*		
						Timber grade	*Insulation performance U [W/m²C]*	*Fire classification*
Roof truss	-	10	9540	2106	84	C24	-	-
Gable element	Gable	2	823	2106	308	C24	-	-

Exterior wall	YV101	1		2503	439	C24 (C14 in 45 mm battens)	0,14	REI30
Exterior wall	YV102	1		2503	1046	C24	0,14	REI30
Exterior wall	YV103	1	8140	2503	1111	C24	0,14	REI30
Exterior wall	YV104	1		2503	798	C24	0,14	REI30
Exterior wall	YV105	1		2503	853	C24	0,14	REI30
Exterior wall	YV106	1	8140	2503	1087	C24	0,14	REI30
Exterior wall	YV201	1	2946	2503	429	C24	0,14	REI30
Exterior wall	YV202	1	7146	2503	896	C24	0,14	REI30
Exterior wall	YV203	1	8140	2503	1110	C24	0,14	REI30
Exterior wall	YV204	1	5026	2503	744	C24	0,14	REI30
Exterior wall	YV205	1	5066	2503	744	C24	0,14	REI30
Exterior wall	YV206	1	8140	2503	1171	C24	0,14	REI30
Floor cassette	MB 1	1	8140	1872	525	C24	-	-
Floor cassette	MB 2	1	8140	2394	517	C24	-	-
Floor cassette	MB 3	1	8140	2394	532	C24	-	-
Floor cassette	MB 4	1	8140	2394	648	C24	-	-
Floor cassette	MB 5	1	8140	1462	392	C24	-	-
Ground slab, reinforcement				581		C24	-	-
Ground slab,concrete				26820				
Ground slab insulation, expanded plastic **s100** **s200**				 563 143				

All elements in the loadbearing structure are judged to have a life span of 100 years.

Design loads

This building was designed for loads given in the building codes relevant at the time for construction.

On site assessments are mandatory

Prior to deconstruction, the building and its loadbearing structure should be assessed by visual inspection on site. This inspection is done to complement desktop studies of drawings and should be done by the person in charge of deconstruction and/or reuse.

This onsite and document inspections should also aim to evaluate the building's performance. Any variation to regulation from the initial build date should also be noted and addressed for the reconstruction phase. Changes in geometry, connections, supports, materials, and loads should be assessed. Special attention should be given to potential changes in load paths caused by new openings.

Methods for onsite inspection could include measuring of moisture content, thermography, and resistance drilling.

Disassembly instructions

Tools needed

- Screwdriver
- Sabre saw with saw blade for wood and metal
- Circular saw
- Hammer
- Sledgehammer
- Crowbar
- Rope

Lifting and transporting facilities

- Lifting loops
- Crane truck
- Truck
- Sludge suction truck for removing blown/loos insulation
- Excavator for chopping ground slab

Stages and activities

The recommended deconstruction process comprises eight stages (Figure 29): preparatory work (I), deconstruction of roof (II), roof trusses (III), gable panels (IV), exterior walls on first floor (V), floor cassettes (VI), exterior walls and core wall on ground floor (VII) and finally demolition of ground floor slab (VIII).

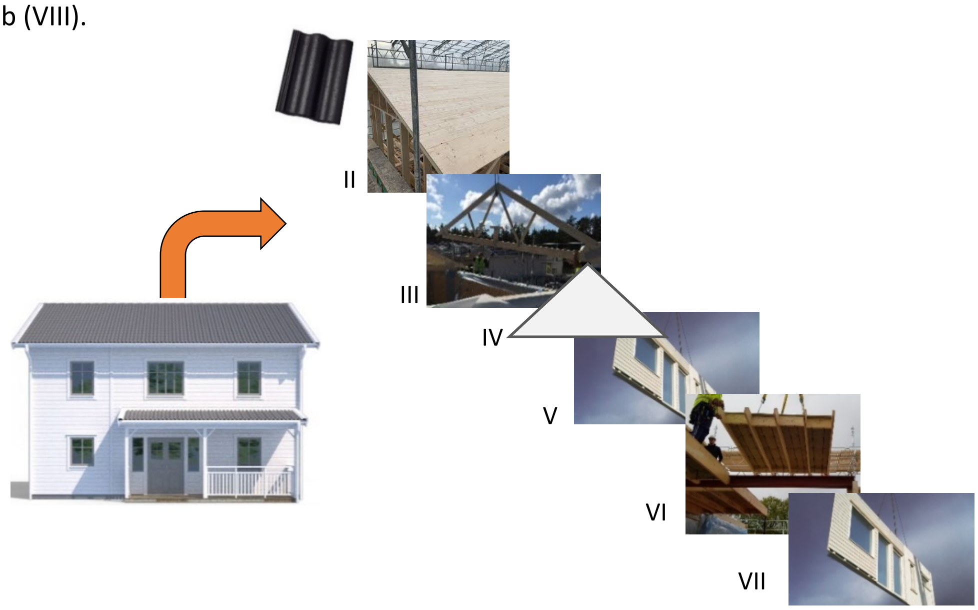


Figure 29 Deconstruction stages II-VII. Not shown are stage I, preparatory work and stage VIII, demolition of concrete slab.

I. Preparatory work

- Surface layers and interior walls are removed to expose the main frame.
- Water pipes and wastewater pipes are disconnected.
- The bathroom is removed for disposal.
- Scaffolding is erected.

II. Roof

- Roof structure, including trusses and gable are braced.
- Concrete roof tiles are removed.
- Battens nailed to the roof-boarding are removed by crowbar. Roofing felt is stripped back for disposal or recycling.
- Roof-boarding is disconnected from roof trusses on site. Alternatively, roof-boarding could be sawn up to panels between trusses and the rest be left on roof trusses or torn off on site.
- Exterior walls on first floor are braced.

III. Roof trusses

- The loose wool insulation in the attic is removed with a sludge suction truck.
- Any mechanical and electrical services in the attic are removed from the building.
- The suspended ceiling that is attached to the roof truss subframe is loosened.
- The joint with screws and brackets connecting trusses to load-bearing walls are disassembled or sawn apart.
- The connections roof to wall are checked for unprescribed nails.
- Loops are fastened to trusses. The trusses are lifted one by one with a crane. Lifting is done carefully in case of unnoticed unprescribed nails.
- Alternatively, several roof trusses are lifted simultaneously with their roof-boarding left on.

IV. Gables

- Temporary battens are fastened to the gables to facilitate the connection of lifting loops.
- The gables are lifted with a crane.

V. Exterior walls, first floor

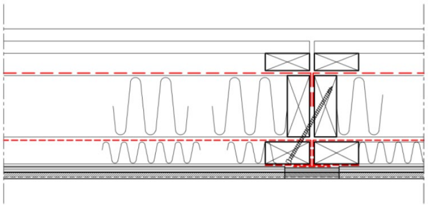


Figure 30 Wall-to-wall connection

- To disassemble wall-to-wall connections (Figure 30), locate the connections from above.
- Remove exterior panel boards covering connections on the outside.
- Remove timber skirting boards.
- Remove strips of plasterboard and OSB covering connections on the inside by undoing screws.

- Wall-to-wall connections are then disassembled from the inside by unscrewing structural screws.

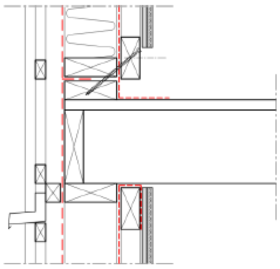


Figure 31 Wall-to-floor connection

- The wall-to-floor connection (Figure 31) is disassembled by unscrewing structural screws.
- Loops are mounted and wall elements are lifted by crane.
- Base plates are removed.

VI. Intermediate floor cassettes

- Exterior and core walls on the ground floor are braced.
- Flooring, board material and sound-insulating layers are removed for disposal. Floor-to-floor cassette connections are now exposed.
- Screws are unscrewed.
- The joint connecting floor cassettes to exterior wall on ground floor is disassembled by unscrewing structural screws from the outside.
- Loops are attached to floor cassettes and they are lifted by crane.

VII. Exterior walls on ground floor

- Process like that of exterior wall plan 2.

VIII. Slab

- The reinforced concrete slab is broken down with an excavator and the reinforcing is subtracted before the broken concrete is suitable as structural fill elsewhere.

Security during deconstruction

During deconstruction the following, but not exclusively, health and safety concerns apply:

- Scaffolding.
- Safety/security hoarding to prevent access by any unauthorized persons.
- Signage with contact information stating site safety procedure.
- Site security to ensure no unauthorized persons gain access while disassembly is in progress.
- Sequence of disassembly to avoid undermining key structural components.
- Monitoring of weather to ensure suitable external conditions during disassembly.
- Crane size and location of hard ground to accommodate deconstruction machinery.
- Identify site access and egress, site office, machine traffic routes and site storage.

- Personal protective equipment through (safety shoes, goggles, hearing protection etc.).
- Valuation and identification of other risks for the building in question. Deterioration of materials is a likely hazard with old and derelict buildings.
- Sufficient area to handle and pack the building parts in a way that means that they remain:
  - Undamaged
  - Dry
  - Clean
- Packaging /assembly. Transport of the building parts must be rational and safe. Traffic safety must not be compromised. Safety during loading and reconditioning must be considered.
- Lifting aids for lifting the assembled components on a truck.
- Safe loading of truck and securing of load.
- Truck adapted for this type of transport.
- Building components must not be attached with additional or hidden attachments in addition to those reported on assembly / disassembly documents.
- On-site monitoring of building element connections for additional and potentially hazardous fixings not included in the pre-demolition report. This is to ensure that materials can be lifted clear of on-site personnel, thus providing a safe disassembly practice.

Assessment of condition and performance

All elements must be assessed regarding damage by a structural engineer. For the assumed scenario (where all parts are reused to form a building identical to the original), additional strength and stiffness assessments are not mandatory for undamaged parts.

Storage

- Roof tiles can be stored in outdoor climate if protected from dirt and damage.

- Building elements can be stored outdoors for a limited time if they are protected from rain and snow. No exposure to rain or snow is allowed, not even for a few hours. Outdoor storage can only be allowed if elements are covered with plastic or are stored under roof. Elements should be monitored with respect to relative humidity. When plastic covers are used, measures must be taken to avoid condensation. With these conditions, roof trusses can be stored for a maximum time 10 days outdoors. Wall and floor elements can be stored for a maximum time of one week. It is possible to reach time limits of up to 1-2 months in well controlled situations, with special precaution and close supervision.

- When stored, all parts shall be well separated from the ground so that contamination caused by splashing is avoided.

- Parts can also be stored indoors in unheated climate if monitored with respect to relative humidity. Precaution must always be taken to prevent moisture damage.

Reconditioning

The parts may need to pass through the factory for reconditioning before reassembly.

Wall elements are reconditioned after assembly on site by adding 6mm gypsum plaster boards on the inside of all elements.

Second assembly

Assembly is equal to original assembly. Instructions are found at Derome, se contact information below.

Document storage and distribution

Date of creation of this document

2021-05-21

This documentation is stored and managed by the owner of the building. When transferring the property, this documentation and the documents mentioned in it must be included in the sale. Any new owner must document and build on this documentation if the building is modified in such a way that it affects future dismantling and reuse.

This documentation could/should also be stored and managed by the local authorities, together with the building permit.

Contact information, manufacturer Derome

For further information, please contact manufacturer Derome.

Website: www.a-hus.se, www.derome.se

Mail: info@derome.se

Visit: Bjurumsvägen 14, Veddige, Sweden.

Health and safety and maintenance files

Health and safety and maintenance files should be prepared by the building contractor (overseeing agent) at each construction.

4. Discussion and conclusions

In this section, we discuss how well we reached the objective of the case study, to identify:

- The inherent strengths of the current design of Villa Anneberg regarding deconstruction and reuse.
- What weaknesses it has in the same respect.
- How the design could be improved with respect to future deconstruction and reuse.

- How much wood that could be reused in the future with the current design and how much wood that 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 Terminology.)
- How guidelines for deconstruction and reuse could be formulated for this object.

And to test and develop a method for carrying out case studies.

4.1. Conclusions

The study filled a gap in the published knowledge on how timber buildings could be designed for deconstruction and reuse. We have identified advantages and obstacles to deconstruction and reuse of the current design of Villa Anneberg, showed how the design could be improved, how the improvement could be measured, how guidelines for deconstruction and reuse could be formulated and also, in general, a way to work to find new designs.

Strengths of the current design of Villa Anneberg regarding deconstruction and reuse

The current design of Villa Anneberg is relatively well prepared for disassembly already today. The building is designed for efficient transport and assembly and the process is judged to be reversible to a high degree. Many connectors are screwed, and the building can be deconstructed with common and simple tools. Mechanical and electrical services should not pose problems in deconstructing the structural frame.

Weaknesses of the current design of Villa Anneberg regarding deconstruction and reuse

The drawbacks in the current design are for example connections designed so that deconstruction causes damage to elements (which makes refurbishment before reuse mandatory), sequential connections that make deconstruction time consuming, the use of plasterboards that are sensitive to damage, use of plastic vapour barriers with unknown service life beyond 50 years and a risk that unprescribed connectors complicate deconstruction.

How the design could be improved with respect to deconstruction and reuse

New design concepts have been developed within the study as examples that illustrate what can be achieved. Three connections were modified to facilitate deconstruction and minimize the damage to elements caused by deconstruction. This change minimizes or eliminates the need for refurbishment of elements in factory prior to reuse.

These improvements were achieved with small adjustments in design and within existing technology. Other changes could also be envisaged, based on the identified strengths and weaknesses of the existing design.

Amount of wood that could be reused with the current design and with the improved design

The amount of wood that can be reused is relatively high already with the current design. More than 80 % of the wood could be reused with the scenario envisaged (deconstruction of the whole building and reuse of elements in an identical building). With the suggested new connections this figure would raise somewhat (from 82,7 % to 86,4 %).

How guidelines for deconstruction and reuse could be formulated for this object

Guidelines for deconstruction and reuse have been produced based on Morgan & Stevenson (2005) and include a mix of text, pictures and references to documents and files describing the design.

The case study method

The case study method was found to be simple and straight forward. The method led to focused discussions and new design solutions based on weaknesses and strengths in current design regarding DfDR. The method can be used more generally for assessing and improving other timber building structures.

4.2. Quality of and limitations in findings

In this section, we discuss the quality in our findings, the limitations in filling the identified gap in knowledge and the limits in generalization from the findings.

A single scenario studied

Within the frame of this work, one limited scenario for future reuse was studied. The design was assessed and improved for the scenario that the building will be taken apart to its original elements after several decades of use, and that the parts will be reused in an identical building in the future. Other scenarios could and should be studied too, as for example the scenario where the whole building is moved without deconstructing it (Figure 32). For that scenario, it is likely that there would be a different set of demands on the design. Assessing and modifying Villa Anneberg for that scenario would not necessarily lead to reversible wall-to-wall connections. More likely, there would be a need for a new ground structure and new connections wall-to-ground, to make the building easily detached and to produce less waste from the ground structure when the building is moved. The scenario might lead to a design where the concrete slab is replaced with a timber-based floor.

Figure 32 Buildings can be moved in their entirety as an alternative to demolition. The photo shows a two-storey timber building being moved in Kiruna. Image: Kiruna municipality

Consider design for adaptability and consider recycling

The study was limited to design for reuse. Equally, the design can be assessed to verify its potential to be adapted to new purposes in the future (that is, designed according to principles of Design for

Adaptability, DfA). Furthermore, we have not considered recycling. This study showed for example that the roof boarding will be wasted. If recycling was to be considered, roof boarding could have been considered as a material that can be used to produce particleboard. A ptoportion of wood could then be taken care of, than the around 85 percent that was found here.

Frame was studied: surfaces can be important

The load bearing structure was in focus here. Other studies could show how much of the *surface* materials that could be reused or recycled.

LCA and LCC should be studied

We focused here on *technical* design questions to solve to facilitate deconstruction and reuse. The study is also mainly qualitative. To get a picture of the environmental impact and costs with todays and improved designs, quantitative studies can be carried out, using life cycle analysis and life cycle cost analysis. (Such studies are in fact carried out in a separate part of the InFutUReWood project.)

Important key competences are represented, but assembly teams could contribute further

The study was carried out by industry and researchers in cooperation. In the analyses and discussions competences were represented to make sure that knowledge on production, logistics, structural engineering, customer needs and preferences was considered. One person participated who had deconstructed a Derome building, reassembled it and now lives in it.

It would have been preferable to have disassembly teams represented, but as buildings are not deconstructed in the envisaged way today there are no regular teams to include. Also, it would have strengthened the study and might have given new insights to have someone from an assembly team represented (even though Derome has good knowledge of the assembly process of the existing design).

This is a theoretical study: practical studies and verifications needed

The most obvious limitation of the study is that it is theoretical. Both strengths and weaknesses in design have been identified by discussions. New design concepts exist as drawings. No actual building has been built, deconstructed, moved, and rebuilt and no laboratory studies have been conducted.

To increase knowledge further, it should be verified with laboratory tests and field studies of ongoing deconstructions:

- That the assumed stages in a deconstruction process are relevant in practice. This would need to be studied by following an actual deconstruction on site.

- That whole/integral elements can be deconstructed and reused in practice: that damages are not more extensive than assumed here and that the fitting of a reassembled structure is satisfying.

- That a vapour barrier, placed within a wall between insulation layers, has a sufficient life span for reuse in a second building. This would demand a special study, for example using accelerated aging methods in laboratory.

- That the new design proposals work in practice. Especially, it should be confirmed that the proposed new connection floor-to-floor meets demands regarding acoustics and vibrations.

- That screws can be unscrewed with reasonable effort, time consumption and energy consumption. Preferably screw connections that have been subjected to loads for many years should be studied.

- How time-consuming it is to remove plasterboards and how much material you can expect to keep. There were, in our discussions, different opinions on this.

- That original gypsum plasterboards can be kept through deconstruction and in reuse, if a new 6 mm thick plasterboard is added to cover superficial damage.

Studies on connections

Further studies on connections should be carried out to find new innovative techniques adapted for deconstruction and reuse. We discussed if some form of mortice and tenon joint be used to join floor and wall, but this question would need a separate study. Also, using bolts is an option that was not examined here.

As this is a case study, there are "natural" limits in generalization

The results concern Villa Anneberg. The new connections developed might not be interesting to all other manufacturers, as they have their own solutions.

Still, the specific can illustrate the general. For example, the fact found here that unprescribed connectors can be an obstacle in deconstruction can also be found in literature (see Chisholm 2012). Other general facts were illustrated by the specific case, as the sinsitivity of plastic vapour barriers and gypsum boards being sensitive to damage.

Case study method did not make systematic use of ISO 20887 – a general set of principles

To identify the flaws in the design of Villa Anneberg with respect to DfDR, we used the simple method of imagining the future deconstruction work and reuse and discussing the problems that can be foreseen. Aspects were considered such as tools needed for deconstruction, damage that may occur to components and materials during deconstruction, need for reconditioning, repair, and controls, foreseen problems with transport or intermediate storage, foreseen waste and risks.

Alternatively, the design could be assessed according to *ISO 20887 Sustainability in buildings and civil engineering works — Design for disassembly and adaptability — Principles, requirements, and guidance*. Chapter 5 of the standard deals with principles relevant for design for disassembly (Table 6).

Table 6 Principles relevant for design for disassembly according to ISO 20887

Section in ISO 20887	***Short explanation/Portal section in ISO 20887***
5.3.2 Ease of access to components and services	Allows for a material, component, or connector to be easily approached, with minimal damage.
5.3.3 Independence ISO 20887 5.3.3	Allows parts, components, modules, and systems to be removed or upgraded without affecting the performance of connected or adjacent systems)
5.3.3.2 Reversible connections	Reversible connections can be disconnected and/or disassembled for easy alterations and additions to structures.
5.3.4 Avoidance of unnecessary treatments and finishes	Choice of finishes can limit the options for reusing or recycling the substrate, particularly if potentially hazardous substances are included. To support disassembly, finishes that can prevent the substrate from being re-used or recycled should be avoided. Finishes should serve a specific purpose, e.g. for fire and/or corrosion protection.
5.3.5 Supporting re-use business models	General This principle is concerned with supporting the market for re-used, refurbished, remanufactured and recycled materials and products now and in the future, in support of circular economy business models
5.3.5.2 Reusability	The ability of a material, product, component, or system to be used in its original form more than once and maintain its value and functional qualities to accommodate reapplication for the same or any purpose
5.3.5.3 Refurbishability	The ability to restore the aesthetic and functional characteristic of a product, building or other constructed asset- to a condition suitable for continued use
5.3.5.4 Remanufacturability	The ability of a product to be disassembled and refabricated at the end of its useful life in a manner that provides restoration to a condition suitable for resale
5.3.5.6 Future recycling (recyclability)	Recyclability is the ability of component parts, materials, or both to be separated and reprocessed from products and systems and subsequently used as material input for the same or different use or function
5.3.6 Simplicity	The quality of an assembly or system to be straightforward, easy to understand and meet performance requirements with the least amount of customization
5.3.7 Standardization	Standardization is concerned with the use of common components, products, or processes to satisfy a multitude of requirements
5.3.8. Safety of disassembly	Requires a disassembly plan that is considered at the onset of design

An attempt to use the ISO 20887 was made but was interrupted as it was too time-consuming for the time frame of this study. The attempt to assess parts or connections in the building lead to several questions and it became clear from the attempt that the standard needs to be interpreted.

Also, it would probably be necessary to choose which properties to assess. To evaluate five different main parts of the building and four connections with respect to the twelve properties of ISO 20887 listed in Table 4, more than a hundred considerations/decisions must be made.

To summarize, guidelines and aids that simplify an assessment are needed. To that end, an indicator system, a tool to assess the DfDR and DfA potential of buildings, was developed within InfutUReWood WP2 and is reported on separately (Sandin & Sandberg 2021, Zabala 2021).

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Appendix 1

Appendix 1 is an Excel document with the name “Villa Anneberg Appendix 1.csv” distributed together with this document.

Appendix 2

Strengths and weaknesses regarding deconstruction and reuse, thematized by building component.

	Strengths (properties to maintain)	Weaknesses (properties to improve)
General remarks		
	Industrial production with prefabricated planar elements 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 (does not harm them). They are used to thinking about the entire logistics chain. The process can be reversed; the company can sit down and think about it the other way around. 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. Systems for weather protection have not developed for this building concept as it is not needed in primary construction. As wood and wood-based elements are sensitive to moisture and deconstruction might be more time consuming than construction, there might be a need for weather protection during deconstruction.
The different parts		
ROOF	The roof-boarding comes in larger sections so it should be possible to deconstruct it in sections, that could be reused. If no moisture damage has occurred, the roof boarding should be technically reusable.	The roof-boarding is nailed to the trusses and the battens are nailed to the roof-boarding. Disassembly by tearing them loose with a crowbar means that parts get damaged.
ROOF TRUSSES	Can be lifted out in the same way as they are lifted in place. Easy to mount loops and lift with a crane. The constructions are robust and can be reused as they are. They can withstand the removal of roof-boarding and angle brackets and the lifting and transportation to a new site. It is probably possible to dismantle and lift all the roof trusses with roof-boarding in one single lift, as construction processes like that exist for new buildings.	The disassembly comprises several steps: removing tiles, battens, roof-boarding, extracting insulation and disassembly of roof trusses from external walls. If the building was designed with roof cassettes, disassembly could be done with fewer steps and be less time consuming. There is a risk that there are extra (not prescribed) nails in the structure. This can make disassembly time and energy consuming. Undetected nails might even cause danger if trusses are lifted while still being nailed to the walls.

GABLES	Can be lifted out in the same way as they are mounted and can be reused as they are. For uninsulated attics, studs are visible for visual inspection.	In deconstruction, it might be difficult or impossible to find the original holes and attach lifting loops in the same way as they were attached during original assembly. Nailing new pieces of wood to the gables on the inside will probably be necessary to have somewhere to apply lifting loops in a way that is safe. If the attic is insulated and the insulation is covered with board material, the frame is hidden for ocular inspection.
EXTERIOR WALLS, FIRST FLOOR	It is technically possible to disassemble, remove, transport and reuse wall elements in the same shape as they were inserted, with the surface layers left in place. There is a hypothesis that original lifting loops can be left in the wall to be reused in deconstruction, but this has not been confirmed; it might be debatable.	If you want to disassemble and reuse entire elements as they are, it generally applies that some parts are not visible and therefore cannot be inspected visually after disassembly. In a stick frame with plasterboards, the plasterboards are sensitive. Aesthetic problems will arise if the plaster is wrinkled during disassembly and transport. The elements contain vapour barriers. The service life of these are shorter than that of the studs. Also, they depend on taped joints for their air tightness. One might have to replace vapour barriers after disassembly to guarantee their function. This means that the wall element must be dismantled, which will be time consuming and cause waste. There are question marks over disassembly of screw joints, especially if they have been in use for some years: is it feasible in practice to unscrew screws? It is probably time consuming.
INTERMEDIATE FLOORS	The cassettes can be removed and transported in the same format as they were mounted and with the chipboard left on top.	At least the chipboard on top will be damaged during disassembly, as the connection between cassettes are glued screw connections. After unscrewing screws, the joint will be torn apart with a crowbar. Damages should be repairable but is yet to study how to do it.
EXTERIOR WALLS, GROUND FLOOR	See exterior walls on first floor.	