FÖRÜNN Å FÖRÜNN

[over and over again]

Exploring possibilities with timber buildings designed for disassemble

Sara Bergås & Ida Lundgren

Examiner: Krystyna Pietrzyk

Supervisor: John Helmfridsson

Department of Architecture & Civil Engineering

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CHALMERS

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Master Thesis Spring 2020

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Architecture and Planning Beyond Sustainability

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IDA & SARA

Our interest in sustainable solutions within architecture has been with us during our whole education. We have previous experience from investigating material life cycles, unconventional materials, traditional building techniques, wooden structures, and more. We are both from the northern part of Sweden, which has had a big influence on our interest in building with wood. The north is covered in spruce and pine, making it a big part of the region's identity.

The name förünn å förünn comes from the northern language of our home regions and means over and over again. The soon to be forgotten language is still spoken by parts of the older generation. The project name reflects our aim to keep building material in a material loop and use it over and over again.

ABSTRACT

Today, the building industry is forced to face large transformations to be able to reach the sustainable development goals set by Agenda 2030. This includes reducing CO_2 emissions, waste, and introduce a circular use of materials. Habits of sending large quantities of usable building material to landfills are simply not acceptable in a time of climate crisis. There are in fact several ways to retain the value of a material, by repairing, reusing and recycling, etc.

The purpose of this thesis is to challenge the conventional way of building by exploring the possibilities, and presenting practical ideas, on how to design for disassembly. A theoretical comparison of different prefabrication levels, timber building systems, and joints will indicate which buildings methods are able to prolong the lifespan of a building and its materials.

The case study housing-project of the thesis is part of a larger collaboration, together with RISE, Kiruna bostäder AB and LTU, made for the initiative Kiruna Sustainability Centre. The project is situated in the new city centre of Kiruna – a city in the middle of a great urban transformation.

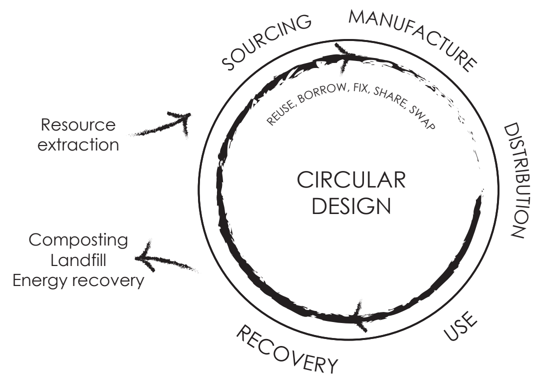

Figure 1. Circular economy diagram, with modification

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01.

BACKGROUND

Traditionally, materials are found in linear production lines, which means that after the first use, the materials are used for energy recovery or end up at landfills. This behaviour is highly resource-intensive and causes negative effects on the climate. In a circular system, materials are preserved by element reuse or material recycling.

Societies need to reduce the number of resources they harvest and use things more carefully and smart. Reducing the use of resources is a global challenge that needs to be considered in all working fields. Within architecture, designing for disassembly and reusing building materials are ways to contribute to a more resource preserving practice.

Figure 2. Lansink's Ladder, with modification

AIM

The thesis aim is to promote design that enables reuse of virgin building material. Thereby, the material can be used more efficiently and become a part of a circular economy. Within the structure of the thesis, we will present a theoretical comparison of different timber building methods, to conclude which method is most suitable when designing for disassembly. Further, our finding will be tested in a large scale housing project in Kiruna. The thesis means to influence not only architects but also self-builders, investors, and the industry.

THESIS QUESTIONS

How can we build and design with timber to promote reuse of building materials?

Which timber building methods are most suitable to use when designing for disassembly?

METHOD

A research for design method is used throughout the thesis, where Design for disassembly has been a guiding strategy. The basis for the theoretical part, chapter one and two, derives from literature studies and interviews with different actors within the timber building industry. Factors in the comparisons have been estimated by the authors of the thesis, after consultations and literature studies. The Swedish building sector's environmental calculation tool, BM1.0, have been used for the life cycle analysis, in order to find the Global Warming Potential (GWP) for each building system. The design project is a collaboration with several stakeholders. The evaluation of the theoretical comparison, as well as the project-specific demands, have influenced the chosen building methods.

DELIMITATIONS

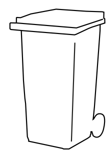
Timber has been the chosen material for the structural part, and no other material has been investigated. Virgin timber has been used to be able to focus on disassembly methods, thus, eliminate time spent on mapping and evaluating reused material. Due to the case study projects expected life length of +50 years, reuse of materials with a shorter expected life length have not been planned for. This includes fixed interiors, installations and exterior claddings. All challenges with reuse of building material haven't been solved within the thesis, such as transport and storage. Main joints of the building have been investigated and are designed to support a reuse concept.

Picture 1 and 2. Demolition site, Handelshögskolan in central Gothenburg, source: authors

THE SITUATION TODAY

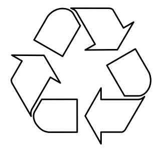
In Sweden, the building sector stands for 31% of the total waste produced (Boverket, 2019). Buildings that are being torn down long before their technical life length has expired are contributing to the high volumes of waste. The average life length of multi-family dwellings demolished between 1999 and 2018, was 55 years (SCB, 2018, Appendix 1).

According to C. Wikström and K. Gren at Miljörivarna, the increased charge on leaving unsorted material has caused the sorting and recycling of material to improve (personal communication, February 20, 2020). Today, 50% of all construction waste is considered recycled (Boverket, 2019), this is measured in weight, not in value. Concrete is typically recycled into road fill, reducing its value significantly. Concrete crushed into road fill has an average value of five euro per ton, a value 50 times lower than that of a new concrete element (Guldager Jensen & Sommer, p. 3, 2016). According to Guldager Jensen and Sommer (2016), almost all building waste today is being downcycled to the lowest value possible.



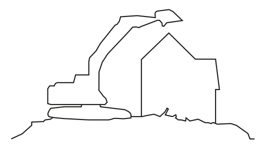
31%

Of the total waste produced orignates from the building sector



50 %

Waste recycled by the building sector



55 years

The avarage life length of dwellings

Picture 3. Restauration after a fire in Öjeby church village, source: authors

REUSED STRUCTURES

- HISTORICAL PERSPECTIVE -

LOGS & JOINTS

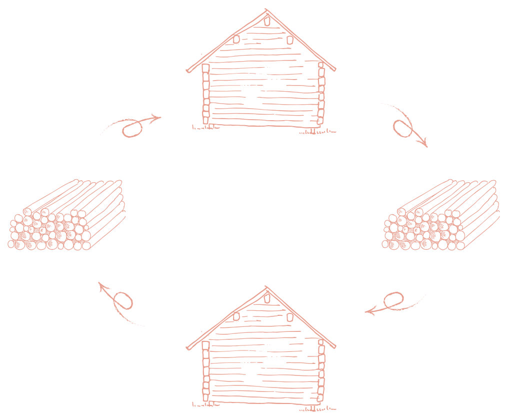
In the past, when people constructed buildings for themselves, it seems they thought of reusing existing material to a greater extent. Well protected structures, made with high-quality massive wood, and joints for disassembly, have enabled old structures to be reused.

NOMADS

The nomadic lifestyle has created a need for building structures to be easily disassembled. The material needs to be brought along when travelling through vast areas.

WHY BUILDINGS MOVED

Societal and technical developments could force buildings to be moved, such as the legislative change of how the land was divided (swe: Storskifte, Laga skifte). Buildings were either reused as it was, though at a new location or reused as parts in new construction (I. Sjölund, personal communication, February 18, 2020, Appendix 2).



REUSED STRUCTURES

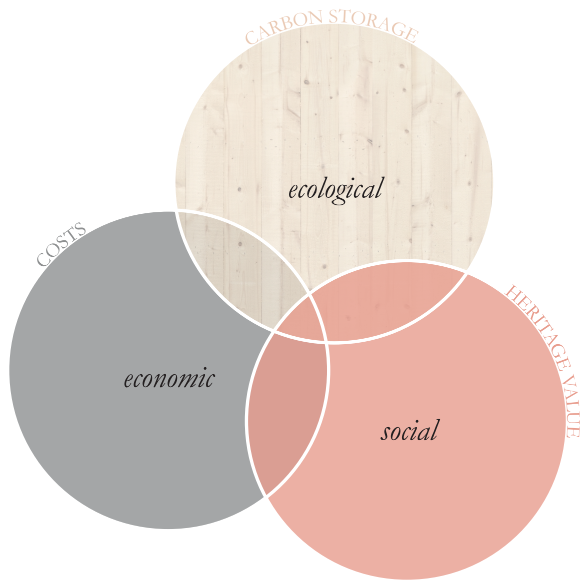
- POTENTIAL GAINS -

HERITAGE VALUE

Social values can be gained from using reused material, as it can contribute to a connection to past lived lives, and preserve architectural identity. It can also increase the sense of contributing to sustainable alternatives, both for the users, workers and commissioners involved.

CARBON STORAGE

CO_2 stored in buildings works as a carbon sink, and the longer it stays in the building, the better, as it keeps the CO_2 from being released to the atmosphere. From the production of the outer wall of our case study building, 32 tons CO_2 is emitted (Appendix 1). If reuse of the existing building material replaces a possible demolition followed by new construction, an equal amount of CO_2 is instead stored in the building. Though, the facade and the wind stopper boards may need to be changed after 50 years, which will give 7 tons of CO_2 emission (Appendix 1).



REUSED STRUCTURES

- POTENTIAL GAINS -

COST

In a circular economy, buildings can be seen as material banks, thus contributing to economical gains, when sold back to the market. In these calculations, the economical differences of demolishing a building, compared to disassembling it, is displayed. The case study project of the thesis has been used as a reference project to calculate costs and values. All costs and values are represented in today's pricing. However, the cost for demolition, disassembling and material values, are likely to increase during the building's life (Appendix 1).

**When calculating the disassembly cost, the cost for machines 5% and workers salary 24%, have been used, to illustrate the assembling of the building, but in reverse. This number might be too high since the dismantling does not require as much precision work and thus, is faster.*

***The material value has been calculated as 34 % of the building cost.*

Production cost/ appartment area	SEK/m²	37 861
Total area	m²	3331
Building cost	SEK	125,8 M
Demolition cost	SEK/m²	600
Total demolition cost	SEK	**-1,9 M**
Disassembly cost	SEK	36,5* M
Material value	SEK	42,8** M
Material net profit	SEK	**+6,3 M**
Difference demolition and disassembly	SEK	8,2 M

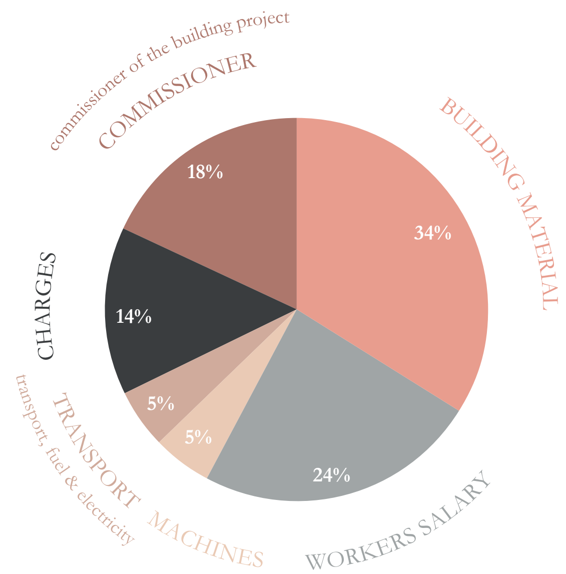


Figure 3. Division of building costs, data from SCB, 2020

REUSED STRUCTURES

- CHALLENGES -

STORAGE

A new building project can rarely find all the material needed from an ongoing demolition project close by. The building process often spans over several years, making it difficult to harvest material from another building directly. Therefore, when a building is demolished, the building material needs to be stored before it can find future use. Today, there are only a hand-full of actors on the market that store and trade second-hand building material.

ECONOMICS

According to Valter Samuelsson, (personal communication, February 16, 2020), who is a retailer of second-hand material, it is hard to sell things with little or no antiquity values, making them decline material from the last decades. For builders today, the cost of dismantling a building compared to demolishing it, is often very high. This is due to the fact that buildings today are not built to be reused, making it a time-consuming process.

"It's an economically hopeless business" - Valter Samuelsson

TRANSPORTATION

The building material to be reused needs to be transported, normally on a truck. This puts some limitations on how big and fragile the building, or building pieces, can be.

ENSURE QUALITY

All new products are tested and described before being released to the market. This lets the buyer know, for example, how toxic or tolerable a product is, before putting it to use. For used building material, this quality assurance can be a complicated and expensive process, making reuse of material an economic venture.

DESIGNING FOR DISASSEMBLY

- INTRODUCTION -

Designing for disassembly enables products to be taken apart into its individual components so that they can be reassembled, reused and recycled to new products of similar value. It is a necessity when moving into a circular economy as it ensures that the produced material stays in a closed material cycle.

There are some common rules to follow when designing for disassembly. For example, when two materials are joint together the connection has to be visible and reversible to ensure easy deconstruction in the future. It is also important to choose materials of high quality, that can be used for a long period of time.

By following these rules, the building becomes easy to refurbish and repair thereby, lowering the maintenance cost. It also contributes to a quick construction process. Last but not least, the building can be used as a future material bank, which is a profit not only for it's owner, but also the environment. (Guldager Jensen & Sommer, p. 41-42, 2016)

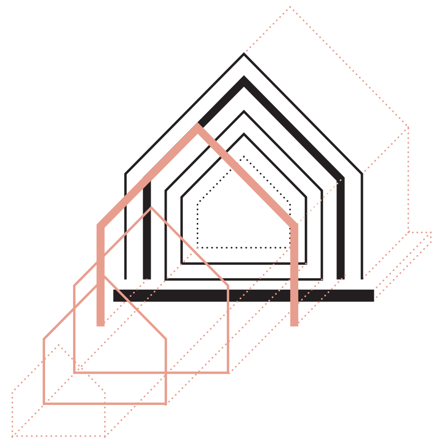


Figure 4. Shearing layers, with modification

DESIGNING FOR DISASSEMBLY

- SHEARING LAYERS -

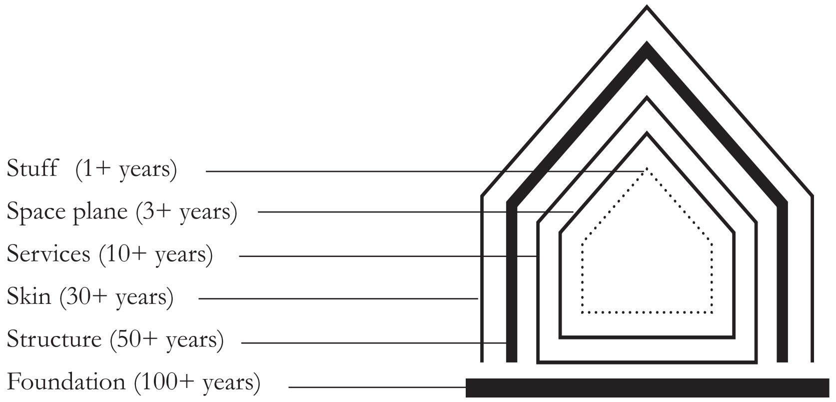
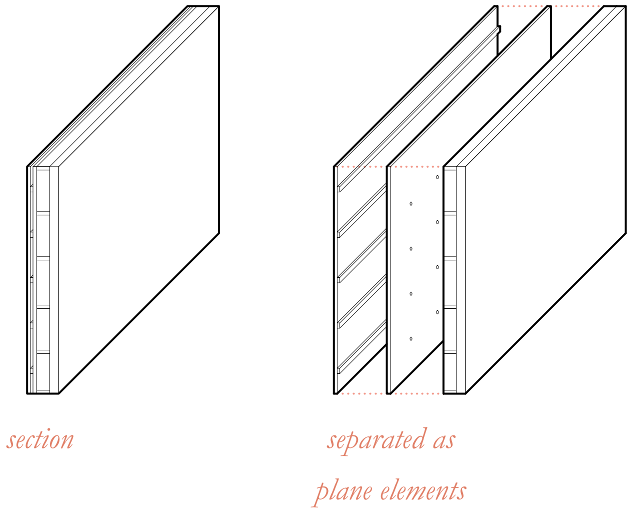


Figure 5. Shearing layers by Stewart Brand.

In 1995 Stewart Brand first described the different shearing layers of a building, divided by their estimated life length. When a building undergoes renovation, is rebuilt or has to be torn down, the different shearing layers have different capacity to be reused. By planning for easy separation of the layers, each layer can be reused to its full capacity. This method has been implemented for the case study project.



DESIGNING FOR DISASSEMBLY

- STRATEGIES -

FUTURE ADAPTABILITY

- Use standard dimensions
- Design high floor to ceiling height
- Use a low number of customized pieces
- Simplify material types
- Ease future transport logistics
- Design separable building layers for changing needs and maintenance

EASY REUSE

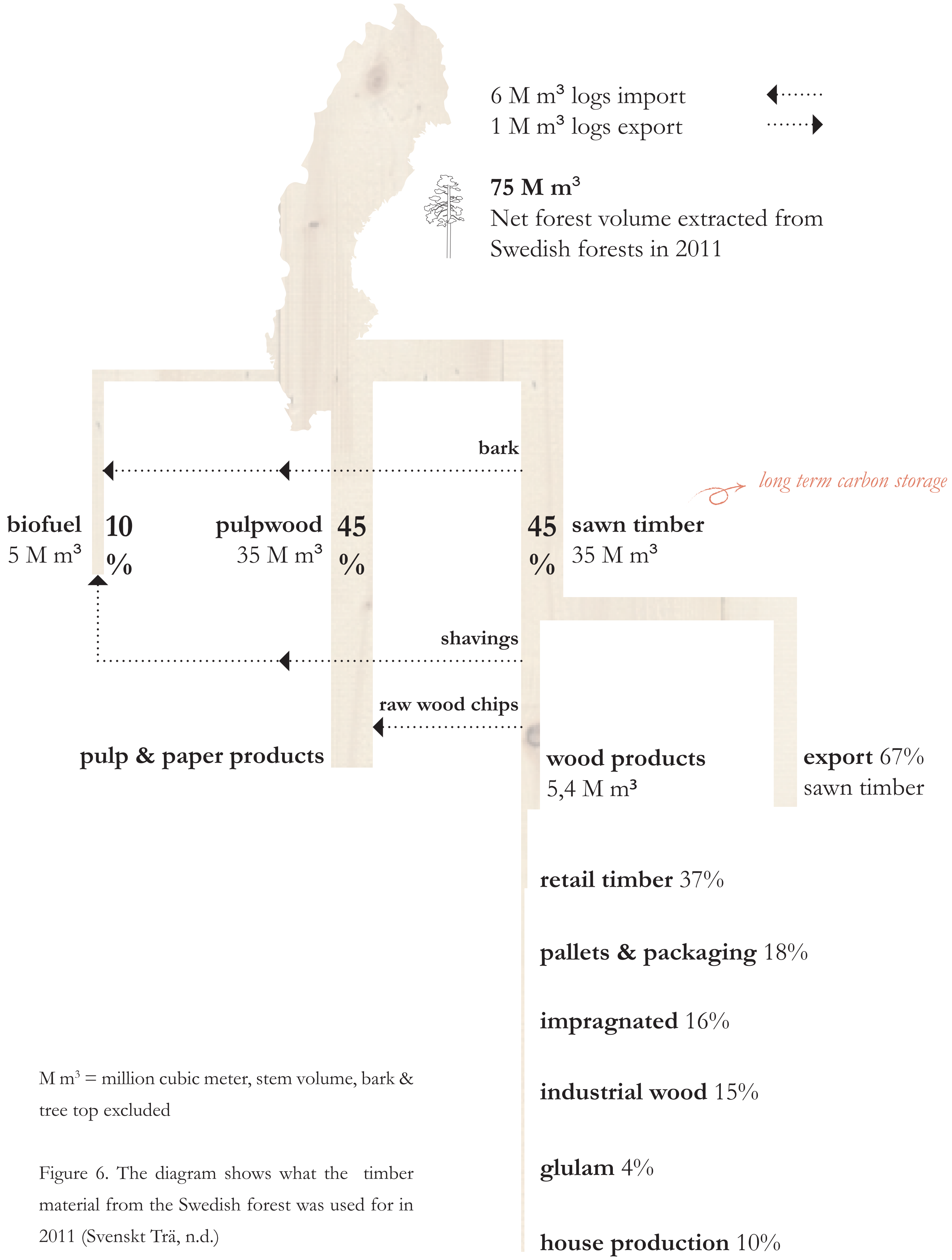
- Use accessible, tolerable and mechanical joints
- Use high-quality material, with a long expected lifespan
- Plan for easy separation of building layers
- Tag material with ID number
- Save instructive documentation

INTERIOR ENVIRONMENT

- Use healthy, non-toxic materials
- Plan for good indoor climate
- Visualise timber

ENVIRONMENTAL IMPACT

- Use renewable energy during production and transport
- Minimize building's embodied energy
- Design for durable aesthetics



M m³ = million cubic meter, stem volume, bark & tree top excluded

Figure 6. The diagram shows what the timber material from the Swedish forest was used for in 2011 (Svenskt Trä, n.d.)

WOOD

- SUSTAINABILITY -

Thanks to photosynthesis, trees, and other organisms capture carbon from CO_2 in the atmosphere and give back oxygen (Skogforsk, 2019). The Swedish forest captures approximately 40 million tons of CO_2 each year (Naturvårdsverket, 2019, A), this can be compared to the 60 million ton CO_2 Sweden emit each year (Naturvårdsverket, 2019, B). The amount CO_2 stored in one m^3 of wood during its lifetime (density 480 kg/m^3) is around 0,9 tons (Van der Lugt, 2012). It is important to understand that only when the global area of forests, and the total volume of wood in the built environment, are increasing, there will be extra carbon sequestration (Van der Lugt, 2012).

A research done by Esbjörnsson & Magnusson (2014) shows how the amount of CO_2 emissions during manufacturing is almost 40% lower in structures made of timber, compared to concrete structures. It also describes that a big part of the CO_2 emissions from a conventional timber construction originates from plastics, gypsum, and mineral wool. By eliminating the use of these materials the CO_2 emissions can be reduced by 63% in the timber construction.

10% of Sweden's wood products are used for house production, and more than half of the amount of the sawn timber is exported. (Svenskt Trä, n.d.). Meaning, there is great potential for using more timber within the country.

1,5 seconds

Time for the Swedish forest to regrow the material used in a house (Appendix 1)

40 %

less CO_2 in timber structures compared to concrete structures

Total length

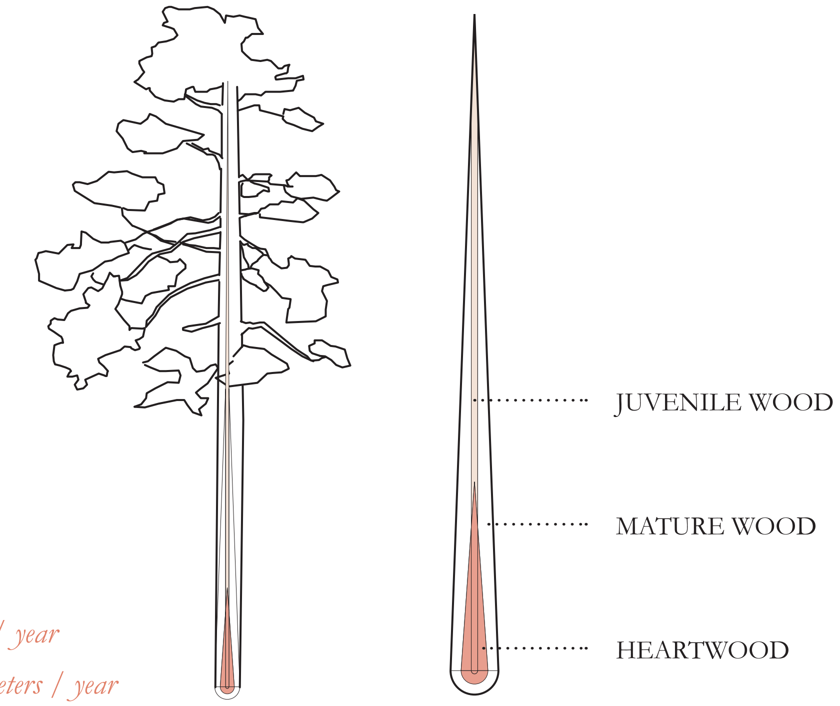
Spruce: < 40 m

Pine: < 30 m

Length growth

Young tree: > 500 mm / year

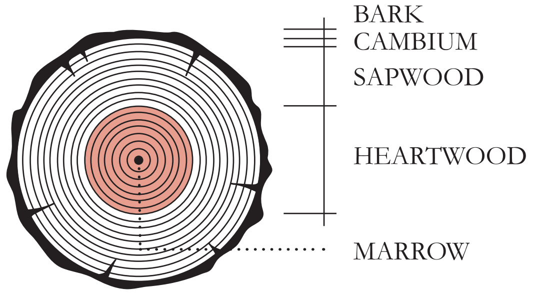
Mature tree: a few decimeters / year

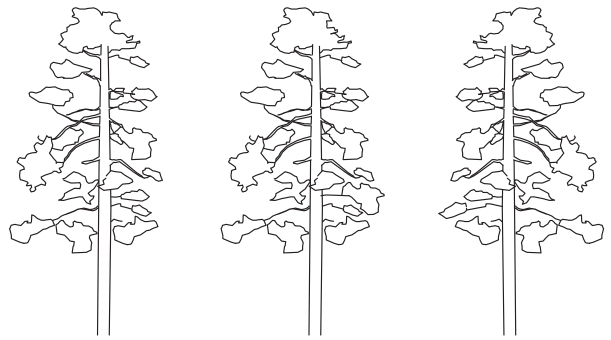


Diameter growth

Young tree: < 10 mm / year

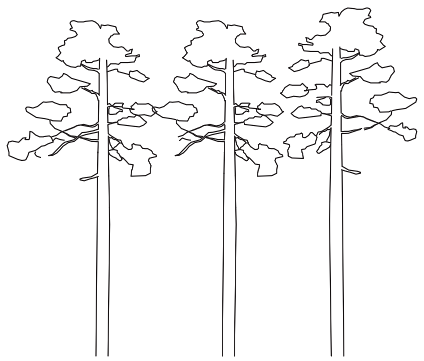
Mature tree: 2-3 mm / year





tree in a sparse stock

- robust branches



trees in a dense stock

- less branches

WOOD

- CHARACTERISTICS -

STEM STRUCTURE

The wood of the stem is divided into the outer sapwood and the inner heartwood. Water with nutritions from the ground are transported through the sapwood. As the tree ages, the older inner part of the sapwood fills with oils, gums, resins, and tannins. When the cells die, the sapwood has converted into heartwood (Berlyn, Everett, & Weber, 2020). This part of the log holds natural protection abilities and is of vital importance when using timber as a structural element; it will endure longer (I. Sjölund, personal communication, February 18, 2020). On the outside of the wood you find the cambium, which is the growth layer of the stem. It produces new wood cells inwards, and new bark cells outwards (Träguiden, 2017). Between the outer bark and the cambium, nutritions from the photosynthesis are transported (Berlyn, Everett, & Weber, 2020).

ANNUAL RINGS

The annual rings are defined by the springwood and summerwood. The springwood is visible as the brighter part of the annual ring compared to the darker summerwood. The colour is due to the density differences between the two, where summerwood is the denser one. The proportion of summerwood in the annual ring can affect the total density of a specific tree (Träguiden, 2017).

GROWTH & WOOD QUALITY

Trees in a sparse stock grow more robust branches, whilst the tree in a dense stock can grow more, but thinner branches, or in some cases no branches at all in the lower parts. The first 10-20 annual rings, closest to the marrow, compose the so-called juvenile wood. This part of the stem has lower strength and shrinks longitudinally (Träguiden, 2017).

Picture 4. Felling area, Granträsk - Nyby, Lycksele, 1921. Source: SLU, Skogsbibliotekets bildarkiv

Picture 5. River filled with timber, Sveg, 1916. Source: Ljusnans flottningsförenings arkiv

WOOD

- IDENTITY -

HISTORY OF THE FORESTRY

Sweden is a country with 68 % of its total area covered in forest (Skogskunskap, 2017). During the middle ages, the population in Sweden was sparse, and the impact these people did on the forest was low. For a long time, the forest was seen as an infinite resource and was expected to manage itself. In the 1700s, people started to talk about the need for forest management. For most people, timber was used as building material and firewood, whilst entrepreneurs used it as charcoal to fuel their ironworks. During the 1800s, sawmills, and paper and pulp industries, were established along the northern coastline. Timber was harvested from the inland forests and transported on the rivers to the coast. It wasn't until the 1960's people started demonstrating against the unsustainable forestry in Sweden. At that time the industry used chemical pesticides and the clear-felled forest areas had expanded, which led to protests. At the end of the 1900s, Swedish forestry started to handle questions about biological diversity and sustainable regrowth of the forest stock. (Skogshistoriska sällskapet, 2020)

WOOD HERITAGE

The large heritage of timber constructions in Sweden is not merely preserved as memories, but a lot of the structures can be seen and touched today. At Vänga church in Borås, there have been findings of constructive timber material that dates back to the 1000s. (Svenska Kyrkan, 2020).

68%

of Sweden's surface is covered in wood

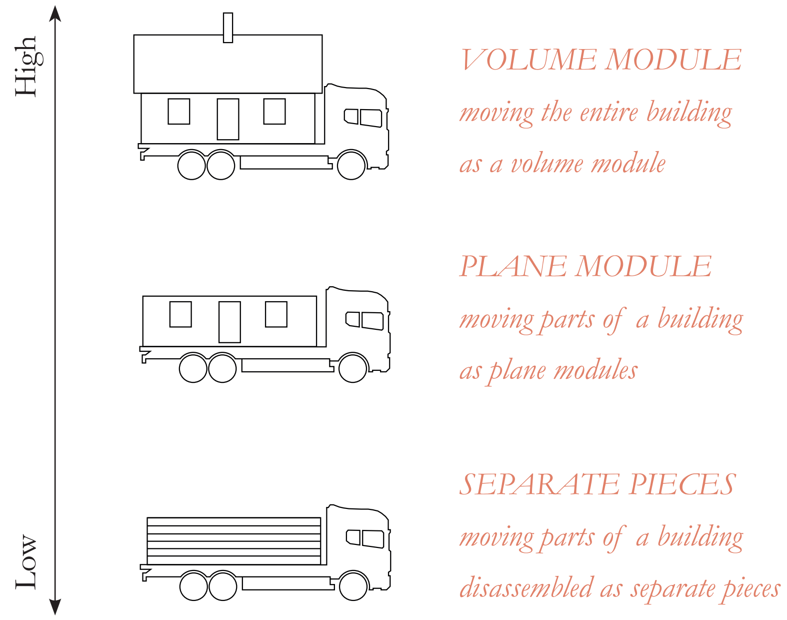
02.

BUILDING WITH TIMBER

This chapter consists of a theoretical comparison, divided into three different areas: prefabrication levels, building systems, and joints. A presentation of the specific area is followed by an in-depth comparison. The comparison aims to inform which building method is most suitable to use when designing for disassembly. The factors included in the comparison concerns reusability, environmental impact and plausibility within the Swedish building context.

The first area describes the pros and cons of different levels of prefabrication, which determines if the building is constructed on-site, or at a factory. In the second area, different building systems are explained, focusing on wall constructions. Last but not least is the comparison of different joints, including wooden joints and metal joints.

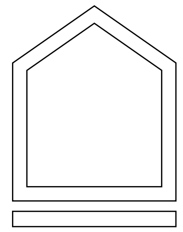
The estimated performances of the different building methods have been made after conversations with different actors in the building sector and through literature studies. Calculations and interviews regarding the estimations can be found in Appendix 1 & 2.



PREFABRICATION LEVELS

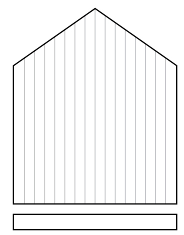
VOLUME MODULE

A weather-tight building volume that is prefabricated, often with ventilation, electricity, interior fixtures and claddings. The volumes are transported to the building site, where they can be stacked to create a finished building.



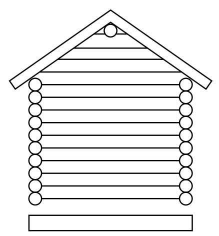
PLANE MODULE

A prefabricated solid wall, slab or roof element, that can be load-bearing and to some extent insulating. The plane modules need to be assembled to form a protecting shell against the weather.



SEPARATE PIECES

A building system with separate load-bearing pieces. Often complimented with insulation and facade to get a weather-tight shell. More time consuming than the other methods.



our choice

REUSE FACTOR:	**Volume module**	**Plane module**	**Separate pieces**
Prefabrication Level (P L)	high	medium	low
Assembly/Disassembly Time (A/D T)	good	ok	poor
Architectural Expression (A E)	poor	good	good
Future Design Adaptability (F D A)	poor	ok	good
Transportation (T)	ok	ok	good
Long estimated Lifespan (L L)	poor	good	good
Large Building Scale (B S)	good	ok	poor
Cost (C)	low	medium	high

preferred

ok to use

least preferred

COMPARISON

- PREFABRICATION LEVELS -

COMMENT:

P L — The more that is constructed at a factory before the assembling on-site, the higher the prefabrication level.

A/D T — A fast on-site construction gives shorter assembly/disassembly time, as well as lower building costs.

A E — Small building elements have the ability to create a larger diversity of architectural expression. Large and similar building elements can be found as repetitive.

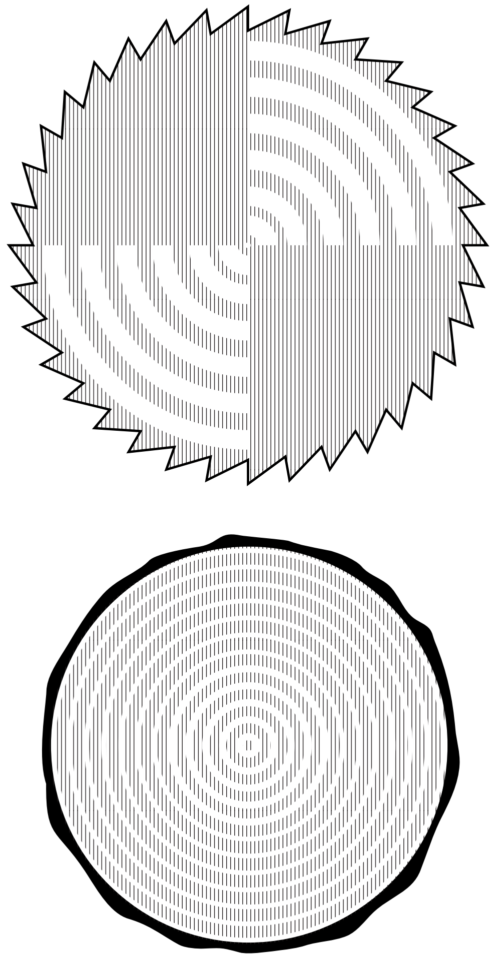
F D A — Building codes change over time, the longer time between a buildings reuse the harder it is to predict.

T — Larger modules may require specialised transportation, which can affect the cost and is hard to transport to a tricky site. Similar pieces can be stacked efficiently, which is helpful when it comes to logistics.

L L — With a long life span, the factor of future design adaptability becomes important to consider, since the function, building regulations, and living habits, may change over time.

B S — Large building scale projects are sensitive to the cost of on-site constructions. In small building scale projects, the assembly/disassembly time becomes of less importance.

C — Today, the cost is probably the most important factor to consider when designing for disassembly. Due to the increasing charge for labour, the disassembly time has to be short.



BUILDING SYSTEMS

When building with timber, there are multiple systems and techniques that can be used. This comparison will include seven different ways of constructing with timber, and present a typical wall section of each building system. The building systems included are a mix of old traditional techniques, conventional methods, and newer systems on the market. All building systems have been adjusted to a low U-value of 0,15, to make the comparison easier.

Volume module:

Stud frame

Plane module/separate pieces:

Glulam post & beam

Stud frame

Plane module:

Cross laminated timber

IsoTimber

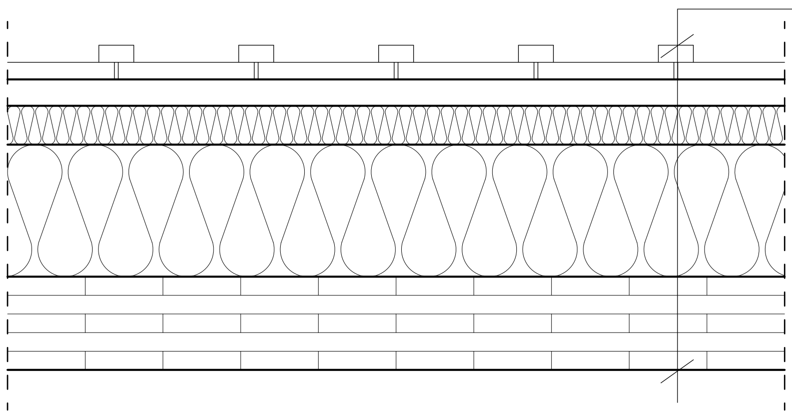
Separate pieces:

Log construction

Bosum building system

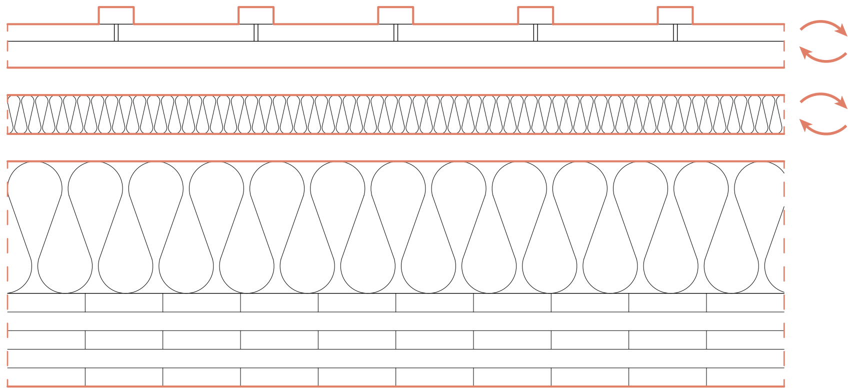
Picture 6. From Martionson's production line of cross laminated timber, Bygdsiljum, source: authors

DETAIL WALL SECTION - CLT 120



	$kgCO_2/m^2$
lath panel 22mm	0,1
panel 22mm	0,6
batten 34 x 70 mm	0,1
wind board 50 mm	3,5
horizontal studs &	0,4
insulation 45 x 170 mm	6,7
vapour barrier	0,3
CLT 120 mm	7,7
Total GWP/m²	19,4

PLANE MODULES SEPARATED FOR TRANSPORT



the loadbearing clt element is complemented with insulation and a facade, no interior cladding needed

standard dimensions (mm)
width: max 3000
length: max 16 000
thickness: 60-280

CROSS LAMINATED TIMBER

- PLANE MODULE -

BUILDING TECHNIQUE

Cross-laminated timber (CLT) is a wooden element, that is premade in a factory using computer numerical control (CNC), which ensures a high precision product, ready-made with customized adaptations. This makes the building element easy to assemble into a weather-tight shell. The material can also be adjusted with tools on site. CLT is most commonly manufactured as plane modules, but can also be made as a volume at the factory (Martinsons, n. d.).

MANUFACTURING

CLT consists of massive timber planks, that are glued together with every other layer placed perpendicular to the previous layer. The combined timber elements create large span rigid plates that can be cut with holes for windows, doors and other adaptations to enable fast erection on site. Cut out pieces are used to fuel the manufacturing. The CLT elements typically require lower quality wood than compared to wood used in Glulam (L. Lundberg, personal communication, February 19, 2020).

PRODUCT PROPERTIES

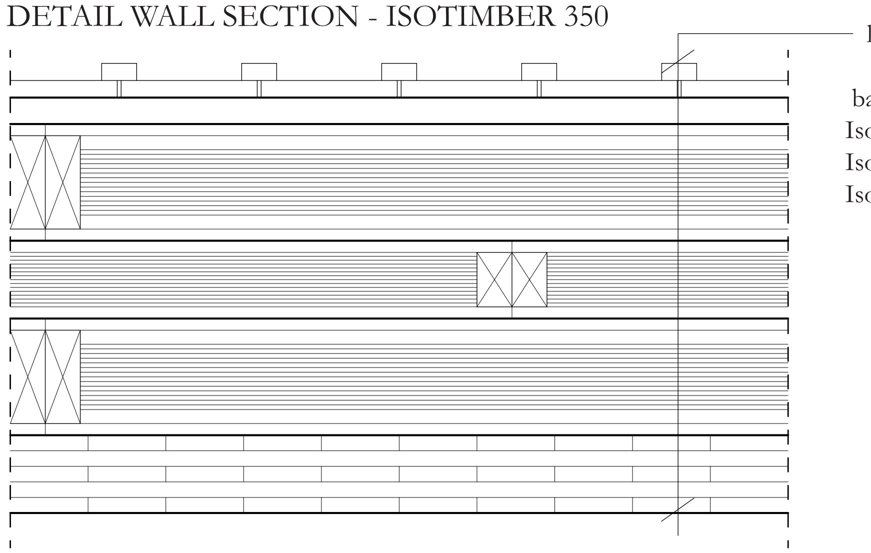
Thanks to the cross lamination, the product can tolerate heavy loads and offer large spans. The CLT element remains rigid even when exposed to moisture. Timber has a relatively low density compared to other structural building materials, such as concrete. Therefore, taller buildings requires to be anchored down, due to the uplifting force caused by wind. Thanks to the hygroscopic properties, the material contributes to a comfortable indoor climate (Martinsons, n. d.).

USE

The rigid plate enables CLT to be used for walls, slabs and roofs. The CLT can be left exposed to the interior, thereby, eliminating the use of plasterboards.

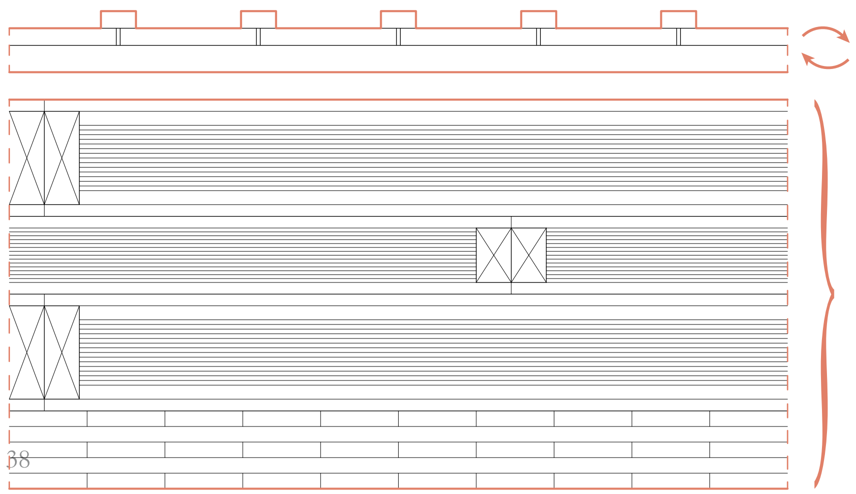
Picture 7. IsoTimber wall section, source: IsoTimber

DETAIL WALL SECTION - ISOTIMBER 350



	$kgCO_2/m^2$
lath panel 22 mm	0,1
panel 22 mm	0,6
batten 34 x 70 mm	0,1
IsoTimber 150 mm	6,8
IsoTimber 100 mm	4,8
IsoTimber 150 mm	6,8
CLT 100 mm	6,4
Total GWP/m²	25,6

PLANE MODULES SEPARATED FOR TRANSPORT



standard plane (mm)
width: 1200
length: 2400
thickness: 60, 100, or 150

the building blocks are layered to create different thicknesses, which affects both the load bearing as well as the insulating ability

ISOTIMBER

- PLANE MODULE -

BUILDING TECHNIQUE

IsoTimber has a pending patent for its building technique. The factory-made elements are quick to form a weather-protected shell. The elements can be assembled at the specific site at any time of the year (IsoTimber Holding AB, 2017).

MANUFACTURING

IsoTimber consists of stacked timber planks that are milled with small air pockets creating a load-bearing and insulating building material. The milled timber elements are held together with glue and plywood boards. Holes for windows, doors and other adaptations are made directly in the production line. Cut out pieces are puzzled into wall elements, thereby, siqnificantly reduing waste. Today the timber is harvested in Piteå and later transported to Hammerdal, Jämtland county, where manufacturing takes place, which is close to their main factory in Östersund (IsoTimber Holding AB, 2017).

PRODUCT PROPERTIES

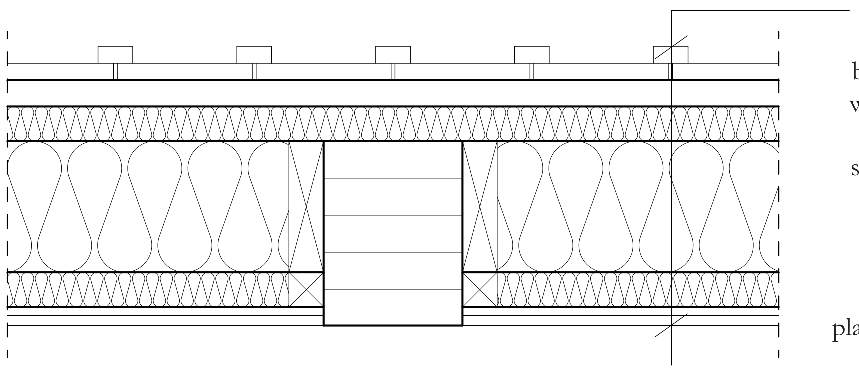
The large number of air pockets give the block's its good ther-mal insulation value. Similar to other massive timber constructions the hygroscopic properties of the material contributes to a comfortable indoor climate. Tests have shown that the product remains rigid even during a fire. To achieve the same insulation values in solid wood, the wall thickness has to be doubled (IsoTimber Holding AB, 2017).

USE

Mainly used for outer and inner walls, and can carry the load of a two-story building. To be able to build higher, the IsoTimber needs to be constructed with an added layer of a load-bearing structure, preferably a CLT element (IsoTimber Holding AB, 2017).

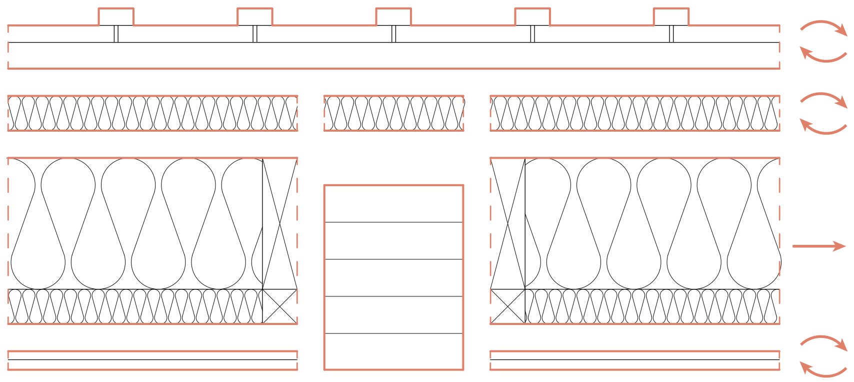
Picture 8. Gluelam beams from Martinsson factory in Bygdsiljum, source: authors

DETAIL WALL SECTION - GLULAM



	$kgCO_2/m^2$
lath panel 22 mm	0,1
panel 22 mm	0,6
batten 34 x 70 mm	0,1
wind board 45 mm	3,1
insulation &	6,7
studs 45 x 170 mm	0,4
vapour barrier	0,5
insulation &	1,8
studs 45 x 45 mm	0,1
OSB 11 mm	1,0
plaster board 13 mm	3,0
glulam 240 mm	0,7
Total GWP/m²	18,1

PLANE MODULES SEPARATED FOR TRANSPORT



glulam posts & beams work as the loadbearing structure, where the in fills are ballon frame plane modules for the walls

GLULAM POST & BEAM

- PLANE MODULE/SEPARATE PIECES -

BUILDING TECHNIQUE

The glulam post and beam is used as the load-bearing part of a structure and has done so for a hundred years. The gaps between the posts need to be filled in order to get a weather-tight shell. The joints can be constructed in various ways.

MANUFACTURING

Glulam consists of massive timber planks, glued together, creating a strong building element. The post or beam is manufactured at the sawmill, from tree to finished product. It can be manufactured in both straight and curved forms. In Sweden, fir is used for manufacturing, but other tree species are available internationally (Martinsons, n. d.).

PRODUCT PROPERTIES

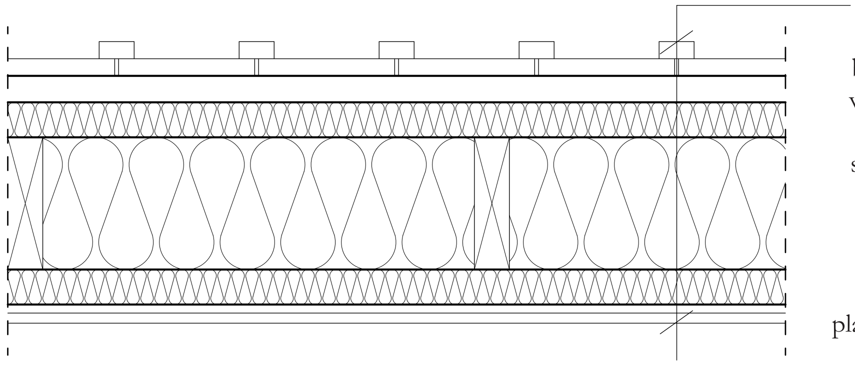
Glulam is an effective product as it can take great loads and is very strong in relation to its weight. The material is stable in its form and doesn't turn and curve after time. A correctly dimensioned building element can be fire resistant for a long period of time, as the timber burns, but very slowly.

USE

Glulam can be used in small and big buildings, in walls, slabs and roofs to handle great loads over long spans. It is also frequently used as the load-bearing structure in bridges (Träguiden, 2018)

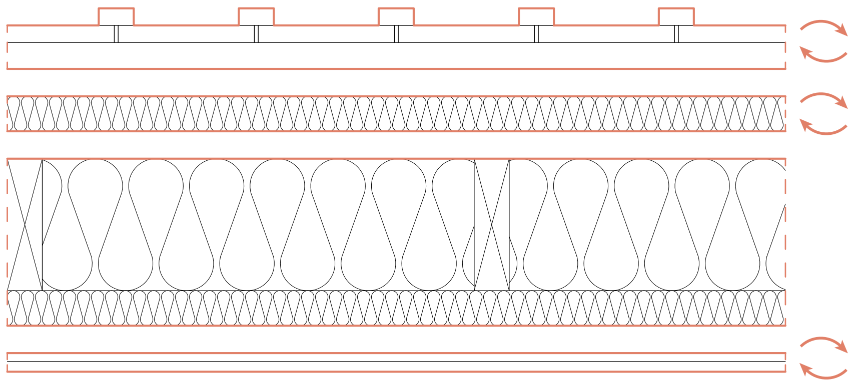
Picture 9. Stud frame timber structure, source: OCH Thermé.

DETAIL WALL SECTION - STUD FRAME



	$kgCO_2/m^2$
lath panel 22 mm	0,1
panel 22 mm	0,6
batten 34 x 70 mm	0,1
wind board 45 mm	3,1
insulation &	6,7
studs 45 x 170 mm	0,4
vapour barrier	0,5
insulation &	1,8
studs 45 x 45 mm	0,1
OSB 11 mm	1,1
plaster board 13 mm	3,2
Total GWP/m²	17,7

PLANE MODULES SEPARATED FOR TRANSPORT



the stud frame can be constructed at site with separate pieces or prefabricated as a plane module

STUD FRAME

- PLANE MODULE/SEPARATE PIECES -

BUILDING TECHNIQUE

The building system of the Stud frame derives from the traditional timber framing, but instead of using massive timber for pillars, construction timber is used. The studs are most commonly placed with a fixed centre distance of 600 or 450 mm, except where doors, windows or other openings will be placed. An insulating material is put between the studs, and OSB or plasterboards, cover the insulation. If it is an outer wall, it is fronted with a facade material (Träguiden, 2019).

MANUFACTURING

Standard dimensions of construction timber are sawn at the sawmill and transported to retail stores, where it is bought for each specific project. The thickness of the studs must be at a minimum 45 mm, in stabilising walls, while the width can vary from 95-220 mm. The load-bearing and insulating constructing are sealed with OSB and/or plasterboards. Typically, the stud frame is constructed with separate pieces at site (Träguiden, 2019).

PRODUCT PROPERTIES

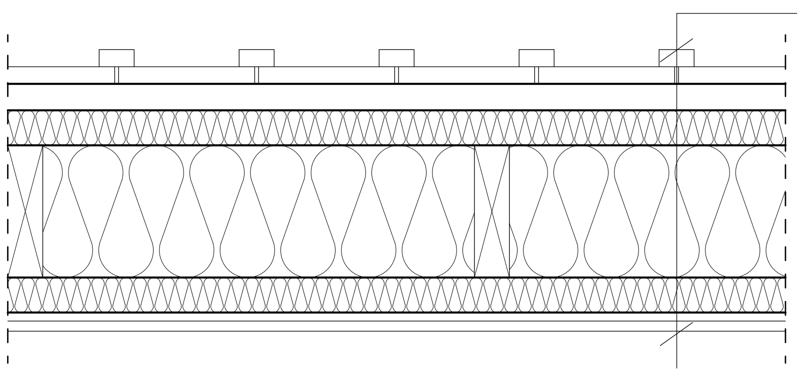
The stud frame is a relatively easy and well-known building system in the Swedish context. It is a high performed wall, achieving all basic demands, with a low amount of constructive material, making the construction lightweight. When used as a plane module, the length of the wall is only limited by transport as the manufacturing has no technical limits. Installations, such as electricity and plumbing, are easy to hide inside the structural wall (Träguiden, 2019).

USE

A stud frame structure can be used as both outer and inner walls; in smaller buildings as well as complement in larger structures.

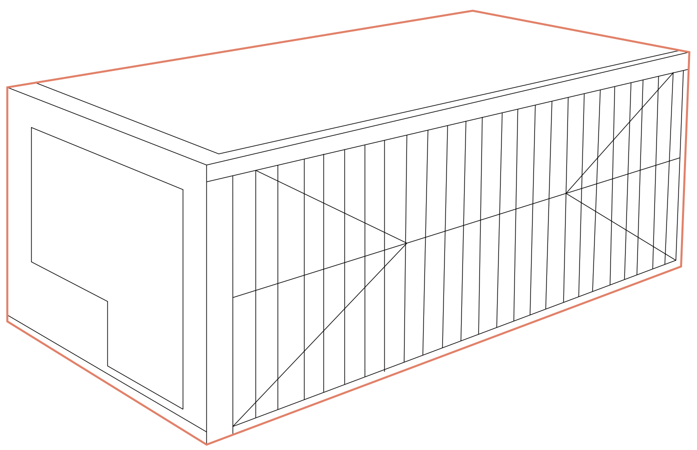
Picture 10. Volume modules in the production line at Lindbäcks factory, source: Lindbäcks Bygg AB

DETAIL WALL SECTION - BALLON FRAME



	$kgCO_2/m^2$
lath panel 22 mm	0,1
panel 22 mm	0,6
batten 34 x 70 mm	0,1
wind board 45 mm	3,1
insulation &	6,7
studs 45 x 170 mm	0,4
vapour barrier	0,5
insulation &	1,8
studs 45 x 45 mm	0,1
OSB 11 mm	1,1
plaster board 13 mm	3,2
Total GWP/m²	17,7

VOLUME MODULE READY FOR TRANSPORT



The volume module manufacturer Lindbäcks buy all timber cut in the correct dimensions, which gives them low timber waste at the factory

STUD FRAME

- VOLUME MODULE -

BUILDING TECHNIQUE

A volume module is a prefabricated building system. The load-bearing body can be made in various materials. In Sweden, the most common building system is the stud frame, but cross-laminated timber can also be used. The volume modules are stacked next to, and upon each other, to form a complete building. For a smaller building, one volume can be enough. The volume modules can be completed at the factory with slabs, walls, ceiling and fixed interiors (Lindbäcks, n. d.).

MANUFACTURING

Building material is transported to the factory for assembly, before being transported as a module to the building site. The modules can be manufactured as followed: Project development - investigation, planning and purchasing - production at the factory - production at the site - delivery to client - service and management (Lindbäcks, n. d.).

PRODUCT PROPERTIES

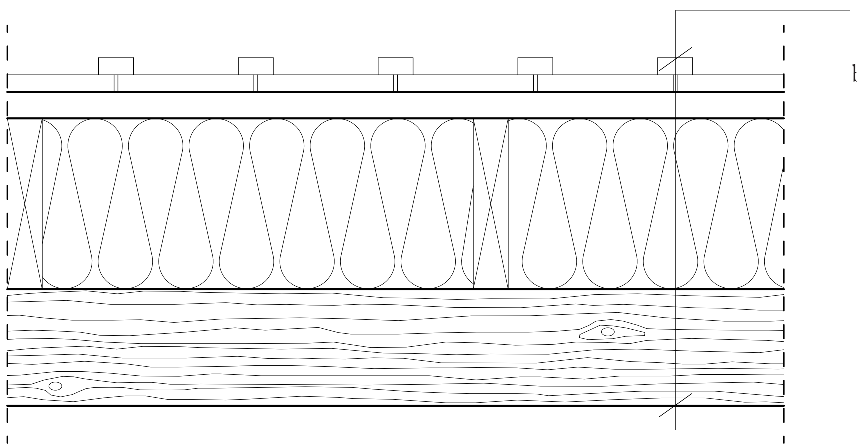
Large structures become easier, faster and cheaper to build when using volume modules. In some cases these are positive qualities for a project. Having a volume module using timber to compete with similar products, but which uses concrete is good for the market and for actors to have the possibility to choose sustainable alternatives (Lindbäcks, n. d.).

USE

Volume modules can be used as parts of a larger volume, but a villa or a smaller structure can also be prefabricated as a volume module.

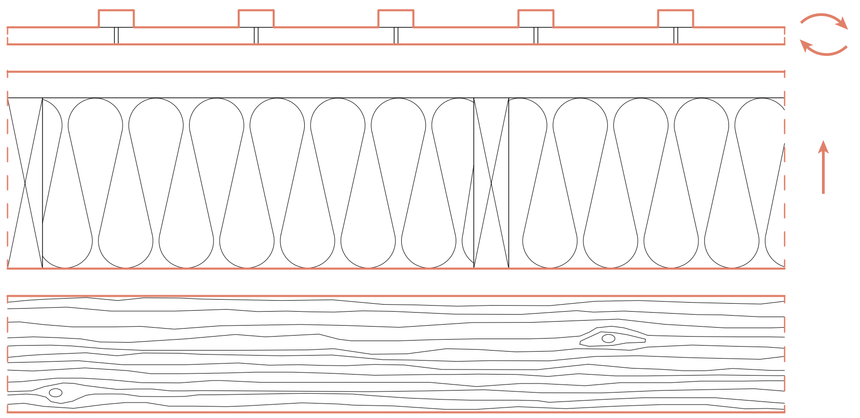
Picture 11. Two common corner joints found in the church village of Öjebyn, Piteå, source: authors

DETAIL WALL SECTION - LOG HOUSE



	$kgCO_2/m^2$
lath panel 22 mm	0,1
panel 22 mm	0,6
batten 34 x 70 mm	0,1
wind stopper	0,5
insulation	8,7
& stud 220 mm	0,6
log	3,7
& flax 150 mm	0,0
Total GWP/m²	14,2

SEPARATED FOR TRANSPORT



the log can be 150 mm in diameter if you add insulation and a facade. If no insulation is wanted, the massive log needs to be 250 mm in diameter, to achieve similar insulating properties

LOG CONSTRUCTION

- SEPARATE PIECES -

BUILDING TECHNIQUE

The technique uses horizontal logs, stacked upon each other, where the corner joints are stabilising the structure. Dowels are put in drilled holes between two logs, preventing the logs from separating. When stabilising the logs in an opening, such as a window or a door, a track is cut out (swe: gåt) to make room for a T-shaped plank (swe: svärd) (Af Malmborg & Månsson, 2016). It's highly important to air tighten between the logs to prevent drafts. On each layer, either moss or flax is used to create an airtight structure (Gudmundsson, 2001).

MANUFACTURING

The tree needs to be grown in a dense forest stock and for a long time in order to ensure high-quality timber, with a big amount of heartwood. After the material has been transported to the building site, a log carpenter shapes the log with a traditional broad-axe. If the timber is shaped in forehand with a chainsaw, the carpenter finishes the shaping with the axe. After that, all joints are sawn and/or carved out from each log (I. Sjölund, personal communication, February 18, 2020).

PRODUCT PROPERTIES

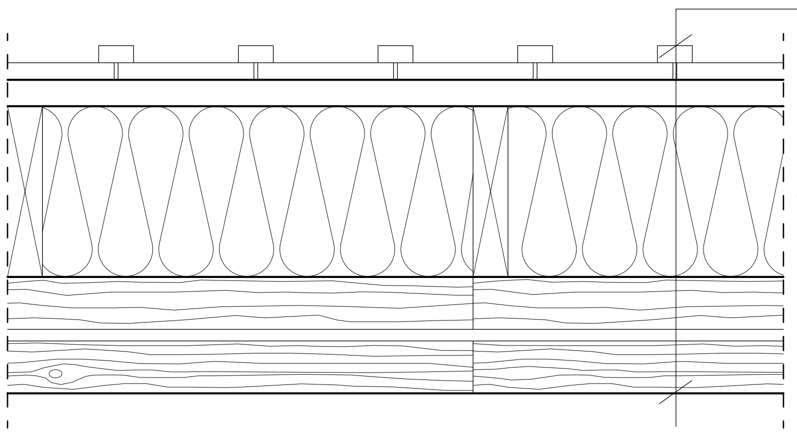
This technique is proven to endure for a long time, if it is well protected. Massive wood has the capability to slowly store and release heat. The assembly technique, using only the logs with shaped corners and dowels, are easy to disassemble and reuse again. The log technique is also a building and architectural heritage in the north (I. Sjölund, personal communication, February 18, 2020).

USE

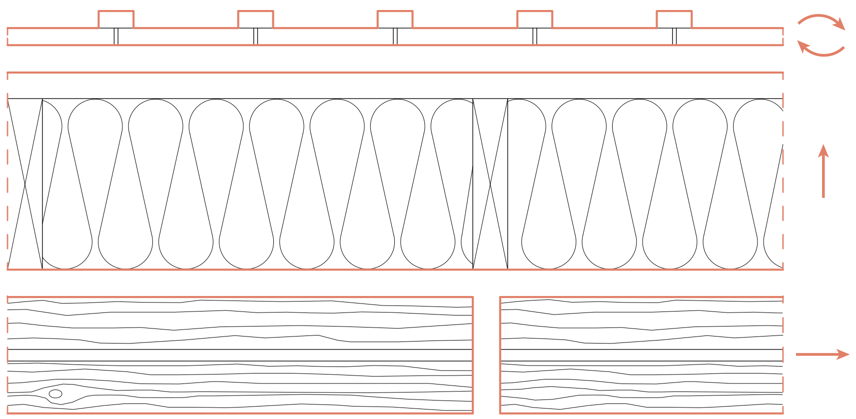
The technique is used for load-bearing walls, mostly seen in barns, farm buildings, and private housing.

Picture 12. Bosum building system, assembling at building site, source: Bosum AB

DETAIL WALL SECTION - BOSUM



SEPARATED FOR TRANSPORT



BOSUM BUILDING SYSTEM

- SEPARATE PIECES -

BUILDING TECHNIQUE

Bosum building system consists of massive wooden blocks, put together with plywood strips. Heartwood from pinewood is used for the blocks. It is typically supplemented with 100-145 mm cellulose insulation, a vapour barrier and a facade material. Two floors is the maximum building height (P. Malmberg, personal communication February 4, 2020).

MANUFACTURING

The massive wood blocks are produced at the sawmill in Ballingslöv, Hässleholm, Skåne, where they are dimensioned and milled with cuts (P. Malmberg, personal communication February 4, 2020). The blocks leave the sawmill with 18 % moisture content, compared to the normal moisture content of 16%. Bosum building system is similar to the log construction but with more connecting pieces, thus the sealing is solved with a plastic vapour barrier and insulation (Bosum, n. d.).

PRODUCT PROPERTIES

Heartwood is hard, durable and does not absorb as much moisture as sapwood does. It contains a lot of natural impregnation agents and can thereby resist decay and provide good fire resistance (Berlyn, Everett, & Weber, 2020). There is no set life length for the house. If management is done correctly the company refers to old timber buildings from 1200. The plywood strip isn't needed structurally when the construction is built and completed. Its function is to steer the woodblock during the assembly (P. Malmberg, personal communication February 4, 2020).

USE

Used in small houses, as both outer and inner walls.

our choice

FACTOR:	CLT	Iso-Timber	Stud frame	Log	Glulam	Bosum
GWP *kg CO_2/ m²*	+19,4	+25,6	+17,7	+14,2	+18,1	+14,3
Carbon Sequestration* *kg CO_2/ m²*	-72,5	-213,8	-21,4	-86,2	-35,9	-86,2
Cost (C)	medium	high	low	medium	medium	medium
Thickness (TH) *mm*	418	578	362	449	362	448
U-value (U) *W/ m²K*	0,15	0,15	0,15	0,15	0,15	0,15
Specialized Pieces (S P)	high	medium	medium	medium	medium	low
Separation Building Layers (S B L)	good	good	poor	good	ok	good
Number of Materials** (N M)	3	1	5	4	5	3
Waste During Manufacturing (W D M)	medium	low	medium	medium	medium	medium
Visible interior Timber (V T)	yes	yes&no	no	yes	no	yes

preferred

ok to use

least preferred

** 1 kg wood stores ~ 1,875 kg CO_2 (Van der Lugt, 2012), 50 % can be counted as long term storage (J. Helmfridsson, personal communication, April 29, 2020)*

*** nails & screws not included, wood facade in all examples*

COMPARISON

- BUILDING SYSTEM -

COMMENT:

GWP — The Global Warming Potential (GWP) looks to greenhouse gases and how they affect global warming.

CO_2 S — Carbon Sequestration refers to how much CO_2 is stored in the wood in each building system. IsoTimber stores the most CO_2, due to its high amount of timber in its structure.

C — IsoTimber and Bosum are not yet conventional building systems, which can have some impact on the cost. CLT has become a useful alternative when building large scale projects, even though Lindbäcks and the stud frame is still unbeatable when it comes to the lowest costs.

TH — The stud frame is material-efficient and highly insulating, even in thinner dimensions. The thickness of the wall is especially important to consider when m² are scarce, as it affects the rentable area of the project.

U — A fixed U-value have been chosen to be able to compare the preformance of the different building systems. This causes GWP, carbon sequestration and thickness to vary.

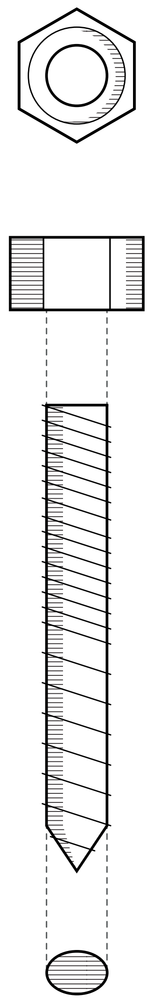
S P — A low number of specialized pieces gives a higher future design adaptability. Both CLT and IsoTimber have fixed holes for openings while Bosum building system has almost no specialized pieces.

S B L — In a stud frame, plasterboards are often used together with wallpaper or paint as interior cladding. This layer is hard to separate without damaging it.

N M — Reducing the number of materials used in a building will help the separation and sorting process at the end of the building's life.

W D M — Log and Bosum have the least waste of wood during manufacturing. Waste from plastics and insulation are often produced when assembling a wall, since IsoTimber has wood as insulation and no vapour barrier the waste is lower.

V T — By exposing the timber structure, plasterboards and paints, which have a big environmental impact, can be excluded. High amounts of visible interior timber require sprinklers. A structure with IsoTimber can have visible timber when CLT is added.



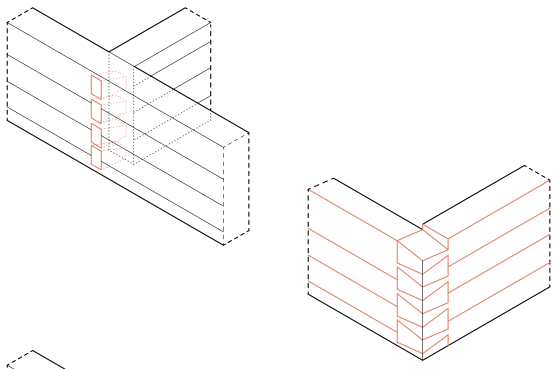
JOINTS

Joints are commonly considered ugly, therefor, they are often hidden in different ways. This includes covering with paint, wall fillers, boards etc. However, in this comparison, we will not evaluate the aesthetics of each joint. When designing for disassembly access to the building's joints is a necessity, regardless of its looks. Choosing a high performing joint is a crucial factor when designing for disassembly. If a joint complicates the disassembly, the building components, and even the joint itself, may take damage, causing the components to be sawn into pieces or broken apart. With wrong joints in place, a disassembly can become costly or even impossible to implement.

Several joints, both based on wood and metal, will be presented. The chosen joints are compared by its reversibility, strength, self instructiveness, and more.

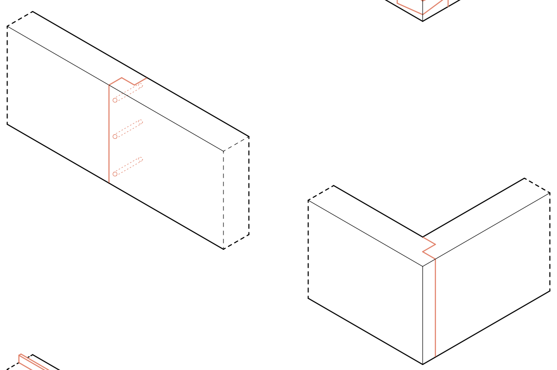
WOODEN JOINTS

- JOINTS -



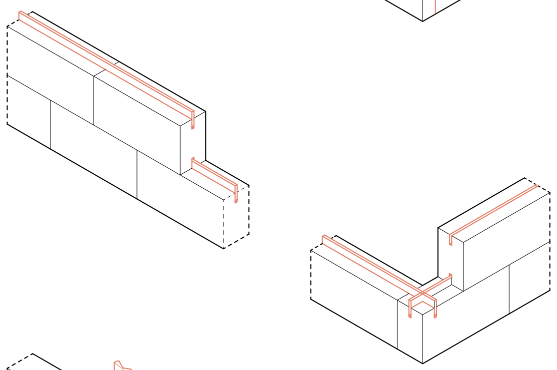
DOVETAIL

Traditionally used in log structures and furniture design due to its high stability for outward pressing forces. In Swedish called a *laxknut*. (I. Sjölund, personal communication, February 18, 2020, see Appendix 2)



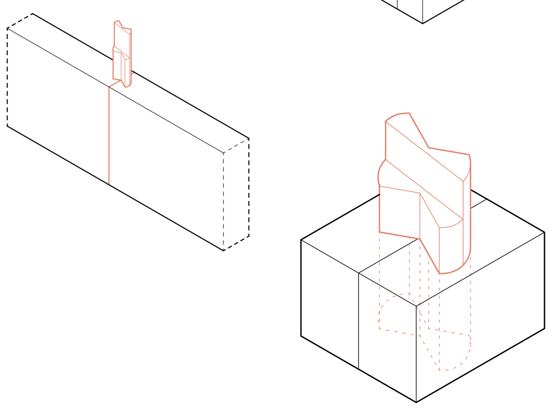
TIMBER DOWEL

A timber dowel can be used in combination with a half and half cut of the connecting material.



BOSUM BUILDING SYSTEM

Smaller pieces of logs that are held together by plywood strips. No extra screws of metal are needed. Assembled together as lego pieces. (Bosum, n.d.)

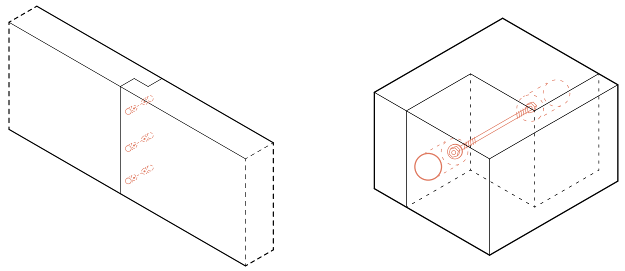


X-FIX WOOD-WOOD CONNECTOR

Inspired by the dovetail, this new product only uses wood as joints. The joint is assembled from above. The same kind of joint is used for the corner. (Timbertools, 2020)

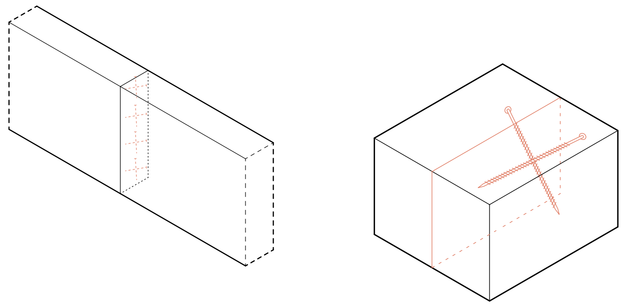
METAL JOINTS

- JOINTS -



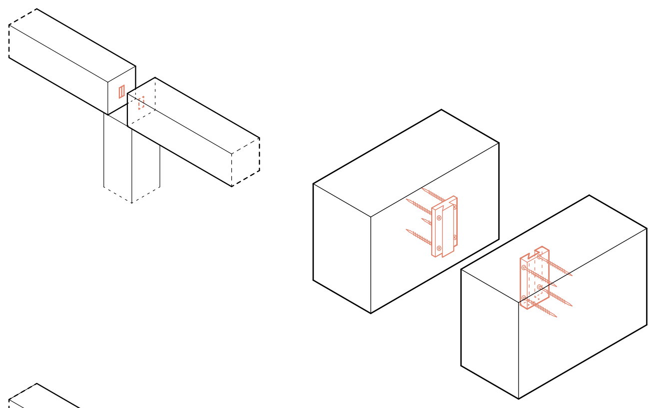
BOLT

The bolt has either a threaded or unthreaded cylindrical body. It is commonly used together with nuts for joining pieces together. (Wikipedia, 2020)



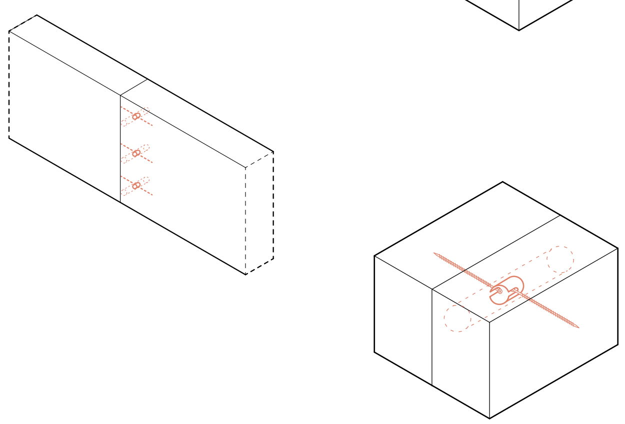
SCREW

In combination with other joints or just as it is, the screw is a fast, strong, and conventional joint when working with timber. (Gustafsson, 2017)



HOOK JOINT

A hooking system where the fittings are screwed onto Glulam beams after which the panels can be mounted together. High precision is required. (Gustafsson, 2017)



STEEL SLEEVE

The screws are mounted at the factory, only the sleeve is added at the building site in order to assemble the construction. (Gustafsson, 2017)

our choice

FACTOR:	Dove-tail	Timber dowel	Bosum	X-fix	Bolt	Screw	Hook joint	Steel sleeve
Pre-Processing (P)	high	medium	medium	high	medium	low	high	high
Assembly Time (A T)	high	high	low	high	low	low	low	low
Equipment Needed (E N)	special-ized	basic	basic	basic	basic	standard today	none	basic
Strength/Joint (S / J)	ok	poor	good	good	good	good	ok	ok
Self Instructive (S I)	good	good	ok	poor	good	ok	poor	ok
Reversability (R)	good	ok	good	poor	good	ok*	good	poor
Condition after Disassembly (C D)	good	poor	poor	poor	good	poor	good	poor
Conventional (C)	no	no	no	no	yes	yes	medium	medium

preferred

ok to use

least preferred

**hard to reverse if the screw is for example, painted over, or screwed in to deep*

COMPARISON

- JOINTS -

COMMENT:

P — High required pre-processing can lead to waste of materials, as holes or cuts needs to be made in the building element to fit the joint. However, it can also lead to short assembly time on site.

A T — Short assembly and disassembly time gives lower cost.

E N — Advanced tools should be avioded to ensure that a disassemble is possible in the future. Standardized tools and dimensions of today don't necessary remain standard in the future.

S / J — A low number of joints is prefered in order to get a fast, and thereby low cost assembling/disassembling.

S I — How to disassemble should be easy to understand and visible. Jonits that are hidden within the structure require clear instructions.

R — The materials joint together, and the joint itself, must not be harmed when deconstructing.

C D — Over time, the building's movements can cause joints to be deformed. Therefore, some joints must have parts replaced.

C — Some joints are not widely used in today's Swedish building industry, for several reasons.

PREFABRICATION LEVEL

Depending on the project, the three prefabrication levels, volume module, plane module and separate pieces, have different advantages.

When choosing a prefabrication level, one thing to consider is building regulations, that will inevitably change over time. As the dimensions of a building built with **separable pieces** are a bit flexible, they are the least affected by this. However, the separate pieces have a severe disadvantage in assembly and disassembly time, making it hard to implement in larger projects. On the other hand, as the pieces can be moved without a crane, it can be a favourable option for self-builders.

Volume modules have fixed dimensions in all directions, thus, making them vulnerable to changing regulations. On the other hand, they can be erected in a short amount of time. This combination makes the volume module a perfect fit for projects with a short time horizon, as in the case for temporary building permits. Compared to the other prefabrication levels, the volume module can appear rigid and repetitive in its aesthetic, making it less attractive.

Plane modules are somewhere in the middle, not too rigid in its dimensions and can be disassembled in an acceptable amount of time. The plane module performs good or ok, in almost all factors used in the comparison, and can therefore favourably be used in most building projects, with both large and small building scales.

BUILDING SYSTEMS

The choice of prefabrication level has a direct impact on the number of building systems to chose from. The most conventional building system today, it the **stud frame,** it is highly material efficient, making it thin and cheap, even when low U-values are required. However, the material from the stud frame may be hard to reuse as the different building layers are hard to separate, and the layers with plasterboards and OSB are easily damaged during disassembly. Furthermore, the studs can be deformed over time when the **Glulam** structure is paired with a stud frame infill it is affected by the same disadvantages. Glulam paired with durable plane modules, such as glass panels, can be a better option.

CLT and **IsoTimber** are manufactured and constructed as plane modules, which enables easy separation of the building layers and ensure a fast disassembly time, which is a key aspect to consider. CLT has the advantage of being a bit thinner and cheaper than IsoTimber. The **Log construction** and **Bosum building system** both have a low environmental impact and the load-bearing structure is easy to separate from the other building layers. The log construction is known to be easy to reuse. Since Bosum is new to the market the reuse of its structure is still to be tested. Both constructions have limits in scale and economy. All massive timber structures, exept IsoTimber, can have visible interior timber.

JOINTS

Most important when choosing joints suitable for disassembly, is choosing reversible and self instructive alternatives. Which turned out not be the case for most **wooden joints**. When examining different reference projects, that have been designed for disassembly, the **bolt** is frequently used. Looking at the comparison, it's easy to see why, since it has almost no weaknesses. The **screw** is the most conventional joint used today, it is fast, strong and requires no pre-processing. Sadly it is hard to reuse the same screw after disassembly, as the building's movements cause it to deform.

03.

PROJECT FRAMEWORK

This chapter will present the context for the case study project. It contains an introduction of the chosen prefabrication level, building system, and joints, that is used in the case study project. As well as details of connections between walls, slabs, roof, foundation and additional building elements. The theoretical comparison has acted as a guiding tool to shape the project.

The expected life length of the case study project, before it will be disassembled, have been set to +50 years. This is adapted according to the average life length of multi-family dwellings, of 55 years (Appendix 1). The long estimated life length causes a need for high-quality solutions and materials, to ensure a secondary use. The material is estimated to be sold to a second-hand retailer or directly to a new developer after disassembly.

+50 years

Estimated life lenght of project

Picture 13. Church of Kiruna, source: Fredric Alm

CASE STUDY

CASE STUDY

The case study project is a proposal for a sustainable multi-family housing block on-site no. 91, in the new city centre of Kiruna. The project has been limited to solve one building volume on the site. It is designed to meet the developer and master plan requirements, together with solutions that support a reuse concept.

COLLABORATION

The thesis is part of a larger collaboration together with RISE, Kiruna bostäder AB and LTU, made for the initiative Kiruna Sustainability Centre. The collaboration will result in a building designed for disassembly (this thesis), circular procurement documents and life cycle analysis (RISE), a generative design (LTU), and greenery strategies (RISE), for the site 91 in Kiruna.

CHALMERS

RI. SE Research Institutes of Sweden

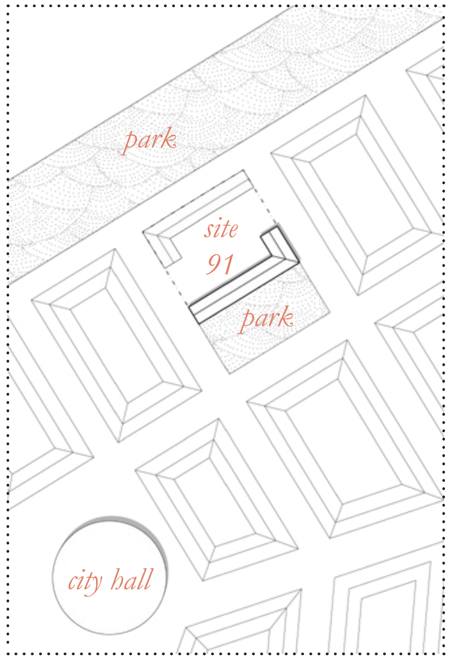
KIRUNA BOSTÄDER

LULEÅ TEKNISKA UNIVERSITET

SITE

- NEW CENTRE IN KIRUNA -

Kiruna is a town undergoing a great urban transformation. The mine located close to the city will expand towards the current city centre. Therefore, a relocation of the city has started and will continue over many years to come. Some existing buildings will, and have been, moved, whilst a lot of new constructions will be added. Our building is located one block away from the new city hall, sandwiched between two parks.



Picture 14. Kiruna town, source: Lantmäteriet

CHOSEN METHOD

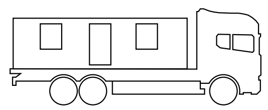
- PREFABRICATION LEVEL -

A couple of things have to be considered when choosing prefabrication levels. For starters the expected life length of the project, which in this case is set to 50 years. After that, it will be disassembled and re-used at another location.

In the case study project, it is suitable to work with plane modules, since the building is a four-storey multi-family house, it is large in scale. Inspired by the Shearing layers, one plane module will contain several separable layers to make the management of the building easier throughout the years.

The plane module holds a lot of advatages when it comes to design for disassembly. Fast assembly time at the building site gives plane modules lower cost, compared to separate pieces. As it simplifies the disassembly, it can make the decision of choosing a disassembly rather than a demolition easier. Compared to volume modules, working with plane modules will give more architectural freedom when designing spaces.

Even though the plane module is the chosen level of prefabrication, we've chosen to work with the bathrooms as volume modules, and the facade will be assembled as separate pieces. The different prefabrication levels hold different qualities, therefore, it is important to evaluate and choose a suitable method for each specific part of a project.



CHOSEN METHOD

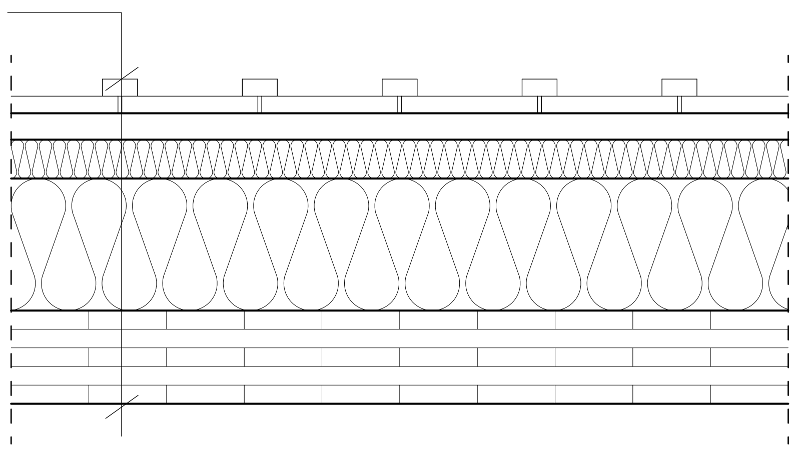
- BUILDING SYSTEM -

As for the building system of the project, it is suitable to work with CLT panels to meet the design for disassembly goal. The CLT panels are manufactured as plane modules, have massive wood thermal qualities, and store a lot of CO_2. Its load-bearing capacity makes it suitable for a four-storey building. Adding a sprinkler system makes it possible to have visible interior timber. This makes the layers of the wall easier so separate since no plasterboard is needed.

The wall section has been modified to lower the GWP, replacing the mineral wool to cellulose-based insulation instead. The CLT comes to the building site, where remaining layers are added. When disassembling, the facade and roof cladding is taken apart, whilst the studs stay on the CLT panel. If the insulation needs to be changed after 50 years, this can be done, otherwise, it stay on and are reused.

MODIFIED CLT WALL

	$kgCO_2/m^2$
lath panel 22mm	0,1
panel 22mm	0,6
batten 34 x 70 mm	0,1
wood fibre wind board 50 mm	2,4
horizontal studs &	0,4
cellulose insulation 45 x 170 mm	2,3
vapour barrier	0,3
CLT 120 mm	7,7
Total GWP/m²	14



Total GWP / m²
+14 $kgCO_2$ / kg

Total carbon sequestration / m²
-91,5 $kgCO_2$ / kg

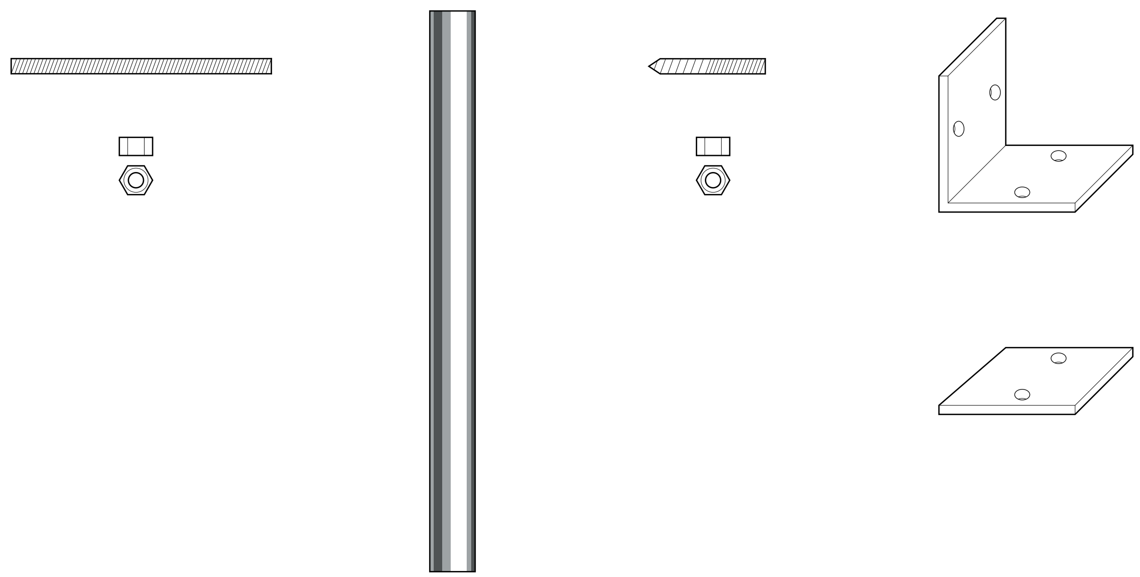
CHOSEN METHOD

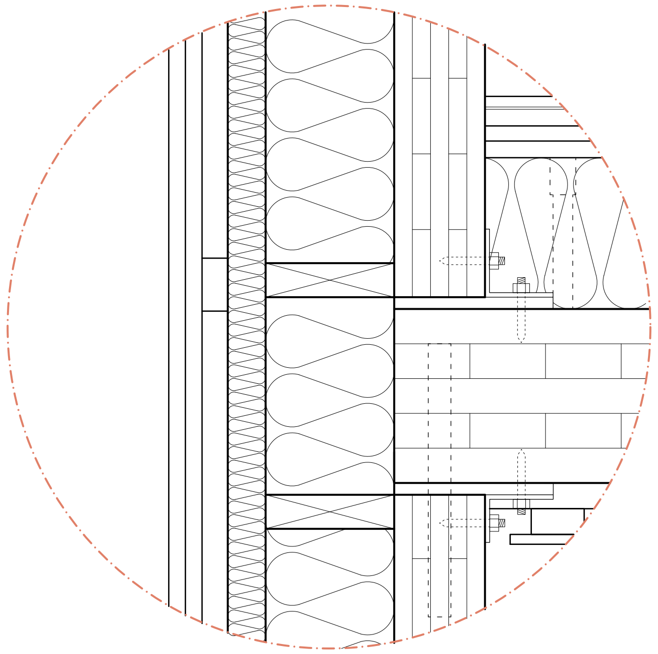
- JOINTS -

For the project, it is suitable to work with bolts and dowels to meet the design for disassembly goal. These traditional joints hold low complexity, are easy to revers and understand. Even though steel consumes a high amount of energy during manufacturing, all chosen joints are in steel. This is due to its high strength, which will lower the number of joints, and will live longer, compared to wooden joints.

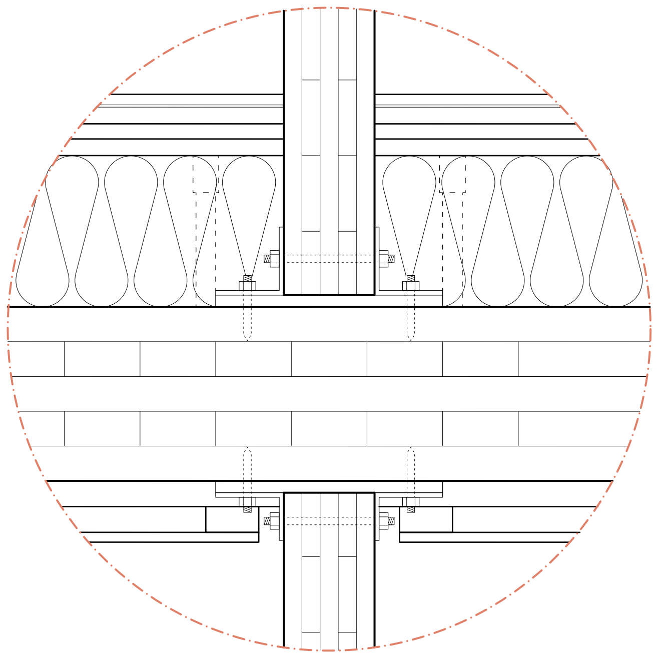
A steel dowel is fixed on top of the wall in order to connect to the load-bearing points at the overlying slab. Threaded bolts and nuts will connect walls and slabs. Where no bolt can go right through the CLT, a screw pin will be used. At one end, it works as an ordinary screw for wood, and at the other, as a threaded bolt. To stabilize further, and to minimize damage to the timber, angled and flat irons will be used.

BOLTS DOWEL SCREW PINS ANGLED & FLAT IRON

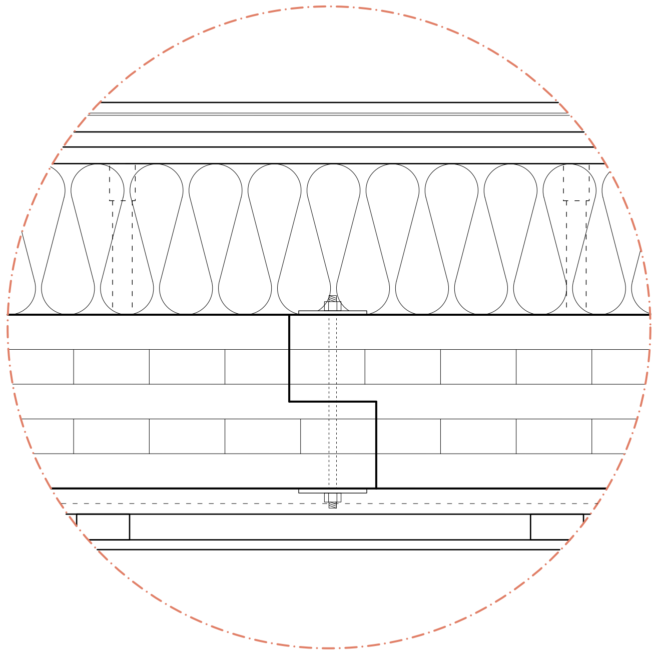




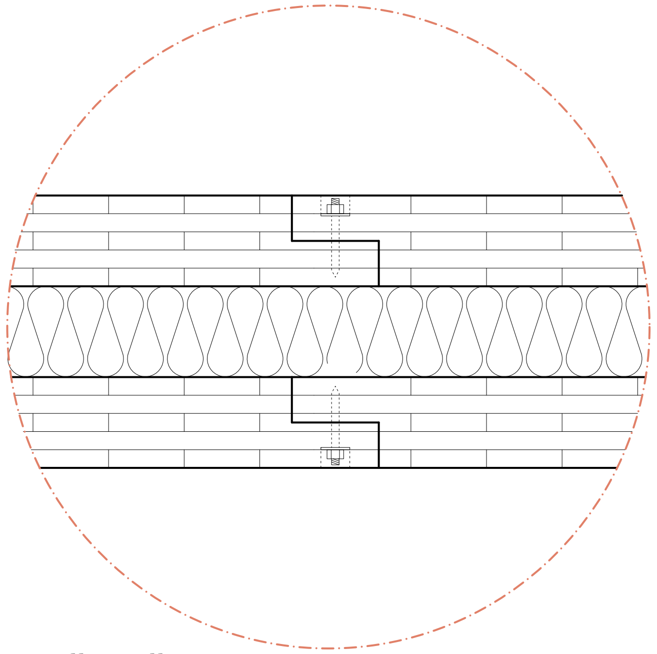
Slab - outer wall
Scale 1:10



Slab - interior wall
Scale 1:10



Slab - slab
Scale 1:10

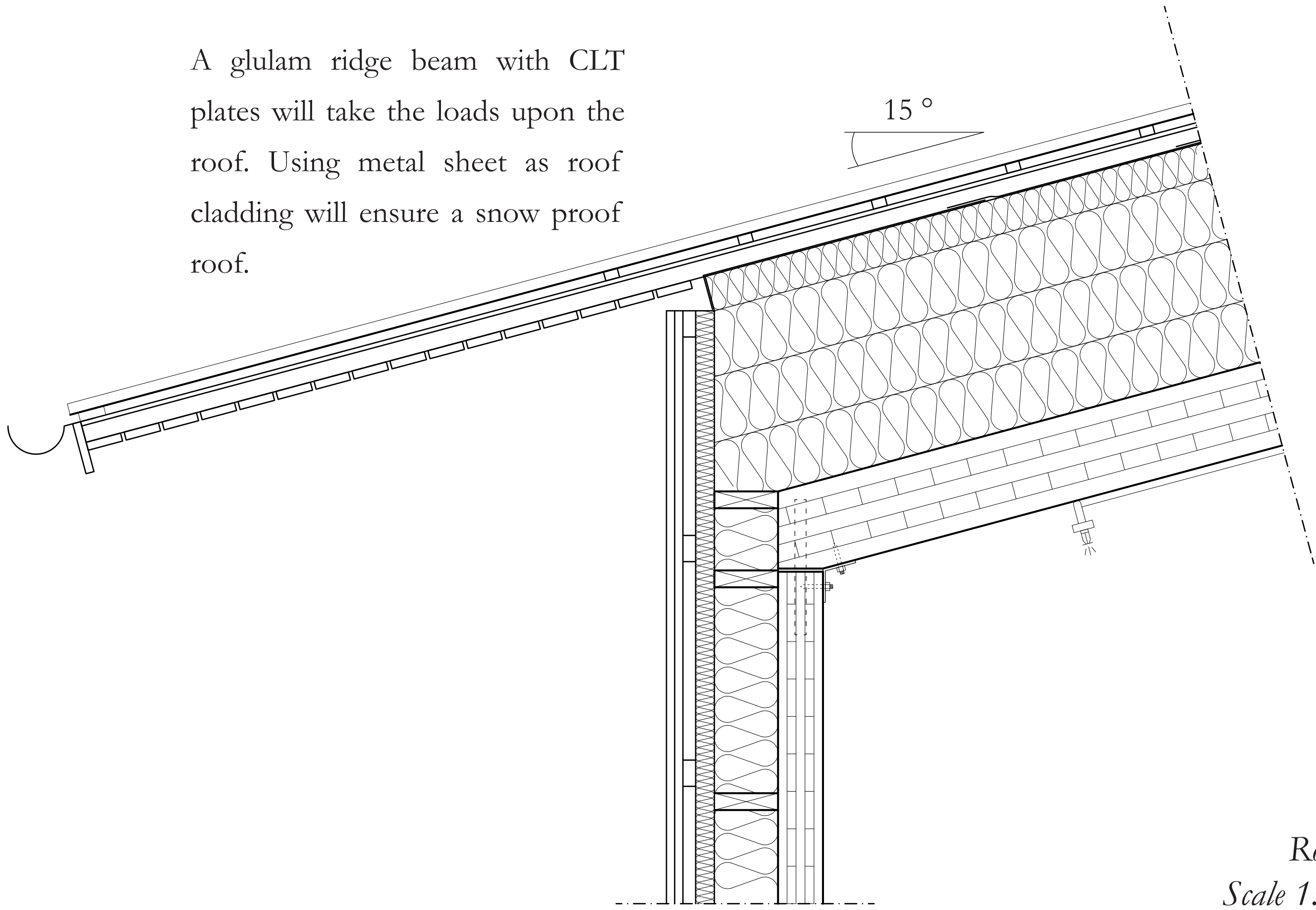


Wall - wall
Scale 1:10

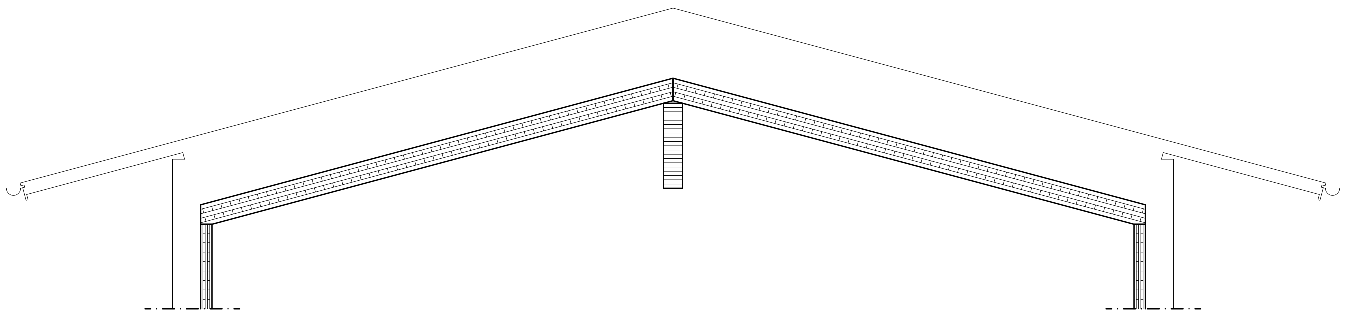
CHOSEN METHOD

- ROOF -

A glulam ridge beam with CLT plates will take the loads upon the roof. Using metal sheet as roof cladding will ensure a snow proof roof.



Roof
Scale 1:20

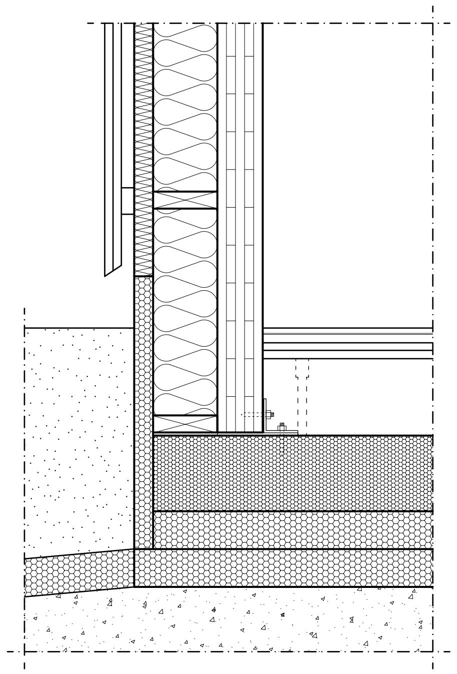


Glulam ridge beam
Scale 1:80

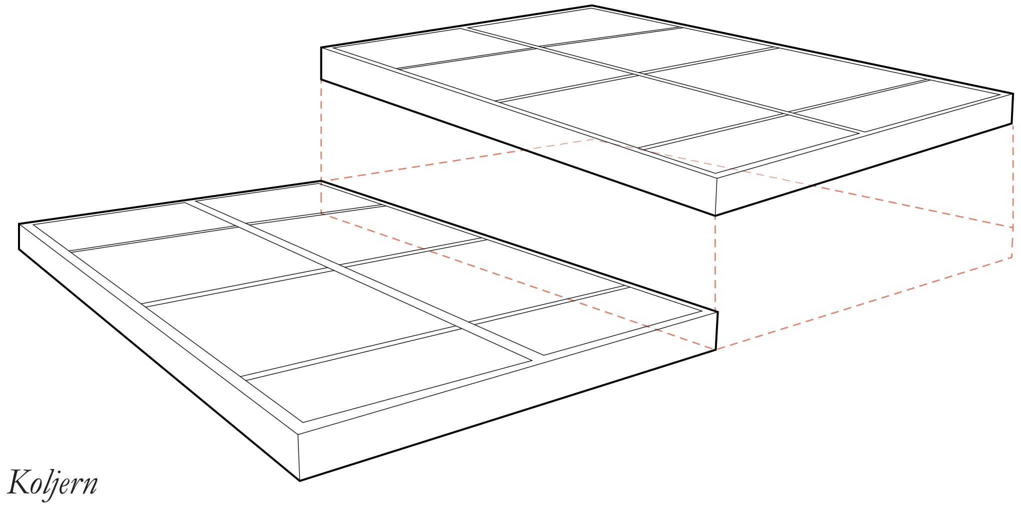
CHOSEN METHOD

- FOUNDATION -

Koljern® is a load-bearing composite product with foam glass and light metal beams. It is made from recycled glass, has lower CO_2 emissions during manufacturing than concrete, and weights 90 % less than the traditional concrete slab foundation. It requires no drying time since the product holds no moisture, which enables an immediate start of constructing the rest of the building. (Koljern, n.d.) The plates can be costumized to specific projects. The plates below are illustrated as 2 x 4 m.



Foundation
Scale 1:20



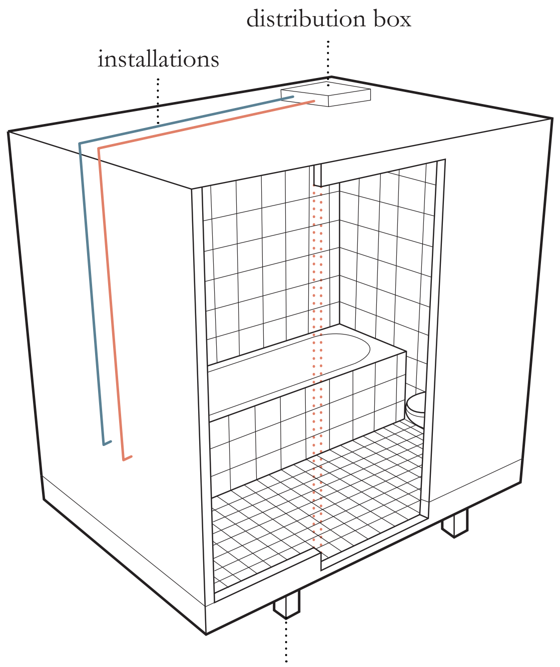
Koljern

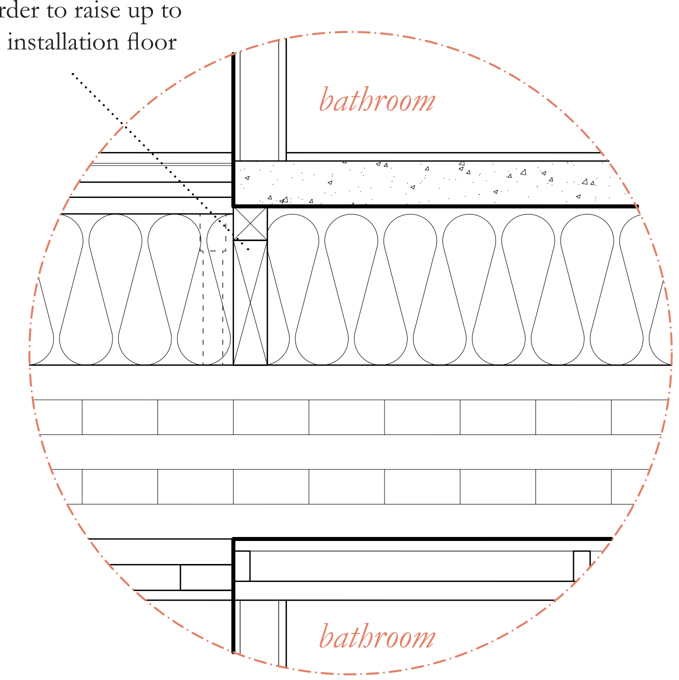
CHOSEN METHOD

- BATHROOM MODULE -

Even though the plane module is the chosen level of prefabrication, we've chosen to work with the bathrooms as volume modules. Interior claddings are complicated to disassemble and reuse, but when you have a volume module prepared with everything needed, this can be reused as a whole in the future.

This is an example of prefabricated bathroom modules from Part Construction AB, amongst several manufacturers. When using such a module in a project, you reduce the construction time on site, lower the project costs, and get simpler logistics. The requirements needed for a bathroom are maintained.





Bathroom - slab
Scale 1:10

04.

DESIGN PROPOSAL

The building's location close to the city core has caused a need for public use, therefore, the bottom floor is largely dedicated to commercial functions. Since Kiruna is a city with dramatic light conditions, the apartments have been designed to achieve high levels of daylight. This is reflected in the building's width of 10 m, which is thinner than in a normal housing project, thus, minimizing dark areas in the apartment core.

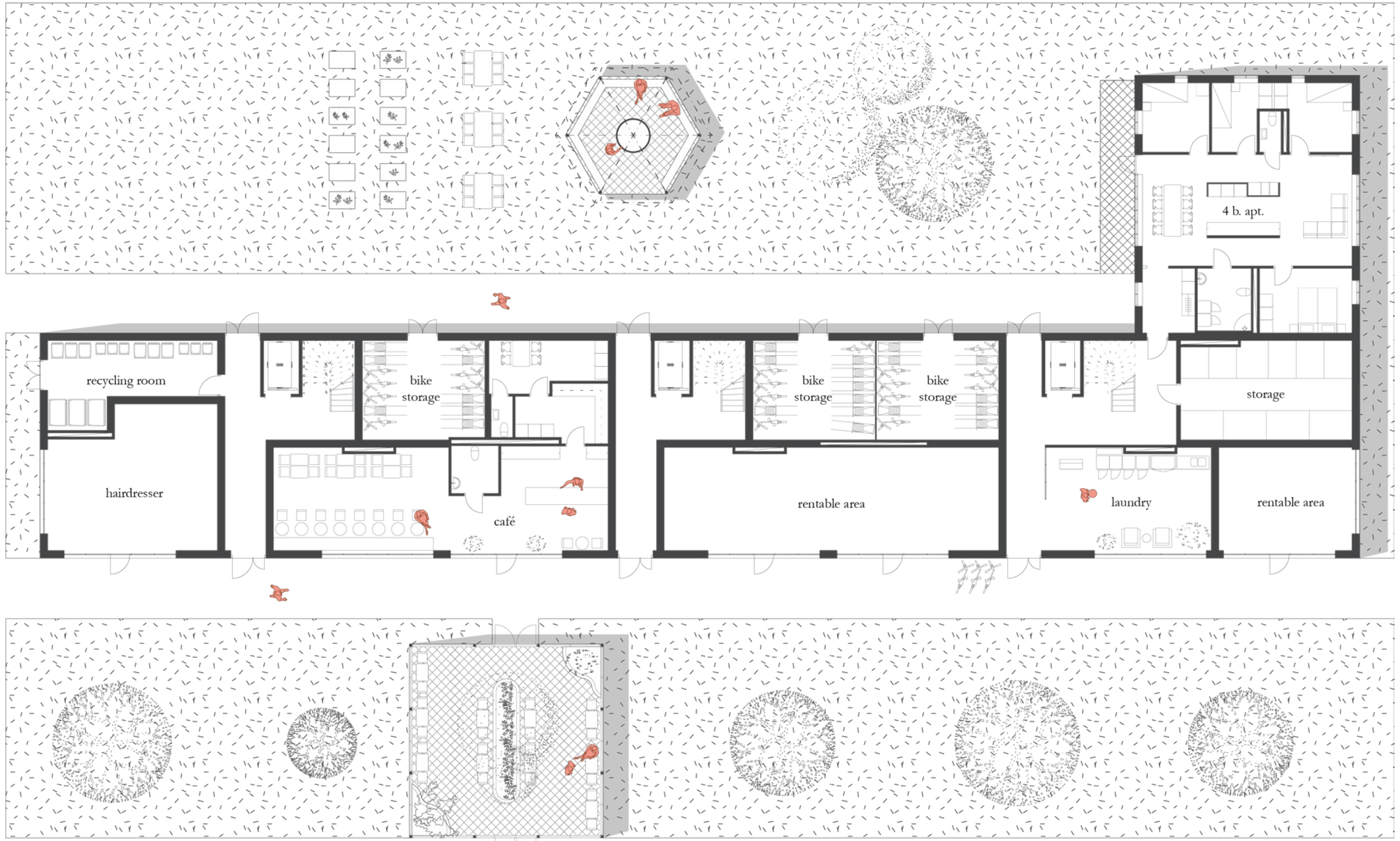
All apartments, except the studio apartment, have windows towards different directions. The smaller apartments have increased accessibility and will be rented by seniors. On the top floor, all residents share a common sauna and winter garden with views over the city park. After the building's first use at site 91, the building can be disassembled according to the disassembly plan.

VIEW

- ELEVATION -

ENTRANCE FLOOR

- SCALE 1:200 -



VIEW

- APARTMENT -

STANDARD FLOOR

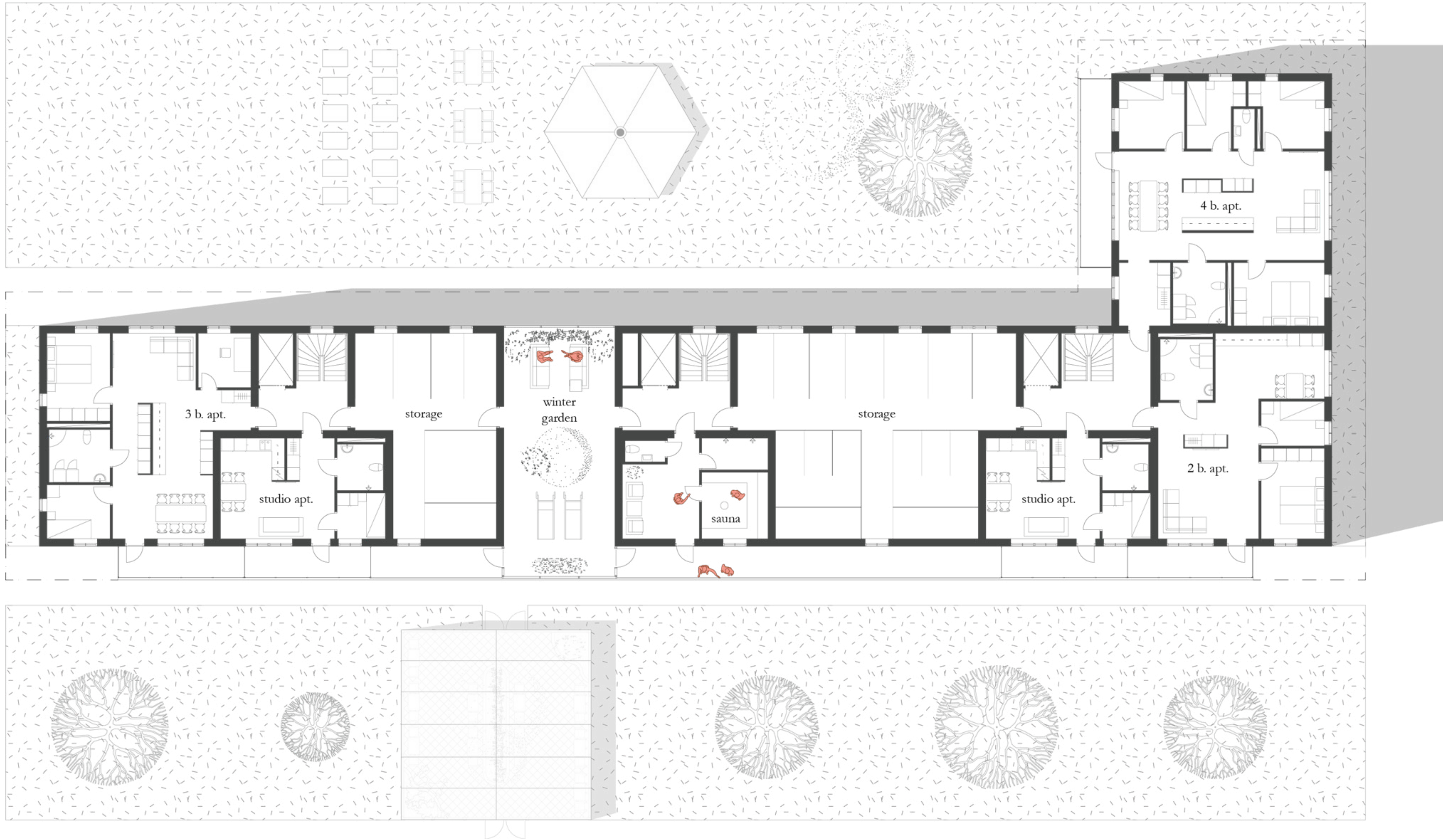
- SCALE 1:200 -

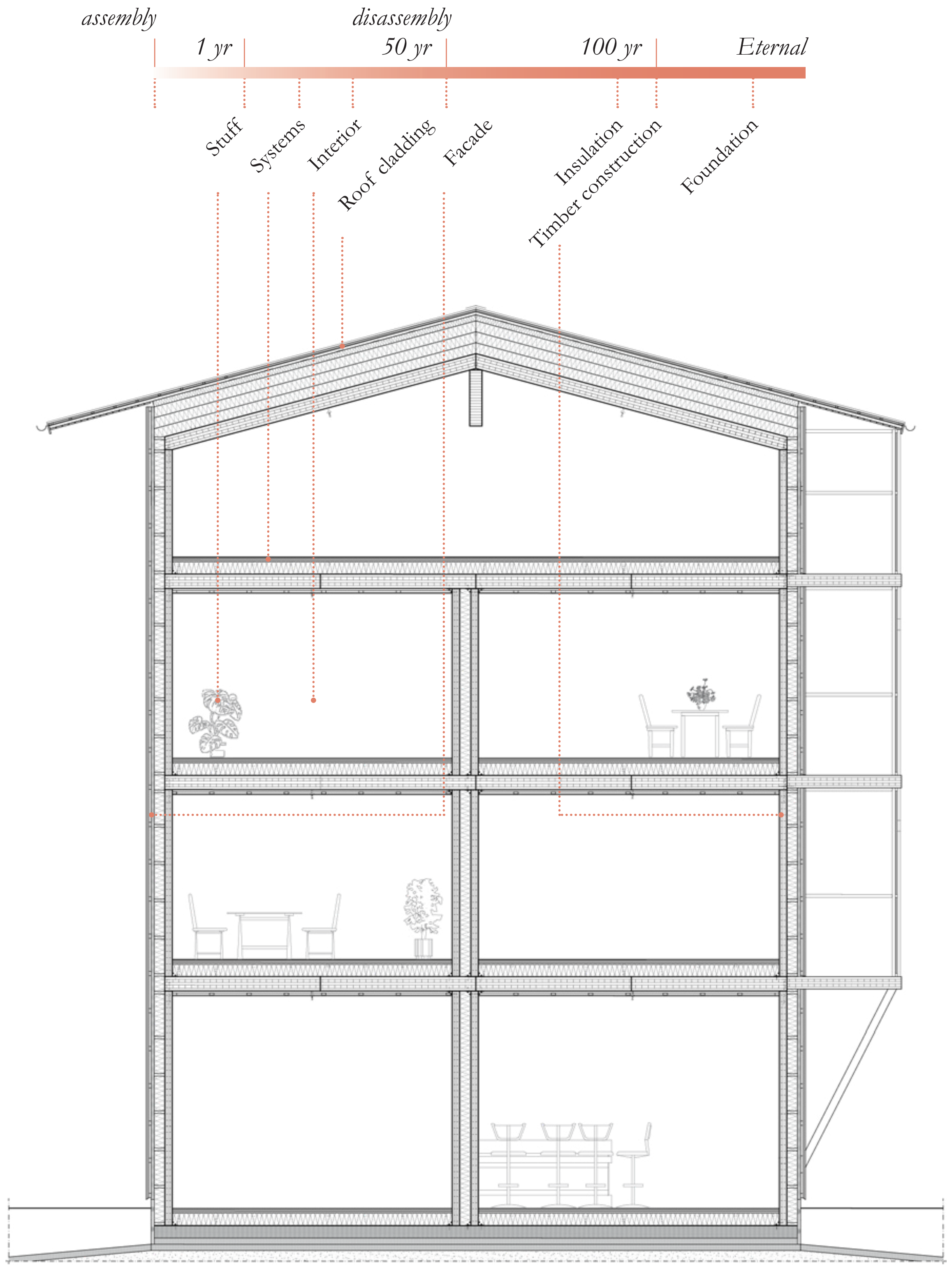
VIEW

- WINTER GARDEN -

TOP FLOOR

- SCALE 1:200 -





BUILDING LAYERS

Similar to the layers identified in Shearing layers, the case study project holds building layers with different lifespans. By sorting them accordingly, it becomes easier to know which layers are eligible for reuse in 50 years. Building layers with similar estimated lifespans can become part of the same plane module, thereby, reducing the number of layers that needs to be separated during dismantling.

Stuff owned by residents is estimated to stay in the building from days up to years. Depending on if a room is commercial or part of a home, the interior layout may change every third or up to thirty years. During this phase, interior claddings, fixtures, walls and openings may be altered. After 50 years, when the building will be disassembled and moved, systems, facade and roof claddings that are in poor condition, can be replaced. Layers that have gone through a renovation earlier, and are in good condition, can be kept.

Insulation made out of mineral wool can typically last 100 years. The expected life lenght for the cellulose-based insulation used in the case study project is generally lower. As the insulation has a potential of lasting longer than 50 years, it can become part of the same plane module as the timber structure. Historically, the life length of a well-protected timber structure can be over 100 years. However, 100 years is the life length that is typically used in calculations (Guldager Jensen & Sommer, p. 79, 2016). The foundation in Koljern is made out of crushed glass and can theoretically last forever.

DECONTAMINATION

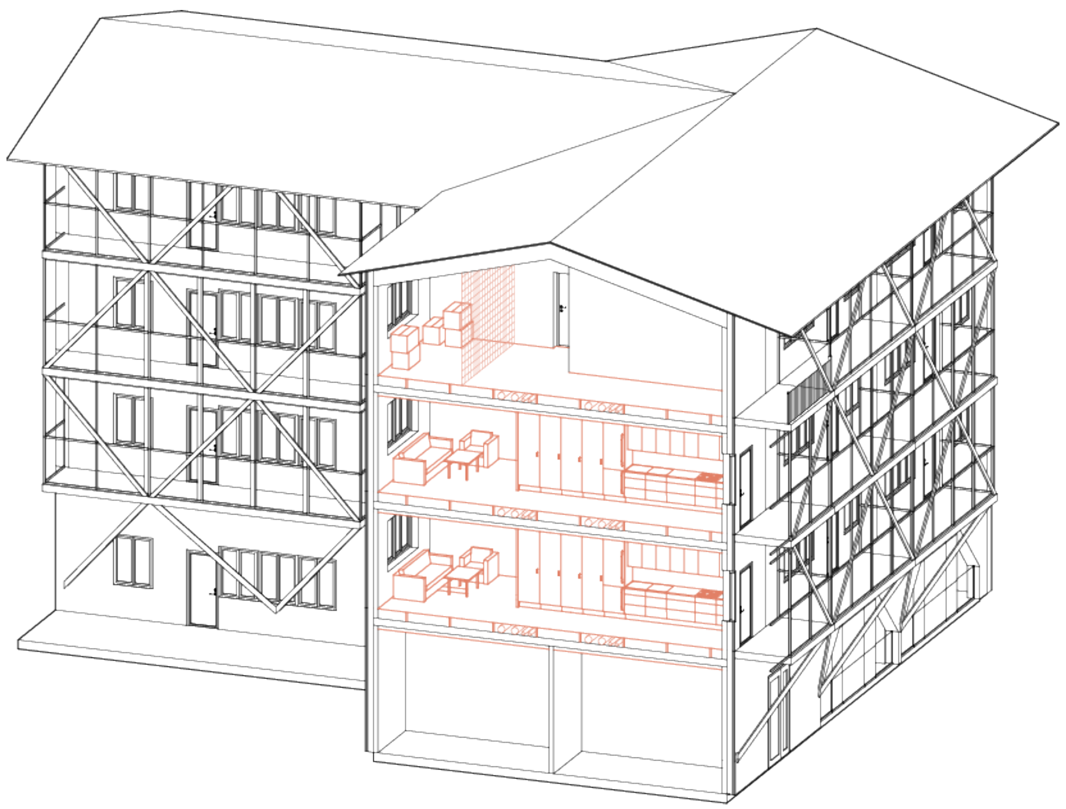
1. evaluate building materials
2. check for toxics, if any
3. remove contaminations

FIXED INTERIORS

1. evaluate condition of fixed interiors, such as stoves, casework etc.
2. material recycle or relocate

INSTALLATIONS

1. evaluate condition of installations, such as ventilation, plumbing and electrics
2. material recycle or relocate



DISASSEMBLY PLAN

- PREPARATION -

Due to the building's expected life length of +50 years, reuse of materials with a shorter expected life length have not been planned for. This includes fixed interiors, installations and exterior claddings. Therefore, these materials will be removed in advance. The disassembly of the remaining structure will be conducted floor by floor, with the exception of the outer shell.

DISASSEMBLY ORDER

Decontamination Fixed interiors Installations	*preparation*
Roof cladding Winter garden Balconies	*outer shell*
Structural roof Interior walls Bathroom modules Exterior walls Slabs	*top floor*
Interior walls Bathroom modules Exterior walls Stairs Slabs	*standard floor*
Interior walls Bathroom modules Exterior walls Stairs Foundation	*entrance floor*
Relocation Material recycle Reconstruct	*reestablishment*

ROOF CLADDING

1. take off the metal sheet
2. break open the laths and planks
3. take away the interior cladding and the insulation
4. sort the material for recycling

WINTER GARDEN

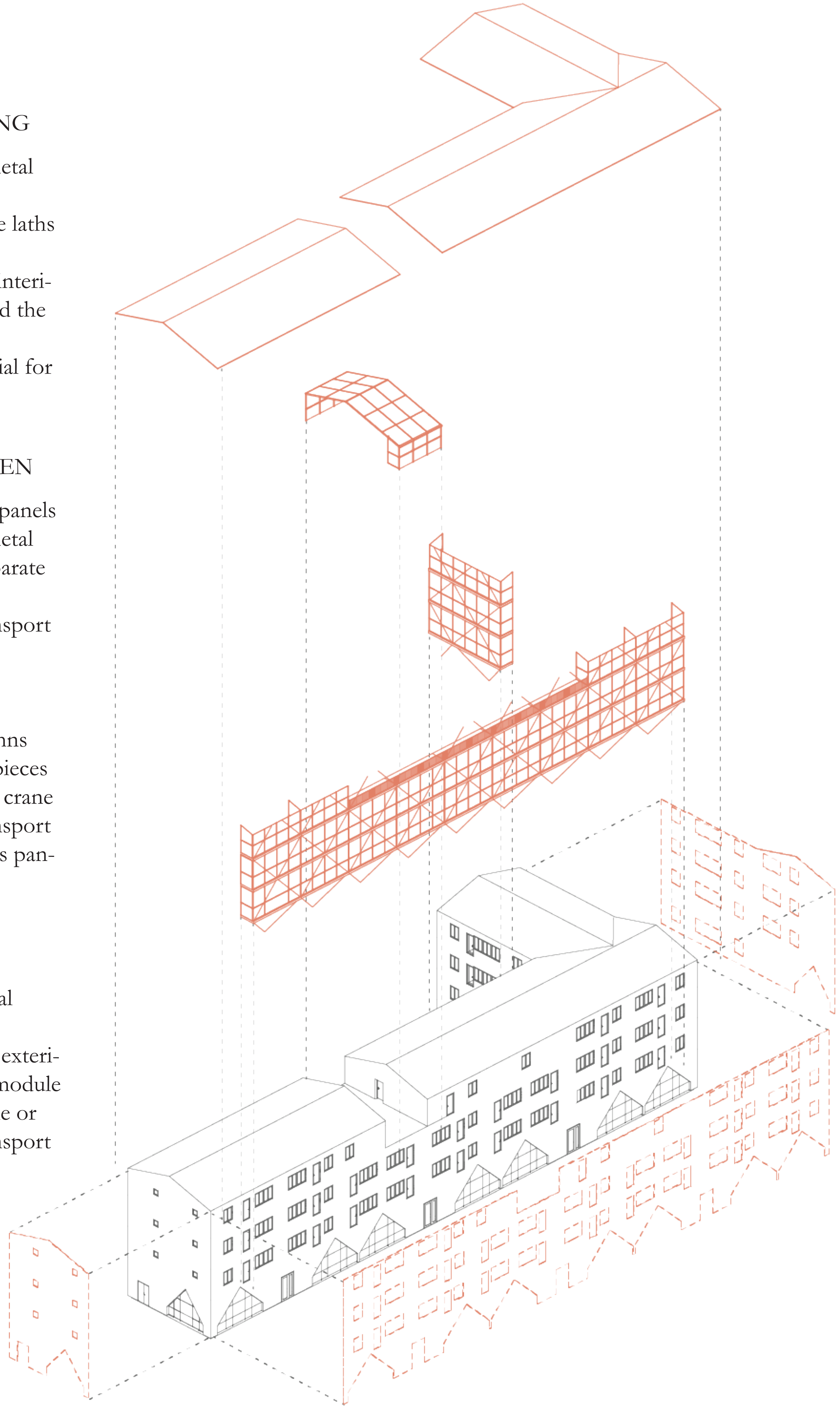
1. separate glass panels
2. deconstruct metal frame into separate pices
3. secure for transport

BALCONIES

1. separate columns into separate pieces
2. lift down with crane
3. secure for transport
4. repeat for glass panels and slabs

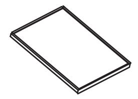
FACADE

1. inspect material condition
2. separate from exterior wall plane module
3. material recycle or secure for transport



DISASSEMBLY PLAN

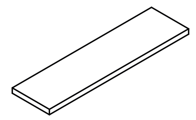
- OUTHER SHELL -



Winter garden glass panel

1,5xX m

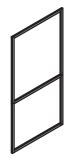
31 pieces



Slab

1,5x12 m

18 pieces



Balcony glass panel

1,5x3 m

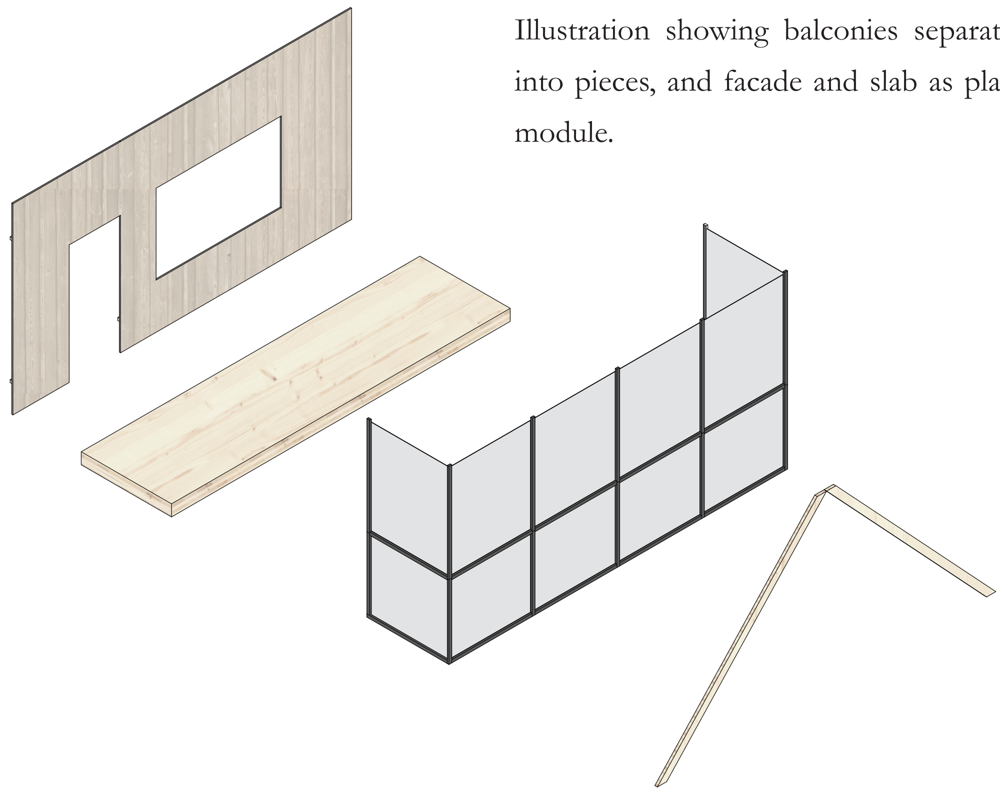
138 pieces

Structural column

3,4 m

84 pieces

Illustration showing balconies separated into pieces, and facade and slab as plane module.



STRUCTURAL ROOF

1. separate roof plane modules vertically and horizontally
2. lift down with a crane
3. secure for transport
4. repeat process for glulam trusses

INTERIOR WALLS & BATHROOM MODULES

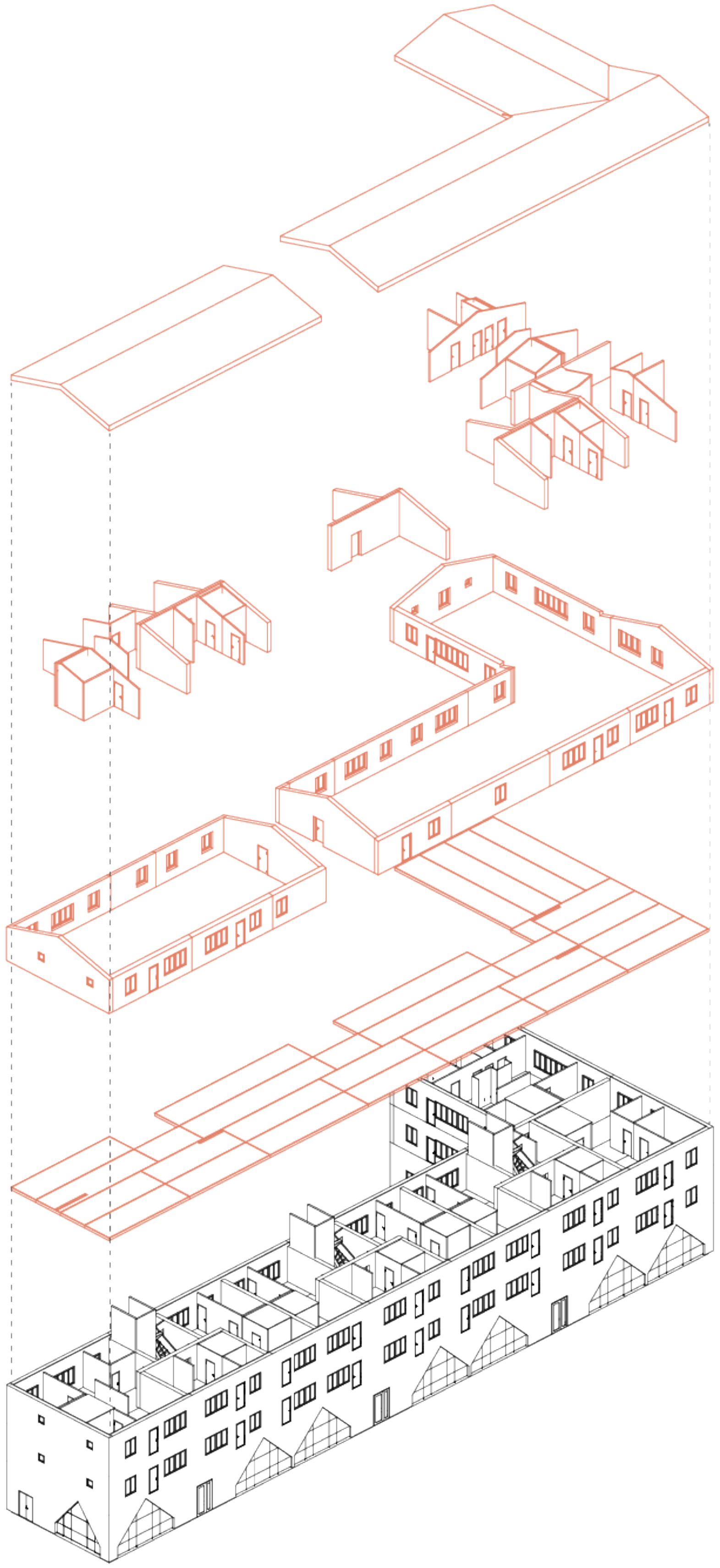
1. separate wall plane modules vertically and horizontally
2. lift down with a crane
3. secure for transport
4. repeat process for bathroom modules

EXTERIOR WALLS

1. inspect insulation condition
2. material recycle or secure for lift
3. separate wall plane modules vertically and horizontally
4. lift down with a crane
5. secrure for transport

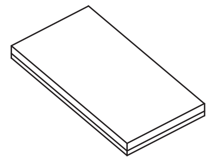
SLABS

1. separate slab plane modules vertically and horizontally
2. lift down with a crane
3. secrure for transport

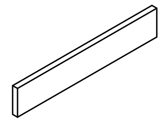


DISASSEMBLY PLAN

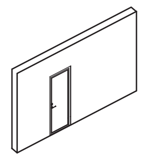
- TOP FLOOR -



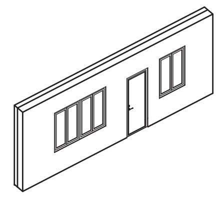
Structural roof plane module
3x5 m
48 pieces



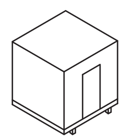
Structural roof beam
0,9x12 m
6 pieces



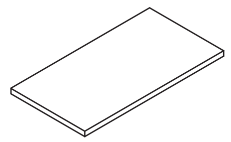
Interior wall
3xX m
46 pieces



Exterior wall
3xX m
20 pieces



Bathroom module
7 modules



Slab
3xX
30 pieces

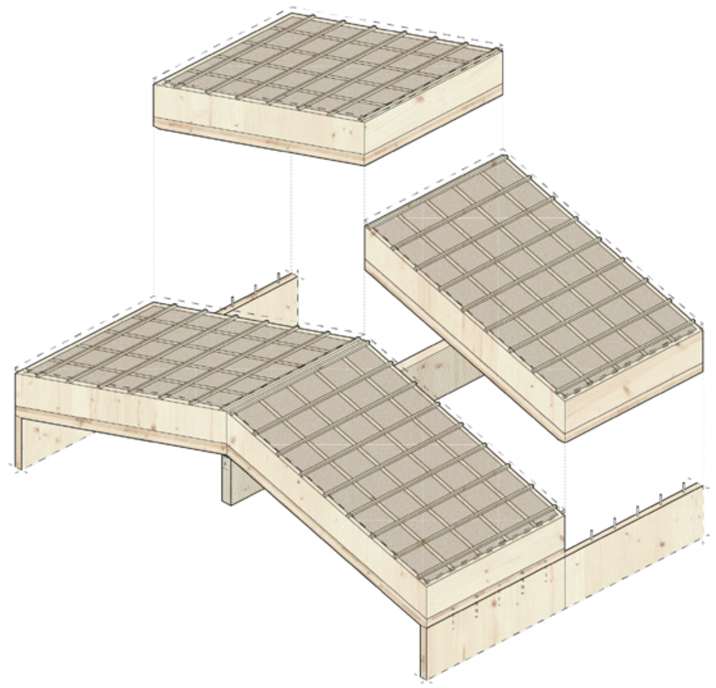


Illustration showing how to separate the structural roof and insulation as a plane module.

INTERIOR WALLS
& BATHROOM
MODULES

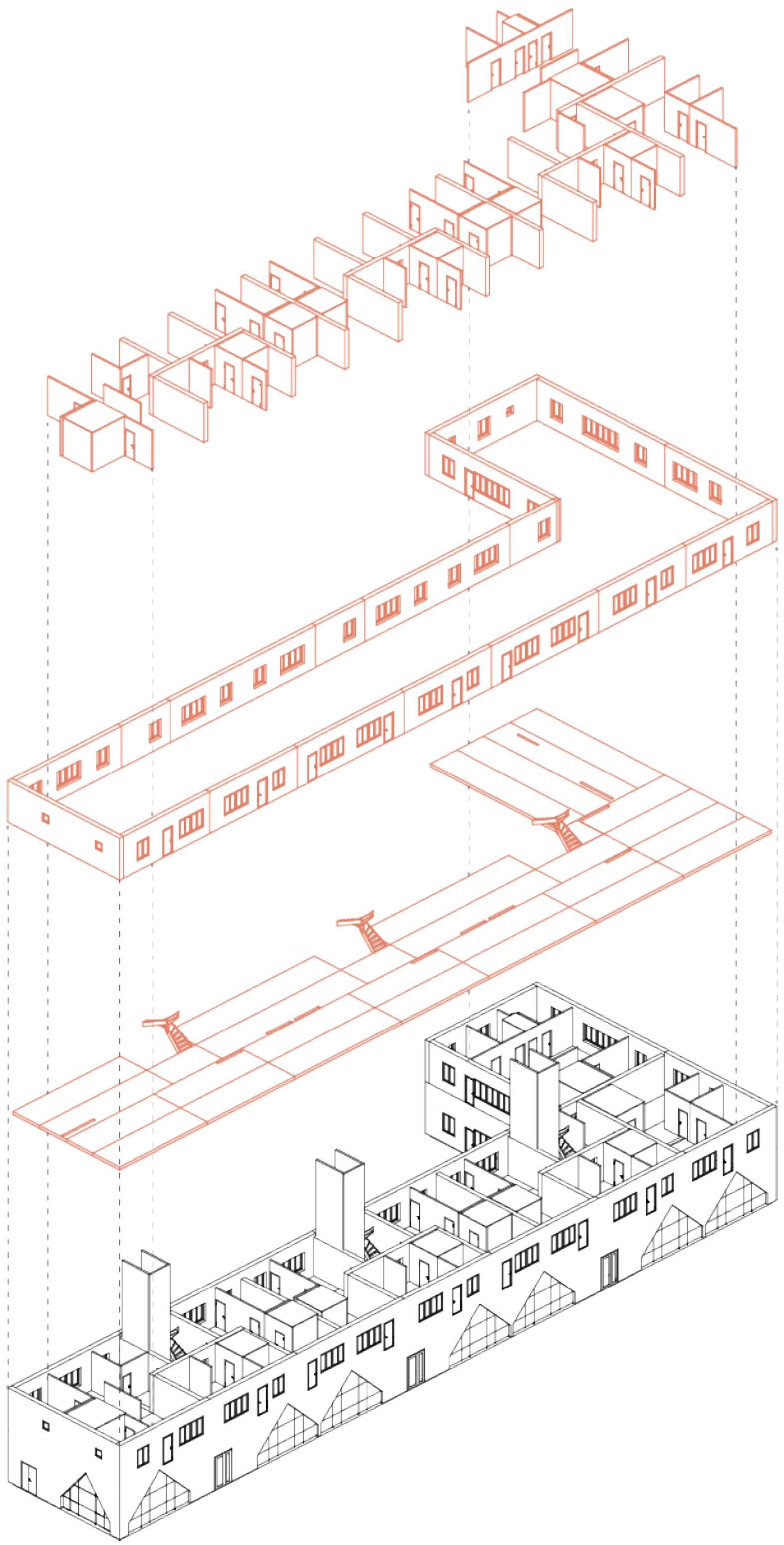
1. separate wall plane modules vertically and horizontally
2. lift down with a crane
3. secure for transport
4. repeat process for bathroom modules

EXTERIOR WALLS

1. inspect insulation condition
2. material recycle or secure for lift
3. separate wall plane modules (keep doors & windows) vertically and horizontally
4. lift down with a crane
5. secrure for transport

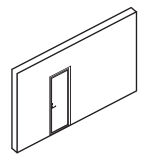
STAIRS & SLABS

1. separate stair volume modules vertically and horizontally
2. lift down with a crane
3. secure for transport
4. repeat process for slabs



DISASSEMBLY PLAN

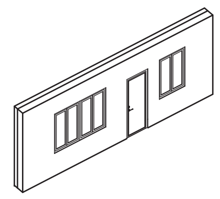
- STANDARD FLOOR -



Interior wall

3xX m

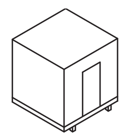
78 pieces



Exterior wall

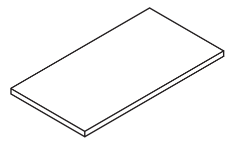
3xX m

18 pieces



Bathroom module

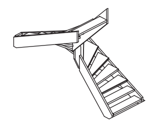
12 modules



Slab

3xX m

30 pieces



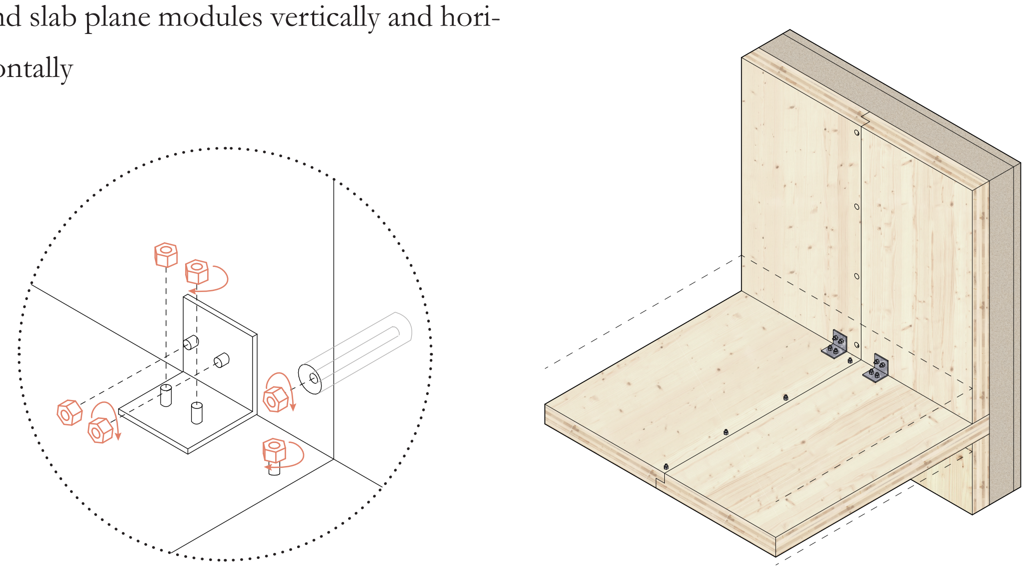
Stair

3 modules

x2

to include all standard floors

Illustration showing how to separate wall and slab plane modules vertically and horizontally



INTERIOR WALLS & BATHROOM MODULES

1. separate wall plane modules vertically and horizontally
2. lift down with a crane
3. secure for transport
4. repeat process for bathroom modules

EXTERIOR WALLS

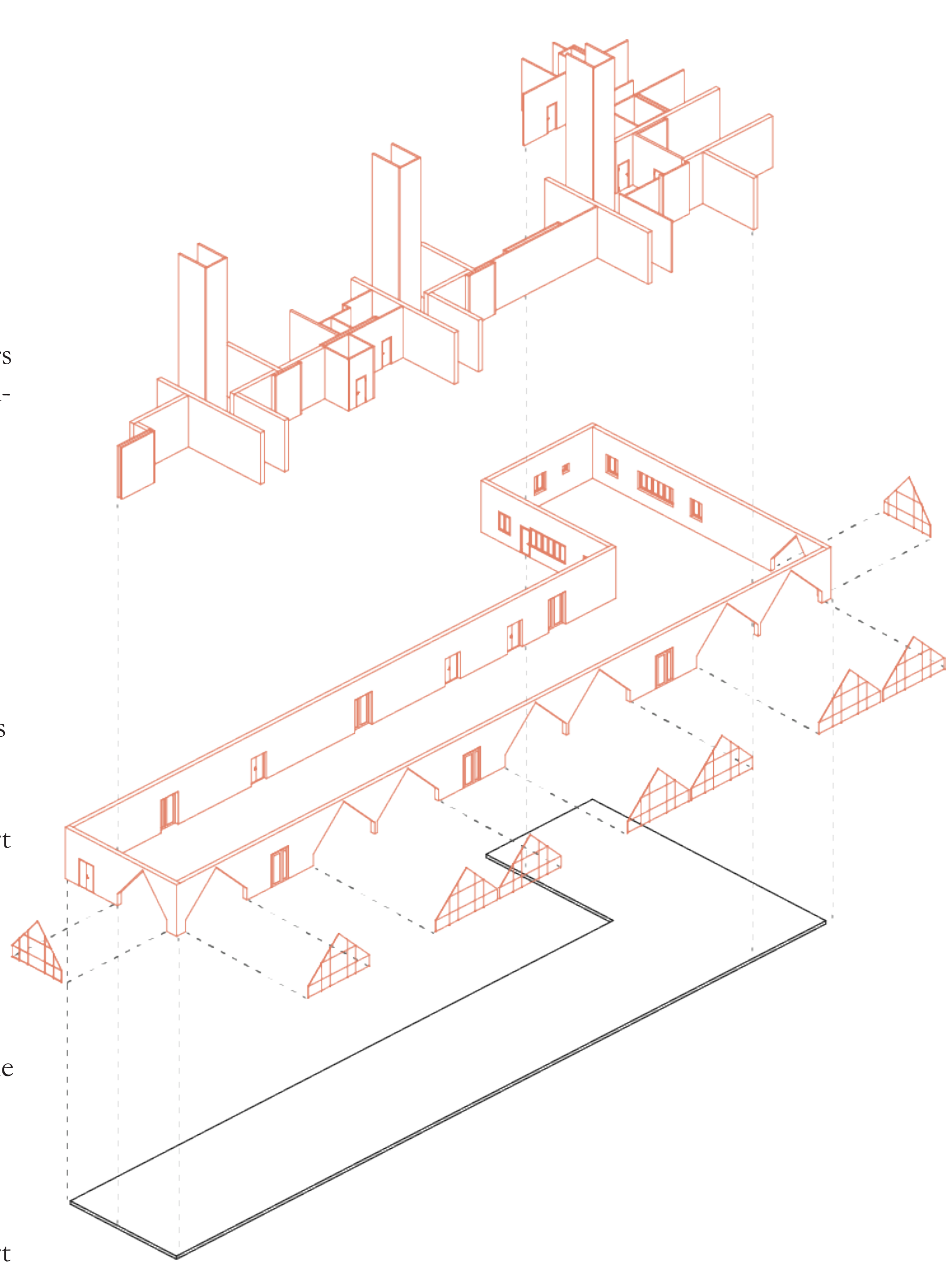
1. inspect insulation condition
2. material recycle or secure for lift
3. separate wall plane modules (keep doors & windows) vertically and horizontally
4. lift down with a crane
5. secure for transport

STORE FRONT WINDOWS

1. separate glass panels
2. lift down with a crane
3. secrure for transport
4. repeat process for slabs

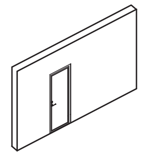
FOUNDATION

1. separate stair volume modules vertically and horizontally
2. lift down with a crane
3. secure for transport
4. repeat process for slabs



DISASSEMBLY PLAN

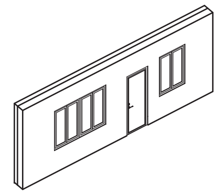
- ENTRANCE FLOOR -



Interior wall

3xX m

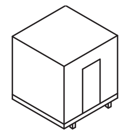
38 pieces



Exterior wall

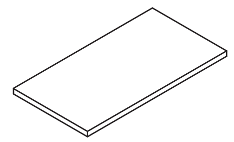
4xX m

18 pieces



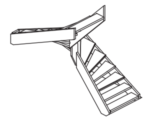
Bathroom module

3 modules



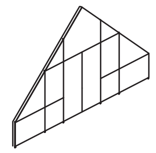
Foundation

X pieces



Stair

3 modules



Storefront window

9 pieces

DISASSEMBLY PLAN

- REESTABLISHMENT -

After the disassembly is finished it is time to transport the material to a new building site, a second hand retailer or another type of storage. Intermediaries and secondhand retailers may have increased in 50 years, and become more widely spread throughout the country. The remaining building waste is recycled and the building site is cleared and restored.

05.

CONCLUSION

1. How can we build and design with timber to promote reuse of building materials?

2. Which timber building methods are most suitable to use when designing for disassembly?

1.
We have found that a good way to prepare a building for future reuse of its material, is using the strategy Design for disassembly. The strategy ensures that building methods chosen in an early state are simplifying the disassembling at the end of the buildings life. Furthermore, by identifying that a building consists of several building layers with different life lengths, and ensure that they can be separated, more material can be replaced, reused and recycled in the future.

The thesis promotes reuse of building material by giving a clear overview of which prefabrication levels, building systems, and joints that are suitable to use in a design for disassembly project. Thereby, demonstrating that the goal of reusable building material is reachable, thus, lowering the threshold for builders, investors and architects, to implement building methods that support a reuse concept.

Despite today's challenges, the thesis shows that there are potential gains from reusing building materials, as the cost of a demolition is more expensive than the dismantling and sale of the building material. This provides motivation for long term owners to step away from the conventional way of building. The thesis also shows that a design for disassembly project doesn't require large or complicated alterations to be realized.

CONCLUSION

2.
Depending on the scale and context of the project, as well as the expected life lenght the building, different building methods are suitable. By using the comparisons as a guiding tool, all projects can find suitable options. In large, the plane module is the most applicable prefabrication level, while the volume module can be suitable for temporary building permits and the separate pieces can be used in small scale projects.

The choice of prefabrication level will have a direct impact on the number of building systems to choose from. All compared building systems have their own advantages, depending on the context of the project. All systems can be reused, but the stud frame has its challenges due to its method of fixing the building layers together, making it hard to separate the different materials without damaging it. Limiting the performance to solely reusability Bosum building system stands out, as it has a low number of specialized pieces and can be reused similarly as a brick.

When choosing joints suitable for disassembly, it is important to choose reversible and self instructive alternatives. Also, choosing a strong joint will shorten the disassembly time, since the number of joints can be reduced. In our comparison, the bolt and nut stand out as an exceptionally good choice.

DISCUSSION

THE COMPARISON

By evaluating three prefabrication levels: volume module, plane module and separate pieces, we got a good understanding of how the different building systems are affected by their prefabrication level in terms of reusability. In other reports, timber constructions are divided into massive timber structures, post and beam structures and modular systems. However, this division would have classified the log construction, Bosum building system, CLT and IsoTimber, as the same - massive timber structures.

The selection of building systems and joints were made with the expectation that they would be possible to reuse. Additionally, we wanted to include conventional building methods, such as the stud frame. When comparing joints, more conventional options could have been used. Our selection was based on low environmental impact and what we thought would be easy to reuse, this turned out not to be the case, at least for the wooden joints, hook joint and steel sleeve.

The estimated performance of each building method that was presented in the comparisons, came from assumptions made by the authors and was based on literature studies and interviews. The quality of such a comparison is limited to the sources used, and if using other sources the results may vary. Using Sweden's building sector calculation tool, BM 1.0, where not all materials are included, led to some guesswork, and in some cases replacing a material into a material with similar qualities. Which of course lowers the accuracy of the value presented. The selection of factors also affected the result, for example, all massive timber structures, such as CLT, Isotimber, log construction and

DISCUSSION

Bosum building system are affected negativly by limiting the insulating capacity to U-values. The time lag generated by the thermal mass in those structures, contributes to a comfortable indoor climate.

THE CASE STUDY PROJECT

Working with timber and design for disassembly haven't affected the architecture in the case study project significantly. When comparing the case study project to a conventional timber building, some architecture expressions are prominent. This includes exposing the timber structure to the interior, as well as a generous floor to ceiling height, to ensure that the structure is usable even with changing building regulations.

During the design phase, we tried to limit the number of different dimensions used for the plane modules. This affected the layout of the apartment negatively to some extent. A question was raised on whether or not to optimize the building for reuse, even if it meant sacrificing other qualities. For our case study project, we decided not to take it that far and focused on creating a project for its first users as much as for its second.

We mention how joints have to be accessible, which can imply that they are visible in a design for disassembly project. However, in the case study project the vertical joints are hidden under the installation roof and floor, while the horisontal joints are found behind the walls separating each apartment, thus, no joints will be visible inside the building.

The typically high effort laid on hiding joints, witness about an aesthetics where smooth surfaces are

DISCUSSION

desirable, whereupon wallpaper or paint is commonly used. Choosing wallpapers or paints can be a part of creating a personal home. The wallpaper or paint can stand for identity, tradition and participation.

It would have been fantastic to contextulize the building reassembled in a future project. This would have given us some idea of how the pieces can be put together in a bulding with a different function or design. This excercise could have altered our first design of the building.

FUTURE CHALLENGES

Economy, logistics, and quality ensuring are challenges to overcome when promoting reuse of building material, which haven't been solved within this thesis. Changes within the building industry concerning attitudes and norms, is large step to overcome. Pointing at the potential gians to be made and showing that it is possible to design for reuse of materials, will hopefully contribute to a change in norms, making the building industry transform into a circular economy system.

SCOPE

The focus of the thesis have been on how to reuse building materials, but preventing materials to become of less value are equally important to ensure a susainable use. In this case, the affection for a building can have a large influence on whether or not preventive actions against decay are taken. Therefore, aesthetics should not be overlooked, as it may prolong the building's life.

Another urgent matter is to move towards a building industry where regenerative and low energy demanding materials, such as timber, are norm. Planning for disassembly can be considered the next step to reach a sustainable use of materials.

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Figure 1: Circular economy diagram. Retrieved 2020.05.31 from https://www.anthesisgroup.com/procurement-opportunities-in-the-circular-economy/

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CHALMERS

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