CIRCULAR ART RESIDENCY

Student: Vigdís Bergsdóttir
Courses: Sustainable Architecture, NTNU
Key words: Circular design, Box-in-Box concept, Circular economy and Life Cycle Assessment
Supervisors: Per Kristian Monsen, Alise Plavina and Tommy Kleiven.

ABSTRACT

PURPOSE

The **circular economy** in the building industry is about creating new innovations and solutions to problems that are causing eccessive waste in the world. This waste is harming communities by contributing to GHG emissions in landfills and waste processing but also by harming poorer countries in the world as the western world transport waste to other countries as well. The concept of **circular economy** is a tool we can use to rethink how our economy operates and help us move from the linear economy to a more circular one that enhances sustainability in our society.

DESIGN METHODOLOGY

This essay will address the problem around waste by repurposing an old stable by designing an art residency in Reykjavik, Iceland, and use **Life cycle assessment** in One Click LCA as a methodology to minimize the environmental footprint of the materials in the design. A circularity calculator in One Click LCA was used to measure the circularity of the design. The design methodology of this thesis focuses making a **circular design** by reusing what is already on the site, reuse material from other places in Iceland and then use new materials and design methods that make the design more adaptable and easier to dismantle if the building will be removed.

FINDINGS

The design of this thesis is 76% circular according to the circularity calculator. 91.6% of the mass of materials used in the design are reused and only 1.7% is from virgin materials. That showes that reusing already built concrete creates huge potential for high reuse percentage. 9597 kgCO2e were saved from the atmosphere by reusing materials compared to buying similar new materials. Productions of building materials and extraction of raw materials is very little in Iceland and it is heavily dependent on import over sea. Using materials again instead of landfilling can therefor help the economy.

DEISGN LIMITATIONS

There are already building that have been built with the circular economy in mind but there are not many examples in Iceland. There is a lack of EPDs of materials in Iceland and an EPD of greenhouse plastic does not exist for example.

PRACTICAL IMPLICATIONS

The design could help achieve environmental benefits such as reduced GHG emissions by reducing production related emissions and prolonging lifecycles. Other important factors could be the potential around food growing and lower energy demand that the greenhouse could create but that topic was out of scope in this thesis.

VALUE

The value of this thesis is to show the possibilities of different design methods that help us accelerate the transition from a linear economy to a circular economy.

KEYWORDS

Circular design, Box-in-Box concept, circular economy and life cycle assessment

PAPER TYPE

Master thesis in Sustainable Architecture, Design project

CONTENT

11 SUSTAINABLE CITIES AND COMMUNITIES

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

13 CLIMATE ACTION

1. INTRODUCTION TO THE PROJECT: A CIRCULAR DESIGN

The goal of this project is to design a circular artist recidency for two people by repurposing an old stable in the suburbs of Reykjavík, Iceland. A concept was developed with reuse of materials in mind both straight from the site and then from local markets that resell reusable building products. A life cycle assessment (**LCA**) was used as a tool to develope the design further and into more details when new materials were added to it.

Designing from the inside out was the starting point in this project; looking first at what I have in hand (the site and the materials on site) and then what could be done with it. Instead of thinking in terms of bringing resources from the outside, a focus was set on using resources that have already been transported to Iceland. According to the 2021 Pritzer prize winners Anne Lacaton and Jean-Philippe Vassal, we should never demolish as quoted „Always consider what is already there, this memory and life that existed there before, even in difficult conditions" (Vimeo, 2021).

After reading and collecting information on projects, research and reports about the **circular economy** in the building industry, I came to the conclusion that it is still very unclear what this concept includes and defenitions vary from a simple sentence to a whole paragraph. According to the Ellen MacArthur foundation the concept of **the circular economy** is about creating interconnected solutions to meet interconnected challenges, such as climate change, biodiversity loss, waste and pollution (Ellen MacArthur Foundation, 2021). This circularity is not only about how we treat materials in the economy but also about how we fundamentally live our lives. It can vary from reusing bricks from an old building to harvesting seeds from a home garden made with compost from your waste. It can be about fostering a healthy connections between people as the circular economy requires close connectinos and co-operation to find new purposes around the waste we create. It is even about building disciplined responsibility around caring for the building over its lifetime. As this thesis has a limited time frame here at NTNU, the focus was set on reusing materials and therefor lowering consumption of new materials. Starting from all the information about the **circular economy** and by working on my own project I landed on my own definition that resonated better for my design work:

Circular design (conceptual description): A circular building is a building that meets nature midway in its lifecycle by adapting to its circular flow of resources while bringing joy within and outside the building's boundary.

Circular design (technical description): A circular building is a building that has been designed and built with minimal waste creation and minimum extraction of virgin materials in mind while using research based tools to reflect on all significant design decisions. First step is reducing the amount of materials needed and then reusing as much as possible of existing materials.

2. INTRODUCTION TO THE PROBLEM: WASTE

*Image from the Slow Factory Foundation (The Slow Factory Foundation, 2020)

WASTE IN THE EU

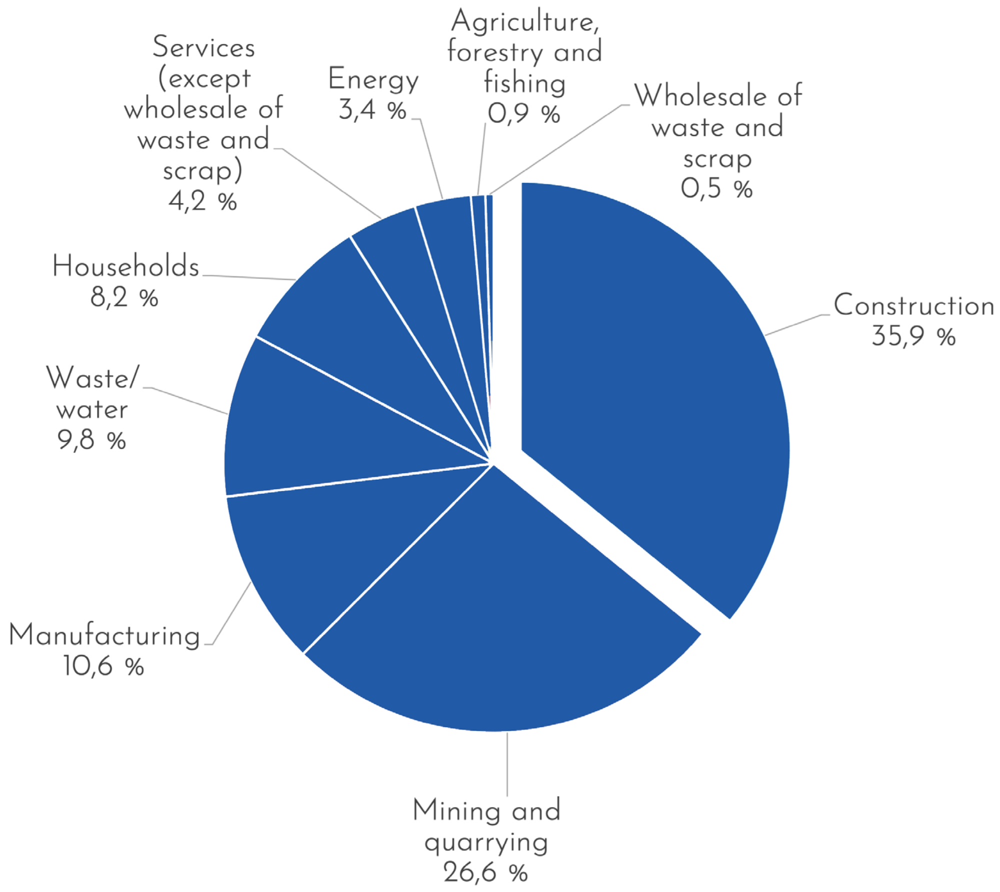
According to the EU in 2018, 5 tonnes of waste is produced by the average European each year, only 38% of waste in the EU is recycled and 38.5% landfilled. Landill takes up land space and causes pollution in air, water and soil. One of the main objectives for EU's transition to a **circular economy** is limiting landfilling (European Union, 2018).

WASTE DISPOSAL IN UNDERDEVELOPED AREAS/COUNTRIES

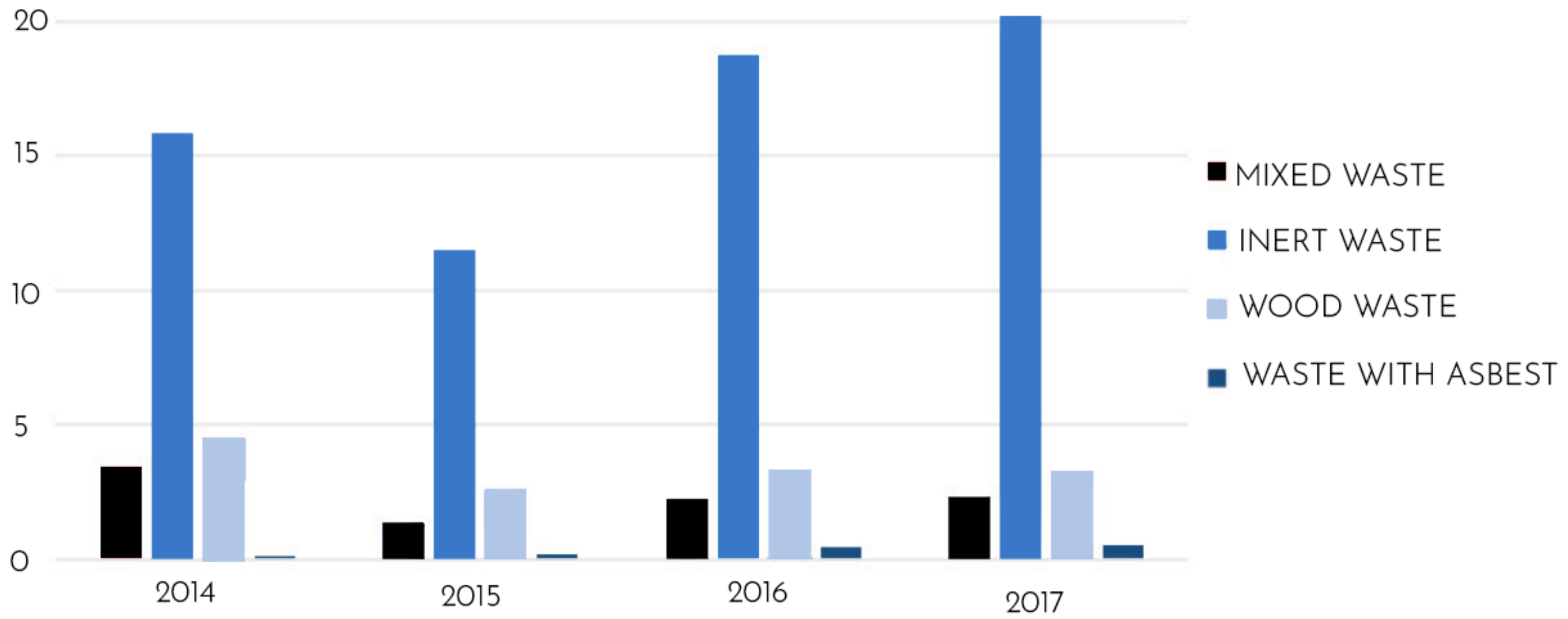
The practice of exporting hazardous waste to developing countries through end-of-life vessles in richer countries is a good example of how serious the problems can be around waste in a linear economy. The developing countries lack knowledge, political organization or capital to resist the practise and to treat the waste in a safe way. That creates serious health and pollution problems in those countries (Giriyan et al., 2008).

WASTE CREATED IN THE BUILDING INDUSTRY

Construction and demolition in this industry is the biggest source of waste in the EU and is around 1/3 of all the mass of waste created. The waste consists of concrete, bricks, gypsum, wood, glass, metals, plastic, solvents and excavated soil. Well controlled recovery of these materials could lead to high sustainability gains. It is done by direct reuse of materials after demolition, recycling of materials or backfilling. Backfilling is currently the most used recovery of waste in the EU but has the least sustainability gains of the three mentioned (Europeam comission, 2018). This applies to Iceland as well. Inert waste is by far the biggest part of construction waste created and is mainly backfilled at the end of the lifetime (Sigurbjörnsdóttir, Þ. A., Svavarsson, G. , 2019).



*Waste generation by economic activities and households, EU, 2018, (% share of total waste) (Eurostat, 2018).



*Waste from the construction industry in Iceland is divided into 4 different categories. In 2017 Inert waste was the largest categorie with 15-20 tonnes each year and consists of concrete, creamic, class and such waste. Wood waste comes after that, where wood is either landfilled or put into energy recovery (Sigurbjörnsdóttir, Þ. A., Svavarsson, G. , 2019).

3. INTRODUCTION TO THE TOOLS: LCA AND CIRCULARITY CALCULATOR

ONE CLICK LCA

According to the Slow Factory Foundation it is essential to understand the waste streams in a linear economy to develop a **circular economy**. **Life Cycle Assessment** (LCA) is the tool to identify the total environmental impact of the product (the building) (The Slow Factory Foundation, 2020). In this project the LCA tool is used to calculate the greenhouse gas emissions from new materials in the building in accordance to EN 15978 or NS 3720 (One Click LCA Life Cycle assessment tool, n.d.). One click LCA has developed a circularity assessment tool that measures the circularity of buildings (One Click LCA circularity assessment tool, n.d.). These two tools were used as the research based tools needed to reflect all significant design desicions.

OTHER TOOLS

The building was designed by handsketching and then moving into AutoCAD for more detailed design. The program SIMIEN was used to calculate the energy use of the building in combination with the One Click LCA tools. Excel was used to store data and calculate as well as work more with data from One Click LCA and SIMIEN.

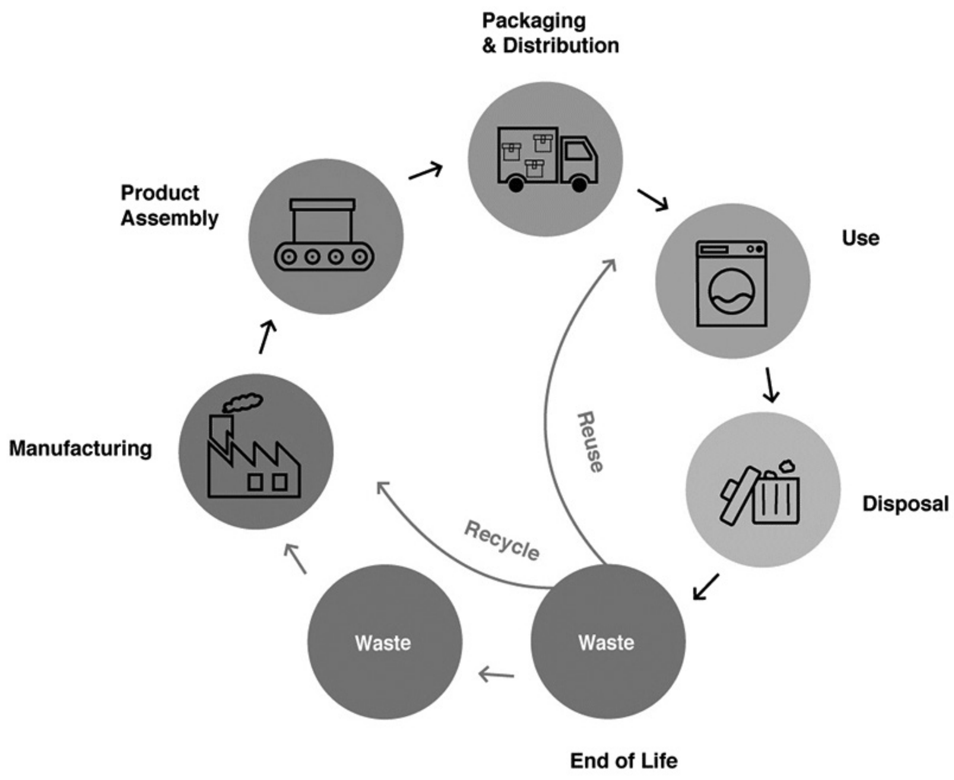
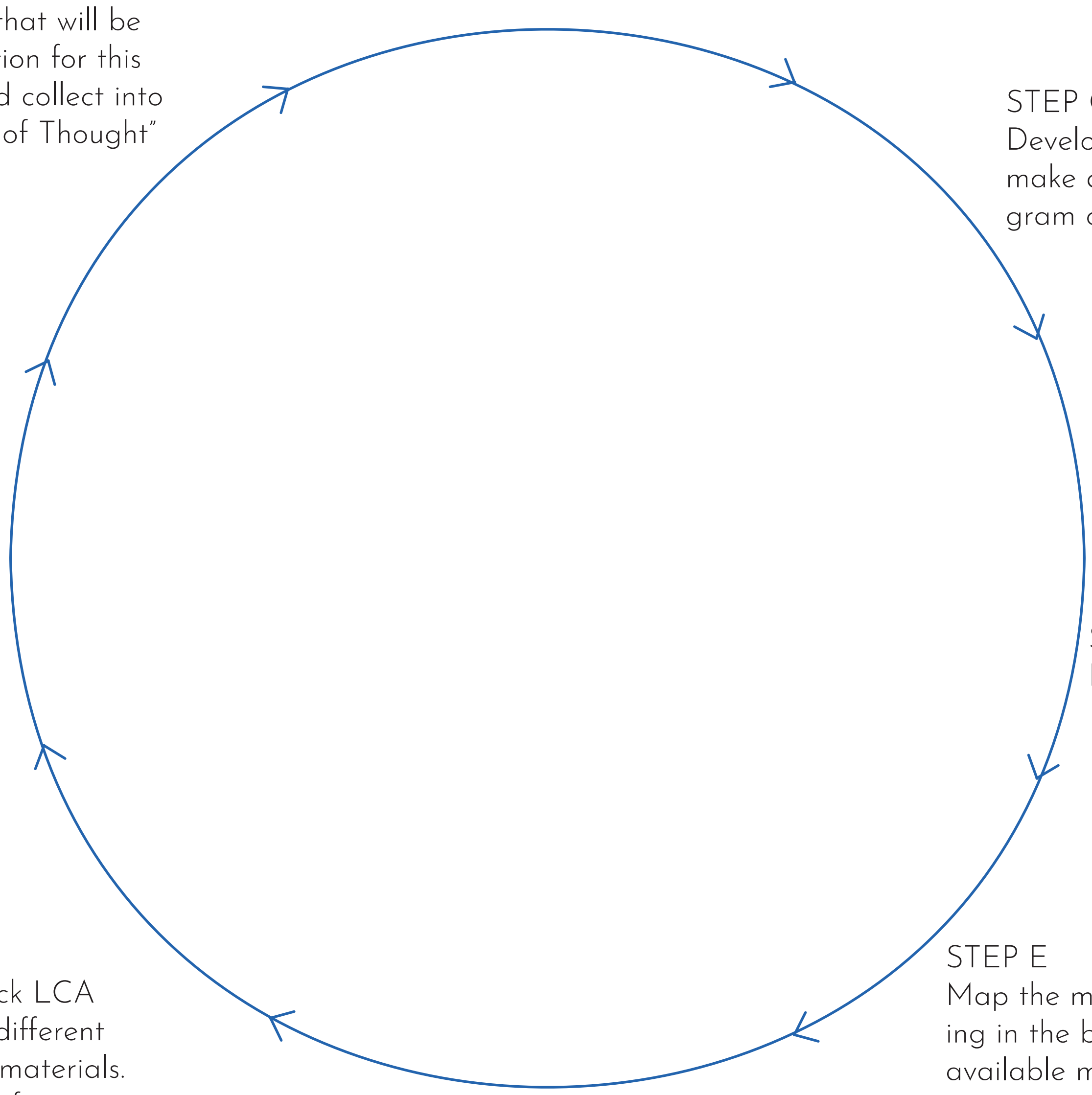


*Image from the Slow Factory Foundation (The Slow Factory Foundation, 2020).

4. STEP PROCESS



STEP A
Literature review of existing research on the topic and making notes to remember. Read about different CE tools and what to use. Read into artists and designers that will be an inspiration for this project and collect into a "Library of Thought" document.

STEP B
Collect and analyse information about the site (climate, weather, landscape, local services and so on).

STEP C
Develop a concept and make an environmental diagram of the design.

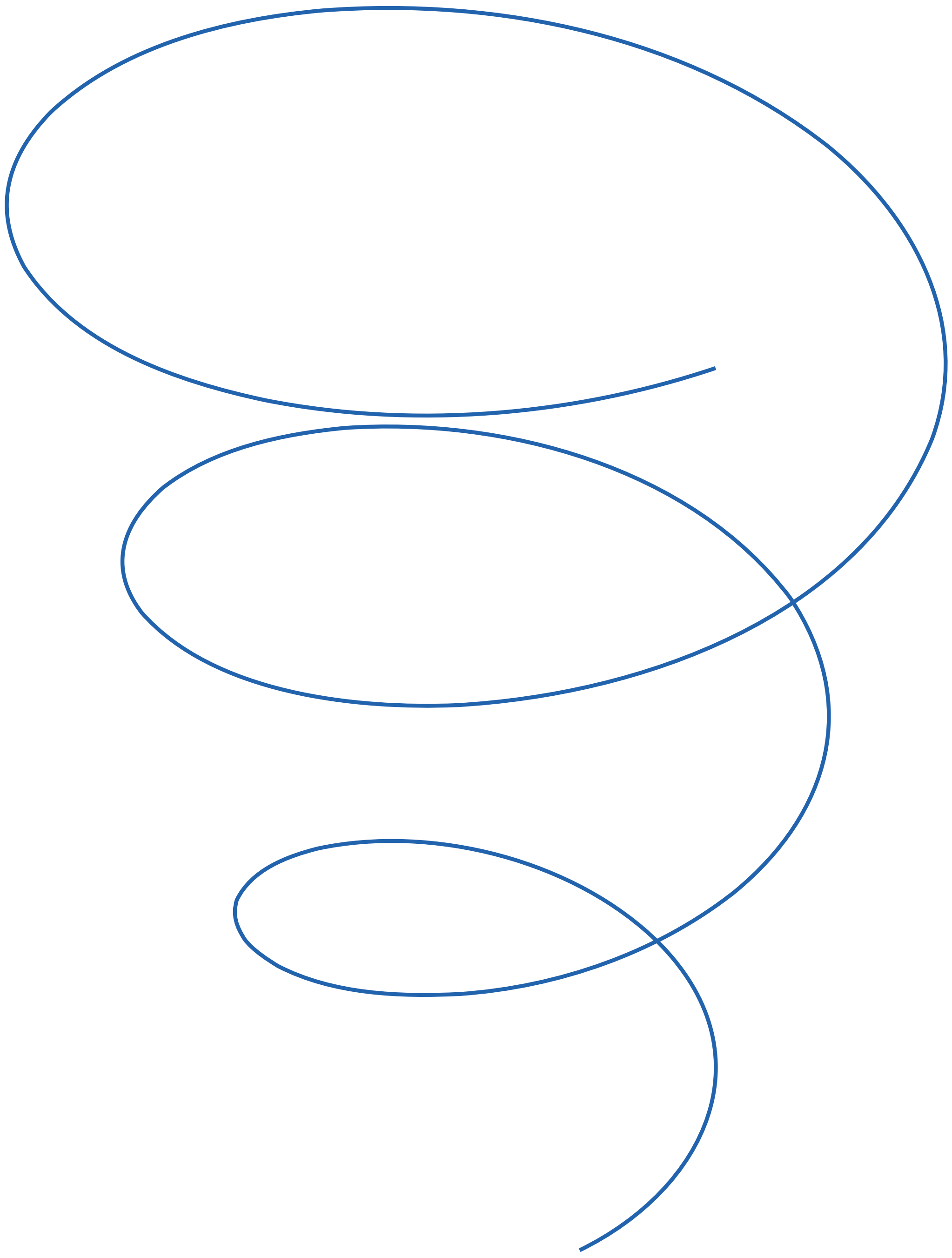
STEP D
Develop a floorplan.

STEP E
Map the materials existing in the building and available materials for reuse in Iceland.

STEP F
Evaluate what materials are needed according to the design and what is reasonable to do in relation to my current knowledge.

STEP G
Use One Click LCA to compare different options and materials. Use SIMIEN for energy calculations.

STEP H
In this phase the creation of the final product starts. Here it is in the form of a thesis.



INSPIRING PROJECTS

Here I show four inspirational projects that had the strongest impact on me in the design process.

1. UNINSULATED GREEN-HOUSE SPACE

Designer: Yoshichika Takagi + Associates

Location: Hokkaido, Japan (43°N and 142°E).

The project: Renovation of a house built in 1974 in Hokkaido. By adding an uninsulated extended part with semi translucent polycarbonate facade that serves as a greenhouse, windbreak room and a "dirt room". The project is located in one of the coldest regions in Japan with cool summers and icy winters. The project brought inspiration for the use of an unheated buffer space in a cold climate and how a translucent facade can look on a big scale with openable glass windows installed into it.

2. CENTERED COMMON SPACE

Designer: Yasuyuki Kitmura

Location: Osaka, Japan

The project: The concept of the design was to build a house were people would co-exist with nature with a vague boundary. The house is organized like a box-in-box concept where the boxes with the basic functions like bedrooms, restroom and kitchen are located on the east and west side while the center has more freedom as a common living and work area. Over the center area is a semi translucent roof that creates lightness in the room. That brought inspiration for the arrangement of a floorplan in a **box-in-box concept**.

3. REUSE OF CONTAINER
Designer: IMPACT FARM CPH by HUMAN HABITAT

Location: Copenhagen, Denmark (55°N and 12°E).

The project: **circular design** that reused a container by locating it within an uninsulated wooden frame building with a translucent polycarbonate facade.

4. HIGH REUSE OF MATERIALS
Designer: La Paisanita Refuge by STC Arquitectos

Location: Cordoba, Argentina (31°N and 64°W).

The project: **Circular design** where materials for the design were recovered, processed in a workshop and transferred to the site for assembly. The technical solutions and rest of the materials were picked with local climate and low environmental impact in mind.

5. CONCEPT DEVELOPEMENT

THE CLIMATE

Iceland is a rather cold island located in the north Atlantic. It is in the subartic climate zone, within 63°-68°N and 21°-13° W. This means the winter is long with fluctuating cold weathers and summer is short with cool or mild weather. The island has an average temperature ranging from -3°C to 1.9°C in the coldest month and 8.3°C to 13.3°C in the warmest month. The northern location of the Island results in change in the day length with great difference in light between seasons. (Ingólfsson, Ó., n.d.).

THE GEOGRAPHY

The nature in Iceland is very extreme compared to the Scandinavian countries, with lack of trees in the landscape to protect for rather frequent and sometimes strong winds. In Iceland the energy from the sun has very little effect on heating surfaces during winter because of the low sunlight. It is not until 20th of Febuary that the corner of the sun becomes 15° and the sunlights starts to make a difference (Petersen, G. N., Berber, D., 2018). The energy from the sun was measured between 2008-2018 by the local weather station in Iceland. On a horizontal plane it is minimum in January as 1,8 kWh/m2 and highest in July as 139,8 kWh/m2. The monthly average is 64,8 kWh/m2 and over the year the total is 777,2 kWh/m2 (Þrastarson, S., 2019).

SUNPATH

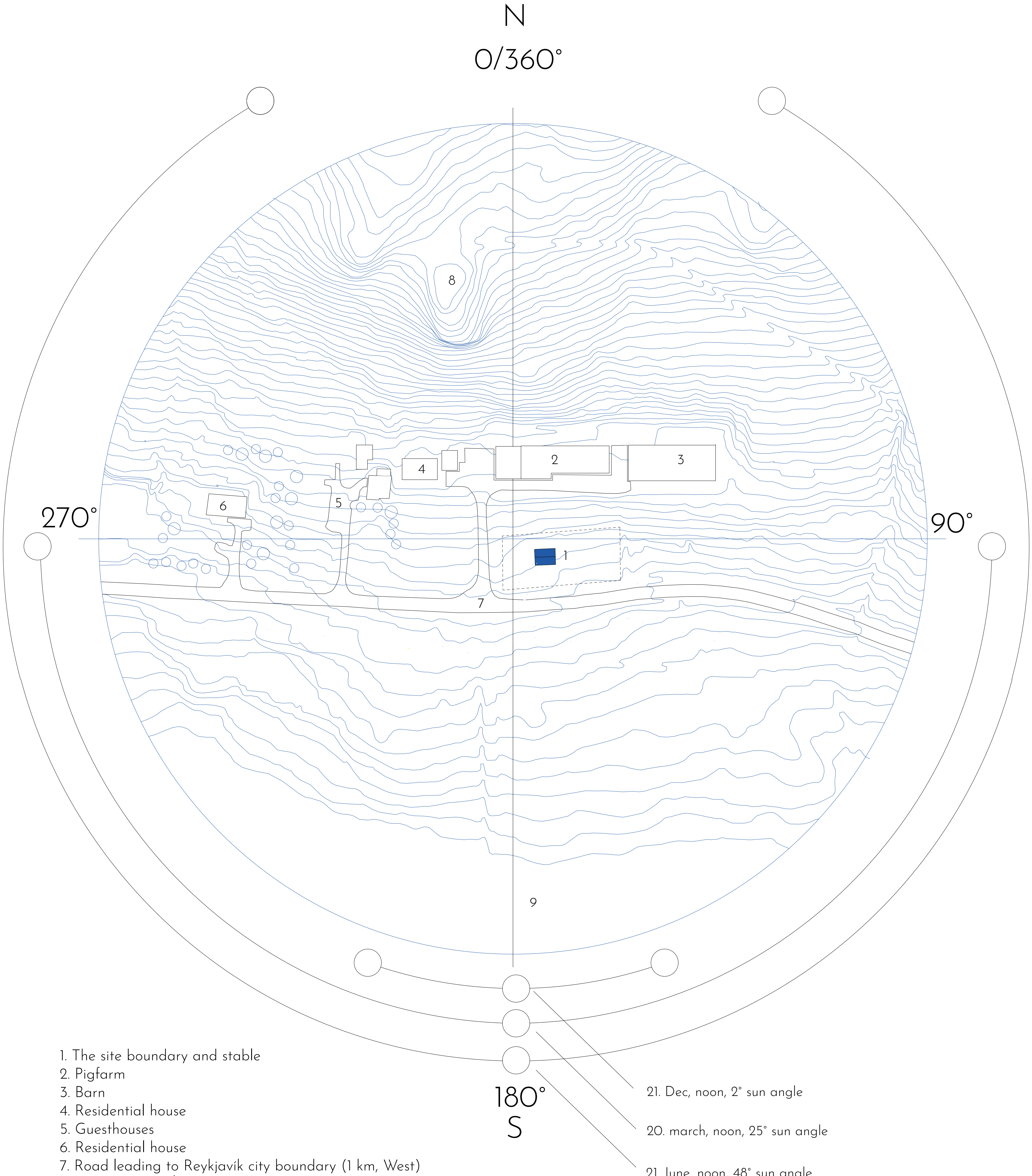
Information about the sunpath around the site was assembled in local epw weather files. The location of the site can be seen on the site map to the right. The difference of the sun-angle is large between summer and winter. The sun has little obstruction to the site but the only obstruction is the morning sun in spring, summer and fall from the east because of a hill. An angeled roof can make a difference in capturing the energy from the sun. A 40° roof has been calculated to have the optimum angle for solar panels in Iceland (Þrastarson, S., 2019).

WINDROSE

Information about wind was collected from a local epw weather file. The prevailing wind direction in fall, winter and spring is from the east. The wind can go up to 25.2 m/s and storms are frequent. Therefor snow can easily assemble on the west side of the house. Growing trees or a forrest east of the building would be a good option. In summer the wind is quite evenly distributed around the house but comes mostly from the north. The house is positioned to the south of a mountain and gets shelter from the cold wind from the north.

VIEW

The site has a high quality view to the east, south and west. From the east and south is a long view over a valley, mountains, volcanos, lake, vegetation and grazing animals. The west shows a view over the city Reykjavík.



1. The site boundary and stable
2. Pigfarm
3. Barn
4. Residential house
5. Guesthouses
6. Residential house
7. Road leading to Reykjavík city boundary (1 km, West)
8. Mountain top Úlfarsfell, popular hiking trails
9. Valley Úlfarsfellsdalur, future outdoor activity area

*1 m contour lines on the map

THE SITE

After a month of reading into inspirational design solutions and research for a **circular design,** my design sketches and ideas all seemed to point towards a house that includes a greenhouse technology in some way. The next step was then taken towards going deeper into the topic of greenhouses to understand them as structures, why we build them and how they would work in Iceland.

WHAT IS A GREENHOUSE

A greenhouse is a structure where the exterior walls and roofs are made out of transparent or translucent materials. The sun shines through the transparent/translucent material and is absorbed by the the objects and surfaces inside the greenhouse. The heat is unable to leave the greenhouse easily. This forces the air inside to heat up more than the outside air, and creating a microclimate (Souza, E., 2021).

WHY GREENHOUSES WERE BUILT

The use of Greenhouses in tempered climates in Europe can be traced back to when Europe was suffering a cold period called the Little Ice Age. Glass was not easy to come by and produce in this time so the only glass that was used for trapping heat from the sun was a small-scale bell jar placed on top of a plant and horse manure was used to create extra heat inside the jar. The structure for large-scale greenhouses had no glass and were only a thermal wall built and placed with southern exposure to create a microclimate to help with growing crops. If the walls were placed densely the effectiveness of the microclimate was much higher. The wall reflected sunlight and absorbed heat that was released by night and made the temperature near the wall up to 10°C warmer than the surrounding climate. The methods of building these walls were different based on the climate. In France the walls were straight lines, in the Netherlands the walls had curves that made the microclimate warmer and in England they were more active and put extra heat inside the wall in the form of fire or heated water. When production of glass became easier, a glass structure was added on the south side of the thermal wall to make the microclimate even more effective. Eventually when production of glass was cheaper the thermal wall was replaced by a glass wall and the glass structure we know today as a greenhouse took over (Decker, K., D., 2015).

GREENHOUSES IN ICELAND

Greenhouses started to show up in Iceland around 1930, when the horticultural society came up with the idea of using geothermal energy for heating them (*The mythical Banana Kingdom*, 2013). The typical design of greenhouses was a rectangular glass house with a pitched roof that was heated with ducts of geothermal water. The ventilation was passive by placing long windows on the top of the roof, creating a stack effect. Today greenhouses are a very common sight around the island.

PASSIVE SOLAR DESIGN IN ICELAND

Even though greenhouses in Iceland are generally built with produce growing in mind the technology has been used for passive solar heat gains in dwelling design.

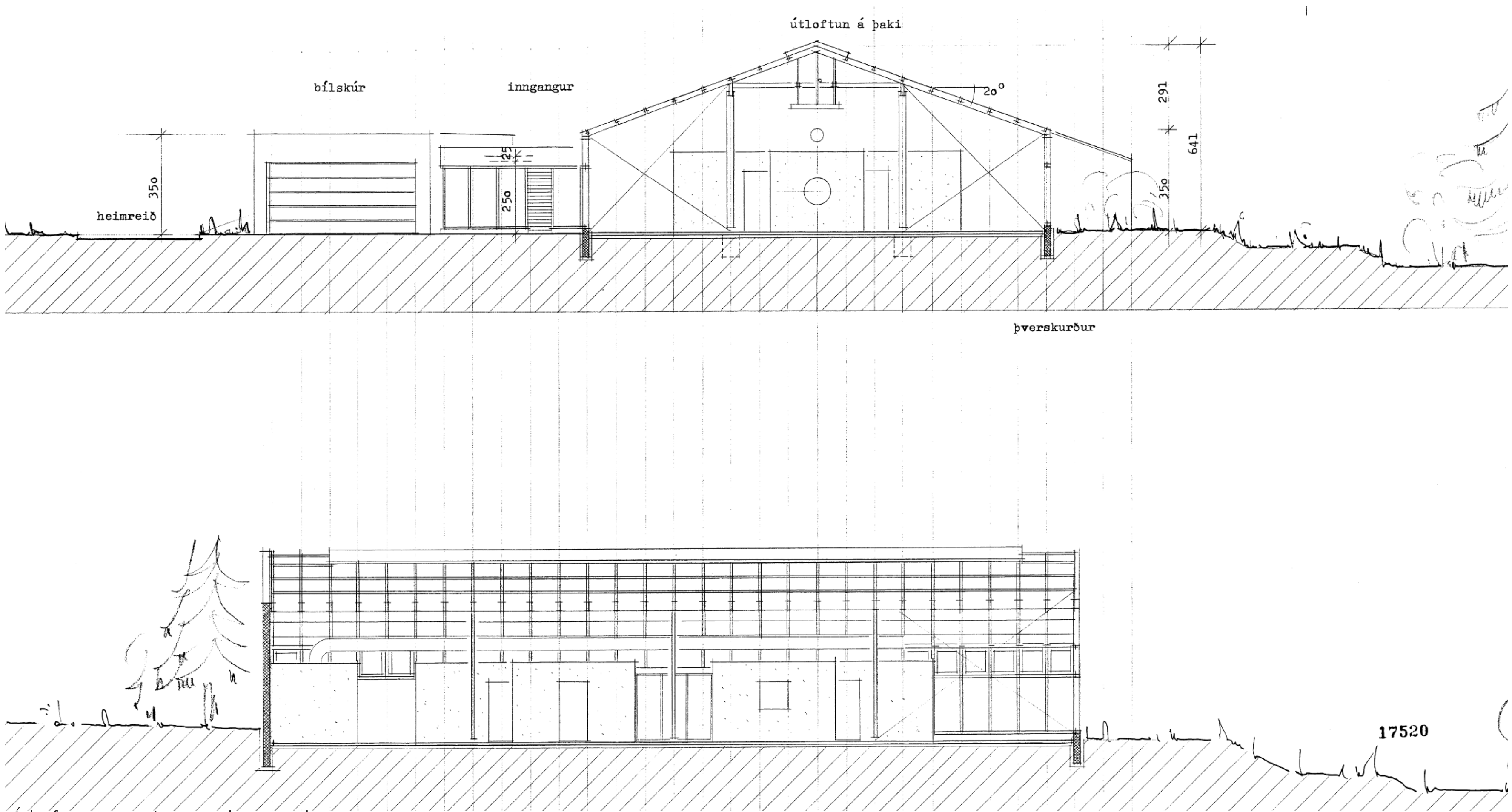
Two Icelandic architects experimented with this concept as a so called **box-in-box concept:**

The first one is Ólafur Sigurðsson who in 1998 designed and built a 460 m2 greenhouse as a weather buffer around his 100m2 house (see figure to the right). There are no windows on the inner house but sliding doors are all around it that can easily be opened to the weather buffer. His wife grows plants and trees that can only grow in warmer climate zones than Iceland. The house uses district heating and the temperature in the greenhouse is kept at 20 degrees Celcius by opening and closing a long window on the ridge of the roof. The ceiling height is quite high to achieve this and there is a heat sensor in two-meter height to monitor it. On the long sides of the greenhouse are 20 meters of windows that can be opened. Even in the middle of winter, if the sunshine is enough, they can sit outside in the greenhouse. The spring comes 2 months earlier and fall starts 2 months later. The materials in the outer box are timber and glass (5mm in walls and 6mm in roof) with the east facade made out of cocrete and the box inside is concrete and timber (no added insulation) (Kristján, 2006).

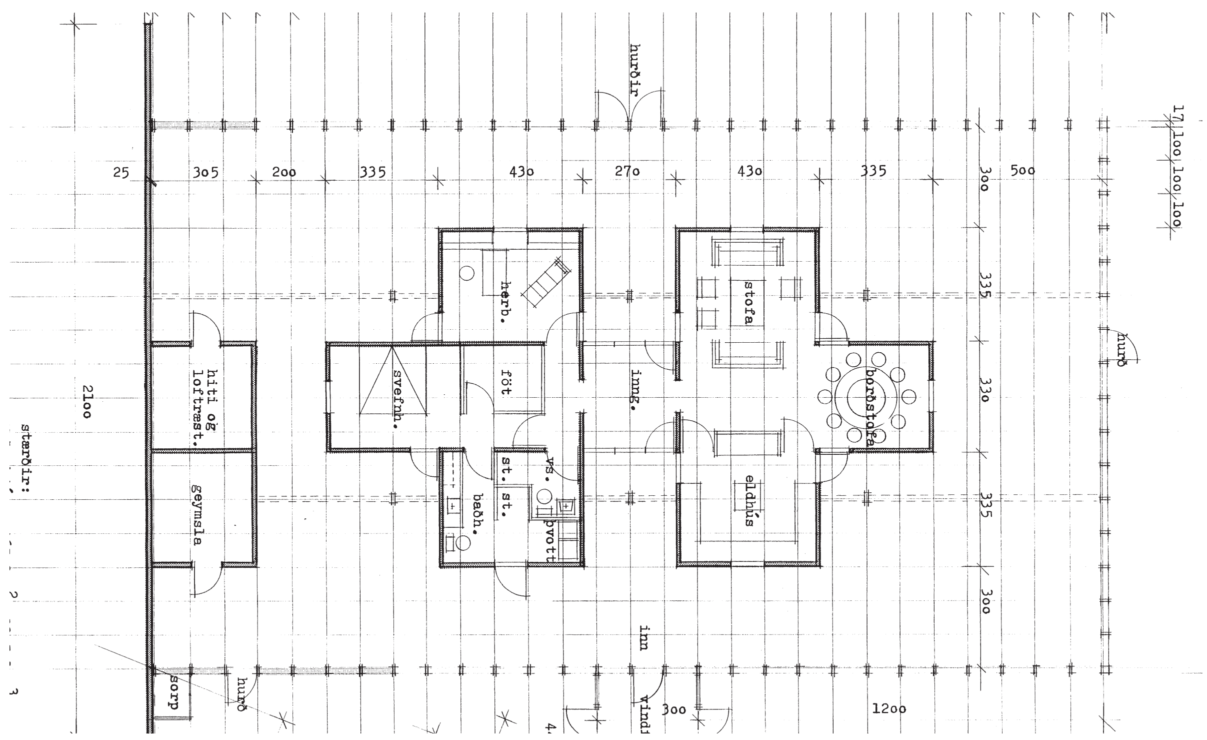
The second architect that has experimented with the **box-in-box concept** in Einar Þorsteinn Ásgeirsson. He was an Icelandic architect and a follower of a global architecture movement created by Buckminster Fuller in the 1970s. That movement introduced a greenhouse structure in the form of a dome to reduce heat loss. One of Einar's projects was a dwelling built in 1994 in the south of Iceland. The house is shaped as a dome and the south, west and east facing side is entirely glass. The house is heated actively and ventilated naturally with stack ventilation. The same woman has lived in this house for 27 years and thinks it is highly comfortable to live in (*Þótti klikkuð að vilja byggja kúluhús, 2019).*

GREENHOUSES IN **CIRCULAR DESIGN**

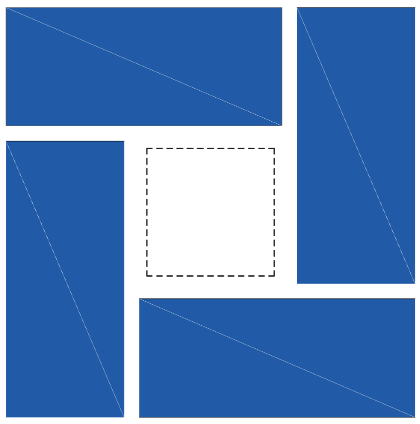
The two architects that won the 2021 Pritzker prize in architecture, Anne Lacaton and Jean-Philippe Vassal, have been passioned by greenhouses as a technology for many years and made numbers of project with the **box-in-box concept**. The fact that it protects from the cold or from warm while still allowing lightness of the structure and good performance with saving energy. With their thinking around architectural design they have used the greenhouse rechnology to repurpose older building and with that shown that demolision-rebuilding is not a neccesary approach (Vimeo, 2021).



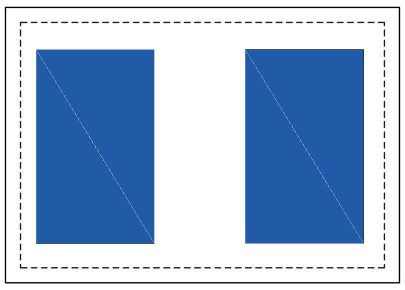
Ólafur Sigurðsson, box-in-box



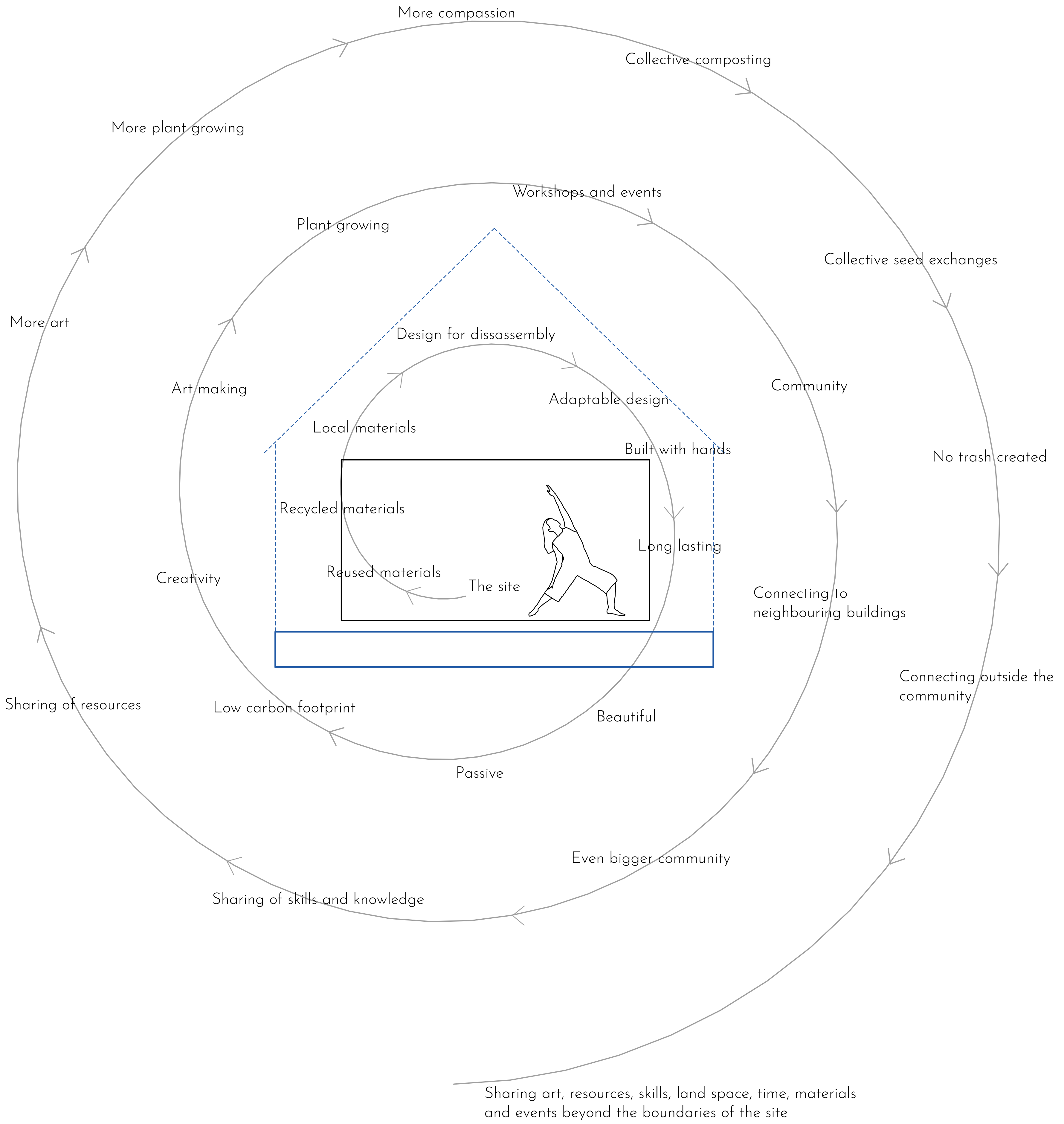
NO GREENHOUSE:
The first concept idea began by speculations on only making minimal changes, while improving the existing building and using the concrete foundation as it is.



GREENHOUSE IN MIDDLE:
The next concept idea was to put a greenhouse in the middle as a courtyard and surround it with reused containers with continuous insulation on the outside. The floorplan would need extra foundation. After some exploration, containers were not considered to be a good option for reuse in this context.

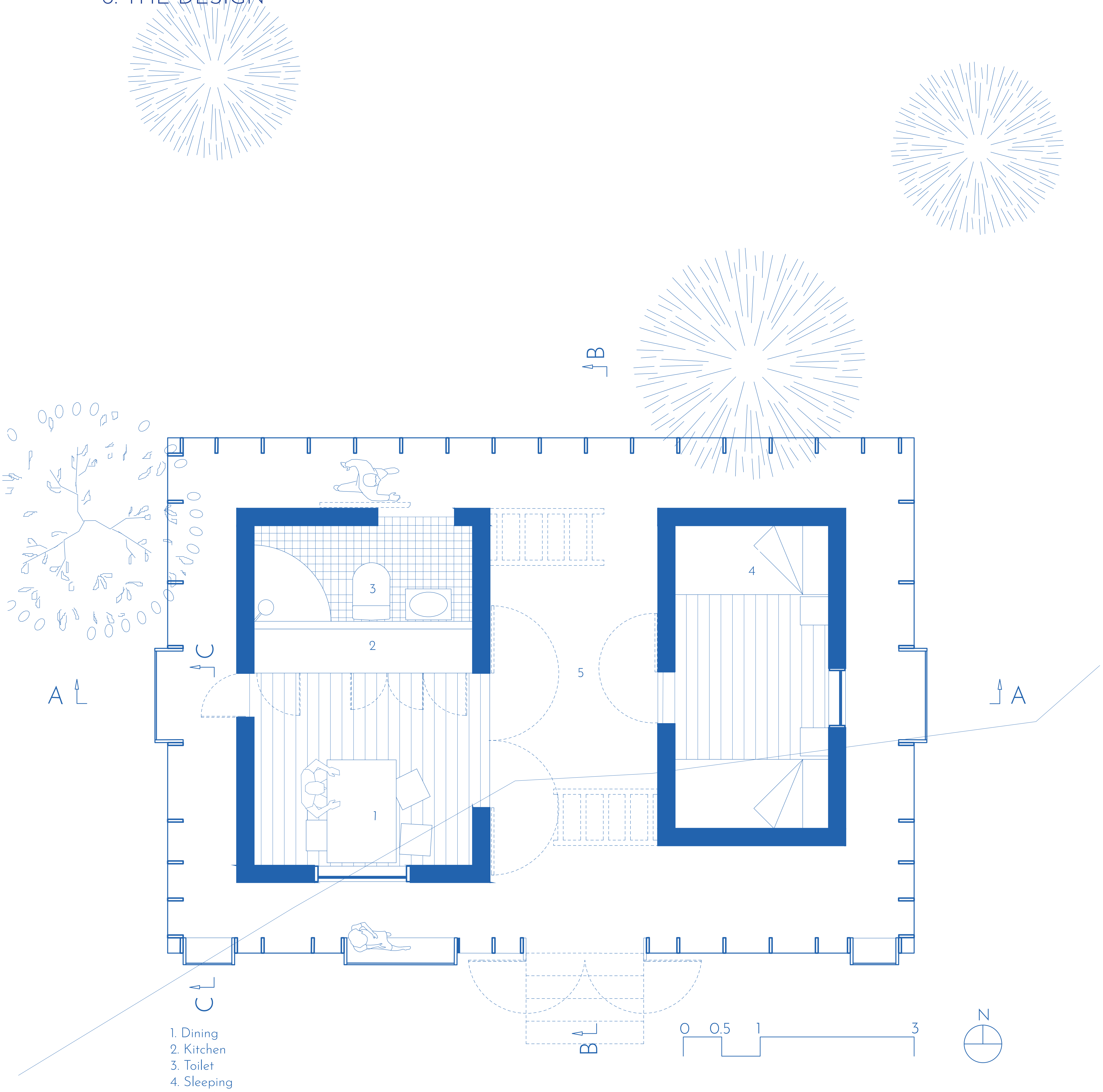


GREENHOUSE AROUND:
The third and final concept was to surround insulated boxes with a greenhouse and reuse materials in the boxes that would be protected from the weather by the greenhouse.

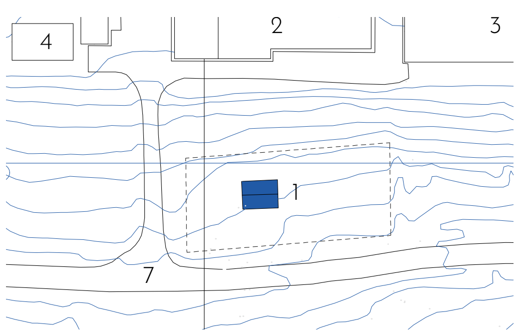


THE FINAL CONCEPT: BOX-IN-BOX

6. THE DESIGN

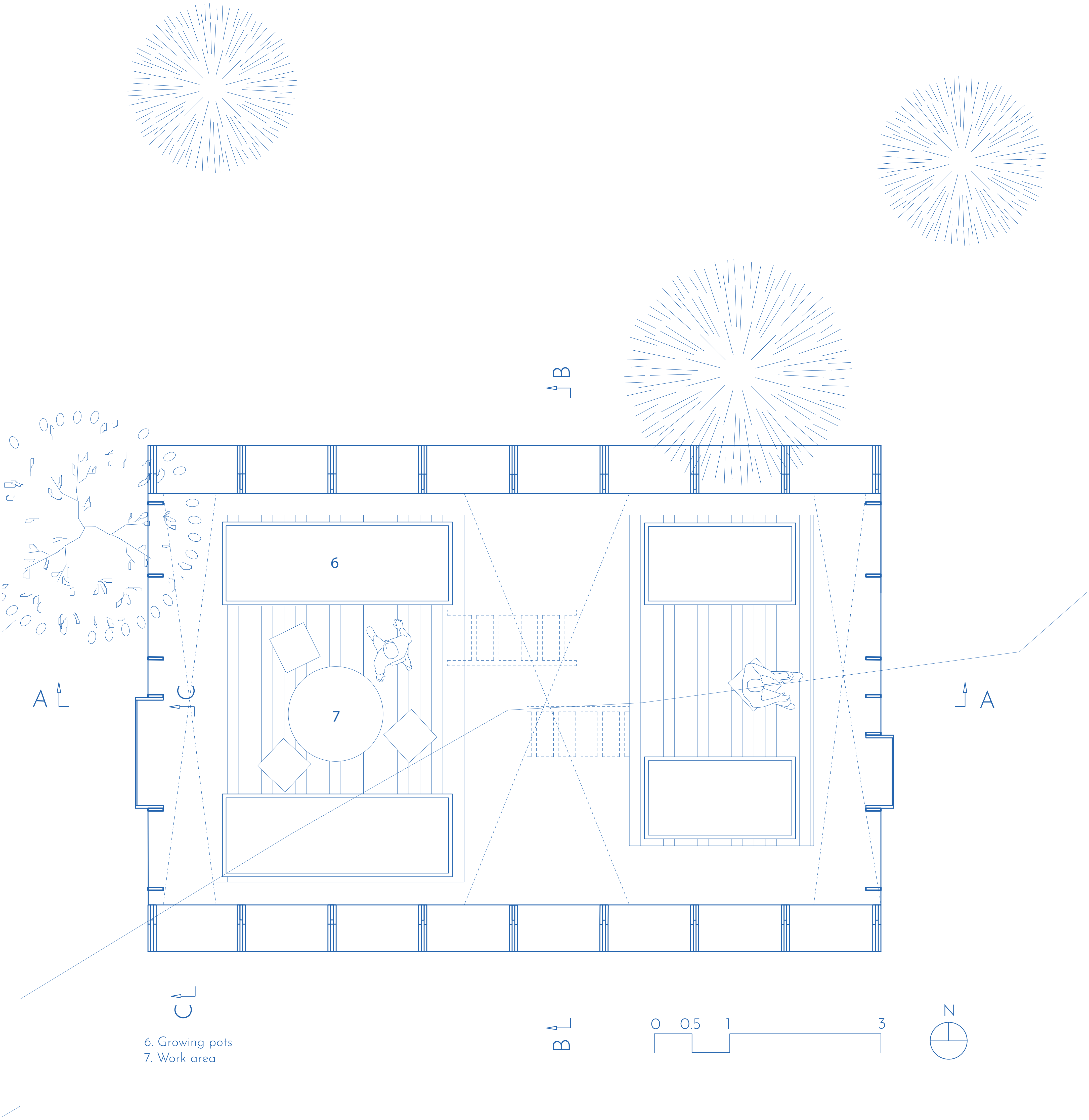


1. Dining
2. Kitchen
3. Toilet
4. Sleeping
5. Freedom area



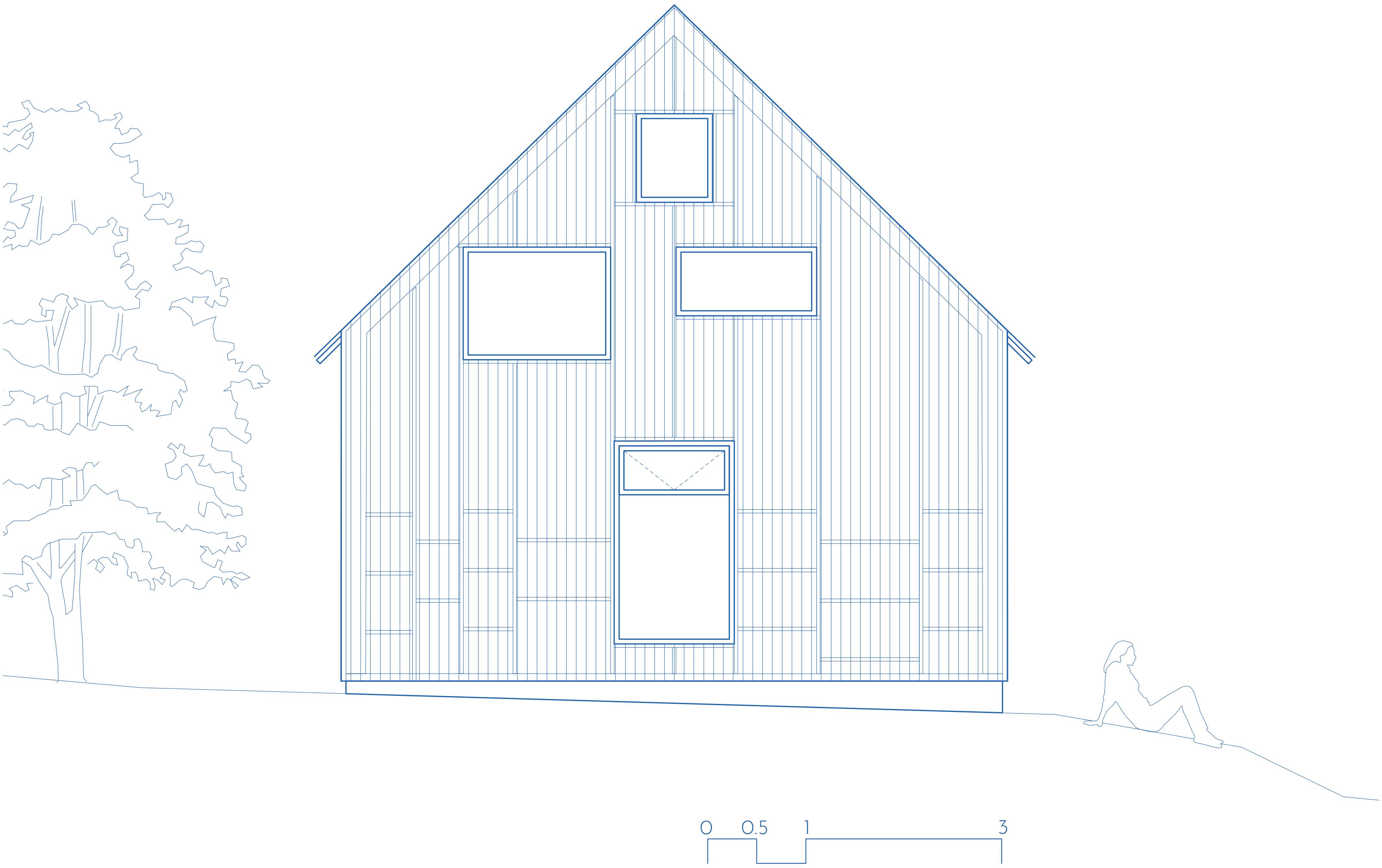
FLOOR PLAN, 1ST FLOOR, 1:50, A3

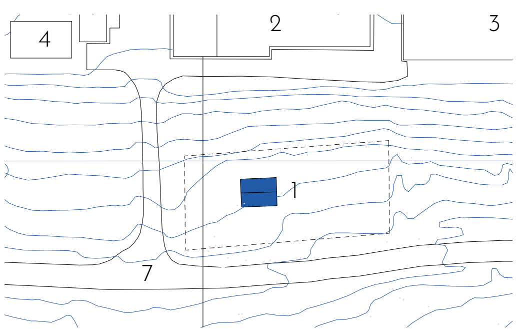
The floorplans are made as simple as possible and in a minimalistic style to highlight the flexibility of the space. The space could need to change with each artist as their work and methods are unique and unpredictable. Therefor the design focuses on providing a space that is more like a canvas for the artist and provides basic needs for him. The inside boxes of **the box-in-box** concept have the main things that are needed; kitchen and dining area, toilet, shower, beds and small storage under the beds. The outer box (the greenhouse) provides a colder space used for storage and workarea with shelter from the weather and good view and light. Extra clothing would be needed in that space .



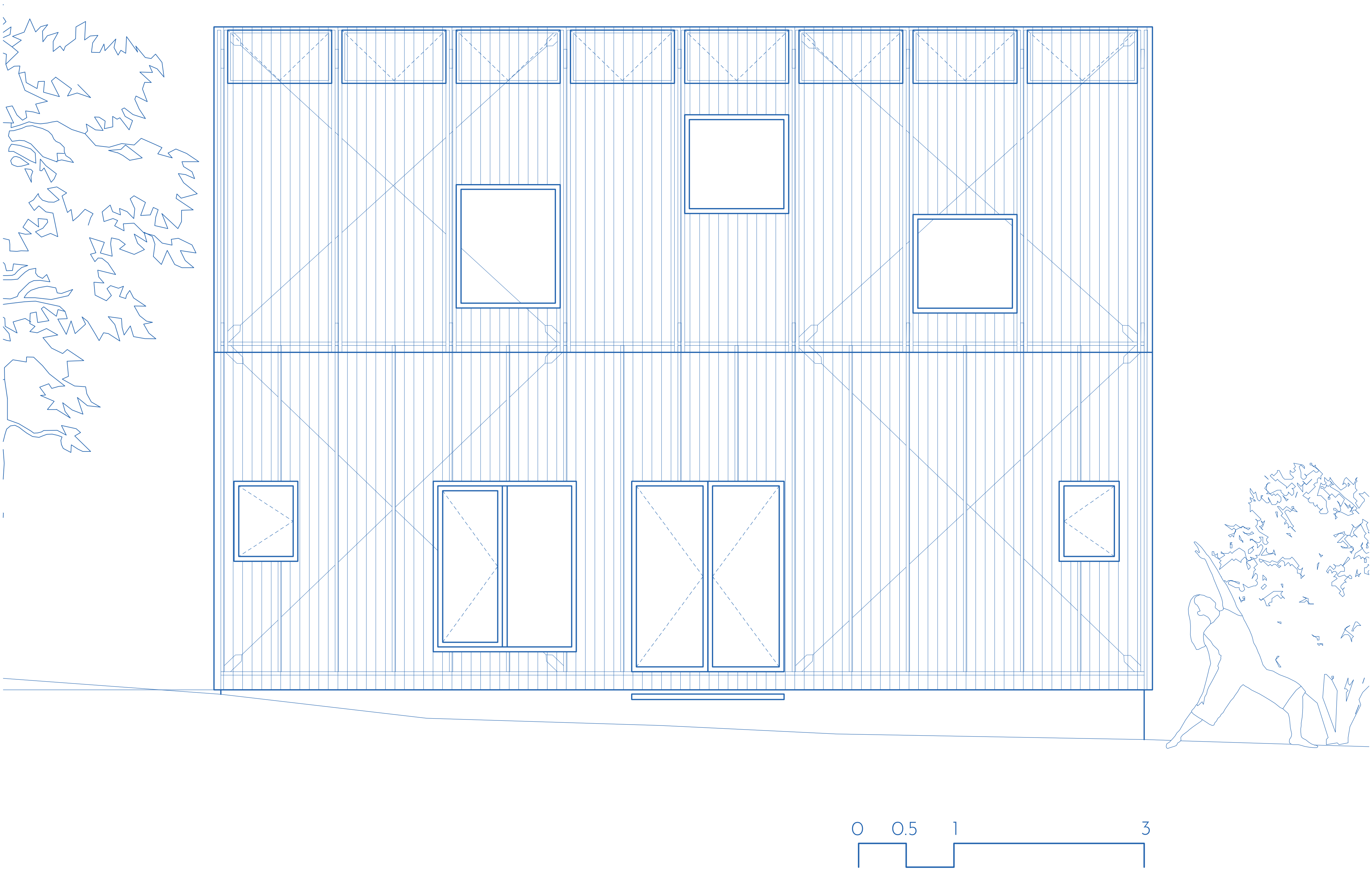
FLOOR PLAN, 2ND FLOOR, 1:50, A3

The second floor is only a space in the outer box (the greenhouse) of the **box-in-box** concept. the rooftops of the inner boxes provide a space for the artist to work. As the greenhouse facade is only semi translucent there are windows placed on the west, east and south to provide a view.

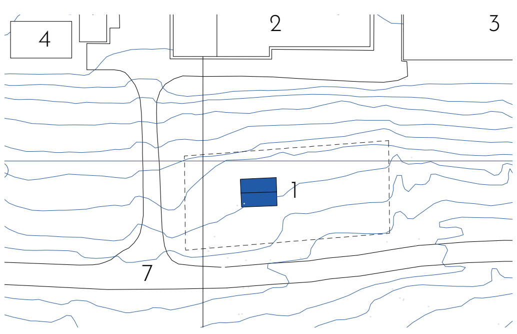




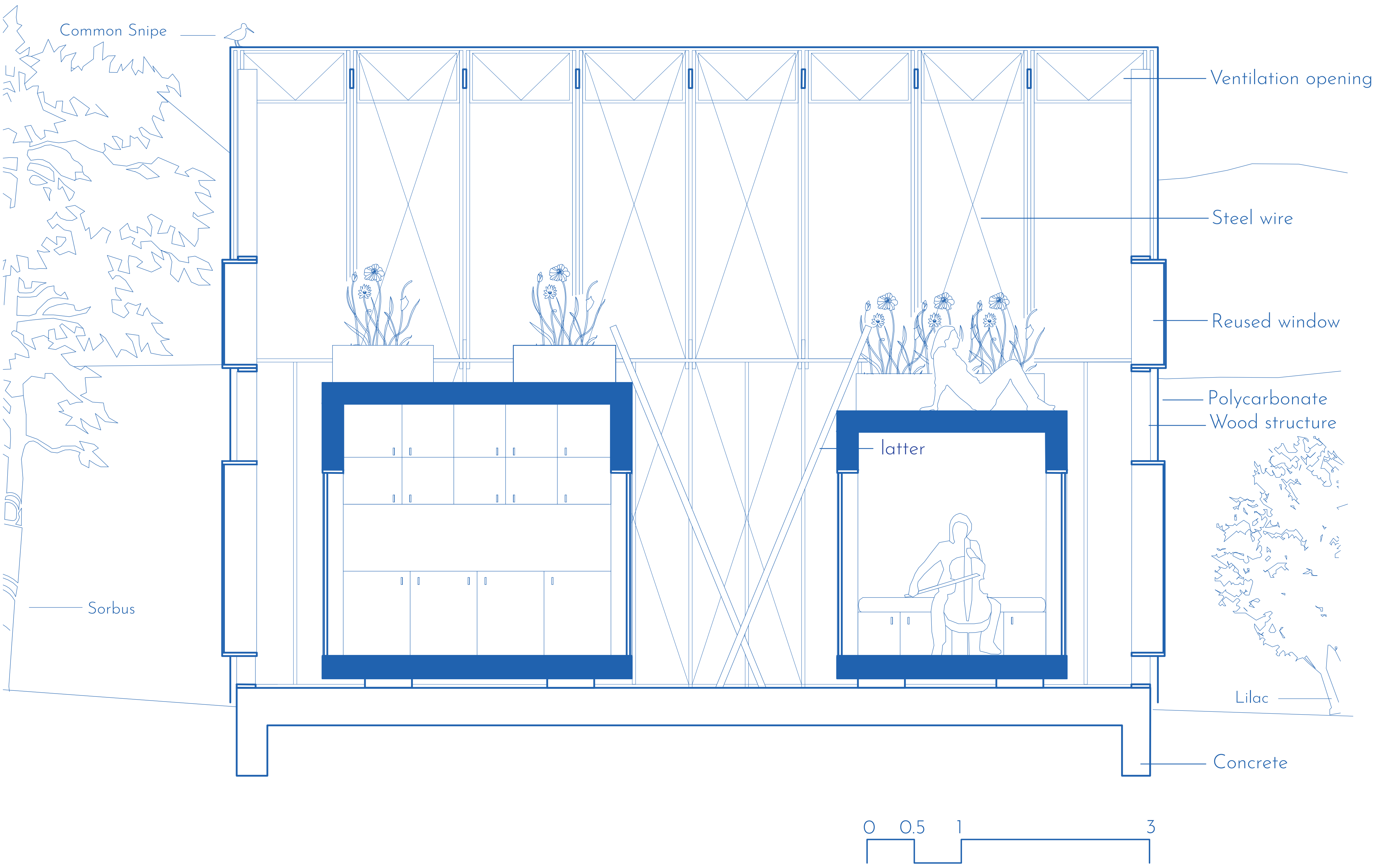
ELEVATION WEST, 1:50, A3

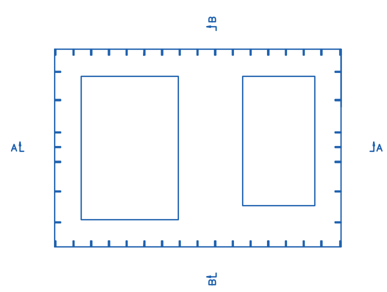


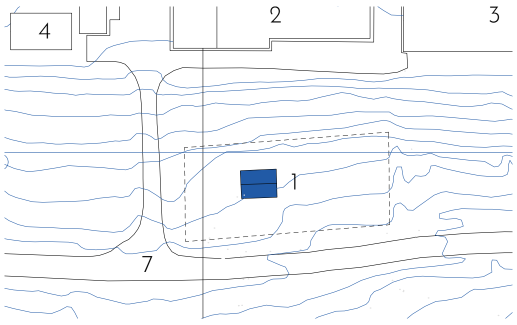
ELEVATION SOUTH, 1:50, A3



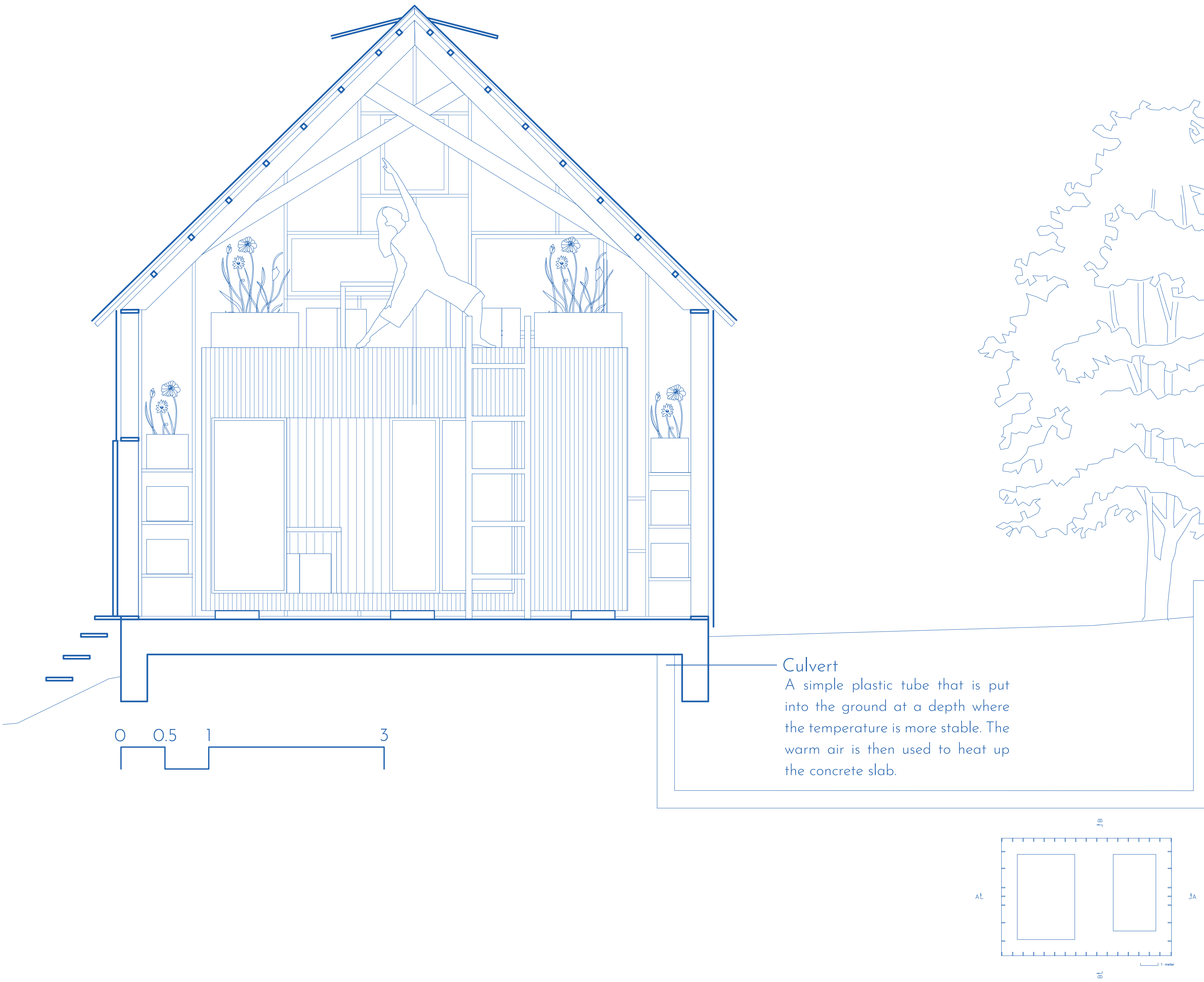
SECTION A-A, 1:50, A3


Common Snipe
Ventilation opening
Steel wire
Reused window
Polycarbonate
Wood structure
latter
Sorbus
Lilac
Concrete
0 0.5 1 3





SECTION B-B, 1:50, A3


Culvert
A simple plastic tube that is put into the ground at a depth where the temperature is more stable. The warm air is then used to heat up the concrete slab.
0
0.5
1
3

7. REDUCE, REUSE AND RECYCLE

REDUCING

Reducing the amount of materials needed for the design is best done by making a floorplan for that purpose. Simple and clean design that provides a freedom for the user and adaptability for future changes.

REUSING

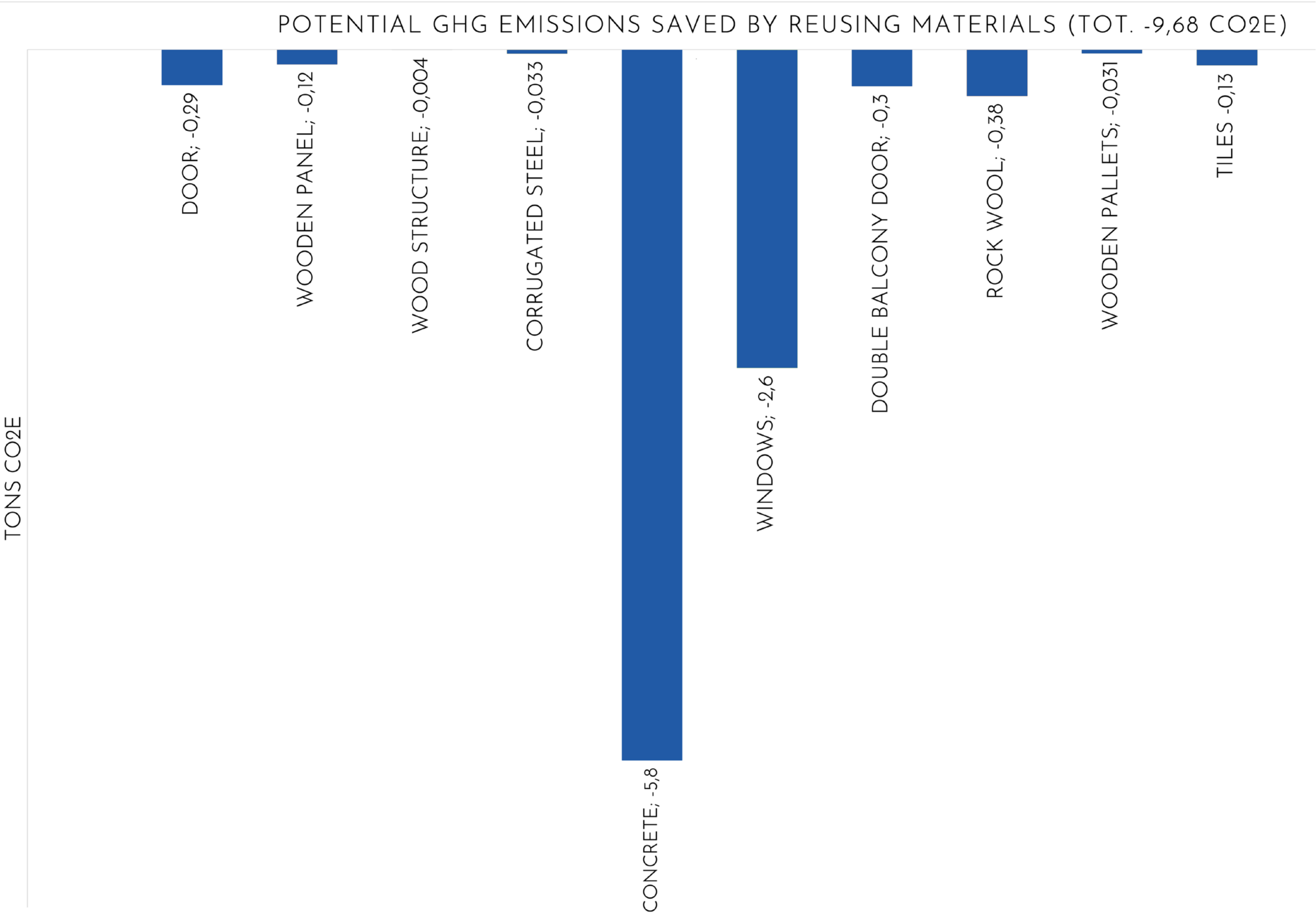
As the site has already a building on it, the materials on site will be reused as much as possible. In table to the right are the results from the mapping of materials in the building. The materials went through visual inspection and were photographed. A decision was made, based on this information, for which material could serve a new building lifetime and wich were unusable. Reusable materials not found on this project site, can be purchased at markets reselling used materials. The main reseller used in this project is Efnismiðlun Sorpu that is located 10 km from the site. The main materials that can be found there are timber pallets, containers, mineral wool, windows, sink, toilets, tiles, showers and construction wood cut-offs. In 2020 they sold 12.6 tons of tiles and 17 tons of timber for reuse. (Efnismiðlun magntaka, 2020). The impact of emissions from reused materials was considered as zero in the **life cycle assessment** for the new design as more detailed calculations were out of scope for this thesis. In the graph to the right the materials are compared to similar products, or products that would have been used instead, to see the potential GHG emissions saved. The embodied emissions of the compared materials include the phases A1-A3, B1-B5 and C1-C4.

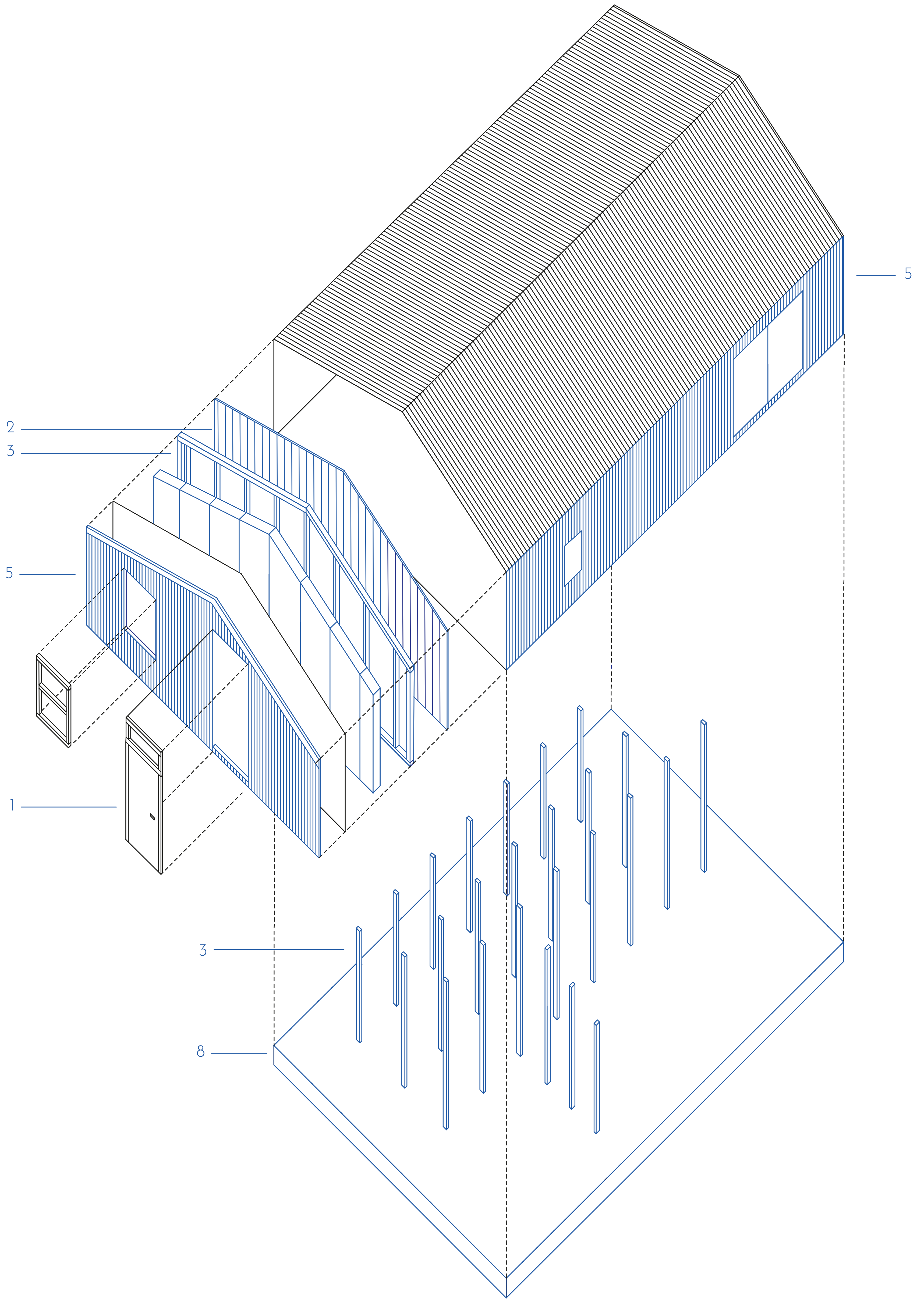
RECYCLING

Using new materials that have been made out of waste materials is important in a **circular design**. Example building products that can be made out of recycled waste are metal products, wood chip insulation, PVC pipes and more. Recycled materials are included in the EPDs of susch products that comes into the calculation of the life cycle assessment of the new design.

NUMBER	MATERIAL FROM SITE	USABLE/UNUSABLE	QUANTITY	UNIT	NEW PURPOSE
1	Door	100% usable	2	pc	Door in box
2	Wooden panel	100% usable	30	m2	Interior finish in box
3	Wood structure	90% usable	1,5	m3	Structure in boxes, rest for energy recovery
4	Wood in roof	Unusable	40	m	Energy recovery
5	Corrugated iron	80% usable	80	m2	Cladding for boxes, rest for recycling
6	Plastic foam, glasswool and mineral wool	50% usable (mineral wool)	30	m2	100% Incineration
7	Windows	Unusable	2	pc	50% Landfill, 50% Energy recovery
8	Concrete	Usable	26	m3	Foundation
9	Outdoor	Unsable	3	pc	100% landfill
10	Wind and vapor barrier	Unusable	50	m2	100% landfill
	MATERIAL FROM SECOND HAND MARKET		**QUANTITY**	**UNIT**	**NEW PURPOSE**
	Window		13	units	Windows in greenhouse
	Double balcony door		2	units	Entrance to greenhouse
	Rock wool		36,9	m2	Insulation in boxes
	Wooden pallets		12	units	Support under boxes
	Tiles		30,4	m2	Surfaces in the bathroom

*Overview of materials from the old building. Rows with colored outline are reused in the new design. Data collected with visual inspection.

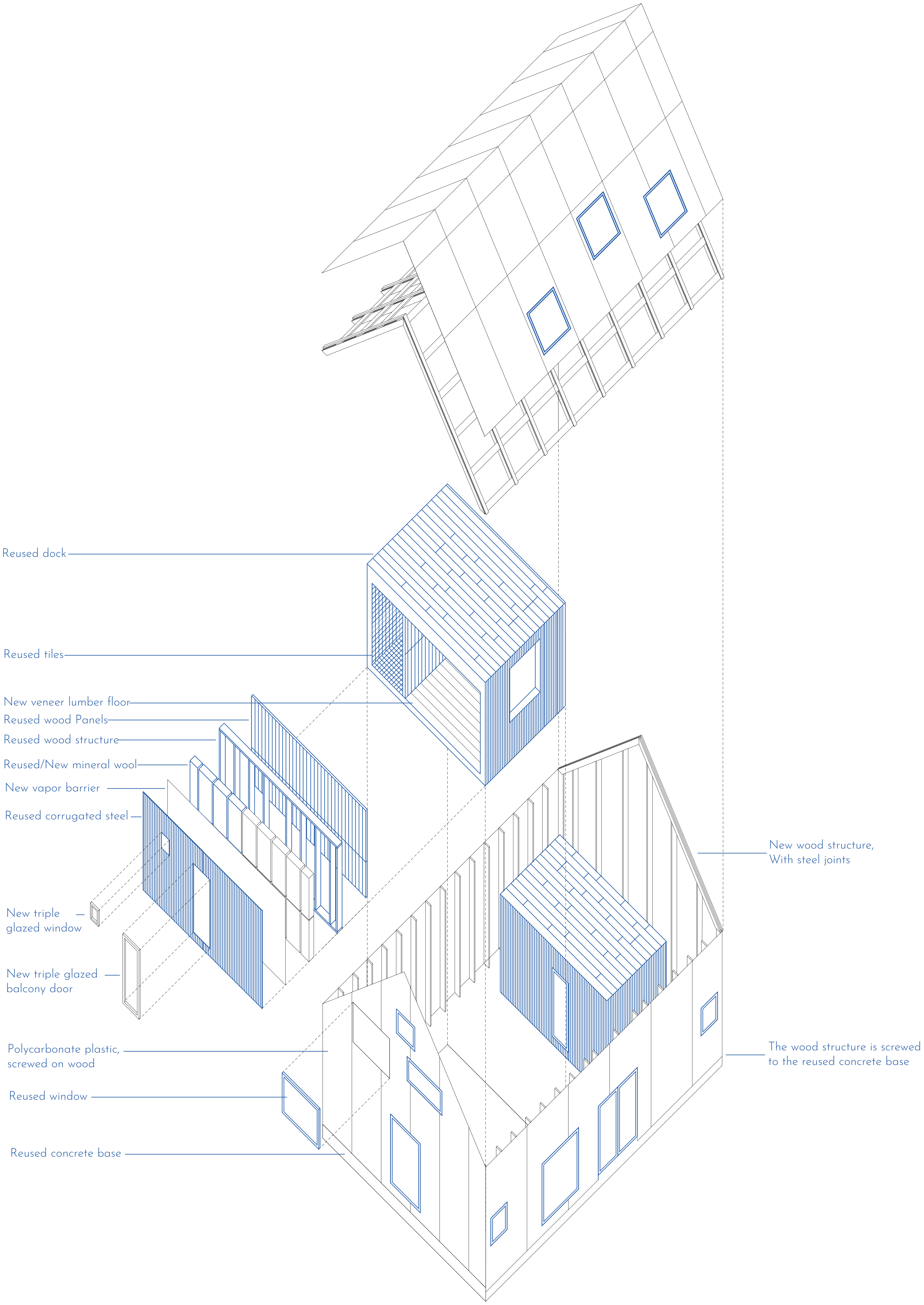




AXONOMETRIC OLD BUILDING, 45°-45°, 1:100

*Blue color represents reusable materials

Building element	NS 3451	Product group	Material	Sourced (% Reused/recycled/new)	EPD	Transport (Yes/No)	Quantity	End of life	Lifetime	Comment
Foundation/ substructure (21)	215	Construction foundation	Concrete	100% Reused		No, on site	26m3	100% Backfilling	60	
Foundation/ substructure (21)	214	Steel wires for the greenhouse	Steel	100% New	EPD-ARC-20200193-CBA1-EN	Yes, Germany	420m (0,13m3)	88% Recycling, 11% Reuse and 1% Landfilling	60	Calculated as if 6 wires were braided into a rope around a central wire.
Structural frame (22)	222	Separate colums of the greenhouse	Construction wood	100% New	NEPD-308-179-EN	Yes, Norway		100% Energy reconvery	60	
Structural frame (22)	223	Separate beams of the greenhouse	Construction wood	100% New	NEPD-308-179-EN	Yes, Norway		100% Energy reconvery	60	
External wall (greenhouse) (23)	235	Exterior finishing of the greenhouse	Polycarbonate sheets (2100 x 7000mm)	100% New	INIES_ DGRA20191220_143140, 13649 used as a reference but made 50% lower as it should be around 7,6 kgCO2e/kg	Yes, Germany	219m2 x 16mm	100% Incineration	30	Iceland transports PVC from Germany
External wall (greenhouse) (23)	234	Doors for the greenhouse	Reused balcony doors	100% Reused		Yes, on site	2 units	50% Landfill, 50% Energy recovery	30	NEPD00258E used as reference for waste and maintainance
External wall (greenhouse) (23)	233/234	Windows for view out of the greenhouse	Reused windows	100% Reused		Yes, Reykjavik	6 units	50% Landfill, 50% Energy recovery	30	NEPD00258E used as reference for waste and maintainance
Internal walls (boxes) (24)	241/242	Bearing structure of the boxes	Wood	100% Reused		No, on site	1,295 m3	100% Energy recovery	60	
Internal walls (boxes) (24)	241/242	Insulation of the boxes	150-300mm Rockwool	50% New, 50% Reused	NEPD-1856-803-EN	Yes, Northern Iceland	14,76 m3	100% Landfill	60	
Internal wall (boxes) (24) (24)	246	External wall coverings	Corrugated galvanized iron	100% Reused		No, on site	88,2 m2	100% Recycling	60	
Internal walls (boxes) (24)	246	Internal wall coverings (bathroom)	Tile adhesive	100% New	S-P-00911	Yes, Italy	0,125 m3	100% Landfill	30	
Internal walls (boxes) (24)	246	Internal wall coverings (bathroom)	Tiles	100% Reused		Yes, Reykjavik	30,4 m2	100% Backfilling	30	
Internal walls (boxes) (24)	246	Internal wall coverings (ceiling included)	Wood panel	100% Reused		No, on site	94,7 m2	100% Energy recovery	60	
Internal walls (boxes) (24)	246	Vapour barrier (all surfaces)	Classic vapour barrier	100% New	NEPD00273N	Yes, Norway	141,8 m2		60	
Internal walls (boxes) (24)	244	Doors	Balcony glass door, wood frame, 1.23 x 2.18, U-value 0,84	100% New	NEPD00258E	Yes, Norway	3 units	50% Landfill, 50% Energy recovery	60	Lifetime extended 20 years because of greenhouse cover
Internal walls (boxes) (24)	244	Windows	Wooden frame window, 1.23 x 1,48, triple glazed, U-value 0,62	100% New	NEPD-1574-601-EN	Yes, Norway	2 units	77,8% Landfill, 21% Energy recovery, 1% Recycling	60	Lifetime extended 20 years because of greenhouse cover
Ground floor/ Upper floors (Including separating floors) (25)	251	Decks on top of the boxes (second floor)	Wooden boards	100% Reused		No, on site	26,7 m2	100% Energy recovery	60	
Ground floor/ Upper floors (Including separating floors)	255	Flooring of the boxes	Veneer wood flooring	100% New	S-P-01338	Yes, Sweden	20,5 m2	100% Incineration	25	Floor clicked togeather and therefor no need for tools or chemicals.
Roofs (26)	261	Supporting structures	Construction wood	100% New		Yes, Norway	1,947 m3	100% Energy recovery	60	
Roofs (26)	262	Roofing	Polycarbonate plastic	100% New		Yes, Norway	3,2 m2	100% Incineration	30	
Roofs (26)	263	Skylights	Reused windows	100% Reused		Yes, Reykjavik	2 units	50% Landfill, 50% Energy recovery	30	NEPD00258E used as reference for waste and maintainance
Stairs/balconies (28)	281	Int. Stairs	Wooden moveable latter	100% New		No	0,5 m3	100% Energy recovery	60	

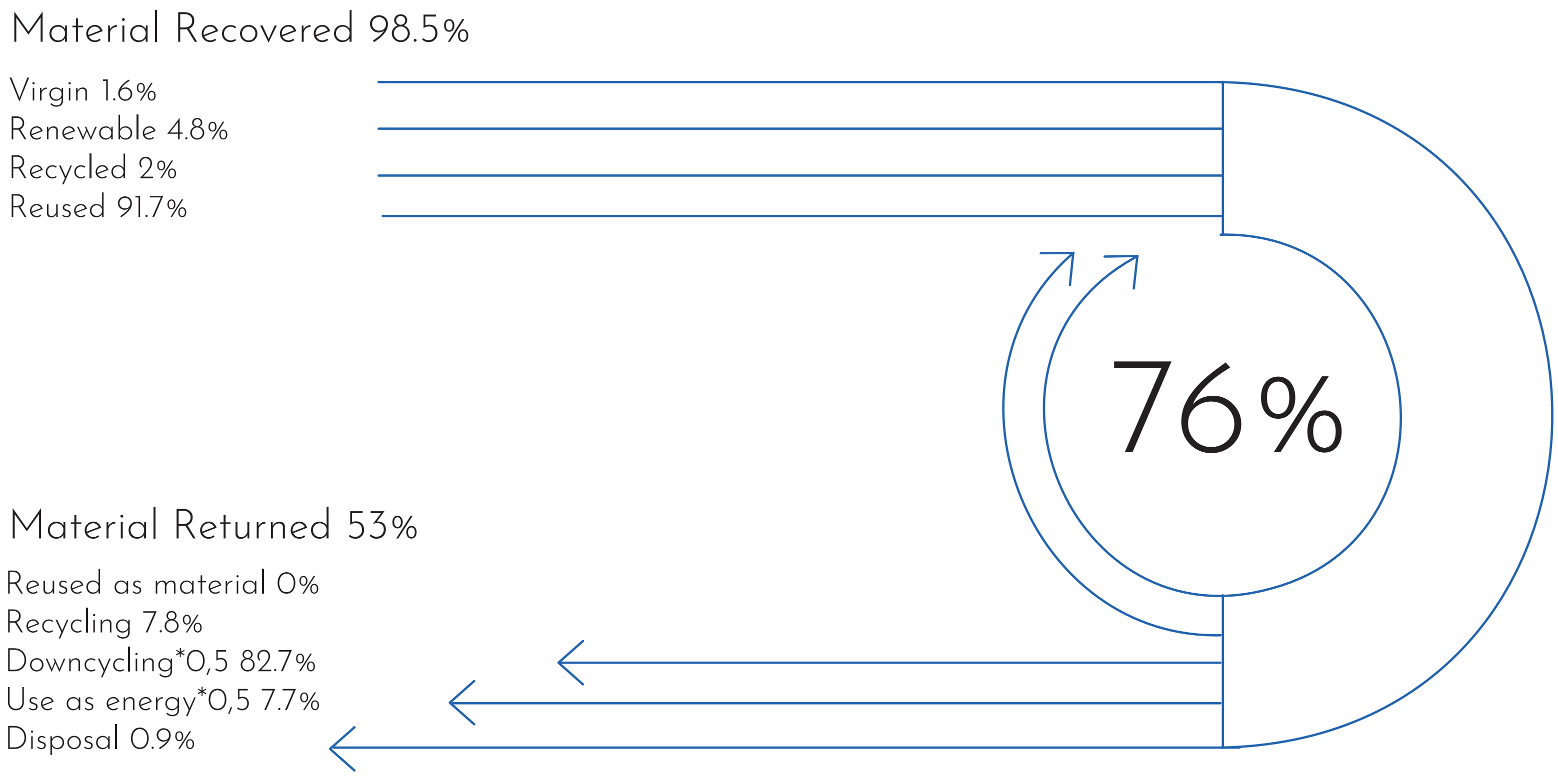


AXONOMETRIC NEW BUILDING
45°-45°, 1:100, A3

*Blue color represents reused materials

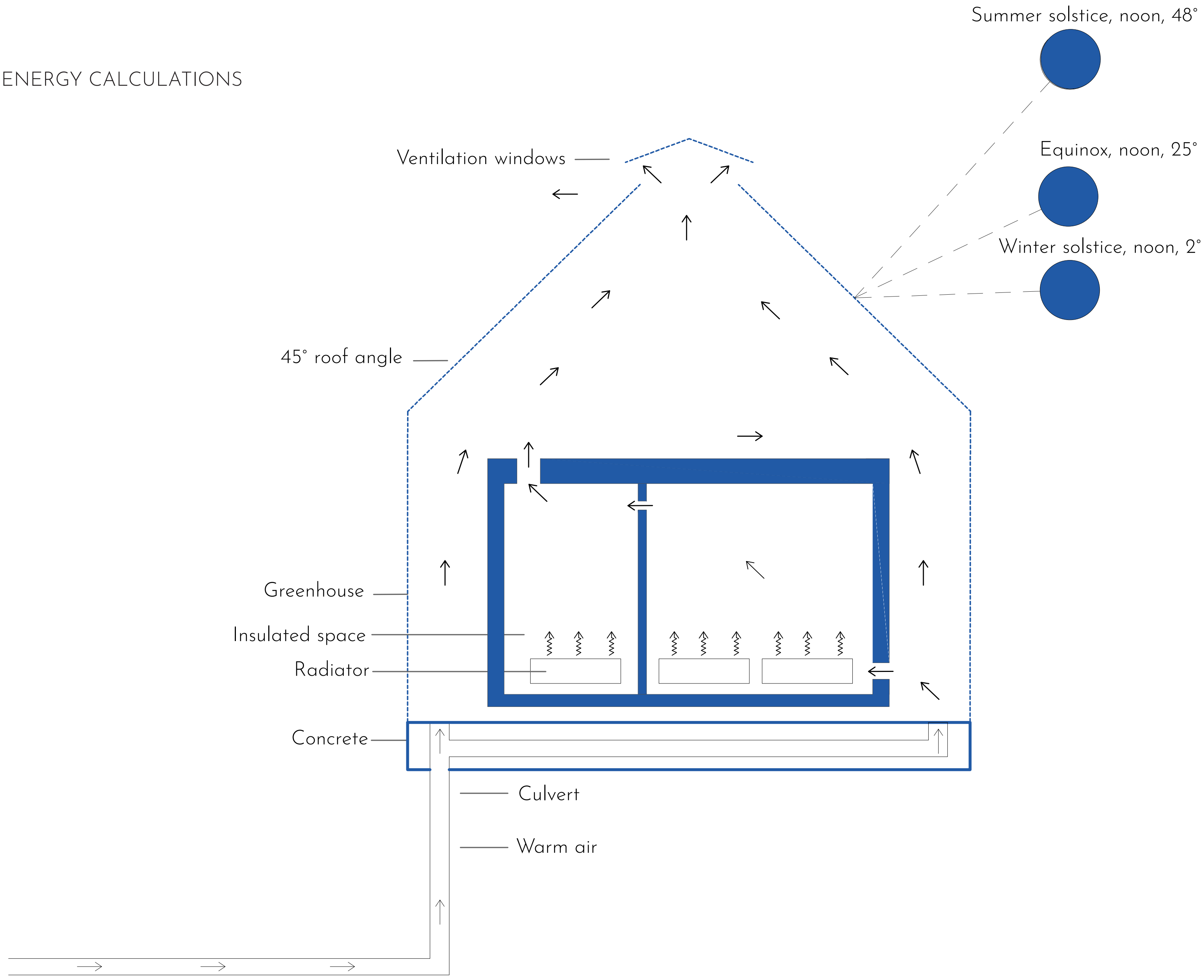
CIRCULARITY ASSESSMENT

The circularity assessment calculation in One Click LCA uses values from EPDs and average values about the materials. The assessment also takes into account what part of the building is made out of reused materials, what parts are designed for disassembly or for future adaptation. Values are derived from EPDs as average values from One Click LCA. The results can be seen on the diagram below and shows that the building is 76% circular.



*In Materials Returned, 82.5% of the materials are downcycled

ENERGY CALCULATIONS



ENERGY SECTION

	Value	U-value	U-value improved by greenhouse (10%)	Added information
Area exterior wall	85 m2			
Area roof	21 m2			
Area floor	25 m2			
Area windows and exterior doors	15 m2			
Heated floor area (BRA)	20 m2			
Heated volume	51 m3			
U-Value Exterior wall (Greenhouse)		2.4 W/m2K		Polycarbonat (16mm) and timber studs
U-Value Floor (Greenhouse)		0.1 W/m2K		Uninsulated concrete slab
U-Value Ceiling (Green-house)		1.2 W/m2K		Polycarbonat (35mm) and timber studs
U-Value Doors (Greenhouse)		3 W/m2K		2 reused double glased balcony doors
U-Value Window (Green-house)		3 W/m2K		13 reused double glazed windows
U-Value Exterior wall (boxes)		0.22 W/m2K	0,198 W/m2K	Wood panel, 200mm insulation, timber frame, vapour barrier, corrugated steel cladding.
U-Value Floor (Boxes)		0.283 W/m2K	0,255 W/m2K	Wood panel, 150mm insulation, timber frame, vapour barrier, corrugated steel cladding.
U-Value Ceiling (Boxes)		0.153 W/m2K	0,1377 W/m2K	Wood panel, 300mm insulation, timber frame, vapour barrier, corrugated steel cladding.
Doors (boxes)		0.84 W/m2K	0,756 W/m2K	3 balcony triple glazed glass doors with wooden frame
Window (Boxes)		0.62 W/m2K	0,558 W/m2K	2 triple glazed window
Normalised cold bridges (average value)		0.05 W/m2K		

*The U-values are collected from BKS 471.401 and EPDs. The improvements of the u-values is 5% according to NS 3031, the value was increased to 10% improvement after discussions with my supervisors.

ENERGY USE

The site is connected to the national grid with an earth string. According to the Icelandic National Energy Authority 69,07% of electricity production comes from hydro power, 30,88% from Geothermal energy, 0,03% from wind and 0,01% from fuel. (EPD Steinull hf, 2019). Therefor most of the energy is renewable. The number of grams of CO2 per kWh in One Click LCA was 24,5 g CO2e/kWh but according to an Icelandic EPD for minearal wool it should be 20,7 g CO2e/kWh. (EPD Steinull hf, 2019). If electricty would be produced on site the options would be Solarpower cells. Wind mills are not know to be used in this scale in Iceland and are therefor discarded as an option.

PV

IKEA in Reykjavík has used 65 270 W solar panels sloped 20° and 90° since 2018 to produce total 12092 kWh of energy yearly. A slope of 40° is optimum but to evaluate this a measured value was used as the effect snowcover has an effect as well. To produce 4779 kWh/yr approximately 26 units of 270 W solar panels are needed. (Þrastarson, S., 2019). To run the building for 60 years we need 286740 kWh and the embodied emissions of the PVs are 19 tons CO2e. As can be seen in the table below, PVs emit around 3 times more of greenhous gases per kWh compared to using the local grid and are therefor not used in this project.

Electricity option	CO2/kWh
Local grid	20,7 g CO2/kWh
PV	66,2 g CO2/kWh

ENERGY CALCULATION

To calculate the energy demand of the building SIMIEN was used. Only the boxes were put into the program as it is not good to analyse the effect of the greenhouse as an unheated space. The Greenhouse does not use active heating but rather free heat from the tube that is shown in the energy section.

The boxes were analysed as separate zones (Zone 1 and zone 2). The effects of the greenhouse were put into SIMIEN by using the lower U-values calculated in the table to the left The G-values of the windows were also made lower as the sun is filtered through the greenhouse before entering the box. Insulation was estimated by comparing different thicknesses in SIMIEN and comparing to the embodied emissions in One Click LCA.

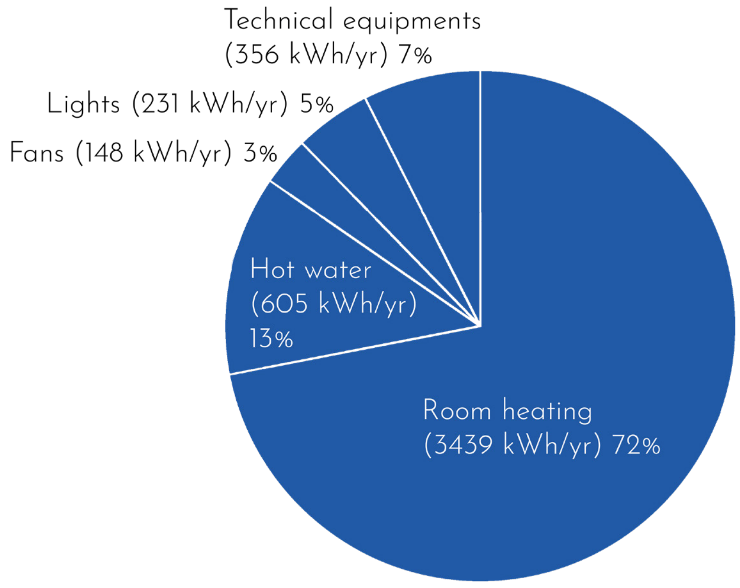
Zone 1

- Function: Kitchen and bathroom
- Activities: cooking, storing food, showeing, toilet and office space
- Size: 12,5 m2
- Ventilation: balanced ventilation with 70% heat recovery
- Heating: Electrical ovens, 1250 W

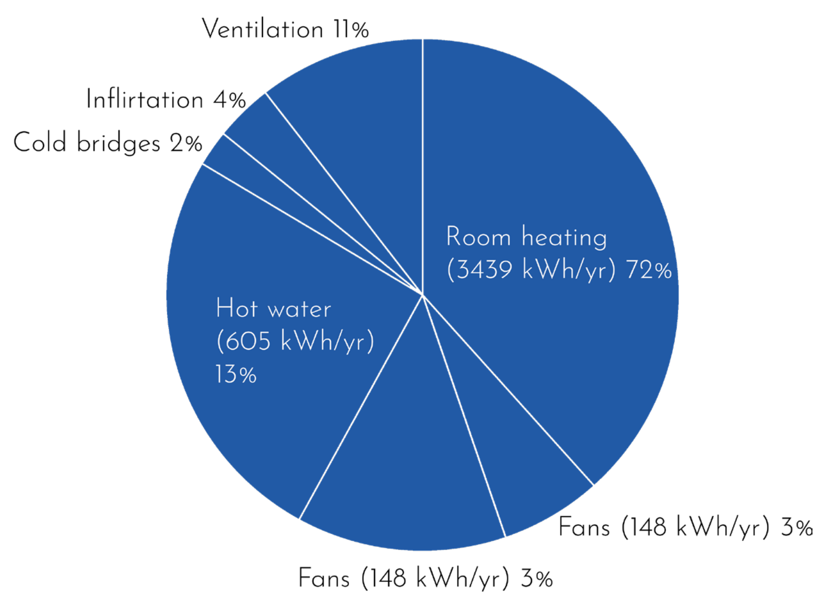
Zone 2

- Function: Sleeping area
- Size: 7,8 m2
- Ventilation: Ventilated through openable windows
- Heating: Electrical ovens, 780 W

YEARLY ENERGY BUDGET (TOT. 4779 KWH/YR)



HEAT LOSS



B6: Global warming from LCA

LIFE CYCLE RESULTS

Life cycle stages in One Click LCA:

Product Stage
- A1 - Raw material Supply
- A2 - Transport
- A3 - Manufacturing

Construction Process Stage
- A4 - Transport to building site
- A5 - Installation into building

Use Stage
- B1 - Use/application
- B2 - Maintenance
- B3 - Repair
- B4 - Replacement
- B5 - Refurbishment
- B6 - Operational energy use

End-of-Life Stage
- C1 - Deconstruction/demolition
- C2 - Transport
- C3 - Waste processing
- C4 - Disposal

Benefits and loads beyond the system boundary
- D - Reuse
- D - Recovery
- D - Recycling

A1-A3: MATERIAL INPUT

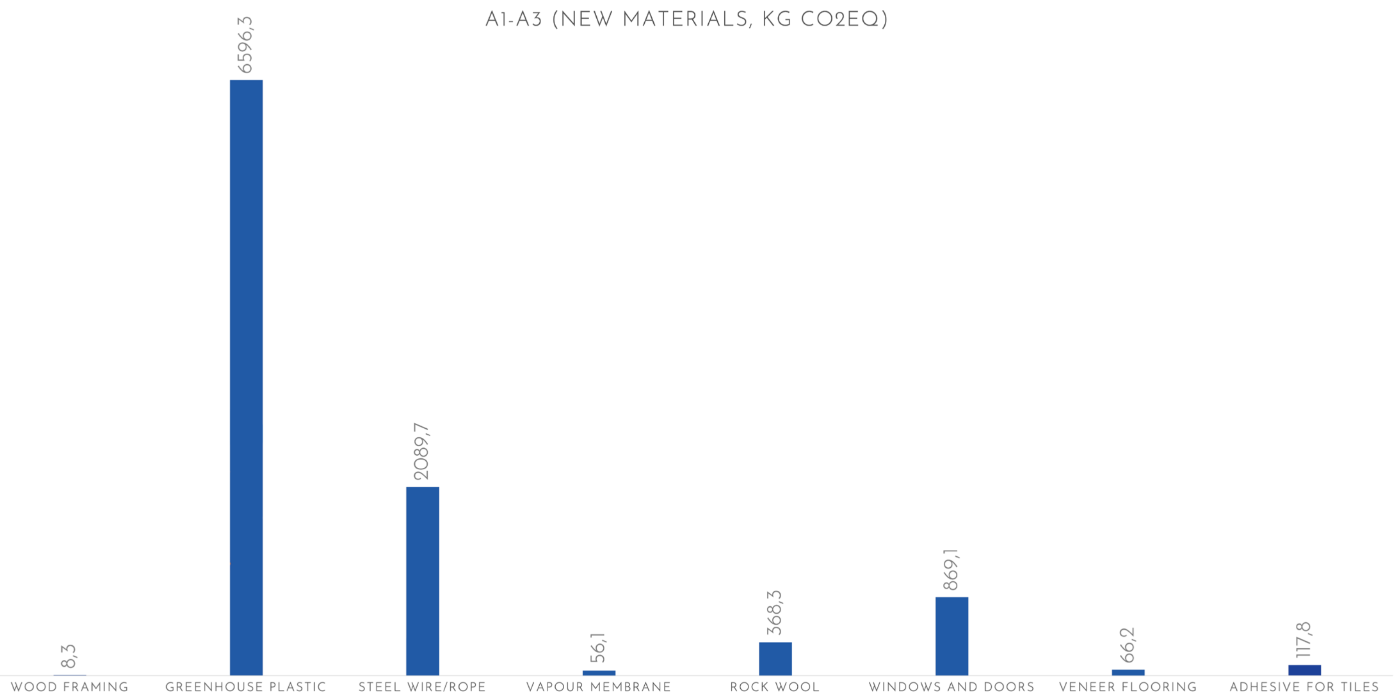
Picking out materials for the project that were new (not reused from the site or a local site) has many aspects to it. When picking out materials they need to have low embodied emissions in the production, little toxins, short transportation distances (If the materials are not produced in Iceland then the local countries are the next option) and serve the purpose of the design. Embodied emissions from electrical equipments were disregarded in this calculations.

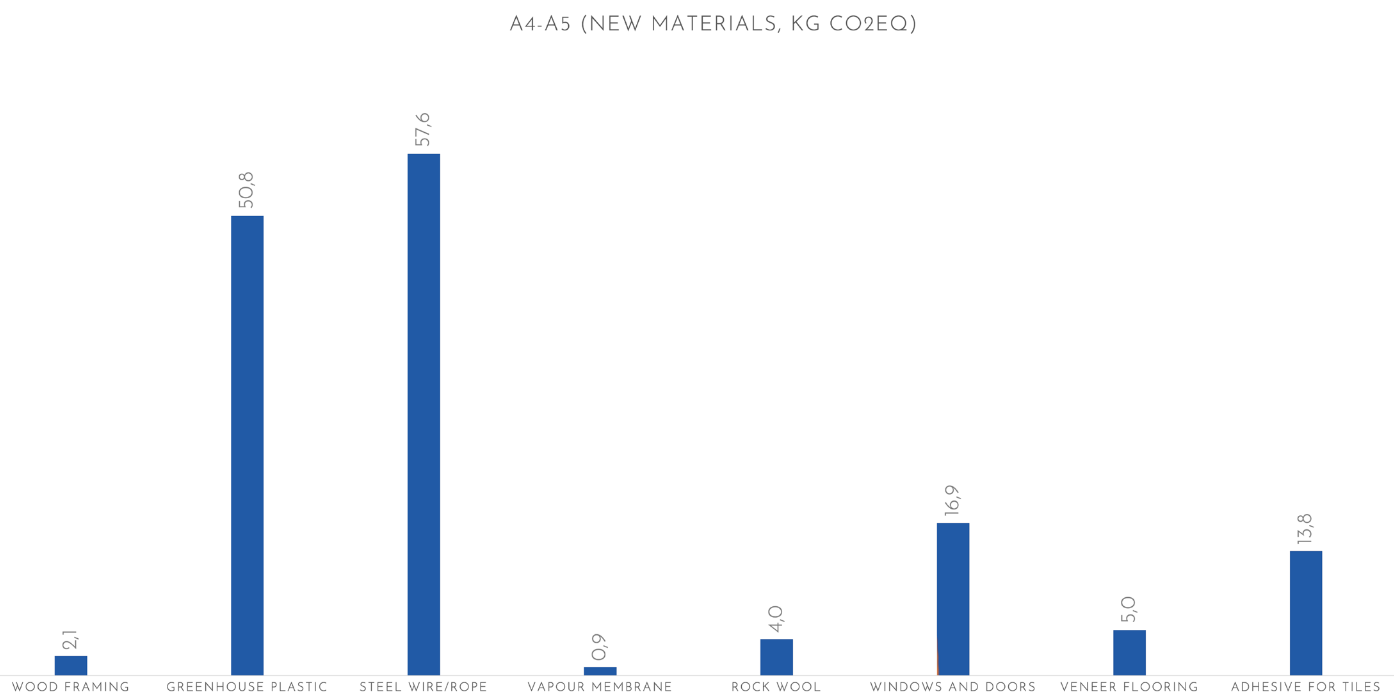
The options compared when choosing a cladding for the facade were acrylic plastic, PVC panels and glass windows. Glass windows are heavy which causes higher emissions in transportation, require a stronger structure, have high embodied emissions in production and reuse can be difficult for covering such a big surface. On the other hand glass allows alot of sunlight through. Acrylic plastic is stronger than PVC, more translucent and comes in many colors. On the other hand it has a very high U-value, as there are no air gaps in it and high embodied emissions in production. Polycarbonate is very light which is good for installing it and transporting it. It has airtubes in it that make the U-value acceptable. On the other hand it is only semi translucent so less sunlight comes through the material and the view is blurred. After evaluating the pros and cons of each product the final choice was to cover the facade with PVC and where view or more sun was required a reused window was added (in total 13 reused windoes were added). The positive thing about having this unheated space is that reuse of windows is easier as the u-value requirements are easier to meet and a triple glazed window would not make sense in this context.

While the wood in the old building is reused for the structure in the boxes, the greenhouse has new wood in the structure. The structure was designed in a way where the same size of wood could be used in most cases and was bolted and skrewed togeather in a way that would make disassembly easier. Wooden products are generally not available in Iceland because of the lack of forrest so Norwegian products were chosen.

According to LCA assessment on a tiny house buying materials not far away i more environmentally friendly (Verhoeven, V.M.G., 2019). The first insulation materials that were considered for this project were products produced in Iceland which are rockwool. Rockwool is made out of virgin materials which is not good in a **circular design**. On the other hand as they are used in most projects in Iceland they are often available at second hand markets and as cut-offs from large scale projects. Wood chip insulation was considered as it is produced in scandinavia and is made out of wood cutoffs that otherwise would be wasted and is biodegradable. The rock wool was picked in the end where 50% of it was reused from second hand markets.

Steel rope crossings are used to strengthen the building. Steel has high embodied emissions in production and is very heavy. On the other hand recycling of steel is good compared





to other materials. These ropes are easy to disassemple when the structure is taken apart and reused elsewere or put into recycling.

A4-A5: TRANSPORT AND INSTALLATION
Transport of materials were estimated based on information in the EPDs. The building was designed with the construction phase in mind where the need for heavy machinery is avoided. Handpower and electrical tools like drills and saws were the main focus. Therefor heavy things that require cranes like big prefabricated modules, glulam beams, CLT and steel structure was avoided.

The first thing in the construction phase is dismantling the building. That can be done with handpower.

The next phase is building the new building. It starts with the greenhouse. As the construction wood is not very dense, the PVC panels are very light and the windows are medium sized everything can be done with handpower. The site requires no digging as the foundation is entirely reused from the old building.

The second phase is building the boxes. All the elements can be carried through the door of the greenhouse and assembler with handpower inside, sheltered from weather.

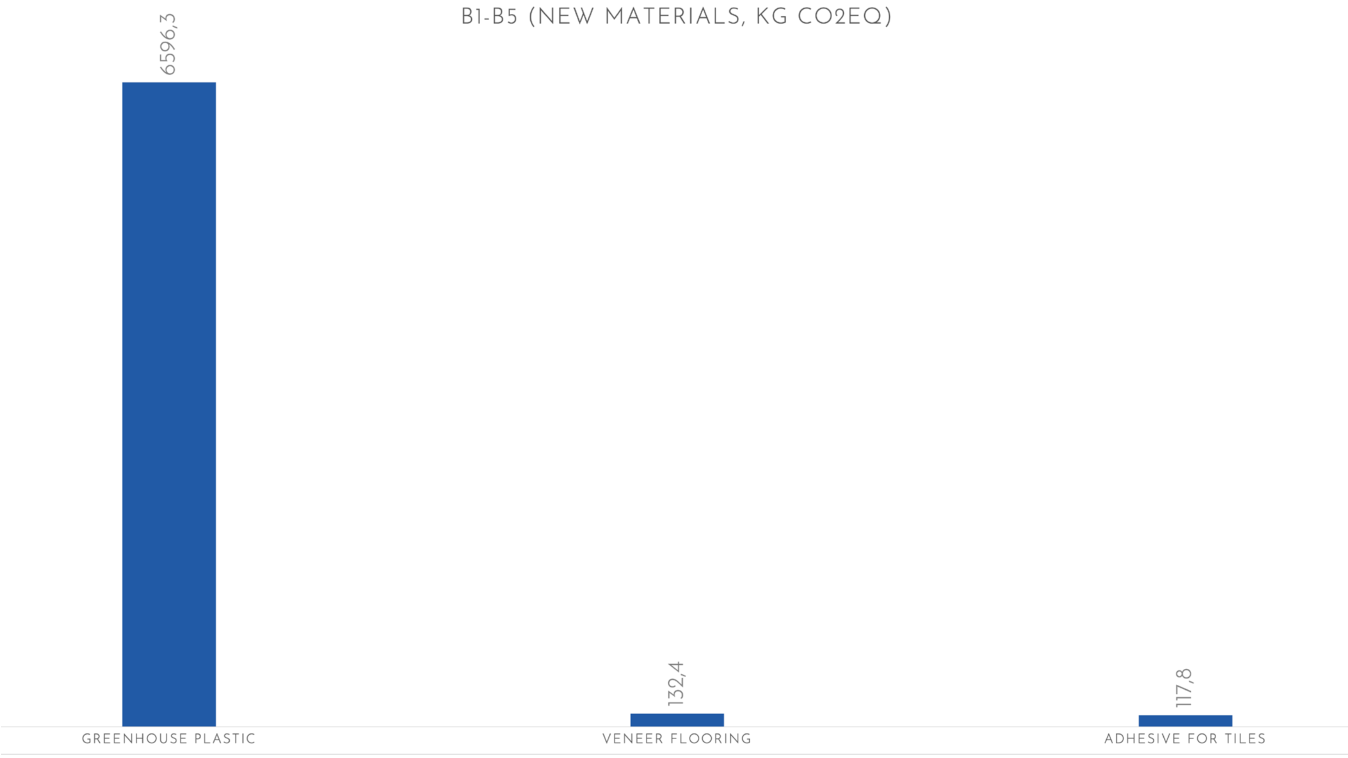
The main emissions from transporation in this phase are from transport of workers and tools and platforms.
Electricity for tools was based on information from a LCA research on a tiny house (Verhoeven, V.M.G.,2019). The building of a tiny house is assumed to be three weeks but in this case the time was estimated to be three times longer (9 weeks).

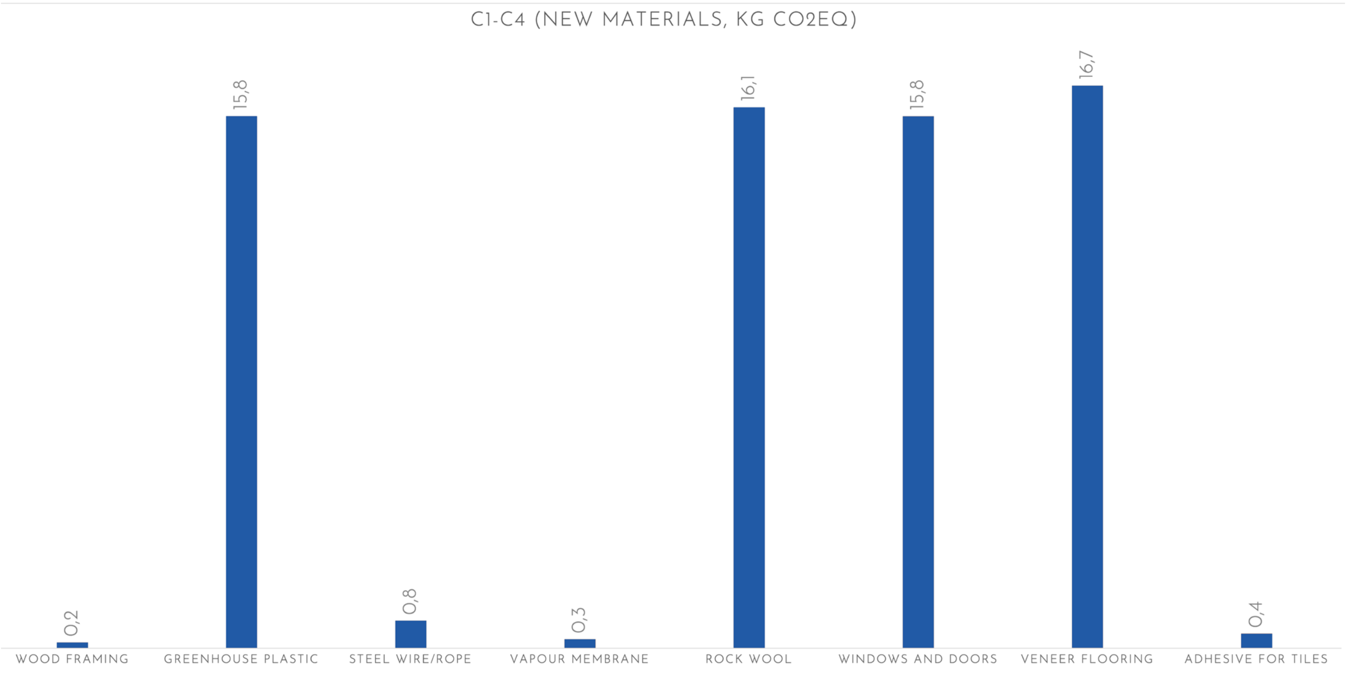
- Walls and floor: 1,14 kWh/m2 based on 75 hours of sawing and 7,5 hours of drilling
- Roofs: 2,46 kWh/m2 based on 48 hours of sawing and 4,5 hours of drilling
-

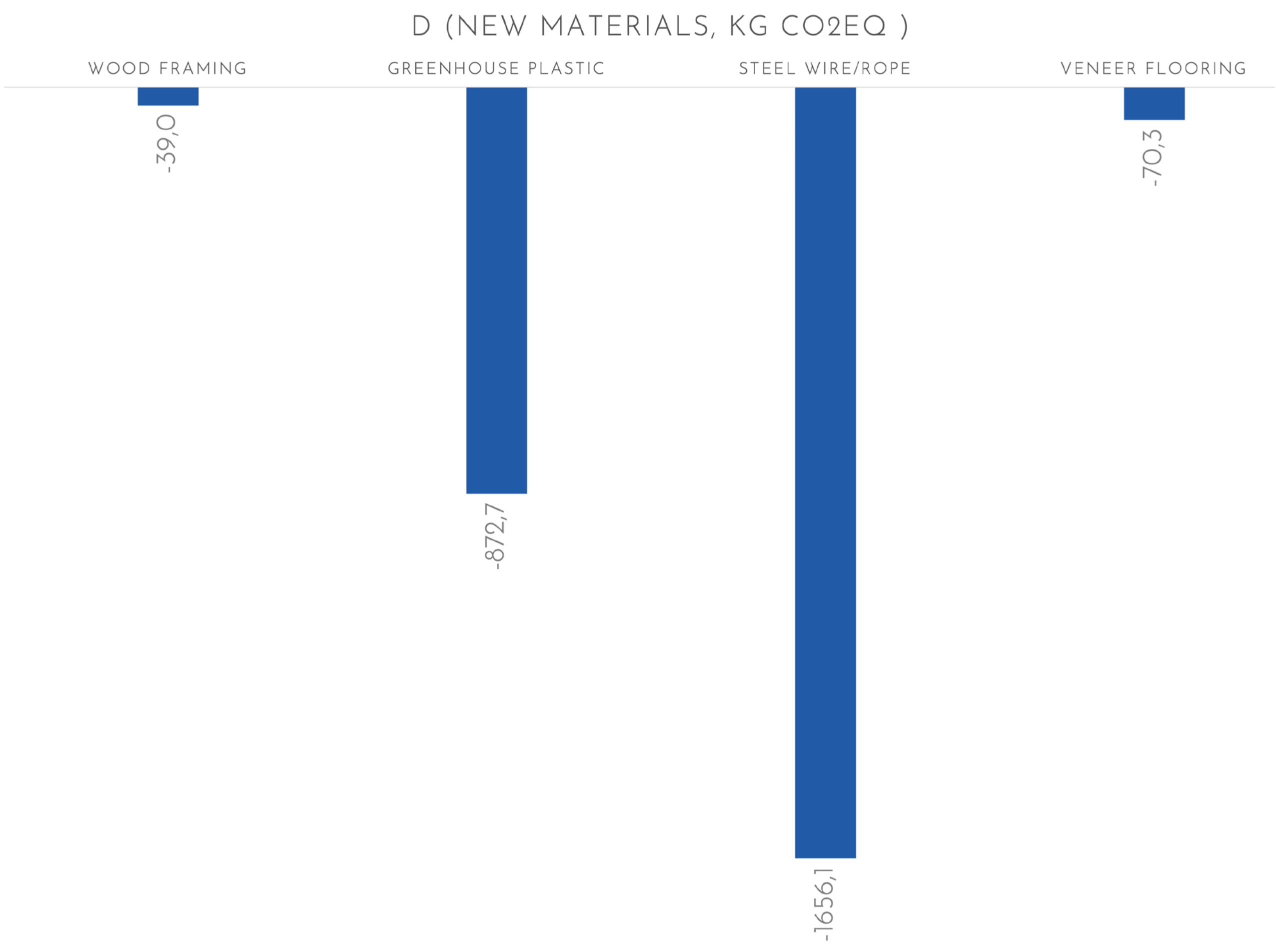
B1-B5: MAINTAINANCE AND REPLACEMENTS
Maintainance and replacement within the 60 year lifetime of the building is only needed for the greenhouse plastic, the flooring inside the boxes and the adhesive for the reused tiles in the bathroom. Lifetime of windows and doors of the boxes was extended to 60 years as it is protected from weather and wind within the greenhouse. The windows and doors in the greenhouse membrane are all reused and therefor not included here.

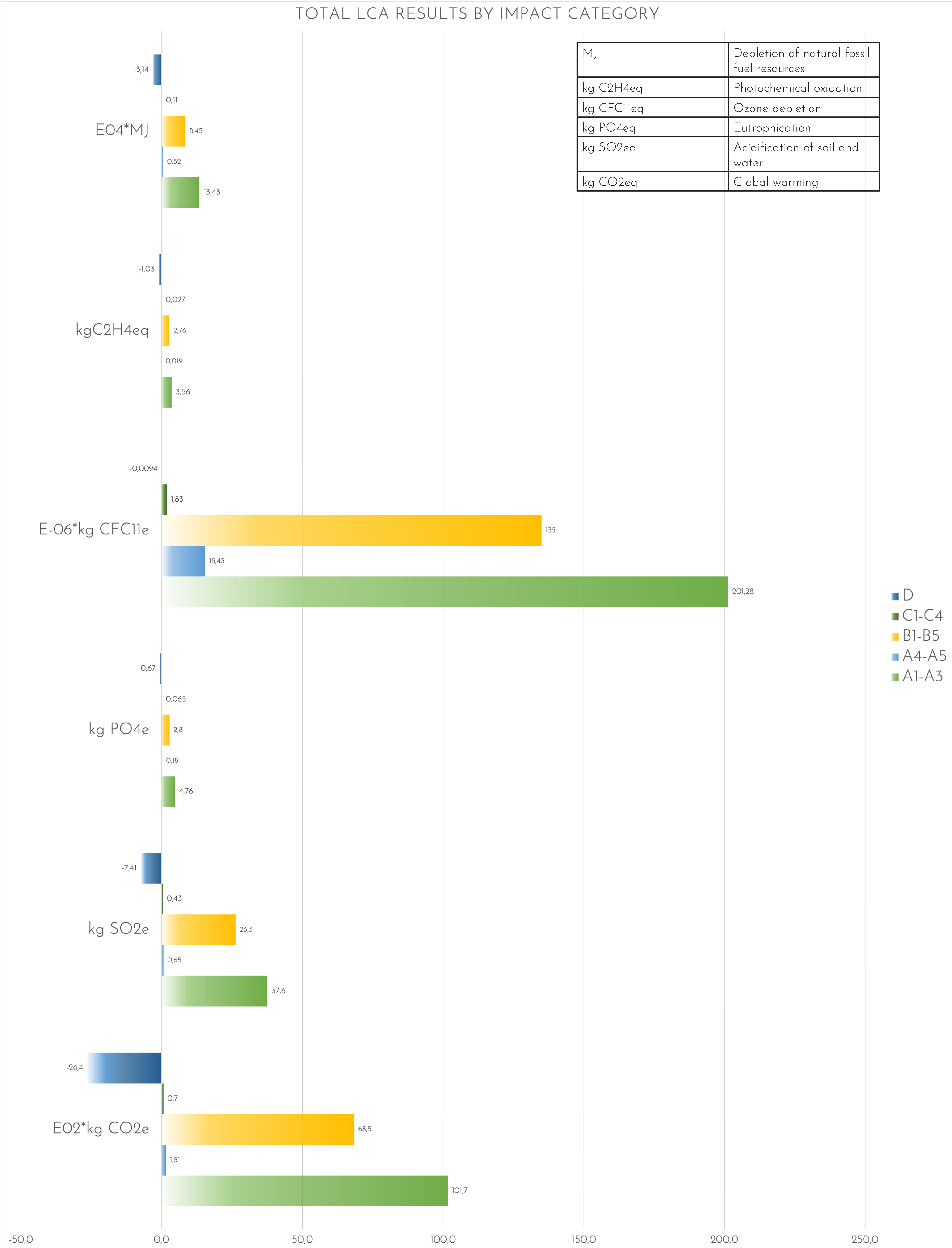
C1-C4: DEMOLITION AND DISPOSAL
In 60 years the building might need to be demolished. Handpower and electrical tool can be used to do that and values about waste transportation and processing are found in the EPDs of the materials.

D: REUSE, RECOVERY AND RECYCLING
Values in this section were collected only from the EPDs and not estimated according to the design.









MJ	Depletion of natural fossil fuel resources
kg C2H4eq	Photochemical oxidation
kg CFC11eq	Ozone depletion
kg PO4eq	Eutrophication
kg SO2eq	Acidification of soil and water
kg CO2eq	Global warming

Total kg CO_2e from new materials

27000 kg CO_2e

Total kg CO_2e per m2 of greenhouse + boxes

415 kg $CO_2e/m2$

Total kg CO_2e per m2 of boxes

1330 kg $CO_2e/m2$

DISCUSSION

The design of this thesis a 76% **circular design** according to the circularity calculator. 91.6% of the mass of materials used in the design are reused and only 1.7% is from virgin materials. That shows that reusing heavy materials like concrete creates huge potential for high reuse percentage. In the end of the lifecycle 53% of the materials are returned to the economy and that is mainly from downcycling; 82.7% of the materials are downcycled in the end of the lifetime. The concrete is the reason for that as it is very heavy and goes all into backfilling, which counts as downcycling. The positive impact of downcycling on the circularity percentage is only half of the impact reuse and recycling can have. Reuse is 0% at the end-of-life as the material lifetime is fully used and recycling is only 7.8% which is very low and is mainly from the metals used.
The main thing that holds the design back from becoming a 100% **circular design** is the end of life for the materials. Heavy materials like concrete are only downcycled which gives the clue that its better to let the concrete structure keep its form and rennovate it instead of tearing it down.

9680 kg CO_2e were saved from the atmosphere by reusing materials compared to buying similar new materials. The final amount of kg CO_2e going into the atmosphere by building this design is 27000 kg CO_2e according to the calculations.

Production of building materials and extraction of raw materials is very little in Iceland and it is heavily dependent on import over sea. Using materials again instead of landfilling can therefor help the economy. Reuse of materials from older buildings to create a new design takes more time and effort than using new materials and limits the design options available. On the other hand it creates an opportunity for creative thinking.

Using life cycle assessment and the circularity assessment tool to measure the environmental impact of the design in combination with SIMIEN was very helpful in developing the design to the right direction.

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APPENDIX

https://www.360optimi.com/app/sec/util

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https://www.360optimi.com/app/sec/util/

Polycarbonate (based on both an EPD and a report from Delft University):
EPD: https://www.360optimi.com/app/sec/util/getEpdFile?resourceId=INIES_DGRA20191220_143140&profileId=INIES

Report: ashttps://repository.tudelft.nl/islandora/object/uuid:98cbdba1-faf1-4267-9917-33b9621455dc/datastream/OBJ