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TRANSFORMATION OF A BARN AT CAMPHILL ROTVOLL

01 06 2012 NTNU
Det skapende universitet

Summary

The barn at Rotvoll farm has a history of 140 years. Nowadays it is owned by Steiner school that uses its part mainly for storage and Camphill Rotvoll that use their part for workshops and keeping a few animals.

The future use of the barn would include residential units for Camphill Rotvoll and living and teaching premises for FRAMskolen, which are both part of the Camphill movement. Camphill commmunities are "life-sharing" communities and schools for adults and children with learning disabilities and other special needs that provide services and support for work, learning and daily living.

The aims of the project included reusing as much as possible from the old structure, while ensuring a good energy performance. Also architecturally, reuse and fitting the existing barn structures was a crucial theme for functional distribution and interior and exterior concepts.

The design project consists of four chapters dedicated to important themes of the project:

1) The Barn - the history and investigations of the existing structure

2) Design - architectural design drawings and considerations

3) Materials - details for new and reused materials and embodied emissions accounting

4) Energy - energy targets, performance and evaluating energy supply options

The programs used for the project include SIMIEN for simulating energy performance and Autodesk Ecotect and Radiance for daylight simulations. Emission accounting for materials was done using database EMPA Ökologische Baustoffliste (Version 2.2e) originating in Switzerland.

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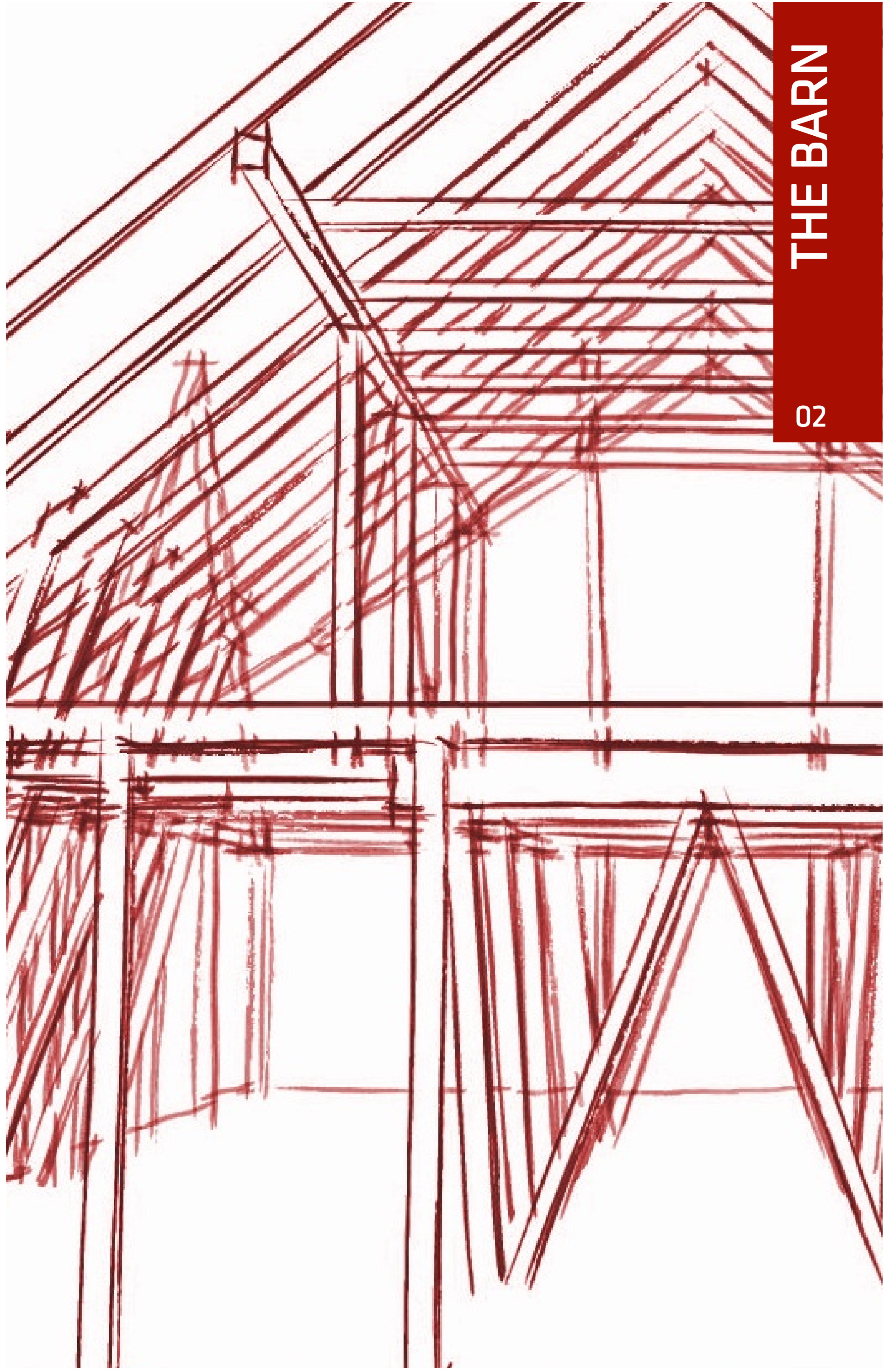


THE BARN

02


Rotvoll 1880
Image source: www.strindahistorielag.no/wiki/index.php?title=Rotvold_asyl


Rotvoll 2012


Rotvoll 1947
Image source: Bratberg, T.V.(ed), 2008. Trondheim byleksikon. Oslo: Kunnskapsforlag


Image source: www.strindahistorielag.no/wiki/index.php?title=Rotvold_asyl

Rotvoll farm history dates back to the late 19th century when the Rotvoll asylum was built. Rotvoll asylum for the mentally ill was among first modern facilities of their kind in the country and included directly connected agricultural activities as part of the therapy.* Thus the Rotvoll farm is closely linked to the history of the asylum, which ceased to be a hospital in 1990. The former asylum building is now used by HiST university, while the Rotvoll farm buildings are shared by Camphill Rotvoll village and Steiner school.

Timeline

1872 Rotvoll Asylum - arch. Ole Falk Ebbell
1928 Rebuilding of asylum - arch. Ole Bjerke Holtermann
1989 Camphill Rotvoll established at Rotvoll farm

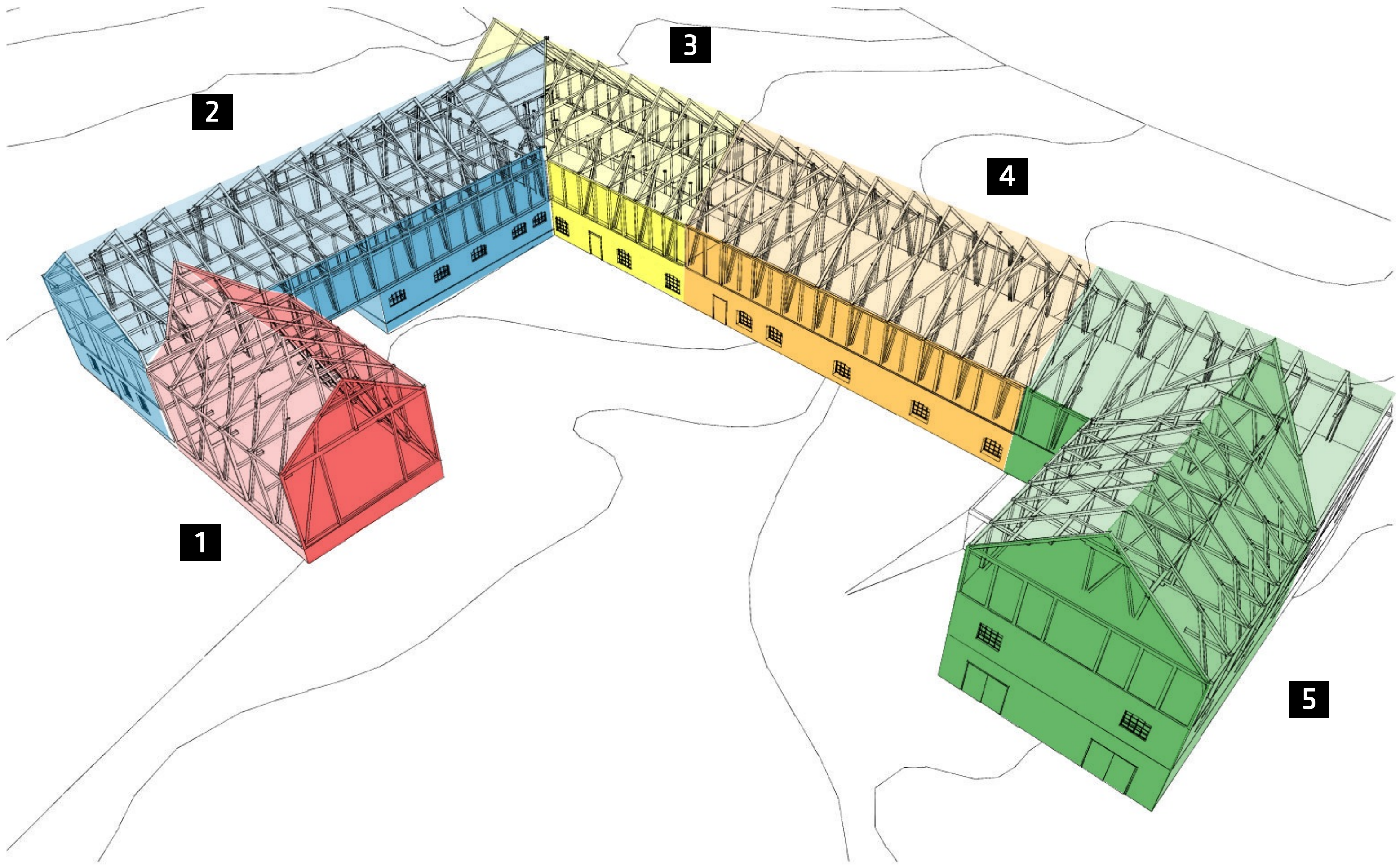
*Solberg, H.(ed),2009. Arkitektur i 1000 år. En arkitekturguide for Trondheim.Trondheim : Trondhjems arkitektforening


Arch. Ole Falk Ebbell (1839 - 1919)

Rotvoll farm history

The barn building(s)

The barn building is built and rebuilt in many phases reusing and transforming existing structures. The building structures have been adapted to specific purposes and changing farming traditions. After investigating the barn 5 distinct building parts were identified that have apparently different building periods, methods or purpose (see image to the right).



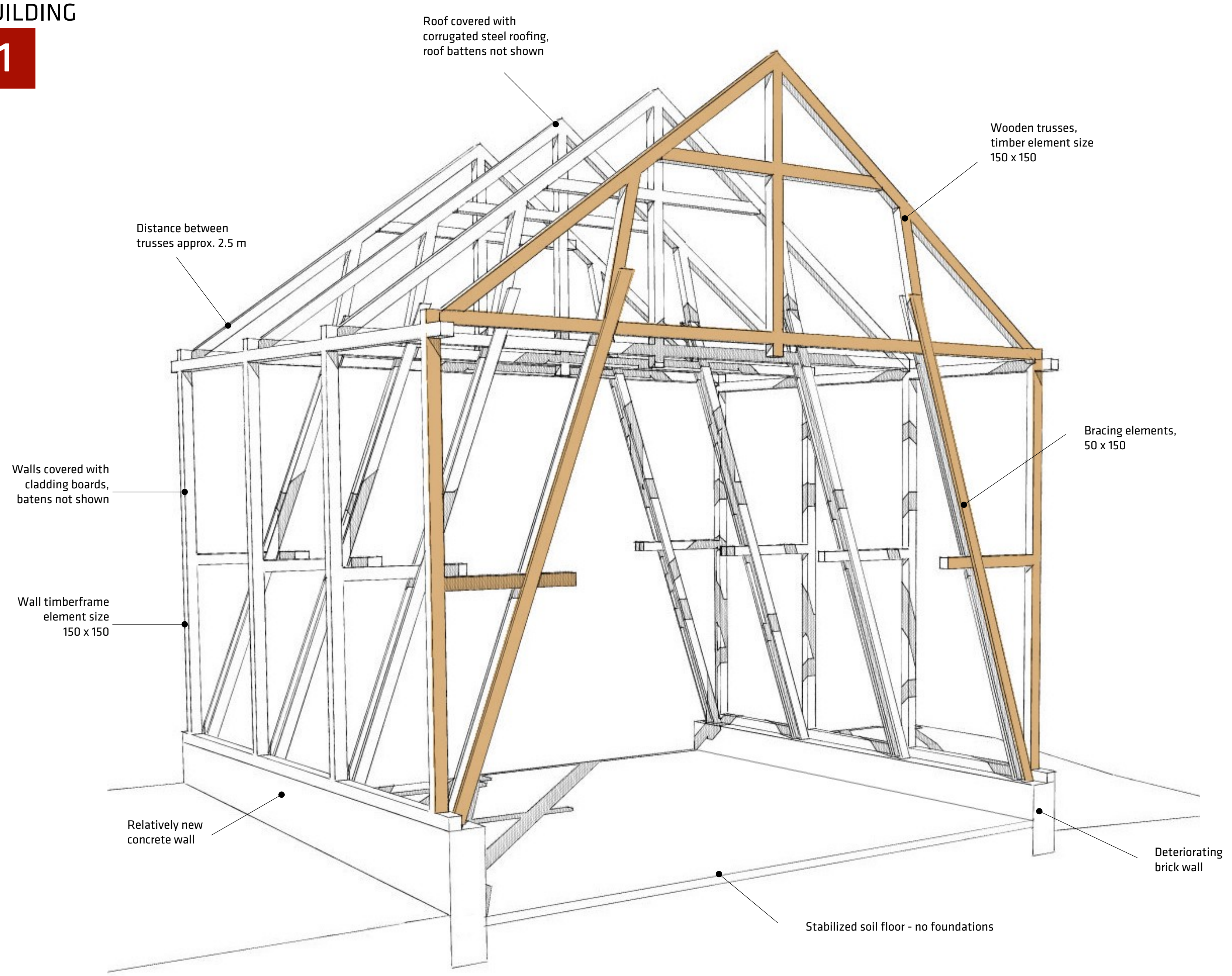
On-site observations of the barn and historical photos led to assumptions about the sequence of building the separate parts of the barn. The oldest structures of the barn can be found in part 2 and some parts could date back to the original barn building from the late 19th century. Materials used in these parts include wood and brick.

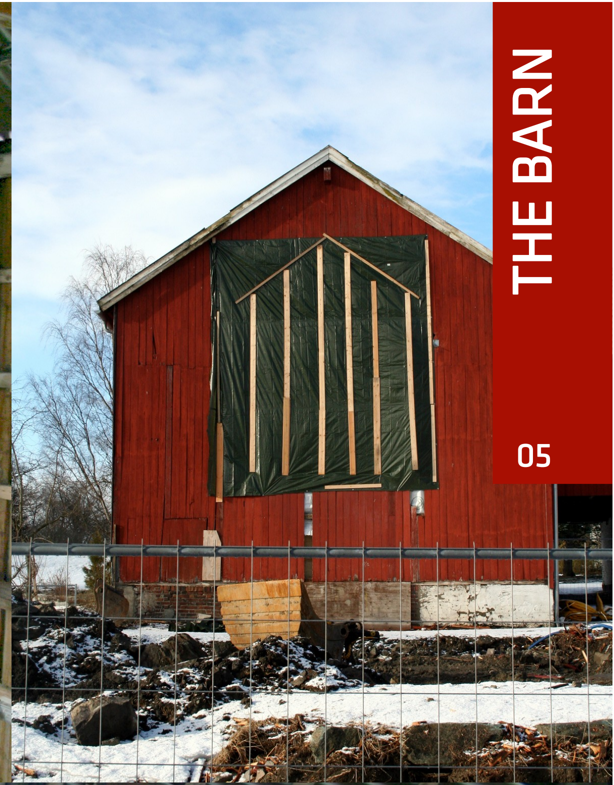
A newer addition which includes use of concrete, steel and sawn timber is building part 5, which was made as a cowshed with purpose-formed concrete floors. This building part can be seen in the photo from 1947, and probably could be linked to the rebuilding phase of the asylum in 1928. Building part 1 could be attributed to se same period as part 5, but probably has been rebuilt on several occasions since the now wooden elements in the existing structure seems to be relatively new.

Building parts 3 and 4 seem to have some historical/older elements, but then changed and adapted later on. The wooden elements in builfing 4 might be reused from older structure adding them on top of new concrete structure (from the same period as in building part 5) on the ground level. Building part 3 has most suffered from alterations and contains mix of structural elements (wood, steel) from different periods intended to fix changing loads in specific points.

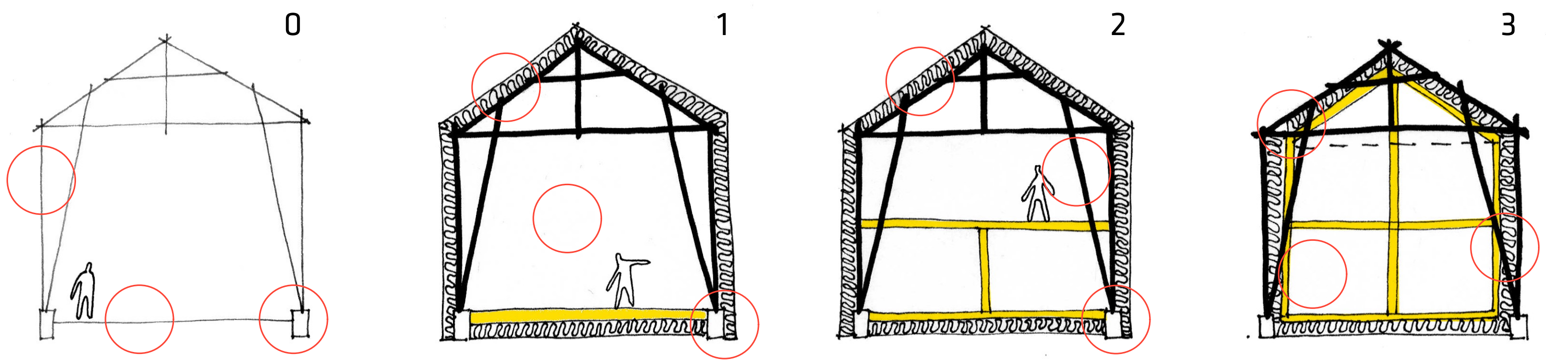
BUILDING

1





REUSE SCENARIOS



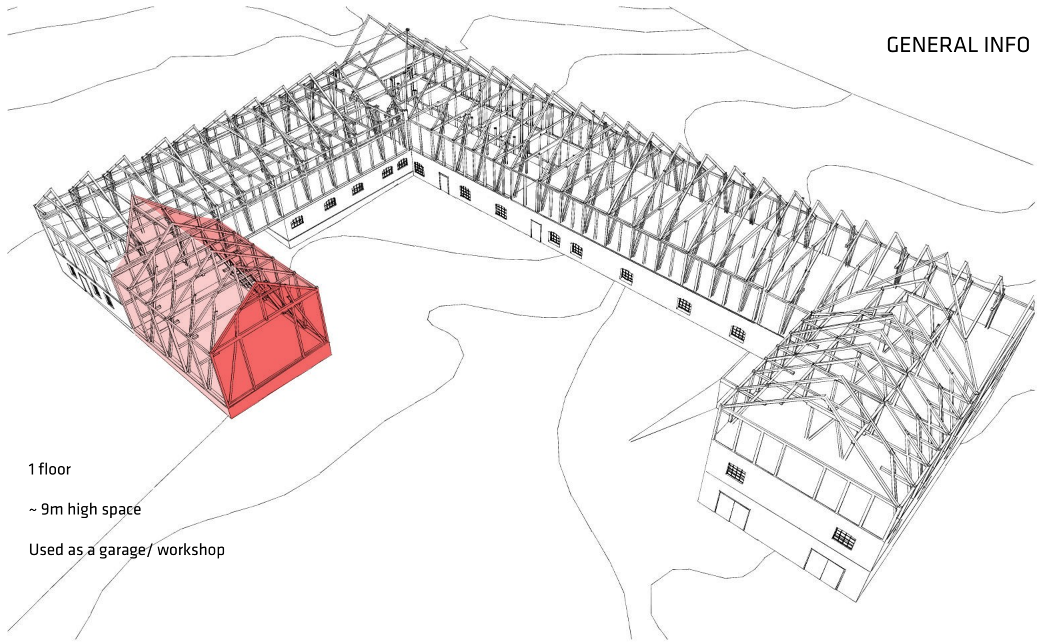
0
- Stabilized soil floor
- Brick foundation wall
- Uninsulated envelope

1
- More load due to insulation
- Thermal bridge to the ground
- Large room volume

2
- More load due to insulation and new use
- Thermal bridge to the ground
- Existing structure limiting use (?)

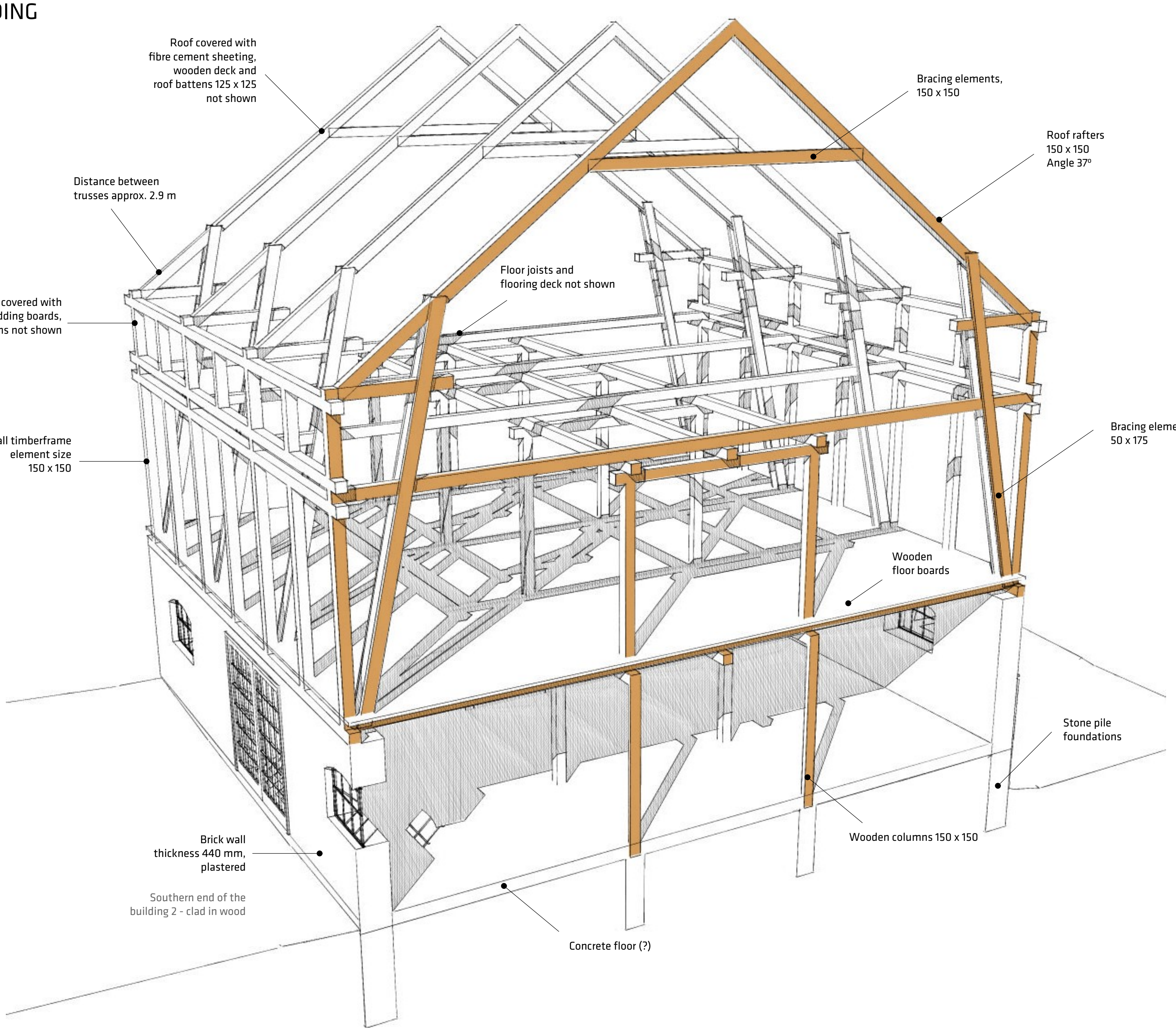
3
- Less floor area
- Doubling of structure (?)
- Existing structure penetrating the thermal envelope (?)

GENERAL INFO

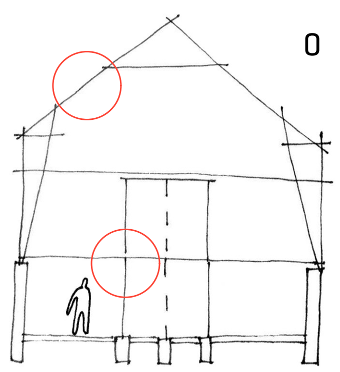


- 1 floor
- ~ 9m high space
- Used as a garage/ workshop

BUILDING
2

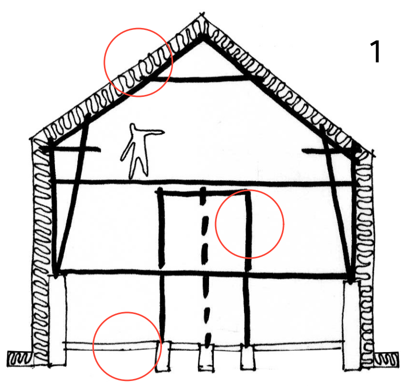


REUSE SCENARIOS



Adjusted/ changed load bearing system

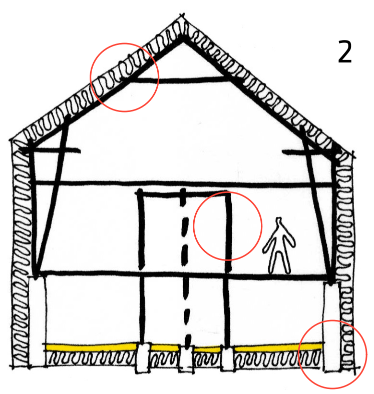
Uninsulated envelope



More load due to insulation and new use

Huge thermal bridge to the ground

Existing structure limiting use (?)

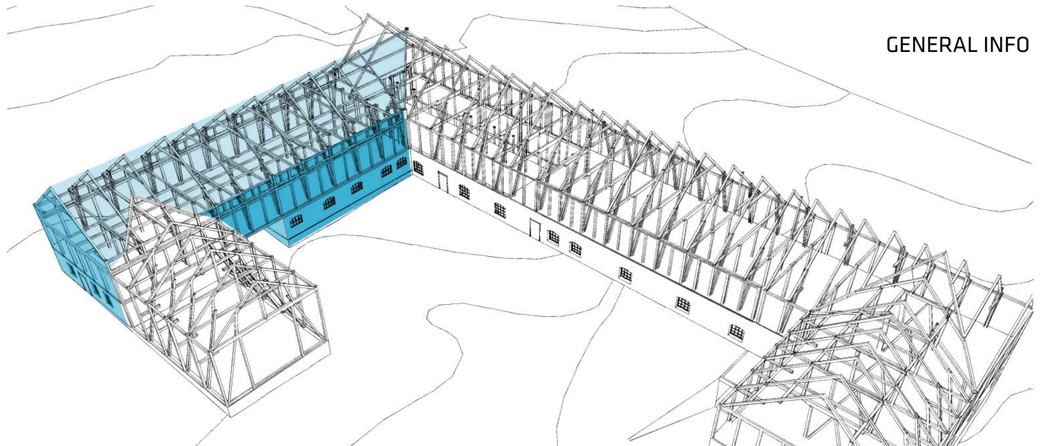


More load due to insulation and new use

Thermal bridge to the ground

Existing structure limiting use (?)

GENERAL INFO



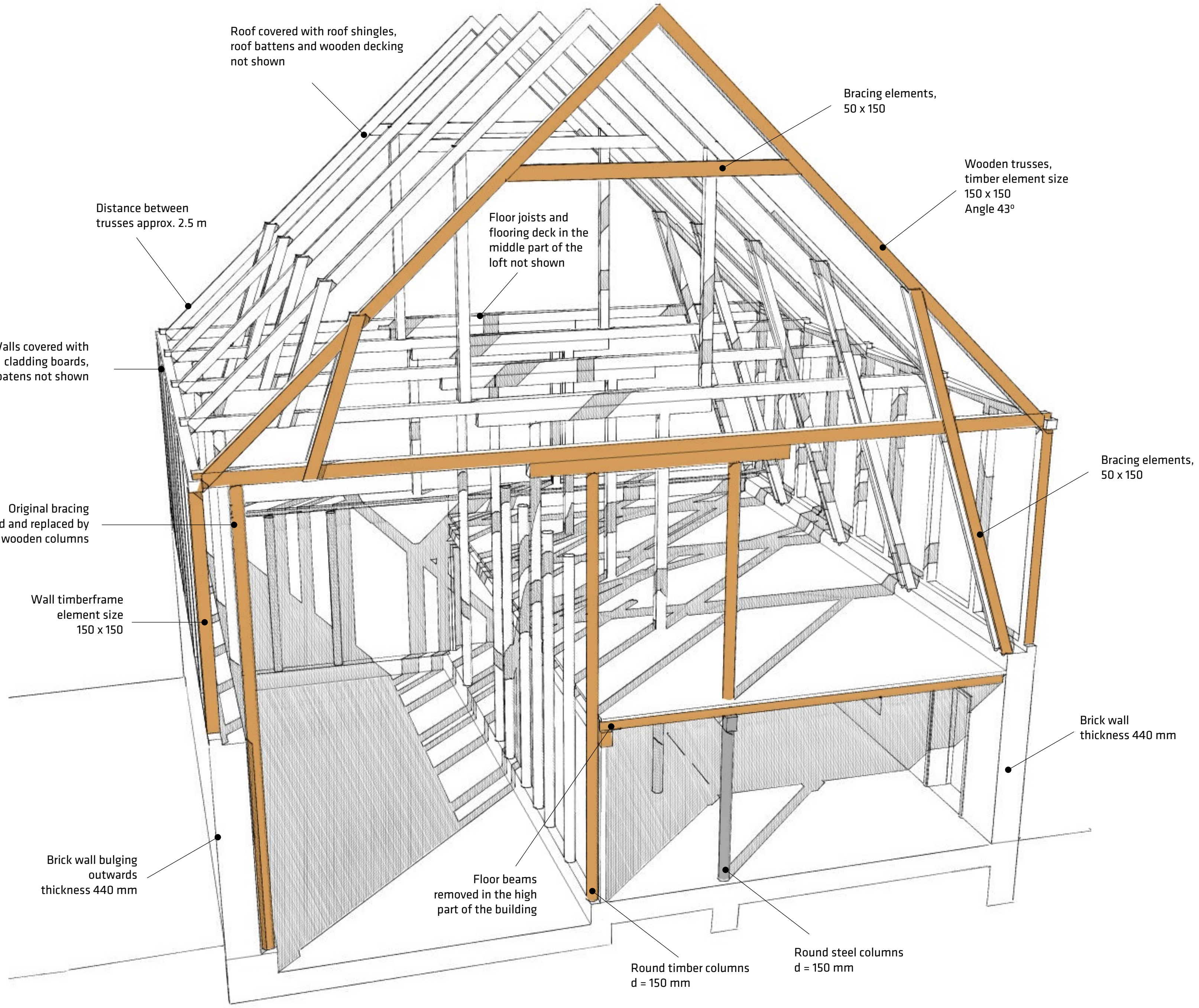
3 floors

Different (re)building periods and materials

Used as a meeting space/ workshops/ “attic” storage

BUILDING

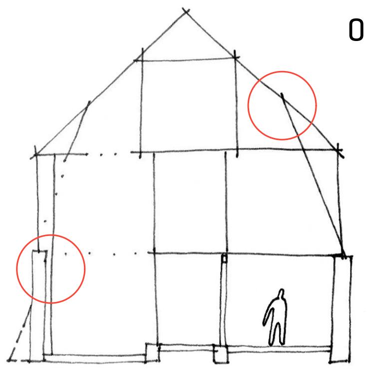
3



THE BARN

REUSE SCENARIOS

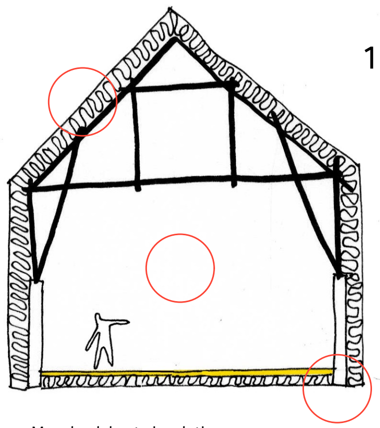
0



Adjusted/ problematic load bearing system (outwards bulging brick wall to north)

Uninsulated envelope

1

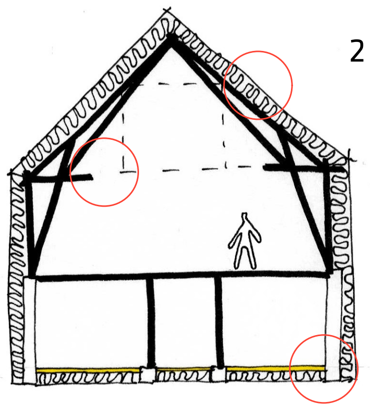


More load due to insulation

Thermal bridge to the ground

Large room volume(adding loft?)

2

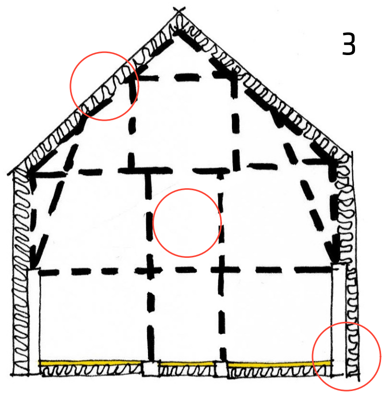


More load due to insulation and new use

Thermal bridge to the ground

Existing wooden structure might need remodelling

3

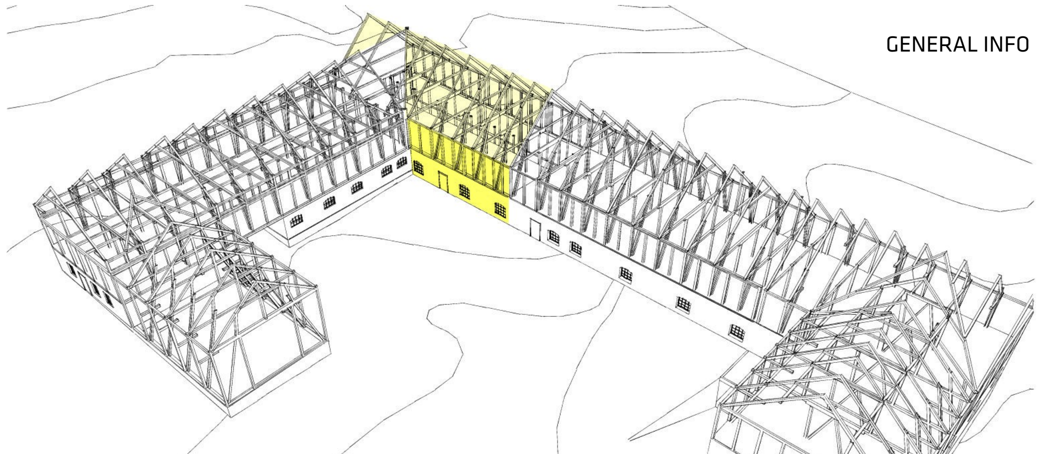


More load due to insulation and new use

Thermal bridge to the ground

Huge effort to restore the original wooden structure

GENERAL INFO

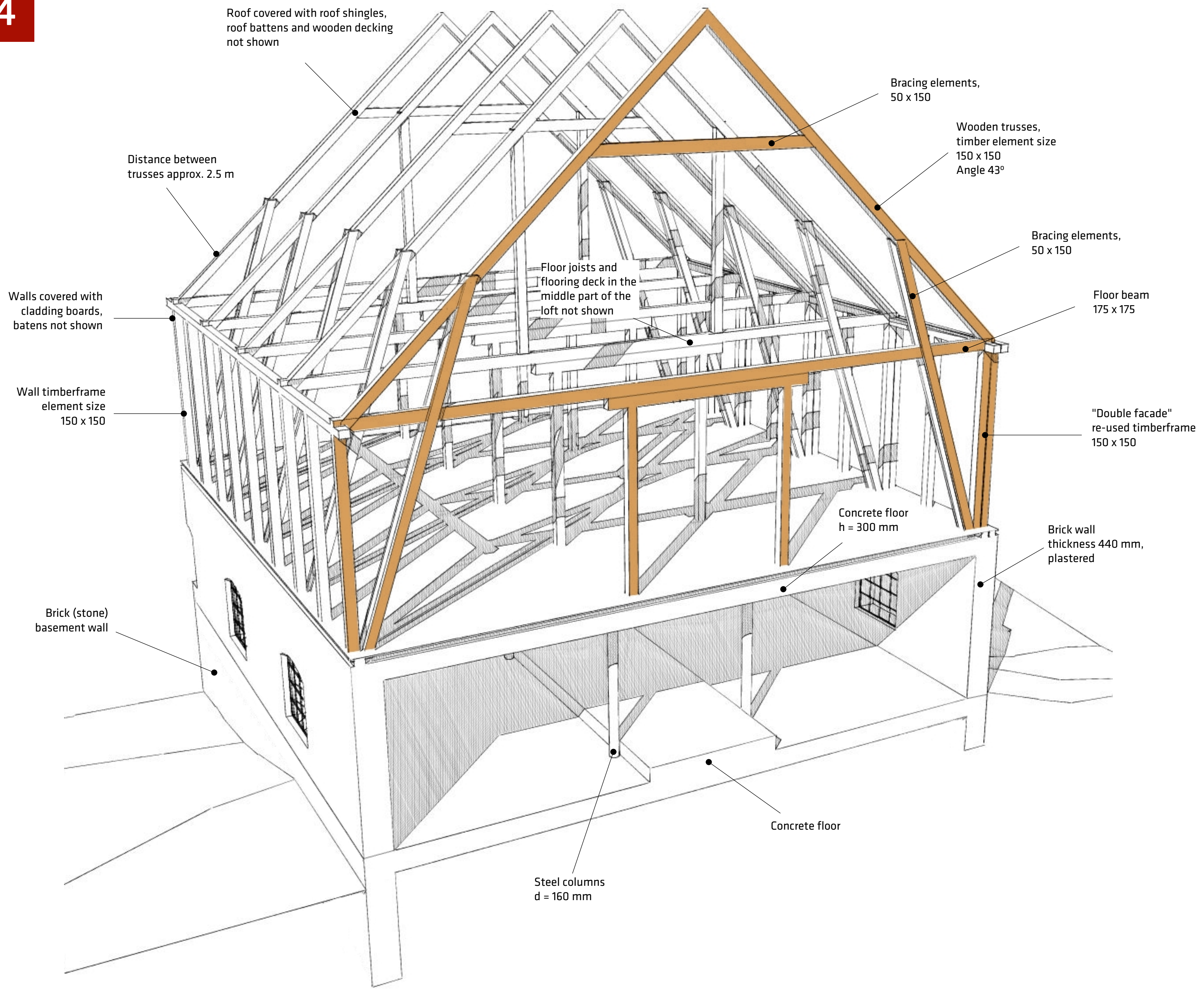


1 floor/ 3 floors

Different (re)building periods, local small adjustments

Used as a stall/ workshop/ "ramp" area for the attic

BUILDING
4



REUSE SCENARIOS

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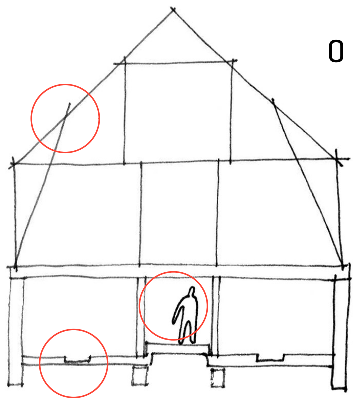
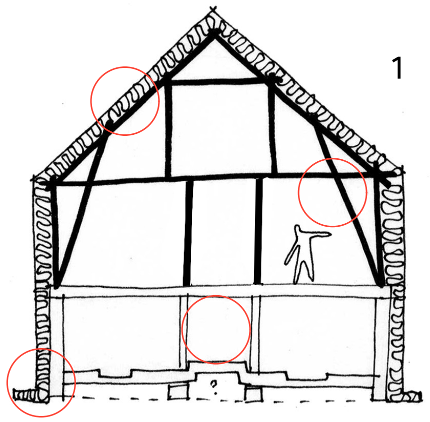


Low ceiling height on the ground floor (>2.30)

Concrete floor purpose-made for a cowshed

Uninsulated envelope

1



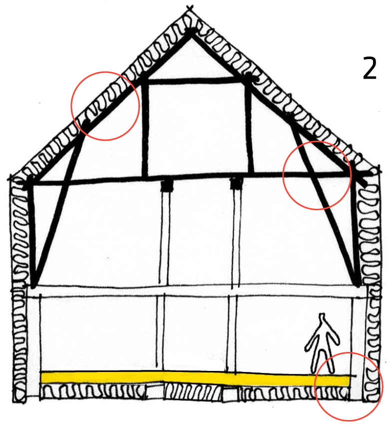
Low ceiling height on the ground floor

Increased load due to insulation and new use

Existing wooden structure limiting use

Huge thermal bridge to the ground

2

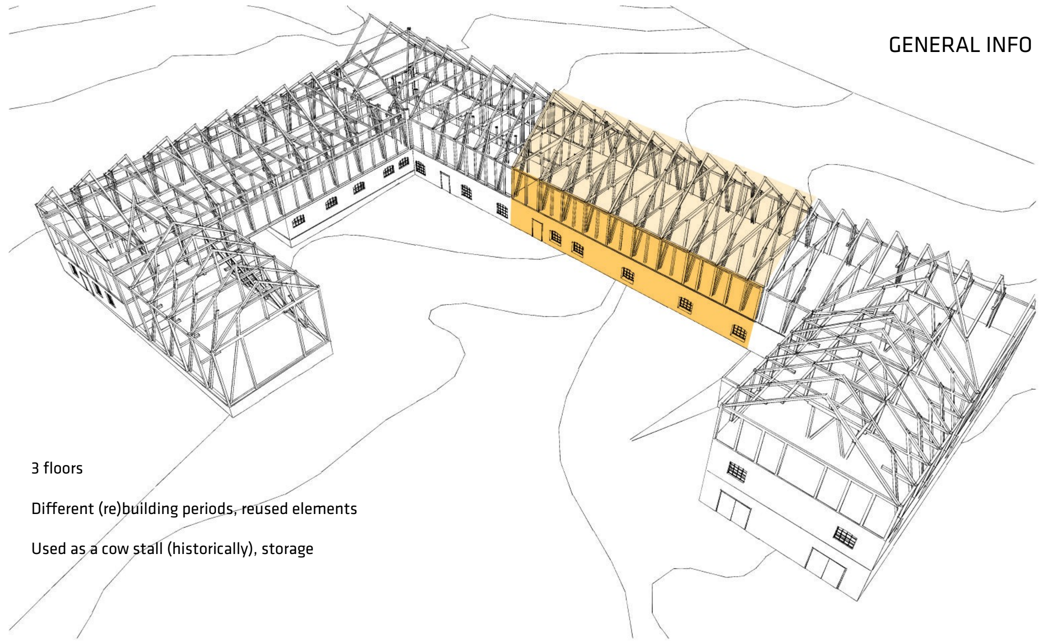


Increased load due to insulation and new use

Existing wooden structure limiting use

Thermal bridge to the ground

GENERAL INFO



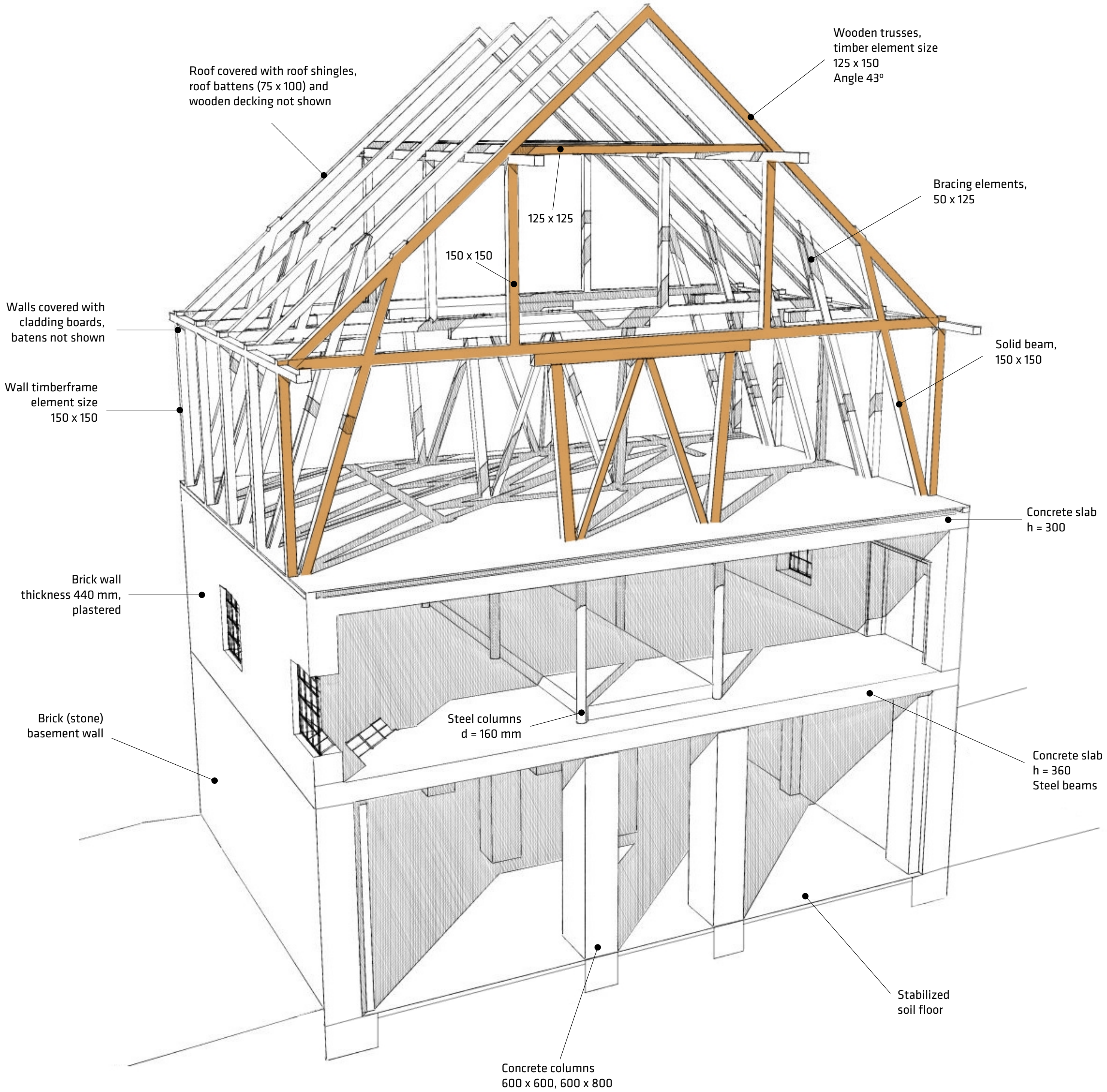
3 floors

Different (re)building periods, reused elements

Used as a cow stall (historically), storage

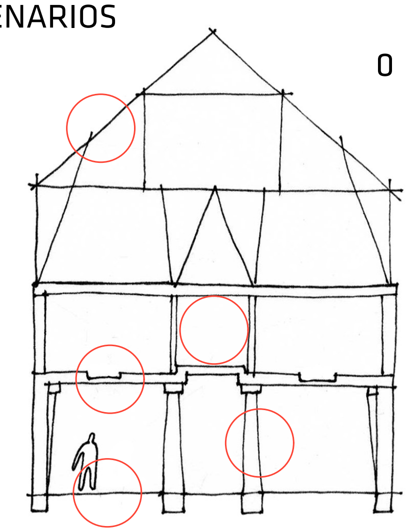
BUILDING

5



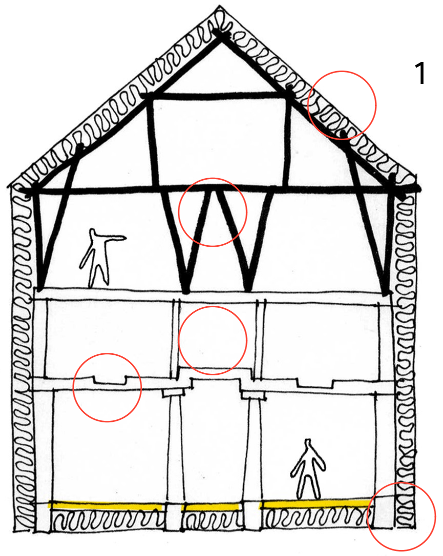
REUSE SCENARIOS

0



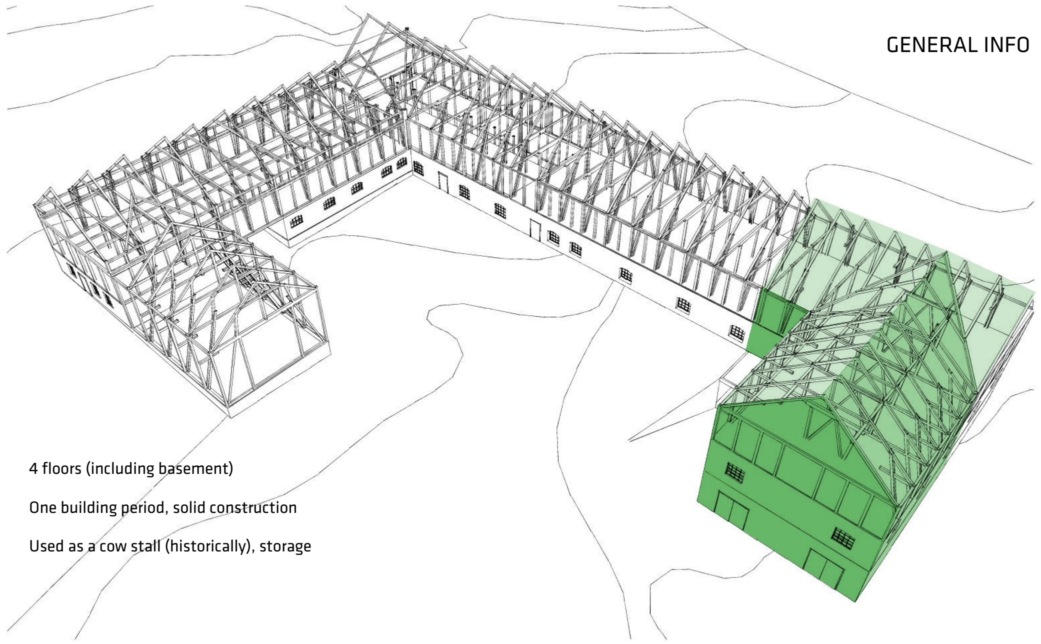
- Low ceiling height on the ground floor (>2.30)
- Concrete floor purpose-made for a cowshed
- Uninsulated envelope
- Stabilized soil floor
- Concrete columns in a bad state

1

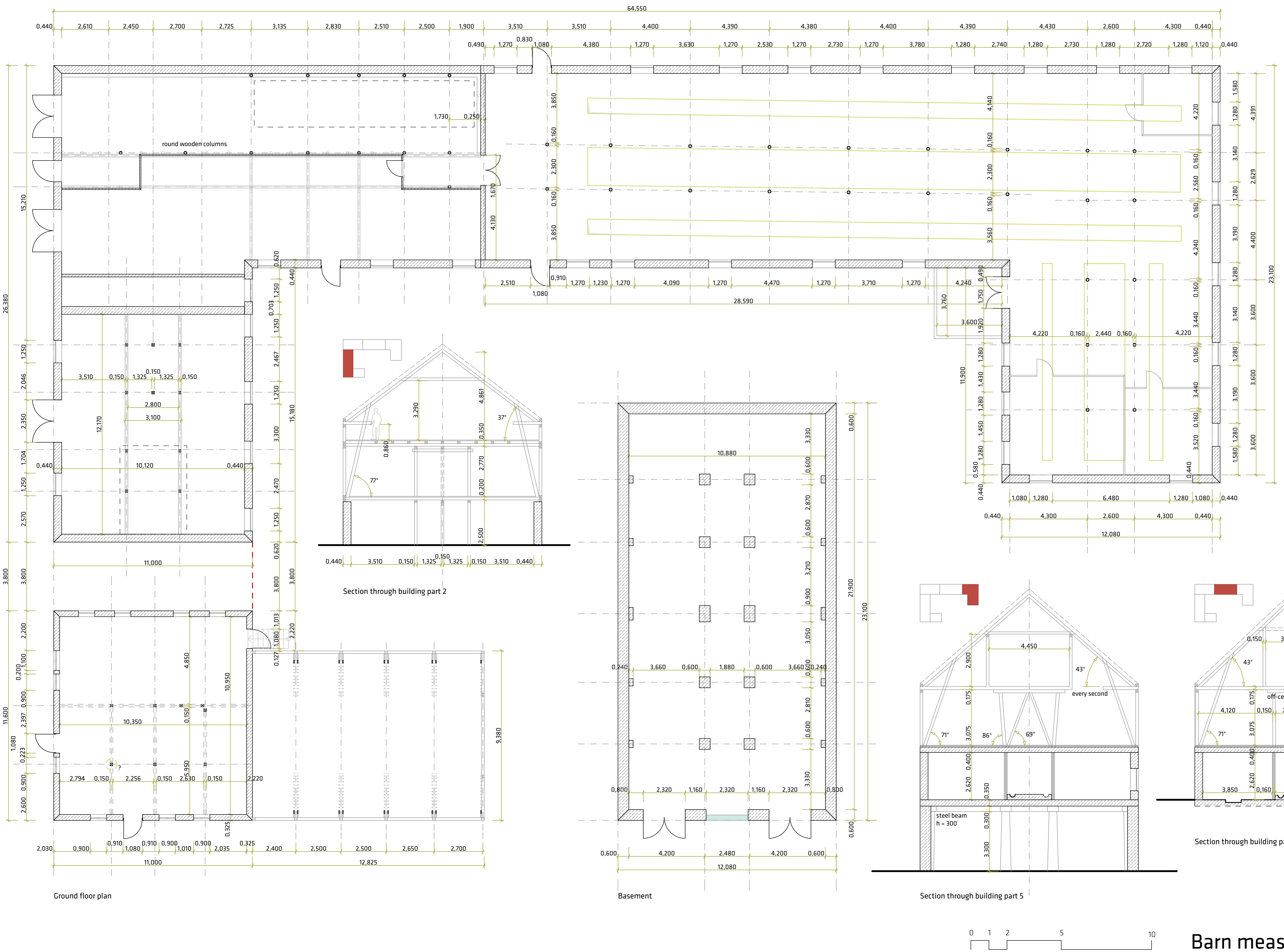


- Low ceiling height on the ground floor (>2.30)
- Concrete floor purpose-made for a cowshed
- Thermal bridge to the ground
- Existing wooden structure limiting use
- Increased load due to insulation and new use

GENERAL INFO



- 4 floors (including basement)
- One building period, solid construction
- Used as a cow stall (historically), storage



Ground floor plan

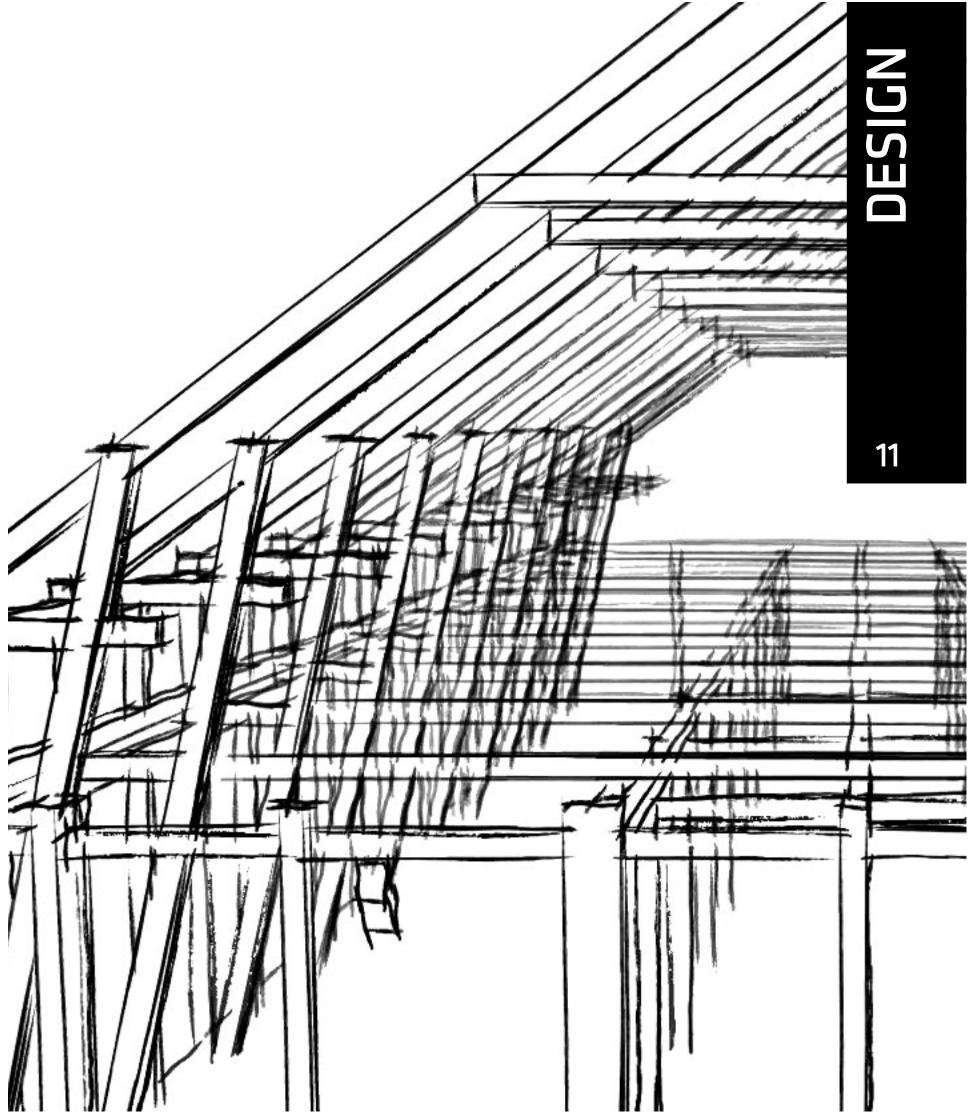
Section through building part 2

Basement

Section through building part 5

Section through building part 4

Barn measurements 1:200



Urban setting

The site

Rotvoll area is located by the Trondheim fjord northeast of the city centre. It is easily accessible by train, bus or car.

An alley of trees leads pedestrians and cyclists to the HiST university, former Rotvoll asylum building.

Rotvoll farm is placed in a relatively open rural area with several bigger buildings nearby - Statoil Research facility and HiST university.

Due to the close placement of buildings in the farm they tend to cast shadows on each other (see solar access diagrams below).

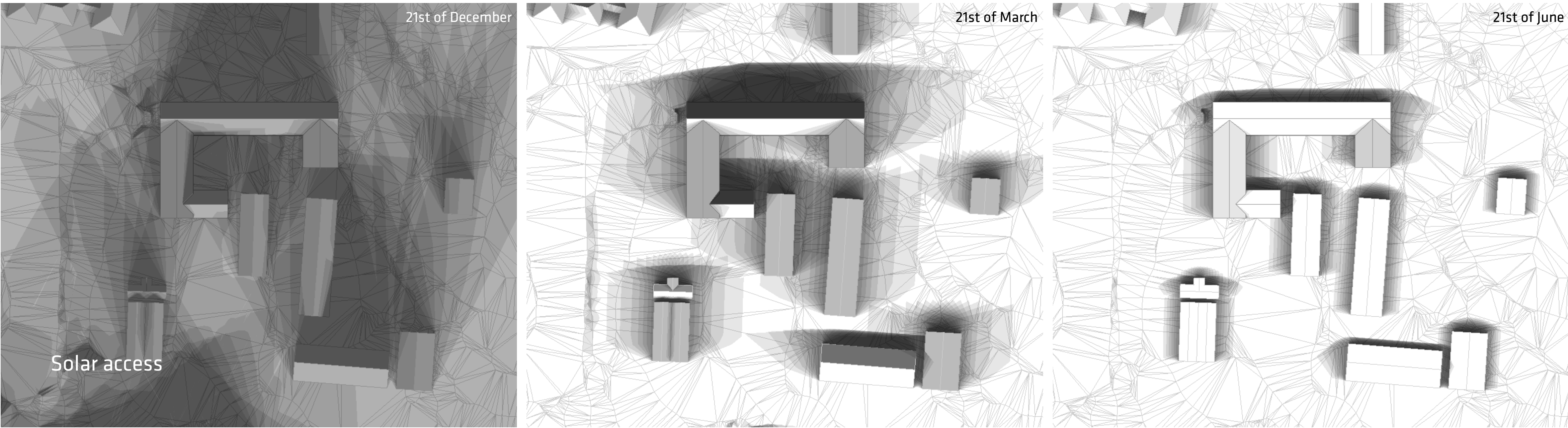
In winter months the terrain limits solar access to the lowest floors of the buildings, since the terrain is downward sloping towards the fjord.

The barn building is central to the farm and shelters other buildings from the road (Rotvoll alle) in the north.

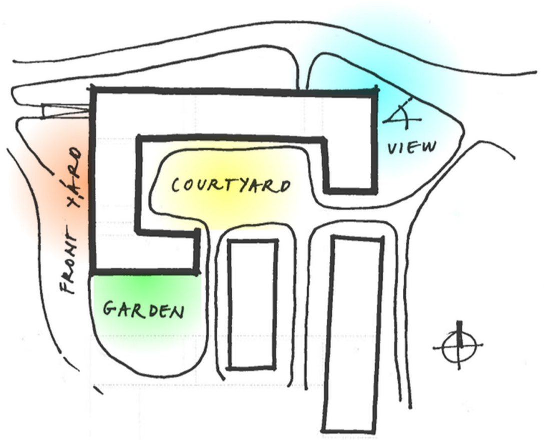
The barn with its winged shape and the surrounding buildings and green spaces create different moods around the perimeter of the barn.

Camphill Rotvoll area to the south-west with frontyard and garden is more secluded and intimate, while the north facade and north-eastern corner of the building faces more publicly active areas and opens up to the fjord.

The barn also creates an inner courtyard, which in future could be the common meeting space shared by all three Rotvoll farm users - Camphill Rotvoll, FRAMskolen and Steiner school.

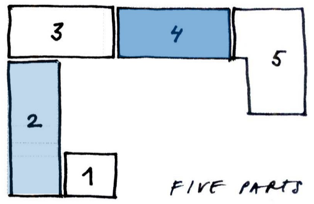


Solar access

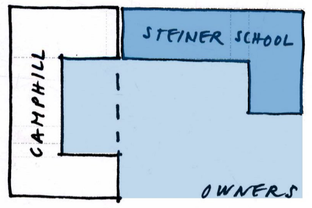


Qualities of the site

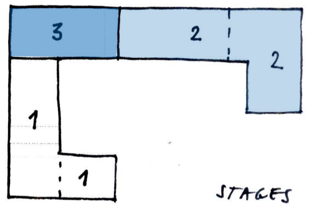
Programme



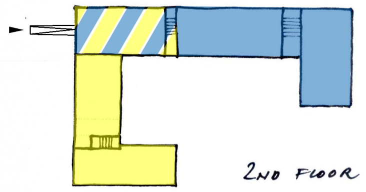
Using the different characteristics of the 5 building parts to fill them with a function that best merges with the existing structure



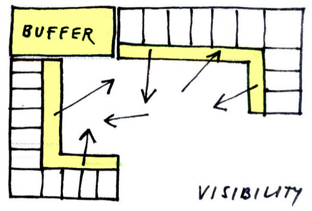
Respecting the ownership, but placing the uses of the building in a way that co-ownership is possible in some parts of the barn



Allowing for the barn to be transformed in stages, starting with most urgent function



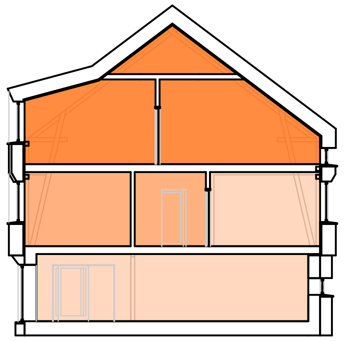
Using a separating/joining space (assembly hall) between the two barn users - Camphill and FRAMskolen



Visually connected common spaces. Sheltered privacy of the individual rooms - no room windows facing each other

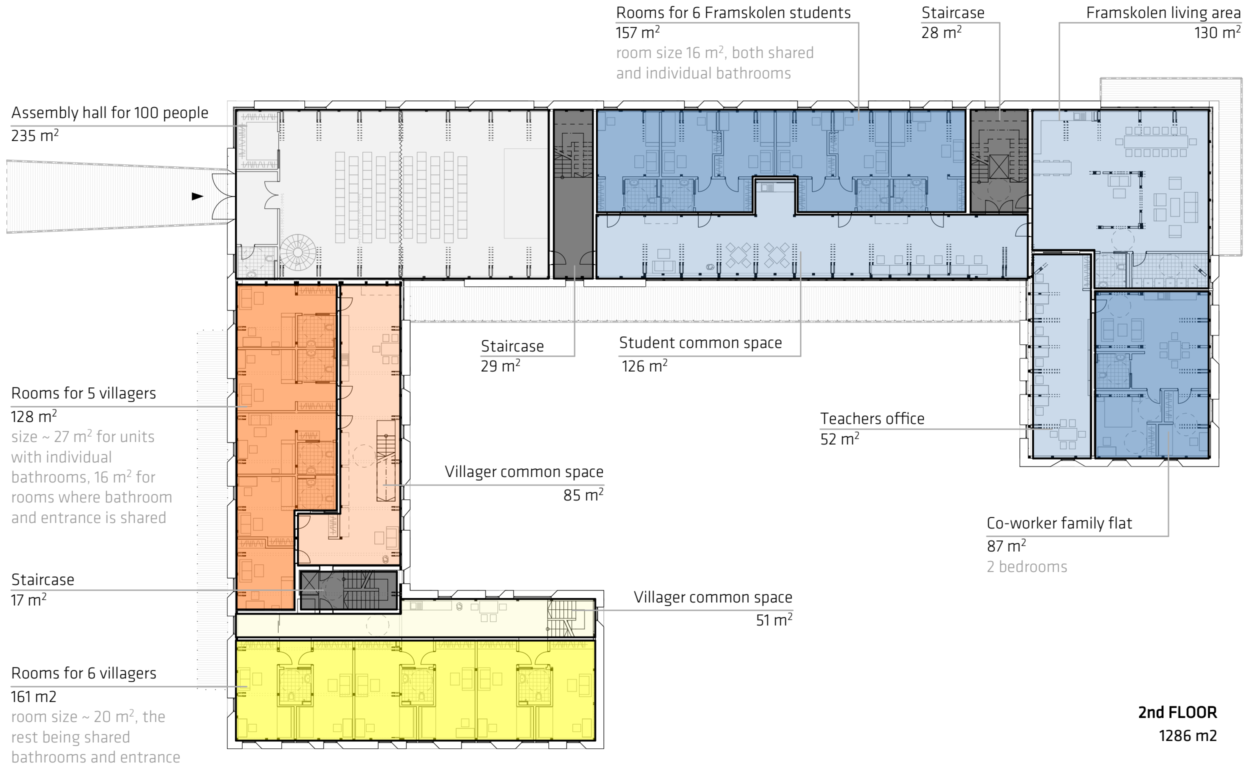
CAMPHILL ROTVOLL

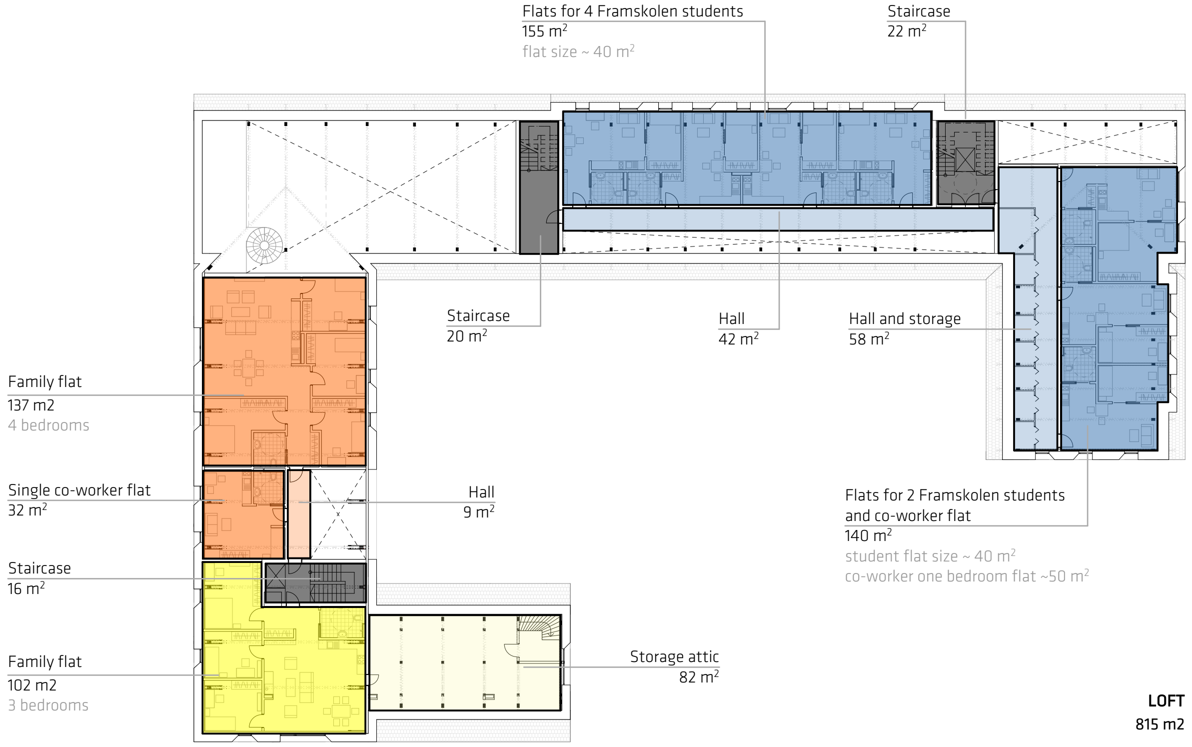
Floor area: 1650 m²



Increasing privacy towards higher floors

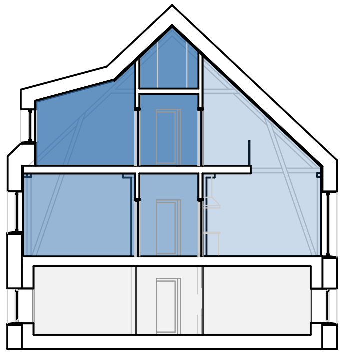
- Co-worker flats
- Villager rooms
- Common living areas





FRAMskolen

Floor area: 1850 m²



Increasing independence towards higher floors

- Last year student individual flats
- First year student rooms
- Common living areas
- Workshops/ classrooms

LEGEND

Camphill Rotvoll family house A

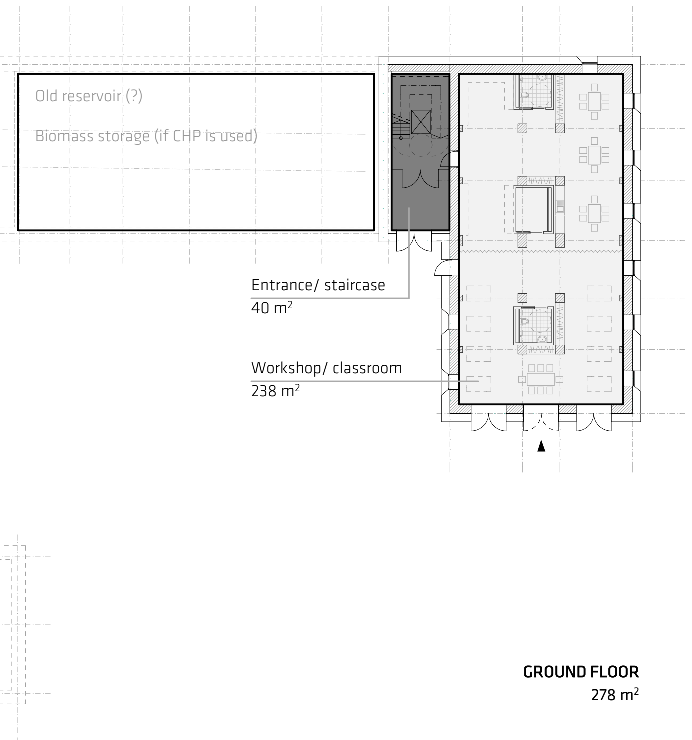
- Shared spaces - living room, hall, laundry
- Individual rooms and flats

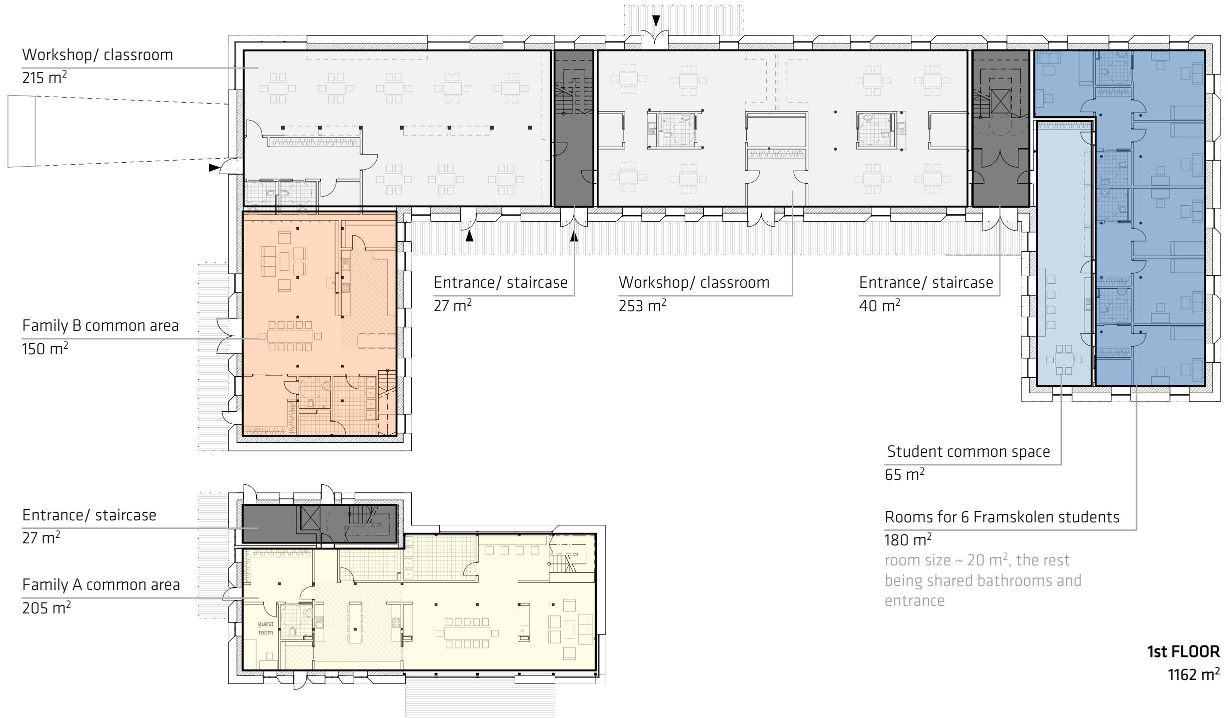
Camphill Rotvoll family house B

- Shared spaces - living room, hall, laundry
- Individual rooms and flats

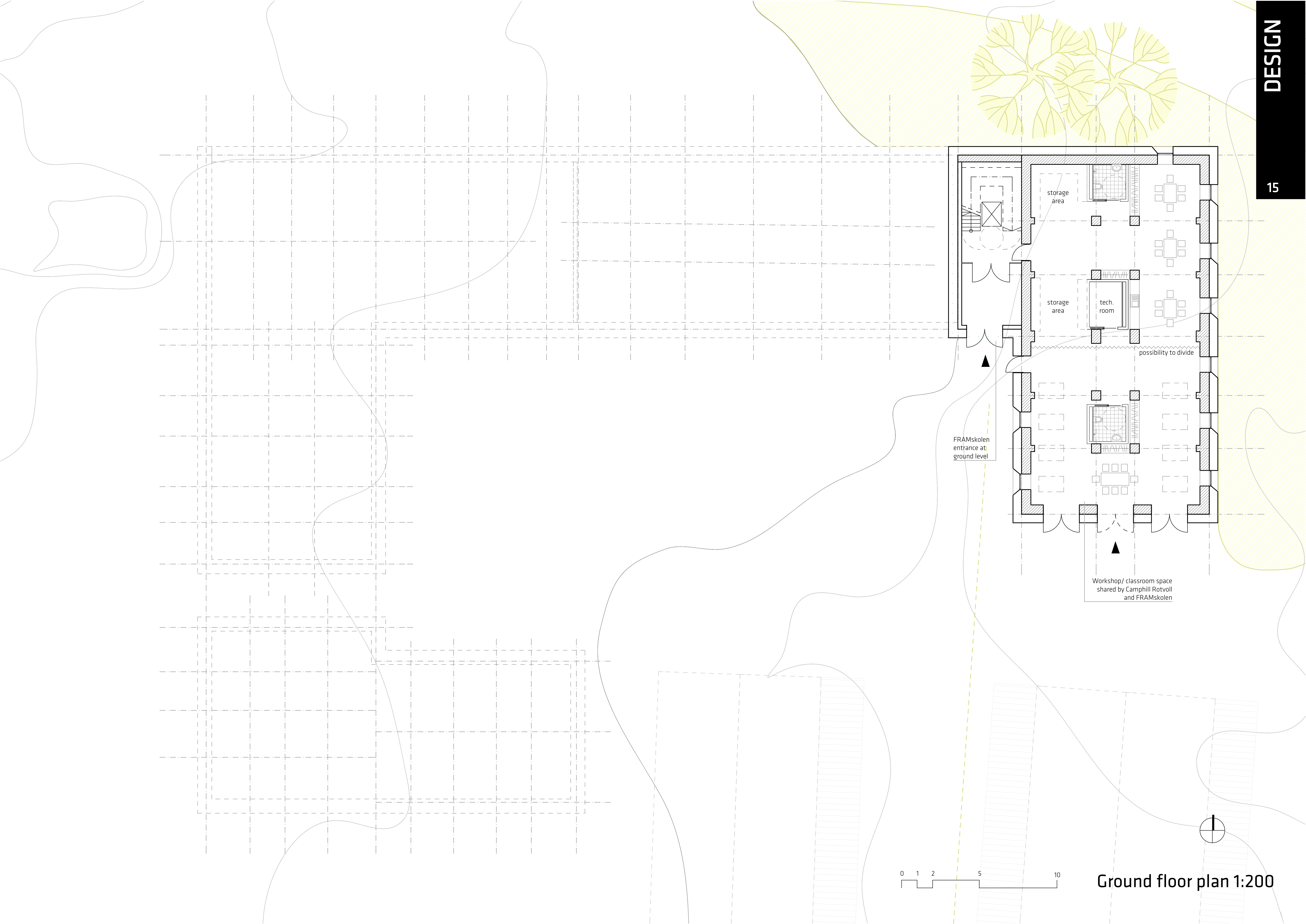
FRAMskolen

- Shared spaces - living room, hall, laundry
- Individual rooms and flats
- Shared workshops and classrooms
- Staircases

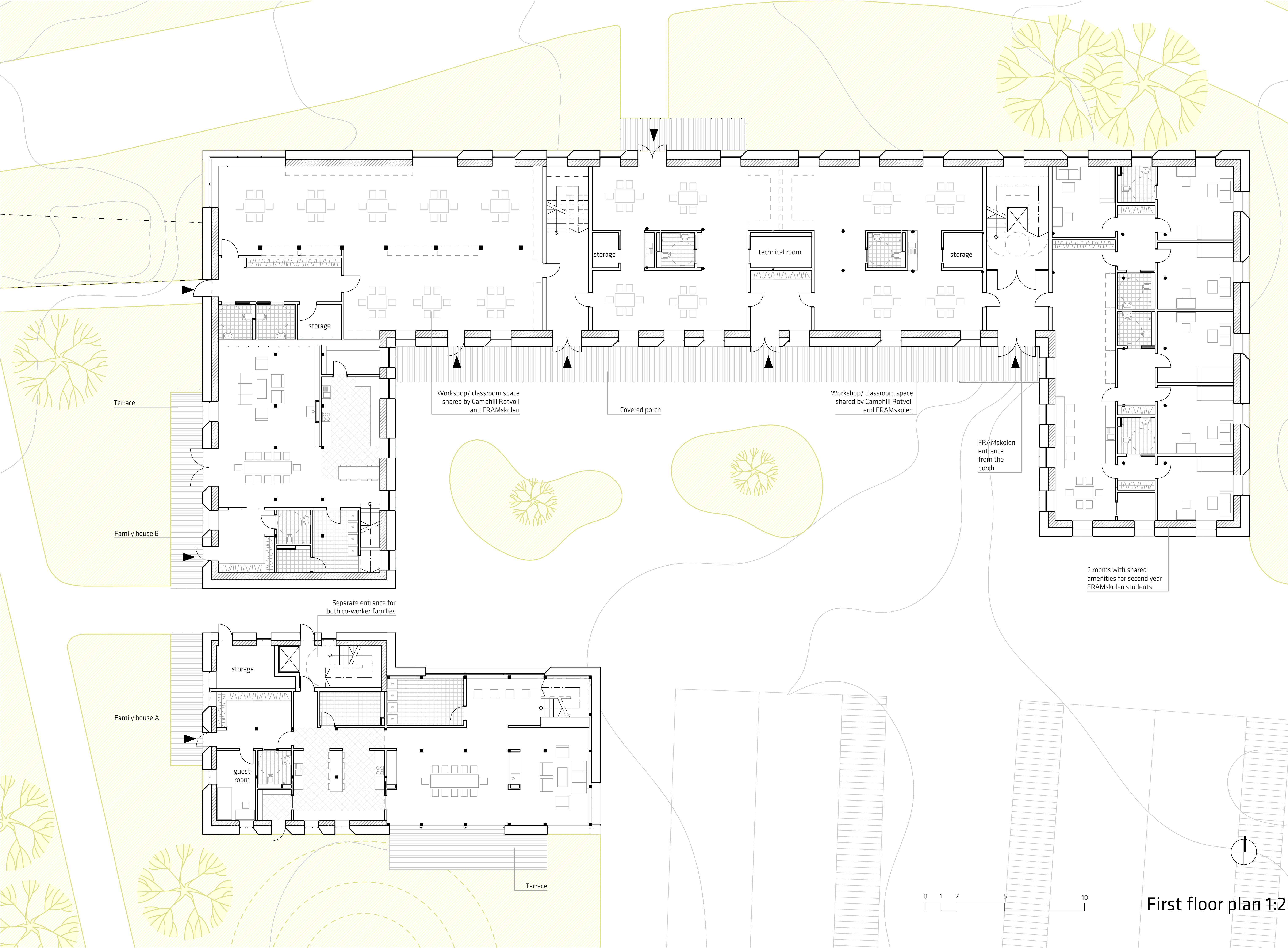




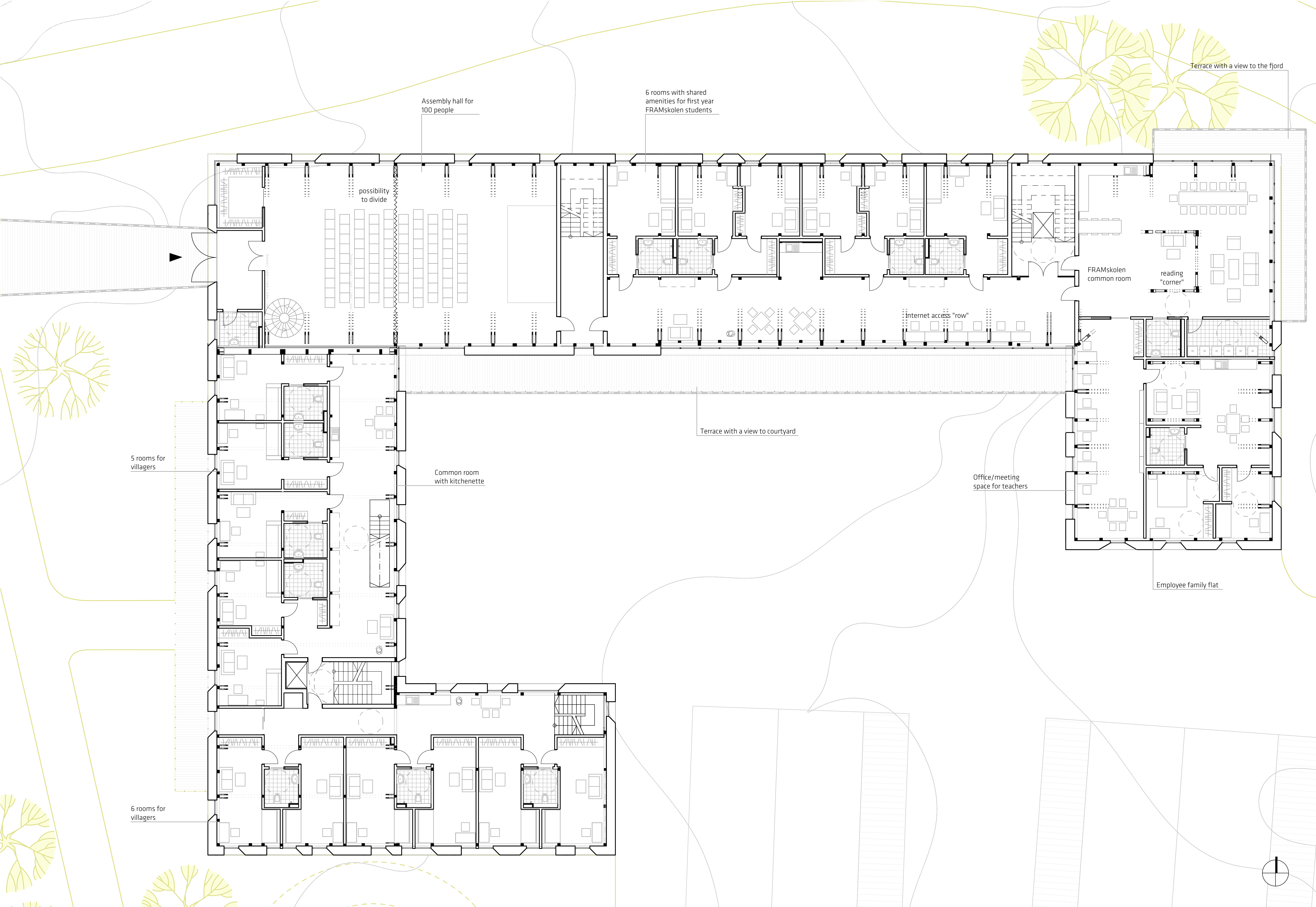
Site plan 1:500



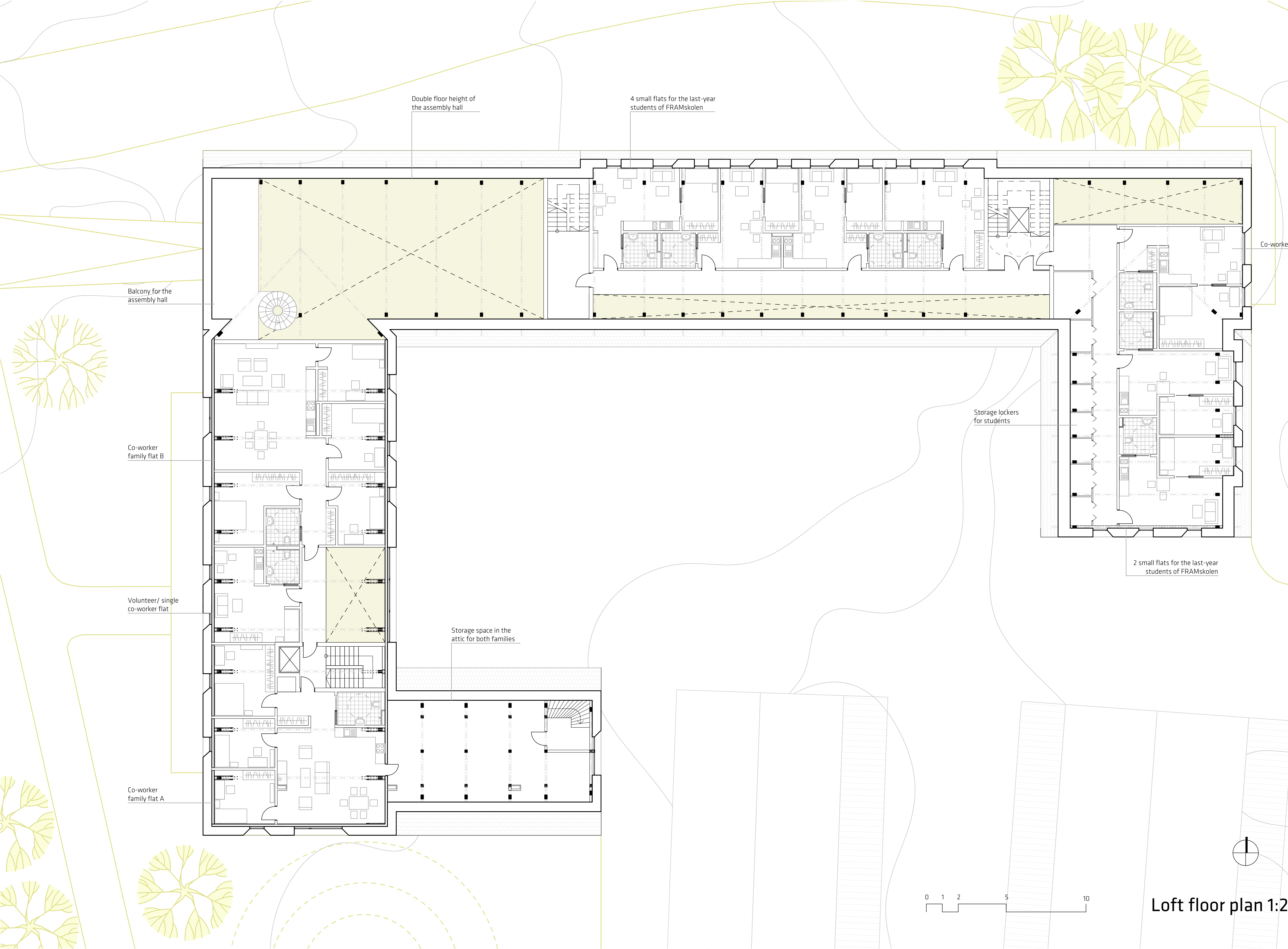
Ground floor plan 1:200



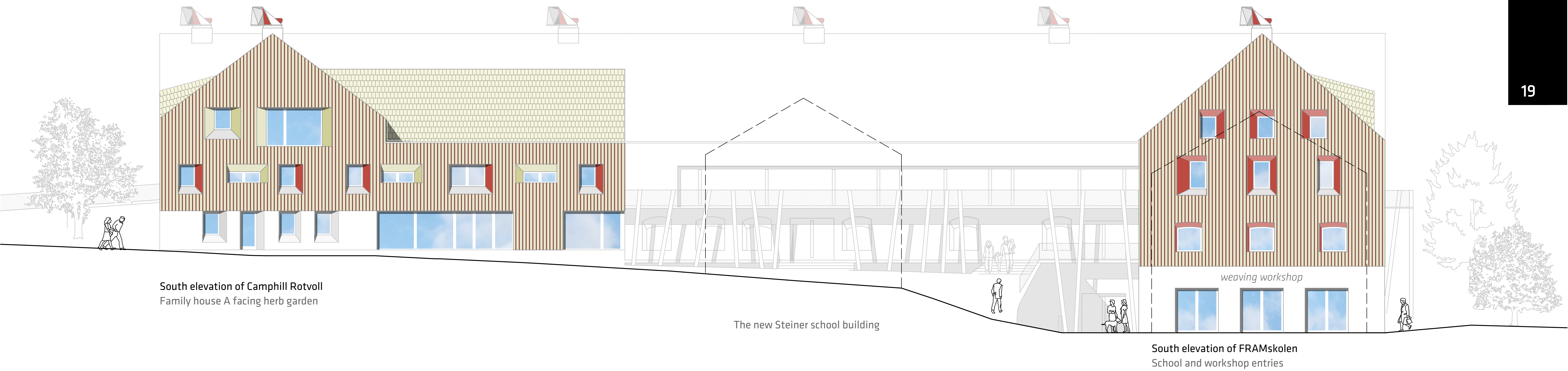
First floor plan 1:200

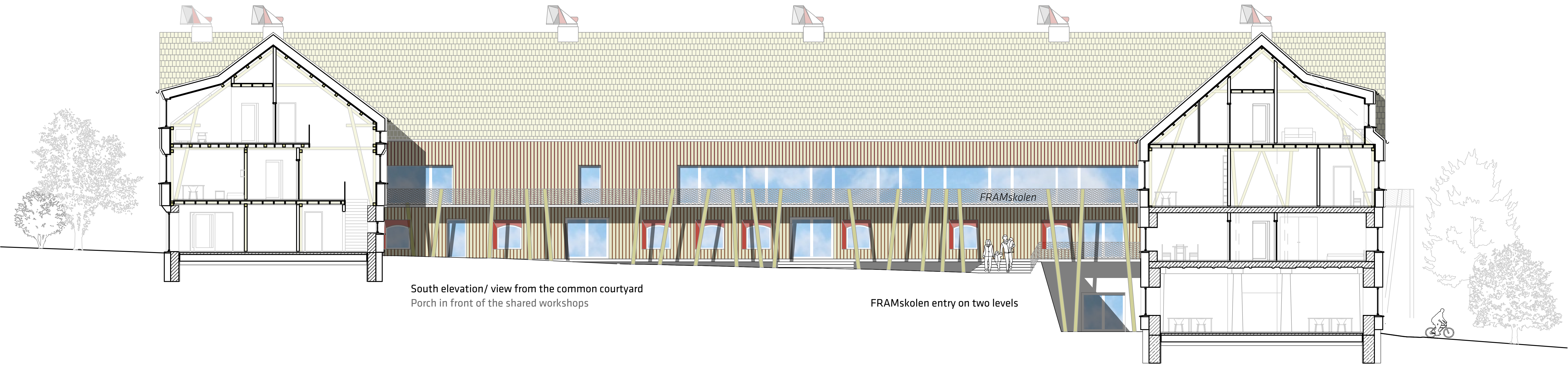


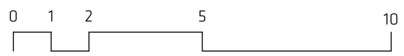
Second floor plan 1:200



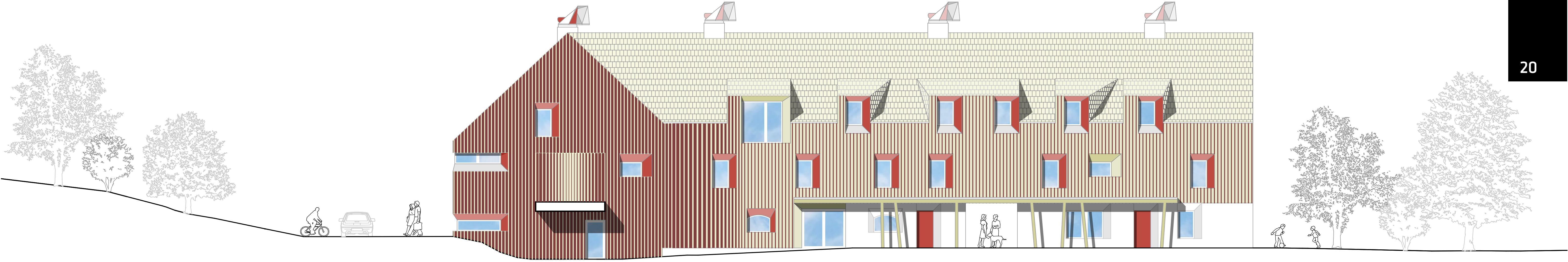
Loft floor plan 1:200







Elevations 1:200

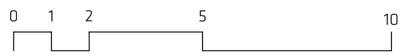


Camphill "Barn"
Assembly hall for 100 people

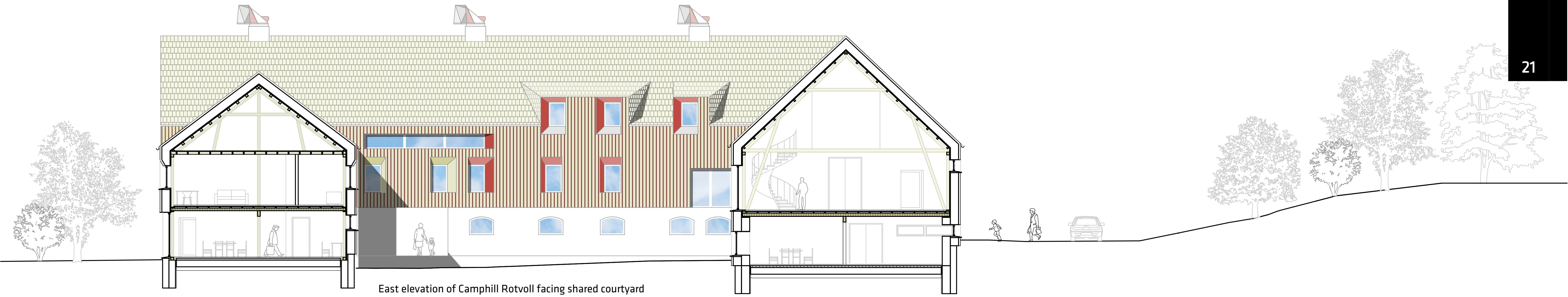
West elevation of Camphill Rotvoll
Entry area for both family houses

Camphill "Barn" entry
Assembly hall for 100 people

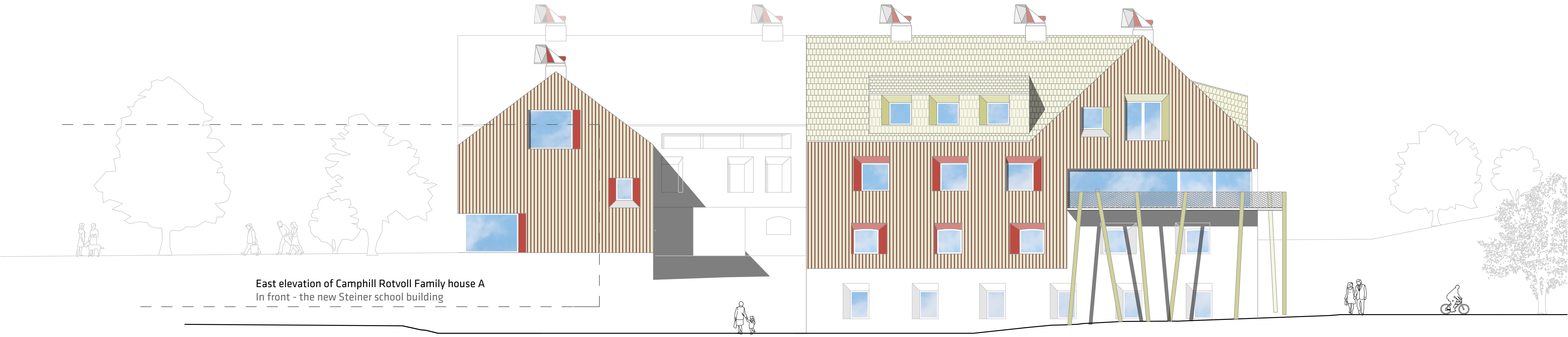
North elevation of FRAMskolen
Terrace facing the fjord view



Elevations 1:200



East elevation of Camphill Rotvoll facing shared courtyard
Drive-through connects Camphill entry space with yard



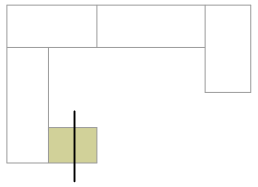
East elevation of Camphill Rotvoll Family house A
In front - the new Steiner school building

East elevation of FRAMskolen facing the fjord
Access to the ground floor workshops

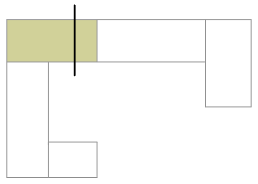
0 1 2 5 10

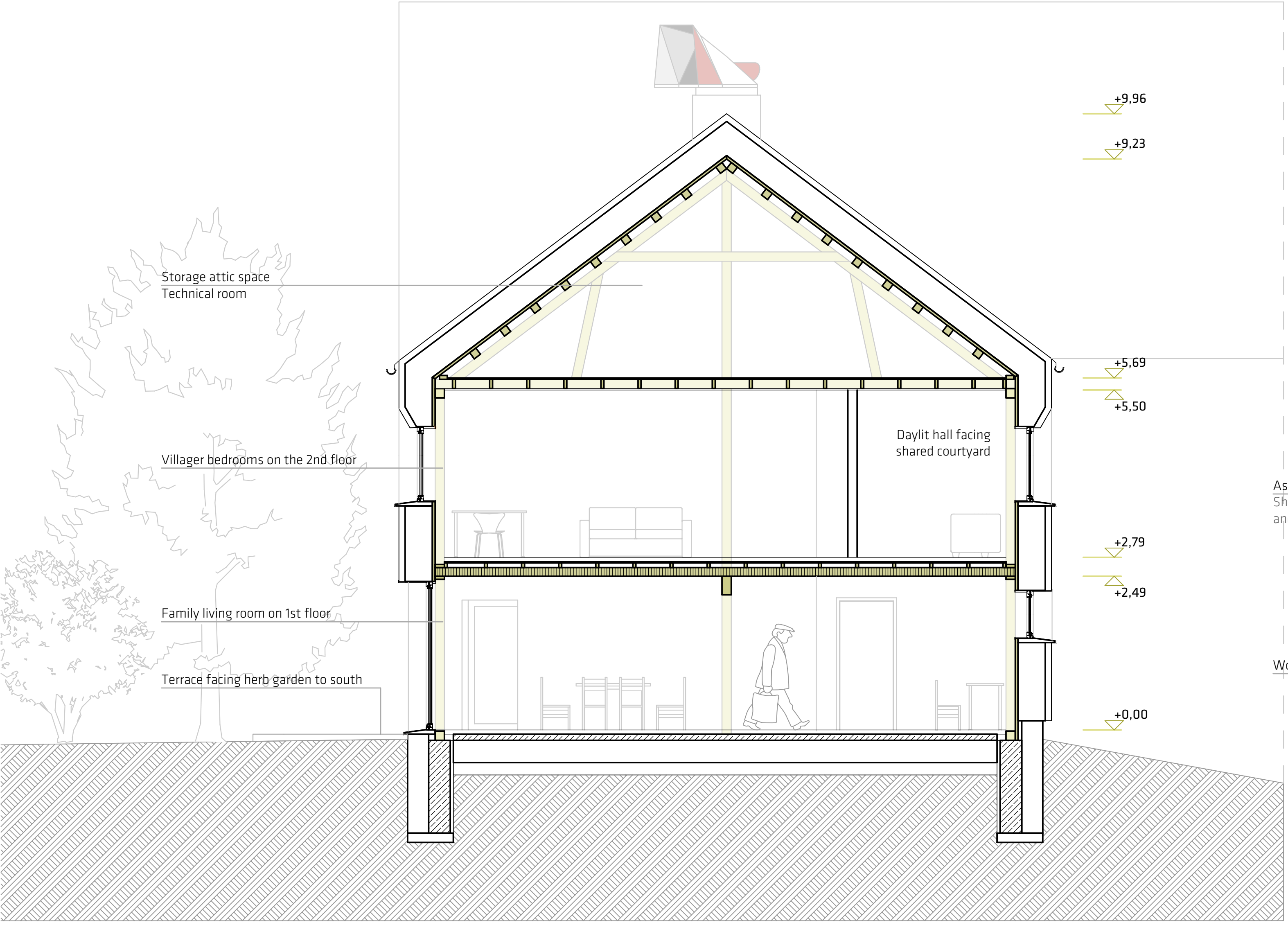
Elevations 1:200

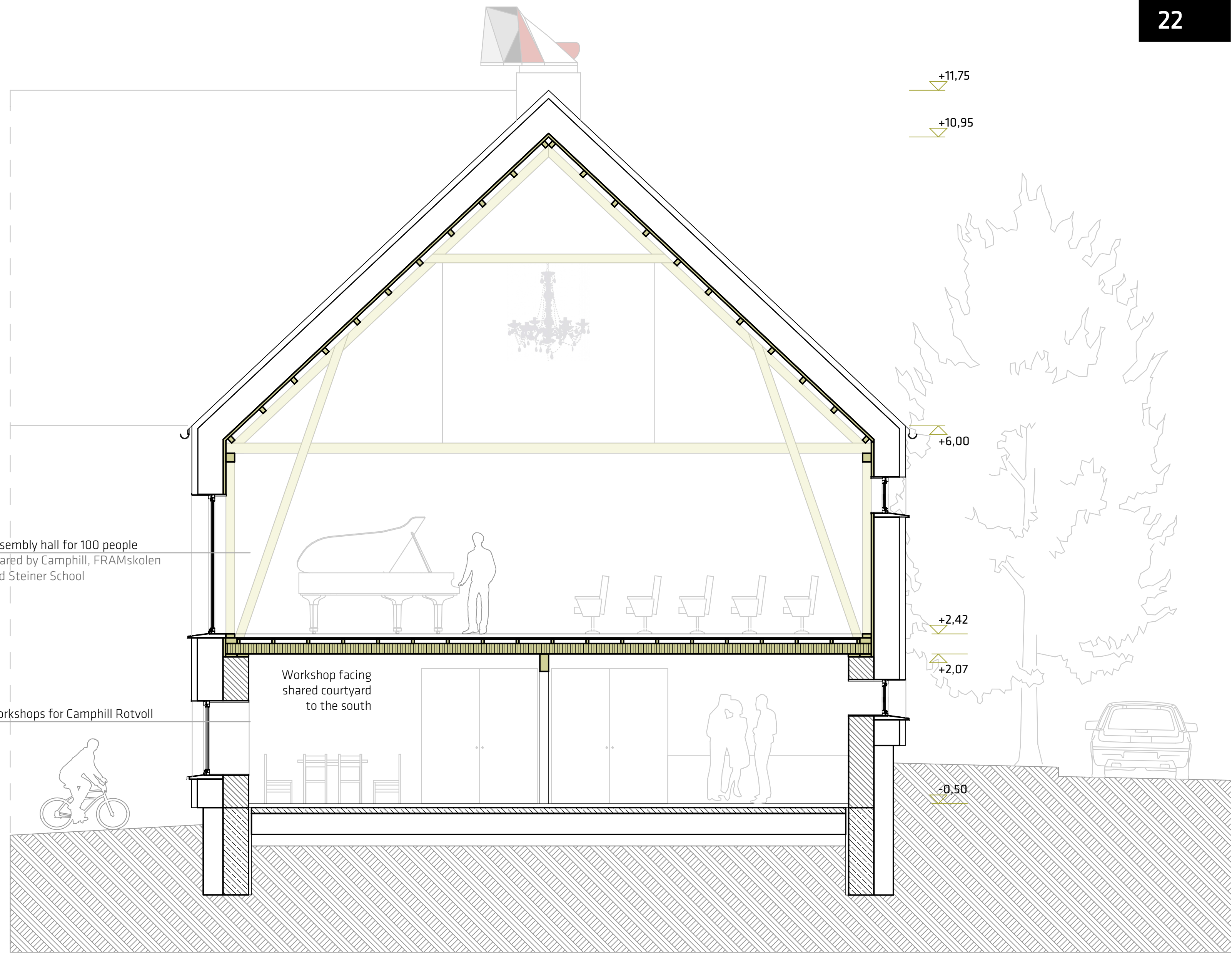
Building 1
Family house A, shared attic storage

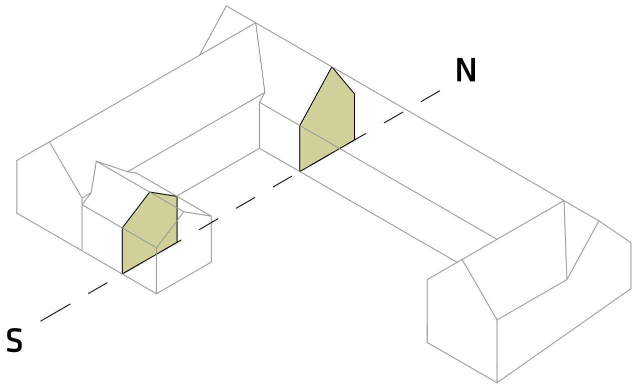


Building 3
Assembly hall and worskhops



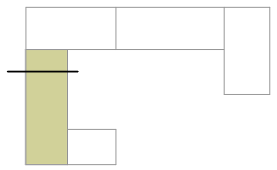




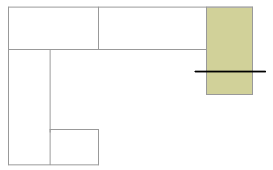


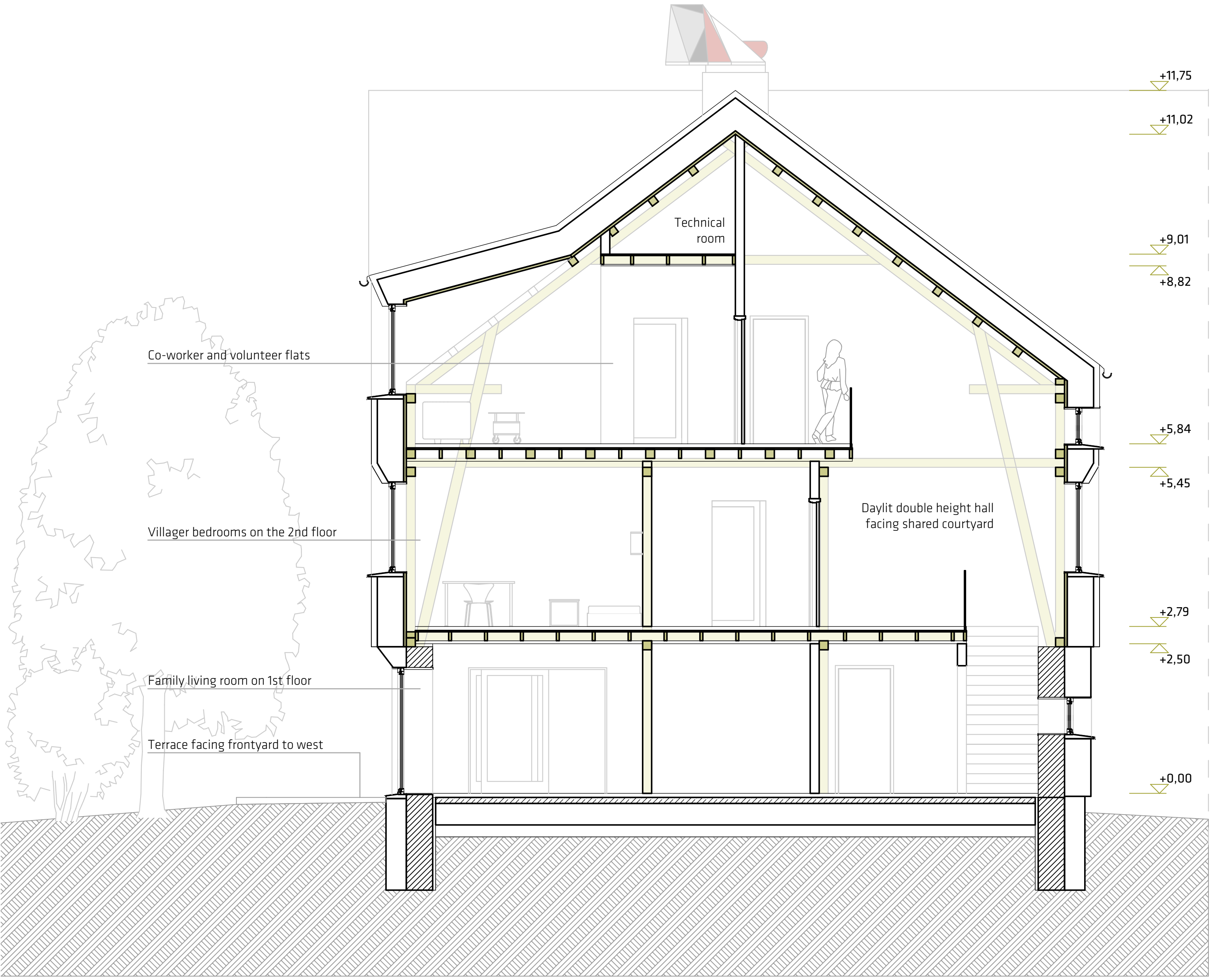
Sections - Buildings 1 and 3 1:100

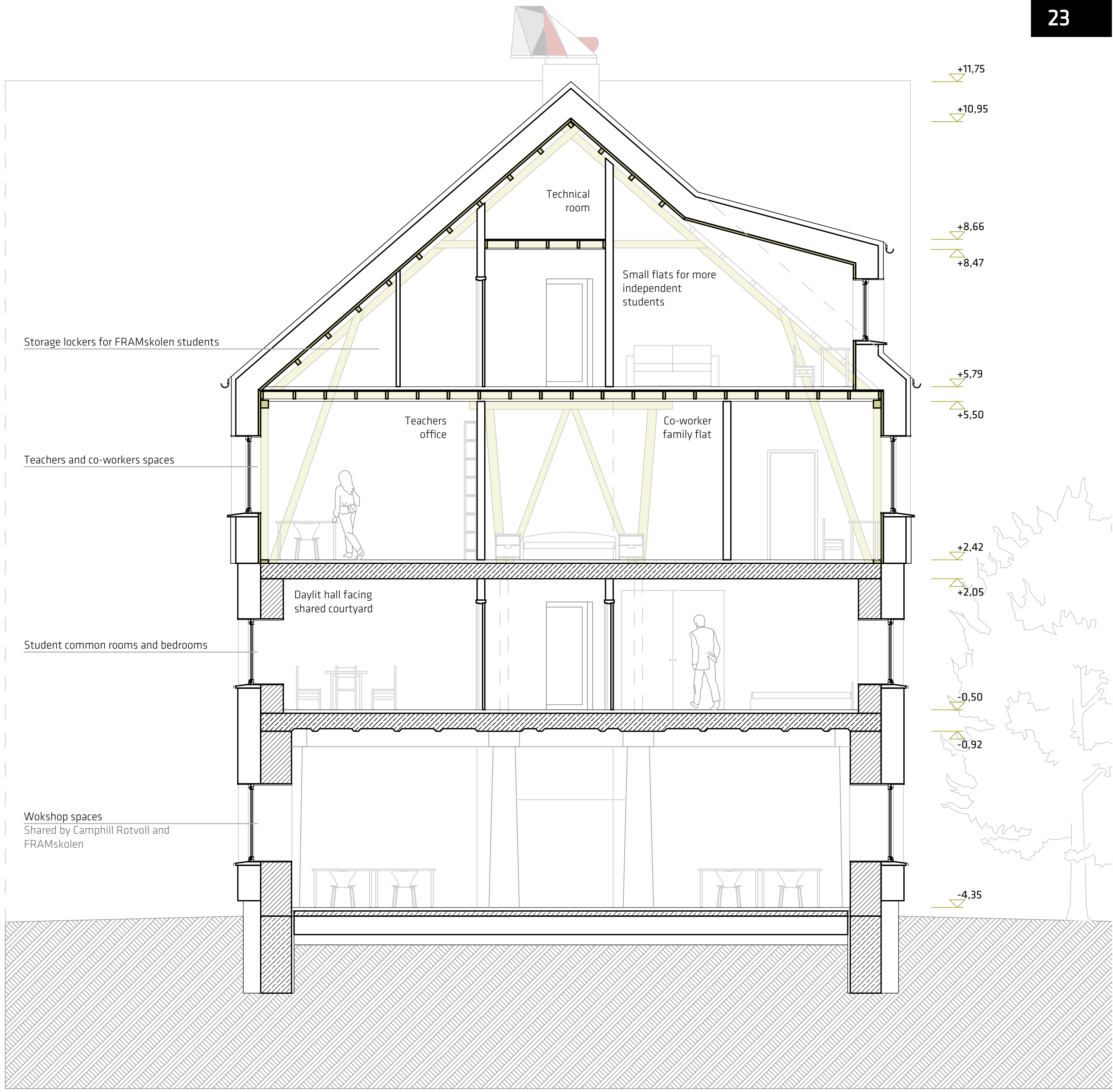
Building 2
Family house B, co-worker flats

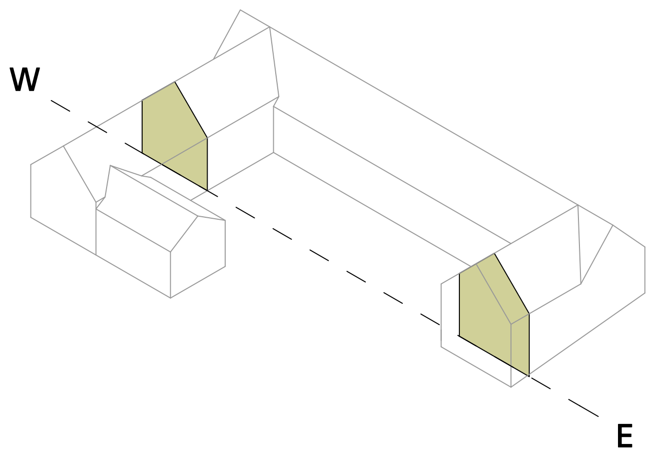


Building 5
FRAMskolen common rooms, teacher and students rooms



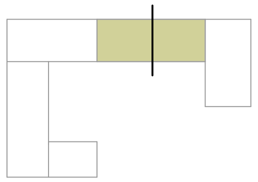


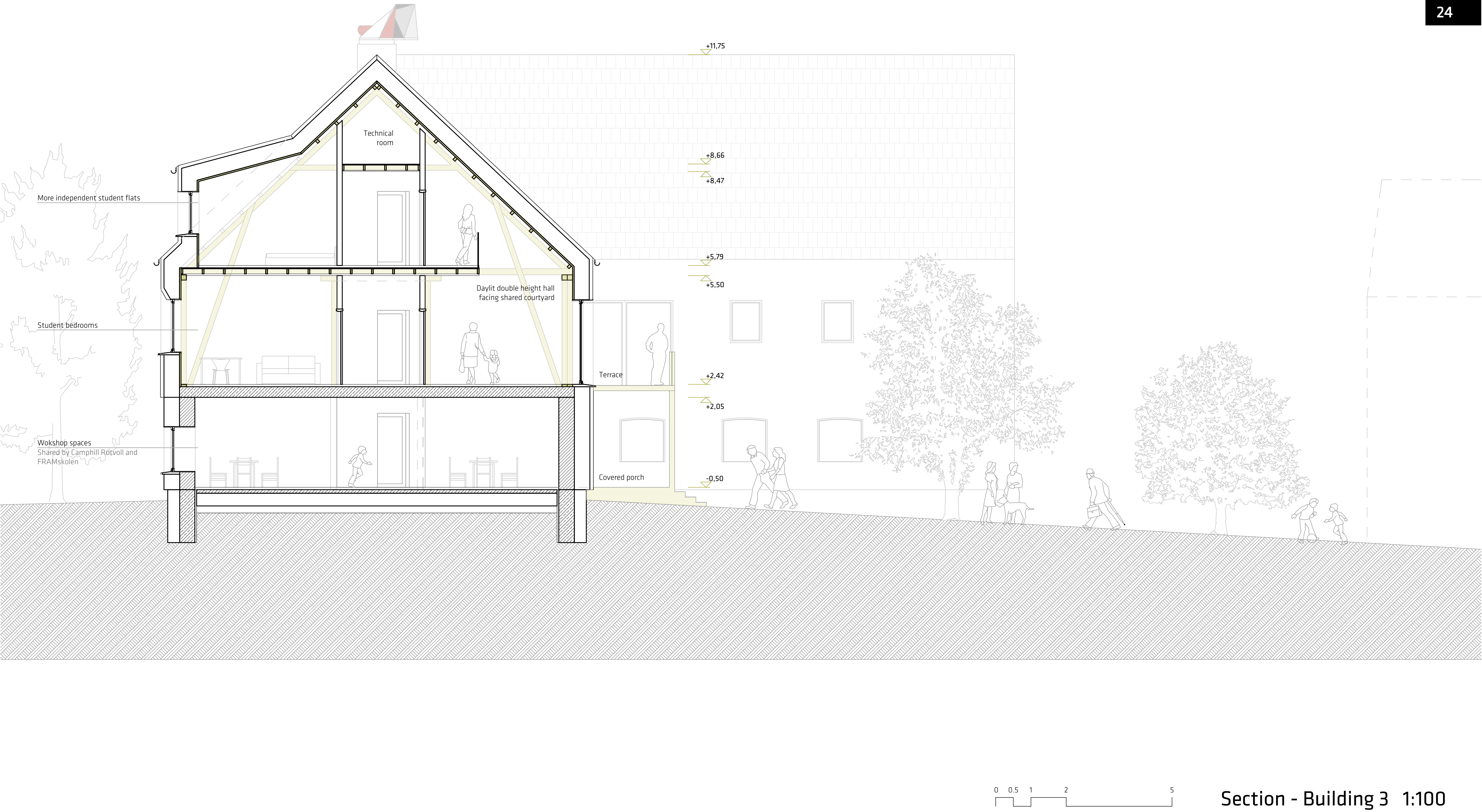




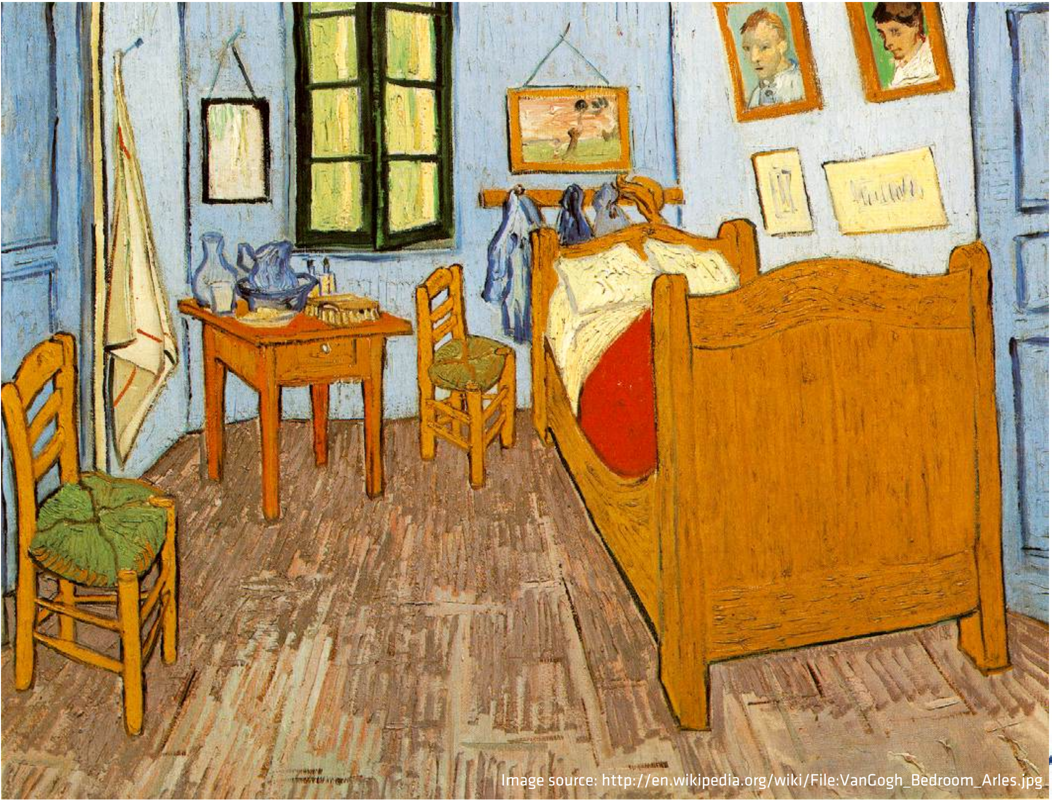
Sections - Buildings 2 and 5 1:100

Building 3
FRAMskolen student rooms, shared work and study spaces

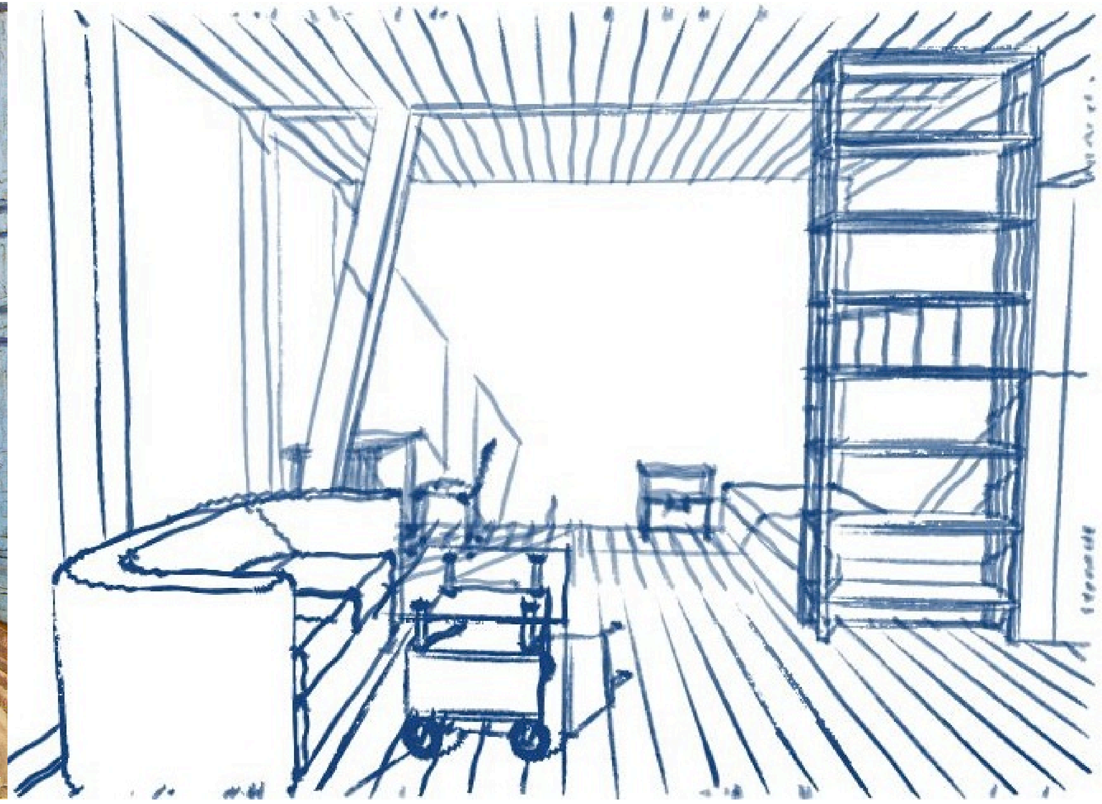




Section - Building 3 1:100



Bedroom in Arles, 1889
Vincent Van Gogh



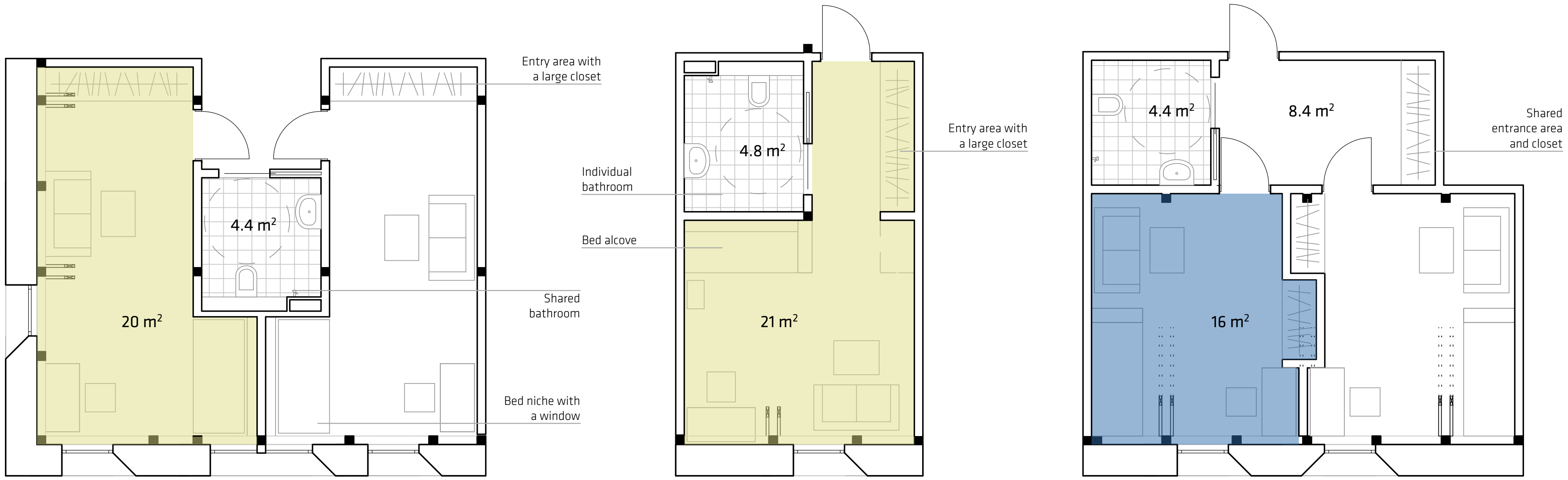
Bedroom in Rotvoll, 2012

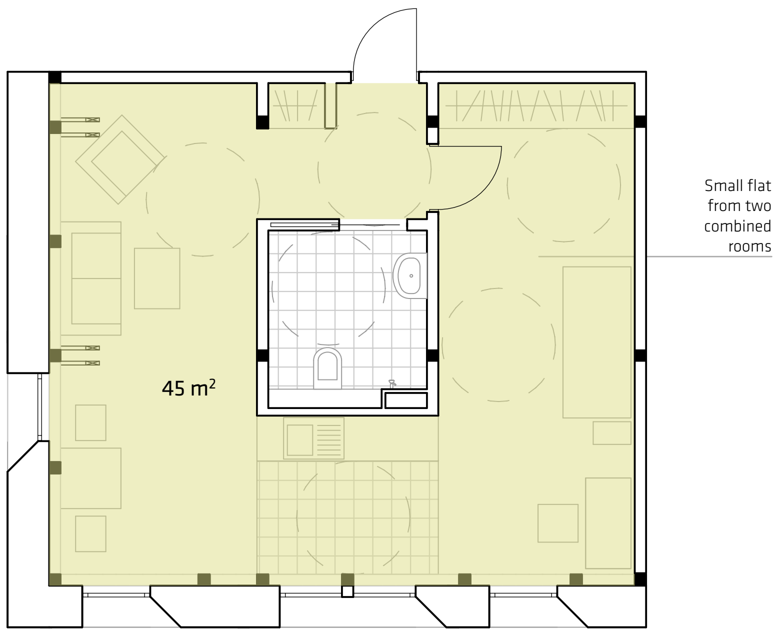
THE ROOM

A room as the only space for privacy

A room as a place for exploring independence

A room for life



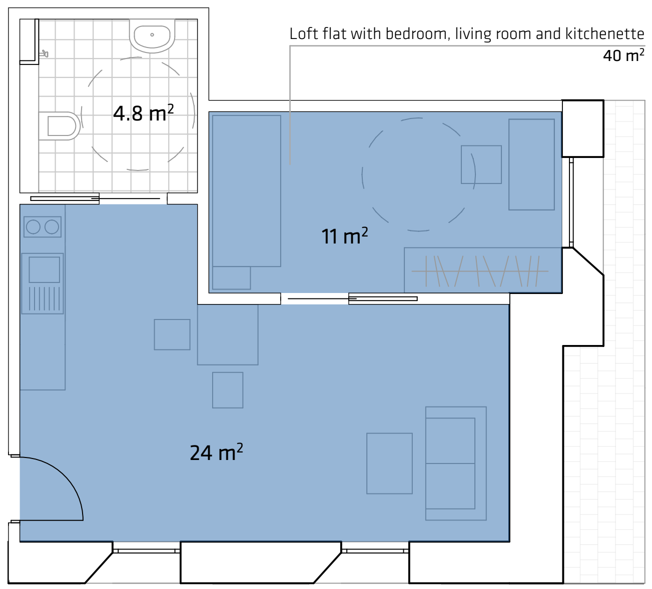


VILLAGER ROOMS AT CAMPHILL ROTVOLL

Since Camphill villages are intended for permanent stay, it is very important to make the private spaces spacious and allowing different uses and users.

To allow the room to be perceived as more than just a bedroom, the bed is placed out of first sight when entering the room.
Making rooms more spacious allows miniature living areas

Some of the rooms are also made to be combined in the future if necessary to fit different user needs.



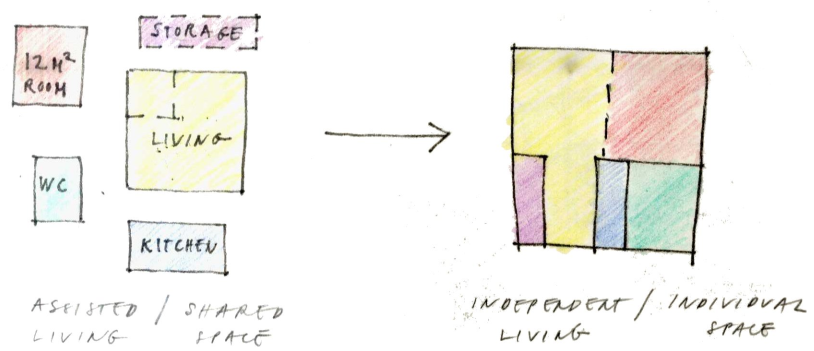
STUDENT ROOMS AT FRAMSKOLEN

FRAMskolen involves a three-year training for people with special needs to live more independently. Thus the rooms were students live are intended for a relatively shorter stay than at Camphill Rotvoll. Thus they are more compact, and with more shared areas - common entrances and bathrooms.

Because over the three year period the students would acquire more independence and also the students vary a lot from the start, a variety of room typologies is proposed - from small rooms with shared facilities for first year students to compact apartments with kitchenettes for last year and more experienced students.

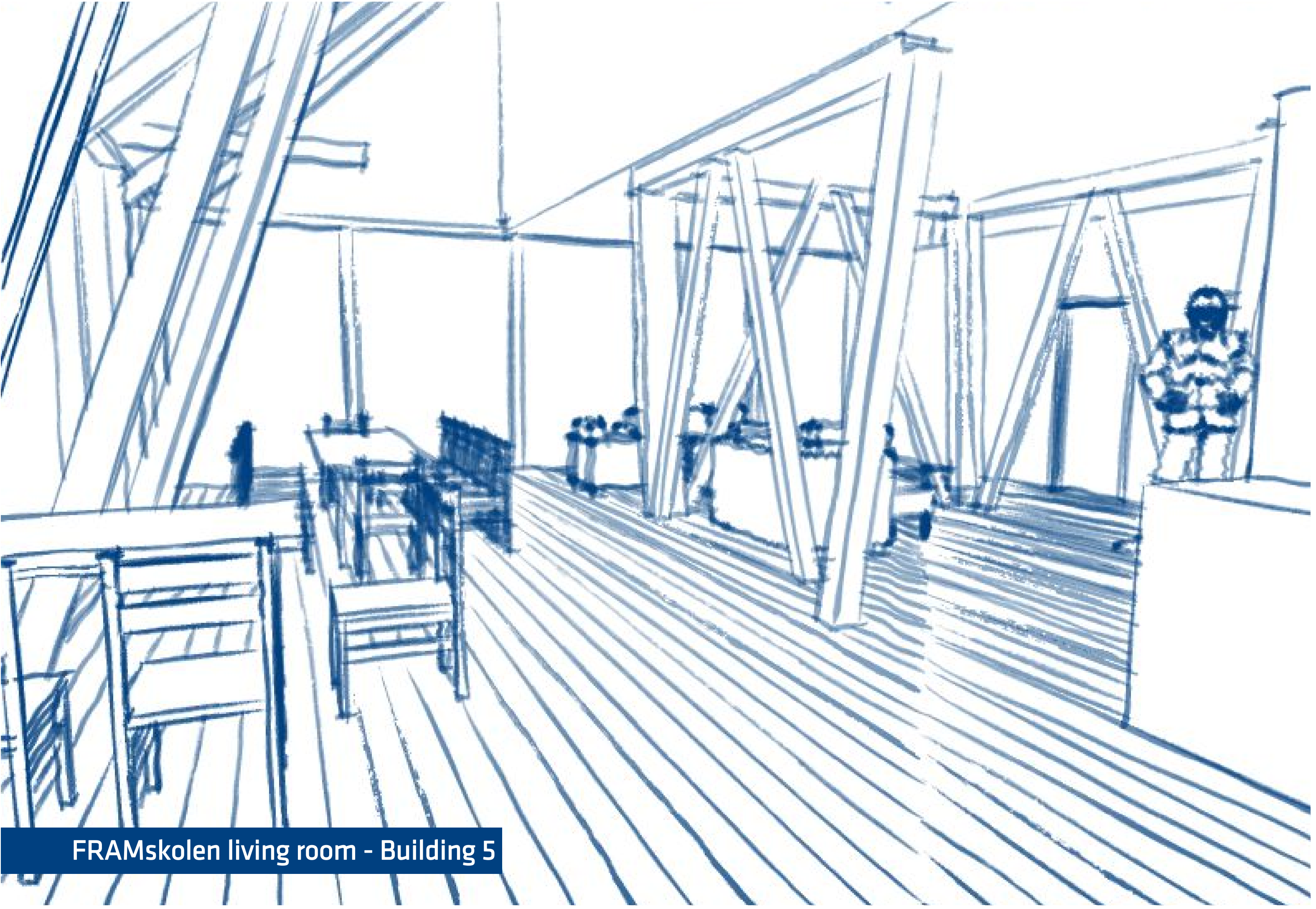
So over the teaching period in the school, the students might change rooms as they progress with their skills and can perform more of the daily routines autonomously.

As in Camphill Rotvoll part of the building, the rooms open to a daylit hall where some of the daily routines or socializing can be carried out together with other students.



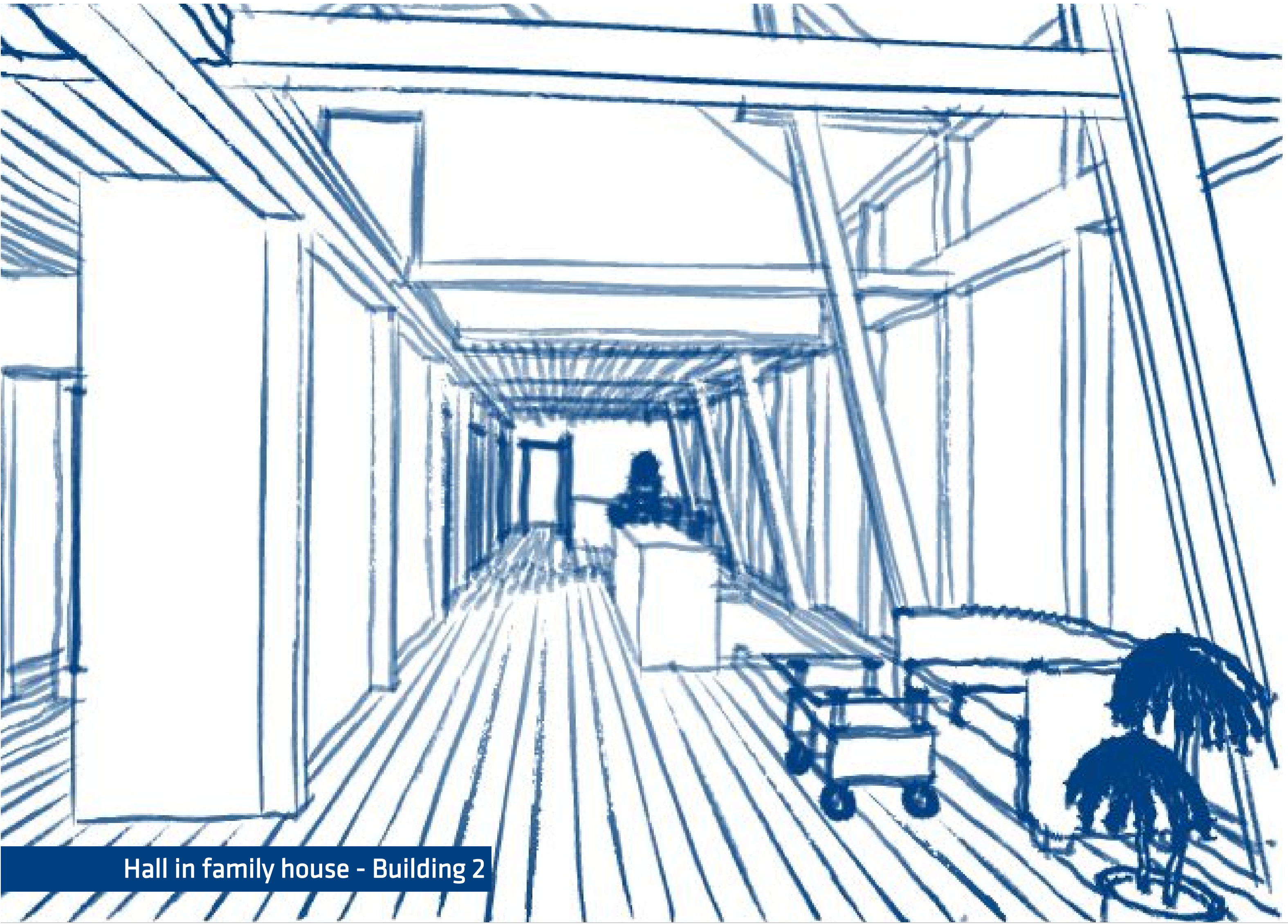
REQUIREMENTS AND REFERENCES

All bathrooms in the building are made accessible according to recommendation from Trondheim kommune "Universell utforming - flerleilighetsbygg" from 2009. SINTEF Byggforsk issues 330.114 "Små boliger" and 330.140 "Omsorgsboliger. Utforming, størrelse og standard" were used as references for room size and other requirements regarding functionality and accessibility of the rooms.

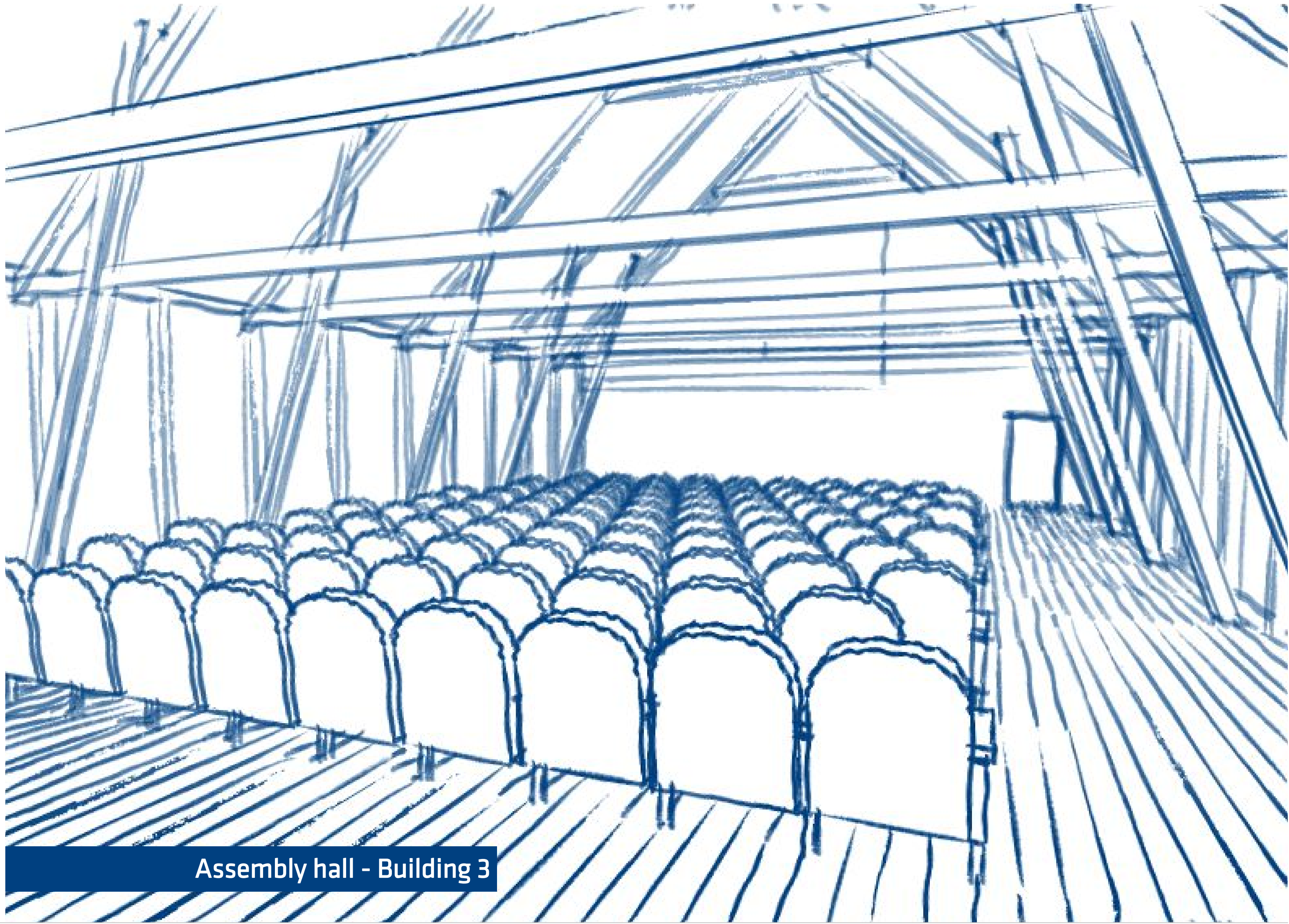


FRAMskolen living room - Building 5

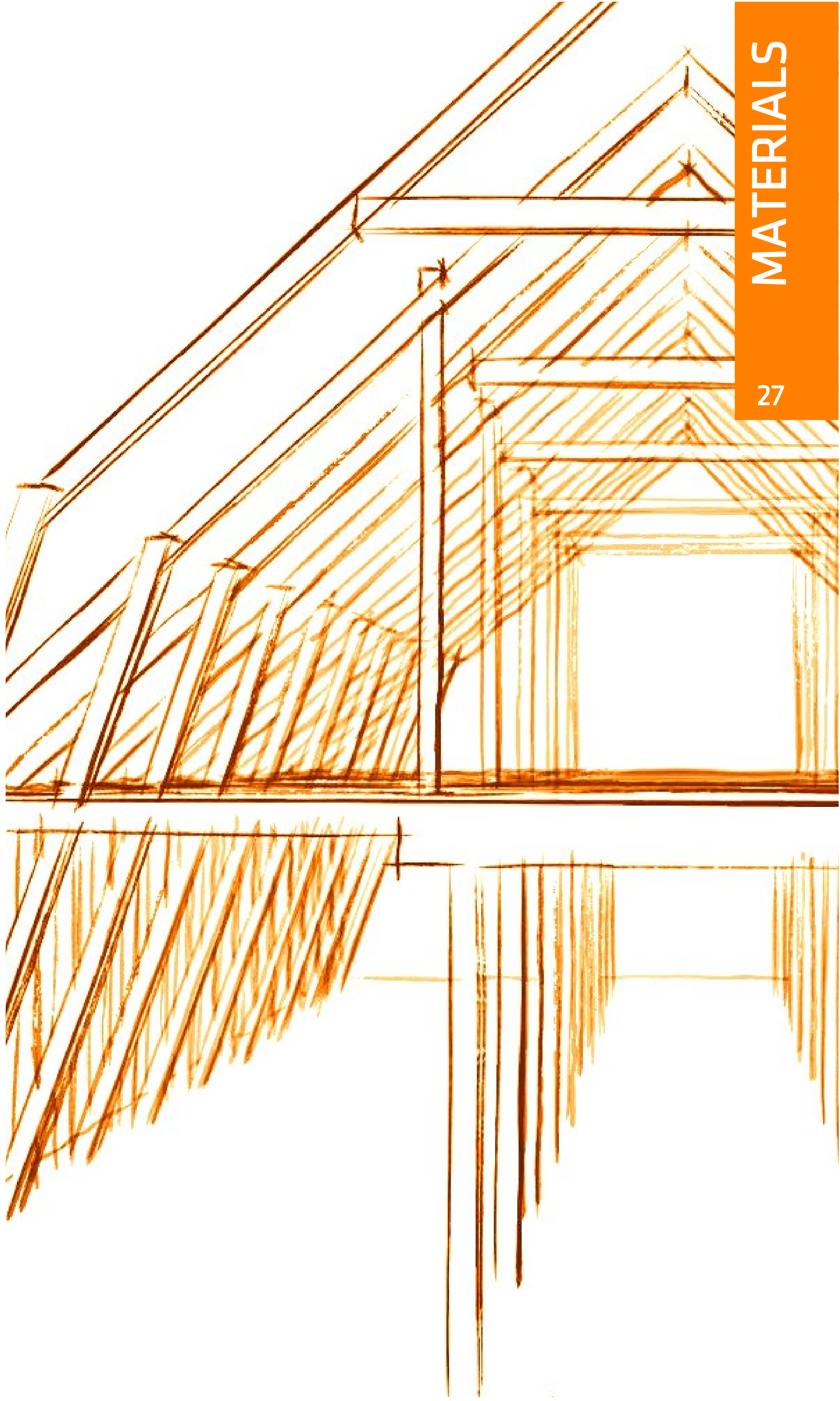
Teachers office - Building 5



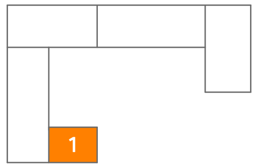
Hall in family house - Building 2



Assembly hall - Building 3



OVERVIEW OF REUSE POTENTIAL



BUILDING 1

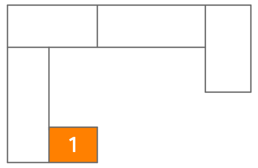
REUSED ELEMENTS

1) roof trusses (wood)
2) roof battens (wood)
3) stats and beams in wall structure (wood)
5) cladding (wood)

Reused elements

New elements

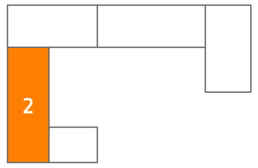
The barn building consists of 5 parts which have different building periods and structural properties. Each of them also represent a different reuse potential - in some whole structures can be reused while in other parts only separate elements.



REUSED ELEMENTS
1) roof truss structure (wood)
2) roof battens (wood)
3) wall timberframe (wood)
4) cladding (wood)
5) wooden decking in floors
(from other parts of the barn)

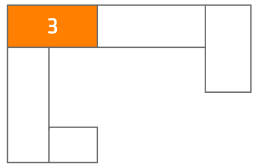
See detail on the right

COMMENT
This existing building part has no foundation floor slab and deteriorating wall foundations. Thus it is proposed to **dismantle** the structure and build it on new foundations by reusing old elements as much as possible.



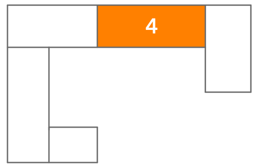
REUSED ELEMENTS
1) load bearing structure (wood)
2) walls (brick)
3) foundations under walls/ columns (brick and stone pile)
4) floor beams (wood)
5) roof battens (wood)
6) cladding (wood)

COMMENT
Needs strengthening and insulating the existing structure and foundations to fit the new use. The changes done to the wooden structure can be performed **without dismantling**. Cladding removed and partly reused afterwards.



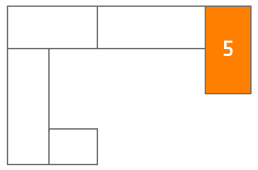
REUSED ELEMENTS
1) roof trusses (wood)
2) wall ~50% (brick)
3) foundation walls ~50% (concrete?)
4) roof battens
5) cladding (wood)

COMMENT
Building part has undergone several adaptations that have caused deterioration of the load bearing wood structure and bulging outwards of the brick wall to the north. Thus the building structure will have to be **partly dismantled** and re-erected using both new and existing elements.



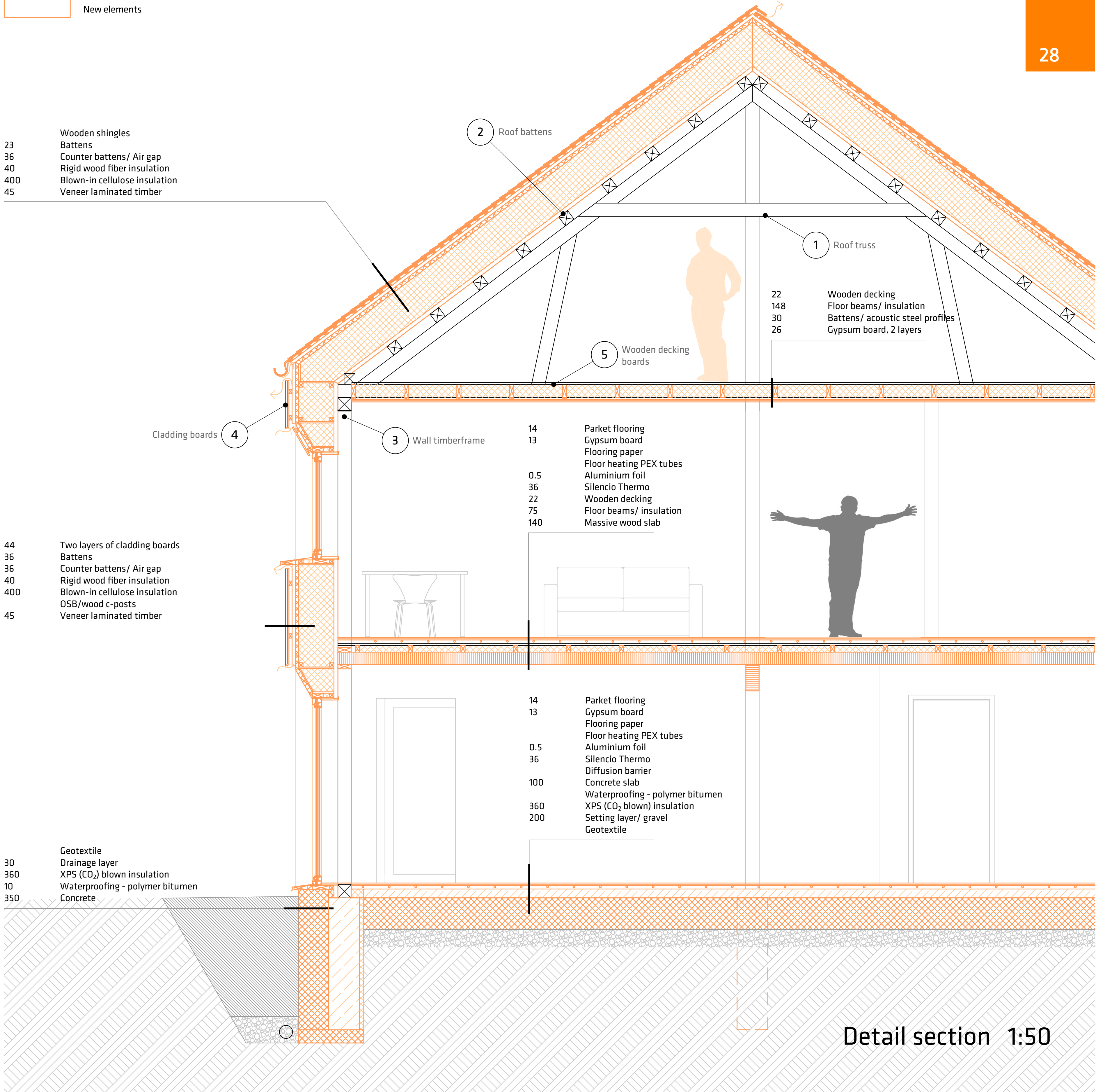
REUSED ELEMENTS
1) load bearing structure (wood)
2) walls (brick)
3) foundations under walls/ columns (concrete)
4) floor slabs (concrete)
5) columns (steel)
6) floor beams (wood)
7) roof battens (wood)
8) cladding (wood)

COMMENT
Needs strengthening and insulating the existing structure and foundations to fit the new use. The changes done to the wooden structure can be performed **without dismantling**. Removal of the existing concrete floor slab is necessary to add insulation to ground.



REUSED ELEMENTS
1) load bearing structure (wood)
2) walls (brick)
3) foundations under walls/ columns (concrete)
4) floor slabs (concrete)
5) basement columns (concrete)
6) columns (steel)
7) floor beams (wood)
8) roof battens (wood)
9) cladding (wood)

COMMENT
Needs strengthening and insulating the existing structure and foundations to fit the new use, also repair of concrete columns in the basement. Upgrade can be performed **without dismantling**. Largest proportion and potential of reused elements and materials of all 5 building parts.

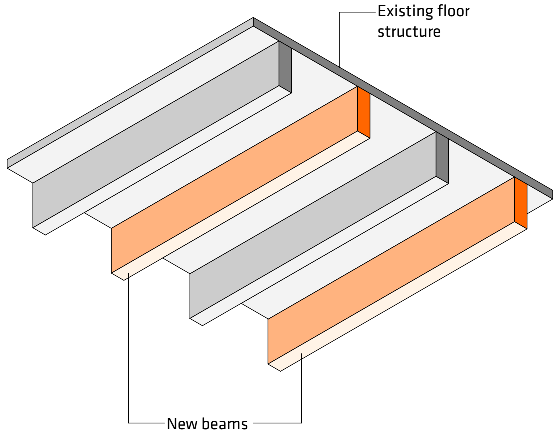


Detail section 1:50

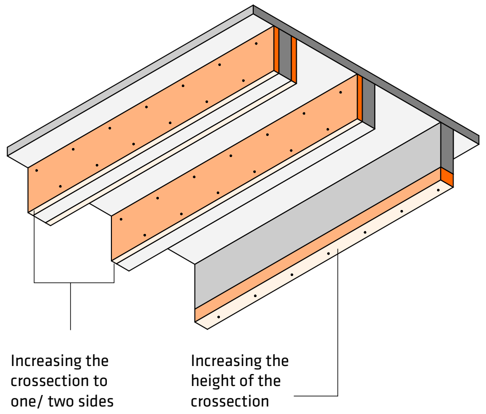
STRENGTHENING WOODEN STRUCTURES

Converting a barn to a building that is permanently used for residence is linked to an increased load on the existing structure. A variety of methods exist to improve the stiffness and load-bearing capacity of wooden structures, the most relevant of which are illustrated below.

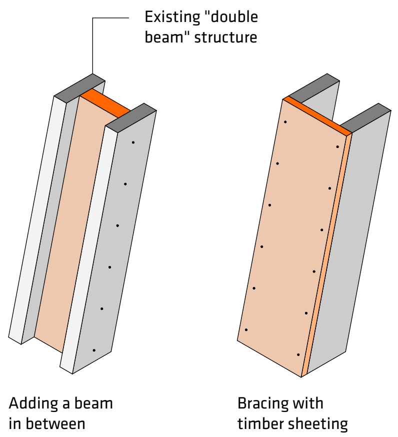
1 ADDING NEW FLOOR JOISTS



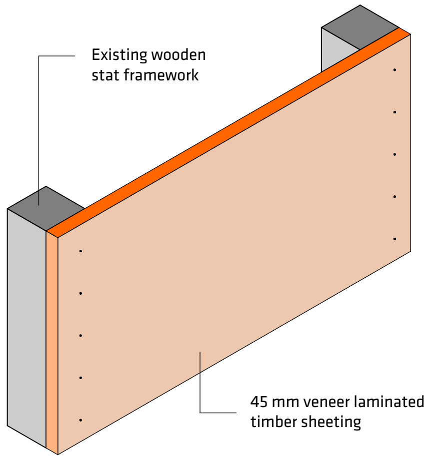
2 STRENGTHENING BEAM SECTIONS



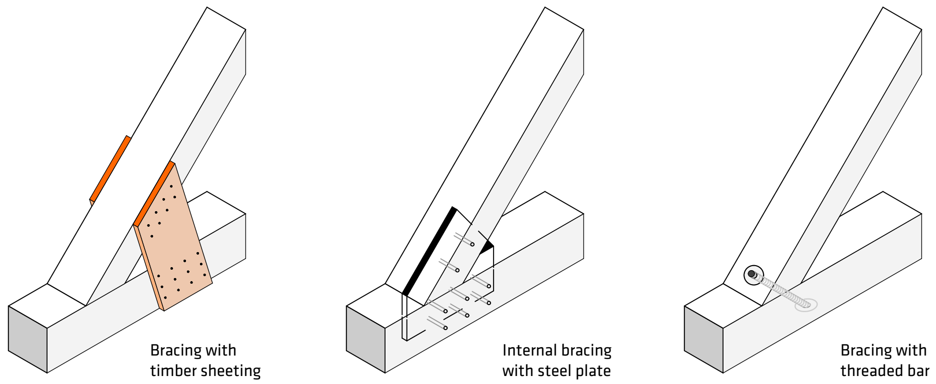
3 IMPROVING STIFFNESS OF TRUSS ELEMENTS

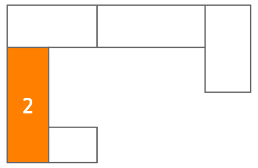


4 BRACING TIMBERFRAME WALL



5 STRENGTHENING CONNECTIONS





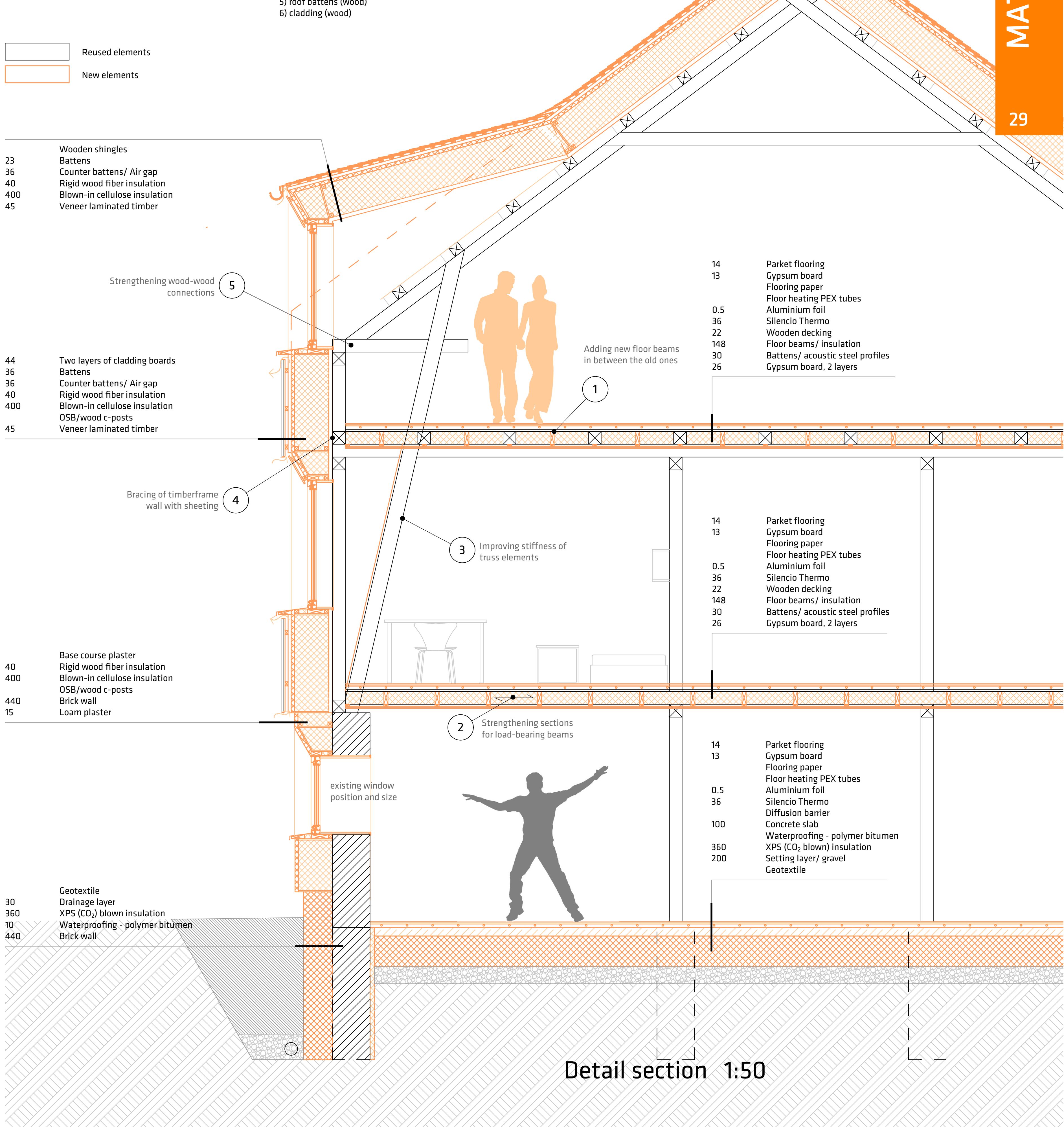
BUILDING 2

REUSED ELEMENTS

1) load bearing structure (wood)
2) walls (brick)
3) foundations under walls/columns (brick and stone pile)
4) floor beams (wood)
5) roof battens (wood)
6) cladding (wood)

Reused elements

New elements



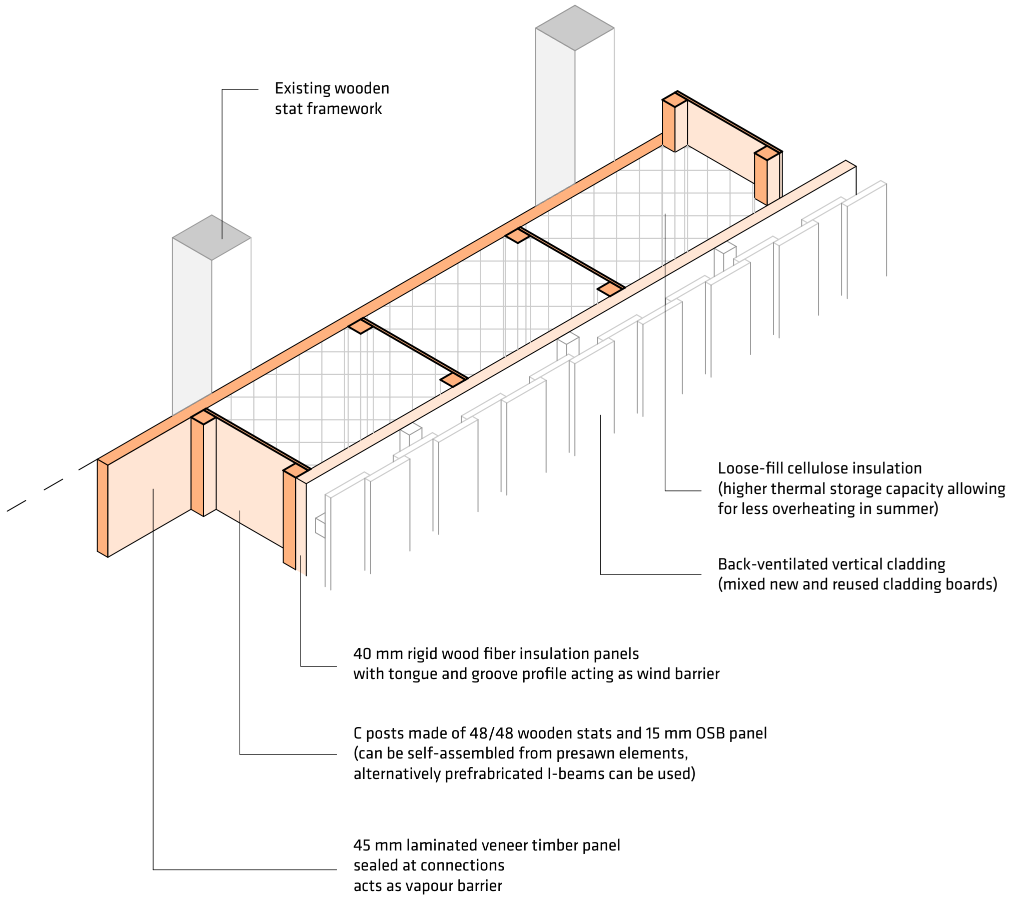
Detail section 1:50

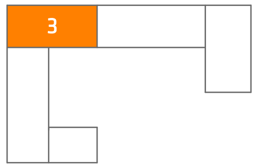
NEW MATERIAL CHOICE

Choice of the new materials for building envelope and added internal elements was guided by a number of principles:

1) environmentally friendly/ lower CO_2 emissions
2) U-values below 0.1 W/m^{2}K for the building envelope
3) allowing for simple, fewer layers - thus simpler/faster building process
4) wood based materials (avoiding concrete/steel where possible)
5) avoiding use of plastic materials (e.g. vapour, wind barriers)
6) insulation material with higher thermal storage capacity
7) allowing some building steps to be done by self-building

AXONOMETRIC VIEW OF THE LAYERING OF THE ENVELOPE



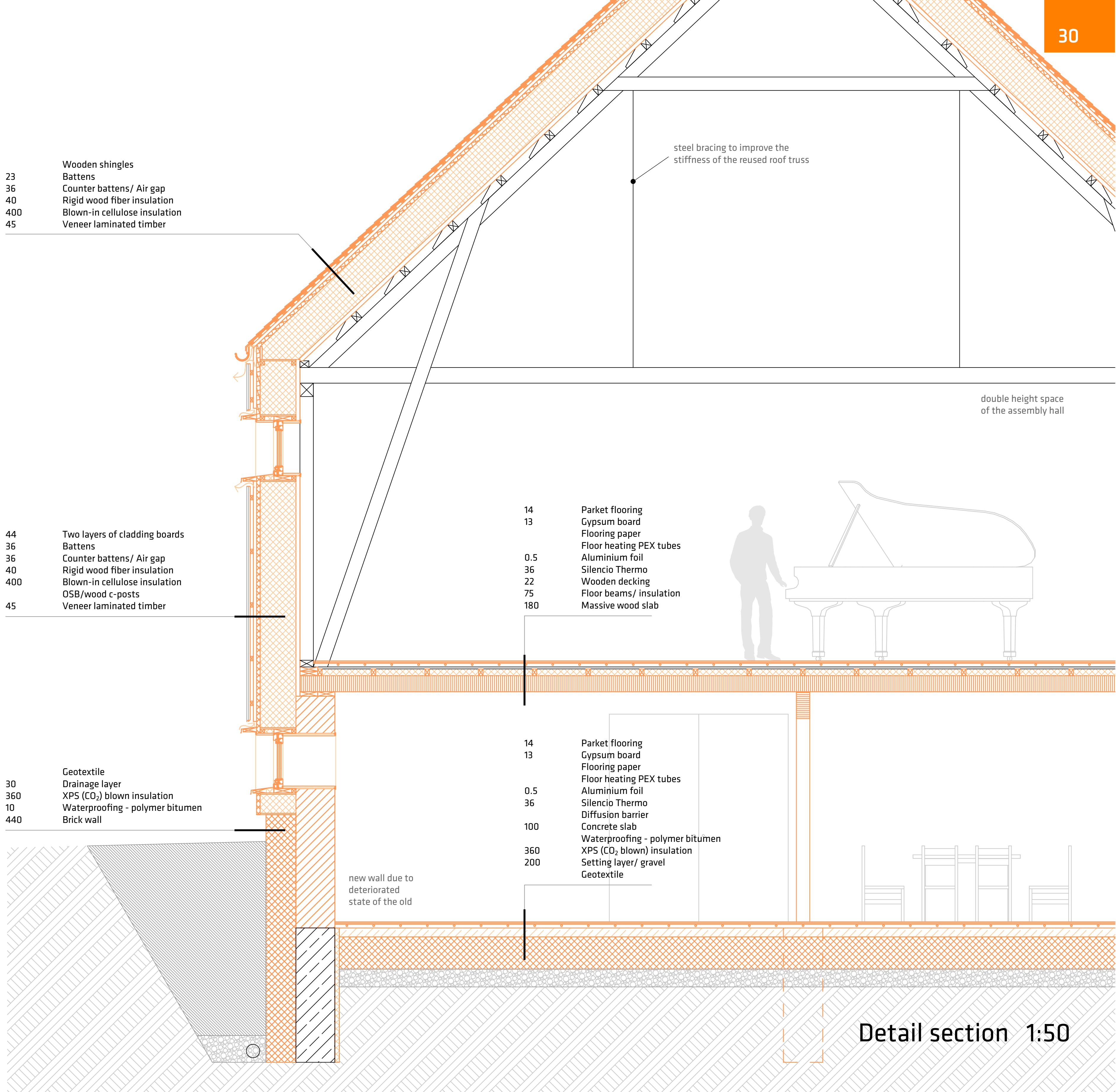


BUILDING 3

REUSED ELEMENTS

1) roof trusses (wood)
2) wall ~50% (brick)
3) foundation walls ~50% (concrete?)
4) roof battens
5) cladding (wood)

Reused elements
New elements



Detail section 1:50

EXTERNAL CLADDING PRINCIPLES

Most of the wall surface of the barn is clad with vertical boards in distinctive red colour often used for farm buildings in Norway.
All the non-damaged cladding boards are proposed to be dismantled and later reused after the insulating envelope is added to the barn building.

However, the exostong envelope colour is not uniform due to different building/cladding/painting periods and different exposure to weather. Some facades have lost more colour than other sides due to more wind and driving rain, in some cases profiled cover boards are used and in some places boards are damaged from leaking roofs, gutters etc.

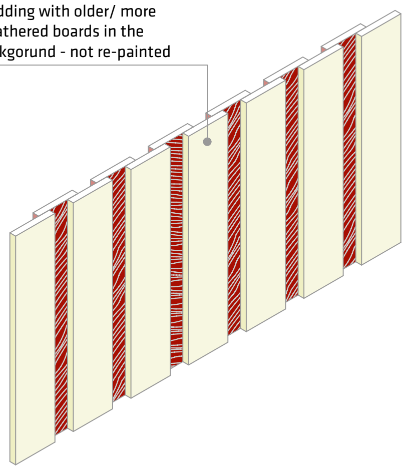
Wooden cladding with weathered paint on a south-west corner of the building

Profiled cladding boards on the east facade facing the fjord

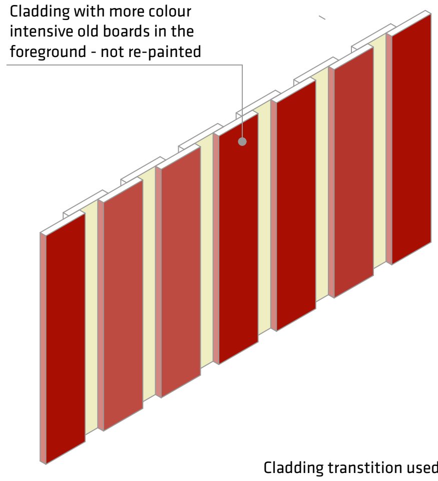
Wooden cladding on the north facade in full colour

To make most use of the existing cladding boards a cladding principle is proposed of mixing the old cladding boards with new natural wood coloured ones. The more weathered boards would be used for "background" cladding with new boards in the foreground and inversed principle with better/ specially profiled boards.

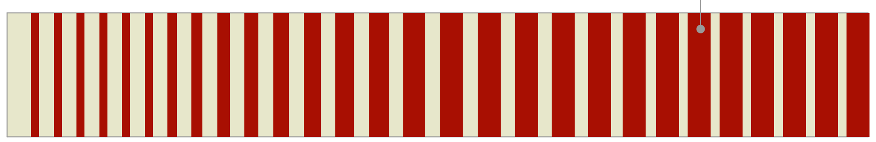
Cladding with older/ more weathered boards in the backgorund - not re-painted

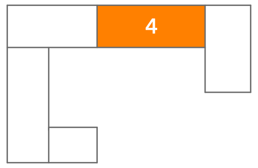


Cladding with more colour intensive old boards in the foreground - not re-painted



Cladding transition used where two cladding patterns meet (only twice along all facade)





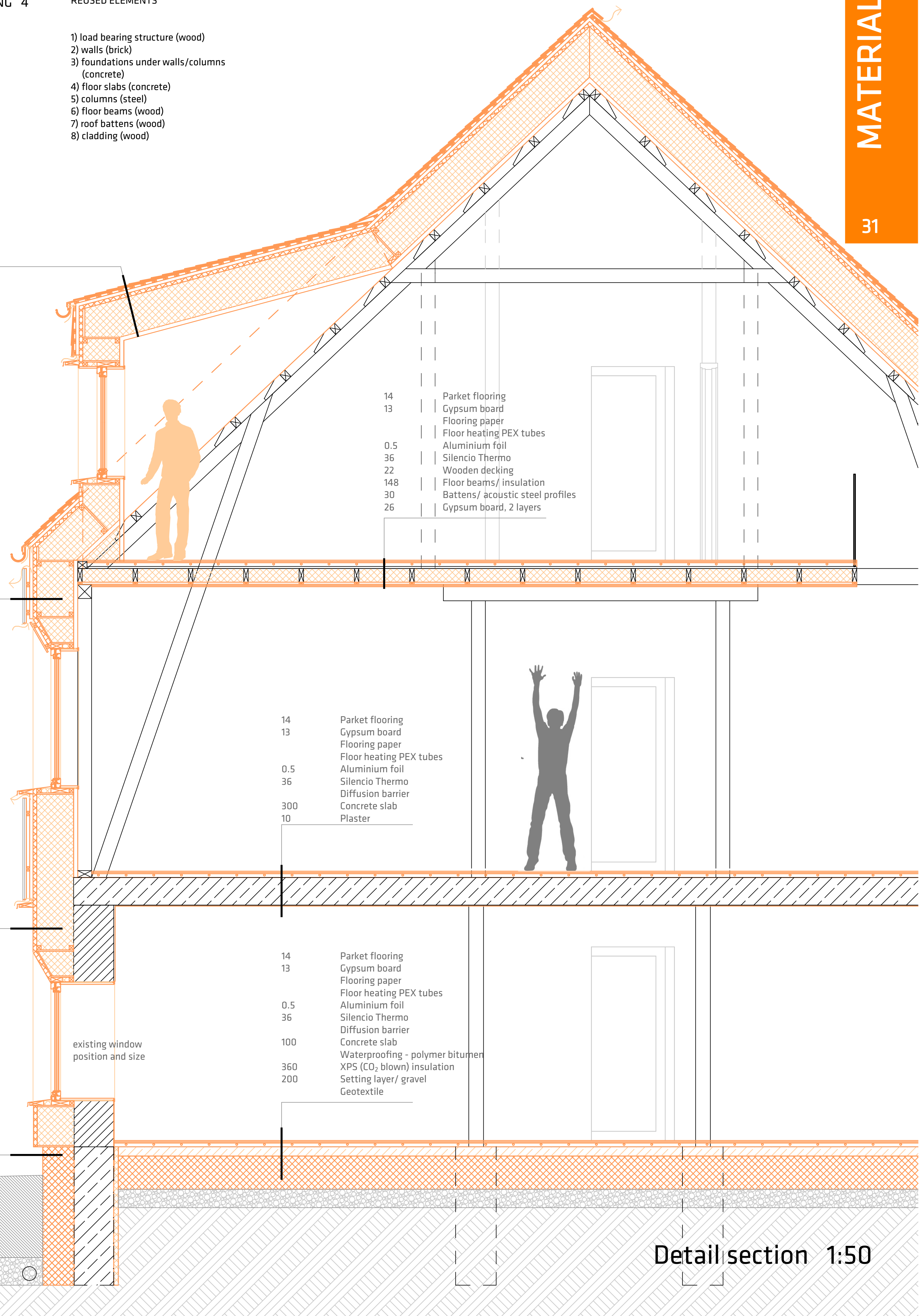
BUILDING 4

REUSED ELEMENTS

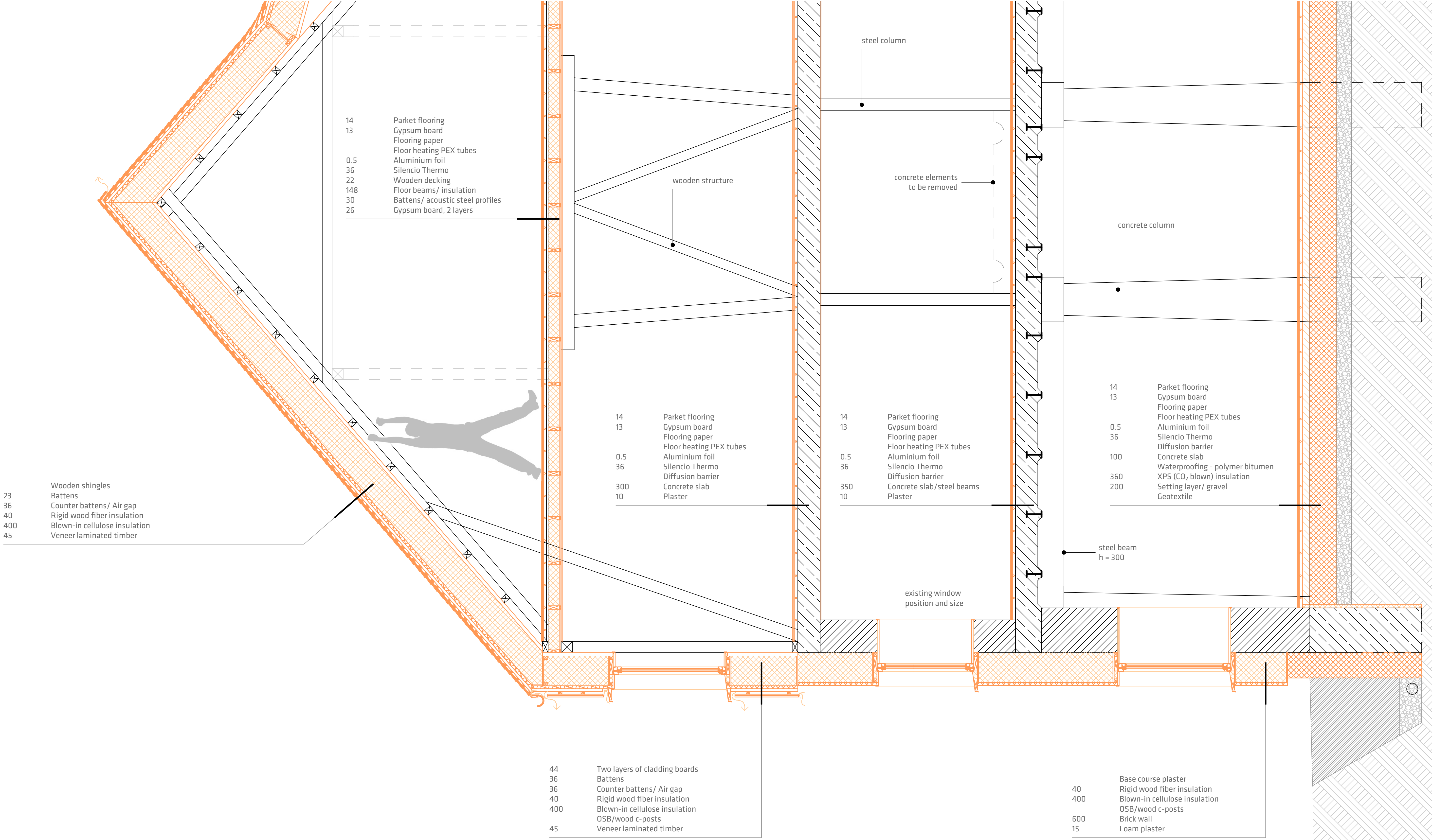
1) load bearing structure (wood)
2) walls (brick)
3) foundations under walls/columns (concrete)
4) floor slabs (concrete)
5) columns (steel)
6) floor beams (wood)
7) roof battens (wood)
8) cladding (wood)

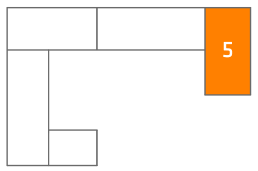
Reused elements

New elements



Detail section 1:50





BUILDING 5

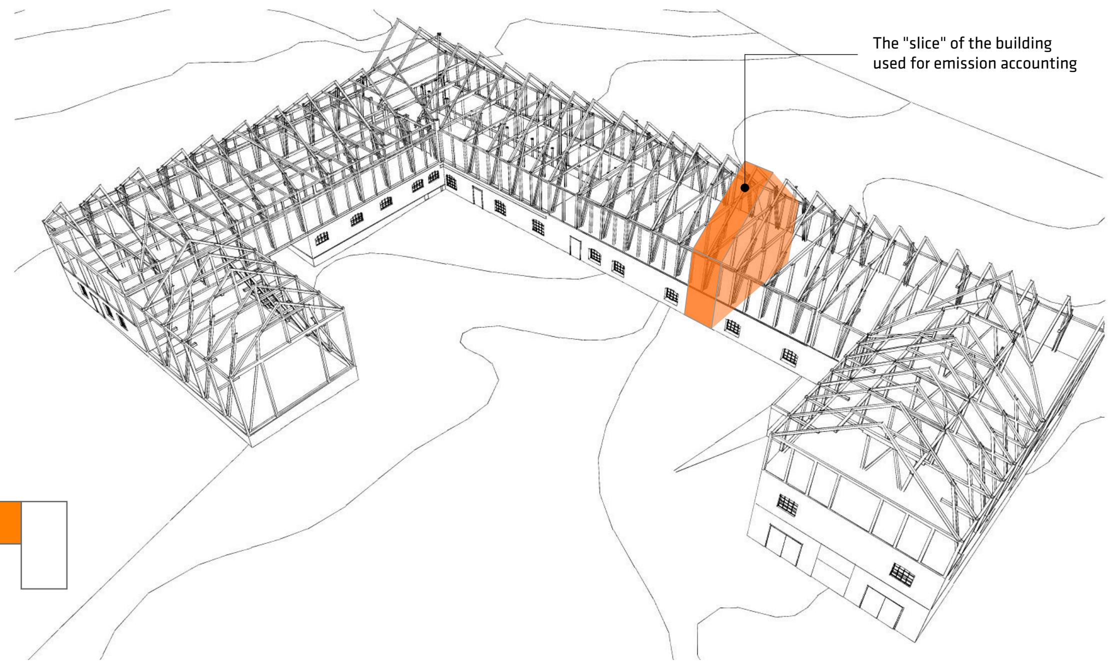
REUSED ELEMENTS

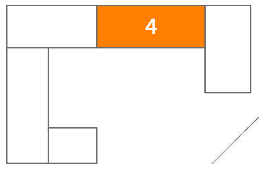
1) load bearing structure (wood)
2) walls (brick)
3) foundations under walls/columns (concrete)
4) floor slabs (concrete)
5) basement columns (concrete)
6) columns (steel)
7) floor beams (wood)
8) roof battens (wood)
9) cladding (wood)

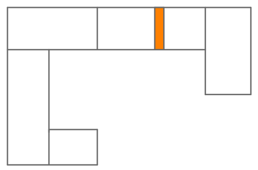
Detail section 1:50

ESTIMATING EMBODIED EMISSIONS
Input values

To provide an estimate of the embodied emissions related to the conversion of the barn building, accounting was performed in detail for a representative reference section of 2,6 m width in building part 4 - corresponding to one bay of existing wooden structures (see page 31 for a detailed section in scale 1:50).

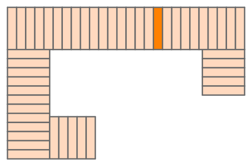






Task 1

Evaluating the proportion of the emissions "stored" in the reused building structures in relation to the emissions of the new added materials - based on the accounting done for the 2,6 m wide section



Task 2

Providing a crude estimate for the embodied emissions for all building parts assuming a multiple repetition of the chosen 2,6 m wide section (48 times).
Only the new added embodied emissions are used in this case, due to differences in existing structures in other building parts and the lifetime of the building elements already stretching beyond 60 years.

Background information and boundary conditions:

1) Database used - EMPA Ökologische Baustoffliste (Version 2.2e)* - Authors: Martin Lehmann, Hans-Jörg Althaus
2) Cradle to Gate (no transport, end of life)
2) Source of values - Switzerland
4) Lifetime - 60yrs for most materials, 40yrs for insulation
5) Elements not included - technical systems, internal walls, connectors (glue, screws)
6) Emission unit used - Global Warming Potential measured in kg CO_2 eq

http://www.empa.ch/plugin/template/empa//98224

GWP: Global warming potential kg CO_2 eq

	EXTERNAL ENVELOPE	SUM volume, m3	DENSITY	WEIGHT	LIFETIME	GWP	GWP_60 NEW	GWP_60 OLD
	STRUCTURE							
1	LVL	2,653	780	2070	60	6,42E-01	1329	
	FILL							
2	Timber (spruce)	0,678	495	336	60	2,14E-001	72	
	Vertical studs							
	Horizontal studs							
3	Cellulose	26,052	60	1563	40	3,41E-001	800	
4	OSB	1,164	594	692	60	5,27E-001	364	
	vertical							
	horizontal							
5	Rigid wood fibre insulation	2,761	140	387	40	3,98E-001	231	
6	Waterproofing – bitumen	0,039	1160	45	60	8,26E-01	37	
7	XPS (C02)	2,964	18	53	40	3,82E+000	306	
8	Drainage layer/gravel	0,390	2000	780	60	2,41E-003	2	
9	Geotextile	0,016	910	14	60	2,36E+000	34	
	SURFACE							
10	Timber (walls)							
	Battens Cladding (50% old)	0,305	495	151	60	2,14E-001		32
	Counter battens Cladding (50% new)	0,285	495	141	60	2,14E-001	30	
11	Base course plaster	0,077	1500	116	60	6,02E-01	70	
12	Timber (roof)							
	Battens	0,108	495	53	60	2,14E-001		11
	Counter battens Wooden shingles	1,334	715	954	60	1,33E-01	127	
13	Rain gutters/ Flashings/ Steel	0,003	7850	21	60	3,59E+00	76	
14	Windows							
	3 layer glass (U<0.5)	8,730		8,73	30	5,69E+01	994	
	Wooden frame (U<1.5)	1,541		1,54	30	1,32E+02	406	
	INTERNAL ELEMENTS	**SUM volume, m3**	**DENSITY**	**WEIGHT**	**LIFETIME**	**GWP**	**GWP_60 NEW**	**GWP_60 OLD**
	STRUCTURE							
1	Timber Roof truss elements	2,544	495	1259	60	2,14E-001		269
2	Steel							
	Steel columns	0,023	7850	181	60	1,76E+00		317
	Steel reinforcement (old)	0,087	7850	686	60	1,48E+00		1016
	Foundation steel	0,040	7850	315	60	1,48E+00		467
	Steel reinforcement (new)	0,029	7850	229	60	1,48E+00	339	
3	Brick	1,803	1000	1803	60	2,39E-01		430
4	Concrete							
	Concrete slab (old)	8,649	2385	20627	60	6,70E-002		1382
	Foundation	3,970	2385	9468	60	6,70E-002		634
	Concrete slab (new)	2,883	2385	6876	60	6,70E-002	461	
	FILL							
5	Insulation							
	Cellulose/ floor	2,974	60	178	40	3,41E-001	91	
	XPS (C02)	9,655	18	174	60	3,82E+000	664	
	XPS (C02)	0,143	18	3	60	3,82E+000	10	
6	Timber floor decking	0,480	495	238	60	2,14E-001		51
	SURFACE							
7	Timber							
	Parquet flooring	1,087	715	777	60	1,56E-001	121	
8	Gypsum fibre board (floor)	1,009	1250	1261	60	2,93E-001	370	
	Gypsum board, 2 layers (ceiling)	2,018	800	1614	60	3,54E-001	571	
9	Flooring paper	0,155	650	101	60	1,69E+000	171	
10	Heating pipes, PEX	0,029	930	27	60	2,33E+00	64	
11	Aluminium foil	0,039	2700	105	60	9,26E+000	970	
12	Wood fibre ins. (Silencio Thermo)	2,793	140	391	40	3,98E-001	233	
13	Diffusion barrier (PE)	0,112	940	105	60	2,70E+00	283	
14	Drain layer, gravel	5,364	2000	10728	60	2,41E-003	26	
15	Loam plaster	0,156	1800	281	60	1,91E-02	5	
						SUM	9255	4611

Emission values for new and existing building elements in kg CO_2 eq

Tab.1 Input overview for the emission accounting for the 2,6 m reference section using values from EMPA database

As dismantling the barn and erecting a new building in its place is an alternative scenario that has already been applied to another building in Rotvoll farm, it is important to evaluate the environmental impact of reusing the existing barn.
To do so, the embodied emissions of existing structures are compared with those of the added materials. In the scope of this project, the existing materials are accounted for by using emission factors or their modern equivalents.

EXISTING vs NEW

The accounting for existing and new materials in Fig.1 shows that the existing structures consitute approximately one third (4611 kg CO_2 eq) of the total emissions (13866 kg CO_2 eq) for the reference section of 2,6 m. Most of the emissions (83%) are related to the concrete slab and reinforcement steel. Wooden structures, although providing for architectural quality of the barn conversion, represent the smallest fraction of the emissions (below 8%).
The selection of new materials for the added building elements was done with reference to their environmental impact, choosing materials and layering principles that would lead to lower embodied emissions. Also the use of steel and concrete was minimized, thus the overall emission values are relatively low. Windows represent the largest environmental impact (15% of emissions) followed by the laminated veneer lumber (LVL) sheeting used to brace the existing wooden structure (14%). However, if all insulation materials would be added together (XPS, cellulose and wood fibre), they would represent the largest portion of embodied emissions - 25%.

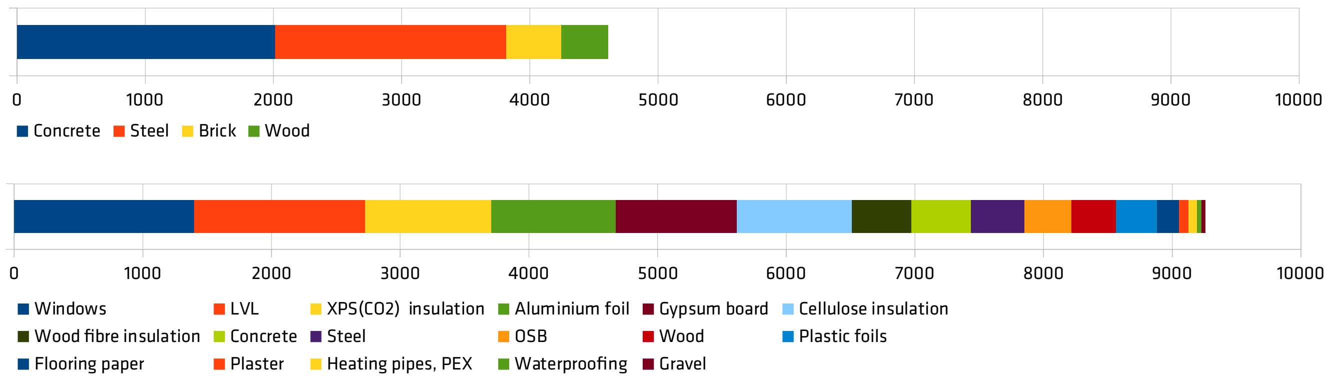


Fig.1 The embodied emission values of building materials in kg CO_2 eq for the existing (top) and new (below) building elements

EMISSIONS vs WEIGHT

When comparing emission values with the corresponding weight of materials (Fig.2), the relative impact of materials becomes clearer. For the existing building elements, steel represented high emission fraction(39%) while having only 3% fraction of total weight.
While the existing building element emission/weight bars show some clarity, for the added materials, almost no correspondance can be noticed. Some materials with high emission fractions have low weight fractions (windows 15/0,6%, aluminium foil 10/0,35%, XPS 11/0,8 %) and vice versa (gravel 0,3/38 %, concrete 5/23%, wood 3/7%).

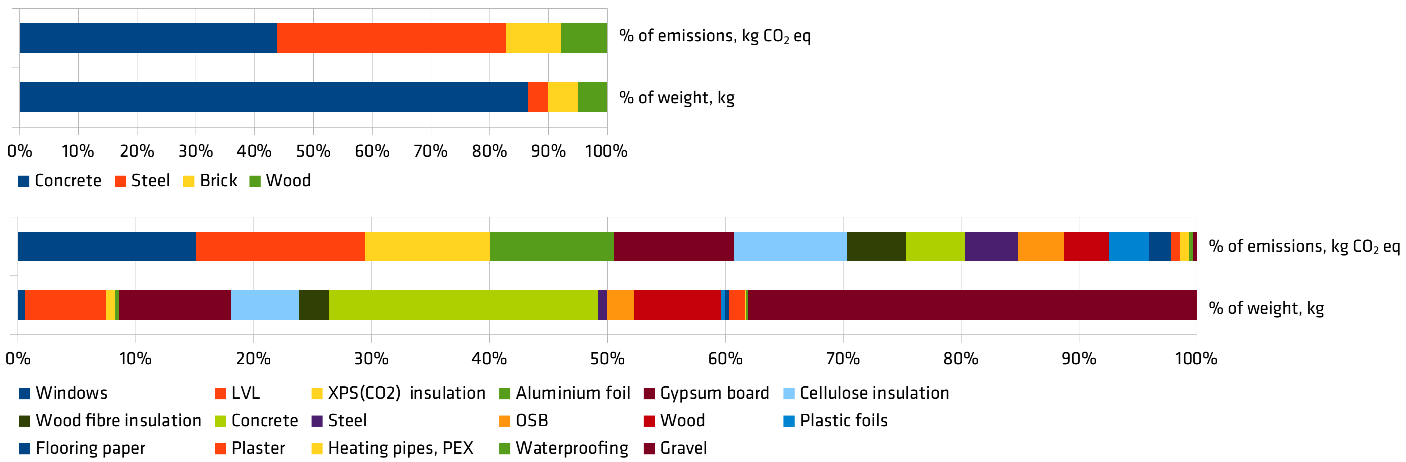


Fig.2 The embodied emission and their corresponding weight values for materials for the existing (top) and new (below) building elements

OVERVIEW FOR COMBINED NEW AND EXISTING BUILDING ELEMENTS

As can be seen from Figures 3 and 4, concrete has the largest emissions and weight - most of it in the existing structure. Also most of the steel emissions are related to existing structure - in concrete reinforcement and steel columns. The existing wood elements represent a significant fraction of the wood materials used in the building. Existing materials together account for 33% of the embodied emissions and more than half (53%) of the weight (with most of the weight in the new added elements is contributed by gravel).

When also accounted for transport and technical systems, the embodied emissions from the added materials would increase, thus reducing the fraction of the emissions embodied in the existing structure. However, even with emission fraction lower than 33%, keeping the existing structure would provide an emission "saving" of 221 000 kg CO_2 eq (section value multiplied 48 times) , which would otherwise be reduced or lost in case of only recycling the materials.

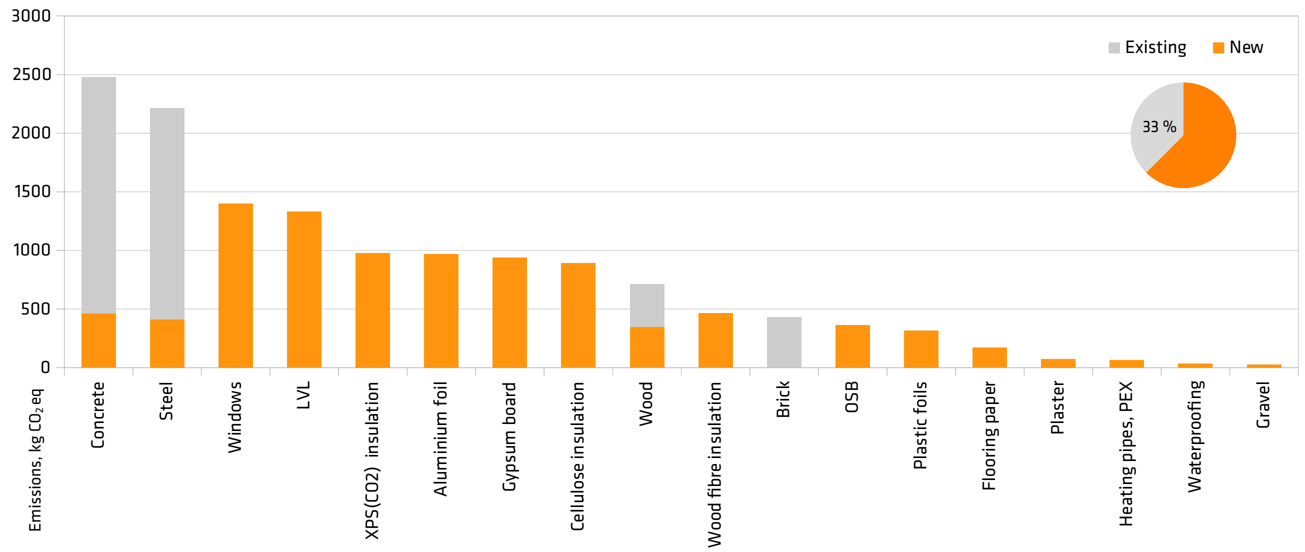


Fig.3 Overview of material emissions for combined new and existing building elements (based on reference 2,6 m section)

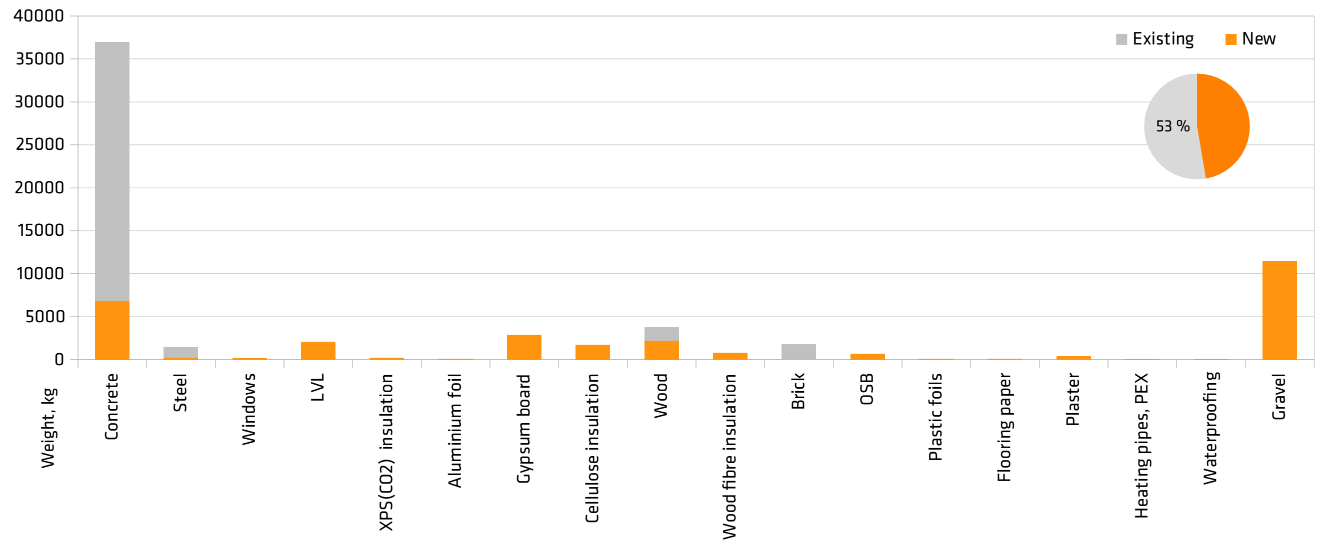
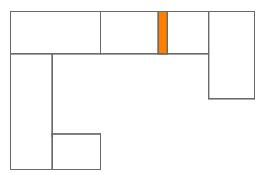


Fig.4 Overview of material weight for combined new and existing building elements (based on reference 2,6 m section)

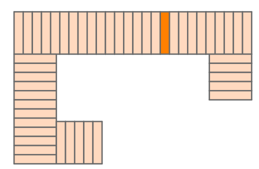


Emissions proportion old/new:

1/2

Weight proportion old/new:

1/1

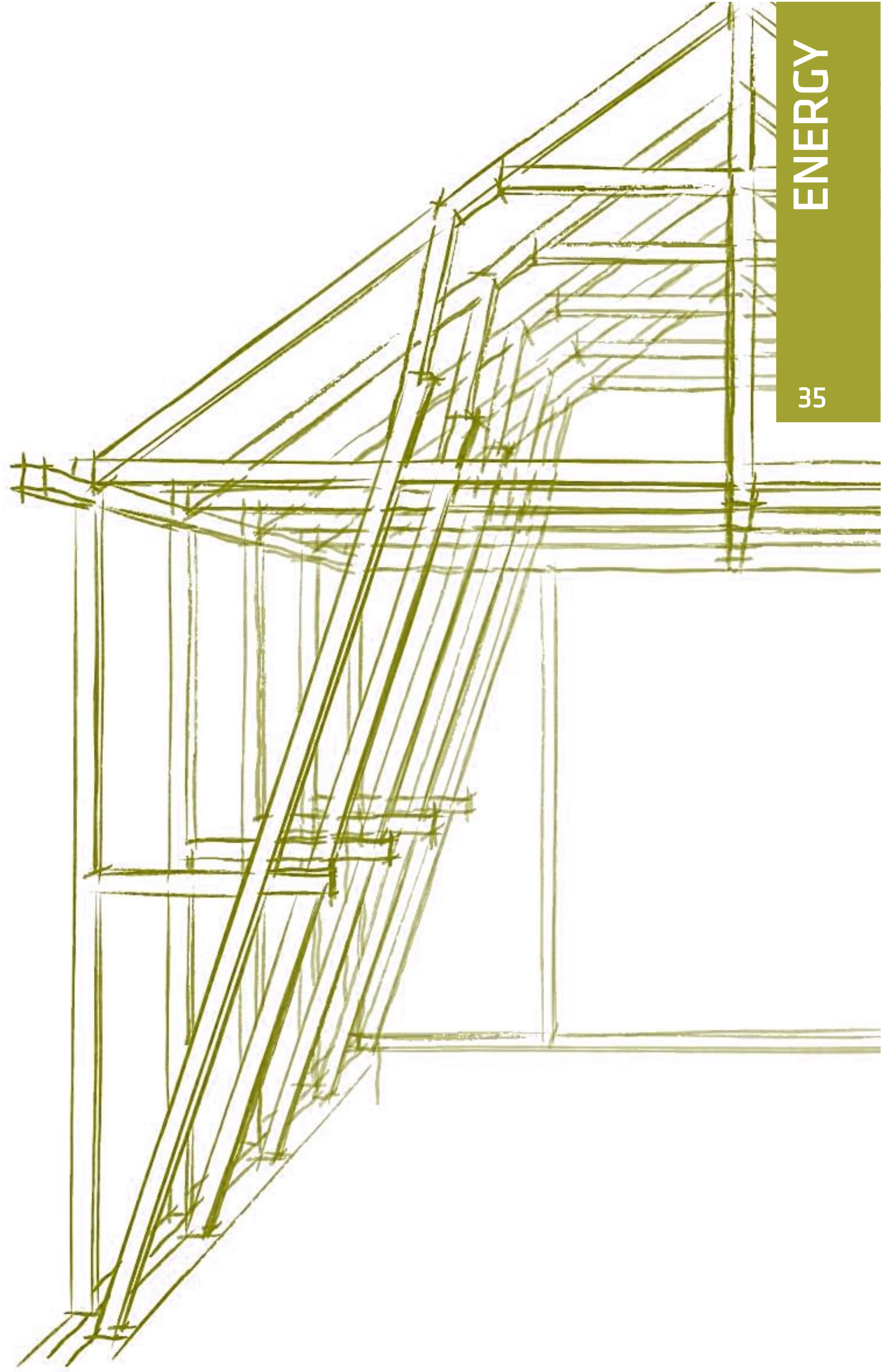


Emissions from one section:

9 255 kg CO_2 eq

Emission estimate for all building:

444 000 kg CO_2 eq



Camphill communities have a reputation of being very energy-conscious and environment oriented. For example, Camphill village in Vallersund produces all its energy on-site with a seawater heat pump and a wind generator (electricity balanced with the grid), as well as treating black and grey water locally with constructed wetlands.

Thus ambitious aims were set also for the barn transformation at Camphill Rotvoll. Taking into account the general trend of Camphill movement to be more oriented towards natural and low-tech solutions, the initial project target was set to reaching **passive or at least a low energy house standard** with a ventilation system other than fully mechanical.

Energy demand was calculated using SIMIEN for Trondheim climate. The building type was set to residential, since it is representative for most of the barn area.

OPTIMIZED BUILDING ENVELOPE

The transformation strategy for the barn included a strong focus on ensuring a low heat loss through the building envelope. This included removing the existing concrete slabs to ground (approx 30% of building footprint) to be replaced with insulated elements. Also number, size and placement of windows was optimized to allow for sufficient daylight in all rooms with smaller glazed area (see page 39 for daylighting strategies).
The U-values for envelope elements was set to 0,1 W/m²K (calculated as 0,09 W/m²K with www.u-wert.net), and U-value for doors and windows to 0,7 W/m²K - both lower than required by passivhouse standard NS3700.

As can be seen from Fig.5, the heat loss number eventually amounts to 0,41 W/m²K that is below the required 0,5 according to standard NS3700. Most of the heat loss occurs due to ventilation - since 70% heat recovery is used. From the envelope elements, windows and doors account for most of the heat loss.

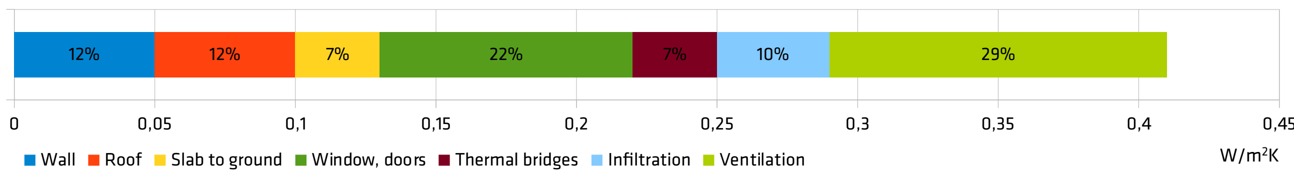


Fig.5 Heat loss number for the barn building in W/m²K (result from SIMIEN)

ENERGY DEMAND

1) Base case

An overview of the specific energy demand of the barn building is represented in Fig.6. As can be seen from the table, most of the energy demand is linked to use of the building - hot water, lighting and equipment together account for 75% of energy demand. Envelope characteristics and thus heating demand for space and ventilation heating account for only 17 %.

Heating demand (space and ventilation heating): 13,5 kWh/m² year - compliant with passive house requirements!
Specific heat energy demand: 43.3 kWh/m² year
Specific electricity demand: 34.8 kWh/m² year

Total specific energy demand for base case: 78.1 kWh/m² year

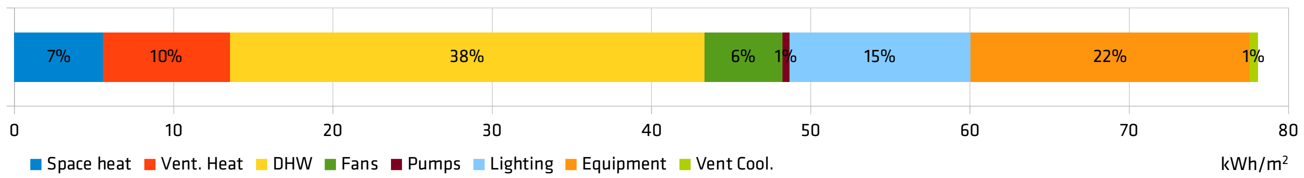


Fig.6 Specific energy demand for base case by category in kWh/m² a year (result from SIMIEN)

2) Low-demand case

In order to reduce the energy demand, a variety of active and passive stratgies were considered to be used in the building. Due to the relatively low lighting energy demand values given for residences in NS3700, no further reduction in this category was considered. Also further decrease in already low heating demand (now 13,5 kWh/m²year) was not considered efficient. Use of energy efficient equipment could reduce the demand further, but is not considered in this calculation since depends on the users.

Instead, other energy demand categories - like hot water and fans were adressed. The strategies used are in more detail presented in the following pages 38 and 39. As can be seen from Fig.7, by using heat recovery for hot water from showering and hybrid ventilation principles with lower fan power demands the energy demand could be reduced by 21% - mostly heating energy.

Specific heat energy demand: 29.9 kWh/m² year
Specific electricity demand: 31.8 kWh/m² year

Total specific energy demand for low-demand case: 61.7 kWh/m² year

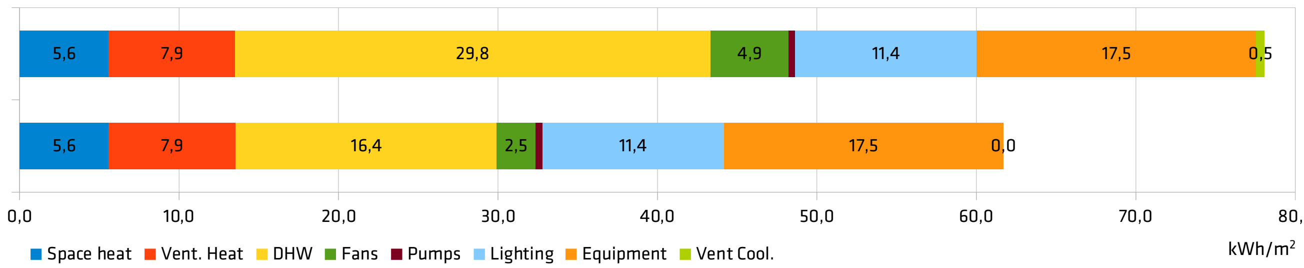


Fig.7 Comparison of base case (top, also Fig.6) and low-demand (bottom) specific energy demand (based on results from SIMIEN)

MONTHLY HEAT AND ELECTRICITY DEMAND DISTRIBUTION

For the low-demand case, the energy demand for electricity is 15% more than for heating energy and as can be seen from Fig.8 - the demand is constant over the year (slight seasonal differences would occur of lighting requirements would be adjusted to seasonal variations in daylighting levels). Heat energy demand, on the other hand, is seasonal - with highest demand in the cold months in winter.

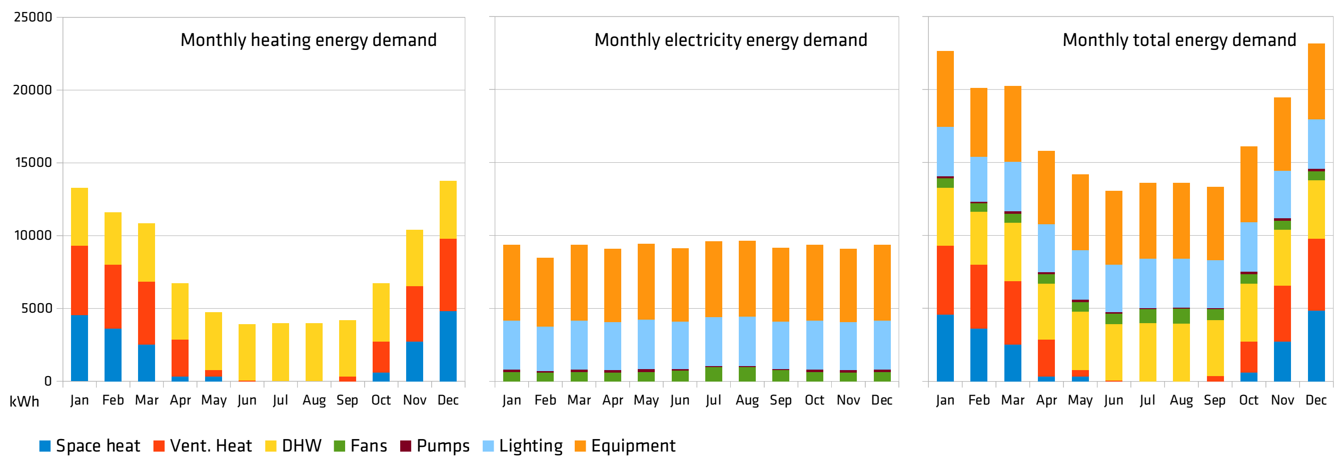
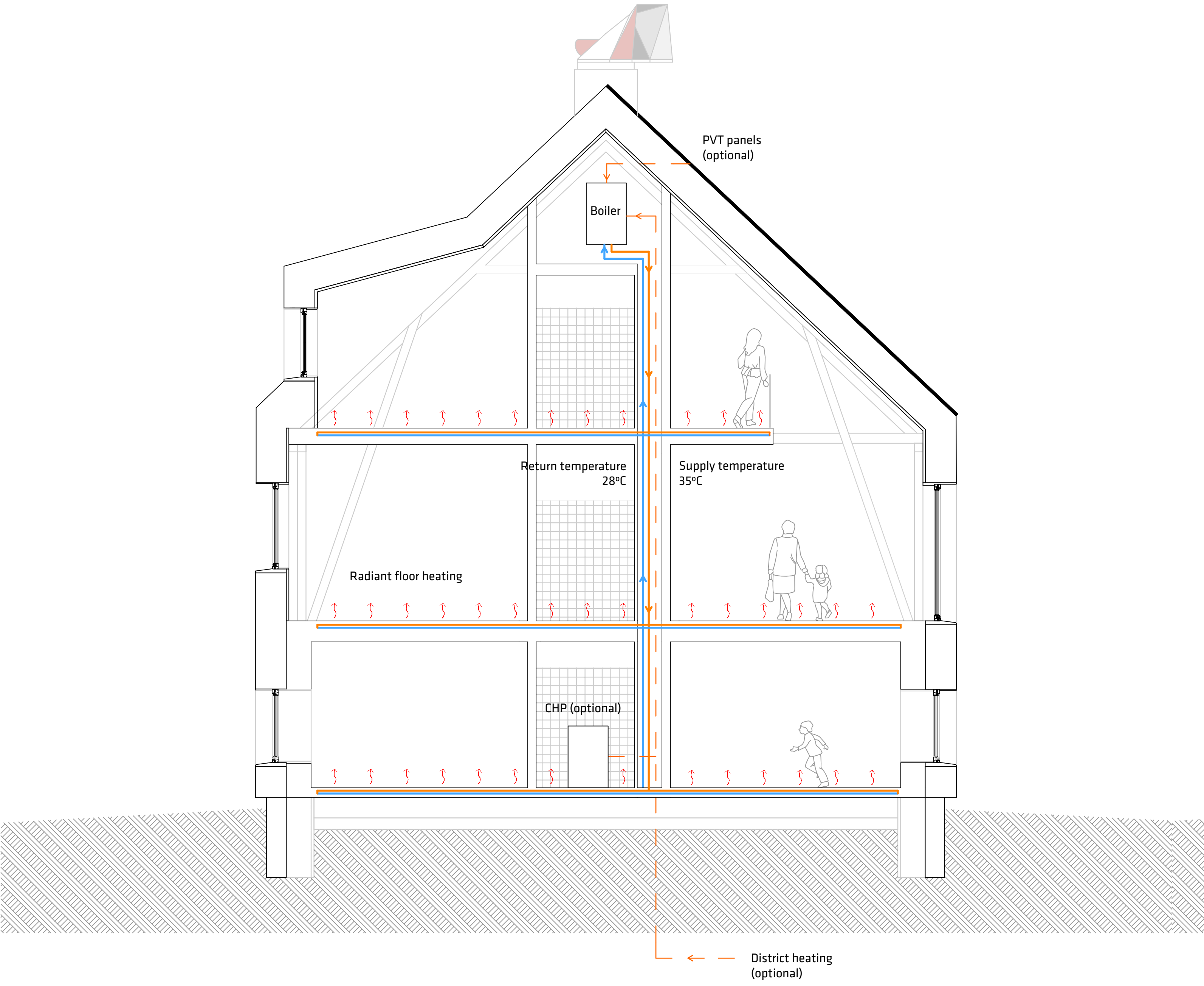
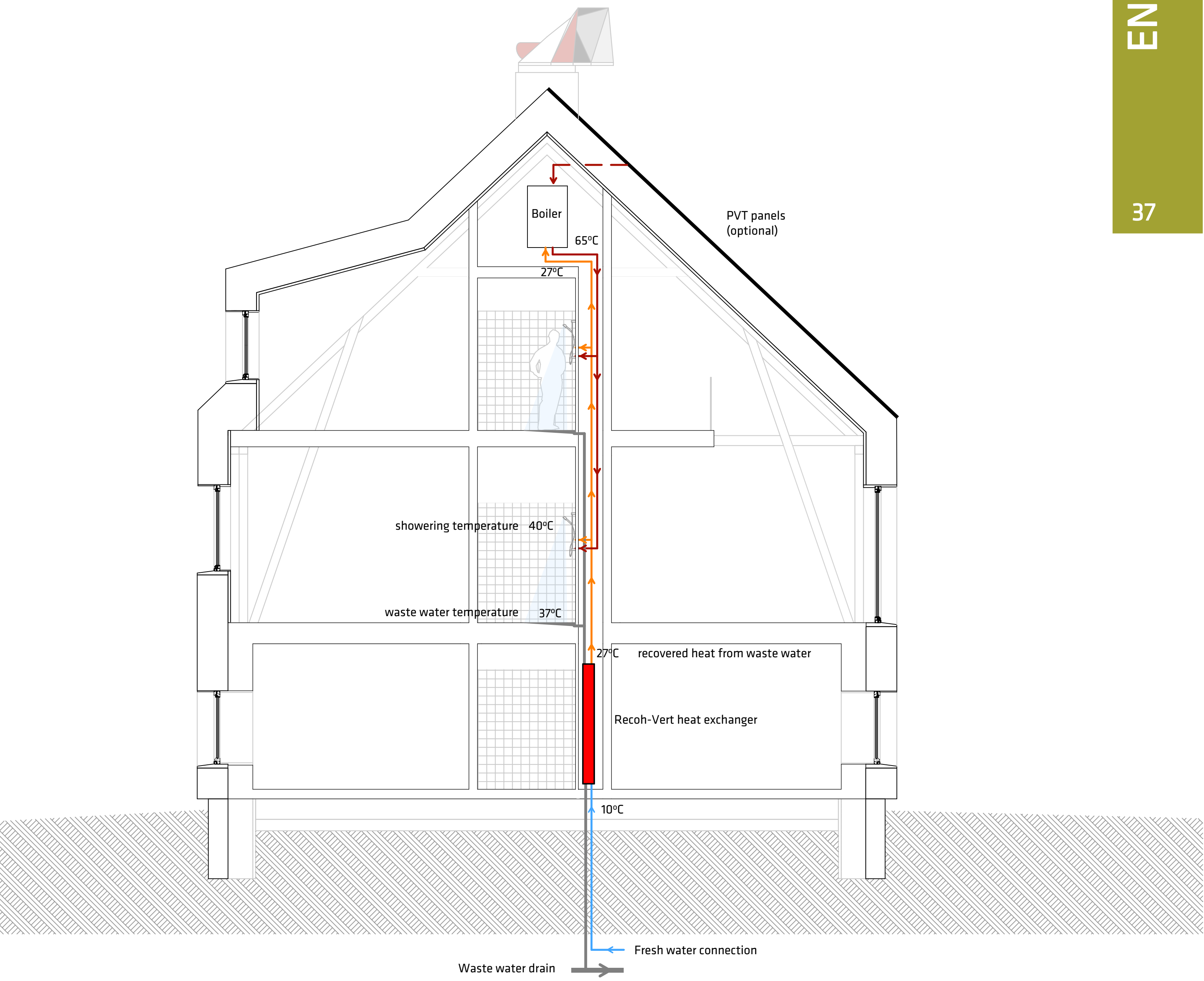


Fig.8 Monthly energy demand values (from left) - heat energy, electricity, total energy demand, in kWh (based on results from SIMIEN)

SPACE HEATING



HOT WATER



RADIANT FLOOR HEATING

Since floor heating was used already in the base case energy demand, no decrease of energy is associated to its use. Howeverm radiant floor heating allows for lower-temperature renewable heat source, as well as more efficient heat distribution and higher comfort in the building.

The system used for this project is Silencio Thermo - a sound impact wood fibre board used for waterborne underfloor heating. The heating pipes are laid in the wood fibre board instead of screed, allowing for a lighter construction. It also results in a low overall height and good sound-insulation properties. Because the pipes lie close to the parquet flooring it is possible to have a lower water temperature which can be adjusted more rapidly. *

* http://english.hunton.no/index.php?p=22-54-52&url=english.hunton.no

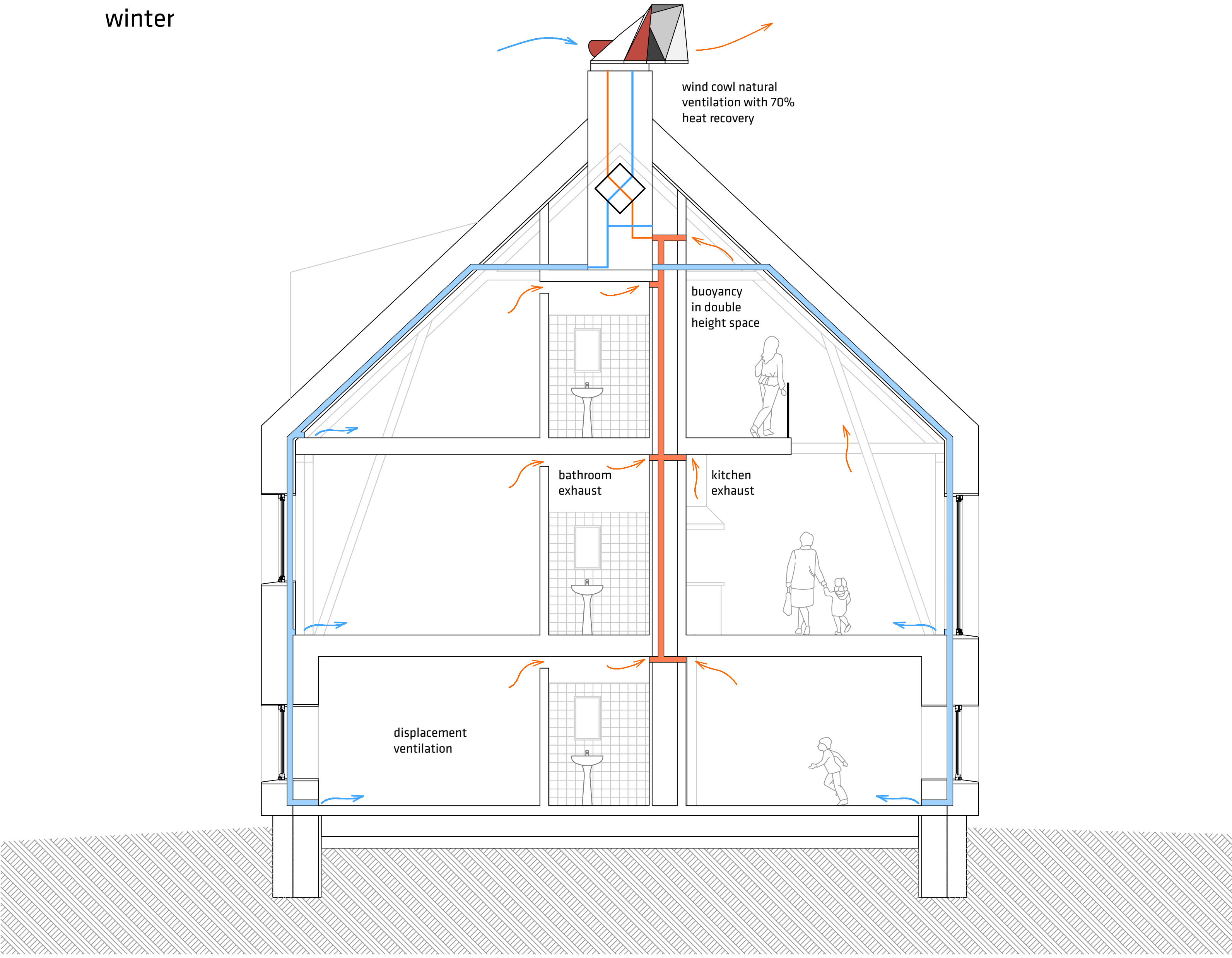
HOT WATER HEAT RECOVERY FROM SHOWERING

Due to the large hot water demand and the large number of showers in the building, hot water heat recovery was considered as being an efficient solution. System proposed is Recoh-Vert - a 2.1 m long tubular heat exchanger that consists of three tubes. The inner pipe, with a diameter of 50 mm, is the waste water drain pipe. The cold water is preheated while it flows upwards through the annular space.*

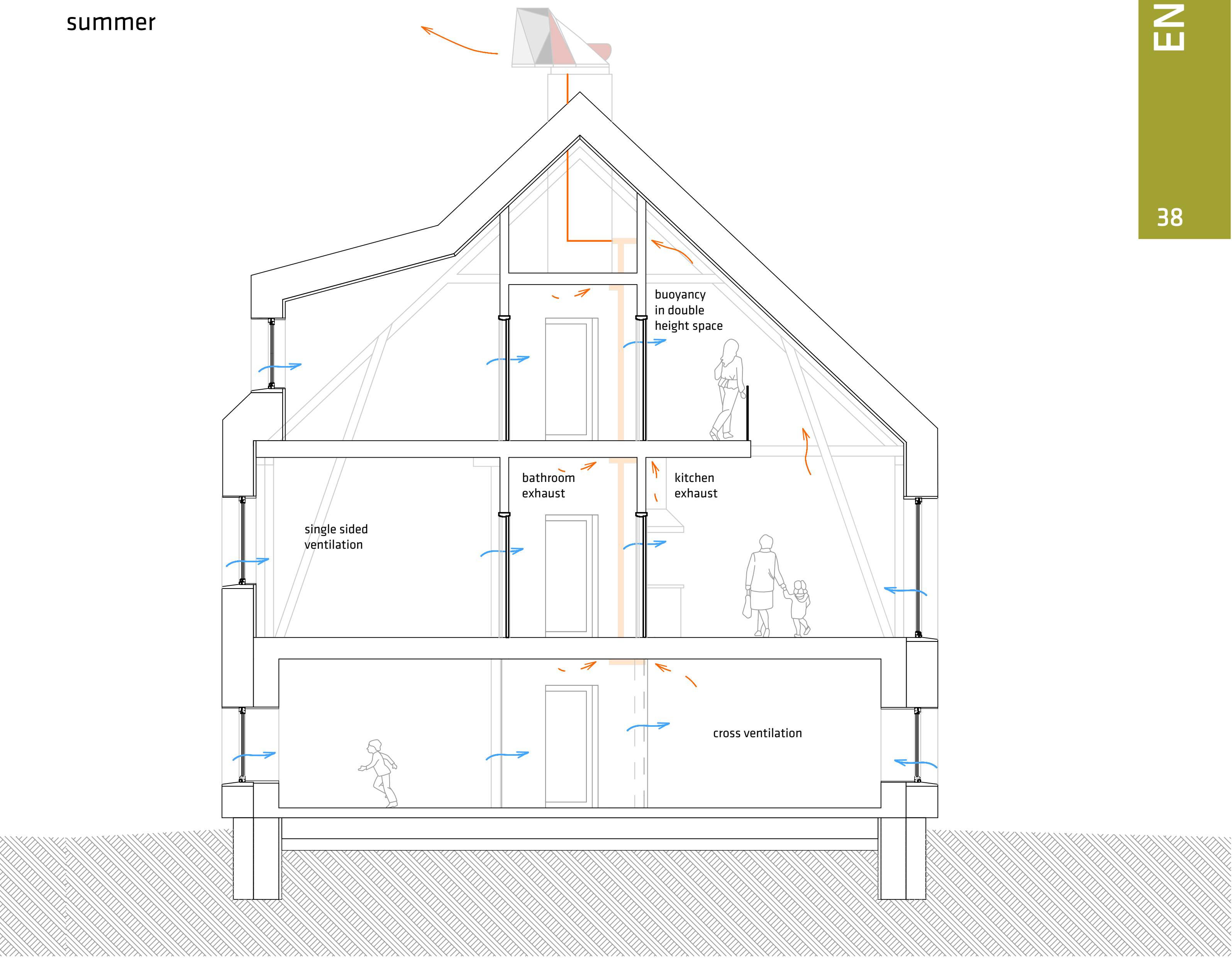
Due to the characteristics of Recoh-Vert system, the shower has to be on the 2nd floor (and the exchanger below the bathroom in a vertical position). This is ideal for the functional distribution of the barn, since all bedrooms and showers are above ground level - thus allowing for efficient use of the Recoh-vert system.
Heat recovery efficiency of the heat exchanger is set to 60 % and assuming a 75% water use for showering (of total DHW), the hot water demand can be decreased by 45% (0.6*0,75).

*http://www.hei-tech.nl/en/recoh-vert.html

HYBRID VENTILATION
winter



HYBRID VENTILATION
summer

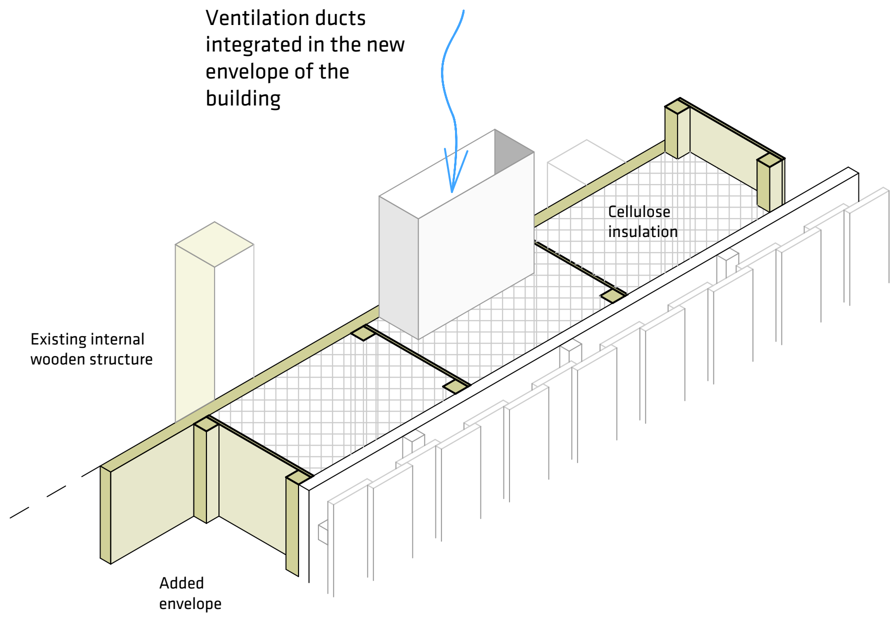


WINDCOWL AND HEAT EXCHANGER

The ZEDfabric Wind Cowl that is used in the project, is a passive heat recovery ventilation system that works like an active ventilation system in that it has dedicated inlet and outlet ducts and a heat recovery system, but instead of using electrical fans to drive the air flow it uses the wind to create both positive pressure at the inlet and negative pressure at the outlet ensuring necessary airflow.
According to the producers, even in low wind conditions it will continue to produce reasonable ventilation levels through stack effect. At an average windspeed of 4m/s in London, depending on the external temperature, the flowrate of the Wind Cowl is between 50-70 litres per second. The heat recovery system used is 70% efficient.*
However, to ensure sufficient airflow at all times for the exhaust from bathrooms and kitchens, installing a backup fan is considered for the barn project, assuming a 50% fan power reduction due to the windcowl.

Ventilation ducts are proposed to be placed in the added envelope, since the ceiling height in some areas of the barn is limited and also to allow more efficient air exchange with displacement ventilation.

*http://www.zedfactory.com/loadreduction.pdf

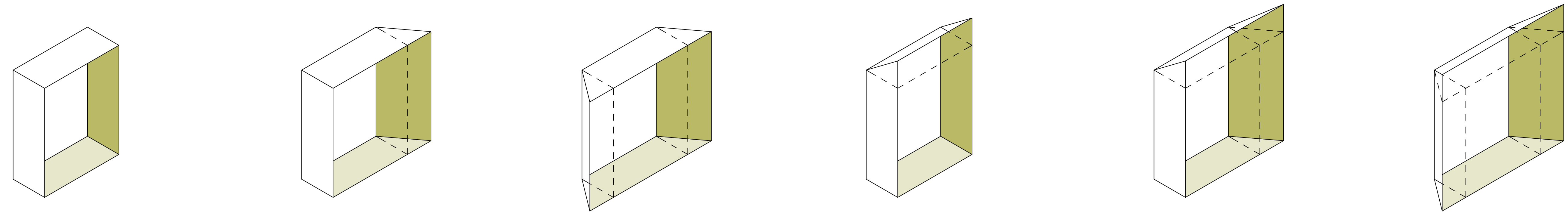


NATURAL VENTILATION

In summer, only exhaust from bathrooms and kitchen would be operating, allowing air supply through natural ventilation. The relatively small depth of the building allows for cross ventilation, with single sided and stack ventilation opportunities throughout the building.

SIMIEN results showed that increased natural ventilation in warmest periods of the year resulted in inside temperatures below 26ºC at all times, thus allowing to omit ventilation cooling.

Ventilation strategies



Case A:
base case, no splayed surfaces

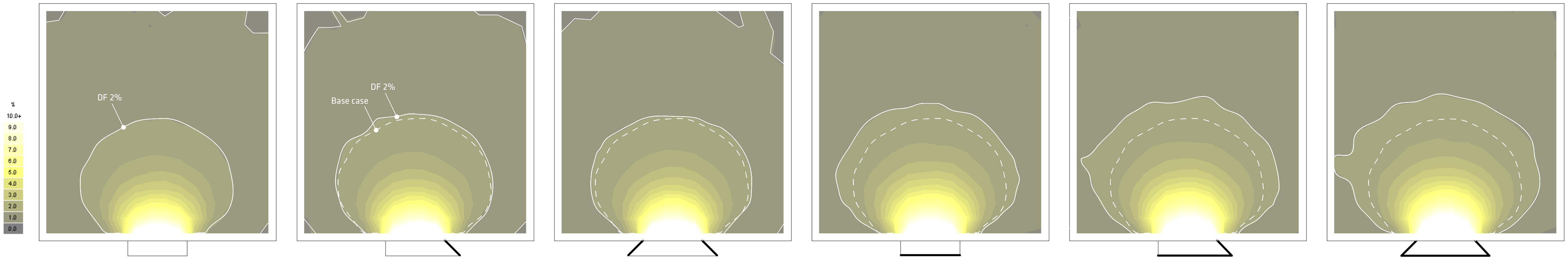
Case B:
one splayed side

Case C:
both sides splayed

Case D:
splayed top

Case E:
splayed top and one side

Case F:
splayed top and both sides



Average DF 1.74 %
Base case

Average DF 1.79 %
+ 2.9 % increase

Average DF 1.83 %
+ 5.2 % increase

Average DF 1.94 %
+ 11.5 % increase

Average DF 2.02 %
+ 16.1 % increase

Average DF 2.07 %
+ 19.0 % increase

BACKGROUND:

Due to limited size of existing window openings and also the added wall thickness of 0.5 m due to insulation, the amount of daylight entering a room is decreased. Also for the new walls the size of the windows is optimized to avoid heat loss through the envelope.
According to TEK-10 § 13-12. Lys, a mean daylight factor in a room for permanent stay should be minimum 2%. Other method to fulfill requirements is to show that window area is at least 10% of the room's floor.

To see if all spaces for permanent residence (living rooms, kitchens, bedrooms etc) in the refurbished barn building would comply with the above mentioned requirement, a daylight simulation is performed for the worst case - a relatively large room with single window which is less than 10% of the are of the room.
To improve the DF value, splaying of reveals is proposed and used in the project.

INPUT VALUES for Ecotect/Radiance:

room size 4.8 x 4.8 m
the size of the largest room lit with just one window in the project is approx. 4.5 x 4.8 m (building part 5, first floor)
based on this a generic square-shaped room was used for simulation

window size 1.2 x 1.2 m
size of the original window openings in the brick walls in building parts 4 and 5 are 1.25 x 1.28 m
a slightly smaller squre-shaped window was used for simulation

reveal depth 0.3 m

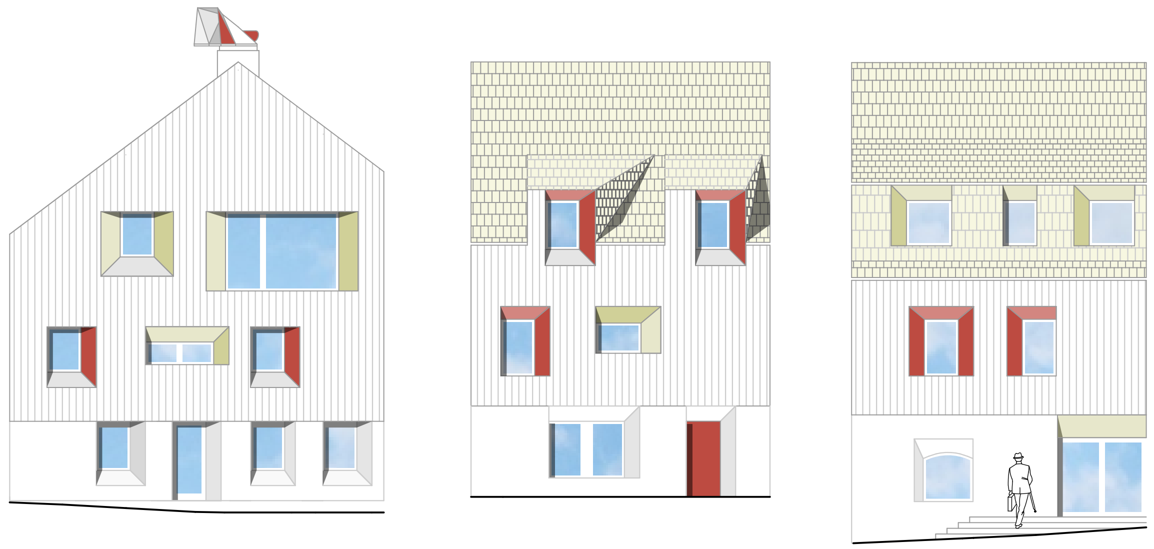
visual transmittance 0.7
for triple glazing

HAUS SIMMA
Arch. Georg Bechter
2011 Vorarlberger Holzbaupreis

http://www.architonic.com/aisht/house-simma-georg-bechter/5101226

http://www.baunetzwissen.de/objektartikel/Gesund-Bauen-Haus-Simma-in-Egg-A_1570931.html?img=2&layout=galerie

APPLICATION IN PROJECT



South facade:

most windows not splayed to top to make use of the shading "overhang" from high summer midday sun

smaller horizontal strip windows also splayed towards top to allow more sunlight

walls splayed primarily to the right - opening up to cooler morning sun

West facade:

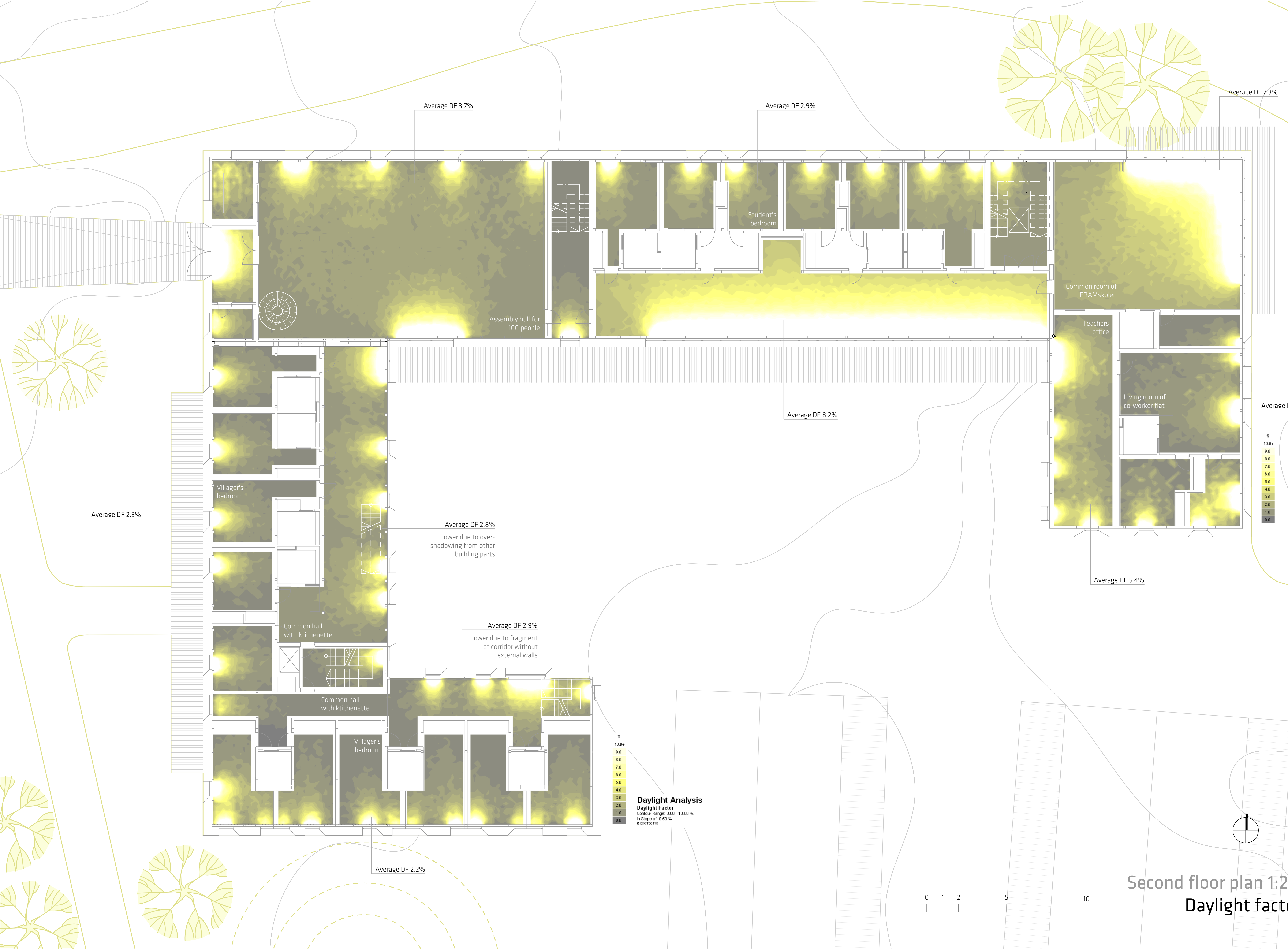
windows splayed to top and one side for optimum daylight accessibility

splaying towards south to allow more sunlight

North facade:

windows splayed on top, top and side or all three sides for more daylight access

Daylighting strategies



Second floor plan 1:200
Daylight factors

Camphill Rotvoll area has recently been added to the concession area of Trondheim district heating. Thus the base case scenario assumes energy supply from grid electricity and district heating. Three alternative scenarios are presented with different combinations of on-site energy production with different targets and characteristics.

The alternatives are compared in terms of delivered energy, CO_2 emissions and relative simplicity of installation/connections of the system. Emission factors from SIMIEN program are used - 395 g/kWh for electricity, 231 g/kWh for district heating, 14 g/kWh for biomass.

BASE CASE
District heating and grid electricity

REFERENCE	ELECTRICITY 100% Grid	HEAT District heating	RESULT
Energy demand, kWh	111078	104561	215639
System efficiency:	0,98	0,84	
Delivered energy, kWh	113345	124477	237822
Emission factor, g/kWh	395	231	
Emissions, kg CO2 eq	44771	28754	73525

Tab.2
Base case energy supply overview

CASE 1 MINIMALIST
District heating and PV electricity (in addition to grid)

Placement of PV panels is proposed on both south sloped roofs and one of the west oriented roofs - all of which have no roof windows or built loft additions. Other building surfaces would not be efficient for PV integration, since they are often shadowed by other parts of the building. PV electricity production was estimated using web-based tool PVgis. PV electricity covers approx. 55% of the electricty demand and has seasonal character (see Fig.9).

REFERENCE	ELECTRICITY 55% PV	ELECTRICITY 45% Grid	HEAT District heating	RESULT
Energy demand, kWh	59760	51318		215639
System efficiency:	100	0,98	0,84	
Delivered energy, kWh	598	52365	124477	177440
Emission factor, g/kWh	395	395	231	
Emissions, kg CO2 eq	236	20684	28754	49675

Tab.3
Case 1 energy supply overview

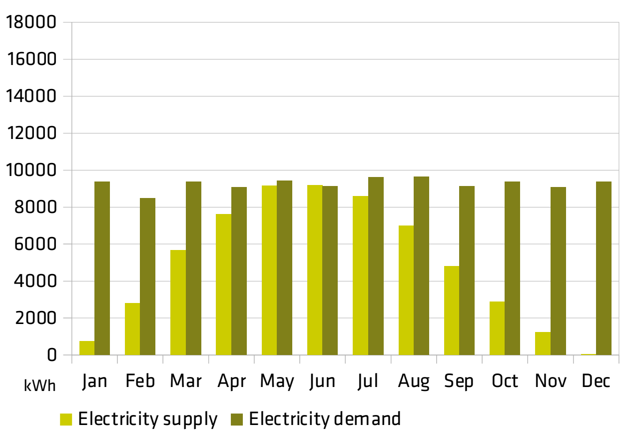


Fig.9 Electricity demand and supply from PV balance

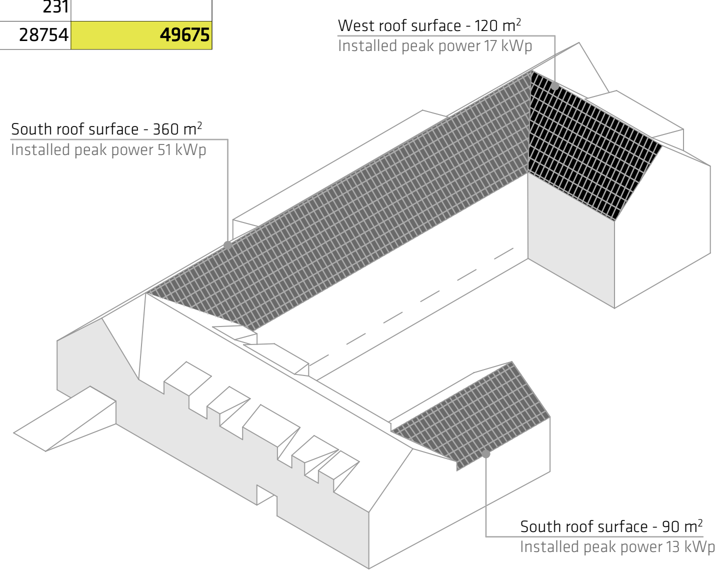
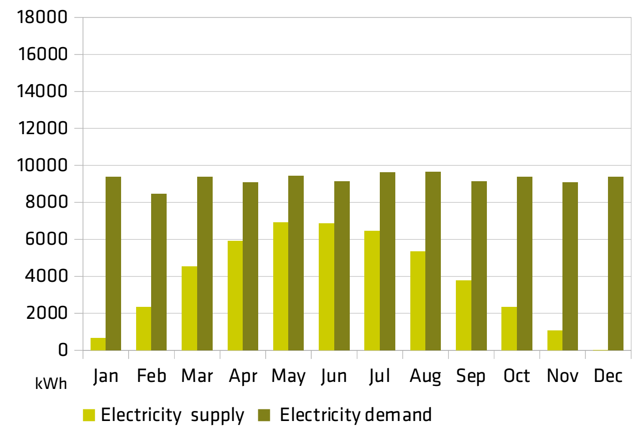


Fig.10 Placement of PV panels on the barn roof

CASE 2 ON-SITE
District heating and PVT heat and electricity (in addition to grid)

REFERENCE	ELECTRICITY 37% PVT	ELECTRICITY 63 % Grid	HEAT PVT (useful)	HEAT District heating	RESULT	PVT heat surplus	Corrected result
Energy demand, kWh	46265	64813	59330	45231	169374		
System efficiency:	100	0,98	10	0,84			
Delivered energy, kWh	463	66136	5933	53846	125915	-7449	
Emission factor, g/kWh	395	395	395	231		231	
Emissions, kg CO2 eq	183	26124	2344	12438	41088	-1721	39368

Tab.4 Case 2 energy supply overview (PVT output - 30% electricity, 70% heat - VOLTHER Powervolt), proposed feed-in of surplus heat of PVT



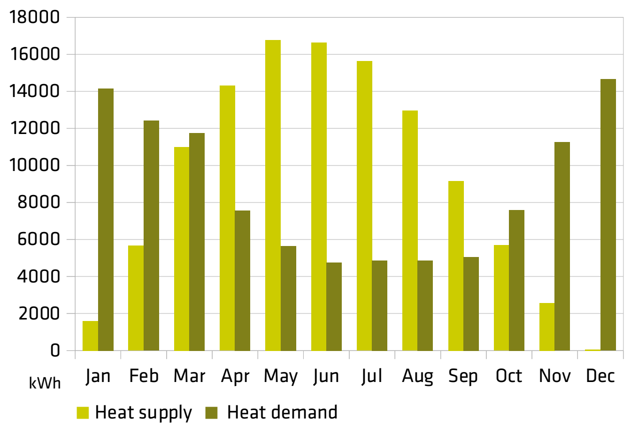
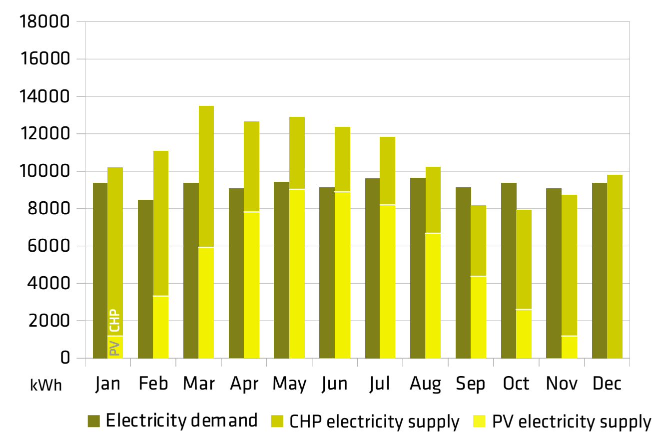


Fig.11 (Right) Monthyl electricity supply and demand from PVT - balanced with grid in winter months, (right) monthly heating energy supply and demand from PVT - balanced with distric heating in winter months

CASE 3 ZERO EMISSION FROM OPERATION
Micro CHP and PV (balanced with grid)

REFERENCE	ELECTRICITY 55% PV	ELECTRICITY 45% CHP	HEAT 100% CHP	RESULT	CHP el. Surplus	Corrected result
Energy demand, kWh	59760	51318	104561	215639		
System efficiency:	100	0,85	0,85			
Delivered energy, kWh	598	60374	123013	183984	-18389	
Emission factor, g/kWh	395	14	14		395	
Emissions, kg CO2 eq	236	845	1722	2803	-7264	-4460

Tab.5 Case 3 energy supply overview (CHP used to follow/cover heat demand. CHP output - 40% electricity, 60% heat. CHP fuelled with wood gas. Emission factor assumed as for biomass.)



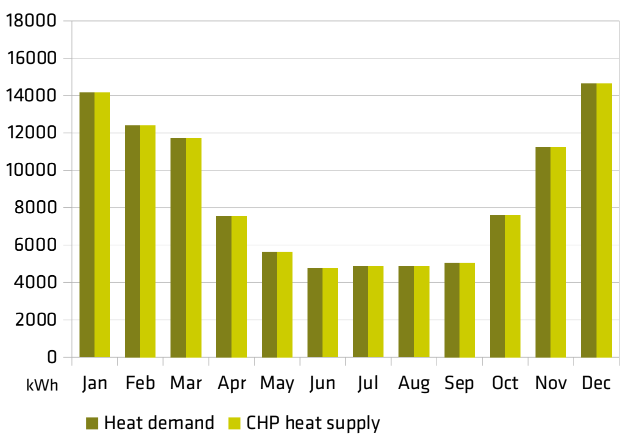


Fig.11 (Left) Electricity supply and demand balance - combined PV and CHP byproduct electricity, (right) CHP covering the heating demand

LIFETIME PERSPECTIVE

Comparing emissions from operation for supply scenarios and embodied emissions

ESTIMATING THE EMISSION FACTORS FROM OPERATION OVER THE LIFETIME OF THE BUILDING

Tor Helge Dokka in his ZEB Memo on electricity CO_2 factor*, proposes using the following formula for estimating the emission factor that would arise from "greening" the grid for a building constructed in 2010, with a lifetime of 60years, with a constant energy use:

$$K_{el} = \frac{361}{2} * \frac{2054 - 2010}{60} = 132 \text{ g/kWh}$$

- where 361 (g/kWh) stands for the current emission factor for electricity used in the report by Dokka.* Year 2054 is set as the reference for emission levels reaching zero based on extrapolation of European electricity system development trend simulations undertaken by SINTEF Energy. 60 (years) represent the lifetime of the building.

To account for a future reduction in emission factors also for district heating the same formula is adapted for use in this project, but instead of assuming a decrease in emission factors to 0, the decrease target is set to 14 g/kWh - the present emission factor value for biomass. For rough estimate the year 2054 is kept as reference for reaching the 14 g/kWh emission level. Trondheim district heating representative at a lecture at NTNU has named the target of district heating being 90% renewable in future, however, to give an accurate future emission factor for district heating in Trondheim more detailed analysis would be required.

$$K_{dh} = \frac{231 - 14}{2} * \frac{2054 - 2010}{60} = 80 \text{ g/kWh}$$

COMPARISON OF SUPPLY SCENARIOS

Energy demand and emissions from operation - current and over lifetime

None of the three scenarios for energy supply show obvious advantages over the others in all aspects shown in Fig.12.
While the "zero emission" level of Case 3 seems to be preferable, the delivered energy is actually higher than in both other cases (Fig.12) and linked to off-site fuel supply for the CHP.

Minimal system approach as in Case 1 - only using PV shows a decrease in emissions of 32 % over the base case and 25% decrease in delivered energy. Using the same surface area of PVT results in a 46% decrease in emissions and further reduction in delivered energy, but involves balancing the heat production with district heating network or on neighbourhood scale.

While the base case would be awarded B label for specific delivered energy of 68 kWh/m^2, all three scenario cases would reach A label for delivered energy (< 64 kWh/m^2), but to a different degree. Case 1 and Case 3 with specific delivered energy of 50 and 52 kWh/m^2 represent 20% lower value than the A label. Specific delivered energy for Case 2 is 34 kWh/m^2, which is 47% lower than A label.

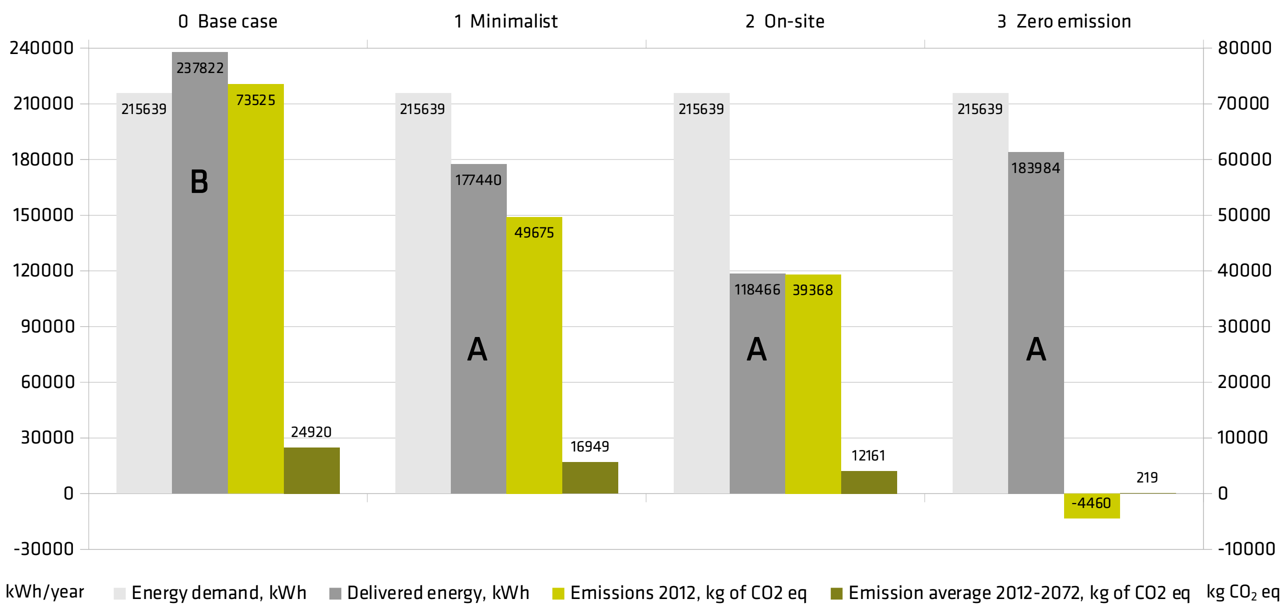


Fig.12 Delivered energy and related emissions (current and lifetime adapted) for the three energy supply scenarios, energy labels for delivered energy shown on the delivered energy bars

*Dokka, T.H., 2011. Proposal for CO2-factor for electricity and outline for a full ZEB-definition. ZEB Memo.

Recalculating emissions over the lifetime of the building resulted in a decrease in emission values by 66-69% for the Base case, Case 1 and Case 2, which all benefited from the lower values for electricity and district heating emission factors.
Case 3, however, shows an increase in emission levels. This is due to the large proportion of emissions from biomass for CHP which remained unchanged. These emissions could no longer be offset with the small amount of surplus electricity with a lower lifetime emission factor. Thus Case 3 would no longer reach the level of "zero emission from operation". To reach this level a higher electricity production would be necessary.

OVERVIEW OF EMISSIONS FROM THE BUILDING

Emissions from operation with different factors (current and lifetime adjusted) and materials

If embodied emissions would be combined with operational emissions calculated with current emission factors over the 60 years of the lifetime of the building - assuming no "greening" of the grid in the next 50 years - the surplus electricity produced by CHP in Case 3 would contribute to offsetting 60% of the embodied emissions over the lifetime of the building (Fig.13).
This is no longer possible with operational energy emissions recalculated with lifetime adjusted emission factors (Fig.14), since at some moment in the building lifetime the emission factors for electricity would be so low that the on-site produced electricity would no longer provide emission offset for the emissions from biomass used in CHP.

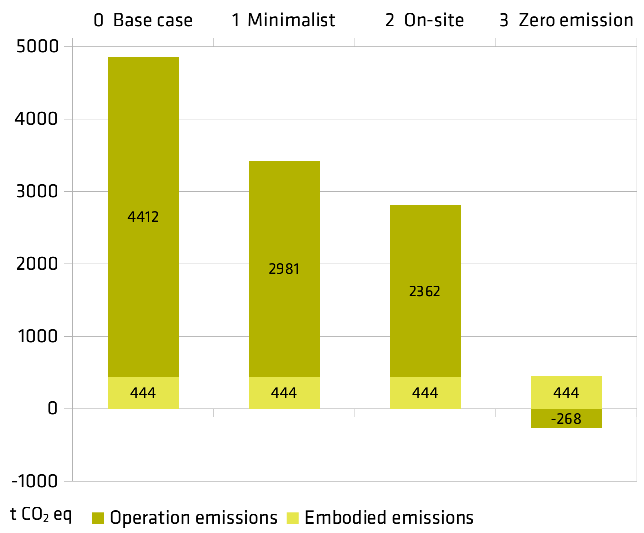


Fig.13 Emission levels of the barn for the supply scenarios using current emissions factors (SIMIEN) and emobodied emissions

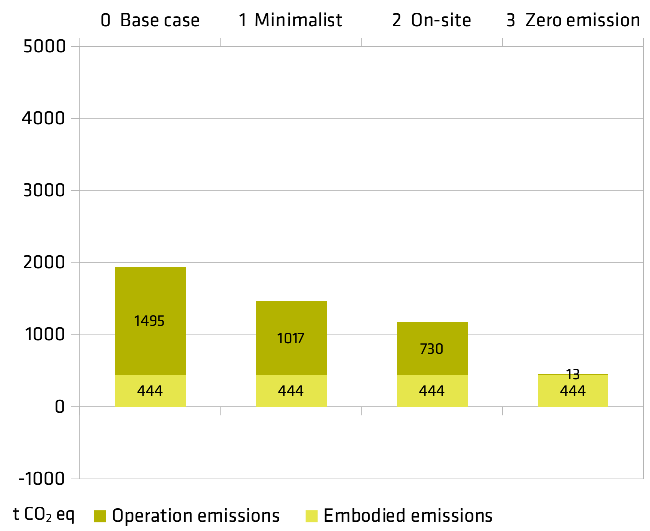
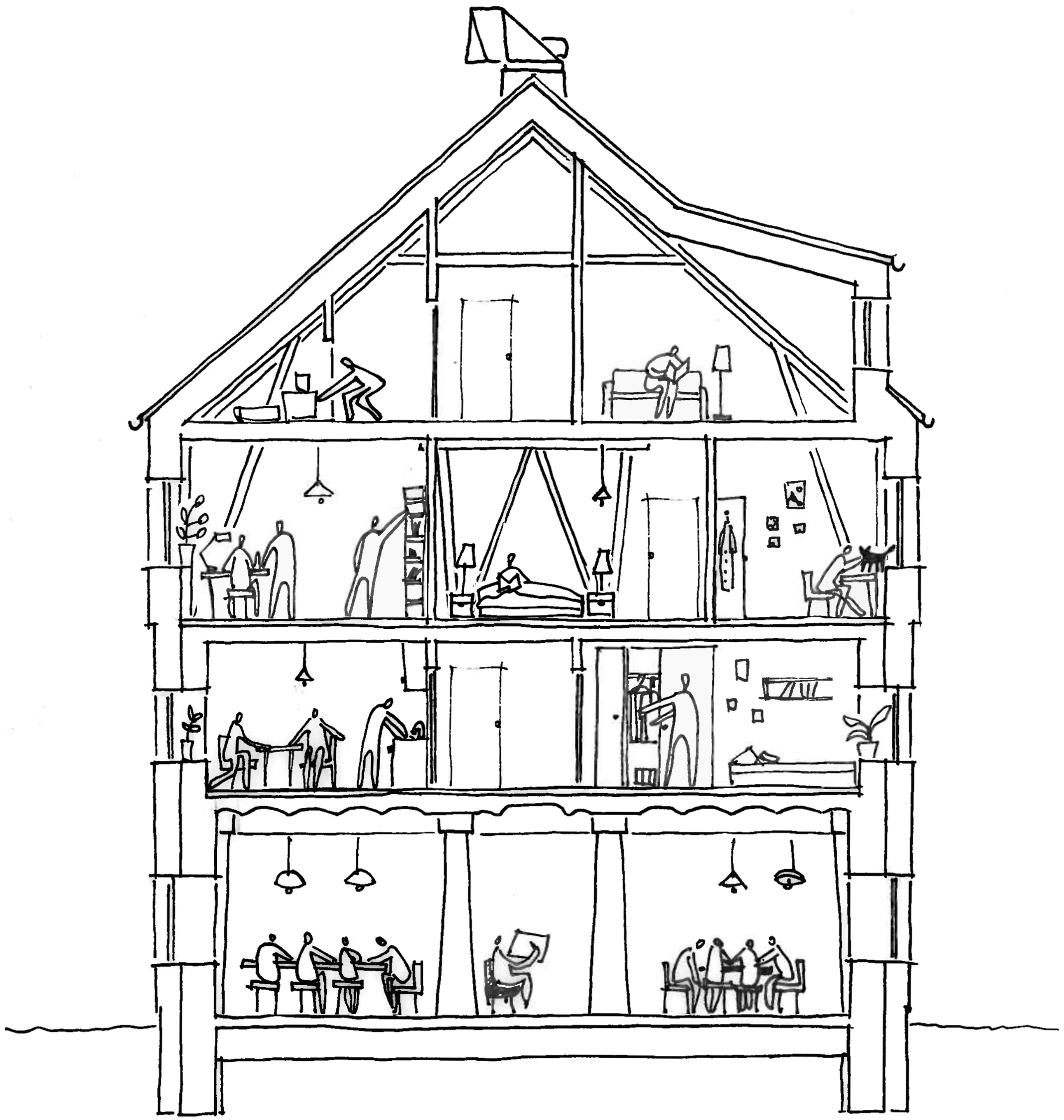


Fig.14 Emission levels of the barn for the supply scenarios using emission factors adjusted over the lifetime of the building

When operation energy emissions are calculated with lifetime adjusted emission factors, the fraction of material emissions increases significantly. With high current energy emission factors the materials would constitute only 10% of total emissions for base case, but 30% with lifetime adjusted factors.
Although Case 3 does not reach the "zero emission from operation level" over the lifetime of the building, the emissions from operation account for only 3% of total emissions - 97% are linked to embodied emissions. For all other supply scenarios the emissions from operation are larger than those from the new materials used in conversion of the barn (see page 34 for details), although embodied emissions represent a significant fraction (30-40%) for Cases 1 and 2. No technical systems (like PV or PVT) have been included in the embodied emission accounting, which could further increase the fraction of embodied emissions.

CONCLUSIONS

Case 3 (PV and CHP) proves to have the lowest emissions although not reaching zero emission from operation over the lifetime of the building. Cases 1 and 2, on the other hand, allow for more self-sufficiency on site and lower delivered energy. Other considerations like costs and complexity of installation can also play an important role.
The resulting emissions levels for both operation and embodied materials are very sensitive to input values and could lead to different conclusions if the boundary conditions would be changed - e.g. to include transport (both for transporthing fuel for CHP and construction materials). For conclusive results, a more detailed accounting should be performed.



Conclusions

As called by a representative of the local heritage authority, the barn is the "king of the area".
This design project attempts to justify the possibility of reusing a large fraction of the old structures and materials while ensuring proper functioning of the building with a changed use.

According to a crude embodied emissions accounting, reuse of the existing building elements would lead to a "saving" of one third of the emissions linked to the transformation of the barn. The existing structures would also account for half of the weight of the materials - due to the extensive use of concrete in some parts of building.
Designing for reuse of the old wooden structures proved demanding, but eventually rewarding, since they contribute to the feeling of "living in a barn" by exposing the historical layers of the building.

Due to energy saving considerations, the insulating envelope was added from the outside, in some cases also removing the existing concrete slabs to ground to ensure minimal heat loss. Energy perfromance calculations showed that passive house standard can be reached for the transformed building with optimized window area and well-insulating envelope.
In order to minimize the energy demand even further, systems like hot water heat recovery and hybrid ventilation was used. These measures helped to reduce the energy demand by 21%.

Lastly three energy supply options were evaluated for the building with regard to their delivered energy, current emission levels and emissions over lifetime. Although all three supply options would lead to an A label for delivered energy, they do so with different levels of delivered energy and related emissions. None of the options showed best results in all aspects, but using PVT technology would lead to lowest delivered energy, while using PV and CHP would lead to lowest emissions.

View of the barn building from north-west

View of the barn building from south-west