CIRCULAR ECONOMY

IN

FUTURE HOUSING

AALBORG UNIVERSITY - ARCHITECTURE
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TITLE PAGE

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ABSTRACT

With the rising focus on the environmental footprint of the building industry, especially in relation to building materials and its production, this project attempts to respond directly by introducing the theory of circular economy into architecture, with the goal of creating a less wasteful building. The building is designed to save space based on the idea behind co-housing and social living, challenging the way housing is now, and how it will be living in the future.

The result is a building project designed as a series of flexible double houses, where each house can freely move around its internal walls, to create unique spaces and configurations, that fit the individual rather than the masses. This is achieved by having an interior wall system that can be disassembled and moved around by hand. The system fits into a grid which in the final buildings is accentuated using wood on the final surfaces, playing with different dimensions to obtain a modular aesthetic. An exterior wall system allows the entire building to be disassembled and relocated, when the framework of the house no longer fits the needs of the future. This way, the houses main structural parts can all be reused for new houses, reducing the demand for material in the future. The materials in the project are all evaluated to be low-emission and have no health risks for users.

READING GUIDE

This reading guide is written to inform the reader about some elements of the report, that will provide a better reading experience.

Due to this report being handed in digitally only, the drawings in the presentation section of the report, have been fitted with scale bars instead of a strict scale. This allows the reader to get a sense of scale regardless of the reader’s screen size and zoom. Please, also utilize this opportunity to zoom in if there are elements that might appear small or hard to read.

Note that due to different screen settings, colours in this report might appear different than originally intended.

Each chapter in this report is structured around an “intro” and a “conclusion”. Each chapter has an intro statement about the intentions of the page, and then a conclusion on what was gained from the chapter. If a quick overview is wanted for this project, these intros and conclusions can be read without reading the full pages. However, it should not be expected that the reader will understand the full perspective of the project, and this reading style is not recommended on a first read.

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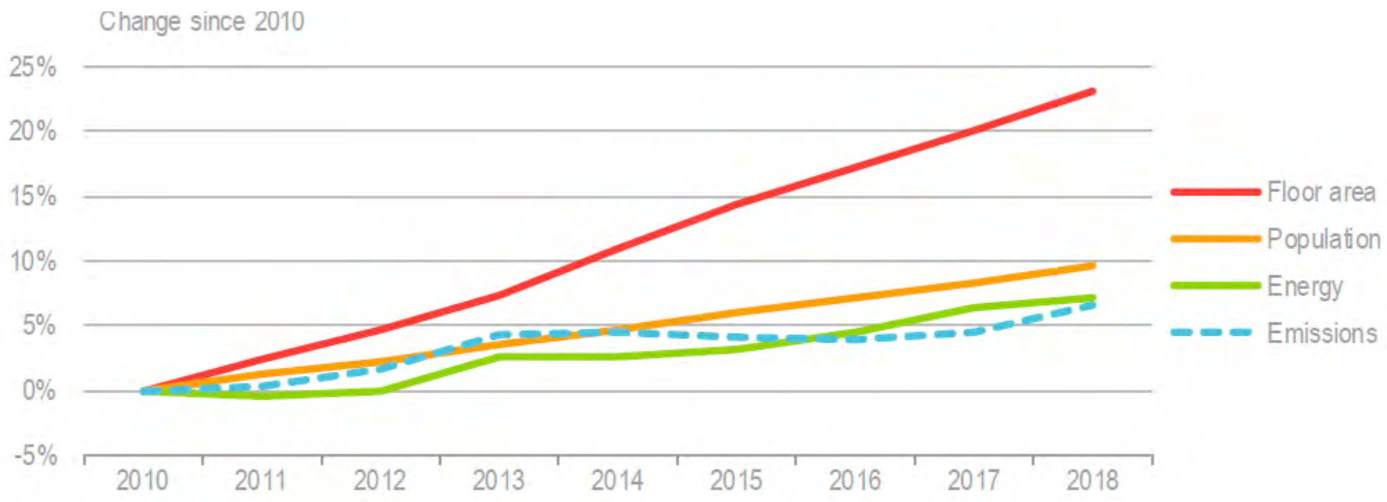
PROBLEM AND DESIGN BRIEF

Problem

With a population increase expecting to go from 7.7 billion in 2020 to 9.7 billion in 2050 (UN, 2019), and an increase in urbanisation expected to reach around 66% of the world's population in 2050 (UN, 2014). It will mean that the need for housing and other building types will increase, which will have a profound impact on the environment if left unchecked at status quo. The construction industry is currently responsible for 36% of all energy usage worldwide, 39% of all CO_2 emissions worldwide, with 11% being strictly from the production of construction materials, and around 35% of all resources extracted worldwide annually; and all numbers are currently increasing each year from 2018 onwards (GABC. 2019).

One of the major ideas that have been identified in the contribution to create more sustainable practices within construction, is the concept of circular economy. The idea of reusing materials in new lifecycles, lowering the need for resource extraction and production of construction materials. This idea both has environmental, economic, and social benefits if implemented, as presented by the Ellen McArthur Foundation (2012). Circular economy is also a political focus in Denmark. With the government creating a task force to create better conditions for a future circular economy in the country (Ministry of Food and Environment, 2018).

The increasing population, and the growth in the construction sector, has also led to another issue. Current trends show that the amount of floor area is rising faster compared to the population growth, as shown on Illu 1. This rise in floor area means increased usage of resources and energy, compared to what is necessary if less floor area was built. There is, therefore, a large potential in creating buildings, that utilize the floor area better. One concept for achieving this is the principle of co-housing, which is proven to potentially save up to 30% floor area in housing (Williams, 2007).



Illu 1: Increase in floor area, emissions, and energy consumption, compared to population growth from 2010-2018.

Design brief

The motivation for this project is to try and find solutions for the problem statement, and the current high emission construction industry. The goal is to achieve design principles that can be used to combat problems here in Denmark. This is to be achieved by delving into the theory behind circular economy, to acquire an understanding of how it can be implemented into architecture. This implementation should be made approachable and doable with technology and products that are available today, as the change starts now. But the perspective and ideas behind it should be for the future of the entire building sector.

This project begins in the housing sector, as it is a sector that can provide scalability of circular concepts. By designing within the housing sector, a focus can also be given to the rising floor areas of contemporary housing, which further extends the negative environmental impacts of the building sector. As stated, the concept behind co-housing can provide a fundamental change not only to build floor area, but also to the way we humans live and interact on a social and cultural level.

This co-housing will be used as a concept project for the development of a modular system based on circular principles. This modular system should be one that works within the design process of architecture, giving architects the flexibility and adaptability to still provide a diverse architecture. This project can then be best explained as a duality between construction and building design, and the interplay between the functionality, aesthetics, and technicalities of both.

For the project, a site has been chosen on the outskirts of Aalborg in the area of Hasseris on a road called Sorthøj. This is a highly attractive site that provides great access to the city, while still giving a somewhat suburban feeling for families. If one were to build a highly sustainable project development which could come a high price, it should be at a site, where the attractiveness of the development comes from both sustainability and location. The site also has a modern and diverse architecture, that fits well with the introduction of this new development.

The project will be around 1200-1500 m², and should fit around 15-20 dwellings of varying sizes, along with common facilities for the users. Using the principles of design for disassembly, there is going to be a focus on both short- and long-term flexibility, so that units can adapt to changing demands. The project should be designed with low-emission materials measured through lifecycle assessments, and materials should not provide health risks to users or construction workers.

Problem formulation

How can the concepts of circular economy be adapted into a modular building system, that provides flexibility in design and functionality? How can future housing units be designed with co-housing in mind, so that floor area is reduced and sociocultural qualities are improved?

METHODOLOGY: PROJECT STRUCTURE

This methodology takes point of departure in the integrated design process (IDP) described by Mary-Ann Knudstrup (Knudstrup, 2005). However, it has been altered to better fit this specific project. It should, therefore, be read as an interpretation of the method, rather than a direct copy. IDP consists of five phases respectively problem, analysis, sketching, synthesis and presentation.

Problem

The problem phase consists of a description of the main problem, a design brief, and a project scope.

The problem description explains the main motivations behind this project, and to explain what problems the project hopes to solve. The design brief describes the core project parameters that must be met, such as building type, size, user, and overall project goal.

The project scope exists to help narrow down the project and define which areas should be focused more in-depth upon. Since the primary focus is on circular economy and designing a modular system. Other technical aspects are still considered, but as they are not the focus, the standards and methods for these will merely be stated. This is to ensure that they can still be involved, without diving deep into the theory.

Analysis

The analysis phase exists to create the necessary background knowledge which is needed before the start of the sketching phase. The analysis also sets design parameters; technically, functionally, and aesthetically, that together become the main point of departure for the design.

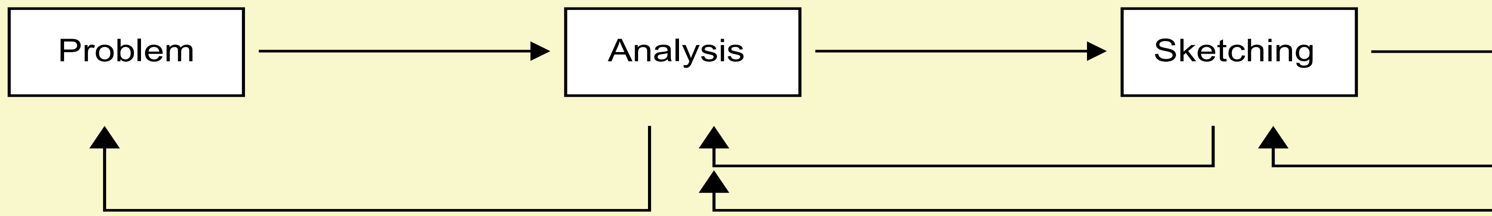
The analysis phase will have a focus on the primary necessary knowledge, which includes circular economy, DGNB, Design for Disassembly, LCA, along with defining the user and analysing the site. This means that in some places, knowledge that is used in the project is not presented, as it is considered common knowledge within the field of architecture, or of lesser importance to the overall project.

Acquiring necessary knowledge is done through a series of literature searches with a focus on state-of-the-art research, or relevant case studies. Knowledge regarding each specific topic, should if possible, be obtained from multiple sources to gain a nuanced perspective.

Sketching

The sketching phase consists of two main parts: the design of a modular system and the design of the building.

The modular system will be designed with a focus on details and principles. By working with the acquired knowledge from the analysis phase, the modular systems are designed, and the best solutions are determined. This involves finding or designing different modular principles and analysing them, to see which one is the best in relation to the theory gained in the analysis phase.



Illu 2: Project structure

The other part consists of designing the building with plan, section and facades. The building design should be based on the modular system; however, the idea is not that sketching of the building design should be based entirely on the modular system, but that they can provide a cornerstone, from which ideas can emerge. It is important to note, that building design sketching should also focus on purely functional and aesthetic aspects, as a means of trying to challenge the modular system to evolve them.

The sketching phase does not necessarily need to concern itself with the full design of the entire building, but can also focus on designing smaller parts, that can later be joined in different ways in the synthesis phase.

The sketching phase will be made by going back and forth between designing the modular system and the building. This will lead to an optimization of both aspects and thus end up as one final design where both parts are represented.

In the sketching phase, different media will be used hereunder hand-sketching, physical models and cad-modelling. The varying media will lead to different understandings and ideas, thus providing the project with the best way to move forward.

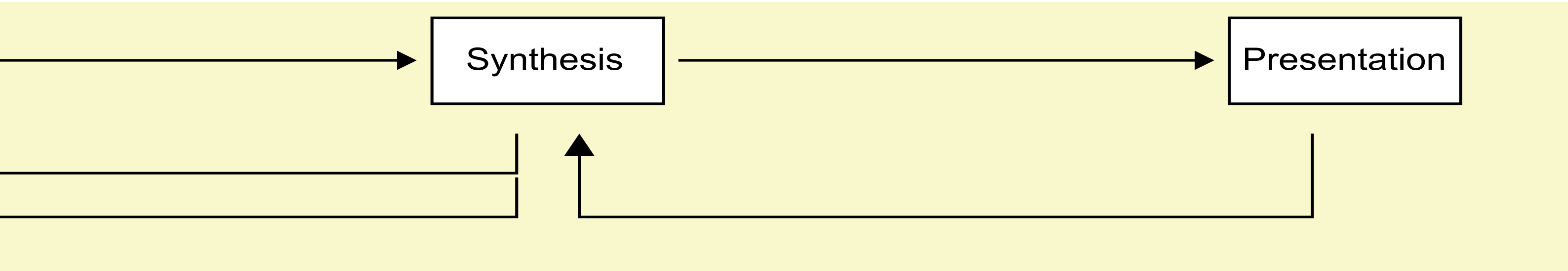
Synthesis

The synthesis phase should not act as a final stage to the final design, but as the final step in an iterative loop of different design proposals. The focus is on verifying the primary focal points of the project and improving the sketched ideas, so they become unified and optimized. It is also here that the secondary technical aspects are evaluated, such as energy frame and indoor environment as set in the project scope.

Based on the verification and evaluation of technical, as well as functional and aesthetical parameters, in relation to all the set design criteria, the synthesis phase then identifies what parts of the design that should be altered to optimize the final design. Which then moves the project back into either analysis or sketching, based on what needs to be optimized.

Presentation

In the final presentation phase, the final design has been chosen, and presentation material is made, to present the project in its different aspects. It is important here, that the material both presents the final design, but also all the underlying ideas regarding circular economy and how the modular system works.



METHODOLOGY: PROJECT SCOPE

Intro

The purpose of this project scope is to make a clear distinction between what aspects are the focus for this project, and what aspects are still an influence but not the focus. By doing this, the project decides what other aspects should be expected to not be mentioned explicitly throughout the project, as it might be considered common knowledge within the field of architecture. These subjects should not be viewed as a non-factor for the project, but rather understood as have been chosen not to directly work with, but they will still influence the project, in order to focus towards the main theme.

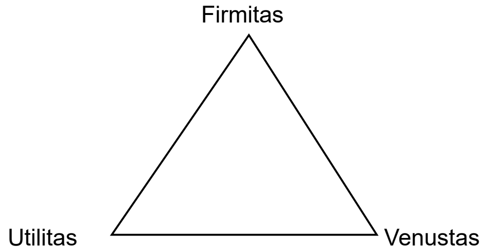
Project scope

The focus of this project will now be explained with each of the three pillars of architecture defined by Vitruvius respectively aesthetically, functionally and technically (Rowland and Howe, 2001). A list of different standards and legislation that will be followed in the project, have also been listed to clarify how the project deals with energy frame and indoor environment. These are evaluation methods to ensure the final design accommodate these aspects but are not prioritized in the design process.

Aesthetically (Venustas) this project will focus on the materiality of sustainable materials. Within the design for disassembly aspect a focus on the appeal of visible connections, and their contribution to the overall aesthetics of the building. Work will also be made into how to create a variation of space and expression within the modular system.

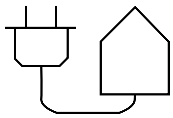
Functionally (Utilitas) the focus is on flexibility and changing demand for the use of the building during its' lifetime. The modularity should provide this flexibility, which at the same time will provide different possibilities in design when using the modular system.

Technically (Firmitas) the focus is on lifecycle assessment of materials, analyzing and choosing materials that are best suited for design for disassembly; and then on the design of the modular system. The focus is not on dimensioning each construction element and HVAC systems. Instead, the focus is on taking a holistic approach that ensures all aspects are thought of on principle levels while diving deep into materials and the principles for design for disassembly.

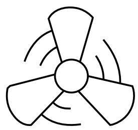


Illu 3: Vitruvius triangle

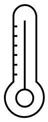
Standards and legislations



- Energy frame:
Energy frame will follow the standard frame for housing set in BR18 §259, as well as following the demands for constructions set in §257 and §258 (Bygningsreglementet.dk, 2019). Calculations will be made in BE18, based on methods described in DS 418 (Danish Standard. 2011).



- Atmospheric comfort
The atmospheric air quality and ventilation rates are based on category II DS/EN 16798 (Danish Standard. 2019) with calculations made based on tables B.6 - B.14.



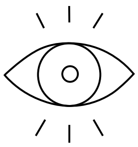
- Thermal Comfort

Thermal comfort is determined based on DS/EN 16798 (Danish Standard. 2019) table B.1 where it is decided to be category II which is normal expectancy levels of indoor comfort with a PPD of 10%. The standard recommends the following temperatures when calculating summer and winter.

In winter: 22C +- 2C (Assuming a clothing of 1 clo) based on Table B.5 (ibid).

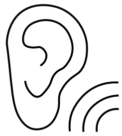
In summer: Max temperature is calculated based on the adaptive method of mean outdoor temperature as described in Figure B.1 (ibid).

Thermal comfort calculation is based on BSim simulations



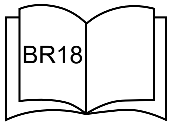
- Visual comfort

Following that all rooms for occupation must have view towards outside BR18 §378 and following the recommendations for daylight calculations given in BR18 chapter 18. Calculations will be made using Velux Daylight Visualizer to achieve 2% daylight factor on half the relevant floor area of the room. (Bygningsreglementet.dk, 2019)



- Acoustical comfort

Acoustical comfort in relation to reverberation time follows the values set in the recommendations in BR18 chapter 17, and the set requirement to meet category C in DS 490 (Danish Standard. 2018).



- Regulations

Unless otherwise explicitly explained, the project will follow the current regulations set in the Danish Building Regulations BR18 (Bygningsreglementet.dk, 2019) .

ANALYSIS

FUTURE HOUSING AND USER

Intro

When creating housing, it is important to investigate what the demands for housing are now, but also what they will be in the future. This is to ensure the dwellings accommodate the functions and demands found now and, in the future, thus making them compatible for future living. In the following, the present and future demands are analysed, followed by an analysis of cohousing which this project will incorporate in the design. The cohousing aspect is also analysed with case studies, which altogether can be used as a design driver for the project.

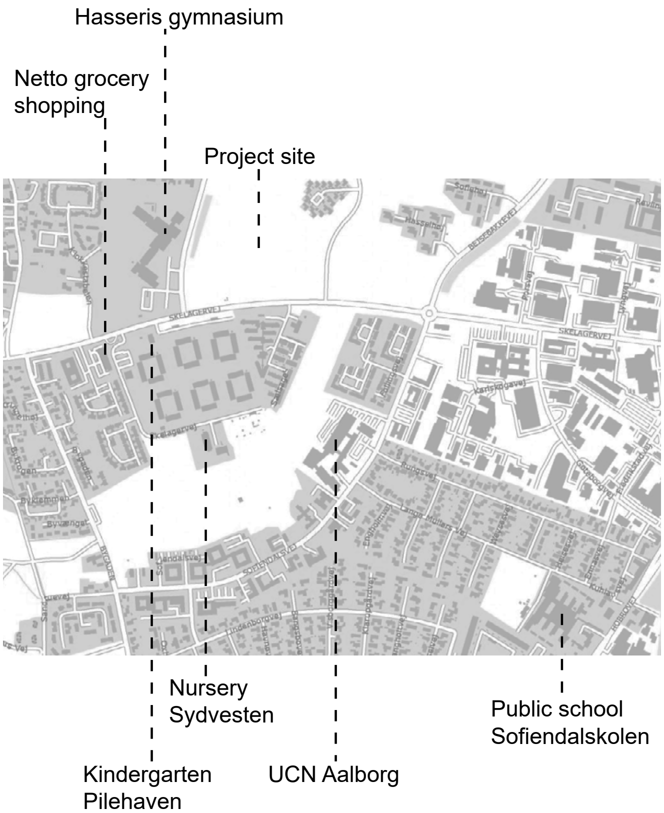
Demands now and in the future

The population in Denmark is going to rise with 200.000 people within 10 years, meaning the demands for dwellings increase as well. The growth is especially with the elderly of +70 years but also a big increase between 20-29, 30-39 and 50-70.

People in their 20’s often move to study or get a job, and the growth of people in their 20’s results in a larger demand for smaller dwellings with 2-3 rooms between 50-99 m² plus a balcony situated close to the city. The group of 30-39 years of age often start having families, meaning they search for single-family homes primarily in the suburbs. The single-family house should be minimum of 140 m² and include a garden for outdoor activities. They also look for a neighbourhood with safety and proximity to school, shopping opportunities, and work. When investigating the people between 50-70, there is a tendency for them to want to move away from their single-family home, into a smaller townhouse or apartment closer to the city where they can be in contact with others. (Levisen. 2016)

The site of Sorthøj is placed relatively close to the centre of Aalborg, as it takes around 15 minutes in car, 24 minutes with bus and 18 minutes on bike to get to the centre of Aalborg from the site (google.dk. 2020). Thereby, this site is located so it can accommodate both the youth and seniors due to the proximity of the city, and the families due to the suburban atmosphere found on-site along with functions like kindergartens, schools, and gymnasium nearby, as shown on Illu 4.

These three groups will be the target groups of this project, which will create an area with diversity in age resulting in a focus of social sustainability. By creating units with focus on different age groups, it allows inhabitants to live in the area for most of their life and their varying demands throughout life can be accommodated.



Illu 4: Important functions found in the area.

Cohousing

As the population grows, the demands of extra dwellings should be accommodated, and it is important to focus upon creating sustainable solutions when designing. If the demands of a growing population and more dwellings on the same area should be met, it is necessary to create smaller and denser dwellings. This will also reduce the energy demand for buildings and the material usage, meaning the solution of smaller and denser dwellings is more environmentally sustainable. One way to minimize the area per unit is by co-housing.

Cohousing is a type of collective living, which is characterized by designing buildings to emphasize community with common areas and where the residents are involved in the happenings of the community.

Cohousing consists of private dwellings, where each household has its own bedrooms, bathroom, living room, and a small kitchen. As well as common areas for all households, which could include a common kitchen and dining area, gym, laundry, a place for big gatherings, and guest bedrooms. The private dwellings are smaller compared to regular dwellings. They accommodate the everyday life and during less frequent activities like having guests staying the night or large social gatherings, the common areas can be utilised. In this way, space is not wasted for less frequent events for each dwelling but rather shared (Williams. 2007). When designing for cohousing, some aspects are important.

Firstly, the presence of a common room which should be placed centrally is crucial, as it influences the participation and social interaction in the cohousing community. Good visibility into the common room, and all other communal spaces, is essential, as it encourages social meetings. (ibid)

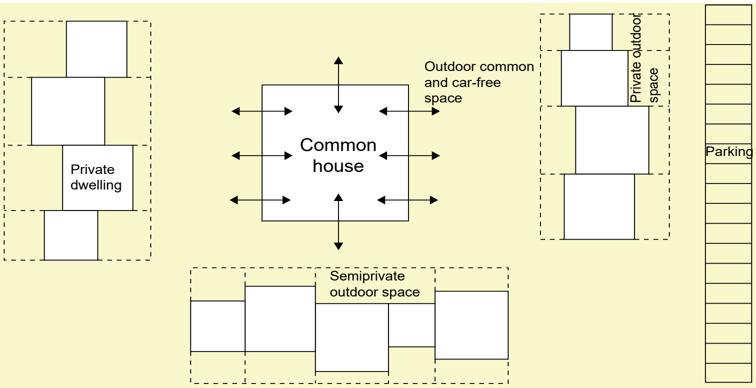
Secondly, a clear division between private and public spaces should create space for being able to socialize but also being private. A semiprivate outdoor area near the private units should enable informal social meetings with the other inhabitants. (ibid)

Thirdly, safety for pedestrians should be prioritized, which can be done by placing the car-parking outside the community and put a focus on paths and walkways. (ibid)

The advantages of creating a cohousing community are the high level of social involvement, where the people can help each other and become more social than elsewhere. Cohousing also encourages environmentally-friendly aspects like saving space and energy, where on average cohousing results in 31% space savings and 57% electricity savings. (ibid)

In Denmark, the average square meters in a dwelling is dependent on how many people that are living in it. A two-person household has on average 60 m² pr. person, a three-person household has 42 m² pr. person whereas a four-person household has 36 m² pr. person. (Bolius.dk, 2017)

In cohousing communities, it also becomes easier to reuse and recycle goods as well as implementing environmentally friendly initiatives along with sharing cars, garden tools, and laundry facilities among others, reducing the amount of equipment per unit. (Krokfors. 2014)



Illu 5: The principles for creating cohousing, centrally placed common house with good visibility, separation between private and common space along with having car-free outdoor spaces

Case study of cohousing: K1 Orchard Park

K1 Orchard Park is a cohousing project situated in Cambridge, England. It is designed by Mole Architects and completed in 2018. The cohousing project has won several awards for good architecture and homes in 2019 and that combined with it being a quite new project, makes it relevant to analyse it. (marmaladelane.co.uk, 2020)

K1 Orchard Park consist of 42 homes divided into nine different units, ranging between 47 m² to 128 m² and from one to five rooms. The big dwellings contain families and are made as houses in two to three stories, whereas the smaller ones are apartments in one story which have fewer inhabitants. All dwellings have their own outdoor space with garden or balcony, meaning they can be private.

Their individual dwellings benefit from shared and common facilities where the inhabitants can, but are not obliged to, socialize. The common facilities include a big common house with hall, catering kitchen, lounge area and guest bedrooms as well as commonly accessed workshop area, storage and a shared garden with room for outdoor activities, playing and food-growing. The buildings are located around a commonly shared car-free path, where the parking happens outside the area, creating an environment focused on pedestrians.
(Townhus. 2016)

Illu 6: K1 Orchard Park Common room

Illu 7: K1 Orchard Park Car-free lane

Illu 9: K1 Orchard Park masterplan

Illu 8: K1 Orchard Park mixture between houses and apartments

Case study of cohousing: Lange Eng

Lange Eng is a Danish cohousing project designed by the architect Dorte Mandrup completed in 2008. The project is developed by four families who wanted to make a cohousing project. They developed some values for the area and spread the words, which resulted in 54 households that went together to finance and build this project (Langeeng.dk, 2020). Thereby, this cohousing project is the biggest in Denmark (Dortemandrup.dk, 2020) and, therefore, relevant to analyze.

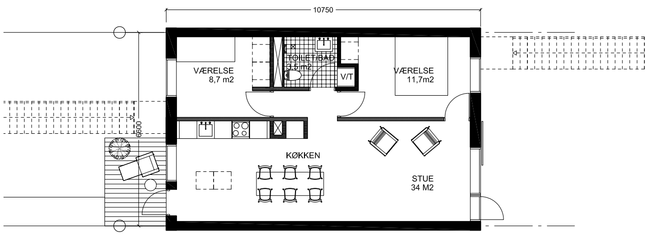
Lange Eng has different common facilities like common room and workshop areas. The common room on 600 m² is situated in the southern corner of the building. It contains a kitchen, dining area with space for 100 people, play area, wardrobe, cinema, multipurpose hall, café with a bar and a lounge, which all together encourage to social gatherings. The inhabitants in Lange Eng have common eating six times a week, with the possibility to either eat with the others in the common room or take the food into the individual dwellings. Thereby, there is the opportunity both to be private and to socialize. The workshop areas contain varying tools and machines along with gardening tools. (Langeeng.dk, 2020)

Lange Eng has 54 individual dwellings, divided into four different units on respectively 71, 95, 115 and 128 m². They each have between two-five bedrooms, a bath and a kitchen-dining area and living room in one. The dwellings are either in one or two stories and have a great view of a common courtyard. The entrance to the dwellings happens through the courtyard, and a semi-private terrace makes a buffer between the common and private space. However, the dwellings do not have a private garden or outdoor space (ibid)

The courtyard is used as a common garden and it consists of common facilities like playground, hammocks, bicycle parking, greenery and barbeques, and thus becomes the social heart of the building. The courtyard is prioritized for pedestrians and, therefore, car-free. The car parking happens outside the courtyard and facilitates both spaces for the inhabitants, guests and shared cars. (ibid)

Illu 10: Lange Eng Common room

Illu 11: Lange Eng Courtyard



Illu 12: Lange Eng Plan

Case study of cohousing: Tinggarden

Tinggaarden is one of the first cohousing projects in Denmark, made of two rounds, the first between 1971 – 1978 and the second in 1983. It is situated in Herfølge, Denmark and designed by the Danish architecture firm Vandkunsten. The users of the project were much involved in the process of designing and making the buildings, which resulted in some, at the time, alternative solutions, (Vandkunsten.com, 2020) which is why this cohousing project is analysed.

Tinggardens buildings are placed as 12 smaller clusters, with 12-18 dwellings pr. cluster. The clusters each have a small common room, which can be utilized for several activities like dining together and laundry. There is also one big common room fitted for all inhabitants in Tinggaarden. (Tinggaarden.nu, 2020) The people in each cluster thereby have the opportunity to be social and can get to know their nearest neighbours along with being social with all inhabitants in Tinggaarden. But it is not obliged to be social, as each household has their own private dwelling.

The dwellings vary from one to six bedrooms and are relatively small with the average square meters being 78 pr. household. Each dwelling consists of two parts, the basic rooms, which is an entrance, bath, kitchen and living room whereas the second part is the bedrooms and other supplementary rooms. All dwellings have the basic rooms, but as mentioned earlier, the number of bedrooms vary. (ibid) The kitchen, dining area and living room are combined to one room, which is one of the first projects in Denmark to introduce that, thus making this project to an ancestor to the kitchen-dining area as we know it today. (Vandkunsten.com, 2020)

Two dwellings with basis rooms are divided by bedrooms or supplementary rooms, and another radical solution, to before seen dwellings, is that the bedrooms can belong to both dwellings. Thus, if one household's demands change and there is a demand for more rooms, it is possible to talk to the neighbour along with the housing association and agree upon taking over one or more bedrooms from the neighbour (Tinggaarden.nu, 2020). Thereby, a family can live in the same dwelling for a long time, and when demands change, adapt the dwelling to them, which provides the household with flexibility. As people can live in the area for most of a lifetime, it makes the area social diverse.

Illu 13: Tinggaarden outside

Illu 14: Tinggaarden common outdoor area in a cluster

Illu 15: Tinggaarden private dwelling, view of basic room and bedrooms.

In all cases of co-housing there is a good balance between private and public, a mix of different age groups, and different unit sizes. The space reduction comes from reducing the individual dwelling sizes and moving some of this space into a shared common space. This way co-housing shares functions that are not used daily by a single dwelling, which as later discussed, fits well into the idea of circular economy. These common spaces then appear to be the main attraction for co-housing projects, along with increased social bonds between the inhabitants.

The theory states that the common room should be centrally placed, however, in the case study of Lange Eng it is situated in a corner but is still used by all users due to the social aspects. There is common eating many times a week in the case of Lange Eng. Thereby, the kitchens in the households can be smaller as they are not used as much as in normal households. In this case, the courtyard works as the common area which all dwellings have a view to.

Conclusion

To use the qualities of co-housing, this project should focus on creating varying and flexible units, to accommodate a wide range of age groups. Space reduction can reach around 30% compared to average values, which is in this project is held up against Danish national average values. Each dwelling should still be its own functional unit, but the common spaces help accommodate the loss of space by providing a large shared kitchen for social dining, washing facilities, workshop areas, and guest bedrooms. There should also be a focus on creating public outdoor space, which is designed for pedestrians and not cars, to create a safe and relaxing environment.

In the case of Tinggaarden, the area is divided into smaller clusters of 12-18 dwellings, which each has a common room along with one bigger one for all inhabitants. However, the thought of dividing this project into clusters which each have a common room is not relevant, as the number of dwellings is much lower in this project compared to Tinggaarden. The idea in this project of sharing rooms between apartments is interesting, as it shows that the idea of flexibility of unit sizes, is not a new phenomenon.

In K1 Orchard Park, all dwellings have private outdoor space and semi-private zones, whereas Lange Eng only has the semi-private outdoor space. This might lead to more social encounters, but a reduced amount of privacy. As the theory states that both privacy and socialization in a cohousing project are important, each dwelling should be provided with a private outdoor space along with the public outdoor space.

User room program

This analysis of the users and cohousing lead to a user room program, where the rooms of respectively the common spaces and the private dwellings are described with area, amount, use and what is meant by them.

Common spaces

Room	Area m^2	Amount	Use	Notes
Common room with catering kitchen	100-150	1	Common	Central placement, visibility and transparency, act as meeting point in the area
Lounge	30	1	Common	Relaxing environment
Playroom	30	1	Common	Kids
Guest bedrooms	10	3	Private	Bedrooms which enable having guest stay overnight
Laundry	40	1	Common	Common Laundry and space for drying
Workshop area	50	1	Common	Bicycle and other workshops
Garden	?	1	Common	Greenery, barbeques, playground

Private dwellings

Room	Area m^2	Amount	Use	Notes
Livingroom with kitchen	30-40	1	Common	The private meeting point in the dwelling
Bathroom	5	1	Private	
Master bedroom	12	1	Private	All dwellings
Other rooms	8-10	0-3	Private	Dependent on the demands for each age groups
Terrace/balcony	10-20	2	Private	Private outdoor space

CIRCULAR ECONOMY

Intro

The purpose of this chapter is to introduce the term Circular Economy (from here on mentioned as “CE”), what it entitles, and how it is understood in broad terms. It is then further investigated how CE is applicable to the field of architecture. The goal is ultimately to find a meaningful way of working with the concept of CE in this project, as it is acknowledged that CE is a huge topic with many facets that are either not relevant for this project, or simply too complex to handle.

The birth of circular thinking

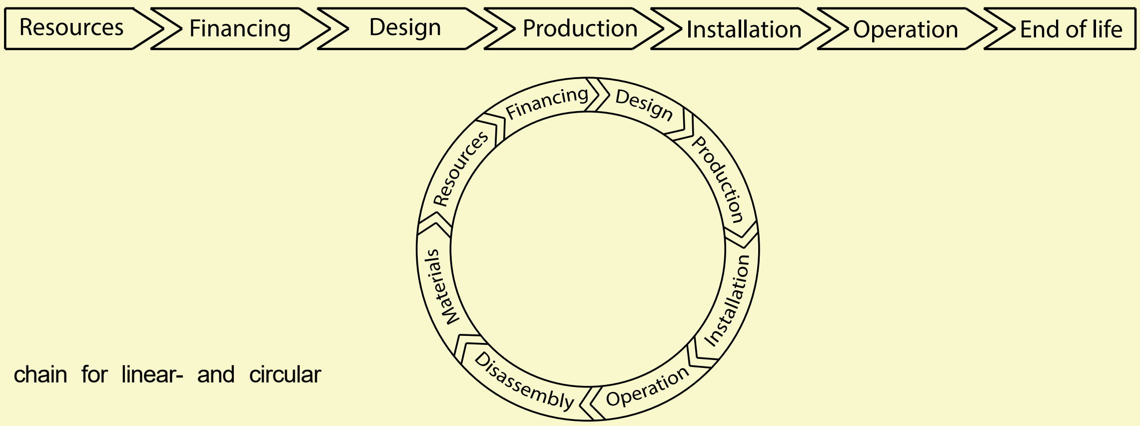
The idea of CE does not have one single author or point of origin, but it is rather something that has grown out of continuous movement within the sector of sustainability. Thus, it lends from a lot of ideas like “Cradle to Cradle” (Brungart and McDonough, 2008) and in many publishings such as David W. Pearce’s “Economic of natural resources and environment” (Pearce and Turner, 1990). No matter which one, the same idea is discussed, that resources being used in a linear economy, will lead to issues in many different facets of the world.

The word CE was born from the report ”Towards the circular economy” (Ellen McArthur Foundation, 2012). While this publication does not deal with CE in architecture, it explains how the implementation of CE in many industries and countries, can have benefits for the economy. An idea that is supported in the architecture field by the study by GXN and partners showing that CE can provide positive income for the building owner, in the demolition phase (Jensen and Sommer, 2019).

The principles of circular economy

CE can be simply explained as the move from a linear value chain of resources as seen on Illu 16, to a circular value chain. A circular value-chain seeks to keep the value of the resource, for as long as possible. This results in: lowering resource demand, lowering the environmental impact of production, improving stability within the products industry, and eliminating waste. (Ellen McArthur Foundation, 2012)

However, though it can be explained simply, the necessary changes for a product or industry are complex. It involves both the change of product design, to allow for easier reuse, and to use better and durable materials. Also, the change to business models, as industries must become much better at recovering products, instead of products being disposed by the user. This also means that the end-users must change the way they use and think of products (ibid). It is then apparent, that the implementation of CE in architecture, is a complex situation. As architecture does not involve one product, but many different products and resources, that do not always share common traits or even industries. Generally, to achieve CE within any industry a new approach to business is needed. (Jensen and Sommer, 2019)



Illu 16: Value chain for linear- and circular economy

CIRCULAR ECONOMY: BUSINESS MODELS

Intro

CE is about moving to a circular value chain, where the value of a resource is kept at its highest. In this chain, different business models can apply. The models are investigated, to see how they apply to architecture. The models are different ways to define CE, but should not be viewed as individually exclusive strategies, but rather as parts of a network that works together. In the end, it will be determined what factors are most important in order to achieve CE in the architectural design process.

1. Circular supply chain

This concept focuses on a business using resources that are either reusable in multiple cycles or biodegradable and renewable, which could be determined through a lifecycle assessment, using healthy materials, and a material passport. It can either be that a business reuses its own products, or that it reuses products/waste from other businesses. (Dam and Gildsig, 2017)

In architecture, this could mean ensuring using materials that come from sustainable backgrounds by doing a lifecycle assessment on the product. And by providing the construction elements with a material passport, it ensures that the element can easily be identified and reclaimed into production again.

2. Recovery and recycling

This focuses on using end-of-life products, that normally are viewed as waste or waste produced from production. This is different from the circular supply chain in that it does not focus on a main product reuse. But rather focuses on reclaiming and reusing a product or waste, that does no longer have the same value as it had earlier in its life. (ibid)

An example of this is how Hunton uses waste sawdust from wood production, to produce insulation. This introduces a new value to the sawdust, that otherwise would just have been thrown out or incinerated. Which it still can be after its cycle as insulation, but extra value has been added through the resource's lifecycle (Hunton.dk, 2019).

3. Product life extension

This focuses on creating a product, that has a longer use cycle. This results in a product that could go from 1 to 2 lifecycles, meaning it can last longer at its highest value before it needs to be transformed into a product of lower value. This can be achieved by making a better product, by supporting the product through its lifetime with renovation and reparation, or by recalling it after use and reselling it, instead of throwing it out. (Dam and Gildsig, 2017)

In architecture, this could mean ensuring, that construction wood is properly protected from moisture while in use, allowing it to not degrade, and being useful for another cycle as construction wood. Or by making sure to treat exterior cladding, so that its lifespan is prolonged. (Jensen and Sommer, 2019)

4. Sharing platform

A focus on sharing products that are not normally fully utilized by only a single user. The idea of sharing is quite open and can take many different forms, in all the different steps of a product life cycle. From a manufacturing machine shared between businesses to products or spaces shared by multiple people in a building, as to better optimize the use of resources, and then negate the need to produce duplicate products. (Dam and Gildsig, 2017)

This also means, that potentially better quality can be achieved. By multiple parties investing together, rather than single users, which in the end results in a product that has a longer lifespan. An example could be a shared high duty washing machine between multiple households, instead of buying multiple regular duty, which in the end is also cheaper for all users. (Jensen and Sommer, 2019)

5. Product as a service

This is a different version of the sharing platform, where instead of multiple users owning something together, one service provider owns the product and rents it to users on different basis depending on the product. This again ensures better utilization of a product, and a potentially better product, because the owner can own multiple identical products, which allows them to acquire better know-how. This also means that the owner is the one servicing of the product, and thus only one owner/producer is involved in the product from its production and until it is recycled/reclaimed/reused (Dam and Gildsig, 2017).

Conclusion

In order to achieve a CE in architecture, it is important to utilize all the different business models. Though the business side of things is not the scope of this project, the idea behind the models still applies to the design process. The concepts of “Design for disassembly”, “lifecycle assessment”, “material passport”, and “healthy materials” have been determined to be the most important factors to achieve CE in architecture seen from the design process point of view. It should be explored how the concepts fit into sustainability.

DGNB

Intro

The purpose of this chapter is to see how the previously identified principles DfD, LCA, MP, and healthy materials, fit into the idea of sustainability as explored through the DGNB scheme. Along with this, other DGNB criteria that can be incorporated into this project with relation to co-housing should also be explored.

DGNB

Danish Green Building Council (DK-GBC) has released a report on how the DGNB scheme fits into the idea of circular economy. They follow the framework for circular economy set in “building a circular future” (Jensen and Sommer, 2019). DK-GBC has chosen DGNB Criteria directly linked to CE (DK-GBC, 2017). The following criteria in DGNB are chosen in regards of the modular system and the concept of co-housing and should be used as design criteria for the project.

Environmental criterions

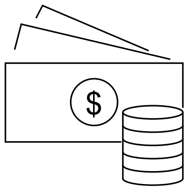
- ENV1.1 and ENV2.1 Lifecycle assessment (LCA) - Environmental impact and Primary Energy:

The DGNB certification requires LCA of the entire building, however, this is not possible in this project as the focus is on the modular system. The idea of LCA should still be used on module level, by optimizing each module and material choice in the LCA, and this can be used as an evaluation tool. The LCA topic has also been identified previously in the business model chapter, therefore, LCA should be treated in depth in its own chapter.

- ENV1.2 Environmental risks related to building materials:

Materials containing toxic substances either for humans or the environment are of a large concern. This criterion has a list of materials and substances that one must be aware of to ensure the materials are good and healthy. The importance of healthy materials has also been previously identified and should be treated in depth in its own chapter.

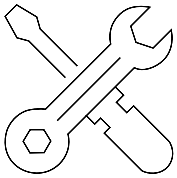
Economical criterions



- ECO2.1 Flexibility and adaptability:

This criterion directly points at measurable parameters to ensure that the building is flexible and can adapt to new types of use. Since a goal in this project is to achieve good flexibility within the modular system, this criterion should be used as the guide for achieving adaptability.

Technical criterions



- TEC1.3 Quality of the climate screen:

A big part of the modular system is the climate screen, and this criterion focuses on the qualities the climate screen must have. The design of the climate screen components should, therefore, follow these qualities.

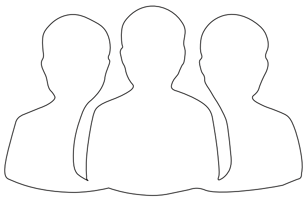
- TEC1.6 Design for disassembly and reuse:

Design for disassembly is an important factor in recycling and reusing resources to achieve sustainability. As design for disassembly has been identified as a core principle of CE, it should be investigated further in depth in its own chapter, rather than this brief overview given by DGNB.

- TEC1.8 Environmental product declaration (EPD):

By using products that have an EPD, more can be known about the product and its impact on the environment and human health. This criterion focuses on using materials and products with an EPD on the major building components.

Social criterions



- SOC 1.1 Thermal comfort

This criterion uses the same evaluation criteria as explored in the project scope earlier, and the chosen evaluation method already responds to this criterion. The thermal indoor environment is important for proper comfort in housing, especially in new developments, and it should, therefore, be a point of contention on this project

- SOC 1.4 Visual Comfort

Visual comfort is also an important part of dwellings as bright apartments are more appealing and better to live in. This criterion has evaluation criteria for evaluation of the daylight, views, and direct sunlight. Visual comfort also is closely related to thermal comfort, and, therefore, this criterion is also relevant to include.

- SOC 1.5 Users control of the indoor environment

In relation to the two earlier criteria, proper user control of the indoor environment is also important, as especially summer thermal conditions are determined by the user's own influence on the indoor climate. This criterion can be further used when evaluating strategies for natural ventilation, window sizes and placement.

- SOC 1.6 Quality of outdoor areas

This criterion relates to the qualities of the visual and functional outdoor spaces for users of the built area. Both in relation to green areas, terraces, private and public, and other social functions. Co-housing highly depends on good public social spaces for interaction between inhabitants, and thus this criterion can be useful in this regard.

Conclusion

DGNB criteria have been chosen, that influence the design of the modular system, or the social qualities of the co-housing project. It is acknowledged that more criteria could be used in the project, but these few have been chosen to better focus on important points in the project. The topics of design for disassembly, lifecycle assessment, and healthy materials should be further explored, in relation to how DGNB can influence the evaluation and design of these. While the other DGNB criteria can be directly translated into design criteria, as they contain objective ways to evaluate each parameters inclusion in the project.

DESIGN FOR DISASSEMBLY

Intro

Design for disassembly (From here on mentioned as “DfD”), has been determined as one of the core principles for designing architecture as CE. The intention of this chapter is to explore what DfD is, expanding on the understanding gained from DGNB TEC1.6, and to see how it applies to architecture, and how it can be approached in this project in relation to a modular system.

Concept

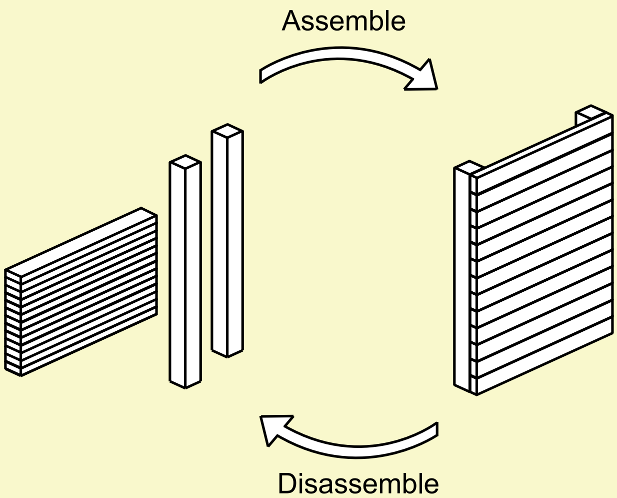
DfD is the designing of a product, that allows it to be disassembled into its basic parts again, that either is being a resource or smaller elements. What is important about this disassembly is, that the act of disassembling the product, cannot result in the parts being in any way damaged, as this is seen as a reduction of value in any business model regarding CE.

By doing DfD, embodied energy in the product is retained, as a replacement does not have to be produced. This results in a lower CO_2 footprint for the overall built environment if it is implemented (Crowther, 1999a).

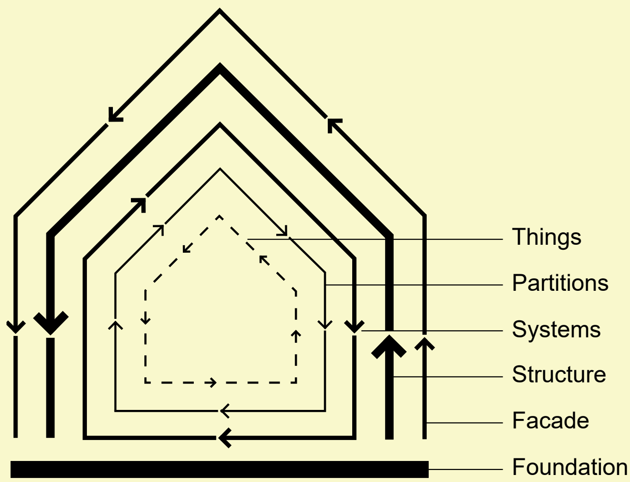
In architecture, the “product” is the entire building. To better understand a building as a product with DfD, an idea was presented by Stewart Brand that demonstrates the idea of categorising a building into elements based on the element’s lifespan (see Illu 18). (Brand, 1994) This directly plays into the idea of designing a modular building system.

By having this categorisation, it is now possible to understand and work with each different element separately. While most structural systems can last for 100+ years, the ventilation system can only last for some 10 years. Another example is that the facade is dependent on material in relation to lifespan, as bricks can last hundreds of years, while a wooden facade becomes worn down in around 30 years. It is, therefore, important to recognize the elements need to be disassembled at different times during a building’s lifespan. (Jensen and Sommer, 2019)

On the next page, it is explained what the focus of each element will be in this project, which allows for more focused experimentation in the sketching phase of this project.



Illu 17: Design for Disassembly



Illu 18: The elements of disassembly

Things
Things will in this project not be handled, as it is a separate entity that does not affect the rest of the building design.

Partitions
Partitions will be worked on with regards to how the element can provide the functional flexibility that is a core user demand. This is directly tied to DGNB criterion ECO2.1.

System
While the systems are not a focus of this project, they will be worked with on a principle level, to ensure that they fit within the full concept of DfD.

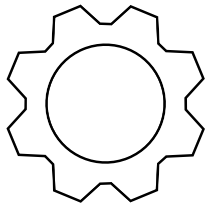
Structure
The approach to DfD for the structure will be based on a modular system as this has the most potential according to research. (Dam and Gildsig, 2017), (Jensen and Sommer, 2019), and (Madsen, 2017; 2018)

Facade
The approach should be on designing a facade that fits into a modular system, and where there is a focus on the materiality of the used materials, to provide a high level of aesthetical and technical quality in the system.

Foundation
The approach to foundation will be on finding a new strategy for founding the building, that does not involve the current standardised concrete foundation. As this type of foundation has a high environmental impact, and it doesn't fit with a DfD way of thinking.

Principles for DfD

By having established what the focus in the design process should be for each element, it is now necessary to establish the principles with which to design DfD. The principles are the actual design decisions and qualities, that must be implemented into the design of each element. The principles are a collection of principles explored in (Crowther, 1999a; 1999b), (Guy and Ciarimboli, 2008), (Madsen, 2017; 2018), and (Jensen and Sommer, 2019). They have been divided into three categories, and it will be discussed how this project will work with each of the categories.



Mechanics

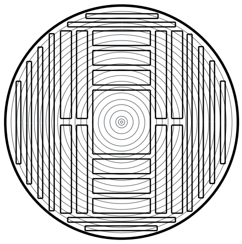
Reduce the amount of construction element types and sizes, use a standardised grid in the construction. The standardisation gives more equally sized elements, that are easier to reuse in other buildings.

Use mechanical and reversible connections that are easily accessible, to make it easy and fast to disassemble elements without damaging them. Do not use glue or other binders unless necessary and use screws/bolts instead of nails.

Chemical bonds or sealants where they are necessary should be non-toxic and easily dissolvable. So that they do not possess health issues both in use of the building and during the disassembly.

Think about how the elements are handled, if they will be installed by hand, make them small and light enough to handle by hand.

In relation to mechanics, this focus will be on creating a modular system for the different building elements, that allow for easy disassembly. The focus will be on creating a modular system that is easy to design with, as in it being flexible and easy to understand. As the focus of this project is not on dimensioning construction elements and connections, these will be evaluated based on a standard construction dimensions used in buildings currently. Connections will also be focused upon from an aesthetical standpoint, as they must be accessible, they should add to the overall architecture in a positive way.



Materials

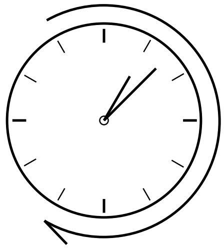
Use materials in their pure form so they can be directly reused, as composites and engineered materials are not easy to disassemble and reuse.

Reduce the types of materials to make sorting easier when disassembling, a material passport can make sorting and reuse easier.

Use materials that are non-toxic, non-hazardous, and with a low environmental impact. If possible, use recycled materials if they can hold standards for the necessary lifespan.

Do not treat materials with surface finishes or coatings that inhibit reusing the material, or that makes it hard to see the connections and need to be removed at disassembly.

To work with materials in this project in relation to DfD, it has earlier been explained that healthy materials and Lifecycle Assessment will be the tools. In accordance with the DfD principles for materials, this fits perfectly together, as especially lifecycle assessment can determine what materials possess all the characteristics mentioned in the principles.



Lifespan

Consider the material lifespan and where it is being placed in the building's layers. Do not put materials with a lower lifespan, behind a material with a longer lifespan. As this results in a need to disassemble more elements than necessary when replacing.

Provide access to HVAC systems so they can be replaced independently from the rest of the construction, as these elements last shorter than other parts of the building.

Ensure flexibility for spatial elements to allow for easy adaptation in future use, elements such as partitions that are not at the end of their lifespan, should be reusable in the new adaptation of the building.

Modularity to ensure that elements that must be replaced, are in a system that allows for easy replacement and that only a small part needs replacing, instead of entire elements.

Lifespan is partly worked with in relation to lifecycle assessment of materials, but also in the sense of creating construction modules where the construction is protected as best as possible; for wood, this could be ensuring that moisture will not build up. It has already been mentioned that the project will work with the different elements of the building separately, so this already plays into the idea of lifespan of different constructions. HVAC systems have been determined to be worked with on a principle level, this will not be dimensioning the systems, but still making sure there is space for them, and that they all fit within the modular system, and can be replaced without issues.

Conclusion

Through the exploration of the concept of DfD, an understanding of the concept has been reached, and it has been determined how it should be implemented in the project. By splitting the building into the six beforementioned elements based on lifespan (things, partitions, systems, structure, facade and foundation), the focus of each element has been defined, and how they are handled in the following project.

Having a focus on the materials used in the project through lifecycle assessment, and on modularity of the different building elements. The facade, structure, and partitions should fit into this modular system, and the HVAC systems should principally be able to adapt within this modular system. The foundation has been decided as a point of content, by wishing to create a new standard that is more DfD friendly.

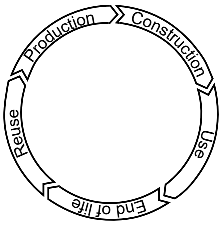
Functionally there is a focus on creating flexible solutions with the construction and partitions of the building. Aesthetically, the focus is on the materiality on visible surfaces and the connections between elements.

LIFECYCLE ASSESSMENT

Intro

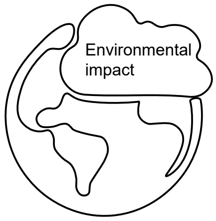
As earlier described in multiple chapters, LCA is an important factor in sustainability and CE. The following chapter will explore LCA further based on DGNB ENV1.1 and ENV2.1, finding a way to apply LCA in this project. The application should focus on finding a way to use LCA on a material and modular level, as this is the focus of the project.

LCA

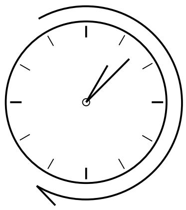


LCA can be used for assessing the environmental impact of materials and entire building through quantitative measures. LCA looks at the entire lifecycle of a product from cradle to grave, which ensures that all materials in a product and their environmental impact are measured (Kanafani et al., 2019).

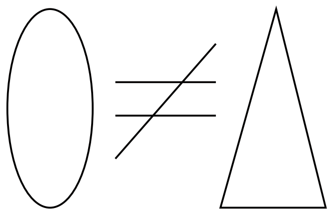
LCA analyses the whole lifecycle of a component, and the analysis consist of five phases with 17 subcategories (Danish Standard, 2012). The five phases are respectively production, construction, use, and end of life along with the opportunity of reuse. By incorporating LCA into CE, the end of life phases becomes reuse, and the product lifecycle moves to cradle to cradle. By analysing different products, it is possible to determine which one has the lowest environmental impact, and this can help inform decisions for materials when designing the modular system.



- Environmental impact: The environmental impact of each material or building component is assessed on nine different criterions such as greenhouse gasses, ozone depletion, acidification, smog formation and embodied energy. These nine criteria lead to an understanding of how big the impact of each product is. (ibid) A product might have a low impact on one criterion but a higher one in another, thereby it is important to determine which criterions are the most important when comparing solutions. The choice is much dependent on the purpose of the LCA analysis and there is not one set way on how to do it. (Stranddorf et al., 2005)



- Lifespan: The theme lifespan is also seen in DfD, and the themes are related yet different. As LCA analyses an entire building over one or more lifecycles, it is important to know the expected lifespan for the elements it is made of; so the correct environmental impact of a product can be measured. If a material has a low environmental impact but a short lifespan, then it must be changed many times over a full building lifecycle and thereby, the impact becomes larger. Then it might be a better solution to choose the solution with a bit more environmental impact from the start, but a longer lifespan and in the end a shorter environmental impact over the building's lifecycle. (Kanafani et al., 2019)



- Comparability: When comparing the LCA of varying solutions for modules or components, they should be ‘functionally equivalent’, meaning the comparison happens upon the same overall function. An example of this could be to analyse different wall solutions in LCA, but for them to be comparable, they should have the same U-value and load-bearing capabilities, as otherwise, the comparison would be based on unequal terms of functionality. (ibid)

LCA in this project

DNGB criteria ENV1.1 and ENV2.2 look at the LCA of an entire building and its lifecycle. In this project, however, the focus is on designing a modular system for a building. But the DGNB evaluation cannot be directly put into the evaluation of building components, as the reference values given are for an entire building (DK-GBC, 2017). Materials or components should, therefore, directly be evaluated compared to each other, with the goal being to achieve the lowest environmental impact for each type of component.

A different method of evaluation must, therefore, be decided on, as the intention of using LCA in this project is to choose the solutions for each component that have the lowest environmental impact. As mentioned, the evaluation is based on five phases, where in this project, end-of-life does not exist for materials as they are reused through principles of CE.

In many cases of evaluating different materials, it can be difficult to assess all nine environmental impact indicators, as information on all indicators is not always available for all the compared materials. If possible, materials used should have an EPD (DGNB TEC1.8) but EPD’s are not always available for a material. Therefore, it has been decided that the evaluation indicators will only be greenhouse gasses and embodied energy of the material; as they are the most commonly accessible indicators for a product (Kanafani et al., 2019). The two indicators also make up 45% and 15% respectively of the joined LCA evaluation made in DGNB (DK-GBC, 2017).

The reason this decision of assessment criteria has been made is also to make the process, of evaluating and deciding on materials and designs for the modular system, much more manageable, while still giving an accurate representation of the environmental impact (60% of total (ibid)). Materials or designs should be assessed based on having the same functional quality. For the climate screen, this would mean that they meet the same DGNB criteria’s set in TEC1.3 (ibid).

In this project, the expected lifespan of the buildings is 50 years, as this is the minimum number of years the DGNB-system calculates (DK-GBC, 2017). This has been chosen because it is expected, that in 50 years, major changes will be made to the building, that requires more adaptability than insured in DGNB ECO2.1. This is where DfD plays an important role, as the individual components of the building system should have a longer lifespan, that allows it to fit into a new building or configuration. The structural system should have a lifespan allowing for 2-3 lifecycles, depending on material and environmental impact; while other parts of the modular system may have shorter lifespans due to other reasons, as is explained in the DfD chapter.

The LCA calculations in this project are made in the program ‘LCAByg’. In this program, a lot of EPDs for products are already included, and if a description for a material is found in this program, then this EPD is used. When calculating the end-of-life phase will be removed, as it is expected that products can be reused. In some cases, however, products may have the end-of-life phase included, if no possible reuse can be imagined, this will preferably be for products that are biodegradable and does not contribute negatively to waste production in landfills or incineration.

When calculating for a component with a lifespan longer than the building, and where the component can be a part of multiple lifecycles, the overall impact of the material, will be split between the amount of building lifecycles it is a part of. As an example, a 150-year lifespan structural system will be part of three building lifecycles, and its environmental impact will hereby only be 1/3 of the calculated for a single building. Compared to a system with a 100-year lifespan, where its impact is ½ of calculated for a single building. Lifespan itself is based on DfD principles and manufacturer information on materials.

Conclusion

The overall focus of LCA is to reduce the environmental impact of materials and components by making quantitative measures on a full lifecycle from cradle to cradle, which is made possible through DfD. Materials or components should be compared directly based on functional equivalence for each type, and it is decided that the evaluation period is a 50-year lifespan. Evaluations are limited to the two environmental impact indicators greenhouse gasses and embodied energy, and the information of these indicators should come from EPDs if possible.

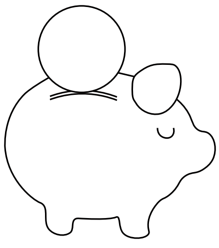
LCA is to be used as a tool to help evaluate materials in relation to which are more ideal to use. Or to compare different module solutions, to inform a decision on what should be brought further into the project. It is important to consider that LCA is not the only evaluation tool, as there is also DFD to consider, along with the materials health properties to consider.

HEALTHY MATERIALS

Intro

Healthy materials and material passports are something that has been identified as core concepts to achieve CE. This chapter will dive into material passports and their use, as well as how to define materials and their impact on health. The goal is to find a way to evaluate healthy materials, and how materials passports can be used in the project.

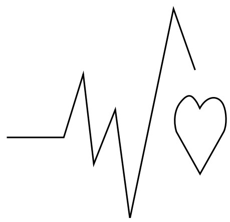
In this project, it is not feasible to create a material passport for the modular system, as it requires information and knowledge beyond the scope of this project. However, since the focus is also on healthy materials, and the material passport supports the use of DGNB ENV1.2 as a measurement of this, it is decided to use this criterion as the evaluation tool.



Material passports as a resource bank

The purpose of the material passport is to ease the disassembly and subsequent redesign with the disassembled elements. Often, this redesign will happen before a building has been disassembled, and it can be hard to know exactly what materials are present in a building. However, this knowledge is crucial if one is to redesign with the exact same materials. The material passport acts as a document, that for each module within the buildings, hold all the vital information necessary to redesign. (Heinreich and Lang, 2019)

A full material passport for a component contains 60+ pieces of information, ranging from the physical dimensions and load-bearing capabilities, to chemical composition and treatment. With this information, the future user of the module can know exactly what the module is, and if it is suitable for the intended future use. For the chemical compounds in a material, it is also suggested to use the DGNB ENV1.2 criterion as a measuring tool, to define if a material is healthy. (ibid)

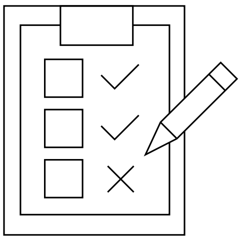


Materials and the human health

When designing a building, it is paramount that the health and well-being of the users is one of the top concerns. As explored through the evaluation methods for atmospheric comfort, the ventilation rates in the standard DS/EN 15978 (2019), are designed based on how polluting the building materials are. The more toxic they are to the indoor environment; the more ventilation is necessary for humans not to become sick. Choosing healthy materials thereby has a direct impact on ventilation which translates directly into energy usage in the buildings use-phase.

Healthy materials also benefit the DfD process. If toxic compounds are used in the building, the process can be unnecessarily complicated, because protection and care must be taken by workers. In some instances, it is possible that one material has a toxic compound that has leaked into other materials, resulting in not only the source material being useless, but the infected materials as well. (Jensen and Sommer, 2019)

Hazardous materials are not only impacting human health though, as hazardous waste is often deposited in landfill instead of being incinerated because the smoke can be toxic. These landfills then become contaminated with toxins that can affect the flora and fauna of the area, and in extreme cases, this can affect areas so much that they are not fit for inhabitation for many years, and ruin entire ecosystems. (DK-GBC, 2017)



Evaluating healthy materials

The best way to avoid all of this is to design with materials that are healthy, and do not possess any health risks for humans or ecosystems. To do this, a careful evaluation of all materials used in the project must be made. In this case, the focus will be on the materials used in the modular system.

As mentioned, the evaluation will be based on DGNB ENV1.2, which holds a list of 40 different indicators (building parts) and the substances in these parts, that one should be aware of; along with maximum concentration allowed for these substances. The substances in the parts and materials are found, either through EPDs or technical data sheets for the material. If neither of these documents are available, and the manufacturer does not provide other product declarations, then it is decided that the product cannot be used in this project, due to the unknown health risks.

Conclusion

It has been decided that though material passports are a critical part of CE, it is not possible to fulfil the requirements for one in this project. However, the focus will still be on the chemical compounds, as it has been explored that using healthy materials both has benefits for human and ecosystem health, as well as a positive impact on energy usage for the building. The evaluation of healthy materials is based on DGNB ENV1.2 and evaluated materials must have a product declaration on its chemical contents for it be valid. In this way, the evaluation of a material's health is one of the criteria for choosing modular systems.

FLEXIBILITY

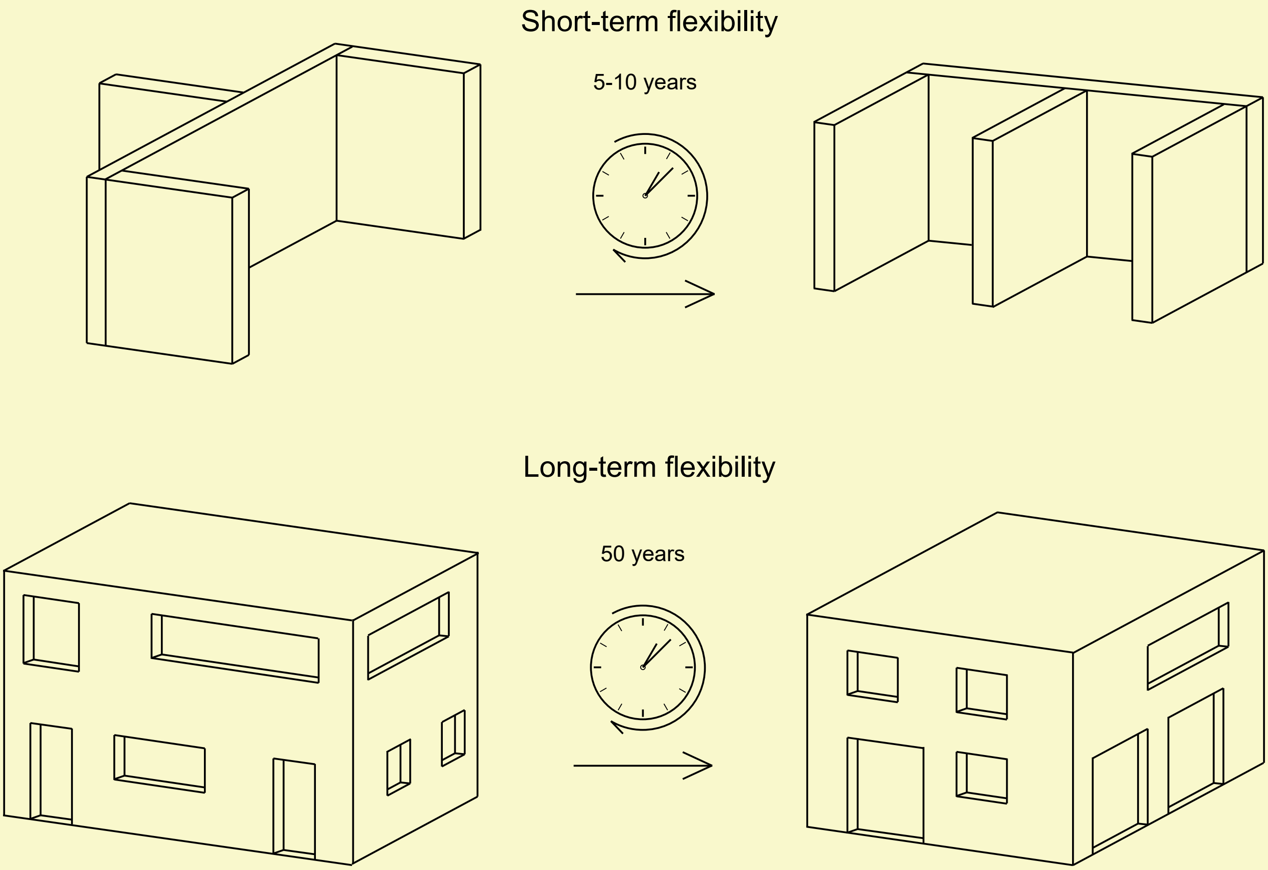
Intro

The word flexibility is mentioned throughout this initial analysis phase, and it has been used to describe a variety of contexts. This chapter intends to explain this project's understanding of the term flexibility, and how it is applied in this project.

Understanding flexibility

The word "flexible" generally refers to a circumstance or object, that can adapt and change according to circumstances. Another meaning is on a material level, where flexibility is a physical property that allows a material to bend or flex without being permanently damaged (Dictionary.cambridge.org, 2020). In this project, the word "flexibility" relates to the first explanation. Flexibility in architecture is a multi-faceted concept, as it can apply to different aspects, in relation to both scale and time. Scale refers to the difference between adaptability of the entire building as in changing the total amount of m² to better fit future use. Time refers to the adaptability needed over different timeframes, from everyday need for flexibility in the use of a specific room, to the long term need for changing a space more drastically to accommodate a completely different function within the building.

It is within this understanding of scale and time, that the distinction for this project is to be made. As the word "flexibility" covers all these mentioned ideas, but architecture can provide flexibility in one aspect, without providing flexibility in other aspects. This project uses two definitions of flexibility: Short-term flexibility and Long-term flexibility.



Illu 19: Short-term and long-term flexibility

Short-term flexibility

Short-term flexibility in this project refers to the flexibility required by the users, in order to adapt plan layouts according to demand. This refers to being able to adapt the floor-area of a given apartment, and the number of rooms within an apartment. This short-term flexibility refers to the DfD principle of partitions, where the idea is that the interior walls can be adapted based on demand, without requiring change to the overall building structure.

Today such changes usually refer to tearing down partition walls and then building completely new ones. This results in time being required for demolition and new construction and can prevent humans from living in the dwelling while the changes are made.

By designing partitions with short-term flexibility, it allows the partitions to be rearranged in a new configuration, that potentially can be carried out by the inhabitants of the apartment, with little to no professional help needed. This allows the adaptation to be easier and less demanding for the user, resulting in it being more likely that adaptation will be made over short-term.

Long-term flexibility

Long-term flexibility in this project, refers to the flexibility in being able to change the buildings entire structure, when future demands require such a vast change to the building layout, that the short-term flexibility no longer can provide the necessary adaptation.

Today this kind of long term adaptability is mostly seen as completely renovating buildings or adding extensions to the building to increase floor area. While this renovation can provide excellent buildings, it still requires the renovation to fit itself into the structure of the original building, which can prevent proper adaptation.

By instead designing the building for disassembly, it allows the building that in 50 years is assumed no longer fulfils the requirements in the future, to be disassembled into its original parts. The parts can then be used to create a completely new building, this allows for completely free adaptation in the future. It is, therefore, important, that the overall modularity of the building structure, allows for flexibility in the combination of modules, to provide the possibility of different adaptations both in layout and future architectural trends.

Conclusion

Flexibility in this project is split into two categories, short-term and long-term flexibility. Short-term refers to the adaptability of interior partitions in the building, that allows them to be rearranged to meet the change in demands within one or more apartment units. Long-term refers to the buildings overall structure, to be able to fit into multiple configurations now and in the future, that allows for variation and creativity in the architectural expression and potential building layouts.

MODULARITY

Intro

The purpose of this chapter is to explore modularity, along with defining how modularity is understood in this project, and to learn from previous examples of modules seen in Denmark.

Defining modularity

When discussing modularity in this project, a distinction is made between two types of modules: System and tailored.

Systematic modularity refers to building systems, where all pieces of the building are predesigned to fit together in different combinations. These systems can range from whole sections of a building as seen in Arne Jacobsen's Cubeflex (Trapholt.dk, 2020) or Jørn Utzon's Espansiva (utzon-archives.aau.dk, 2020), to smaller pieces of the construction that can be combined in different ways such as Rockwools wall system Rockzero (Rockwool.dk, 2020a).

Tailored modularity refers to building systems, where modular elements are prefabricated to a specific project. Here, thought is not given towards future combinations or systems, but rather that a building can quickly be built with the specific prefabricated modules. This is commonly seen within the industry of prefabricated concrete, but also with elements such as EcoCocon's straw wall panels (ecocon.dk, 2020).

Modularity in this project

The definition in this project is system modularity. There are many tailored modular systems out there ready to build with, but none of them meet the principles in CE. For a module to be part of circular economy it needs to be part of a system, that allows it to be replaced or relocated into another building utilizing the same system.

It is then telling that the general use and idea of modularity seen throughout the construction industry, is more guided towards prefabrication and tailored options. When searching to find modular systems, it is much more difficult to find examples of system modularity than it is on tailored. Since this observation is quite easy to make, it offers the question of why system modularity is not more common?

System modularity in Denmark

A history of system modularity in Denmark can be given with the two previously mentioned examples Cubeflex and Espansiva. Both the systems are designed by some of the most esteemed architects Denmark has had, and yet, both examples are only ever realised in a single project each.

The systems were designed in 1970 and 1969 respectively, and both encapsulate the idea of system modularity in different ways. While Cubeflex is a strict cube form-language that can be freely combined, the interior spaces are limited to this form.

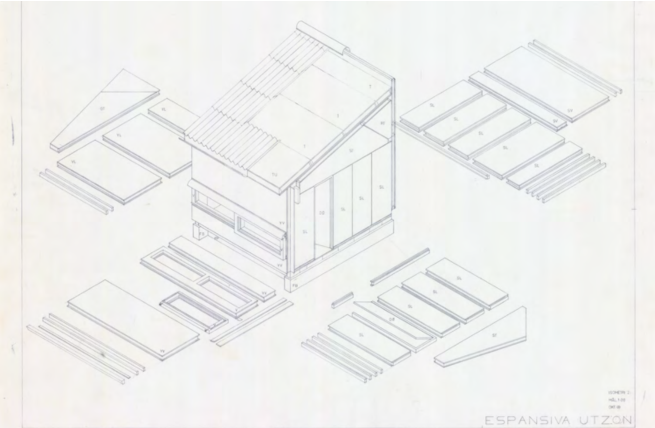
Espansiva provides a much more varied form-language that, however, in the end is just as formulaic as Cubeflex. So even though Utzon proposed many combinations, in the end, combinations would be exceedingly similar both in exterior and interior.

What both of these systems then fail to provide, is freedom and flexibility in the design. None can doubt the architectural quality of both projects, but the lack of true feeling of freedom to design, was most likely the hindrance for these systems.

If this perspective is viewed in today's lens, it can be observed that Denmarks largest supplier of single-family-homes Huscompagniet, which mainly deals in predesigned type-houses, still allows the

Illu 20: Cubeflex by Arne Jacobsen at Trapholt.

Illu 22: Cubeflex by Arne Jacobsen at Trapholt.



Illu 21: Espansiva by Jørn Utzon, principle drawing of components by Utzon.

Illu 23: Espansiva by Jørn Utzon, exterior photo of original building.

buyer to make personalised changes to existing building models. This allows the buyer the freedom needed to feel, that their house is unique (Huscompagniet.dk, 2020). This aspect of being unique, then also explains why tailored modularity is seen much more widely spread than system modularity.

However, newer modular systems are starting to appear, such as the previously mentioned Rockzero system by Rockwool. Though this system is only a wall system, it demonstrates a more anonymous system, that still allows for flexibility when designing building dimensions, and placing window openings (Rockwool.dk, 2020a).

Conclusion

Through the investigation of modularity, it has been defined that the project seeks to create systematic modularity. Early examples of systematic modularity proved too constricting on design freedom. Newer systems show promise, by providing a more anonymous system, that is based on smaller elements, which gives freedom in designing the dimensions and openings of the building.

It is then clear, that the project should seek to create a system that allows for design freedom, while still being contained with a system. This is all to make it more probable that the designed system would be utilized in the design of buildings.

SITE: INTRODUCTION

As the three illustrations Illu 24-Illu 26 show, the site Sorthøj is placed in Northern Jutland, in Aalborg in the part of the city called Hasseris around 5 km from the centre of Aalborg. The following contains an introduction of the site with the purpose of providing an understanding of it, along with being able to use the site and its qualities in the further design.

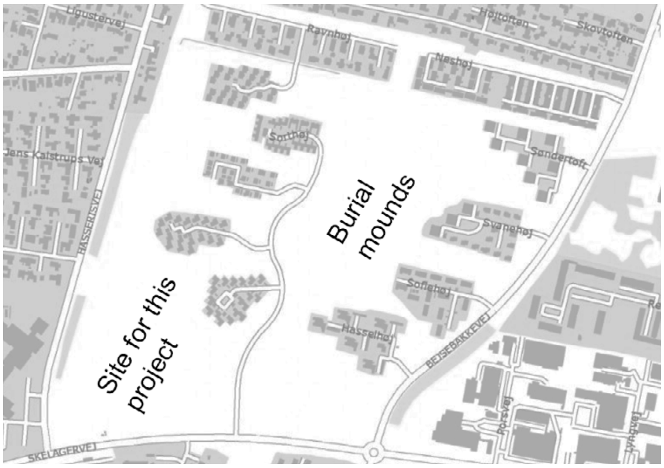
The site is around 66 acres big, and the buildings already placed on the site are used for housing, (Aalborgkommune.viewer.dkplan.niras.dk, (1999)) meaning the function of this project will fit well into the area.

The area towards North of Sorthøj consists of single-family homes, whereas a graveyard is found East of the site, and towards South and West the site is delineated by two roads. In the middle of the site, two burial mounds are found, where one is called Sorthøj providing the whole area with its name. It is not permitted to build within 100 meters of them, as they should be preserved, and therefore, the Southwestern corner of the site is going to be used for this project.

The terrain at Sorthøj is 58 meters over sea-level at the North-Eastern corner and drops to 21 meters in the South-Western corner *(ibid)* resulting in a landscape one must deal with and integrate the buildings with.

Illu 24: Northern Jutland

Illu 25: Aalborg



Illu 26: The site Sorthøj

SITE: LOCAL PLAN

Intro

The local plan of the site Sorthøj is analysed in the following. This is done to discover the plans and thoughts of the area from the municipality, and thereby to extract some parameters that should be followed in the project.

Local plan

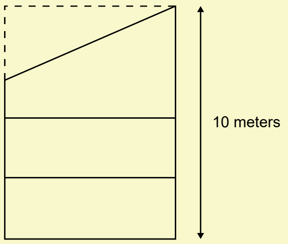
The local plan 05-035, Sorthøj, Hasseris is made in 1999 and describes what the area Sorthøj should include and how the area should be used. The following aspects are the ones found most relevant to this project.

The purpose of the area is to make new housing buildings in smaller groups with some common area included as well. The area should be divided with 60% for recreational and green purposes and 40% for buildings. The area contains a landscape and varying terrain which the buildings should be integrated as much as possible into. The buildings cannot exceed 3 stories, ten meters in height, and should have either flat- or shed roof of maximum 18 degrees. The materials on the walls are determined as either yellow bricks, bricks with plaster in white, light yellow or light grey or wooden facade in white, grey or in natural wooden colour. The roofing materials include tiles, roofing felt, slate or metal plates. (Aalborgkommune.viewer.dkplan.niras.dk.(1999)).

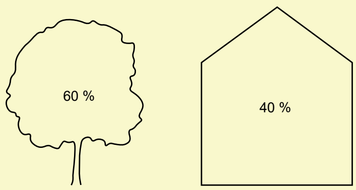
However, as this project focuses much on the materials, their use and reusability, the restrictions from the local plan might not be followed at this aspect, but the buildings will be designed so their appearance fit into the area. It can also be argued that the local plan is quite old and, therefore, it is possible to challenge it with new and up-to-date ideas.

Conclusion

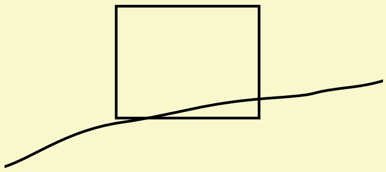
The local plan states some aspects that should be followed in the design proposal, however, it is possible to challenge the local plan due to its age and the focal point of this project.



Illu 27: Maximum 10 meters of height and should have either flat- or shed roof of maximum 18 degrees



Illu 28: 60% for recreational purposes and 40 % buildings



Illu 29: Buildings should fit into the existing terrain

SITE: NOISE

Intro

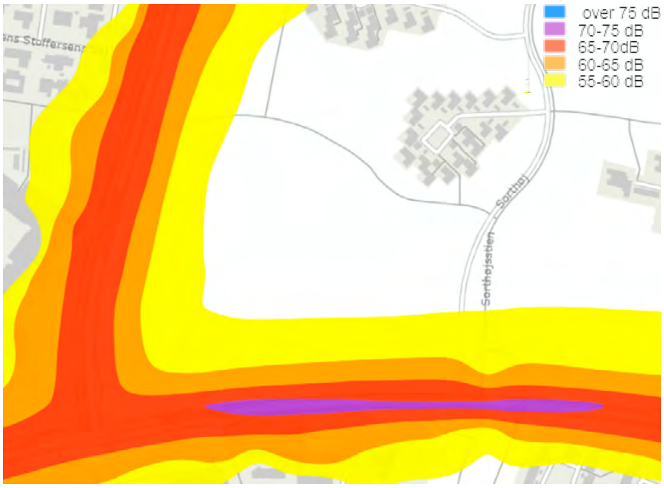
A noise study of the site is conducted to determine potential noise problems, and also to enable placing the specific building site, as far away from the noise as possible.

Noise on site

Two big and busy roads are found towards South and West of the site, respectively Skelagervej and Hasserisvej. As described in the local plan, it is not possible to build within 100 meters of the two remaining burial mounds in the centre of Sorthøj, meaning the available site must be placed towards Southwest, where the two roads meet. As Illu 30 shows, the two roads produce noise which affects the site of Sorthøj, and especially towards Southwest. However, a big amount of the site is still not affected by noise, meaning that the actual building site will be placed as shown on Illu 31 where noise does not cause issues. However, some noise/visual barrier could still be considered useful.

Conclusion

The two roads Skelagervej and Hasserisvej only produce noise that affects some parts of the site. The building site is, therefore, placed outside this zone. Some kind of barrier could, however, be convenient to have, but is not a necessity.



Illu 30: Noise map of the site

Illu 31: Approximate placement of the building site

SITE: TERRAIN AND WEATHER

Intro

The landscape is analysed to get a better understanding of terrain, views, rain, and wind, to see if there are any potentials or challenges, that need special attention in the design

Terrain and weather

The landscape of Sorthøj is dominated by high grass and open fields and the building clusters are placed into the landscape, where at some points, nature and buildings blend into one as seen on Illu 32 and Illu 33. It is important to know the typography of the site if this project and its design should be as integrated into the landscape as the existing buildings.

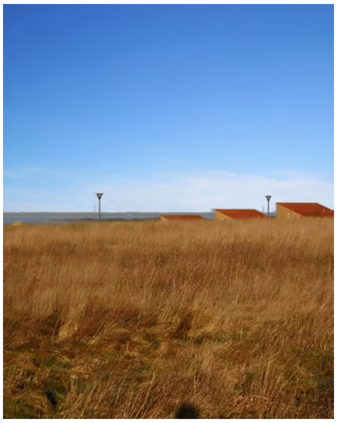
This project site is placed in the Southwestern corner of Sorthøj, meaning it is situated nearly at the lowest point of the site (see Appendix 1 for levels). However, it is still placed high compared to the surroundings and the city providing it with views over the city of Aalborg as well as the fjord (see Illu 34 and Illu 35). These views are important to incorporate and take advantage of in the design.

As mentioned earlier, the site is placed high, meaning that future flooding will not be problematic, as the water is estimated to rise maximum 1,10 meters (Ringgaard, A, 2019), and the site is placed around 30 meters above sea level. The area consists of grass and natural surfaces, meaning that the rain will be absorbed by this and is thereby not a concern to this project.

The wind in Denmark mostly comes from the West (dmi.dk, 2020) and is dominating the Danish environment as the wind can be uncomfortable when being outdoors. The bottom of the site is oriented towards Southwest, and when the wind hits a hill, the wind speed is increased, (Bjerg, 2012) meaning that the wind might cause troubles on this site. Therefore, it is necessary when designing to integrate shelter providing aspects, and thereby creating better and more useful outdoor spaces.

Conclusion

The landscape of Sorthøj is hilly and the buildings are integrated well into the landscape, which this project also should focus upon. The high placement of the site results in good views over the city and the fjord, which the design should embrace and take advantage of. Due to the high placement of the site, the nature, and grass found on-site, rain and flooding are not considered as problems for this project. The site is windy, meaning sheltering aspects is important to integrate into the design.


Illu 32: Nature and buildings blend together


Illu 33: Nature and buildings blend together 2


Illu 34: View over the city


Illu 35: View over fields and the fjord

SITE: ARCHITECTURE

Intro

The architecture found on Sorthøj is analysed to give an insight into the current context. To determine if there are certain materials, colours, or typologies that stand out. The purpose is to determine, if there are any architectural trends, or if the design can be freer, and still relate to the context.

Architecture

Sorthøj contains mainly housing buildings, which vary from each other. Some houses are made as one-family homes, where others are apartment blocks or townhouses, making the buildings differ in height and footprint. The roof-type differs between flat and shed roof, and these different typologies create a diverse area. However, the buildings are placed in small clusters with distance to the others, and one cluster only has one typology of buildings.

The buildings are often oriented towards the greenery found in between the clusters and thereby opening up with transparency towards the greenery and being more enclosed towards the road, which simultaneously ensures a great view and privacy.

The cars are parked towards the road, however, the parking differs between the clusters, where some use shared parking lots, and others have their own in front of their house. And for some, the parking is included in the building and takes up the ground floor.

The materials and colours connect and create a coherence in the area. The materials used are, as described in the local plan, bricks and wood in the colours white, grey and yellow. However, some building clusters are black and brown, meaning they differ from the original local plan and it must, therefore, be possible to challenge it to some degree.

Conclusion

The roof-types, heights, parking options, and materials varies on the buildings found on-site, creating a diverse area. This diversity provides many opportunities for creating a different architecture and does not limit the design options in this project. However, it should still fit into the area using some characteristics as seen in the illustrations.

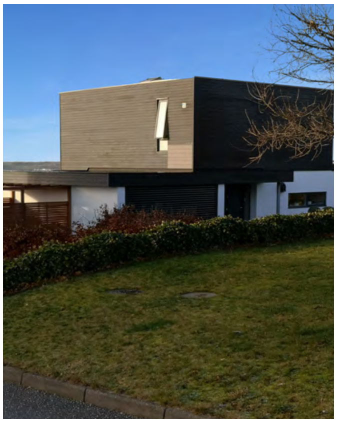
Illu 36: White apartment blocks with flat roof made in bricks and plaster

Illu 37: White apartment blocks with flat roof made in bricks and plaster (different angle)

Illu 38: White apartment blocks with flat roof with wooden details

Illu 39: White apartment blocks with flat roof with wooden details (further away)


Illu 40: White apartment blocks from backside, where parking is integrated in the building

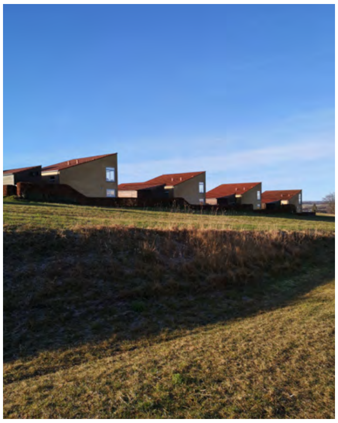

Illu 41: Black single-family house with flat roof made in wood (closed side)


Illu 42: Black single-family house with flat roof made in wood (transparent side)


Illu 43: White rowhouses with brick details and flat roof.


Illu 44: White rowhouses with brick details and flat roof (different angle)


Illu 45: Brick and wood single-family houses with shed roof.


Illu 46: Yellow brick single-family houses with shed roof


Illu 47: Yellow brick single-family houses with shed roof (different angle)


Illu 48: Yellow brick with wooden details single-family house with shed roof


Illu 49: Rowhouses in yellow brick and wooden details with shed roof


Illu 50: Yellow brick single-family houses with shed roof


Illu 51: Yellow brick single-family houses with shed roof (different angle)

DESIGN CRITERIAS: BUILDING

The building design criteria are fixed criteria that focus criteria set for the design of the co-housing project. It includes the project brief, project scope, user demands, and site-specific demands. The criteria are fixed, because the project cannot differ from these, meaning that the module design must be able to fit within these criteria.

Building

- The building(s) should fit 15-20 units of varying sizes

- The gross built area should be around 1500-2000m² in total

- The building(s) must be able to disassemble and reuse

- The indoor environment must be evaluated and designed according to the methodology described in project scope, and the DGNB SOC. 1.1, 1.4, and 1.5.

- Aesthetically the project should be sustainable in its overall expression

- Aesthetically the concepts of modularity and circular economy should be explored and expressed through material choice and detailing.

User

- The building(s) must be a social co-housing building

- The building(s) must provide quality outdoor spaces both private, semi-private, and public as set in DGNB SOC. 1.6

- The building(s) should provide flexibility to change unit sizes depending on user demand

- The building(s) should accommodate users of different age groups

- The building(s) units must be its own functional dwelling

- The building units must be reduced in area compared to average Danish values

- The building(s) must provide common facilities for all users

Site

- The site has been chosen on Sorthøj in Hasseris, Aalborg

- The building(s) can maximum be 10 meters in height

- The building(s) should have either a flat or shed roof with a slope of max 18 degrees

- The building's exterior materials should fit with the existing architecture of the site

- The building(s) should fit into and utilize the existing terrain

- The building(s) should shelter from southern and western wind and noise in outdoor areas

- The building(s) must utilize the views towards South and West

DESIGN CRITERIAS: MODULES

The modular design criteria are flexible criteria, used to evaluate different designs for building modules. The design criteria are split into the main categories explored through the principles of CE. The criteria are flexible because it is expected that not all module designs can meet every single criterion to the same satisfaction. For lifespan and environmental impact, some module comparisons may have similar per building lifecycle impact, but different lifespans. In such a case, the module with the lower lifespan is preferred as it means it has a lower upfront environmental impact.

DfD

- The modules must follow the principles set for design for disassembly

- The modules must only be within one of the six lifespan categories

- The modules must be able to fit within a larger modular system

- The technical systems must fit principally with the module

LCA

- The modules must have a low environmental impact through its lifespan

- The modules must be assessed based on greenhouse gasses and embodied energy

- The modules must be able to be reused or recycled at end-of-life

Materials

The module's materials must be healthy, evaluated through DGNB ENV1.2

The module's visible materials must also be assessed on aesthetical quality and ability to convey the functionality of the module

The module's materials should if possible be reused or recycled materials if available data for the environmental impact is available.

DGNB

- The modules must be assessed based on the chosen DGNB criteria

Functionality

- The modules should be able to provide different architectural possibilities when designing

- The modules should be able to provide spatial flexibility in room layout

- The modules should be able to be replaced by hand or smaller machinery

SKETCHING

MODULAR CONSTRUCTION PRINCIPLES

Intro

The purpose of this chapter is to explore different modular construction principles, in order to determine which ones provide the most potential for utilizing in this project. This should be able to narrow down the focus on certain principles, in the following design chapters.

Principles and evaluation

The module construction principles are separated into four categories and evaluated based on their ability to fulfil the design criteria previously set. The principles are described below.

Column / Beam

- A column and beam system is a simple construction method used for many years, which can be a part of a modular system by having standardised sizes for the elements, and using universal joints.

Apartment unit

- A principle of having entire smaller apartment units already premade in different modular sizes, that can then be stacked or combined together in different configurations.

Structural units

- Structural units consist of separating the construction of a wall/deck into smaller units, that are easier to handle. These units then have modular sizes, that can be combined in different ways to create window openings and wall sizes.

Structural section

- Structural section is an entire section of a wall including window openings, that are prefabricated in different modular sizes, that can then be combined in different configurations.

The evaluation of each principle can be seen on the next page, scored through negative and positive aspects with regards to the design criteria. The column/beam principle provides a lot of flexibility, but it is to the point, where one can ask where the modularity actually is present. It would require multiple construction layers to be functional, and in the end, would produce a lot of elements that have to be tracked individually through MPs. This principle is, therefore, not explored going forward, as it is too component heavy along with barely qualifying as a system.

The opposite can be seen in regards of the apartment units. They have a limited amount of flexibility, and as also earlier discussed in the chapter about modularity, modular units have too many negatives. Therefore, this principle will not be explored going further.

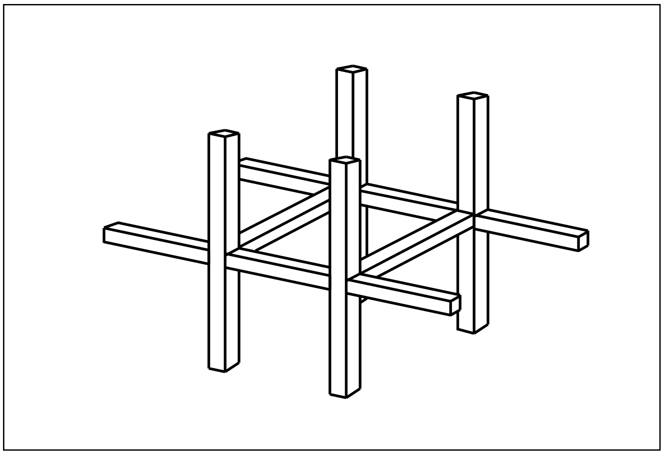
Both the structural units and the structural sections show potential. Structural units might be better fitted for walls, where there is a need for smaller pieces, that can allow for flexibility in the placement of openings. These elements can help provide the needed design freedom when it comes to building dimensions and overall architecture.

Structural sections are less flexible in a system with regards to openings, but could be useful when it comes to deck/roof constructions, that generally have no openings or at least predictable ones such as technical systems.

By combining the flexible structural units for walls, and structural sections for decks, the walls can be designed freely, but the decks are standardised sizes to allow different building dimensions.

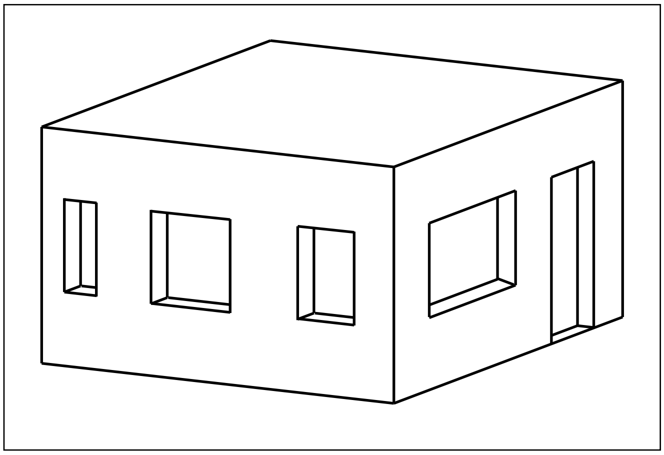
Conclusion

To ensure design freedom, and proper system integration, it has been chosen that structural units and sections are the prefered construction principles. They allow for the most design freedom, and along with other technical considerations prove the most versatile on a principle level. The next step is then to design these constructions with considerations towards DfD, LCA, and flexibility.



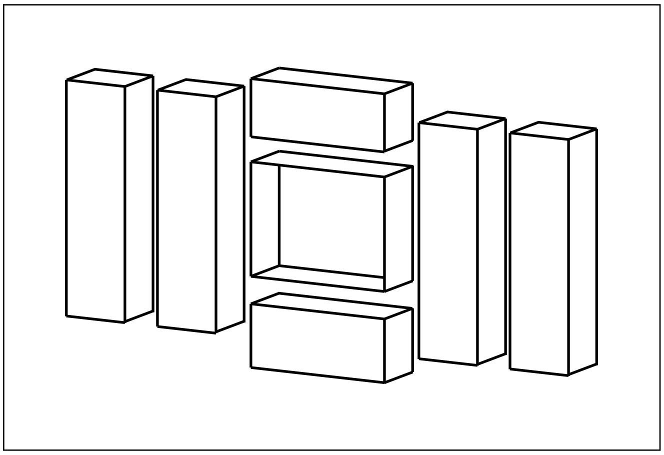
Column / Beam
+ Full flexibility
+ Easy to install by hand
+ Easy to replace parts in future
+ Size variation
+ Easy placement of technical systems

÷ Many small parts
÷ Requires infill between elements
÷ Slow cnstruction



Apartment units
+ Fast to install
+ Easy placement of technical systems

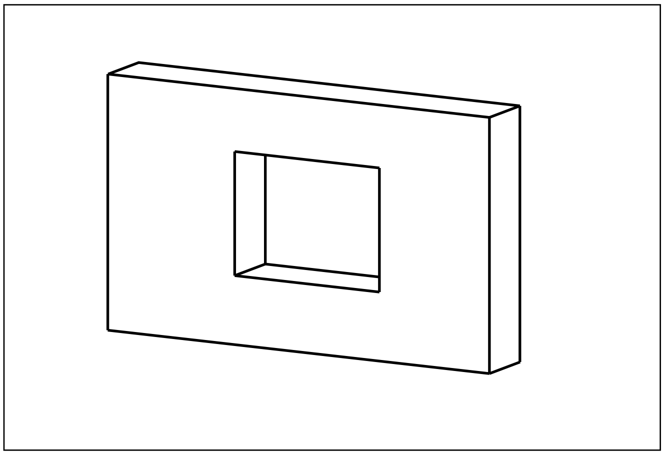
÷ No flexibility
÷ Hard to replace smaller parts
÷ No Size variation
÷ Requires large macinery



Structural units

+ Flexibility
+ Few parts
+ Possible to replace parts in future
+ Size variation
+ Fast construction

÷ Difficult to place systems



Structural section

+ Few parts
+ Size variation
+ Fast construction

÷ Difficult to place systems
÷ Flexibility
÷ Hard to replace parts in future

INITIAL MODULE DESIGN

Intro

The purpose of this design task is to make different initiating modules with the two materials concrete and wood. When looking at the varying modules, it is important to investigate the joints between wall modules, joints between deck and wall, and analysing the modules in regards to flexibility.

Concrete modules

When looking at concrete modules, an effective and easy way to assemble and disassemble them is using Peikko joint (Peikko.dk, 2015), where two modules are fastened together via bolts and metal cases (see Illu 56 on the next spread). A concrete module works best when using structural units, as concrete is quite heavy and thereby it is impossible to make concrete modules that can be handled by hand, thus it is more efficient to make bigger modules. Also, if the modules are small, a lot of these metal cases are needed to assemble the modules, creating many spots where the construction is weaker along with complexing the making of the unit and the assembly on site.

The joining metal cases are pre-casted into the concrete module and are stuck in the concrete by metal rods going into the concrete. The placement of the rods defines where windows can be placed, thus minimizing the freedom to place windows (see Illu 52 and Illu 54)

Wooden modules

The simple squared module (see Illu 61) can be used both as full room-height modules and smaller modules as well as either a structural section or structural unit. The advantages of this module are the simplicity of it, meaning it can be produced easily. It is also relatively easy to join them to the decks. The disadvantages are how to join the modules to each other.

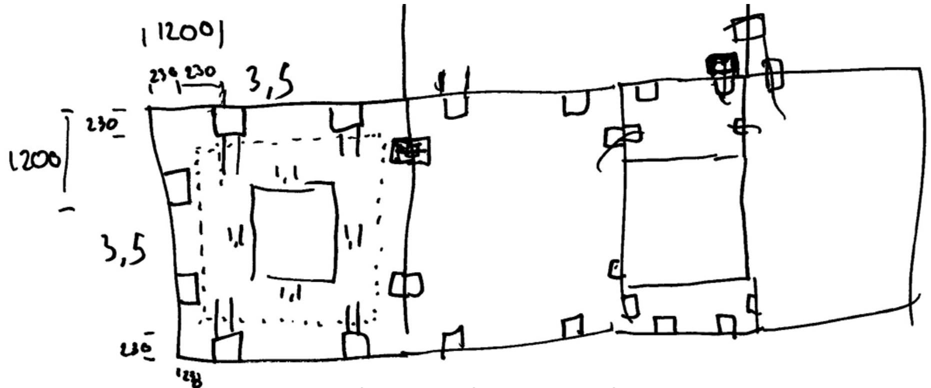
Other shapes than the squared have also been evaluated. The intention with these modules was to have interlocking modules, (see Illu 64 - Illu 68) thereby making the joints easier and reducing the number of joints. However, when sketching these modules, more problems occurred; how to place windows (see Illu 69), how to achieve no thermal bridges and the harder production of the module. It also showed the same problems with joints as the simpler and squared one. The interlocking modules work best by having them as smaller modules.

The joints were likewise designed in regards of the wooden modules. The solution for joining smaller modules could be the usage of hasps (see Illu 58 and Illu 60 on the next spread) which creates easy assembly and disassembly along with the module not being damaged in any way, thus keeping the value of it and making it possible to reuse the module on several lifetimes.

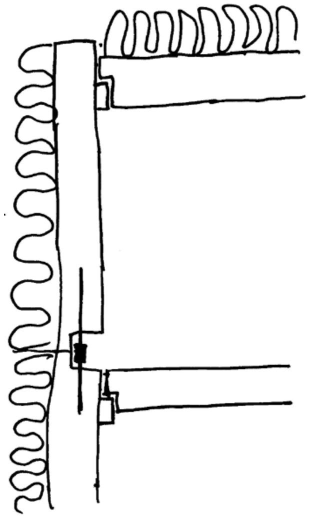
Conclusion

When designing and analysing modular systems with the materials wood and concrete, different advantages and disadvantages occur. The concrete module needs to be a larger structural unit, where the placement of windows is controlled by the joint between the modules. The problems with the placement of windows also occur in the interlocking wooden modules along with the module being complex to produce. The squared wooden module is simple to produce, can accommodate varying sizes of modules and easy to incorporate openings, thereby providing the most flexibility. Therefore, the simple wooden module will be used in the further design.

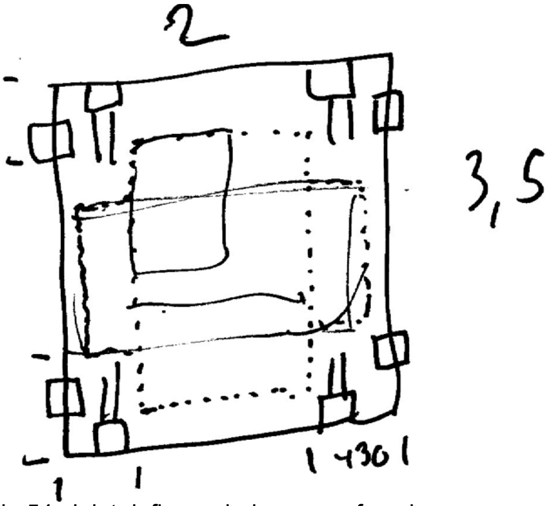
Concrete modules sketches



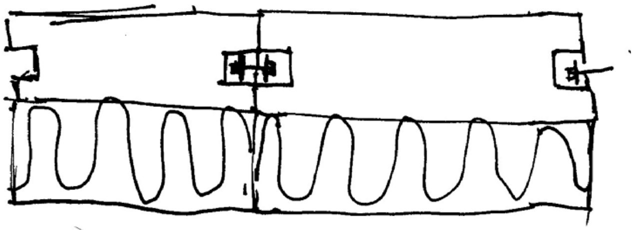
Illu 52: Big modules, joint defines area for windows, facade



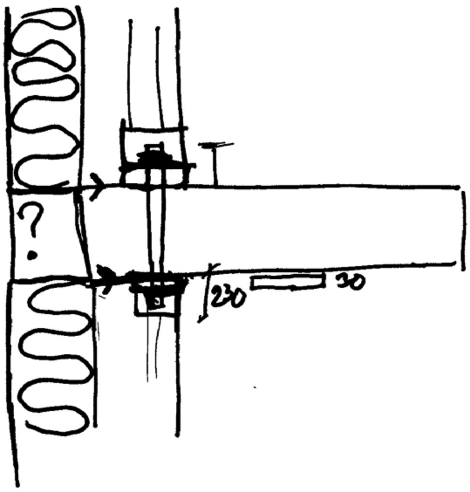
Illu 53: Joint between walls and decks, section



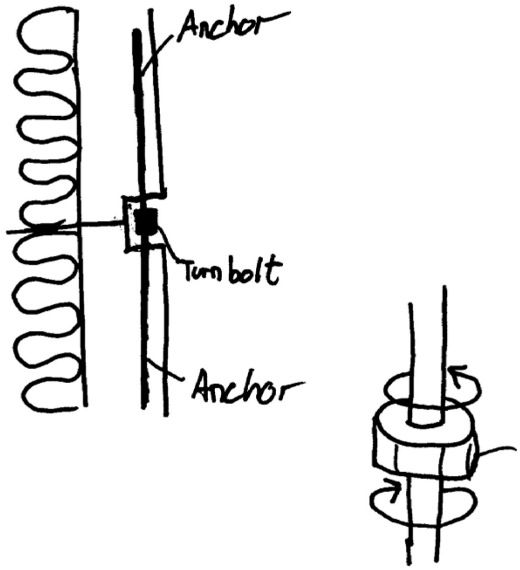
Illu 54: Joint defines window area, facade



Illu 55: Joint between two wall modules, plan

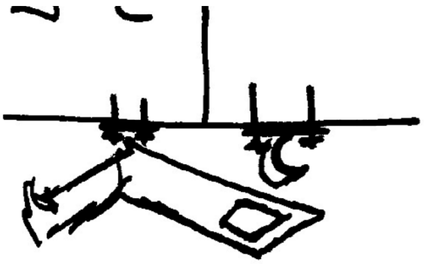


Illu 56: Peikko joint, section

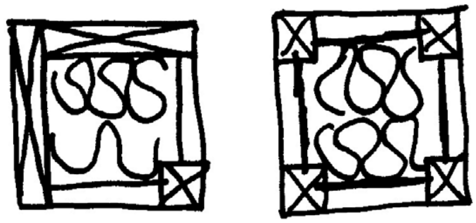


Illu 57: Other method to join two modules together, plan

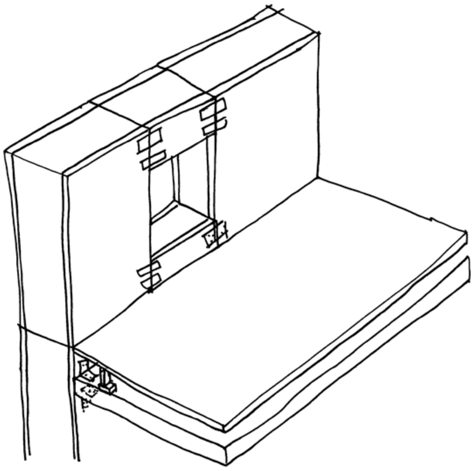
Squared wooden modules sketches



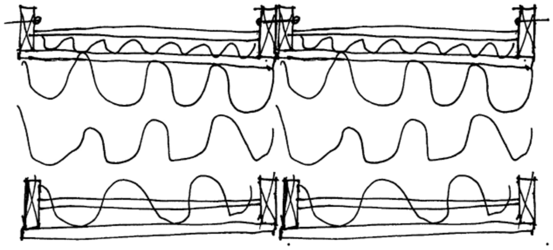
Illu 58: Joints with hasps



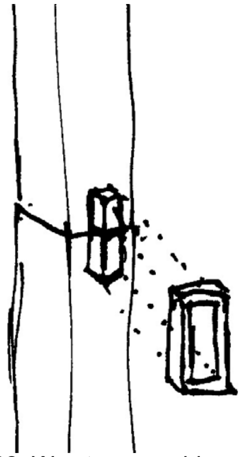
Illu 59: Squared module corner solution, plan



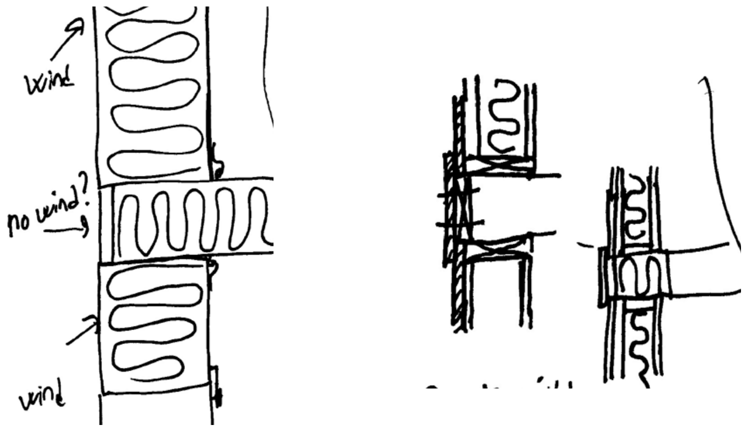
Illu 60: Small modules connected, 3D



Illu 61: Square module, plan

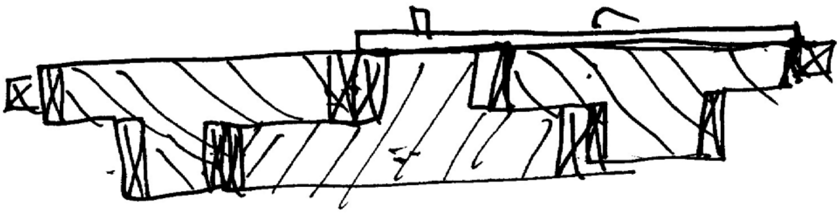


Illu 62: Way to assemble modules, 3D

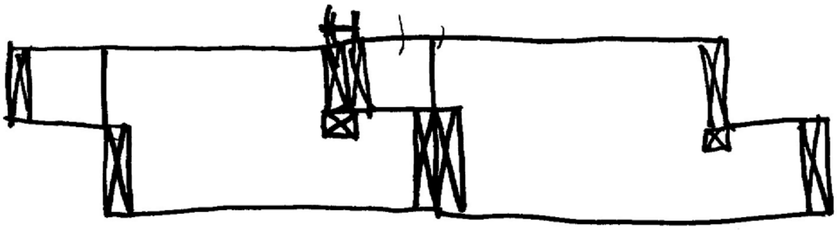


Illu 63: Principles for tight wind barrier, section.

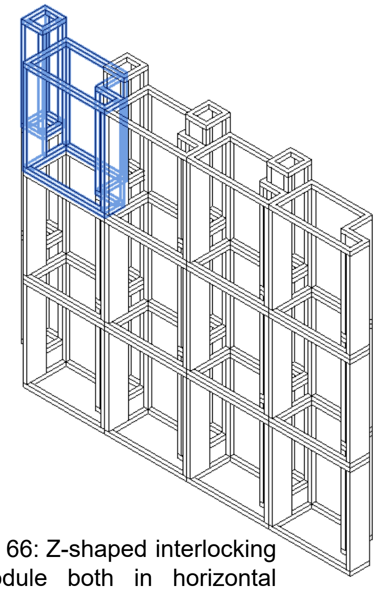
Interlocking wooden modules sketches



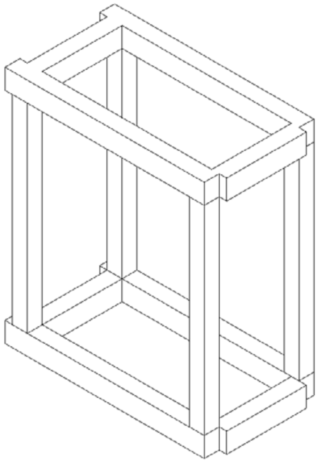
Illu 64: T-shaped module, plan



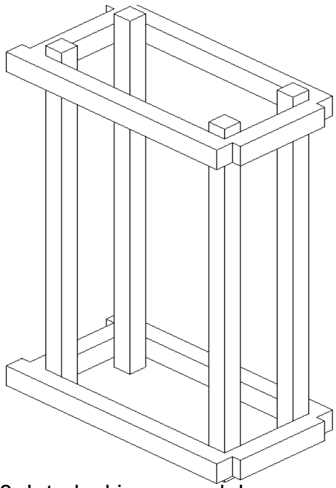
Illu 65: Z-shaped module, plan



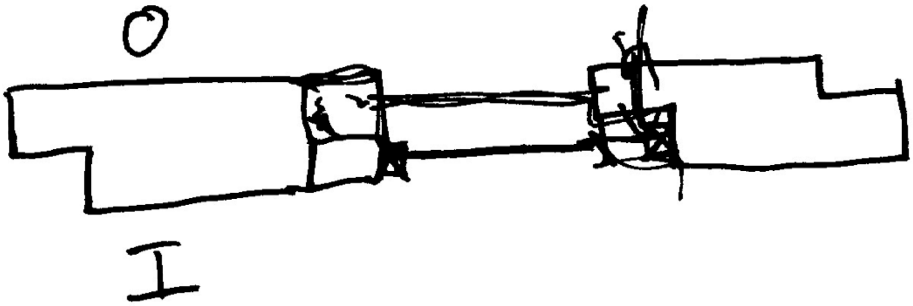
Illu 66: Z-shaped interlocking module both in horizontal and vertical plan, 3D



Illu 67: Interlocking module horizontal plan, 3D



Illu 68: Interlocking module horizontal and vertical plan, 3D



Illu 69: Z-module, how to place windows?, plan

INTIAL BUILDING PLAN DESIGN

Intro

This design task contains the initial plan sketches. The focus of the plan solution sketching is to create flexibility in the dwellings along with trying to reduce the needed space.

Initial plan sketching

The first plan sketches were designed both as rowhouses (see illu Illu 72) and double houses with the thought of different rooms could belong to varying dwellings, thereby achieving flexibility in the plan layout (see Illu 70, Illu 71 and Illu 73). It was discovered that double houses have the most flexibility compared to rowhouses due to the extra facade space and thereby easier and freer placement of rooms. It was later determined that having rooms that could belong to either dwelling was inadequate to achieve flexibility and reduce the space.

Instead, partition walls should be able to be moved around and thus creating more flexibility. This would also lead to a possibility to change living room sizes in the dwellings, creating spaces adequate for the number of people living in the dwelling, and thereby facilitate space reduction. It was also explored that the rooms requiring water (kitchen, bath and technical room) should be as close to each other as possible and thereby creating a core, which would lead to short piping distances and thus lower material usage along with more flexibility in the dwellings.

Core principles

The beforementioned core could be placed on three different locations in the double houses, respectively as interior core, facade core or exterior core. The principle of the core is to have a place which is non-flexible and cannot be removed and then having the rest of the building being as flexible as possible (see Illu 75).

The interior core principle is defined as the core being placed in the middle of the building, with the possibility to have facade all around it (see Illu 76 - Illu 78 on the next spread). The advantages of this core principle are that the core can be shaped in different ways, creates much flexibility and does not take up facade space, which enables freer room placement.

The facade core principle contains the core placed towards one facade (see Illu 79 - Illu 81 on the next spread). This principle can still provide some flexibility, however, the room placement is a bit more locked due to the minimized area towards facades. The technical room should, in this case, be placed towards outside so there is easy access into it and thereby one can access the bathroom and kitchen from inside the dwelling. This solution, however, is not suitable, as this means the piping must go into and through the core, meaning if changes should be made to e.g. the heating, it is necessary to remove the floor both in the dwelling and in the core. This is contrary to the idea of the core, which should not be interfered with, thus making it a bad solution.

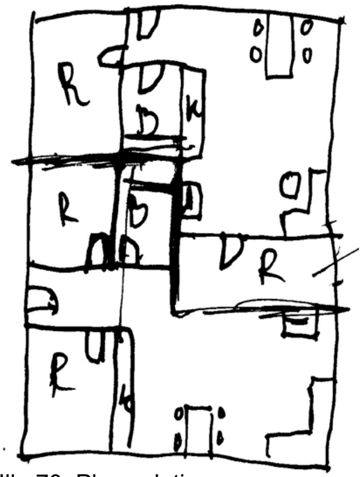
The principle for the exterior core is to place it as an element going out of the regular building shape and thereby keeping the building as free as possible (see Illu 82 Illu 83 on the next spread). This core principle, however, leads to limited flexibility and worse use of square meters as well as causing troubles for daylight, due to the big room depth. Also, some of the troubles regarding the technical room towards outside occurred as well.

It was, therefore, chosen that the interior core principle was the one to include in further work. The interior core was sketched more in detail, which led to some plan solutions where the core remains the same, but everything else is free and can be moved around (see Illu 84 - Illu 87 on the next spread). This creates, on a principle level, the wanted varying and flexible plan solutions, but this principle should be defined more from the modular system and partitioning walls.

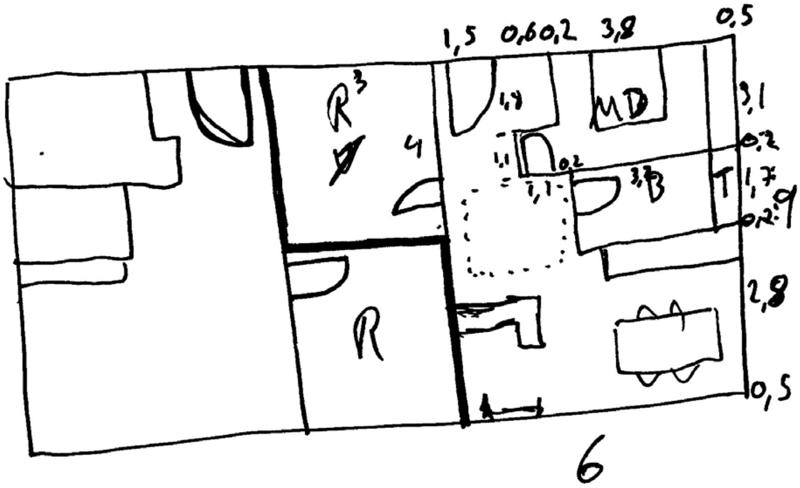
Conclusion

The initial plan solutions were sketched with the purpose to achieve flexibility and lower the area. To achieve this, having an interior core with a technical room, bathroom and kitchen is important. This core should be made as non-flexible area, and the rest of the building should accommodate the possibility to place rooms freely and move partition walls around.

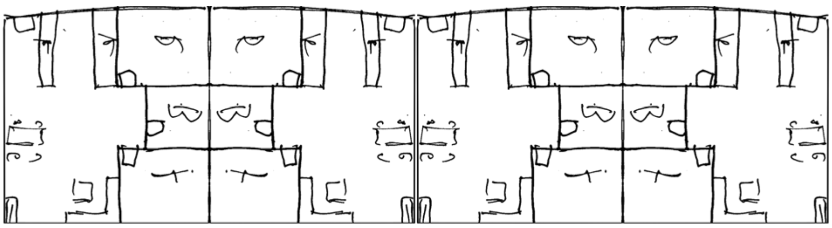
Initial plan sketching



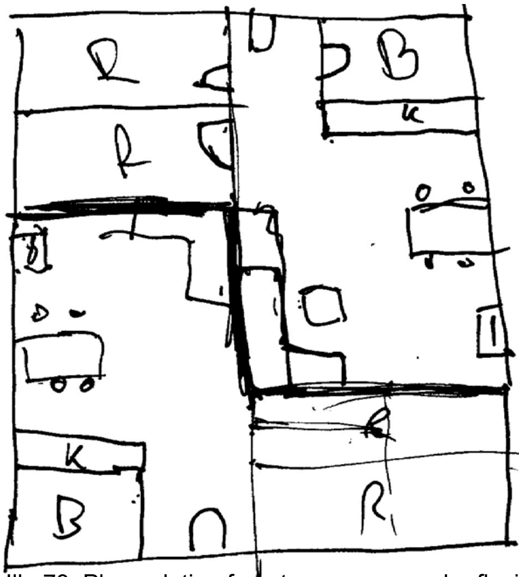
Illu 70: Plan solution one, one room flexibility, long distance between bath and kitchen



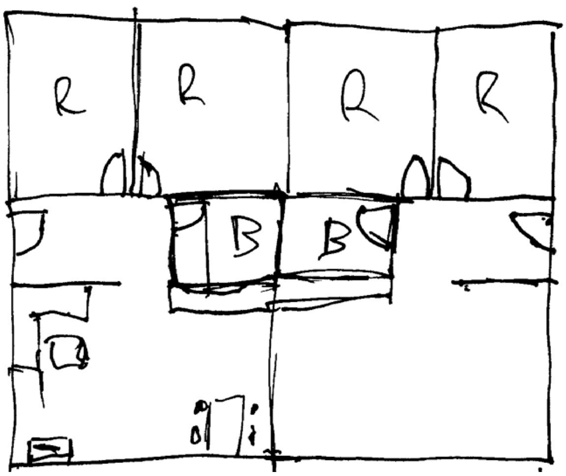
Illu 71: Plan solution two, one room flexibility, long distance between cores



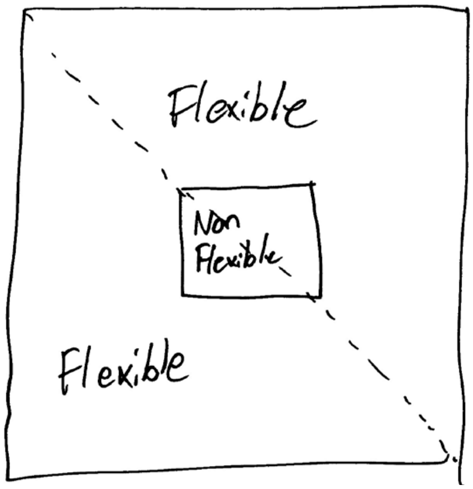
Illu 72: Rowhouses



Illu 73: Plan solution four, two rooms can be flexible, long distance between cores

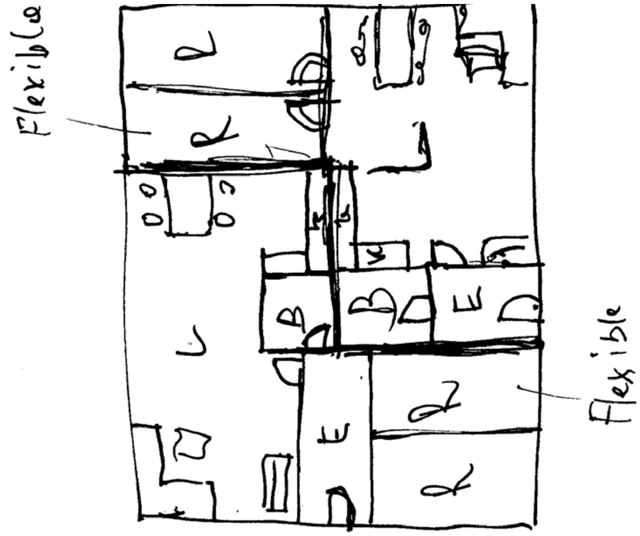


Illu 74: Plan solution five, zero amount of flexibility

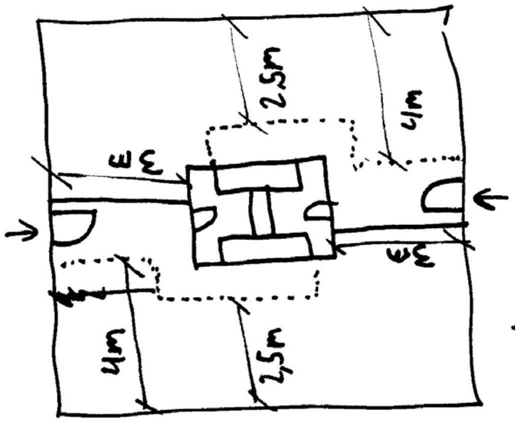


Illu 75: Principle for flexible and non-flexible

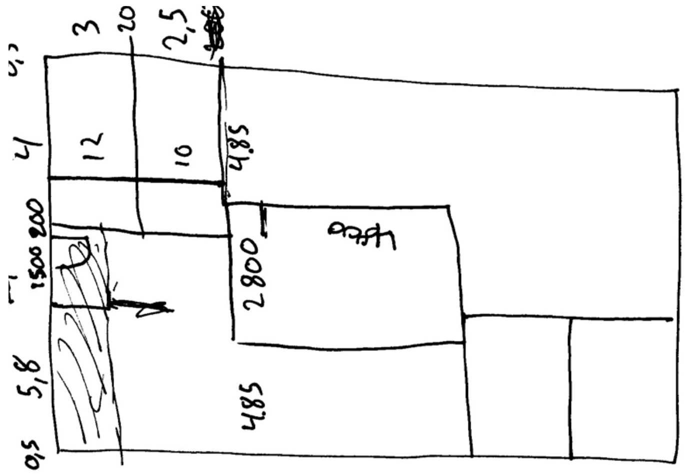
Interior core



Illu 76: Plan interior core, two rooms flexible

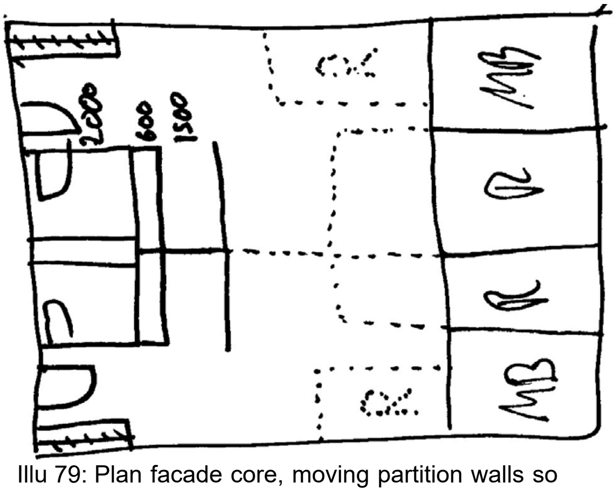


Illu 77: Plan interior core, everything is flexible except for the dotted area

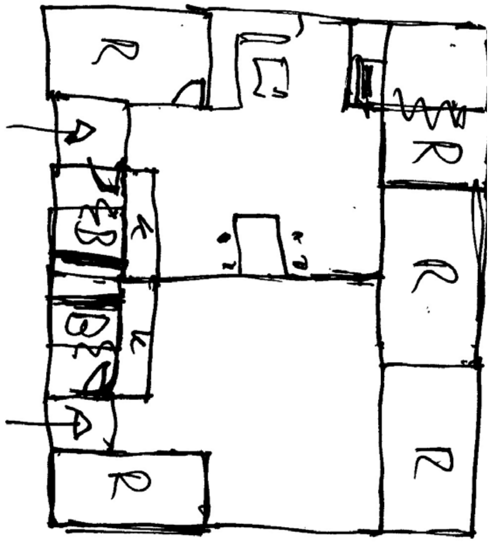


Illu 78: Plan interior core, two rooms flexible

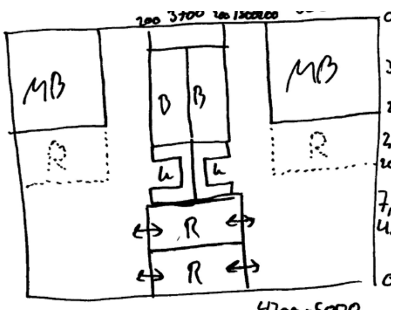
Facade core



Illu 79: Plan facade core, moving partition walls so livingroom adapts to the amount of rooms.

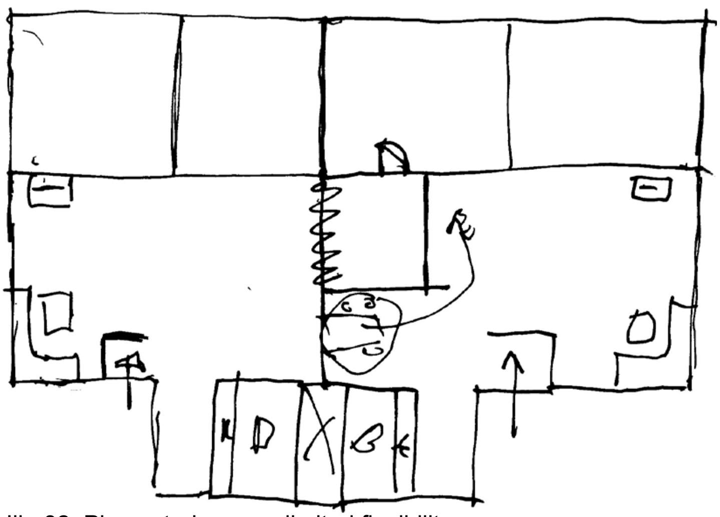


Illu 81: Plan facade core, one room can be accessed from either dwelling.

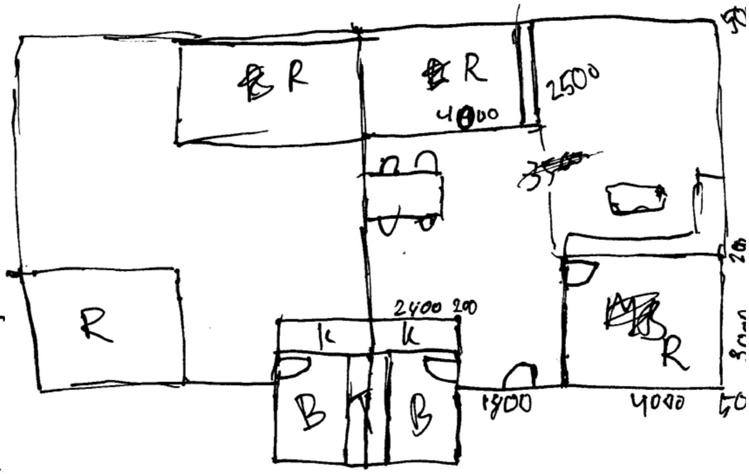


Illu 80: Plan facade core, flexibility, can place rooms in different places and access rooms from either dwelling

Exterior core

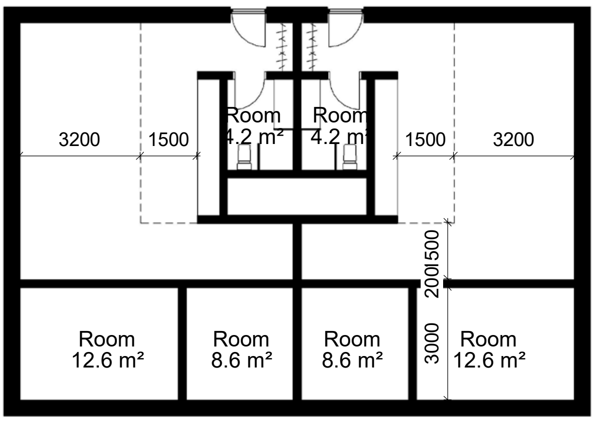


Illu 82: Plan exterior core, limited flexibility

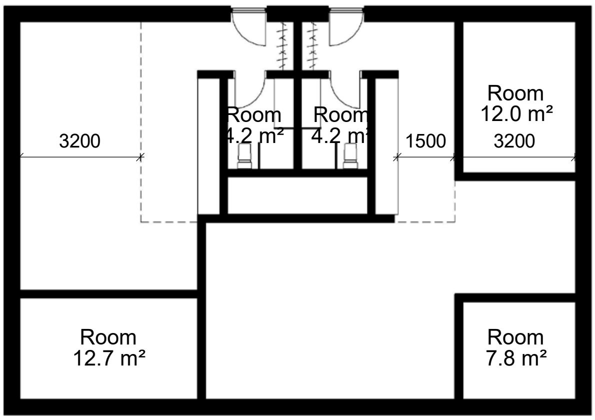


Illu 83: Plan exterior core, limited flexibility

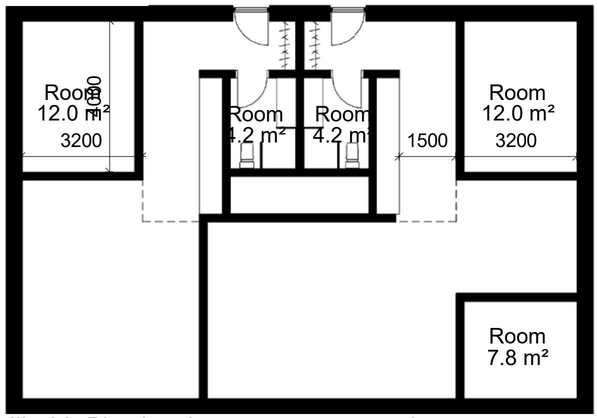
Plans with the same core



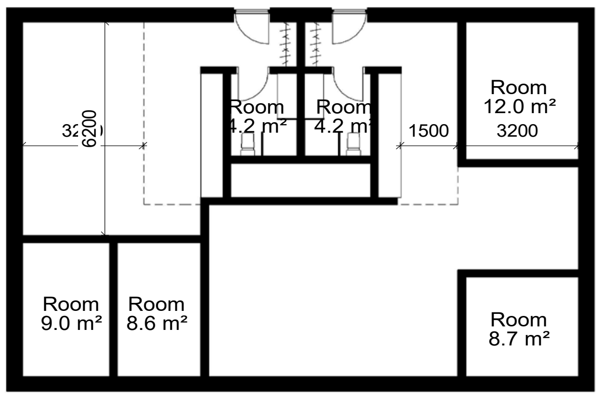
Illu 84: Plan interior core, same core 1



Illu 85: Plan interior core , same core 2



Illu 86: Plan interior core , same core 3



Illu 87: Plan interior core , same core 4

PARTITIONING WALLS

Intro

To enable flexibility in the dwellings, it is important to design the partitioning walls, which is the purpose of this design task.

Partition walls

To ensure short-term flexibility in the dwellings and thus change the dwellings according to demand, the inner walls should be easy to move around, and, therefore, modular and in sizes that can be handled by hand or smaller machinery. They should also have sizes that can be used for creating different sizes of rooms, and thereby fit to a changing plan solution.

When introducing the moveable partition walls, some problems occur (see Illu 88 to Illu 93). The problems are how to allow installations to run through, how to join modules at corners and straight joints, how to fit walls into the ceiling and floor, how to include doors and how to ensure tightness in regards of sound and fire.

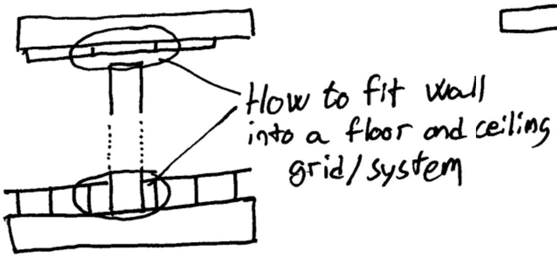
To solve the joints in corners and straight line, a grid in the floor can be used (see Illu 95). The thought is that the smaller parts of the floor can be removed and instead of flooring, partition walls can be placed in the leftover space (see Illu 94). This solution means that two different partition wall modules should be created, respectively the long wall module and a square column module, which could be used for joining the walls. By creating this grid solution, a lot of flexibility is provided, as the partition walls can be placed in many different configurations.

The joints between floor, partition walls and ceiling should be tight, so sound and fire cannot move between different rooms. But to ensure that the walls are moveable, they cannot be the total height between floor and ceiling, as problems then will occur when lifting and moving the wall module. As the module needs to be a bit lower than the beforementioned height, different ways to ensure the tightness to the ceiling are explored (see Illu 99 to Illu 102 on next spread). The best way is compressible and flexible foam, which will provide the opportunity to lift the module, resulting in the compressible foam will be reduced in size, and then when installing the wall in another configuration, the foam will expand and create tightness again.

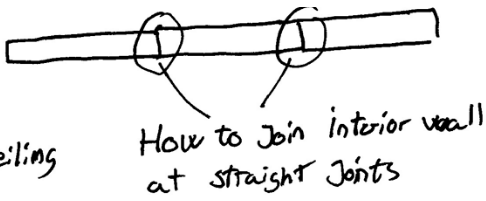
Different ways to tighten the partitioning wall modules to the floor and ceiling has likewise been explored. Pre-mounted joints on the ceiling and on the floor along with bolts can ensure that the partitioning walls are fastened in an easy and reversible way without damaging the walls (see Illu 105 on the next spread). The other explored solutions damage the walls in some way.

Conclusion

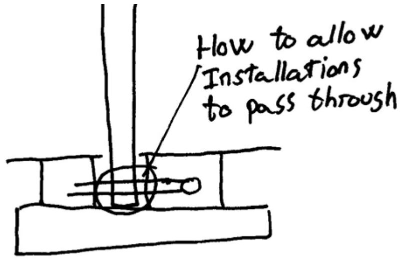
The partitioning walls should provide short-term flexibility and thereby freedom when placing rooms. To achieve this, a grid system in the floor is created, where some parts can be removed, and partitioning walls can be installed. The walls are fastened to the floor and ceiling with pre-mounted joints and compressible foam on top of the module ensures tightness between rooms along with the possibility to move the walls around.



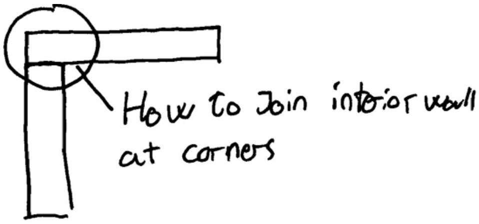
Illu 88: Fit wall into ceiling and floor



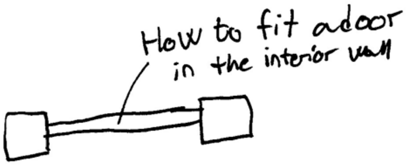
Illu 89: Straight joints



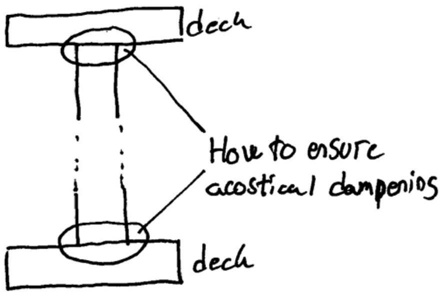
Illu 90: Installations



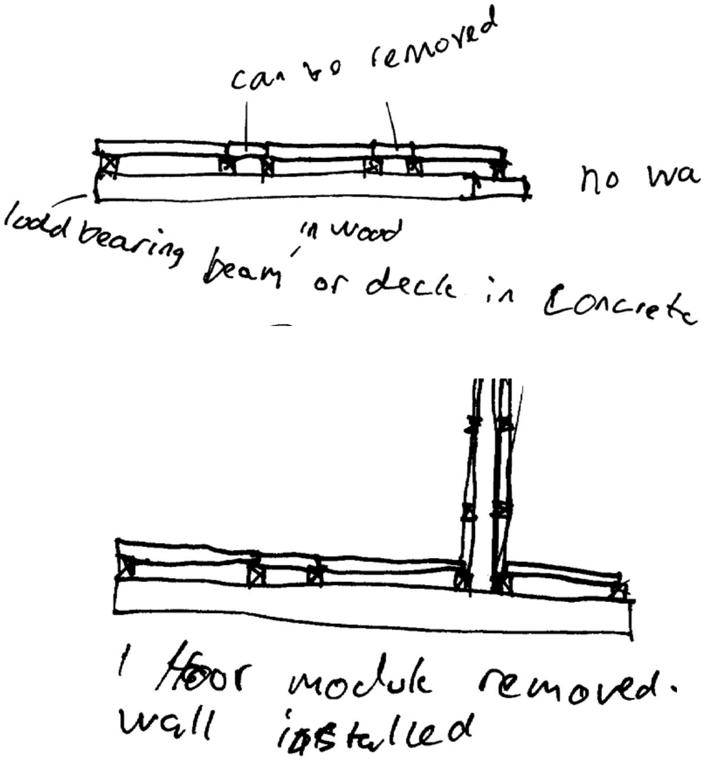
Illu 91: Corner joints



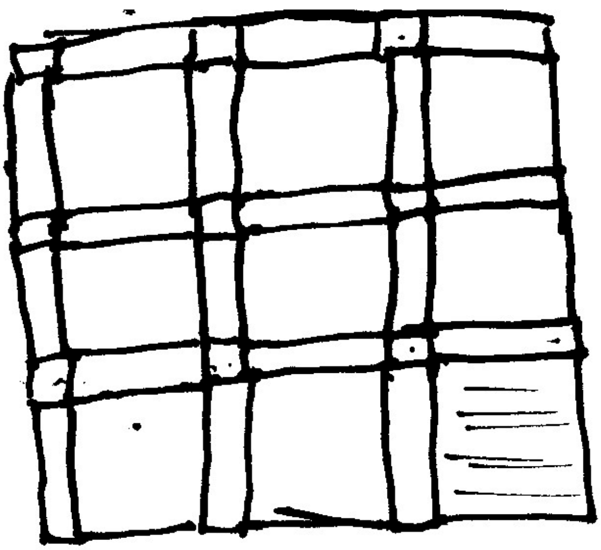
Illu 92: Doors



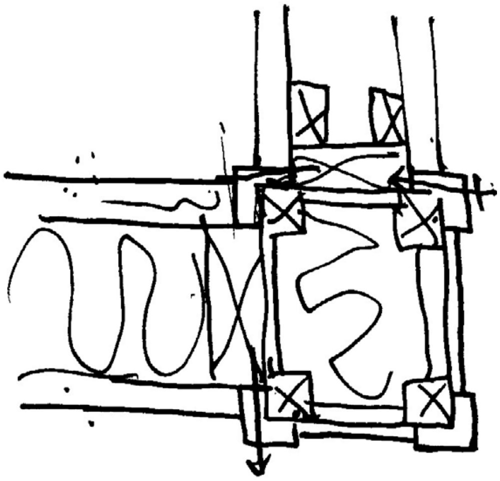
Illu 93: Sound tightness



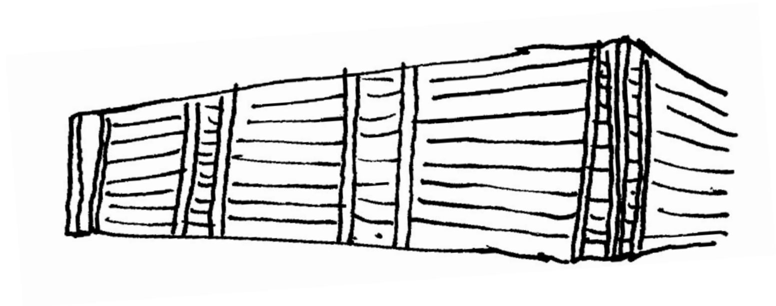
Illu 94: Remove the small parts of flo-oring and insert partition walls



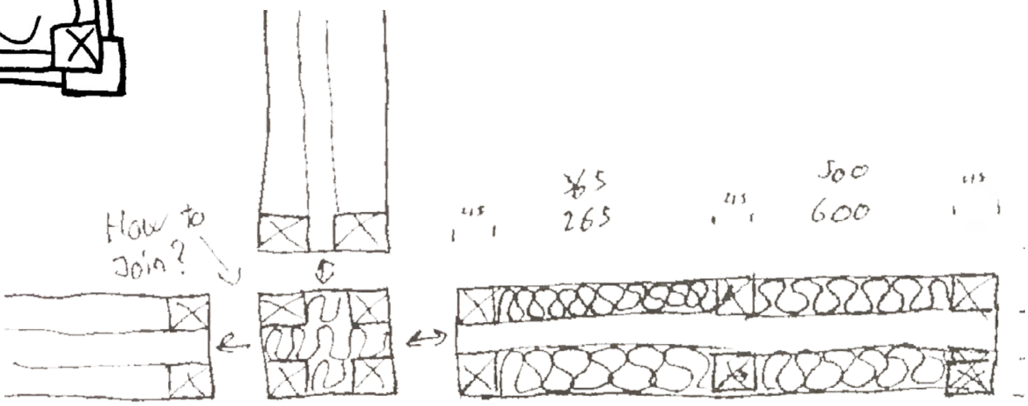
Illu 95: Grid system in the floor



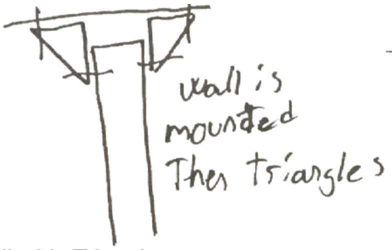
Illu 96: Joint between small wall part and bigger wall



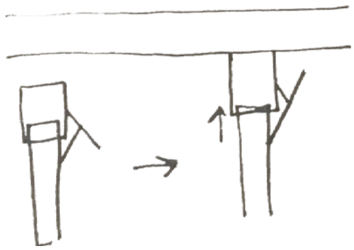
Illu 97: Aesthetics with modular system



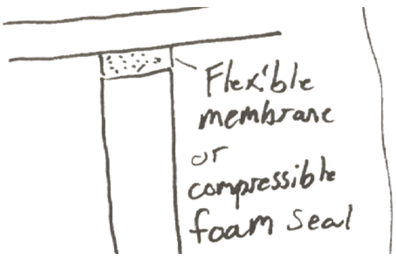
Illu 98: Joint between small wall part and bigger wall 2



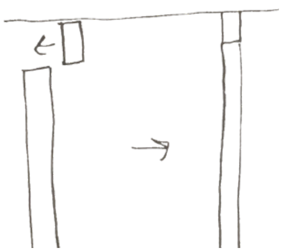
Illu 99: Triangles



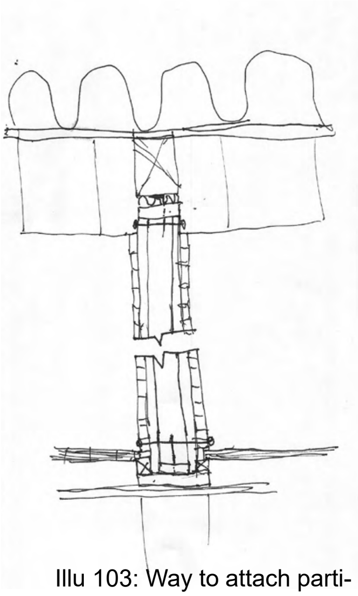
Illu 100: Mechanical expandable



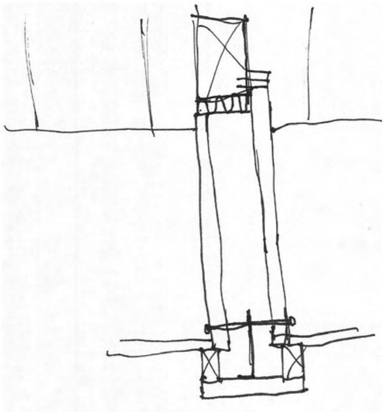
Illu 101: Flexible foam



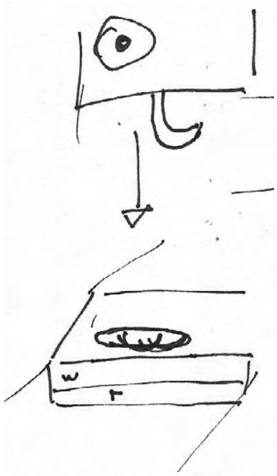
Illu 102: Extra piece

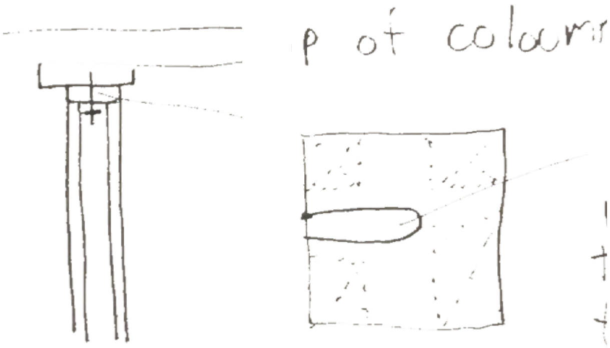


Illu 103: Way to attach partition wall to ceiling and floor

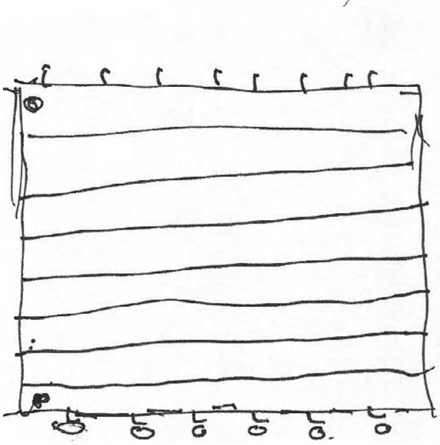


Illu 104: Way to attach partition wall to ceiling and floor 2

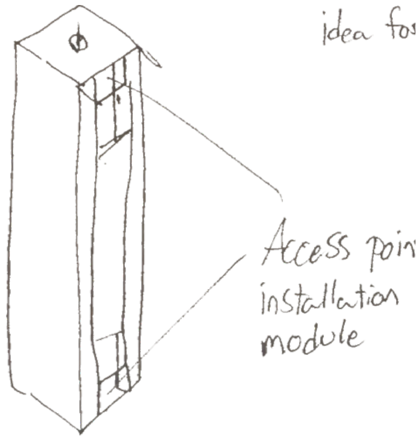




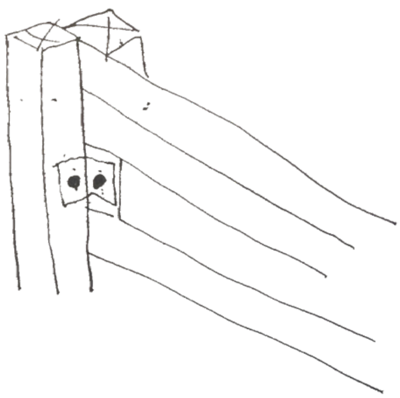
Illu 105: Pre-mounted joints joining the wall with ceiling and floor. Important to have a slot in the top board so the wall does not encounters the joint



Illu 106: Joining the ceiling, partitioning wall and floor with turnable hooks



Illu 107: Access to pre-mounted joints



Illu 108: Access to joints between small module and bigger wall module

WALL MODULE SIZES

Intro

This design task has the purpose to discover different sized wooden wall modules, and which advantages and disadvantages each wall size has. The walls should be analysed upon the usage of materials and the placement of windows and thereby should lead to an understanding of which module size is the most optimal.

Wall module sizes

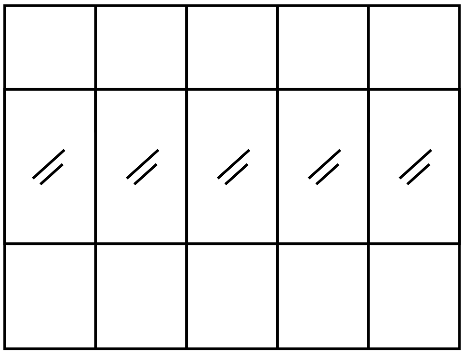
Three different wall modules are analysed and compared, respectively walls with a width of 0,6m, 1,0m and 1,5m, a height of 3,5m and 0,5m in depth. The analysis is made on a building with the minimum size of 15,5m x 11m, which the outer walls are on Illu 84. Thereby, the number of wall modules will vary compared to their width, and then the results will show how much material that is consumed. The calculation is only made upon the usage of construction wood, and thus the insulation is not included.

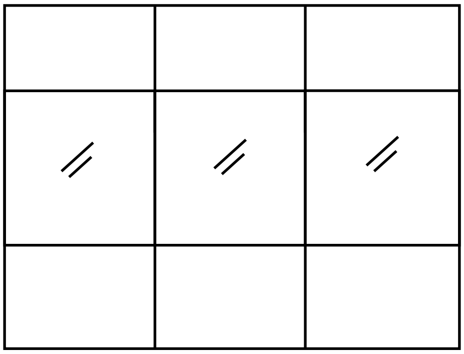
When comparing the three modules, the 0,6 consumes much more material than the two others and the best module with the least material consumption is the 1m module. When comparing the modules with the plan solution, it can be concluded that the smaller the modules are, the easier it is to fit to a given building size, thereby a smaller module provides more long-term flexibility. A smaller module size also results in more ways to place windows and a bigger variation in the width of them.

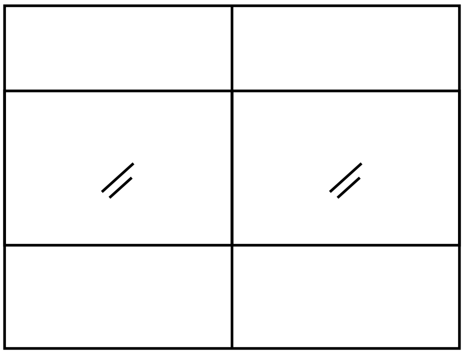
This is due to the width of the windows must be the same size as the modules or several modules put together. This is shown on Illu 109 to Illu 111 where one can see that on a three-meter wall, the 0,6-meter windows have five options for window widths (0,6m; 1,2m; 1,8m; 2,4m and 3,0m), the 1-meter window have three options (1,0m; 2,0m and 3,0m) whereas the 1,5-meter windows only have two (1,5m and 3,0m).

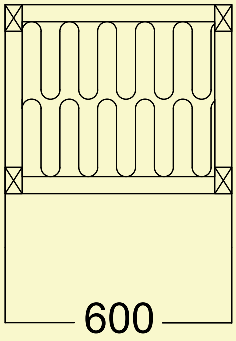
Conclusion

To conclude, the module with the lowest material usage is the 1,0m module. This module can also be quite flexible when addressing long-term flexibility and the module provide good conditions for window placement, however, the last two aspects are better in the 0,6m module. But the much lower material usage of the 1,0m module results in this being used in the further design.

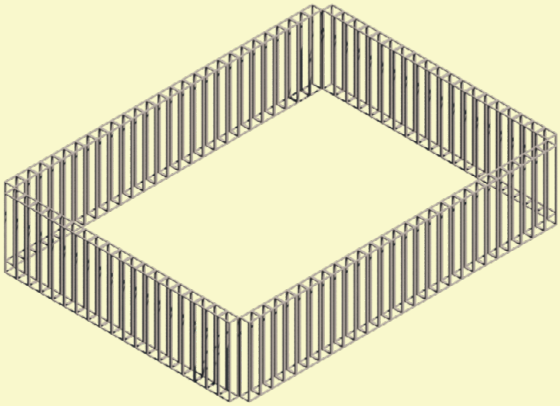

Illu 109: Module 600 mm. Five widths of window placement on a three meter wall


Illu 110: Module 1000 mm. Three widths of window placement on a three meter wall

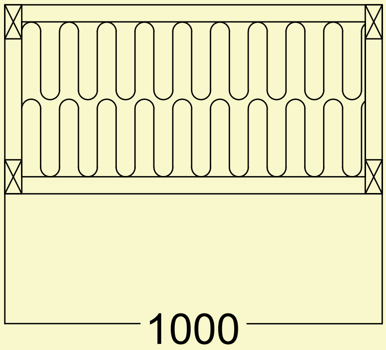

Illu 111: Module 1500 mm. Two widths of window placement on a three meter wall



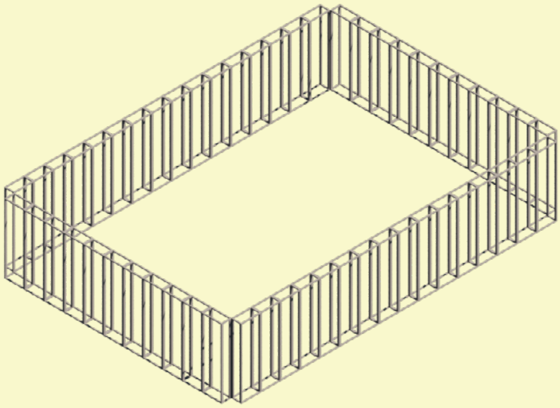
Illu 112: Module 600 mm. Four columns of 70 x 45 mm.



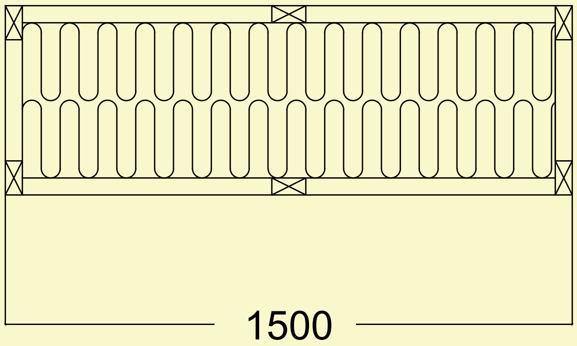
Illu 113: 90 600 mm modules needed. 4,6 m³ in total of construction wood



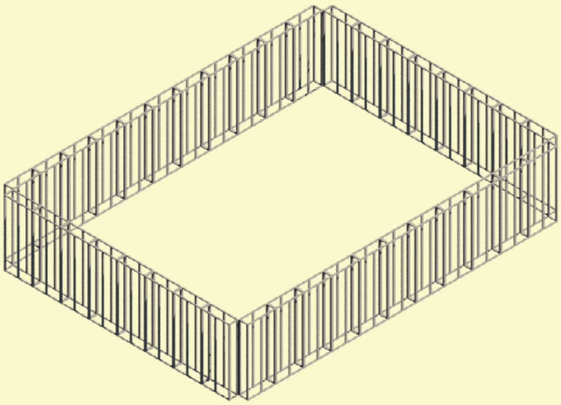
Illu 114: Module 1000 mm. Four columns of 90 x 45 mm



Illu 115: 54 1000 mm modules. 3,6 m³ in total of construction wood



Illu 116: Module 1500 mm. Six columns of 90 x 45 mm



Illu 117: 38 1500 mm modules. 3,7 m³ in total of construction wood

FIRST CONCEPT WALL MODULE

Intro

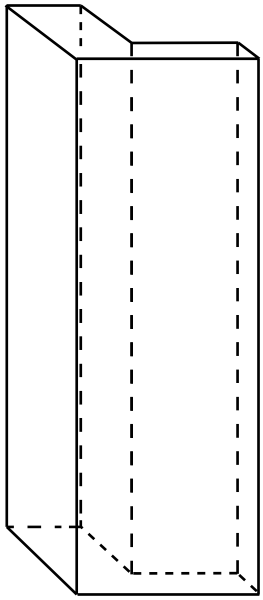
With the beforementioned wall module on one-meter width, it is now important to determine different modules in terms of creating a functional system with opportunity to make varying facade solutions.

Wall module sizes

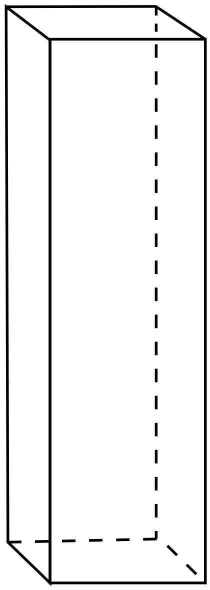
To achieve varying facade solutions, different modules are needed. The first one is the corner module, which can be placed in corners to connect two walls (see Illu 118). The second module size is the one being full room-height, where no windows can be placed (see Illu 119). The third module (see Illu 120) is squared measuring 1 x 1 m and can be used both under and over a window, thus providing space for 1,5 m windows. The fourth and fifth modules (see Illu 121 and Illu 122) are overhang modules on respectively 2 x 1 m and 3 x 1 m, thereby making it possible to include more windows next to each other. The sixth and seventh modules are likewise overhanging modules but with the height being 1,5 m instead of 1 m (see Illu 123 and Illu 124). This is to ensure different windows can be fitted into the facade, and thereby making several facade solutions. The eighth module is a door module (see Illu 125). These modules can be joined in varying ways and thus enabling different facades. (see Illu 126 to Illu 128)

Conclusion

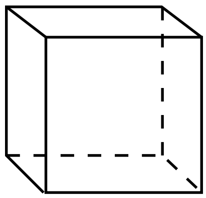
Eight varying modules have been determined, which allows for several ways to incorporate windows in the buildings and thus create different facade rhythms.



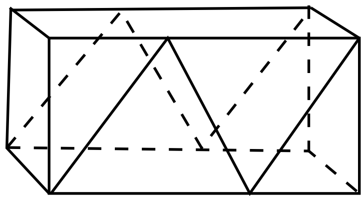
Illu 118: Cornermodule



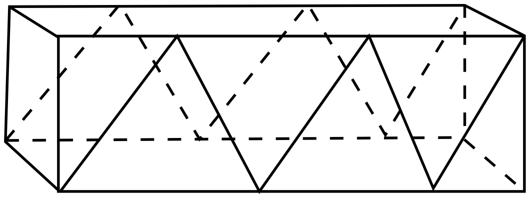
Illu 119: Full height module w1000 x d500 x h3500 mm



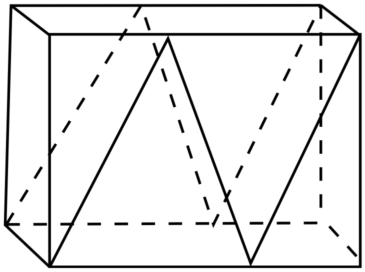
Illu 120: Module for under and over windows w1000 x d500x h1000 mm



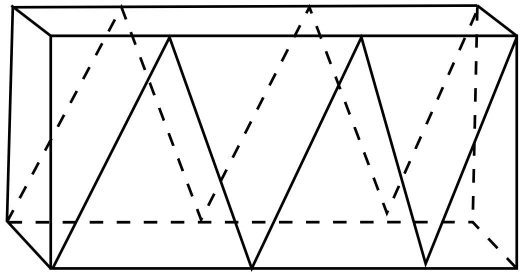
Illu 121: Module used over windows w2000 x d500 x h1000 mm



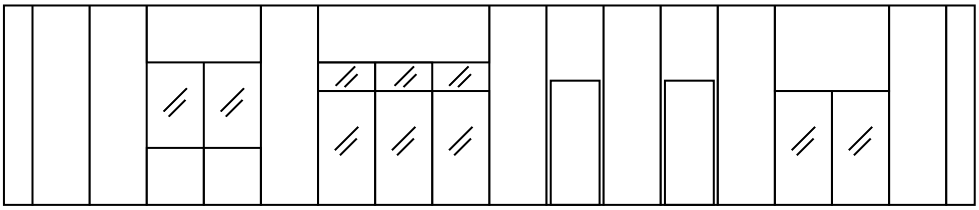
Illu 122: Module used over windows w3000 x d500 x h1000



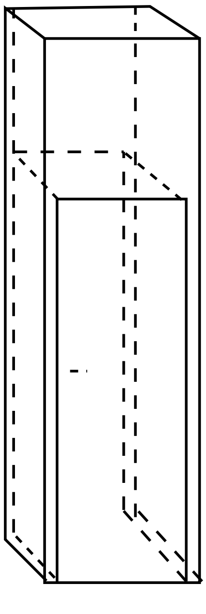
Illu 123: Module used over windows 2000x500x1500



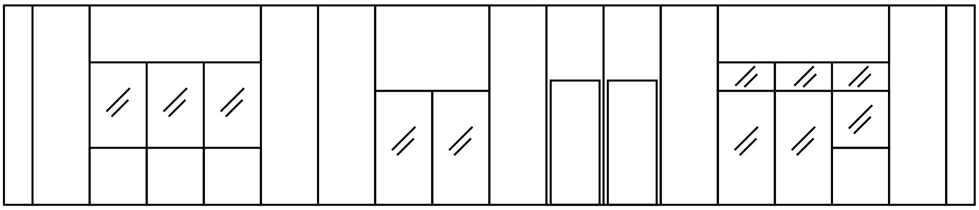
Illu 124: Module used over windows 3000x500x1500



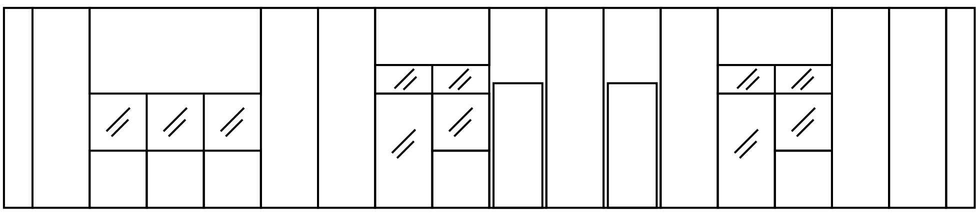
Illu 126: Varying facade made by modules 1



Illu 125: Fullheight module with door 1000x500x3500



Illu 127: Varying facade made by modules 2



Illu 128: Varying facade made by modules 3

LCA WALL MODULE

Intro

In order to use the best materials for the wall module in regards of CE, an LCA assessment of the wind barrier and insulation material has been conducted.

LCA wind barrier boards

As the construction is made in wood, a wind barrier is necessary to stop the wind coming into the building. To determine the best solution, five different types of wind barriers are analysed in LCA. On Illu 129, the five different boards and their emissions are presented, and it shows that the fibre-gypsum board is the least emitting both when looking at CO_2 emission and embedded energy.

This study, however, does not show the Hunton wind barrier, which is a wind barrier made of wooden fibre (Hunton.dk, 2015). There is no EPD for this product, but it has a lot of other advantages. Therefore, a comparison between the Hunton wind barrier and fibre-gypsum boards is made in the following.

The Hunton wind barrier is made of a bi-product of sawmills, and thus is a product which provides added value to another firms' waste and thereby complies well with the thoughts of CE. Hunton boards are made from natural and renewable materials, and the trees used in the production are PEFC certified. (ibid) The fibre-gypsum boards are made of gypsum, paper and water (10-4.dk, 2020). The gypsum is not a renewable material, which thereby is a disadvantage of this board.

The fibre-gypsum boards cannot withstand heavy rain, thereby when mounting a fibre-gypsum board, some sort of waterproof shielding should be added on until the facade is mounted (Ibid). This limits the facade expression by needing it to be completely closed. On the other hand, Hunton is weather-resistant (Hunton.dk, 2019). There is, therefore, a bigger risk of damaging the fibre-gypsum board, which will lower its value and thereby it is being worse in a CE perspective than the Hunton board.

If evaluating them on the healthiness, both materials pollute less than described in DGNB ENV 1.2, and can, therefore, be certified as healthy materials.

Hunton is, by the producer, announced as the leading wind barrier for 45 years because it, amongst others, reduces thermal bridges well, is environmentally friendly and can be made in varying sizes (Hunton.dk, 2019).

The choice of material should be based on both LCA but also the other aspects defined as important in CE, and by taking the advantages of the Hunton boards and disadvantages of fibre-gypsum boards into account, the Hunton board will be utilised as the wind barrier in this project.

LCA insulation

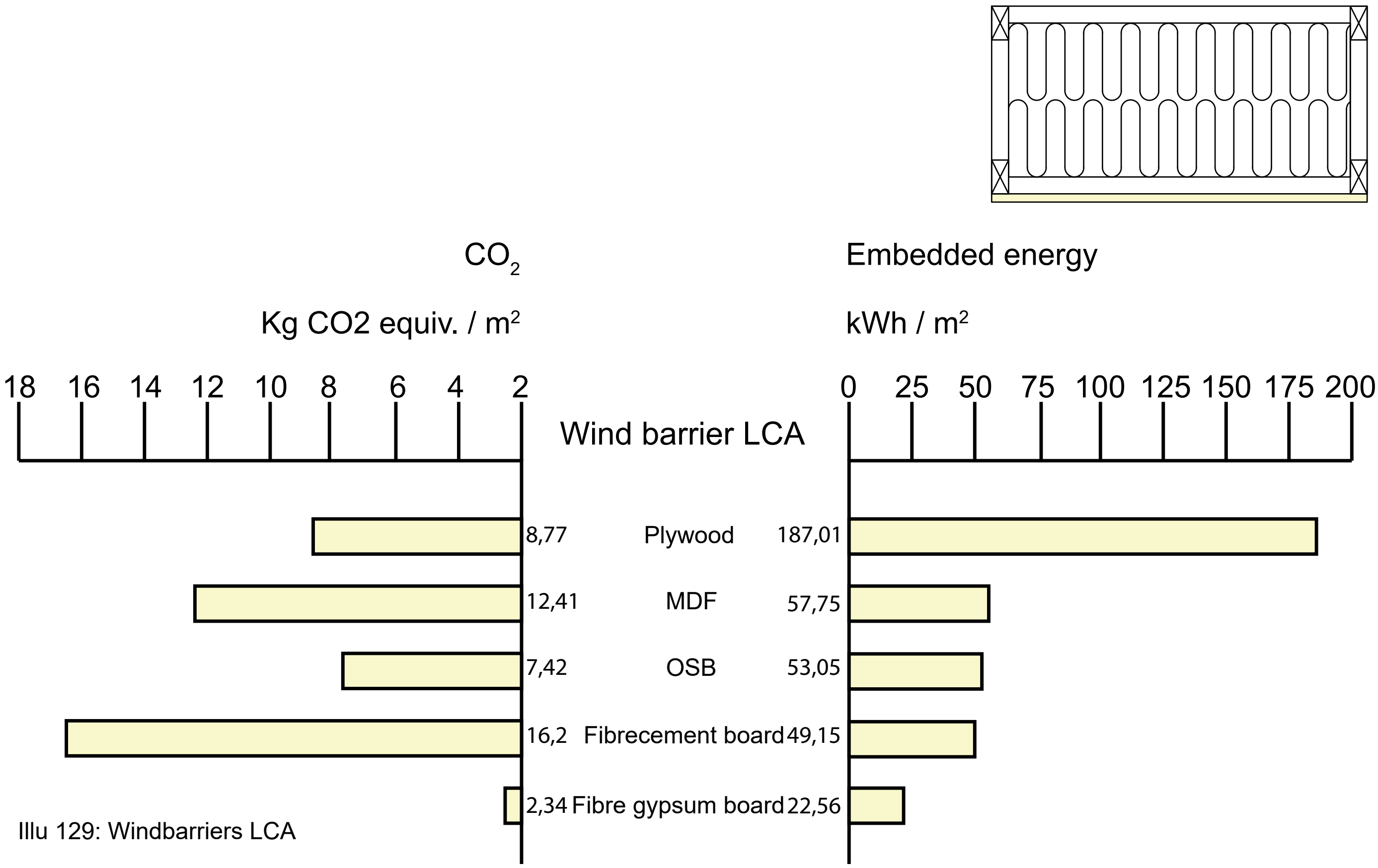
To optimize the construction further, it is important to choose a low-emitting insulation material. To create functional equivalence, the U-value is kept the same, which is determined as 0,12 W/m^2 K (see Appendix 2). As the different insulation materials have varying thermal conductivity and the U-value is kept the same, the thickness of the materials varies.

As Illu 130 shows, the best solution in regards to the CO_2 is the paper wool whereas the best for embedded energy is straw. These two options are however not feasible in the CE perspective, as paper wool is a porous material and when separating the modules from each other, the paper wool will fall out; and the straw insulation has a bad thermal conductivity resulting in a much thicker wall compared to the three other, which also means more construction wood.

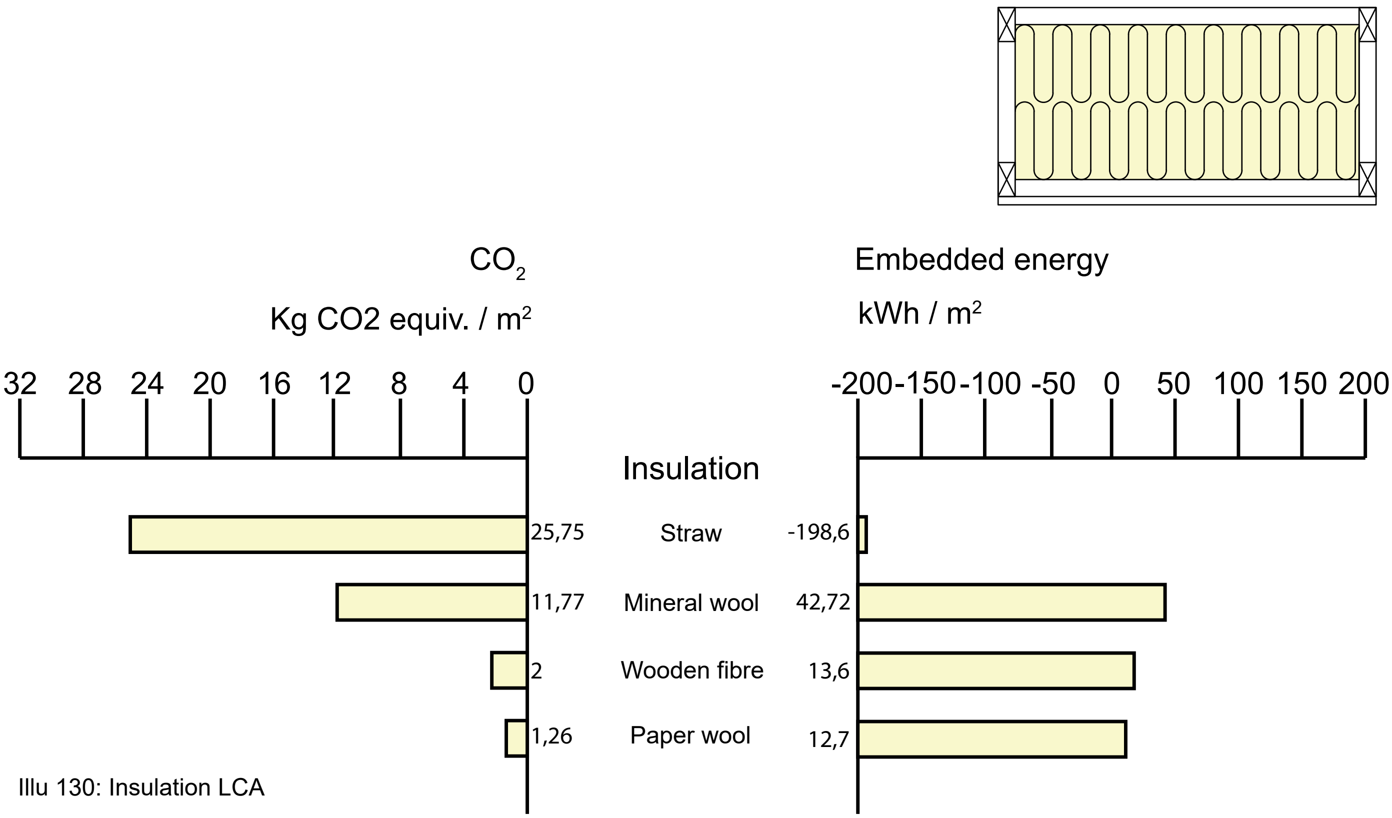
Therefore, the wooden fibre are utilised as the insulation material in the further design, as that has the second-lowest CO_2 emission, is made of wood which stores CO_2 and is a renewable material. This will also be used for the partitioning walls.

Conclusion

The modules are optimized with the best solution in regards to the wind barrier and the insulation. The wind barrier will be a Hunton board, and the insulation will consist of wood fibre insulation, which creates a low-emitting module.



Illu 129: Windbarriers LCA



Illu 130: Insulation LCA

INTERIOR WALL COMPARISON

Intro

Based on previous sketches for the interior wall system, this chapter will compare the chosen system, to that of an ordinary interior wall. The comparison is based in LCA. The goal is to show that a flexible interior wall is not only functionally better but also provides a better environmental footprint.

Construction and materials

A detailed drawing of the interior wall module can be seen on the next page (see Illu 132), along with dimensions and material amounts. The module wall is based on the standard interior wall, and, therefore, they are functionally equivalent. The standard interior wall can be seen in Appendix 3.

It can be seen in both detail drawings, that finishing claddings are omitted, as these are subject to a different investigation later on in the project. The difference, therefore, only lies in the construction of each wall type. Since floor and ceiling are a part of the modular system, these have also been counted into the standard solution.

For the two types of walls to be comparable besides the construction, they must also be used to design the same floorplan and interior wall separations. This floorplan can be seen in Appendix 3.

The material amounts and types can also be seen in Appendix 3. Here it is clear, that there is a large discrepancy between the amount of construction wood used in the standard wall (0.86 m^3) and the modular wall (5.8 m^3).

But as it can be seen in the table on the next page, the environmental impact for CO_2 is much lower for the modular wall. This is due to the fact, that the materials in the modular wall, have had their usual end of life phase removed. This is because the concept is that the wall segments are designed to be disassembled after final use, and can then be reused in another product. The end of life is, therefore, unknown, but it is expected that it is reused. Since the modular wall has no negative end of life, it is easy to say that it, therefore, is better than the standard, because it has a positive impact on the environment.

It might, therefore, also make sense to see, how many times the standard wall needs to be replaced before the same amount of material is used, which is around 7 replacements, while 2 replacements are necessary before the embedded energy is higher than that of the modular wall.

As mentioned in Towards a Circular Future (Jensen and Sommer, 2019) interior walls might only be expected to last 10-15 years, before they become obsolete and have to be replaced. It thereby takes around 90-100 years for the material of the modular wall to be used by the standard wall.

However, this does not account for the need to also change the final claddings for each replacement. Which might prove to be a substantially higher environmental impact than here calculated. This is where the reuse of the modular wall shows its strength, as nothing needs to be replaced material-wise when a functional conversion is made.

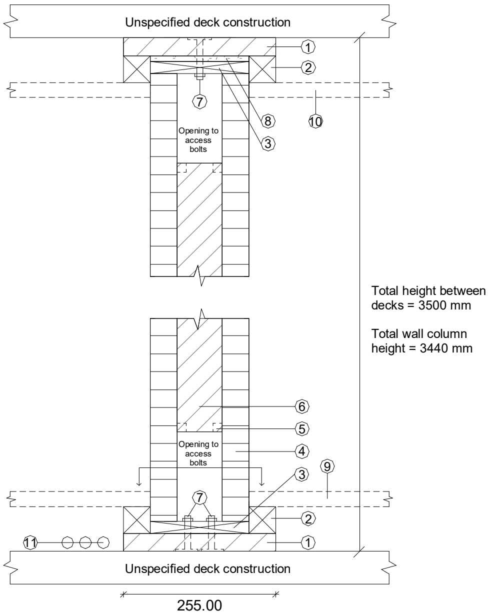
It, therefore, can be summarised, that the modular wall is indeed better for the environmental impact. But it does use a significant amount of construction material. In further iterations, there should be a focus on lowering this material usage, and then a deeper look into each materials healthy properties.

Conclusion

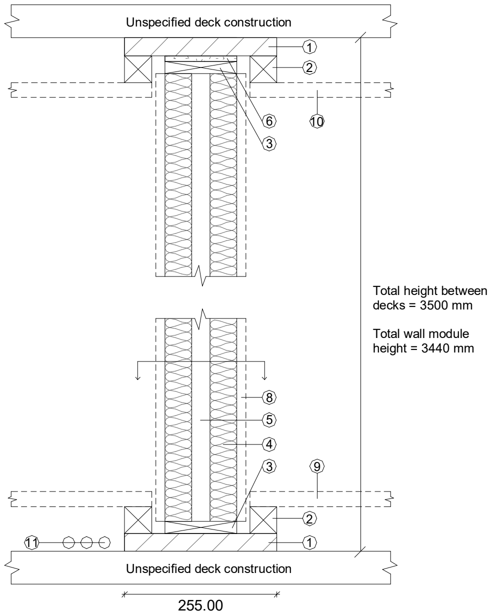
Through this comparison, it has been discovered that a modular wall build around CE does have a much lower environmental impact. But this particular modular wall sketched, needs to be iterated and optimized, so that it does not use as much construction wood as now.

Interior module - Column and Wall

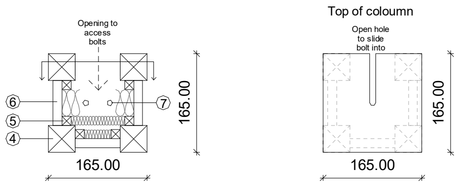
Cross section - Column



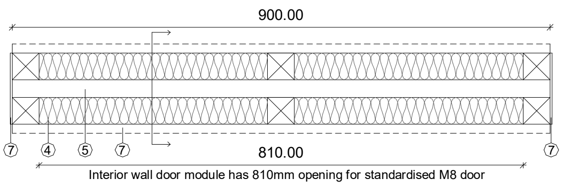
Cross section - Wall



Plan section - Column



Plan section - Wall



Column legend:

1. 255 x 255 x 30 mm Floor/ceiling grid board (0.004 m³)
   255 x 45 x 30 mm at floor/ceiling edges (0.00069 m³)
   90 x 90 x 30 mm at floor/ceiling corners (0.00048 m³)
2. 45 x 45 mm Floor/ceiling latching (0.0072 m³ pr square floor/ceiling)
3. 165 x 165 x 30 mm Top/Bottom board colomn module (0.0016 m³)
4. 45 x 45 mm Vertical latching (0.28 m³)
5. 15 x 15 mm Wood cladding attachment (0.0081 m³)
6. 75 x 15 mm cladding
7. Bolt/nut fixing for colomn
8. 10 mm compressible foam (0.00027 m³)
9. Potential floor cladding
10. Potential ceiling cladding
11. Heating and electrical wiring

Wall legend:

1. 255 x 255 x 30 mm Floor/ceiling grid board (0.004 m³)
   255 x 45 x 30 mm at floor/ceiling edges (0.00069 m³)
   90 x 90 x 30 mm at floor/ceiling corners (0.00048 m³)
2. 45 x 45 mm Floor/ceiling latching (0.0072 m³ pr floor/ceiling square)
3. 120 x 30 mm Top/Bottom board wall module (0.0065 m³)
4. 45 x 45 mm latching with mineral wool insulation (latching 0.038 m³) (insulation 0.23 m³)
5. 30 mm Air gap
6. 10 mm compressible foam (0.0011 m³)
7. 3 mm cork board (0.0025 m³)
8. Potential wall module cladding
9. Potential floor cladding
10. Potential ceiling cladding
11. Heating and electrical wiring

Illu 132: Sections describing the inner walls

Standard interior wall	Global Warming Potential (kg CO2 eq)	Embedded Energy (kWh)
Initial environmental impact	- 1248 kg CO2 eq	+ 14445 kWh
Change with each replacement	+ 1130 kg CO2 eq	+ 10770 kWh
Change with final replacement	+ 2380 kg CO2 eq	- 3680 kWh
Modular interior wall		
Initial environmental impact	- 4756 kg CO2 eq	+ 31700 kWh

Illu 131: This table is based on numbers seen in Appendix 3.

INTERIOR WALL OPTIMIZATION

Intro

The purpose of this chapter is to optimize the inteiror modular wall, based on earlier LCA comparisons. The main purpose will be to lower material usage in the module, along with investigating all materials in relation to health aspects.

Optimizing the interior wall

Because of the modular interior walls high usage of construction wood, additional sketching is needed to find a better solution.

On the next page, sketches showing attempts of removing the need for the column and sketches that try to redesign the column can be seen.

The sketches without the column encounter the same issues as earlier sketching iterations. There is a need for the wall to be mirrored around an axis, for it to be completely flexible. But without a column, this mirroring cannot be achieved.

Redesigning it to a column with a more compact solid wood column, only proves to either use more wood or to again not be able to achieve mirroring. The best solution then found, is to instead design a column, which functions exactly the same, but simplifying the need for construction wood, by using the already existing wood planks, in a wider form, that is then joined with small leftover pieces of wood as seen on Illu 138.

This uses around 2-2.5x the wood planks, which is still large whole pieces that can later be reused. But in turn uses around 80-90% less construction wood, and the construction wood used can easily be leftover wood from production of other parts of the modules.

The largest downside is that this solution has the wood planks going through the entire construction on each side, meaning it can carry some sound through the wall, but this is not deemed to be of any larger significance. It is also evaluated that this is structurally possible because it is non-load-bearing.

Looking into the health of the main materials, the following has been concluded for each. Excluding insulation as it has already been explored.

- Construction wood and wood planks

Both construction wood and the wood planks are massive wood elements of 100% wood, and, therefore, have no dangerous effects on human health. (trae.dk. 2020)

- Cork

Cork is used as a material to seal and insulate the joints between wall and column, both sound and fire. Cork as a material is already used in many types of construction products, such as flooring. There are many examples of sustainable and non-toxic cork. (Timberman.dk. 2020)

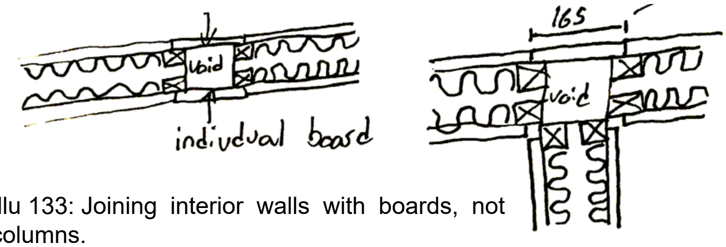
- Compressible foam

The compressible foam makes the interior wall work, by being able to compress and expand, it ensures tightness along the top of the modules. Regular foam materials are often polymers with additives that can have negative health impacts. But new types of biofoam are starting to appear, that prove to be non-hazardous and fully cradle to cradle certified. (Synbratetechnology.com, 2020)

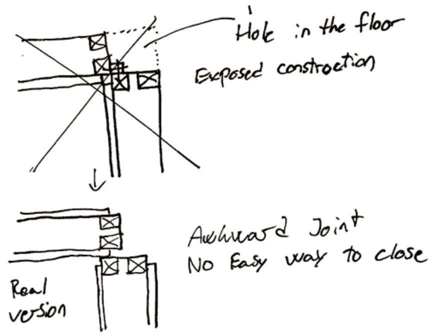
Conclusion

By optimizing the column's construction, it is possible to save around 80% construction wood, while retaining the same functionality. The main materials of the interior walls have also all been found, to have sustainable and healthy options, that can be utlized for the finished product. In this way, the interior walls will have no negative impact on human health, and will help provide a good indoor climate.

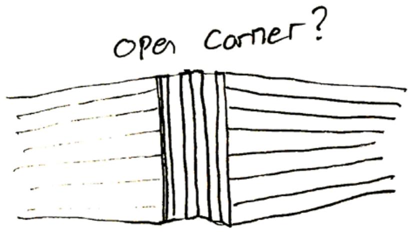
Interior wall without column



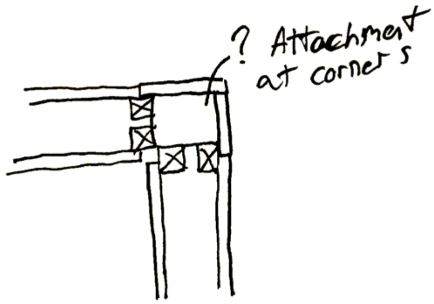
Illu 133: Joining interior walls with boards, not columns.



Illu 136: The issue with not being able to mirror the junction point

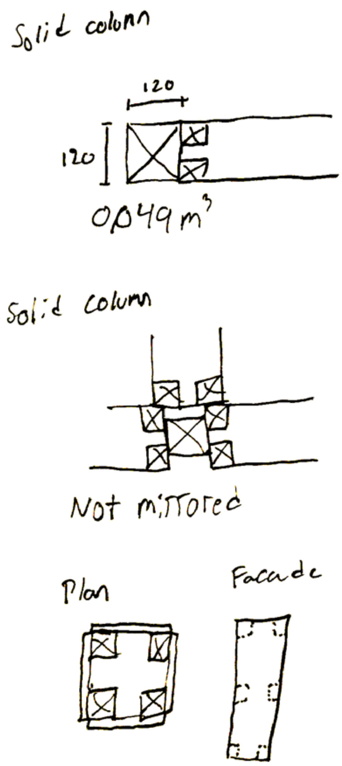


Illu 134: Aesthetic implications of having an inverted corner

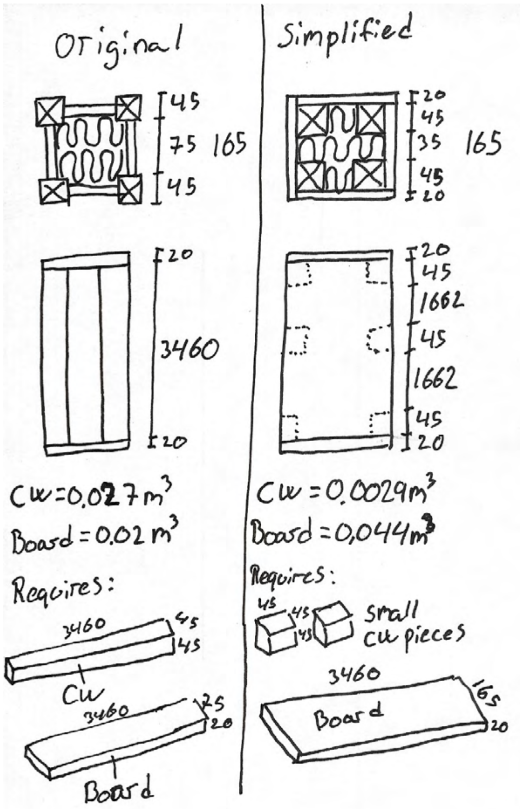


Illu 137: Issues with placing cladding when there is no fixing point at corners

Interior wall with different column



Illu 135: Solid wood columns



Illu 138: Original vs. optimized column module

FOUNDATION

Intro

The purpose to this chapter, is to evaluate existing foundation types to identify which ones fit best into the concept of DFD and CE.

Foundation

The foundation is the transition between ground and the walls of the building and has the purpose to carry the weight of the loadbearing and stabilizing walls, and thereby ensure that the building does not move downwards. The foundation is, therefore, always placed below the loadbearing walls, which in this project is the exterior walls. (Bolius.dk, 2018)

The most used type of foundation is the line foundation (see Illu 139) where a line is dug out in the ground and filled with concrete, the line foundation is placed under all load-bearing walls. Due to the casting of concrete this type of foundation is hard to adjust once it is cast. When disassembling the building again, it is not possible to remove this foundation type without destroying it. There is, therefore, no reuse potential, along with the implications of using a lot of concrete. (ibid)

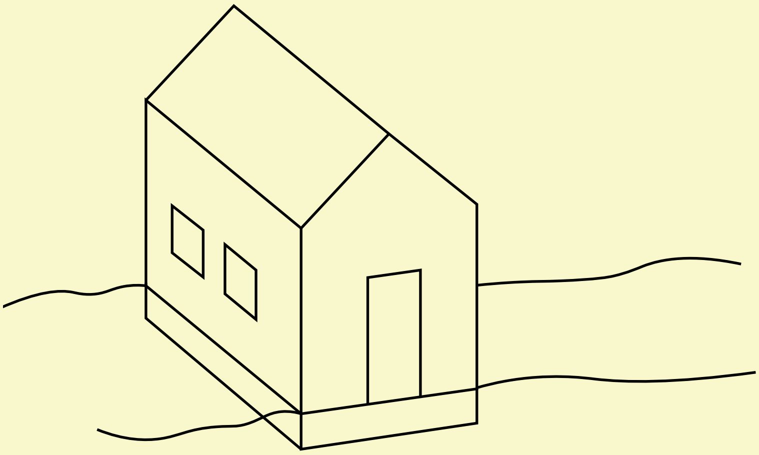
Another type of foundation is the pillar foundation (see Illu 140). This principle includes pillars, often made in concrete but can also be in wood or steel. The pillar foundation is often used when the loadbearing ground-layer is placed more than two to three meters down. The pillars are knocked into the loadbearing layer by a large machine. It is also difficult to remove again, as deep pillars can be impossible to pull out due to their weight, and the vacuum effect of the ground. (ibid)

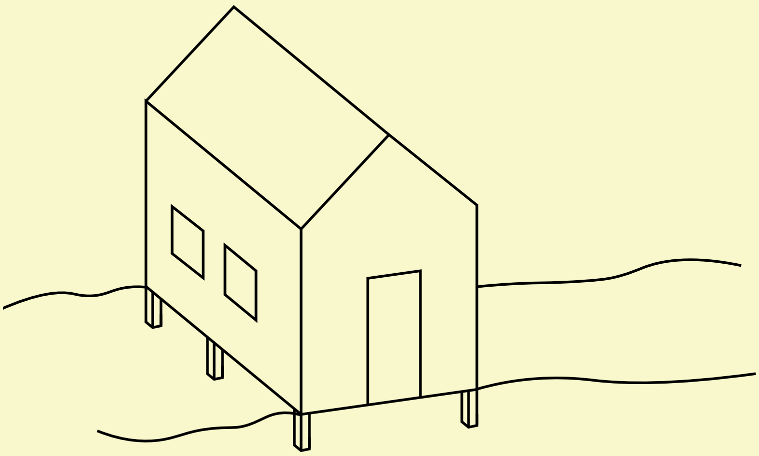
A newer type of foundation is the screw foundation, which is like the pillar foundation, but instead of hammering the pillar into the ground, it is screwed in. This foundation then has a similar function to the pillar foundation but can easily be installed and removed again. The downside is that this only works with lightweight buildings such as wood constructions. Screw foundations can also be installed by smaller machinery, as the same amount of power is not needed. (ibid)

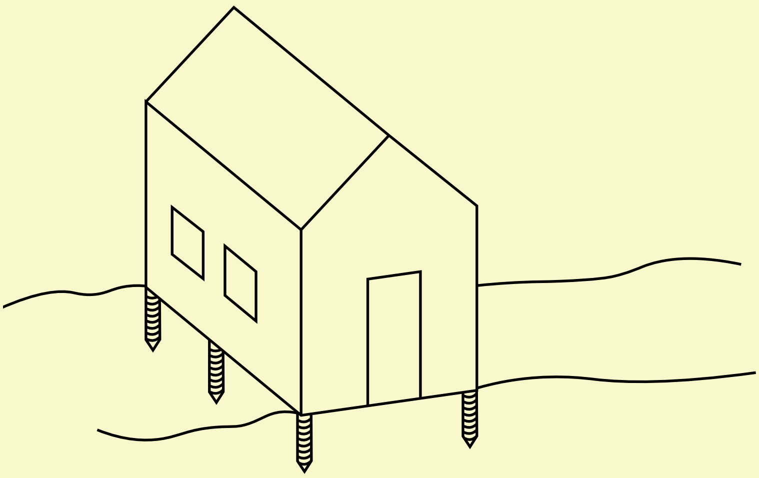
When comparing the foundations, only the screw foundation meets the requirements for DFD, and it should, therefore, be an obvious choice for foundations. It is possible to choose this foundation, as this project has already identified using wood construction, and thereby meets the requirements for lightweight construction. Screw foundations also save the need for using concrete, which can result in savings of up to 90% CO2 emissions from the foundation of a building (Fremtidensfundament.dk, 2020), along with steel being much easier to reuse in a CE perspective.

Conclusion

Through exploration of different foundation concepts, the screw foundation method has been identified as the best solution. It allows for easy assembly/disassembly, along with its carbon footprint being around 90% lower than standard concrete foundations. Screw foundations, therefore, fit perfectly into the different aspects of circular economy.


Illu 139: Line foundation


Illu 140: Pillar foundation


Illu 141: Screw foundation

MASTERPLAN

Intro

The purpose of this design task is to initiate sketching of the masterplan for the proposed co-housing project. The goal is to identify layouts that are beneficial with regards to view lines, sun exposure, private/public outdoor space, and relation to the common room.

Sketching

Initial sketches are carried out and can be seen on the next page. The sketches are made with the idea in mind, that the buildings currently have the same shape, as the plans sketched earlier with regards to flexibility (16x11m double houses), and that the common room is its own separate building. Both of these building types will be detailed much further in following design chapters.

The sketches mainly focus on achieving a common room, that is centrally placed among the living units. It is here concluded, that for the common room to be centrally placed, it must be either centrally placed around a circle of buildings or must be placed south of a line of buildings. This south-facing placement is due to the slope of the site, which allows the living units to look down into the common space, along with open rooms such as kitchen/living room are commonly placed to the south. If the common room is placed north of the buildings, fewer views and interaction is expected.

View lines

Taking point of departure in the sketches, some of the proposals have been created using a scale model, to identify correct layout sizes and possibilities. These model proposals have been analysed with regards to view lines, and this can be seen on Illu 148 to Illu 153.

With this view line analysis, it is important to remember, that there is a topography height difference of 5-7m from edge to edge of the site. Such a big change can allow buildings, that on plan look to be blocked, be able to achieve views because it looks over the building in front of it as it lies lower. From the analysis the following layouts have been chosen: masterplan 2, 3 and 6 (see Illu 149, Illu 150, and Illu 153) because they all provide good views towards the city and water along with all having views to the common room.

Sunlight hours

These layouts will now be analysed with regards to the number of sunlight hours on the ground of the outdoor areas. The purpose of this is determined which layouts provide the best possibilities for outdoor space, both for public and private areas. It can be mentioned that an analysis of radiation exposure on the facades was planned as well. But because of the relative distance between the buildings, no shadowing happens, so this analysis did not make sense.

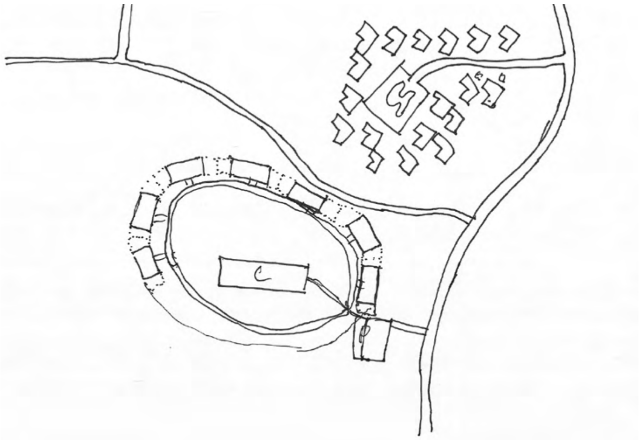
The analysis can be seen on the next spread. This shows that there is not much difference between the layouts and that they all provide adequate outdoor sunlight. It can then be noticed, that the circular shape has 9 buildings, whereas the half-circle only has 7. Along with this, the circular shape also better represents itself, with how one enters the site, being directly open towards the common room centre from the access points to the east.

The circle shape provides public outdoor space around the common room both south and north, while still being within the defined area. The other layouts have their southern and, therefore, preferable outdoor space in relation to the common room, pointing away from the dwellings. The circle space is, therefore, both more defined and more in relation to the other buildings, along with still providing good views as earlier explored. Therefore, the circle shape should be the overall concept for moving forward. It is expected that with further detailing of the apartment buildings and the common room, more precise placement of each building on the site can be created, but the overall conceptual shape has been decided.

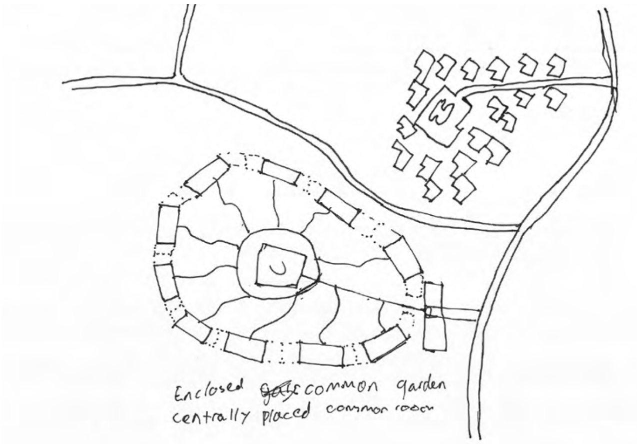
Conclusion

Through sketching and analysis of sketched proposals, it has been decided that the concept for the masterplan, is a circular shape with a centrally placed common room. This shape allows for good views, good and defined outdoor areas, intuitive access from the road, and equal access from all buildings into the common space. To further detail the masterplan, the individual buildings must be further designed and detailed, which should be the next step.

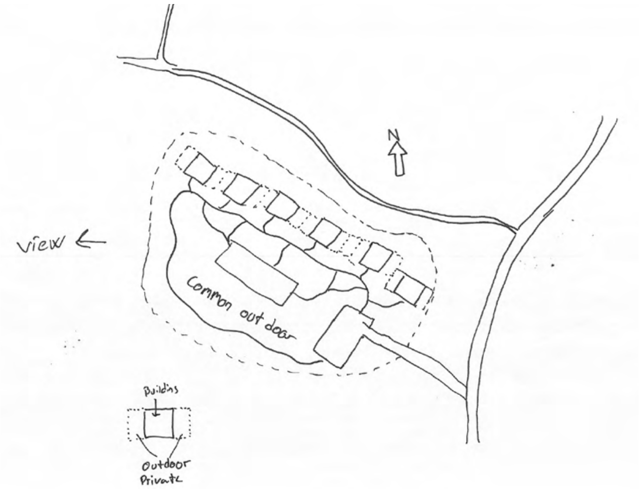
Sketching



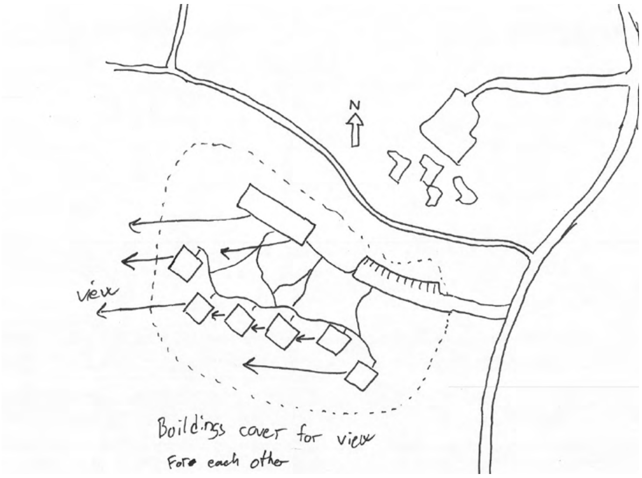
Illu 142: C- shaped masterplan



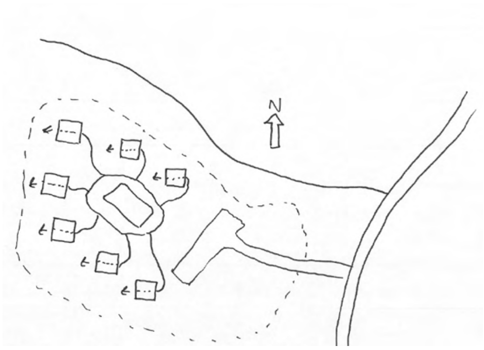
Illu 143: Circle-shaped masterplan



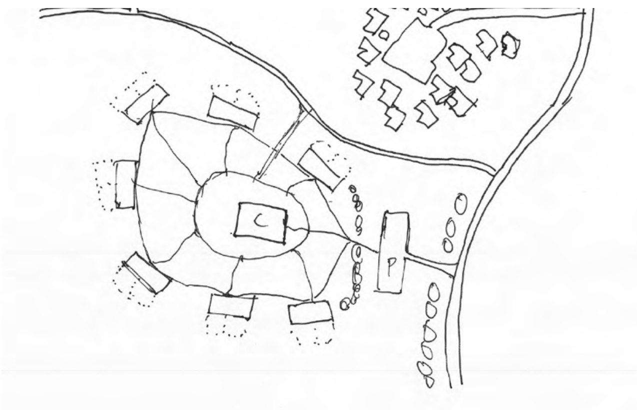
Illu 144: Common room placed towards South



Illu 145: Common room placed towards North

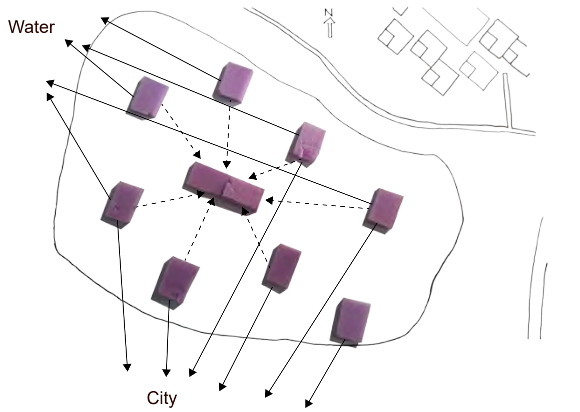


Illu 146: Centrally placed common room

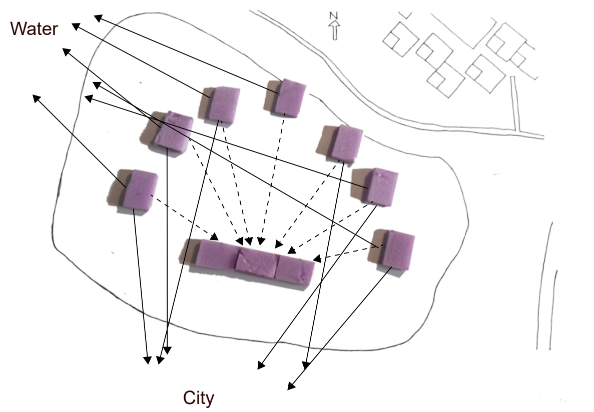


Illu 147: Centrally placed common room 2

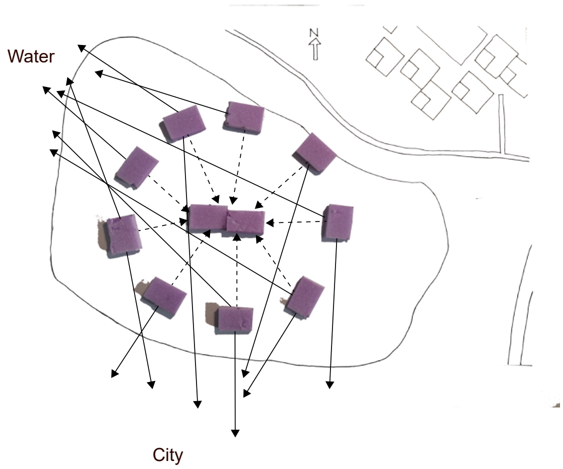
View lines



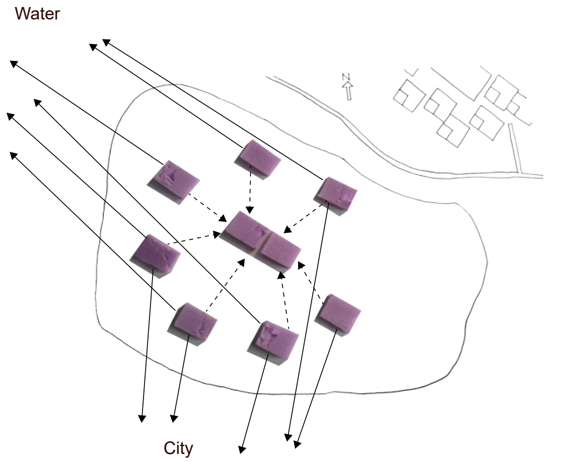
Illu 148: Masterplan 1. Good amount of views towards the city, bad amount of views towards water, not all have view to common room



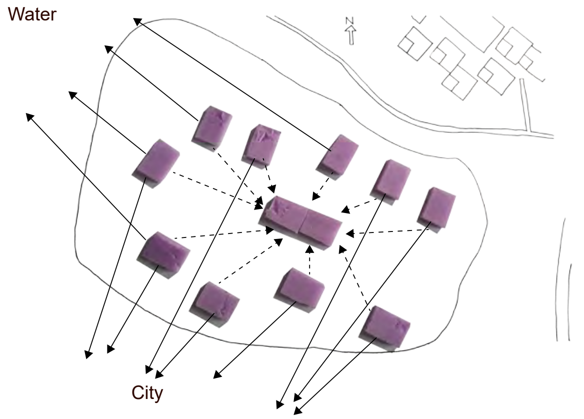
Illu 149: Masterplan 2. Good amount of views towards the city, good amount of views towards water, all have view to common room



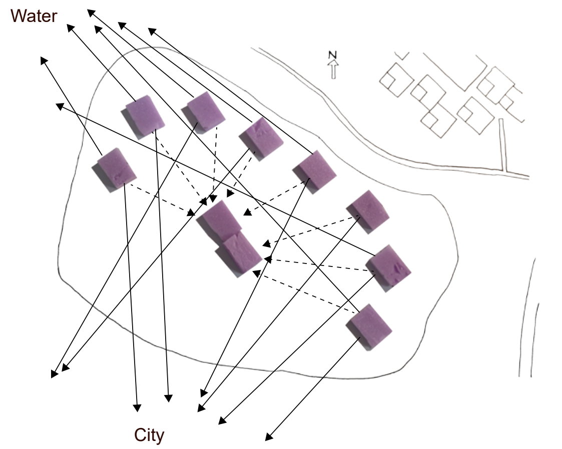
Illu 150: Masterplan 3. Good amount of views towards the city, good amount of views towards water, all have view to common room



Illu 151: Masterplan 4. Bad amount of views towards the city, good amount of views towards water, all have view to common room

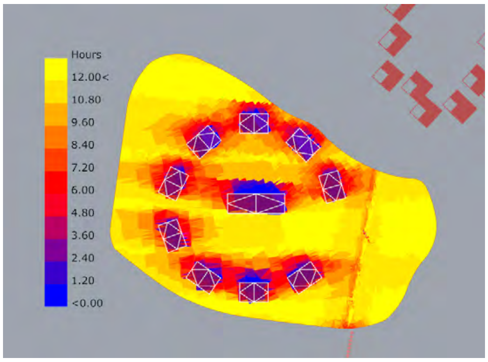


Illu 152: Masterplan 5. Good amount of views towards the city, bad amount of views towards water, all have view to common room

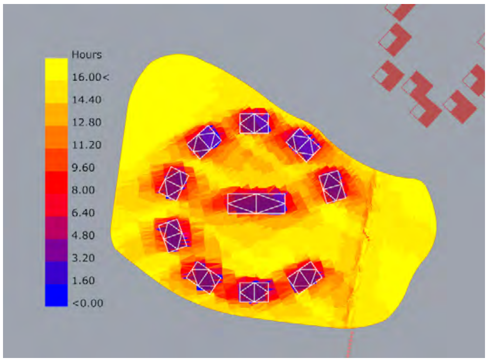


Illu 153: Masterplan 6. Good amount of views towards the city, good amount of views towards water, all have view to common room

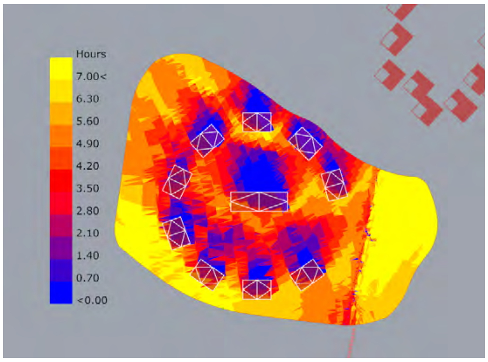
Sunlight hours



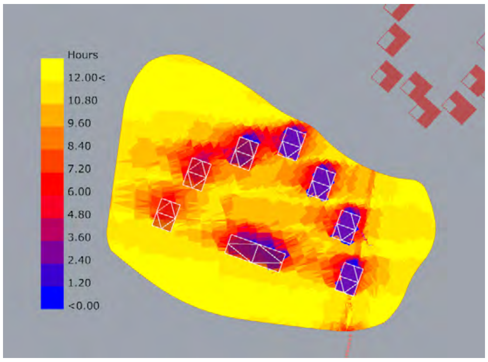
Illu 154: Circle sunlight hours 21/3



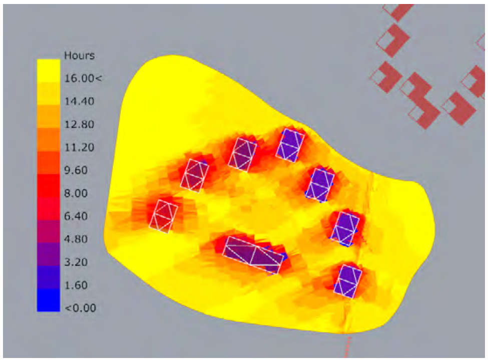
Illu 155: Circle sunlight hours 21/7



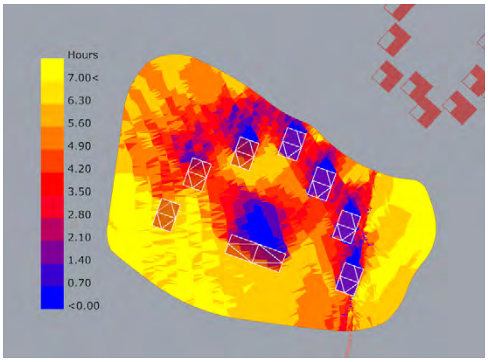
Illu 156: Circle sunlight hours 21/12



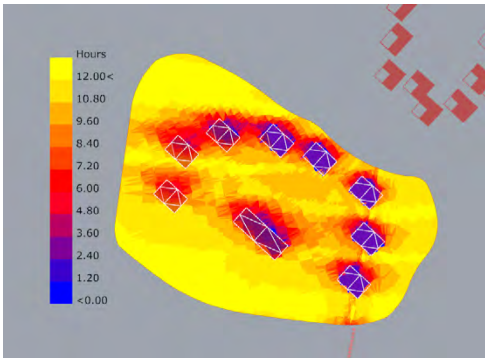
Illu 157: Half-circle sunlight hours 21/3



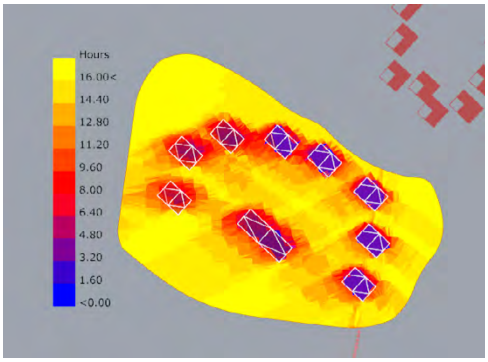
Illu 158: Half-circle sunlight hours 21/7



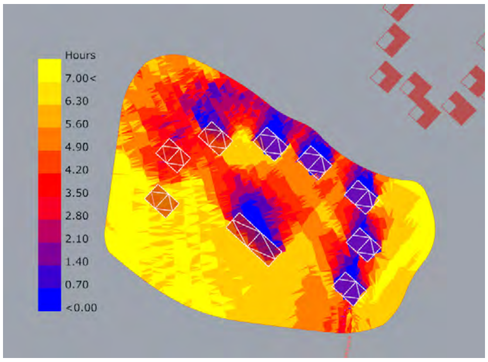
Illu 159: Half-circle sunlight hours 21/12



Illu 160: Half-oval sunlight hours 21/3



Illu 161: Half-oval sunlight hours 21/7



Illu 162: Half-oval sunlight hours 21/12

COMMON HOUSE SKETCHING

Intro

With the masterplan being decided, it is time to sketch the common houses centrally located. Both determining the overall shape of the common houses, and designing the interior spaces using the modular system. The goal is to achieve a proposal for a final layout, that can be optimised through the design parameters.

Sketching the form

Sketches on iterations of the form and orientation of the common houses can be seen on Illu 163-Illu 164. Since the building will be made with the modular system, larger houses will have to be made into rectangular shapes, because of the maximum depth. Rotating such a rectangle does no matter what angle, result in areas of the site that relate less because it is impossible to properly obtain vision into the common house.

Therefore, further sketching is developed, to create a shape that allows for equal accessibility and views from all areas of the site. A circular shape is the obvious, but not possible choice, as the modular system cannot do circular shapes. The shape is then either designed as a cross or a V (see Illu 165 and Illu 170).

A challenge that arises with both cross and V shapes, is that corners or middle sections will result in roof/deck constructions that cannot be supported, as it is only the exterior wall that is fully load-bearing. These corners must, therefore, be voided, which results in a too fractured form using the cross. The V shape is divided into two buildings, which can be split into “utility” and “common”. Where utility consist of a workshop, laundry, drying, and guest bedroom, and the common includes a kitchen, dining, and lounge area.

Further, different orientations of the two buildings have been explored, and it has been finally concluded, that the V-shape is important to maintain.

Floorplan and layout

When sketching the utility house, there was a focus on creating visibility, to allow people to see the work going on in the workshop. The final layout as seen on Illu 176, has two guest bedrooms that utilize a bathroom placed in the common house but is accessed from the outside. The bedrooms are separated from the noisy washing and workshop area, by a drying room, which can be used by the inhabitants to dry clothes, thereby negating the need to use machine dryers.

When planning the layout for the common house, there was a focus on opening up towards the entrance of the site to the east. This is to allow people coming home from work, to see if things are happening in the common area, that they might want to join.

Through the sketching it also became aparrent, that in order to achieve different zones in the common house, the kitchen and technical core could be used to seperate the spaces, as seen in the final proposal on Illu 177.

The layout focuses on having the kitchen and dining space be the heart of the house, and they orient out towards the south facade where outdoor space will be located.

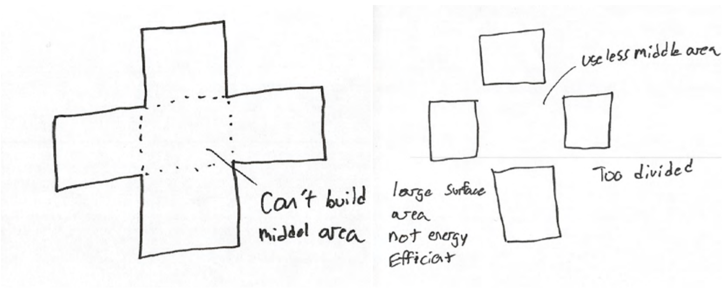
Conclusion

By investigating different shapes for the common spaces, an open V-shape was chosen that allows the space to be split into a utility and common house. The two houses create a natural shape that can allow outdoor space to be sheltered from the wind. The interior of the common house has been designed with a focus on the kitchen and dining area being the heart. While allowing for a smaller setback area for lounging.

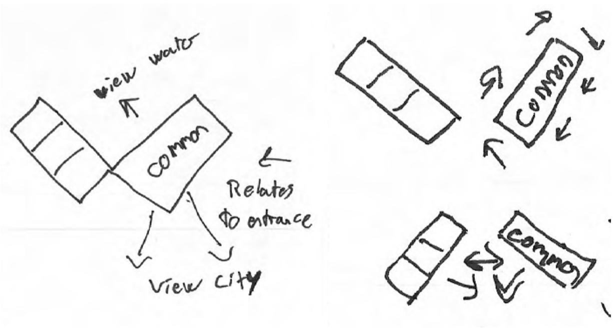
Sketching the form

Illu 163: Rotating a rectangular shape

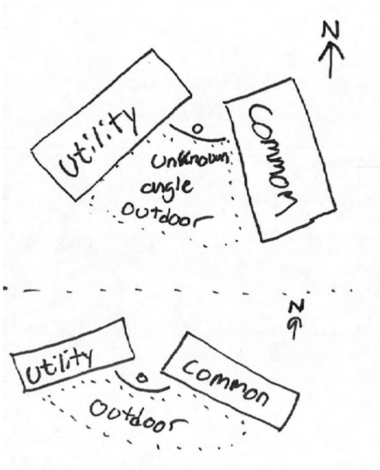
Illu 164: Sketching equally accessible shapes



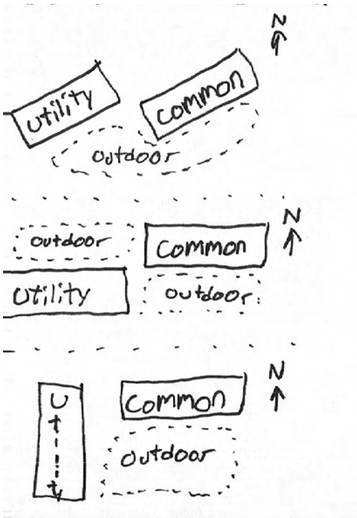
Illu 165: Cross shape sketched further



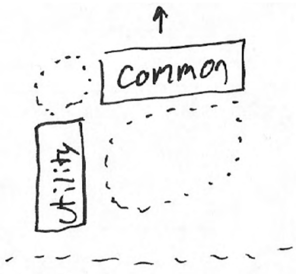
Illu 170: Sketching the V-shape, determining orientation and relation to site



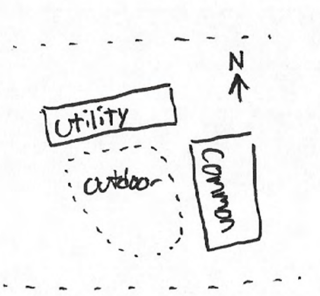
Illu 166: Exploring angles between the building and orientation



Illu 167: Exploring different placement for the two buildings, and the following outdoor space

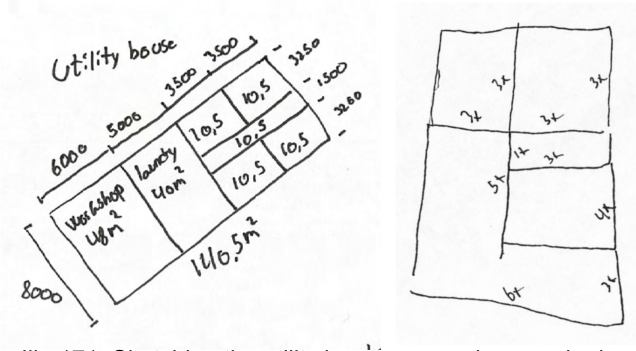


Illu 168: North/South facing common room

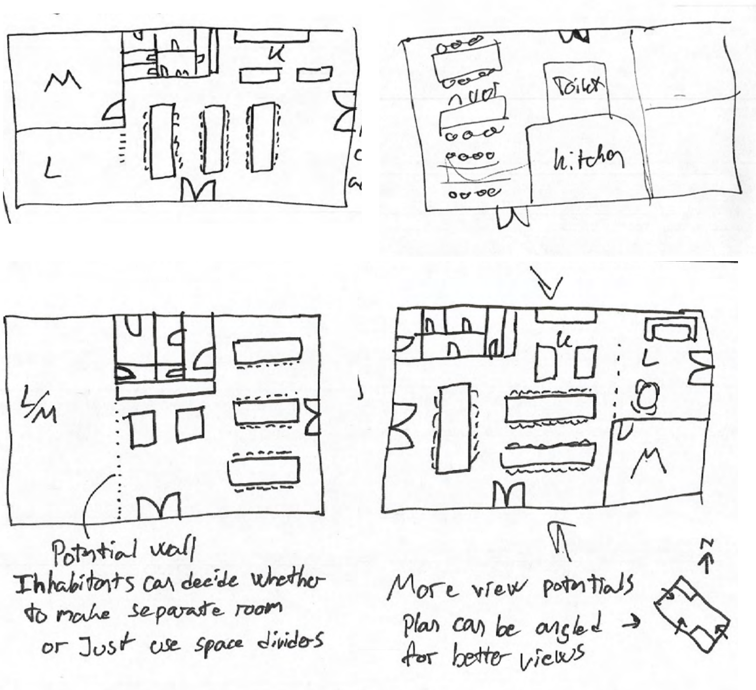


Illu 169: East/West facing common room

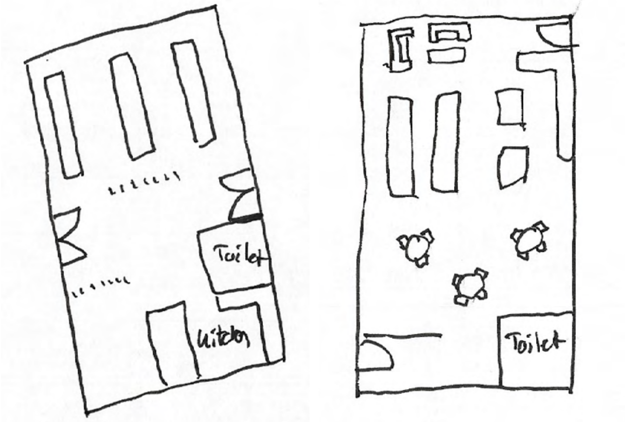
Floorplan and layout



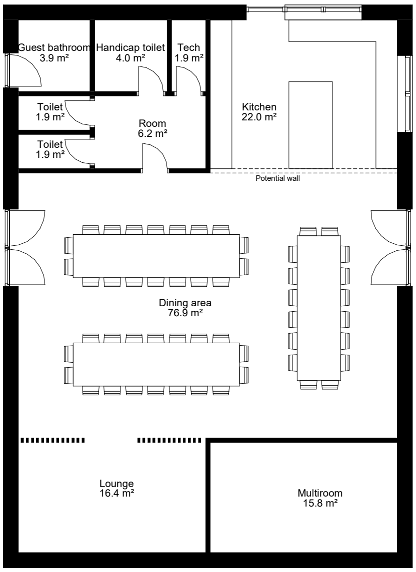
Illu 171: Sketching the utility house, room sizes, and adjustments with the module system.



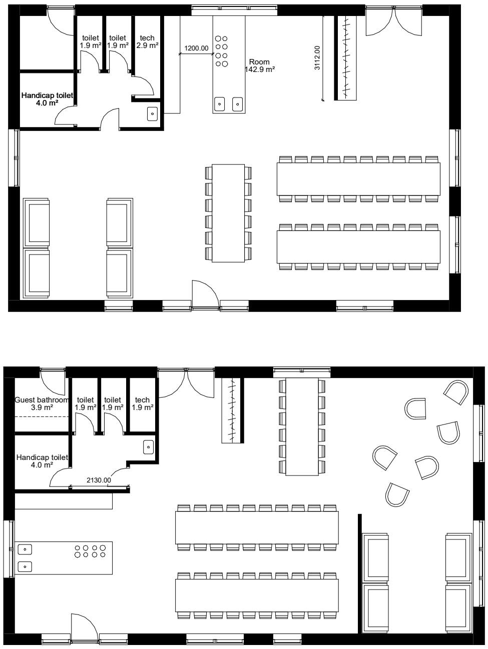
Illu 173: Sketching the common house. Early sketches on a N/S facing building.



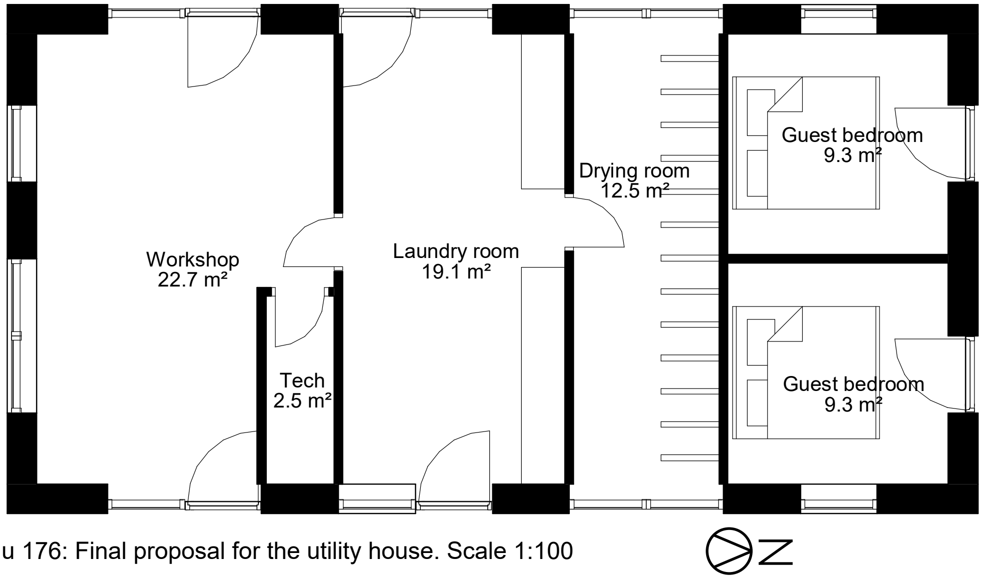
Illu 172: Sketching the common house. Early sketches on a E/W facing building.



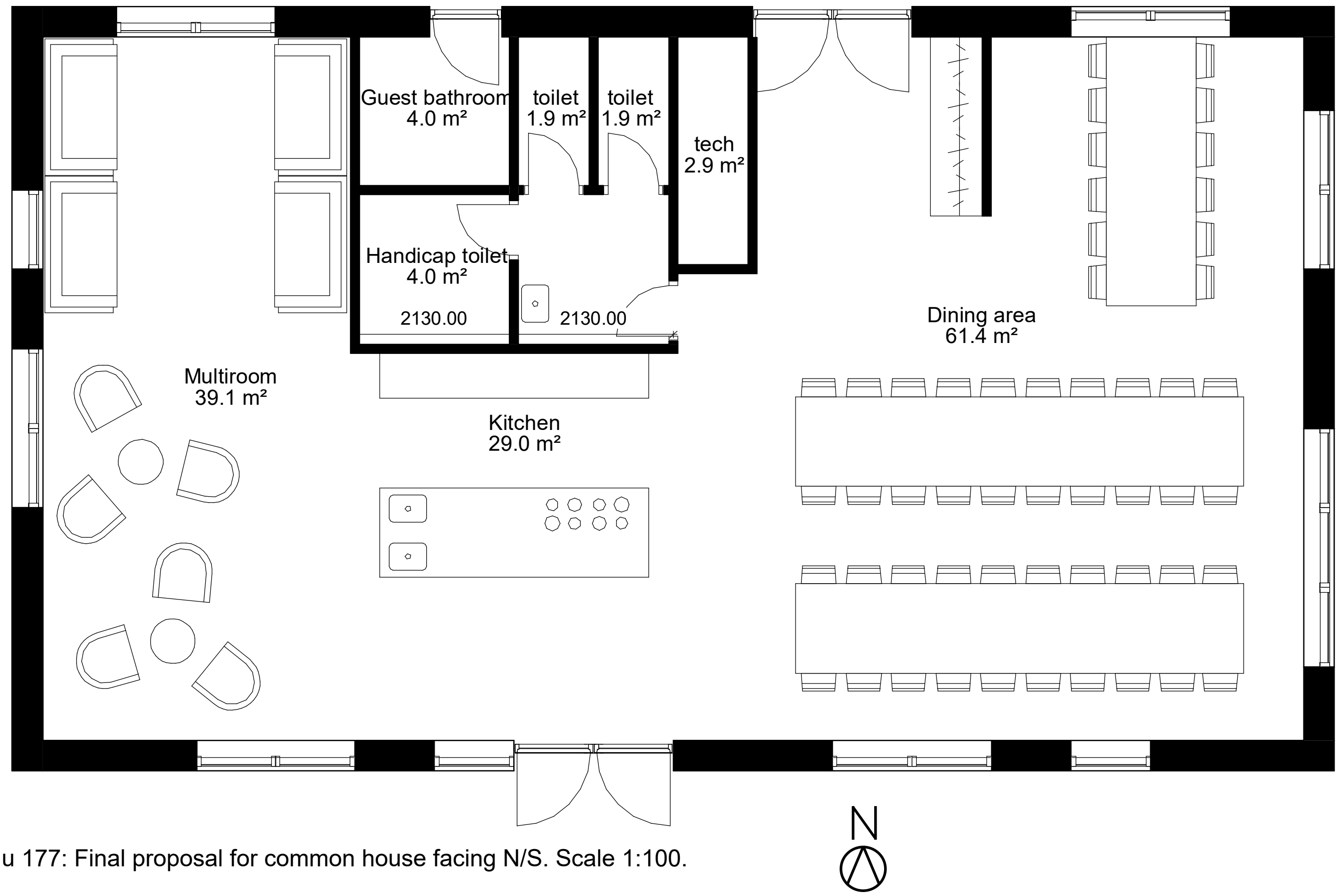
Illu 174: Sketching the common house. Late sketches on a E/W facing building.



Illu 175: Sketching the common house. Late sketches on a N/S facing building.



Illu 176: Final proposal for the utility house. Scale 1:100



Illu 177: Final proposal for common house facing N/S. Scale 1:100.

PLAN SOLUTION DWELLINGS

Intro

The purpose of this design task is to design the plan solutions further, hereunder achieving flexibility within the plan solution, reducing the square meters along with fitting the plan solutions to the modular system.

Plan solutions

The plan sketching had a big focus on creating flexibility in the dwellings, along with reducing the square meters as the theory of cohousing states.

As all buildings should have entrance towards the common area, two overall types of buildings should be designed; one building type north of the common room, and thereby entrance towards the south and another type placed south of the common room and thus with entrance to the dwelling from the north.

Common for all dwellings were, that each household should have between 2-4 rooms each, where one of them is a master bedroom on 12 m² along with achieving common space like the living room or dining area towards the south. It was previously decided that the dwellings should be made as double houses, with a core containing technical room, bathroom, and kitchen.

Three ways to design the core were investigated as seen on Illu 178 – Illu 180. Illu 178 takes up the whole side of the dwelling, which minimizes the possibilities to have flexibility between the two dwellings (see Illu 181 and Illu 184), and, therefore, not further investigated, whereas the two others each provide different advantages and disadvantages.

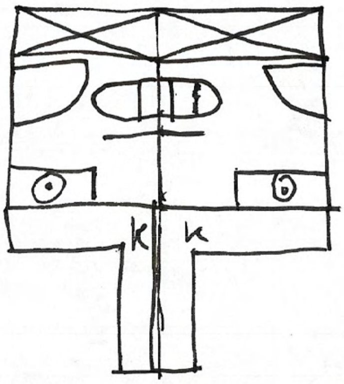
It was also tried that the core should be separated, so each dwelling has their own (see Illu 182 - Illu 183), but this provides more hallway area and reduces the flexibility in the dwellings.

Different sizes of double houses with the two varying cores were investigated for both the north and the south buildings. The core seen on Illu 179, used on Illu 185 and Illu 193 - Illu 195, made the plans longer and narrower and minimised the kitchen area. By having the technical room in between the bathrooms, the separating walls between the dwellings are favoured to one dwelling, which makes the plan uneven (as seen on Illu 185).

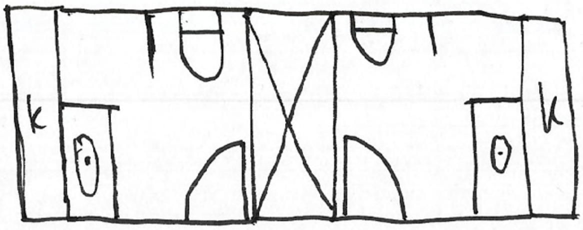
Many of the plan solutions with the third core had difficulties with the rooms and kitchen not aligning, making the kitchen feel more like a hallway than a part of the dining or living area, which is not wanted (see Illu 186 – Illu 188). By extending the dwellings one module further, the rooms and kitchen align, but the entrance area becomes too large (see Illu 189). To solve this, some of the area can be extruded inwards (see Illu 190), which creates a covered entrance which is marked from outside, along with having aligning rooms and a defined entrance in an acceptable size.

Conclusion

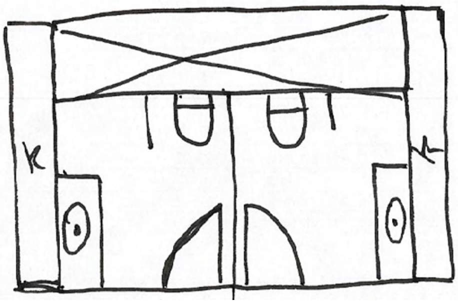
To conclude, two overall types of dwellings are made; one with the entrance towards the south and one with the entrance towards the north. The dwellings should have 2-4 rooms, with one being a master bedroom and having a living area towards the south. The final plans should have a marked and covered entrance, aligning rooms and use the third core, which provides the most flexibility.



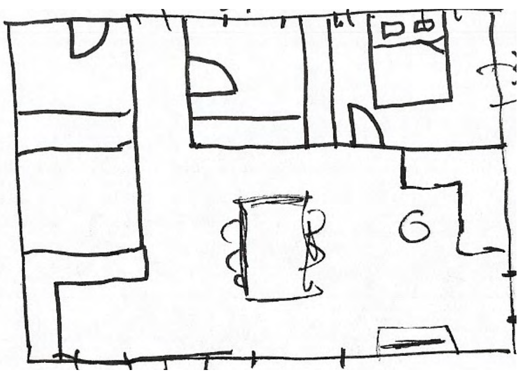
Illu 178: Core principle 1



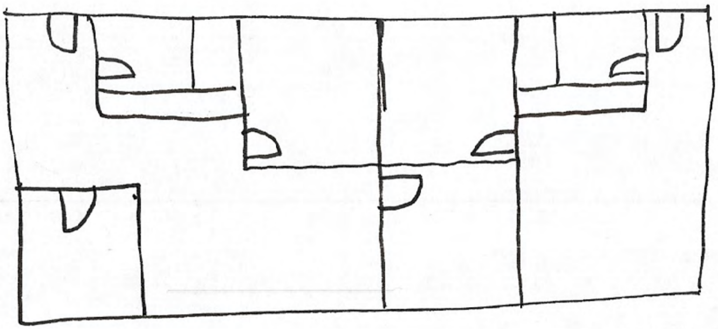
Illu 179: Core principle 2



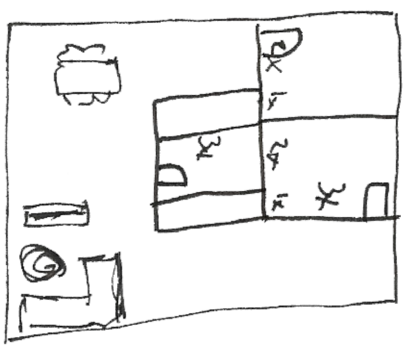
Illu 180: Core principle 3



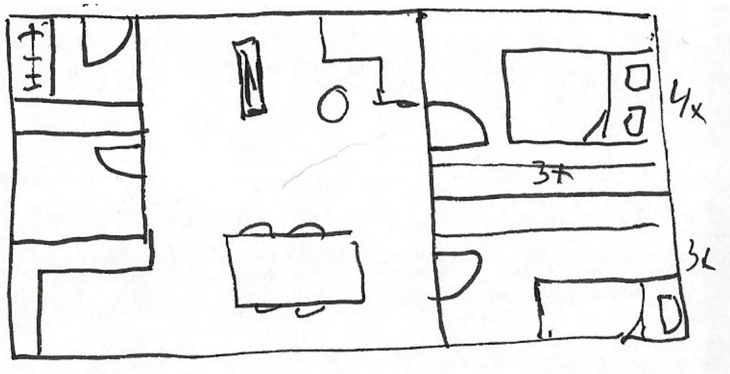
Illu 181: Using core 1, covers whole facade



Illu 182: Splitting the core 1

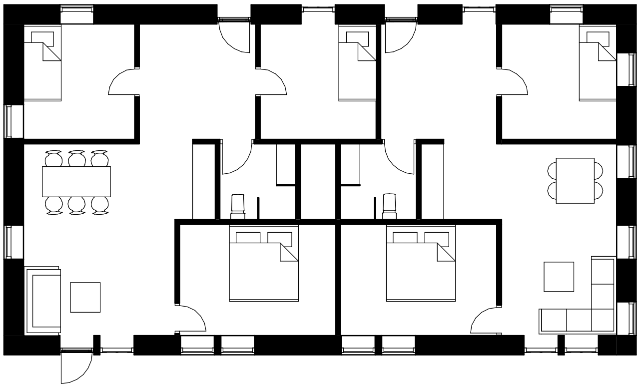


Illu 183: Core placed in the middle of each dwelling

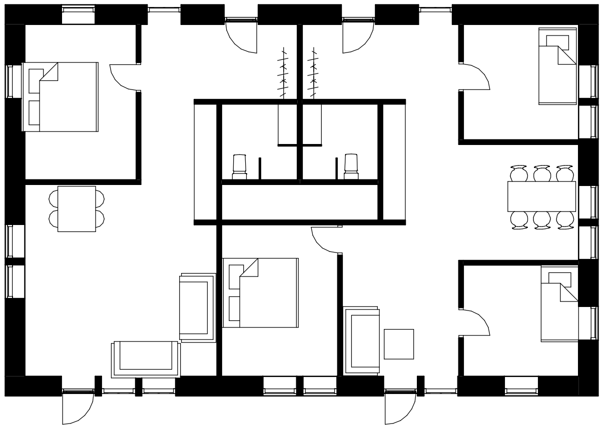


Illu 184: Using core 1 covers whole facade 2

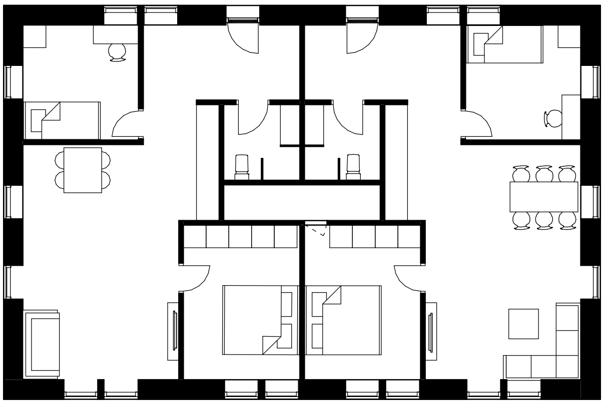
North entrance 1:200



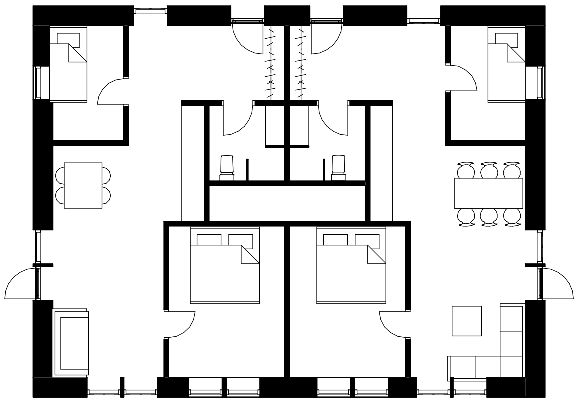
Illu 185: 16,7 x 9,2 m. 1 4-room dwelling and 1 3-room dwelling



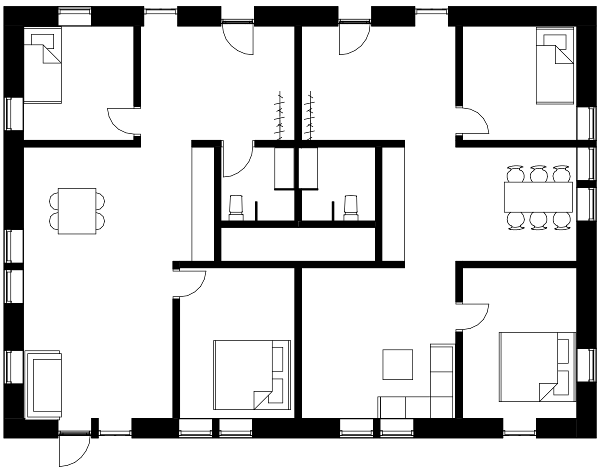
Illu 186: 15,6 x 10,3 m. 1 4-room dwelling, 1 2-room dwelling



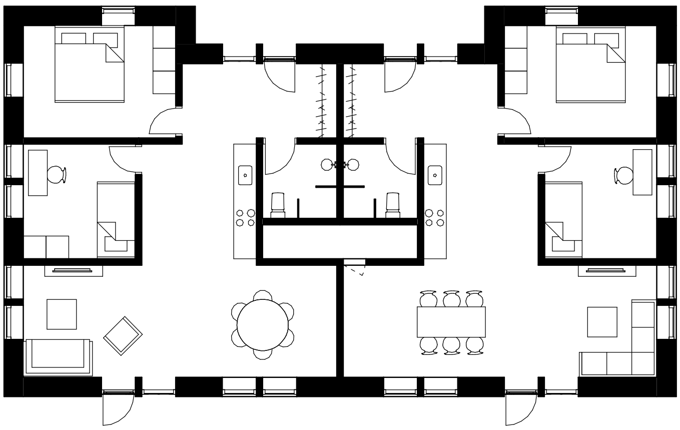
Illu 187: 15,6 x 10,3 m. 2 3-room dwellings



Illu 188: 13,5 x 10,3 m. 2 3-room dwellings

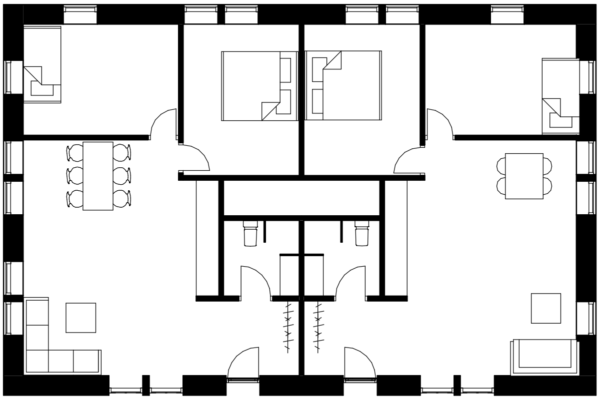


Illu 189: 15,6 x 11,4 m. 2 3-room dwellings

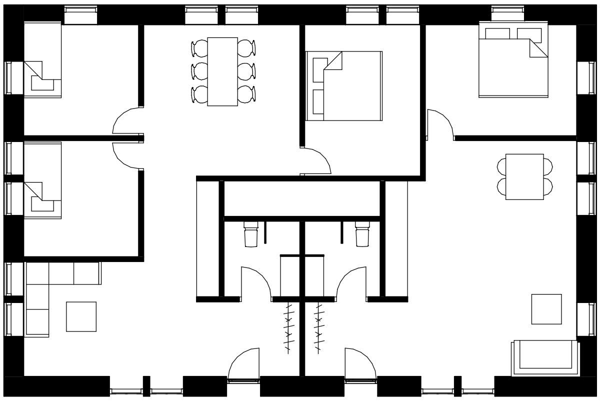


Illu 190: 17,7 x 10,3 m. Two three-room dwellings

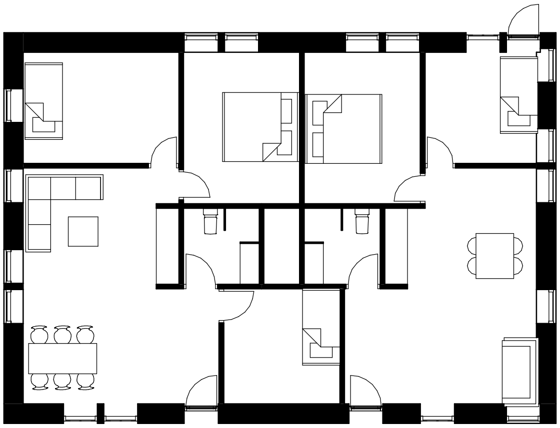
South entrance 1:200



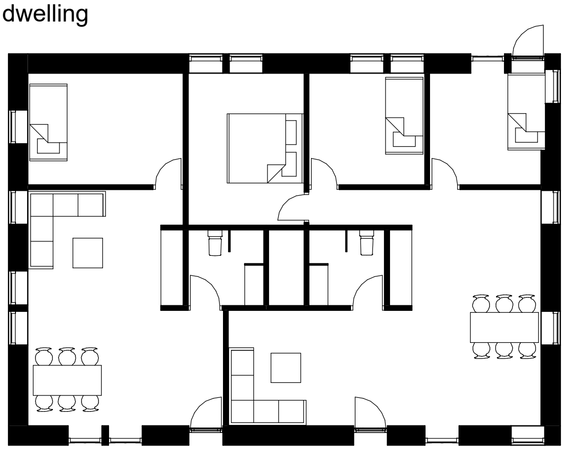
Illu 191: 15,6 x 10,3 m. 2 3-room dwellings



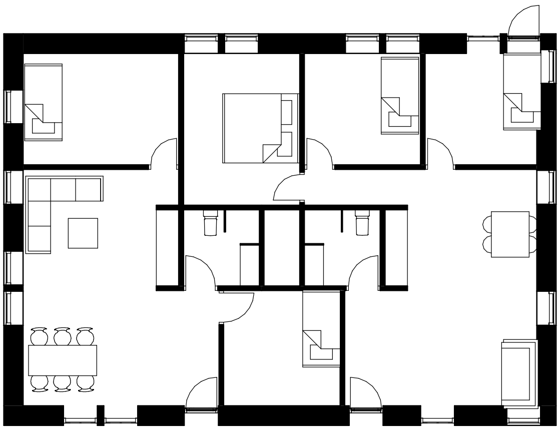
Illu 192: 15,6 x 10,3 m. 1 4-room dwelling, 1 2-room dwelling



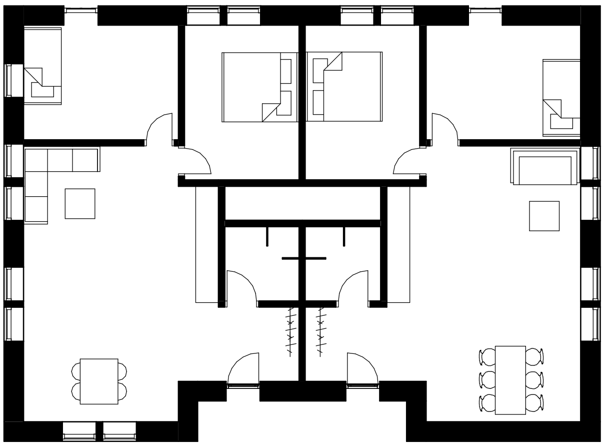
Illu 193: 14,6 x 10,3 m. 1 4-room dwelling, 1 3-room dwelling



Illu 194: 14,6 x 10,3 m. 1 4-room dwelling, 1 2-room dwelling



Illu 195: 14,6 x 10,3 m. 1 4-room dwelling, 1 3-room dwelling



Illu 196: 15,6 x 11,4 m. 2 3-room dwellings.

OPTIMIZE WALL MODULE

Intro

When sketching the plans with the modular system, problems came up regarding the windows placements in relation to interior wall. There also was a desire to expand the wall system, so it can accommodate shifts in the facade, instead of only rectangles.

Shifting facades

With the first iteration of the exterior wall modules which can be seen on pp. 66, there is one corner module which has a specific length to ensure that it fits with the interior walls. However, this specific length only works when the corner is an outwards closed corner in a rectangle. If this normal corner is applied to a shift in the facade as seen on Illu 197, the corner does not match with the placement of the exterior walls. Depending on whether the shift in the facade only needs to be one or multiple modules, it was found that two additional corners are needed.

Illu 198 and Illu 199 show two iterations of corner modules for a single module shift, such as the one desired in the project seen on illu 196. The blue pieces show a solution where two special modules are required, while the green solution combines these two to a single module. While this Z-shaped module is larger, it simplifies the number of pieces needed, which is desirable for the modular system.

Illu 200 shows the final sketched idea for the inner corner, to when the shift requires to be more than one module. This could be a deeper entrance area, or it could be a complete shift in the building shape. This module is shown in yellow and is a smaller version of the existing corner. it fits both when joining the orange and yellow corner, and if multiple regular wall modules are placed between the corners.

With these two additions, the Z-corner and the inner corner, the flexibility and design options with the modular system become far greater than before. Had the modules not been tested on the final plans and the plan solutions challenge the system, these additions might not have been found.

Windows

As shown on Illu 201-Illu 202, when joining interior walls and exterior walls, the idea is that the interior wall meets at the joint of the exterior walls. But since the original concept is that the window is a separate module the entire width of a module (1065mm), these windows end up sitting in the middle of the interior wall. A solution, therefore, needs to be designed so that this issue does not occur.

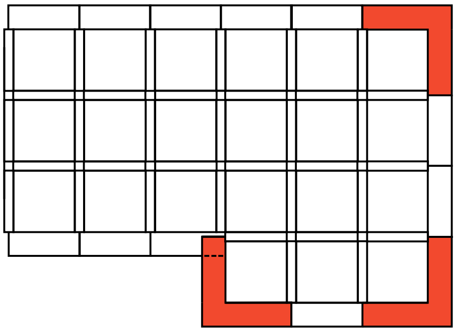
Through sketching the best solution was found to be a complete change in the modules regarding windows (Illu 205). Instead of having multiple overhang sizes and modules, to achieve different windows sizes as shown on pp. 66. This is now changed to use the same construction as the regular exterior wall modules, and instead placing the window inside the module. These changes result in the window being reduced to 900mm in width instead of 1065mm, and that at each exterior wall joint, there now is a combined construction width of 165mm, the same as the interior column, as seen on Illu 203.

By making this change, it both drastically reduces the amount of module types in the system, but it also removes issues with overhanging constructions. Instead each module with a window is now self-supporting in its construction. In this window module, principally any height of window or door can be placed, if it is within the module dimensions.

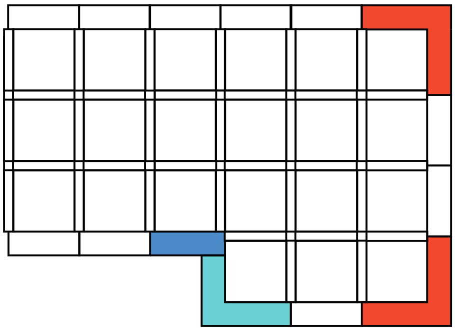
The result of this change to the facade system, also brings about significant implications for the aesthetics of the entire building, because each window now has a 165mm wide wall between as seen on Illu 204. This change plays into the desire, to express the modular system in the aesthetics of the building system. With each window being separated, it directly expressed the modularity and placement of each exterior wall module.

Conclusion

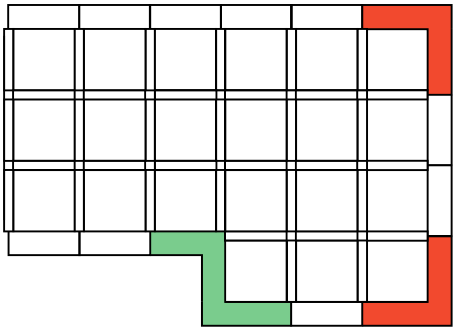
To optimize the exterior wall modules, two new types of corners have been introduced, that allow for shifts in the facade. The corners provide more flexibility and design freedom. The openings in the facade have been changed to a single module that is self-supporting. With this change to the openings, a new aesthetic is achieved, expressing the modularity of the facade directly through the distance between each opening.



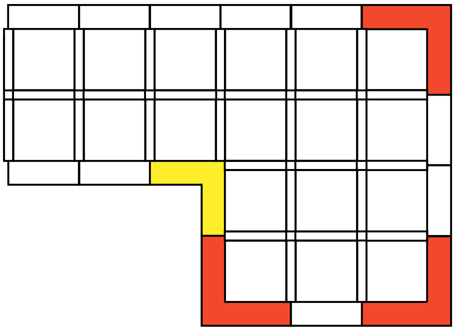
Illu 197: Using normal corner does not fit to shifting facades



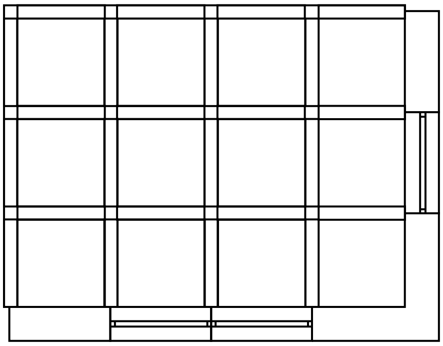
Illu 198: Making the corner module smaller and a bigger wall module



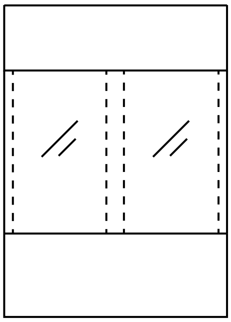
Illu 199: Z-module



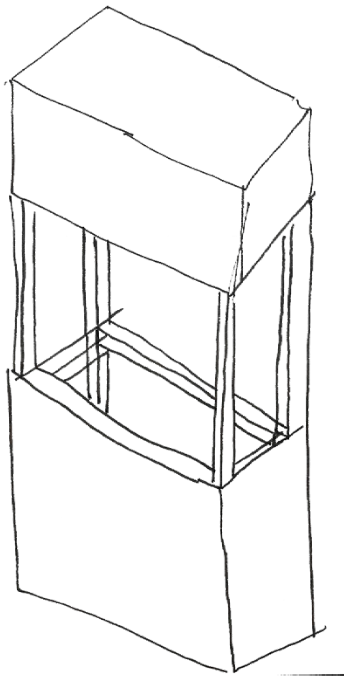
Illu 200: inner corner



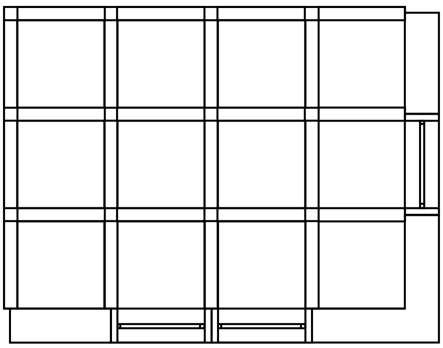
Illu 201: Windows interfere with interior walls placed in grid in floor



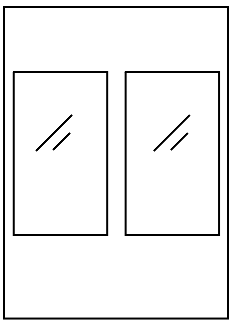
Illu 202: Interior walls will be visible in the facade



Illu 205: Overhangs are suported by columns. Full height module with possibility for different window heights



Illu 203: Windows made smaller so they do not interfere with interior walls



Illu 204: Windows always have 165 mm spacing in between them

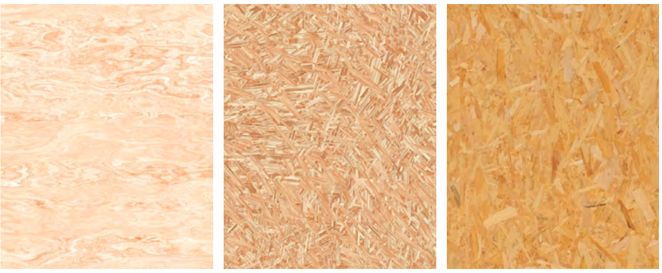
INTERIOR MATERIALS

Intro

To choose interior materials, different materials will be analysed in regards of LCA and healthiness on a material level. On room level, they will be combined and analysed with aesthetics, acoustics and daylight in mind. This should all together enable the possibility for choosing materials that are good in terms of CE, indoor climate as well as aesthetically.

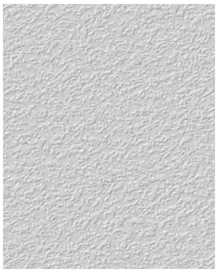
Wall materials

In terms of wall material, seven different types have been analysed in LCA (see Illu 214 - Illu 216). The different materials include boards, plywood, particleboard, OSB, gypsum, and clay, along with three wooden elements, pine, oak, and larch, made as thinner plank cladding.



Illu 206: From left plywood, particle board and OSB board

Plywood, particle boards and OSB-boards are all wooden-based boards which are glued together with glue (Sparenergi.dk, 2016; trae.dk, 2016). The glue the boards are made with, is not harmful to human health, if the boards are PEFC or FSC-approved, meaning all three can be certified as healthy materials. Plywood is made from new wood, whereas the two other types include a big amount of by-products from other productions. Thereby OSB and particle boards work better in a CE perspective, as they use waste to create new value. When comparing them in LCA, the particleboard has a much lower environmental impact, both on CO_2 and embodied energy, therefore, this wooden board will be analysed further on a room level.



Illu 207: Gypsum

Gypsum is the most commonly used material on inner walls. It is made from organic materials, is non-toxic and as seen on the LCA analysis, has a low environmental impact. At the end of life, gypsum boards can be recycled to produce new gypsum boards (Gpda.com, 2020), thus it operates in a CE perspective.

Illu 208: Clay board

Clay boards can be used in the same way as gypsum. They provide a good indoor climate, as it can balance the humidity. There are no chemicals used in production and can be reused 100% (Sparenergi.dk, 2016). The LCA shows a medium CO_2 emission compared to the other wall materials, but a low embodied energy. Therefore, this material is also relevant to analyse further.

Illu 209: From left pine, oak and larch

The three wooden claddings are all good in terms of it being made of wood and thereby having obtained CO_2 throughout their lifetime. When analysing them in LCA, the pine and oak are nearly similar in terms of CO_2, but pine has much lower embodied energy. The larch is almost three times worse when analysing for CO_2, and worse in embedded energy too. It is, therefore, chosen that the wooden plank cladding to analyse on room-level is the pine cladding.

Flooring materials

The wooden plank cladding can also be used as flooring, but bamboo flooring and tiles will in this section be analysed.

Illu 210: Bamboo

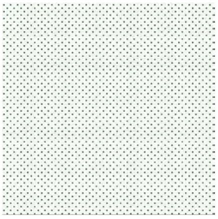
Bamboo is a fast-growing wooden sort, which stores a big amount of CO_2 in it. As bamboo is twice as hard as other wooden sorts, it is durable and can last for a long time (Sparenergi.dk, 2016). When looking at the LCA of bamboo, both the CO_2 and embodied energy is low compared to other solutions. The downside of bamboo is that it primarily grows in the eastern part of the world, and thereby needs transportation. The transportation is not included in the LCA calculations and the actual environmental impact will thereby be higher. How much is hard to tell, but the fact that it can last for a long time and have a low impact when excluding transportation, makes the material interesting to look further into.

Illu 211: Tiles

Tiles are made from burned clay. Tiles are durable and can last for 100 years, but cannot be recycled or reused, which is a big downside in terms of CE. (ibid) When looking at LCA, they have higher impact compared to other solutions. They are however waterproof, and thereby can be used in bathrooms, but should not be used in the rest of the dwellings.

Ceiling materials

The ceiling materials can also be made from the previous named wooden planks, but the two ceiling materials perforated gypsum and Troldtekt will be analysed in the following.



Illu 212: Perforated gypsum

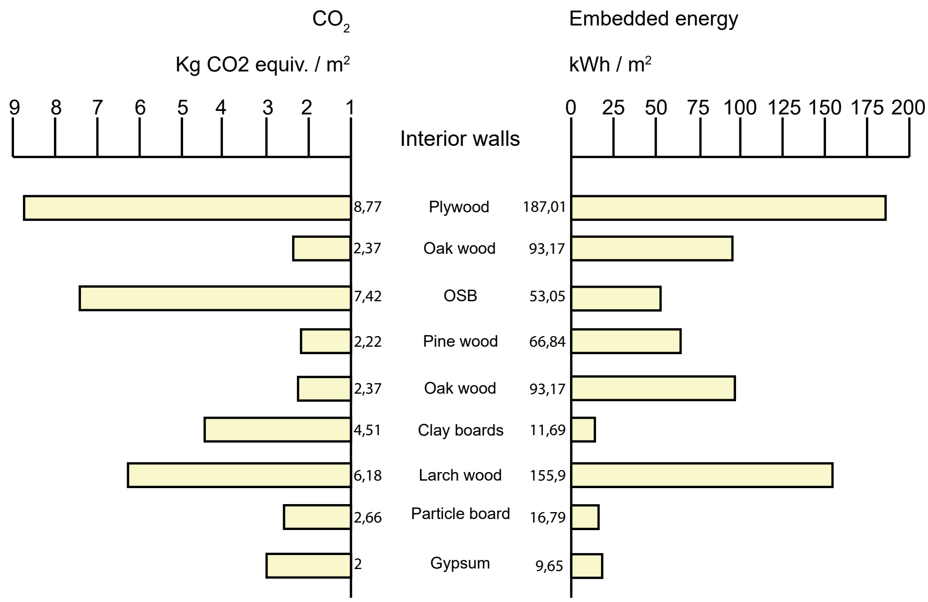
Perforated gypsum has many of the same properties as regular gypsum, but perforated gypsum is a great sound-absorbant material, and thus can lower the reverberation time.

Illu 213: Troldtekt

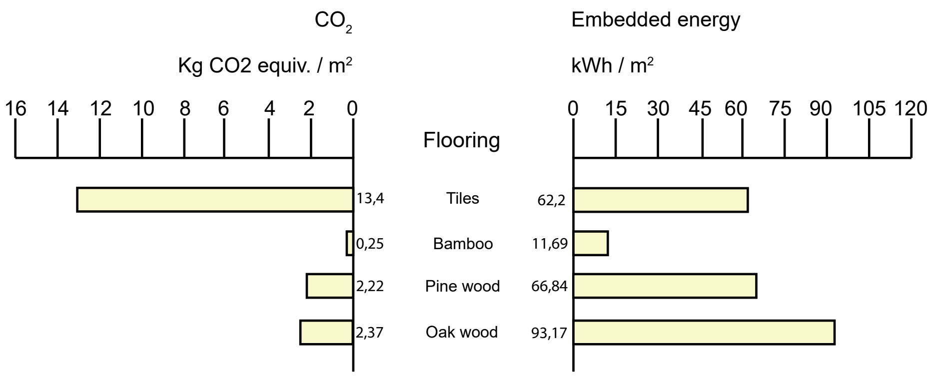
Troldtekt is made from wood and cement and has good acoustical properties. Troldtekt ceilings are robust, and can, therefore, be reused in other projects, as they are assembled by screws and thereby easily disassembled. Troldtekt does not have any toxic or unhealthy properties (Troldtekt.dk, 2020), but when looking at LCA, Troldtekt has a bigger environmental impact, compared to some of the other ceiling solutions, so by that reason, this will not be further analysed.

Conclusion

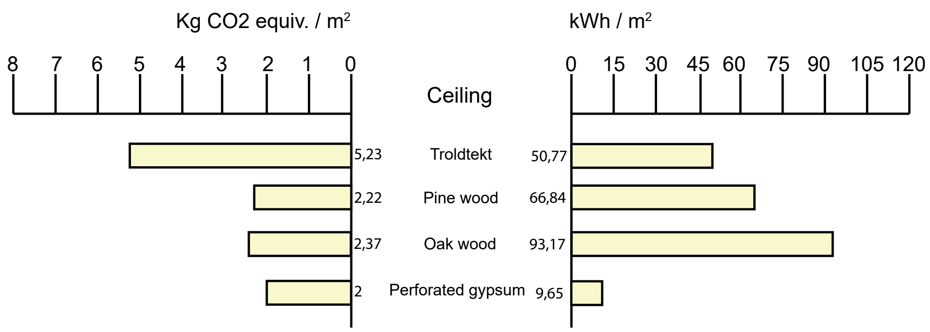
To conclude, the materials of the walls that will be assessed on room basis are particle-board, pine cladding, gypsum and clay boards. The flooring will be analysed upon upon the wooden flooring types bamboo and pine. The ceiling can consist of wooden planks and perforated gypsum.



Illu 214: LCA wall interior materials



Illu 215: LCA interior flooring materials



Illu 216: LCA interior ceiling materials

INTERIOR MATERIALS

Intro

The before chosen materials will in this chapter be combined and analysed upon aesthetics, daylight and acoustics.

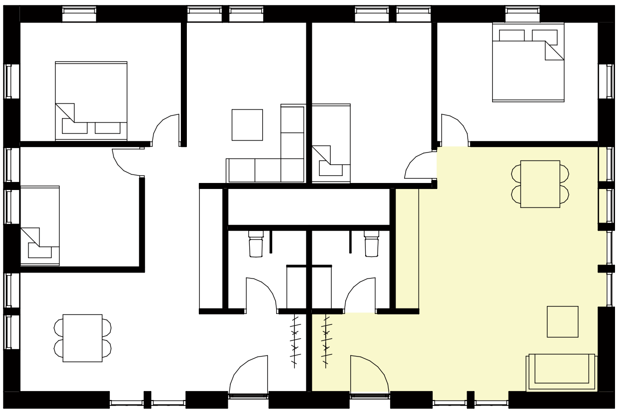
Room analysis

Eight different versions of the same living room (see Illu 217) have been created.

The grid in the floor is defined by the flooring being perpendicular on each other, which creates visibility to which parts of the floor can be removed and partitioning walls can be inserted instead, and which flooring parts that should stay untouched.

Illu 218 consists of clay on the wall modules, particleboard used on the column modules, bamboo flooring and perforated gypsum as the ceiling. The combination of particleboard and clay looks dark and makes the room look smaller, which is a negative and unwanted feature. This observation also applies to Illu 224.

Illu 219 and Illu 221 has pine wood on the wall modules and particleboards on the column along with bamboo on the flooring and gypsum used as ceiling material. The pinewood provides the room with warmth, but the use of three different wooden materials makes the room look a little messy. By only using pine as seen on Illu 223 and Illu 225, it creates a cohesion between the different surfaces in the room. However, by only using pine, the aesthetics of the modular system is minimized, and it is hard to distinguish between the individual modules.



Illu 217: The analysed room

Gypsum on the wall modules and either particleboard or pine on the column module as seen on Illu 220 and Illu 222 creates a great contrast between the two modules and thereby creates aesthetics out of the modular system. This also applies to the ceiling, where having perforated gypsum and pine creates focus on the modular system instead of only using one material.

Analyzing for daylight (see Appendix 4), clay is darker and absorbs more light compared to the other solutions. Having pine or gypsum on the walls does not make the biggest difference, so either material can be used to provide good daylight. The use of different floorings and ceilings does not impact the daylight factor much, thus should be decided from the acoustics.

Looking at the acoustics (for calculations, see Appendix 5), it shows that having an acoustic ceiling is mportant, as having a wooden ceiling makes the reverberation time too long.

Conclusion

The chosen materials to go further with are pine or bamboo for the flooring. For the ceiling it has proven important to have an acoustic ceiling for good reverberation times, in this case perforated gypsum is chosen. By using pine on the grid lines of the ceiling, a good contrast and aesthetic of the modular system is achieved. On the walls either gypsum or pine cladding can be used, depending whether a more cohesive wood expression is wanted, or if a more contrasting and modular expression is wanted.

Illu 218: Clay, particle board, bamboo and gypsum
Daylight factor: 2,8%
Reverberation time average 125-4000Hz: 0,4s

Illu 219: Pine, particle board, bamboo and gypsum
Daylight factor: 3,7%
Reverberation time average 125-4000 Hz: 0,5s

Illu 220: Gypsum, particle board, bamboo and gypsum
Daylight factor: 3,8 %
Reverberation time average 125-4000 Hz: 0,5s

Illu 221: Pine, particle board, bamboo and gypsum
Daylight factor: 3,7%
Reverberation time average 125-4000 Hz: 0,5s

Illu 222: Gypsum, pine, pine and pine
Daylight factor: 3,8%
Reverberation time average 125-4000 Hz: 1,0s

Illu 223: Pine, pine, pine and gypsum
Daylight factor: 3,7%
Reverberation time average 125-4000 Hz: 0,5s

Illu 224: Clay, pine, pine and gypsum
Daylight factor: 2,7%
Reverberation time average 125-4000Hz: 0,4s

Illu 225: Pine, pine, pine and pine
Daylight factor: 3,6%
Reverberation time average 125-4000 Hz: 0,9s

EXTERIOR MATERIALS

Intro

The purpose of this chapter is to identify and analyse different exterior materials for both facade, roof, and underside of the building, that can work within the theory of CE. The evaluation is based on both LCA and the materials health properties. The goal is to achieve one or more options for each surface, that can be chosen for each building, depending on the final aesthetical vision of the project.

Exploring and evaluation materials

The materials will be split into two categories: Facade/Underside and Roof. The underside of the house is exposed due to the building standing on a raised screw foundation. It is evaluated that the materials that can apply on the facade, can also apply on this underside.

For facades, the evaluation is based on 1 m² of exterior cladding including any underlying construction attached to the wind barrier. For roofs, the evaluation is based on 1 m² of roofing including any underlying construction placed on top of the rafter construction.

In this project, there has, from the beginning, been a desire to work with and compare new types of materials made from recycled products. However, due to these products state of being so new, any data about their environmental impact is not known.

An example of this is the product Pretty Plastic, which is a facade tile made from recycled plastic (prettyplastic.nl. 2020). While it is recycled, it is still known that plastic is troublesome, the production of this still requires energy, and there still is an issue with its end-of-life. Another example is the reused ventilation ducts used for facades, as seen in Circle house (GXN. 2018). Such examples are impossible to estimate in terms of available resources, and thereby if it is a viable material to use on a broader scale. It is, therefore, chosen, contrary to what the original intent was, to instead focus on commonly used materials and identify which ones fit into CE or have the potential to fit in.

Facade materials

Illu 226: Sagawood

Wood claddings are a natural material, and as such it deteriorates over time when being exposed to rain and sun on a facade. As a goal of CE, the idea is to utilize materials that are not treated in any way, so that they can be best reused or recycled into new material streams. Regularly used wood types for facades that are untreated generally have a lifespan between 5-25 years ranging from Ash to Cedar wood (trae.dk, 2020). This is not a long time as it is determined the building should last 50 years. For this project, the best choice for wood is from the producer SagaWood which is an Aalborg local firm producing sustainably harvested and treated wood. The product is all natural and is treated with heat to extend its lifespan. In an untreated state, it can last at least 25 years and treated it can last at least 50 years (Sagawood.dk. 2020).

Illu 227: Slate

Slate is a naturally occurring stone material that is often used for both facade and roof. Though slate is a non-renewable resource, it has a has long lifespan of over 150 years, requires no maintenance, and can be taken down and reused repeatedly. In CE this is viewed as a product with a high initial value, though after its primary use, it currently has no meaningful use in a secondary life. Slate also has no health issues as it is 100% natural stone. (Saxosolution.dk. 2020)

Illu 228: Rockpanel

Rockpanel is a newer type of board designed for facades. This material is produced from naturally occurring basalt stone, it includes no harmful substances, can be recycled, and has a lifespan of at least 60 years requiring no maintenance. The panel can be cut into pieces as desired and can be disassembled as it is attached with screws. The panel is available in different colours and finishes. (rockpanel.co.uk. 2020)

Roofing materials

Illu 231: Corrugated fibre cement

Corrugated fibre cement sheets are a commonly used material for roofing in Denmark and can aesthetically have different colours and shapes. Newer types of this product do not contain asbestos or other harmful substances. The sheets are maintenance-free in their around 50-year lifespan, however, the use of fibre cement currently does not have any options for secondary life or recycling. (Hocre-board. 2020)

Illu 229: Bitumen

Bitumen roofs are currently one of the only options for flat or low slopes on roofs and is also a commonly used product for roofs. This type of roof suffers from a short lifespan (around 20-30 years) but the company Derbigum does take back bitumen roofs they sell and recycle them, which does help a bit on its impact. (Derbigum.dk. 2015)

Illu 230: Sedum roof

Green roof or sedum roofs are roofs build to both aesthetically please with its green appearance, and to deal with rainwater in its absorption. The green also helps to combat climate change throughout its lifespan. Sedum roofs can apply to both flat and sloped roofs, making it comparable to bitumen. An EPD for a full extensive green roof system has been found that covers both sedum and the underlying layers. (urbanscape-architecture.com. 2016)

Illu 232: Steel roof

Steel roofs are a modern and simple solution to roofing, that allows for quick assembly and minimal maintenance throughout its 50-year lifespan. The roof is thin and, therefore, does not require much steel. The material can also be recycled into new roof sheets at the end of the lifespan. (Ds-staalprofil.dk. 2020)

Illu 233: Thatched roof

Thatched roofs are an old roofing method involving reeds to secure waterproofing the roof. The material is low maintenance and can have a lifespan of around 40-60 years depending on how well it is installed. The slope of the roof should, however, be at least around 45 degrees. (epddanmark.dk. 2017)

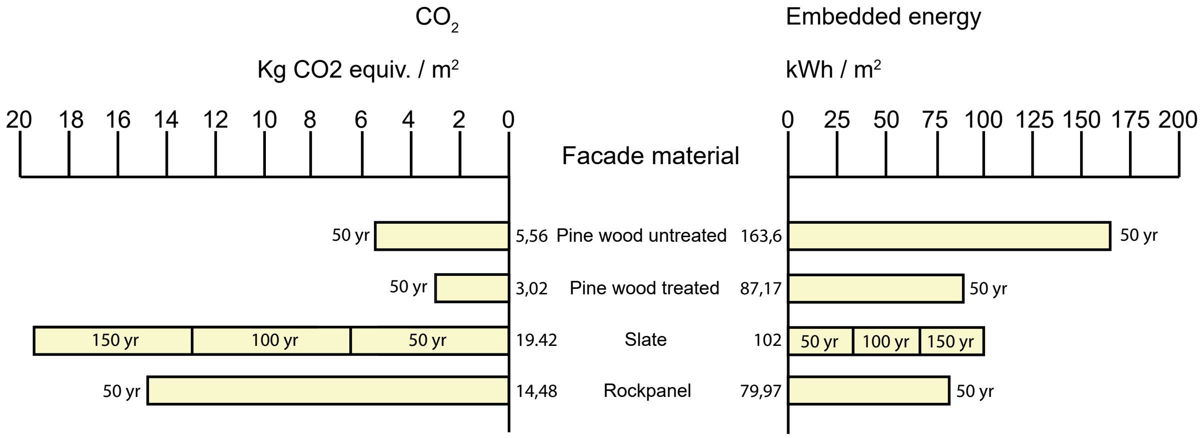
Evaluating LCA

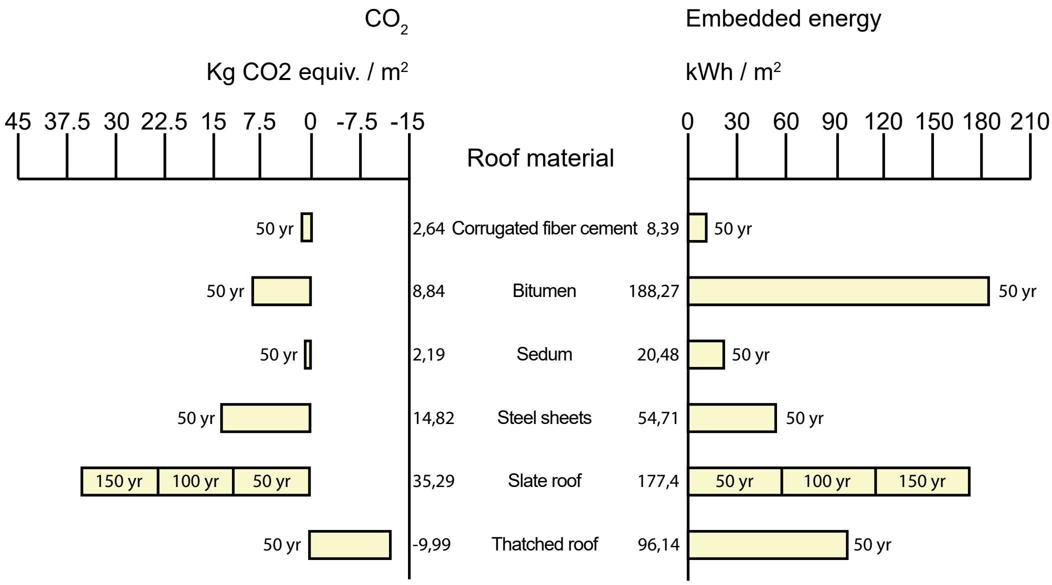
The LCA analysis (see Illu 234) shows, that for facades, wood is the best option, whether the wood should be treated or not, comes down to more than just the LCA. Treating wood every 5 years requires time spread out through the lifetime, while replacing it once every 25 years requires more intensive work only once. In both cases, it can be argued that the material after its lifecycle, will be in such a state that it cannot be repurposed for cladding, and will have to be recycled into lower grade materials. It is, therefore, also an aesthetical choice, where the treated wood will have a warm wood colour, the untreated will fade to a silver-grey. Slate could also be a possibility, as it over its multiple building cycles, will have a similar impact to wood if untreated. The initial impact, though, is much larger than wood, which is the clear decider between the two. Slate could be chosen for a few surfaces such as the common houses, to give a different expression compared to the dwellings.

For roof the clear choice is to do a sedum roof, as this both has one of the lowest environmental impacts, but also other positive effects. These effects are things such as storing rainwater, providing green and sustainable aesthetics. Sedum works on flat and sloped roofs, this is one of the main drawbacks that thatched roofs have, as they require steep slopes to have a long lifespan. The local plan dictates roof slopes between 0-18 degrees, which again provides ideal conditions for sedum. The large differing in the impact of slate in roof compared to the facade is due to slate overlapping much more on roofs in order to be waterproof, which makes it less ideal for roofs.

Conclusion

Through evaluation of materials for exterior surfaces based on health and LCA, it has been decided that the main material for facades is pine cladding that can either be treated or untreated depending on the aesthetical desire, with the possibility of slate being used in a few places. The roof is decided to be sedum roof, as it both has the lowest environmental impact, but also provides aesthetics to the project that work into the idea of sustainability and makes the buildings fit into the landscape.





Illu 234: LCA outer materials based on a 50 year lifespan

ROOF SLOPE

Intro

With the materials for the roof being decided as sedum, a major aesthetical aspect of the roof is that it is visible from within the site. The purpose of this chapter is to determine the slope and orientation of the roofs on the site, with a focus on visibility from within the site.

Orientation and slope

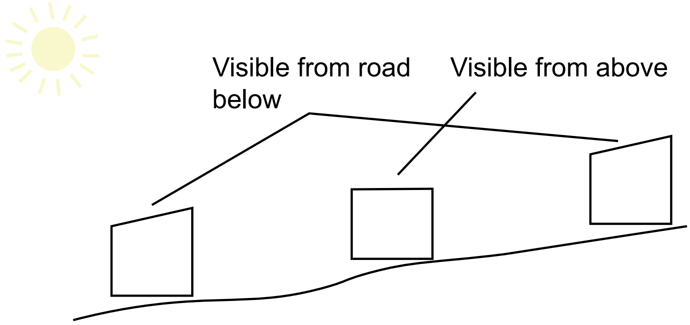
When orienting the roofs there are only a few combinations to consider, as the local plan only allows for flat or unilateral slopes. It has been decided that the common house in the middle has a flat roof to not have any front/backside due to taller facades caused by roof slopes. Due to the common room always being flat, it is always visible from the further up the slope of the area. As a result of this, choosing the roofs to orient towards north or be flat as in Illu 237-Illu 238, would mean that the green roofs would not be visible from the road below the site. Having this visibility helps provide the site with a sustainable aesthetic, that people who pass by can easily identify.

The result is, therefore, that the best orientation, when both considering visibility from outside the site and inside the site onto the roofs, is Illu 236 where the roofs slope in towards the middle from both sides. The next task is determining the necessary roof slope for the roofs to be visible from within the site. On the next page, the same view taken from the middle of the site towards the south has been analysed for different roof slopes.

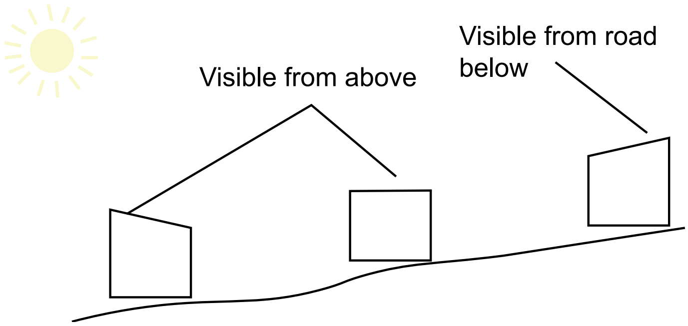
It is important not only to consider the visibility but also the facade height that a higher slope brings with it. The slope should, therefore, be as low as possible while still providing a visual of the green roofs. Based on these criteria, it has been chosen that 10-degree slopes are the best balance between vision and height.

Conclusion

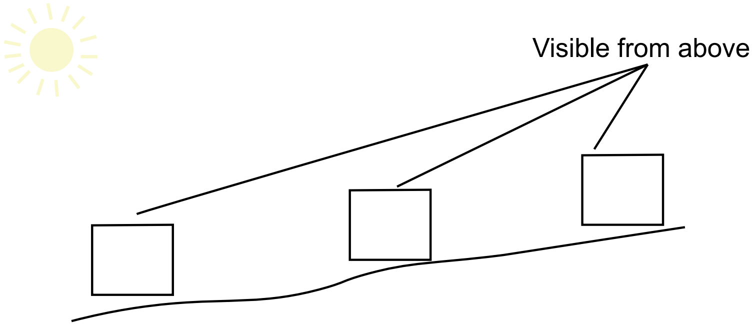
It has been decided that the roofs should orient themselves towards the middle of the site, to allow for the best visibility of the green roofs on the site. The slope of the roofs has been determined to be 10 degrees, as it provides the necessary angle to see the roof surface while keeping the facade height to a minimum.



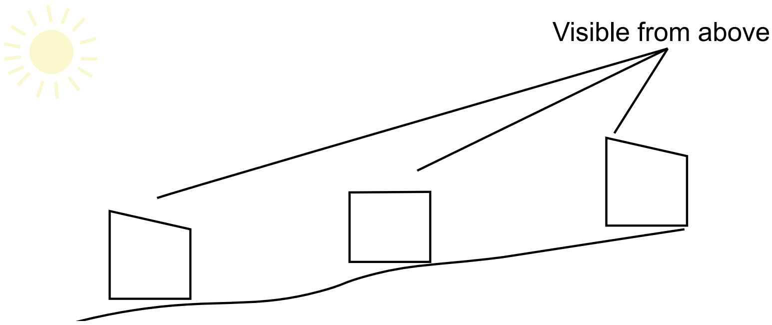
Illu 235: Sloped roof towards south and flat roof on common room.



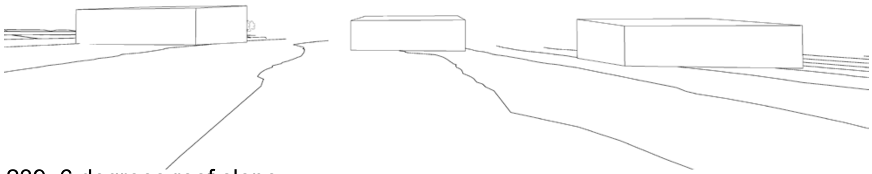
Illu 236: Sloped roof towards common room with flat roof.



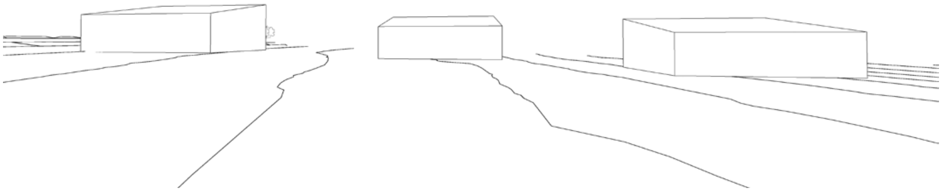
Illu 237: Flat roof



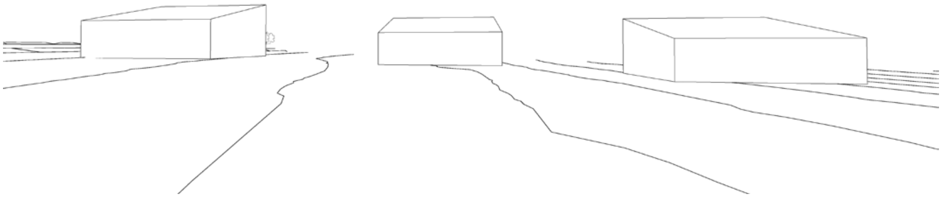
Illu 238: Sloped roof towards north and flat roof on common room.



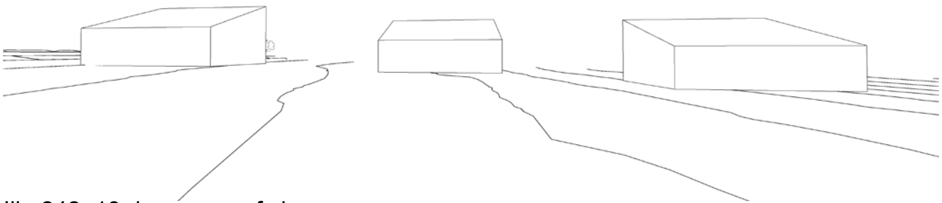
Illu 239: 6 degrees roof slope



Illu 240: 10 degrees roof slope



Illu 241: 14 degrees roof slope



Illu 242: 18 degrees roof slope

FACADE

Intro

The purpose of this chapter is to sketch and detail the exterior facade, both in terms of overall expression, and detailing joints at corners and windows. The goal is achieving a facade design that expresses the modular system the buildings are constructed with.

Expression

The sketches seen on Illu 243-Illu 248 are a selection of sketches made based on wood cladding. There are different ways of expressing the modular system, both with horizontally cut cladding, with a shift between wide and narrow cladding at module joints or shifts between module sections.

When deciding between horizontal or vertical cladding, the considerations were towards the reuse of the material, as longer pieces of material can be reused for more purposes. In this project that results in vertical cladding being better, as it provides longer pieces. It also allows the bottom cladding to reach below the deck construction, making the gap between the ground and the deck shorter and protect the bottom of the construction as seen on Illu 250.

Vertical cladding is also chosen because it plays well with the facade expression seen on Illu 244. This system allows a wider plank to fill the thin strip between windows as seen on Illu 249 and can be combined with narrower cladding profiles. This creates a contrast in the facade that can be applied to all facades, this is what was desired in expressing the modular system.

The vertical cladding also provides a variation of the facade space, above the windows, on the sides that have a tall facade due to the roof slope. Combining this with some kind of solar shading as will be explored in the next chapter of this project, can create an interesting facade despite the empty space.

Detailing the facade

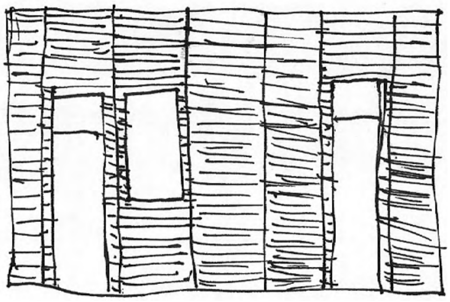
The details that have been focused on is the corner, as it must fit within the expression earlier decided, and on the window frame to decide what best fits the overall aesthetics.

For the corner, three solutions have been designed as seen on page 102. Corner 2 and 3 are more defined corners, which is desirable as the rest of the expression is equally as well defined. When choosing between the two, corner 2 has been chosen, as it provides more depth and detail to the corner, both being shifted out and wider. It can also help enclose the corner construction, preventing the need for special corner joints of the regular cladding pieces.

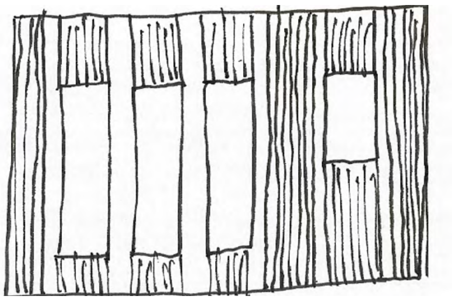
Window 1 has a hidden frame that sets back the window from the facade and exposes the end wood of the cladding below the window. Window 2 solves this issue by creating a frame around the window, which also helps to define the window and provide more contrast and detail. Window 3 is an extended frame painted black, which is an attempt to create even more contrast and detail to the building. Window 2 is chosen as the best expression of detail and aesthetics while being technically sound.

Conclusion

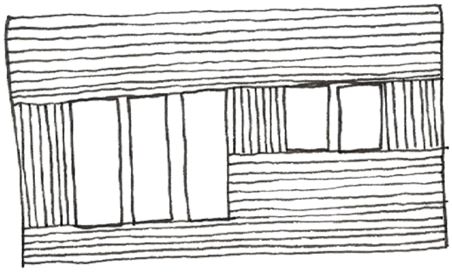
The final facade has been chosen as a narrow vertical cladding using wider cladding pieces at each outer wall module joint. This both expresses each joint and allows the gap between each window to be filled out at the same time, which also plays well into a subtly set window frame that allows for further detail. This is all framed by corner pieces that are shifted out from the rest of the cladding to both emphasize and protect the corner.



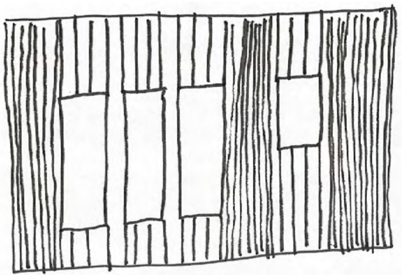
Illu 243: Horisontal cladding in the length of one module



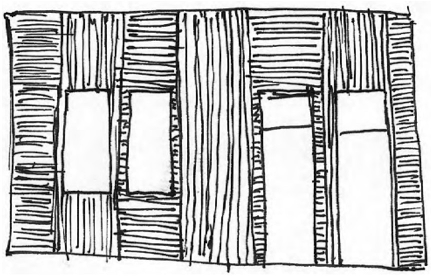
Illu 244: Vertical cladding, broader plank defines each module



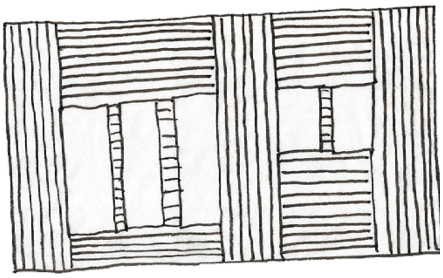
Illu 245: Horisontal cladding, between windows there is vertical cladding



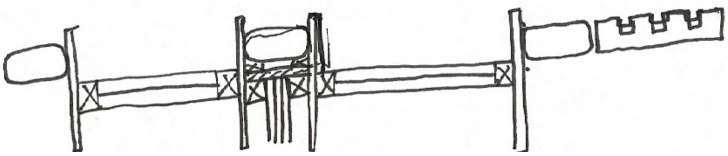
Illu 246: Vertical cladding, where there are windows the planks are broader



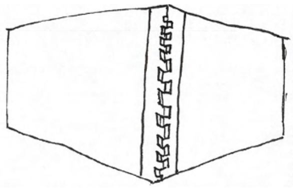
Illu 247: Modules defined by perpen-dicular cladding



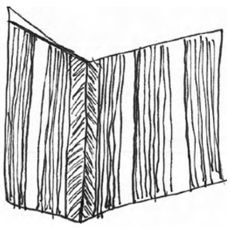
Illu 248: Vertical cladding where there are no windows, horisontal cladding on the modules with windows



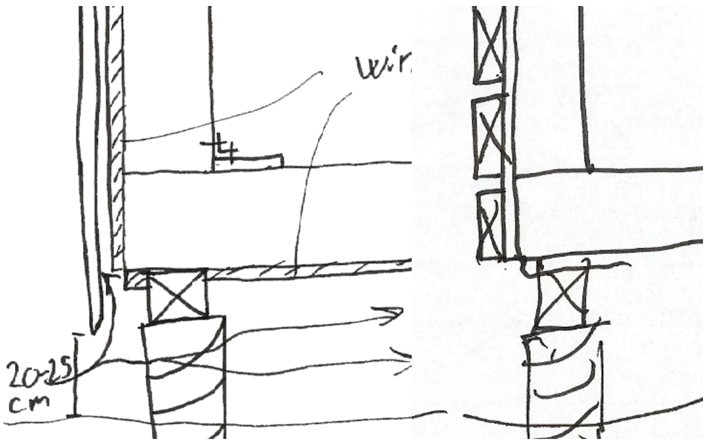
Illu 249: Plan showing broader plank defining each module, and thinner cladding (Illu 244)



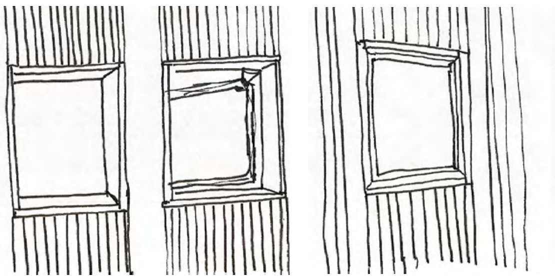
Illu 251: Mortise-and-tenon joint



Illu 252: Steel corner

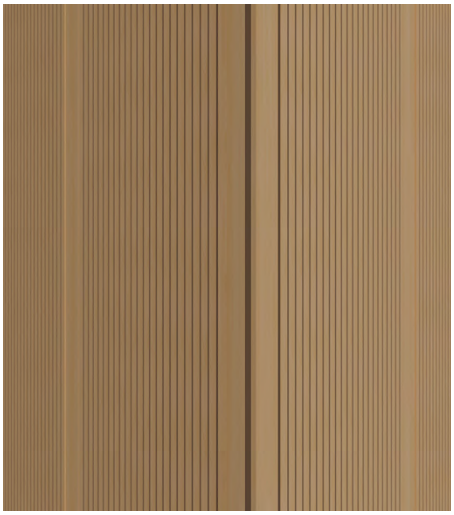


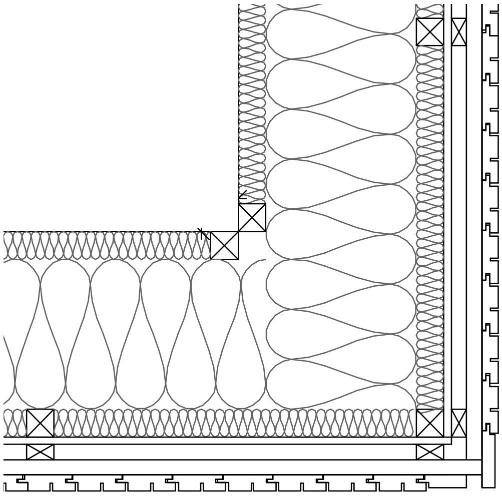
Illu 250: Sections showing vertical and horisontal cladding. Vertical cladding can sheild for the bottom

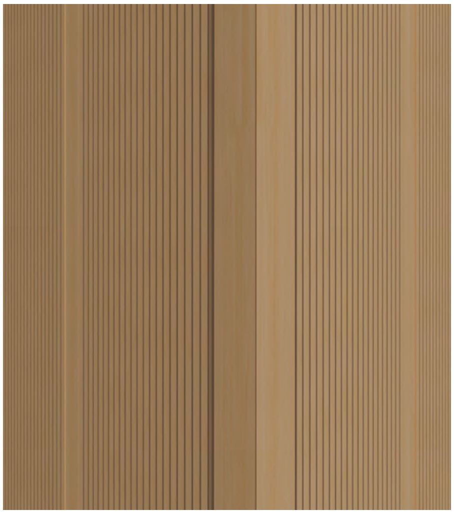


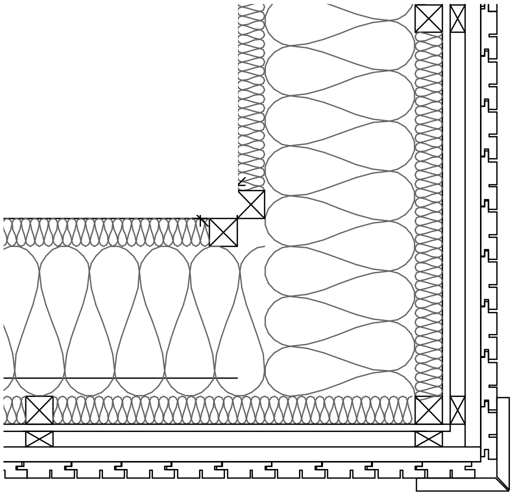
Illu 253: Different window frames

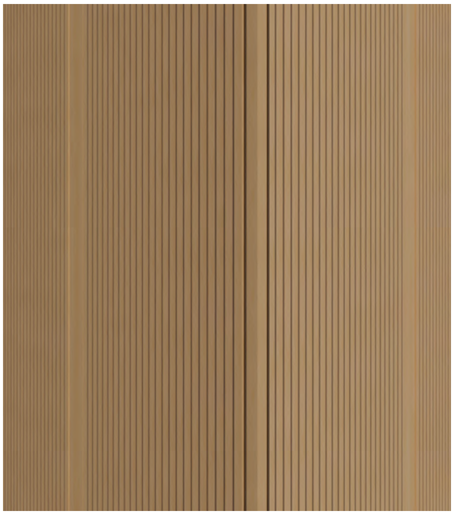
Facade corners

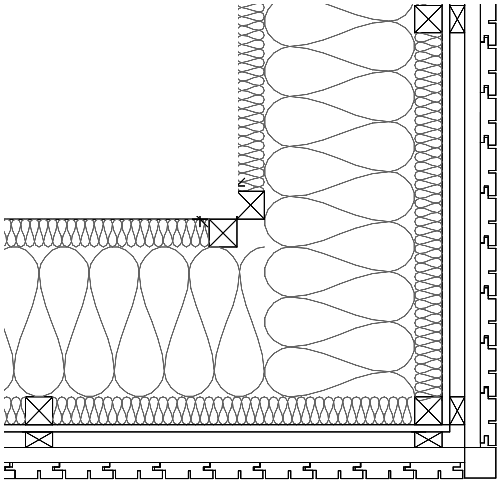

Illu 254: Corner 1


Illu 255: Corner 1 detail


Illu 256: Corner 2

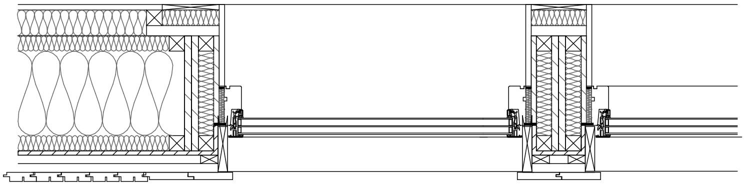

Illu 257: Corner 2 detail


Illu 258: Corner 3


Illu 259: Corner 3 detail

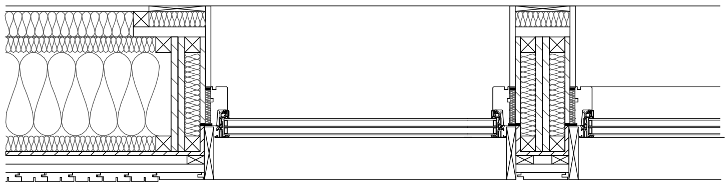
Facade and windows

Illu 260: Window 1 hidden frame



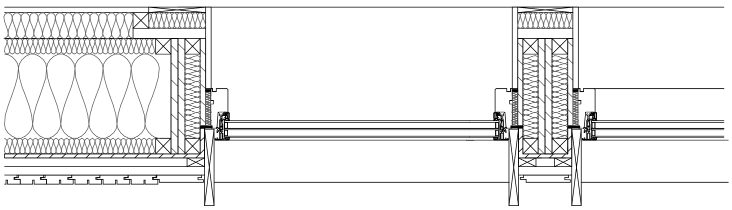
Illu 261: Window 1 hidden frame detail

Illu 262: Window 2 marked frame



Illu 263: Window 2 marked frame detail

Illu 264: Window 3 extended frame



Illu 265: Window 3 extended frame detail

ENERGY AND THERMAL COMFORT

Intro

The purpose of this chapter is to evaluate measures towards achieving the set energy frame and thermal indoor environment set in the design criteria. The measures that will be evaluated are natural ventilation in relation to window openings and their functionality. Another measure is solar shading in relation to its aesthetics on the facade and its cooperation with natural ventilation. The goal is to find principles for window opening design and solar shading, that can be used to apply on final building designs.

Floorplan and daylight

The evaluation is based on the generic floorplan presented on Illu 266, with the floorplan being placed in the house most southern on the site, as this will have no shading from other buildings, and is, therefore, worst-case scenario. The generic floorplan layout is designed to fit the flexibility required when changing around the interior walls. The windows are strategically placed so that no matter how you decide to place rooms, they will always have a window.

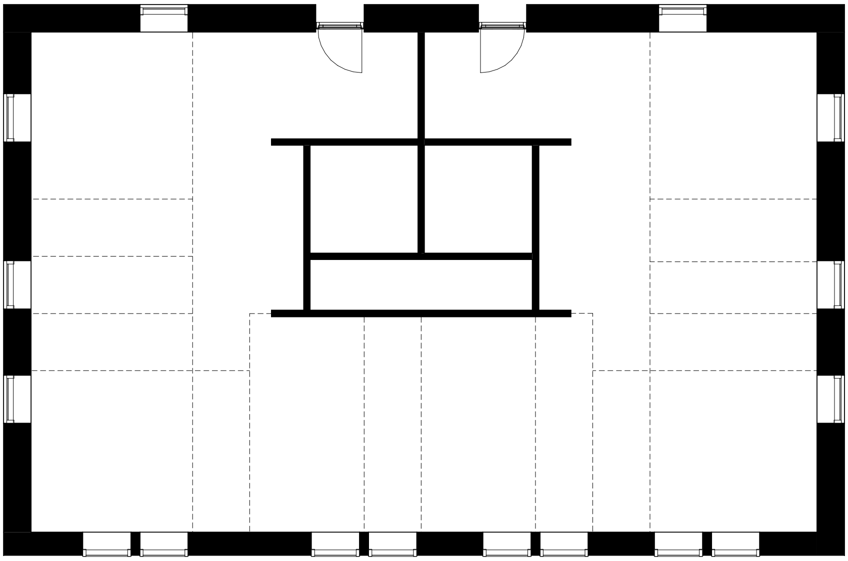
Since the number of windows will not be changed, the daylight impact will be the G-value of the windows, and with the chosen windows Velfac-200-Energy there are two options for G-value either 0.53 or 0.61 (www.produkter.velfac.dk. 2020). The difference in daylight between these two G-values can be seen in Appendix 6 and on Illu 267 showing the plan that is assumed for this full evaluation. The plan is not final but acts as a placeholder for approximate size, room placements, and windows. Both G-values fulfil the lighting criteria set for 2%, but the 0.61 value shows a significant increase, and, therefore, this value will be used for all evaluations to come.

Natural ventilation and solar shading

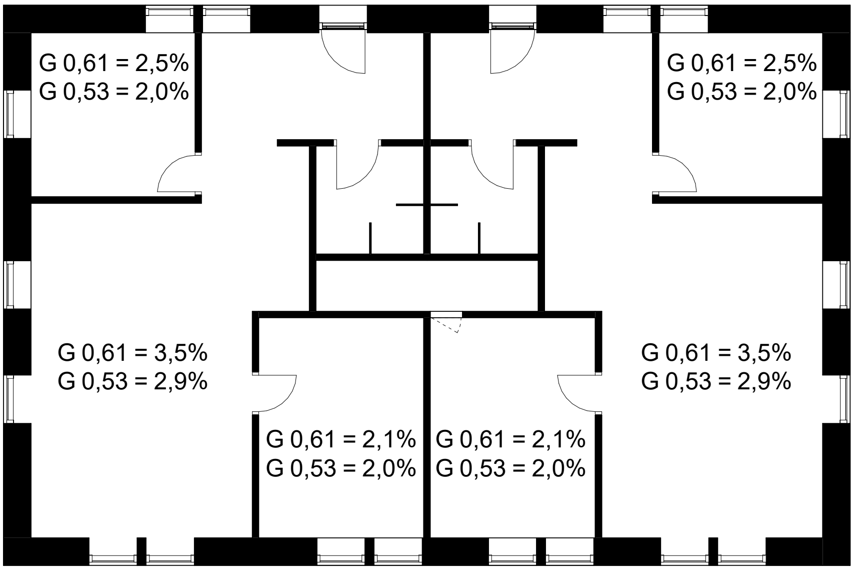
Since the evaluation is not based on the number of windows, but rather the window design, different possibilities with window openings and types have been explored. The goal is to always achieve enough natural ventilation to combat overheating, but also to provide enough functionality for the user in terms of how windows can open, both during the day, but also windows that are safe enough to keep open at night. Solar shading is designed both for its aesthetics, its function to provide shade, and how well it functions with natural ventilation at the same time.

For each iteration, the energy frame is evaluated in BE18, the thermal indoor environment and natural ventilation is evaluated in BSim. The BE18 calculations and BSim model, inputs, and calculations can be seen in Appendix 6.

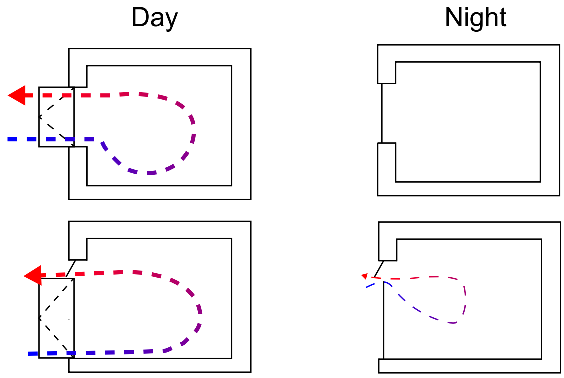
The baseline model has been limited in its natural ventilation, to 0.5 h^{-1} which is a low air change rate. This is to better compare the solar shading solutions, as the overheating in these iterations will primarily be prevented by shading, as there is not much ventilation. It is important to do this, as else it can be hard to determine whether it is the natural ventilation or solar shading that prevents overheating. The baseline then presents a building example, where the users do not use windows to ventilate, and where there is only regular interior solar shading such as venetian blinds or lamella curtains. In the natural ventilation iterations, the cap for natural ventilation is set at 5 air changes pr hour, and it is viewed as the upper limit for how much ventilation should be gained. A discussion of the evaluation results and the choice and combination of the two measures can be seen at the end of this chapter.



Illu 266: Generic floor plan

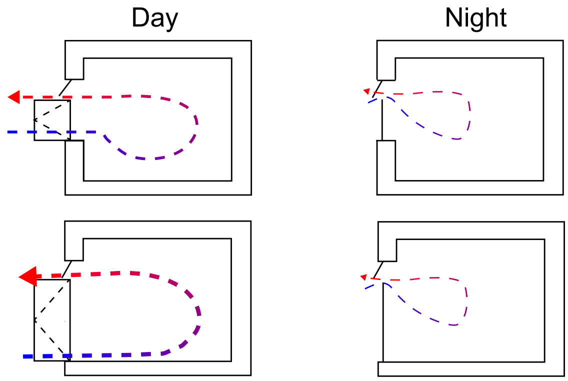


Illu 267: Plan used for evaluations



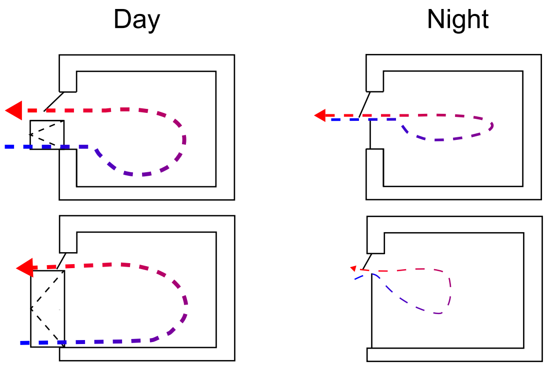
Illu 268: Baseline

Energy usage kWh/m² pr year		Temperature	Hours above		Summertime day	Summertime night
Heating	24,3	>26°	516	Factor	1	0,06
Electricity	10,5	>27°	280	Max vent m³/s	0,0016	0,0016
Overheating	9,9	>28°	120	Max air change h⁻¹	1,99	1,92



Illu 269: Natural ventilation 1. Mullions placed high on the small windows

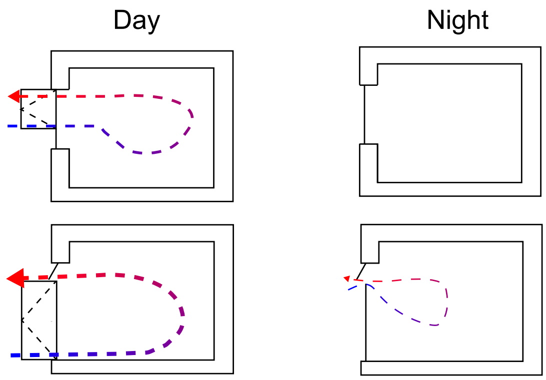
Energy usage kWh/m² pr year		Temperature	Hours above		Summertime day	Summertime night
Heating	23,1	>26°	153	Factor	1	0,1775
Electricity	10,5	>27°	37	Max vent m³/s	0,2592	0
Overheating	0	>28°	5	Max air change h⁻¹	6,57	1,92



Illu 270: Natural ventilation 2. Mullions placed in the middle of the small windows

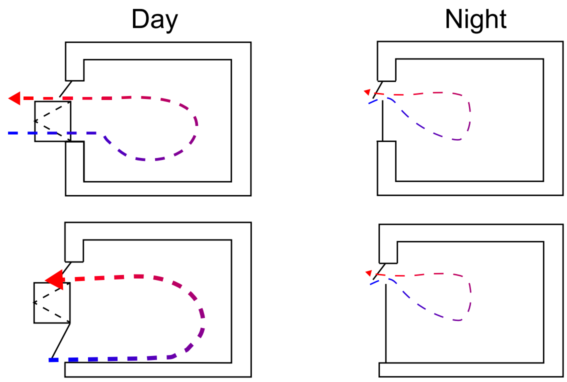
Energy usage kWh/m² pr year		Temperature	Hours above		Summertime day	Summertime night
Heating	23,1	>26°	131	Factor	1	0,232
Electricity	10,5	>27°	34	Max vent m³/s	0,2592	0
Overheating	0	>28°	4	Max air change h⁻¹	6,57	1,92

Illu 271: Natural ventilation 3. Mullions placed low of the small windows



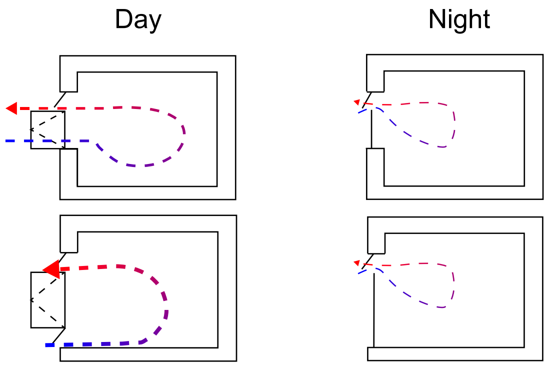
Energy usage kWh/m² pr year		Temperature	Hours above		Summertime day	Summertime night
Heating	23,1	>26°	143	Factor	1	0,05
Electricity	10,5	>27°	36	Max vent m³/s	0,2592	0
Overheating	9,9	>28°	5	Max air change h⁻¹	6,57	1,92

Illu 273: Natural ventilation 4. Mullions seperating the tall windows in the middle

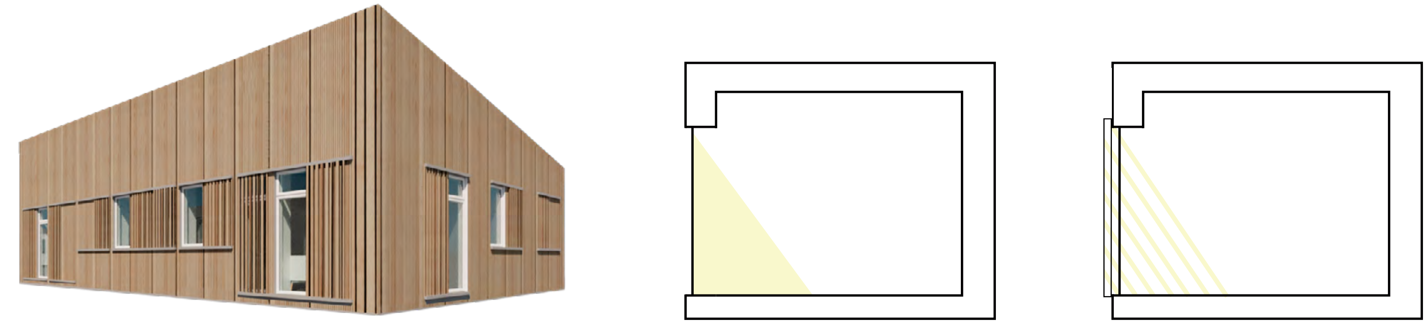


Energy usage kWh/m² pr year		Temperature	Hours above		Summertime day	Summertime night
Heating	23,1	>26°	122	Factor	1	0,138
Electricity	10,5	>27°	30	Max vent m³/s	0,2592	0
Overheating	0	>28°	3	Max air change h⁻¹	6,57	1,92

Illu 272: Natural ventilation 5. Mullions seperating the tall windows

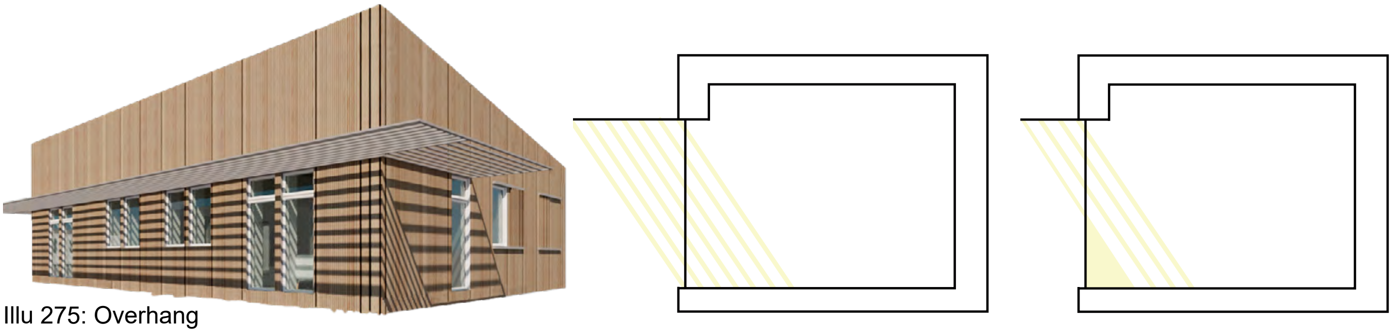


Energy usage kWh/m² pr year		Temperature	Hours above		Summertime day	Summertime night
Heating	23,1	>26°	129	Factor	1	0,135
Electricity	10,5	>27°	32	Max vent m³/s	0,2592	0
Overheating	0	>28°	4	Max air change h⁻¹	6,57	1,92



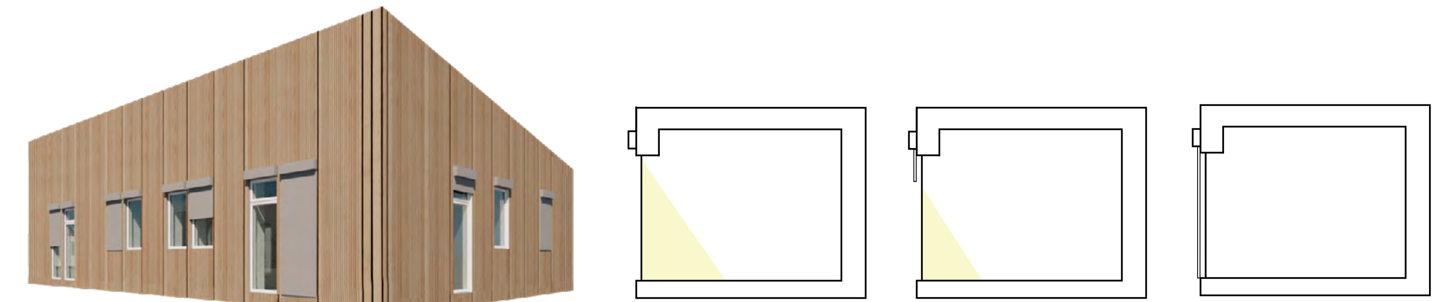
Illu 274: Shutter

	Energy usage kWh/m² pr year	Temperature	Hours above
Heating	22,9	>26°	280
Electricity	10,5	>27°	92
Overheating	16,0	>28°	23
Natural ventilation	Lowers ventilation when in use but does not prevent		



Illu 275: Overhang

	Energy usage kWh/m² pr year		Temperature	Hours above	
	1,7 m	0,85 m		1,7 m	0,85 m
Heating	27,1	25,0	>26°	218	284
Electricity	10,5	10,5	>27°	69	108
Overheating	8,4	11,3	>28°	19	28
Natural ventilation	No impact on ventilation				



Illu 276: Screens

	Energy usage kWh/m² pr year	Temperature	Hours above
Heating	22,9	>26°	278
Electricity	10,5	>27°	84
Overheating	15,6	>28°	20
Natural ventilation	Prevents ventilation for windows it covers		

Results and discussion

In all iterations for the natural ventilation (see Illu 268 to Illu 263), the max cap for air change is reached, but there are still relative changes to the overheating hours. Interestingly the simulation shows that there is no need for night ventilation, this is because the building has such a low thermal mass that no significant heat is build up in the construction. Night ventilation is however still a good functionality for users.

Iteration 4 is the best option, as it both provides night ventilation in all windows at the top. For the tall windows the multiple sections in the window, allow for more functionality for the user, because there is both different size windows and different opening types. This gives the user good control over their indoor environment and natural ventilation needs.

For solar shading (see Illu 274 to Illu 276) it can be seen, that though the large overhang combats the overheating best, it also causes a significant change to the heating requirements of the building during winter. This is due to the overhang preventing the solar heat gains in colder months. The overhang is a heavy aesthetic element that does not fit into this project, along with it requiring a strong underlying construction to be stable in high winds.

When comparing an exterior screen and shutters, shutters are only marginally worse in overheating, but provide more functionality, as it can better be used in conjunction with natural ventilation. It provides a more dynamic aesthetic to the facade, and it can be manually controlled requiring no electronics. The shutters are also sturdier in the high winds of the site and are, therefore, the best choice all around for solar shading.

Combined

In the combined iteration (see Illu 277) there still are a few overtemperature hours, though none that exceed the limits set in the design criteria. An explanation for the overtemperature can be found on Illu 429 in Appendix 6, showing temperature graphs for two different summers days both interior and exterior. On a day where the temperature exceeds 27 C^0, the exterior temperature is also at 27. Without cooling it is almost impossible to go below this temperature without high thermal mass. However, because the windows allow for control of the natural ventilation, the adaptive thermal comfort model dictates, that higher temperatures can be tolerated.

Conclusion

Throughout multiple iterations of both window openings and types, and solar shading, it has been determined that exterior shading with shutters is the best option. This shading allows both shading and natural ventilation to still function. For the window openings, an option has been chosen, that allows for night ventilation in all windows, and provides different opening sizes and types for each room, to give the user full control of the indoor air quality and temperature.

Illu 277: Combined shutters and natural ventilation iteration 4

	Energy usage kWh/m^2 pr year	Temperature	Hours above
Heating	23,1	$>26^{o}$	26
Electricity	10,5	$>27^{o}$	19
Overheating	0	$>28^{o}$	0

	Summertime day	Summertime night
Factor	1	0,138
Max vent m^3/s	0,2592	0,0066
Max air change h^{-1}	6,57	1,92

INTERIOR WALL JOINTS

Intro

Detailing is needed for the joints of the interior wall system, so that it can be ensured that this can be easily assembled and disassembled. Therefore, sketching is carried out for the joint between these elements, with a focus on both functionality and aesthetics.

Joints

When assembling the column itself, there is a need to screw together the wood board on each side and the battens behind. If there then also is a joint between the wall and the column, this results in many holes in the wood board. This can be solved by utilising threaded screws, which are screws that are hollow and allow another screw to be screwed into it, as demonstrated on illu 278-279. When this screw hole is not used for attachment of the wall, then another screw can be inserted into it, which can be used for hanging pictures, shelves, or tea-towels in the kitchen.

Having centrally placed “slot in” brackets as in Illu 280, requires the possibility of sliding the wall into the column. This is not possible with this system, as the columns on both side of the wall must be placed first, and the wall then pushed in between them.

On illu 281 and 283 is an example of a bracket that can rotate and be used to attack the column and wall. This joint is visible and easy to understand but needs to be removed when not in use for walls, as it otherwise is in the way. It also requires screw holes in the cladding on the walls to attach, which is not good in a CE perspective.

Another type of joint that can be utilised is a magnetic screw (see Illu 282), such as the one seen from the producer Lamello and their Invis Mx2 series (Lamello.com, 2020). This screw can help create a non-visible joint that does not damage the cladding on the interior walls. This can be combined with the threaded screw concept of using it for other purposes when not in use.

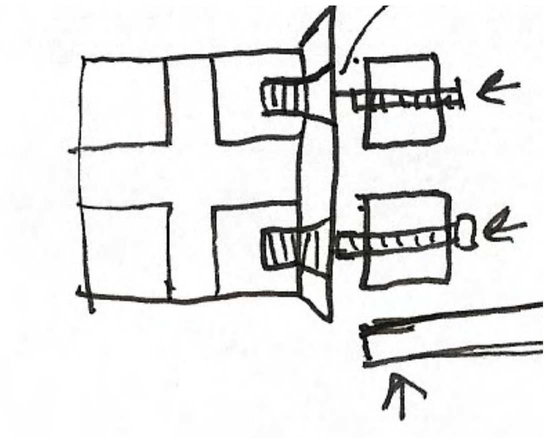
From the sketches, the idea of the magnetic screw is further investigated, and so is the use of a rotating bracket. Both ideas have been further conceptualised with detail drawings of the assembly process (the reverse being the disassembly process), and its visual aesthetic. This can be seen on the next spread.

The magnetic screw though provides more practical assembly, as it both has fewer steps and does not require the handling of the brackets. Not having to screw in the wall cladding also prevents it from being damaged, allowing for more possibilities for cladding materials. This screw also seals the joint by applying force perpendicular to the corkboard, which allows for tightness.

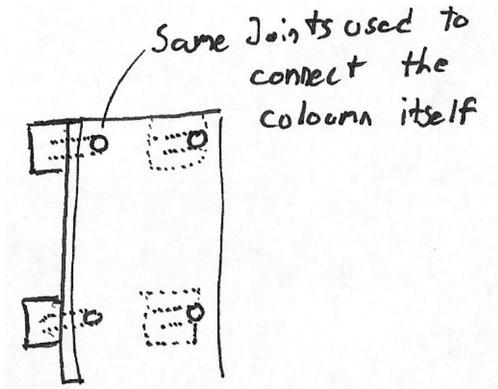
The aesthetic qualities are a matter of perspective, as a vision for the project was to make the modular principles be visibly represented. One could argue that the modular principle is already visible with the difference between the column and the walls cladding, and that a visible joint is not necessary. But one could also argue that a visible joint is easier to understand when disassembling and would provide an interesting detail to the interior. In the end the non-visible joint is chosen as it has more benefits, and a joint is still visible in the non-covered parts of the column.

Conclusion

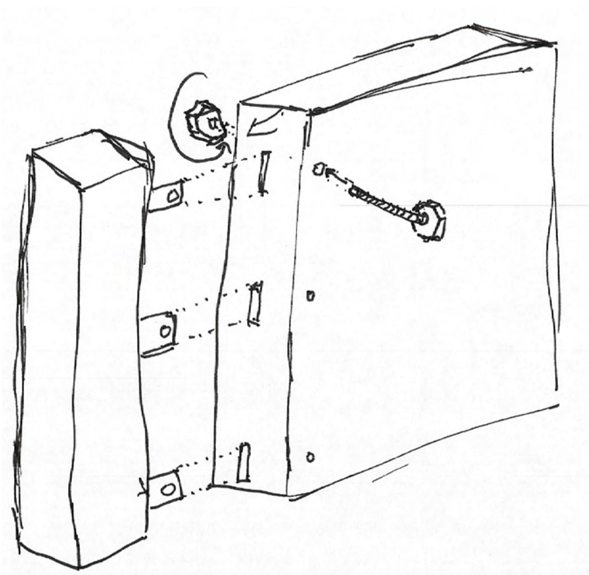
Through sketching and detail drawings it has been decided that the joint will be made with non-visible magnetic screws in the construction. This allows for freedom in choosing interior cladding and does not damage the cladding. This system requires visible threaded screws on each side of the column. These both provide an aesthetical aspect, and functionality by allowing the holes to be used for attaching things to the wall such as shelves and pictures.



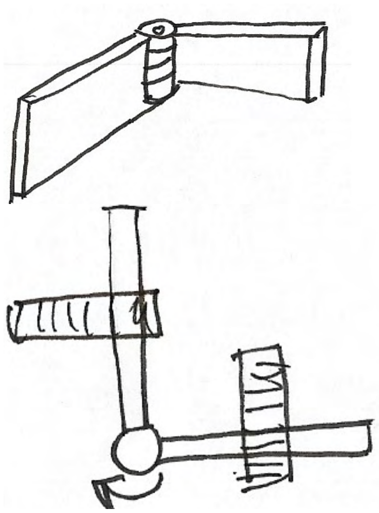
Illu 278: Threaded screws



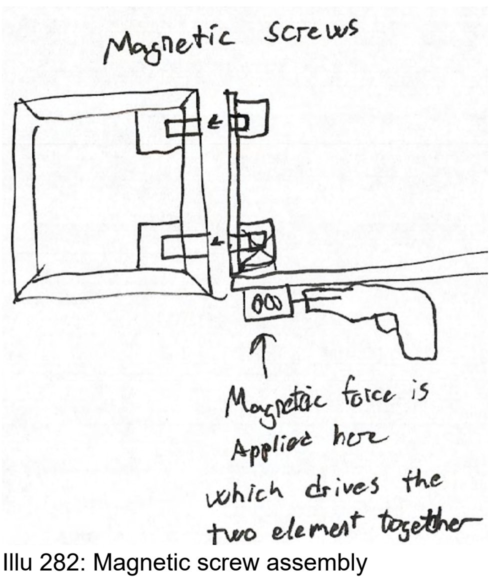
Illu 279: Threaded screws assemble the coloum



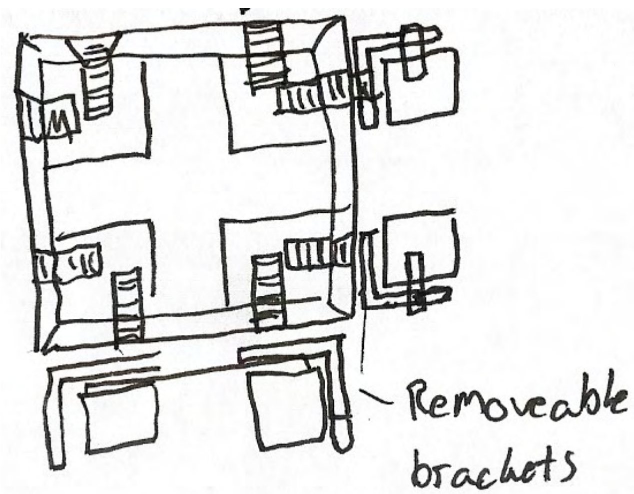
Illu 280: Slot in brackets with wall sliding into them



Illu 281: Rotating corner bracket

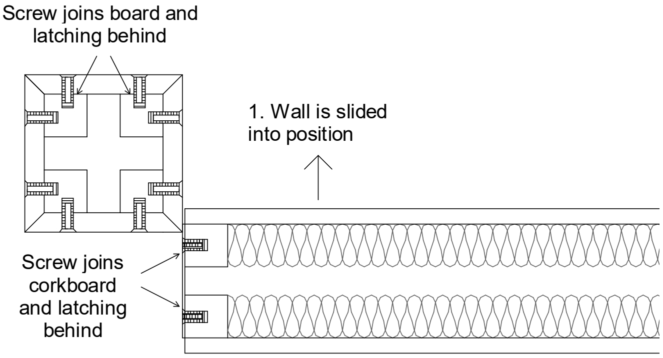


Illu 282: Magnetic screw assembly

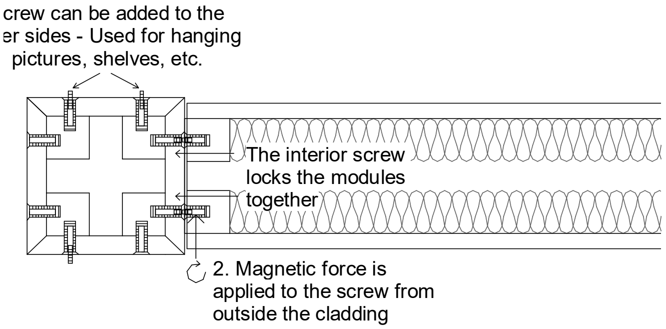


Illu 283: Corner brackets

Magnetic screws

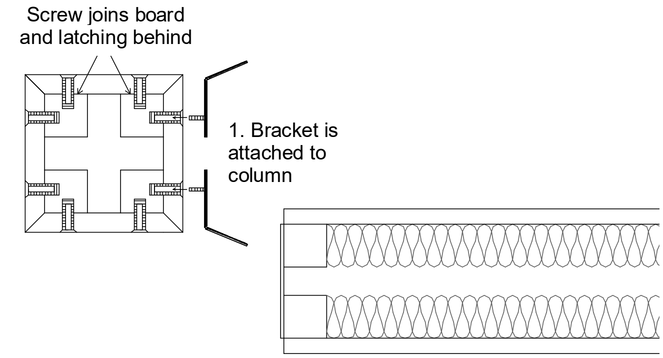


Illu 284: Magnetic screws step 1

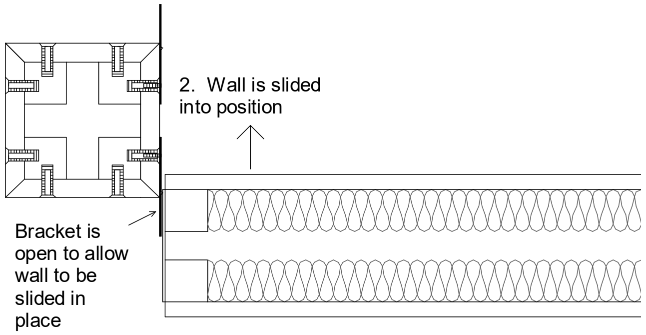


Illu 285: Magnetic screws step 2

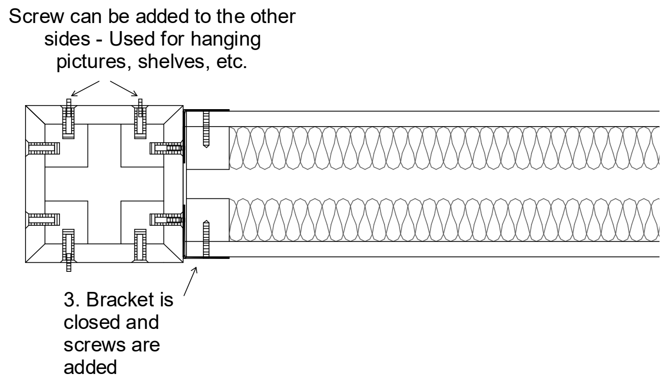
Visible brackets



Illu 286: Visible bracket step 1



Illu 287: Visible bracket step 2



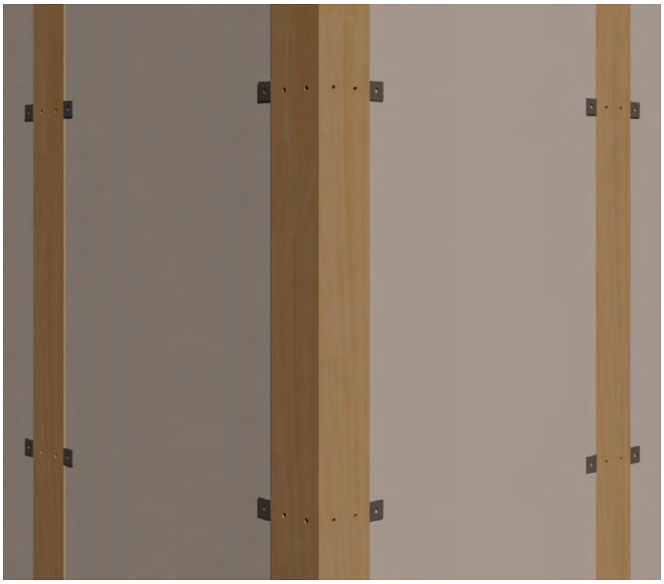
Illu 288: Visible bracket step 3

Visual of magnetic screws


Illu 289: Magnetic screws and gypsum cladding


Illu 290: Magnetic screws and wooden cladding

Visual of visible brackets


Illu 291: Visible bracket and gypsum cladding


Illu 292: Visible bracket and wooden cladding

TECHNICAL SYSTEM PRINCIPLES

Intro

The purpose of this chapter is to explore and evaluate principles for heating and ventilation, based on the principles ability to fit within the modular building system.

Heating and ventilation

Different practices and principles for heating have been evaluated below, based on their ability to fit within the modular system. Floor heating is one of the most popular methods, but because it is heavily based on room layouts, it does not adapt well into a flexible system. Air heating through a ventilation system, removes the possibility of achieving individual heating zones in each room, as the ventilation system has one temperature from the main source.

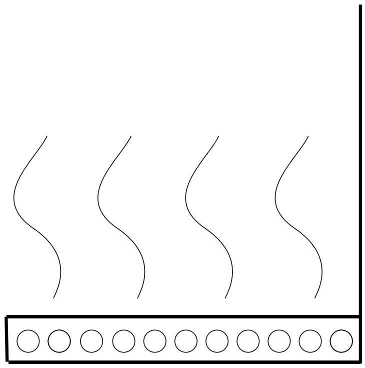
Radiators or radiators build into the floor at floor-ceiling windows, work well into the flexible system as each radiator in such a system already functions independently, and are placed below each window. Meaning no matter how the interior walls are placed, as long as there is a window in a room, there will also be a heating source.

On the next page, two different principles for ”Plug-in” ventilation ducts are presented and discussed. The idea is that both these principles are useful at different times on different floorplans.

Conclusion

Radiators have been chosen for heating, it is the best solution both technically and functionally. For ventilation the best use would be the ceiling system, as it fits well into the modular grid, can easily be moved around, and can supply air anywhere in a room.

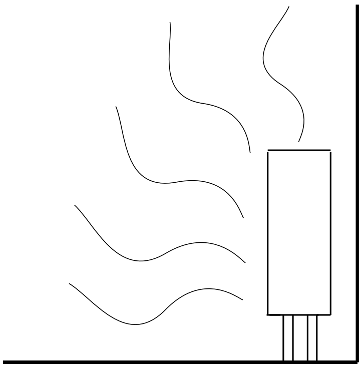
Floorheating



+ Non-visible
+ Lower temperatures
+ Higher comfort

÷ Requires rerouting when changing room layout
÷ Special subfloor needed to work optimally

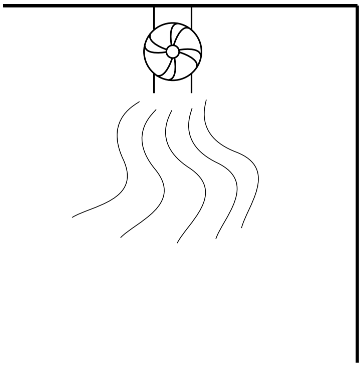
Radiatorheating



+ Independant of room configuration
+ Easy to control for users
+ No changes required throughout building lifetime

÷ Not aesthetically pleasing
÷ Asymmetric heat radiation
÷ Requires special solution for floor windows

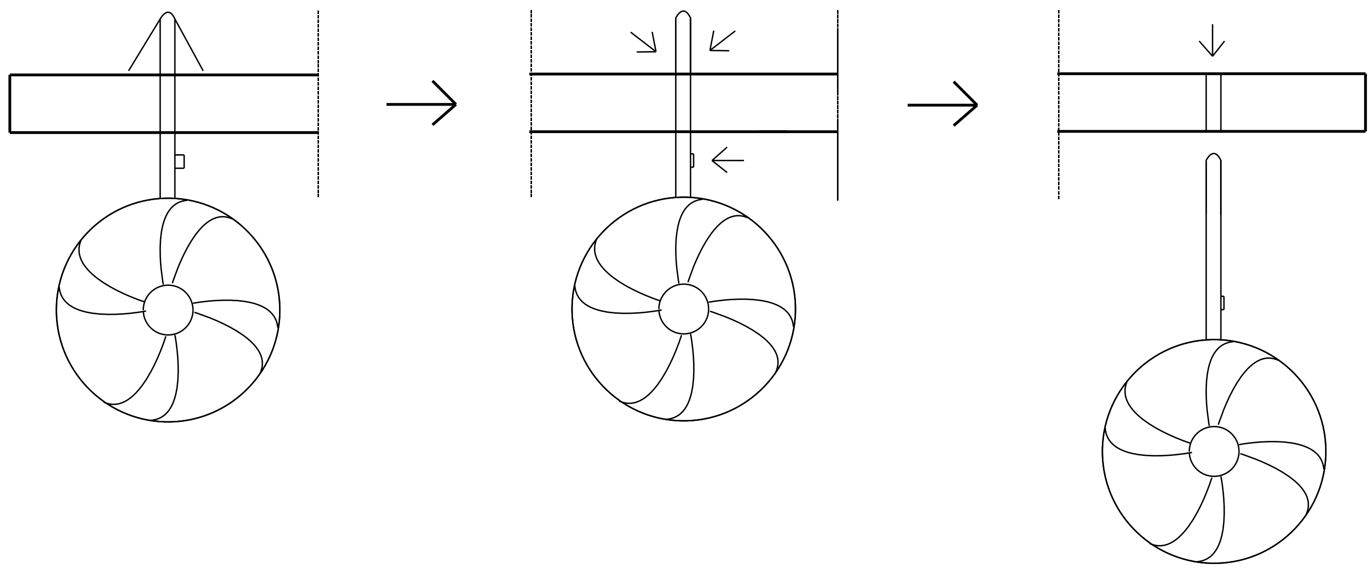
Airheating



+ No piping in floor
+ Flexibility in changing layouts
+ No visible heating

÷ No individual room control
÷ Issues with heating capacity
÷ Downdraft from windows
÷ Larger airflows required

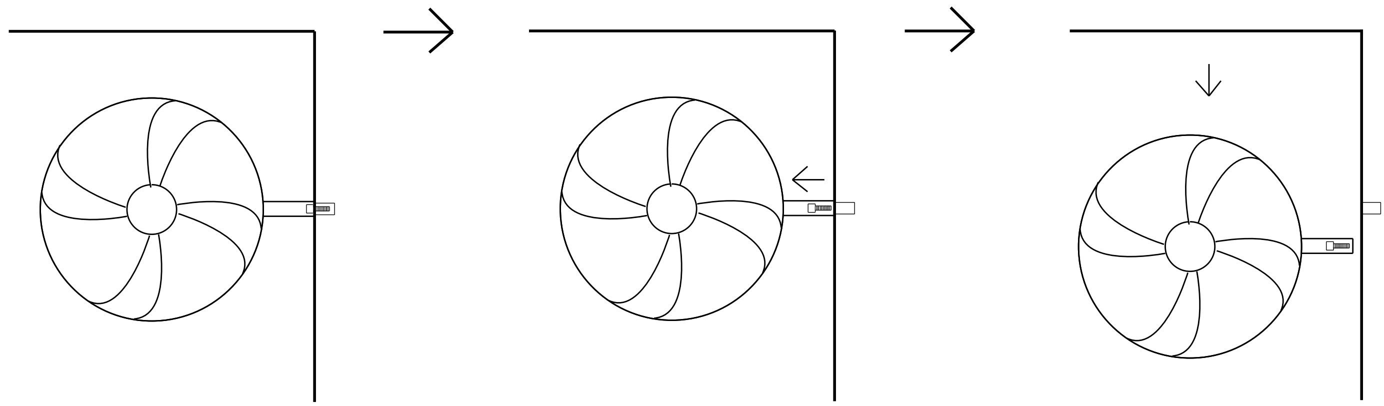
Plug-in ceiling ventilation



A concept has been designed that hangs the ventilation in the ceiling, with the help of a open/release mechanism, that fits into the holes of the perforated acoustic ceiling boards. This allows the user to move the ventilation ducts around themselves.

To fit into the modular system, the ducts should always hang from the centerline of each grid section. This way only one special interior wall module is needed, as the hole for ventilation to pass through, will always be centered on the wall and same height.

Plug-in wall ventilation



This principle utilises the threaded screws placed in the interior columns. It is just as easy to place and move around. However, it is confined to the edge of the rooms along the wall. This is an issue for larger rooms that require fresh air centrally.

Therefore, this system works best for smaller rooms, or as a more discrete way of routing exhaust around a room, while the ceiling principle delivers the fresh air. This system also requires asymmetric interior wall openings, which are less practical.

OUTDOOR SPACE

Intro

The purpose of this design task is to design the common space around the dwellings, and how to access the dwellings which are raised from the ground.

Outdoor space and paths

As mentioned in the section regarding the master-plan, it was determined that the dwellings should be placed in a circular shape. Several ways to get around on the site are sketched (see Illu 293 – Illu 298) and the sketching includes geometric, circular, and organic shapes.

The geometric shape creates well-defined zones, but it does not comply well with the landscape and natural feeling found on the site. Also, having many different smaller paths leading around the site will lead to less social encounters compared to having one clear path all people follow.

The organic and circular shape fits well into the landscape, and the circular shape is chosen, as it signals movement, and the area is joined with one clear path. The area is thought as being car-free and thus promoting safety for pedestrians, however, the circular path can be used for cars during moving or fire trucks if needed. From the circular path, there is access to the individual dwellings via smaller paths, which creates a buffer zone between the circular public path and the private dwellings.

Common outdoor area

Inside this circular path are the common areas. These areas are sketched in relation to outdoor space, and placement of the utility and common houses. The sketches can be seen on the next spread. Next to the common house, a terrace should be placed, where the inhabitants can gather in good weather. The common facilities, besides the terrace, should include different activities the inhabitants can be social around, which can include fireplaces, playground, beehives, flower gardens as well as vegetable gardens.

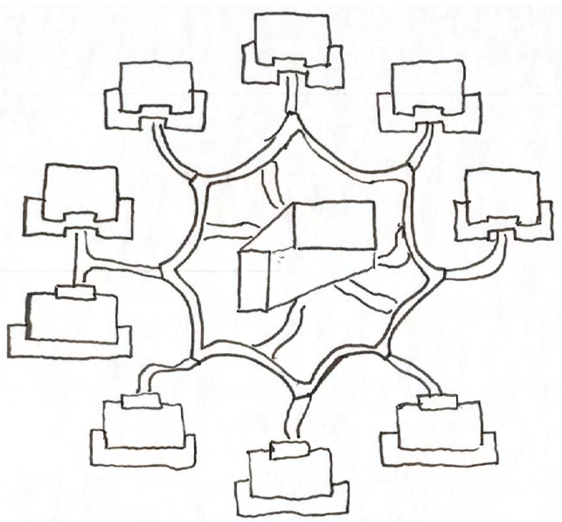
Access to dwellings

As the dwellings are placed above ground due to the raised screw foundation, the access into the dwellings is designed. The first solution is through stairs (see Illu 303), but as the building regulations state that new buildings should have level-free access, the stairs cannot comply. Ramps or elevators should be integrated as well. Therefore, two other access ways are designed, one with a ramp from the circular path leading up to the floor-level of the dwelling (see Illu 304) and one where the landscape is modified so it ends in the same height as the floor (see Illu 305). The latter provides a more natural feeling to the site along with having lower material usage than a ramp.

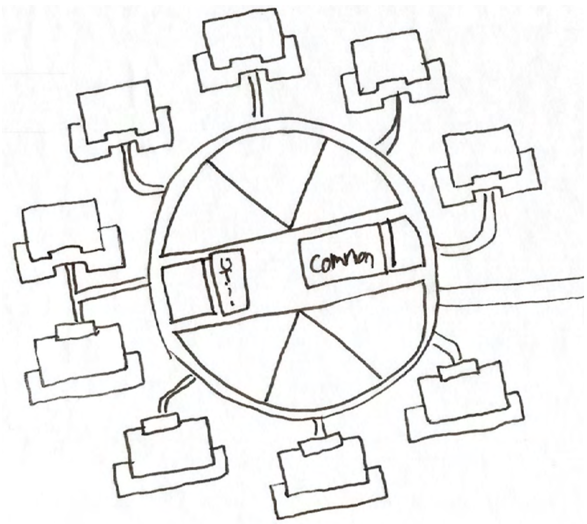
However, due to the quite heavy slope of the site at some points, integrating these natural ramps simply is not feasible. The natural elevation already rises at the allowed 5%, so rising any further up to a building is not possible. Due to the late realisation of this in the project, a reasonable solution could not be found for all dwellings. Therefore, the two houses towards the west have had level free access made through natural ramps, as well as the common rooms on each level. But the other dwellings have simple stairs. This will be discussed in the reflection chapter of this project.

Conclusion

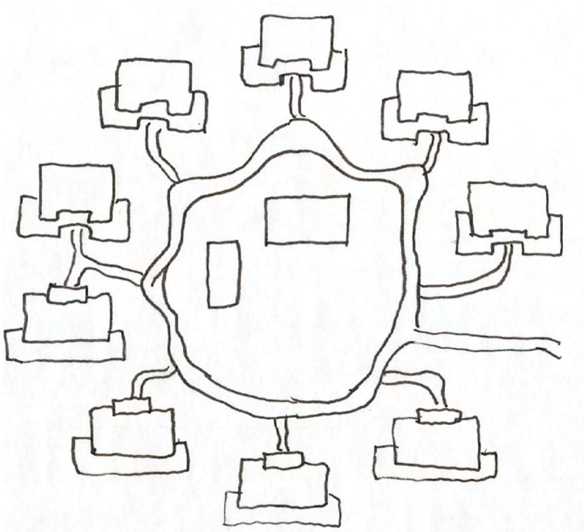
The path leading around the site is shaped as a circle, which accommodates movement and joins the area with one clear path used by all inhabitants. Inside the circular path, the common house along with different common outdoor facilities is be placed, providing the inhabitants with options for gathering both inside and outside. The access to the dwellings should be via a modified landscape ramp. But because of the slope of the site, many dwellings only have stairs and, therefore, does not comply with the building regulations.



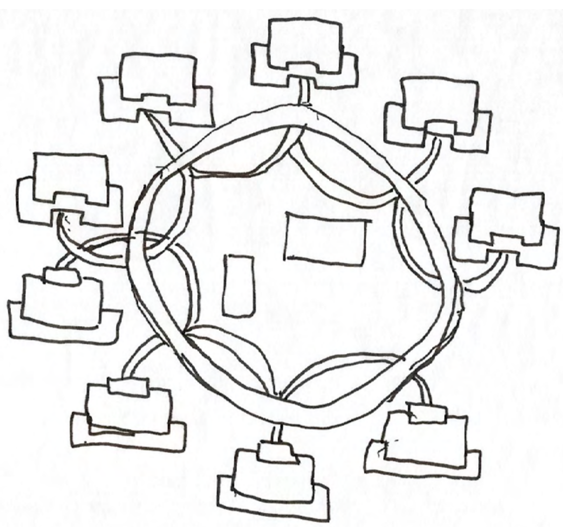
Illu 293: Outdoor space 1



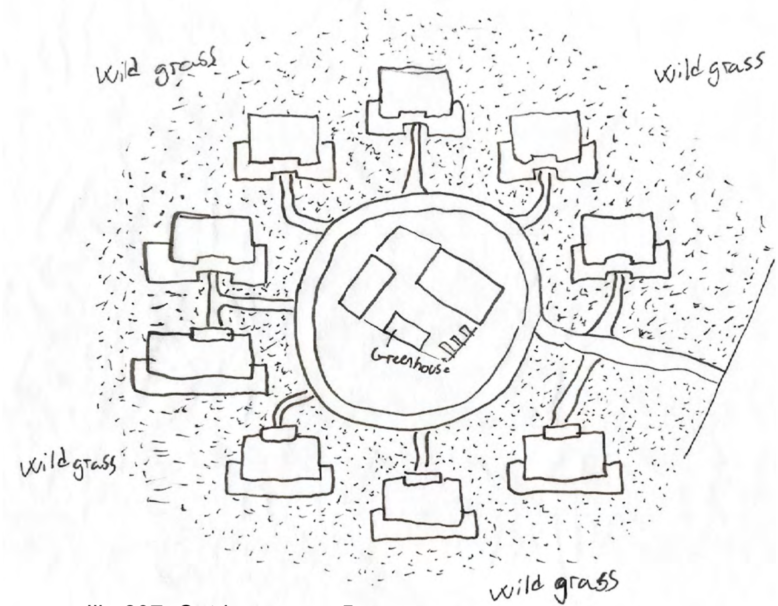
Illu 294: Outdoor space 2



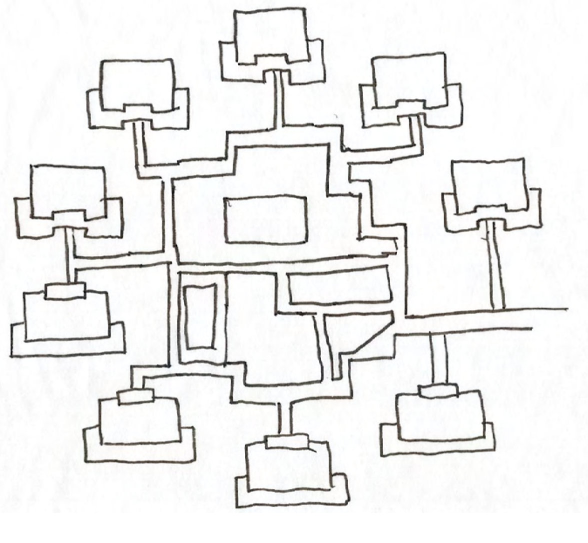
Illu 295: Outdoor space 3



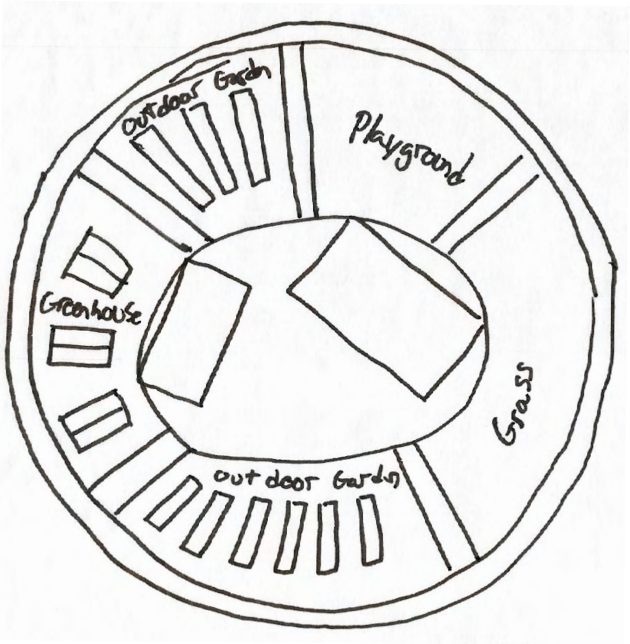
Illu 296: Outdoor space 4



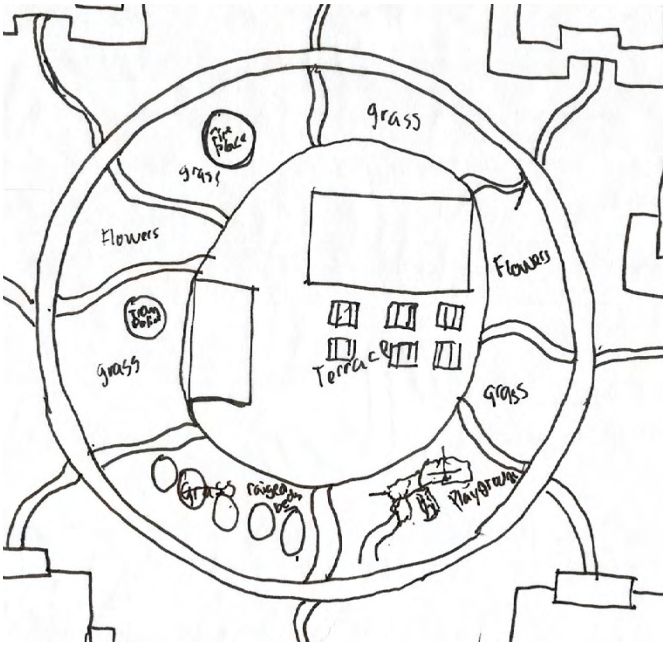
Illu 297: Outdoor space 5



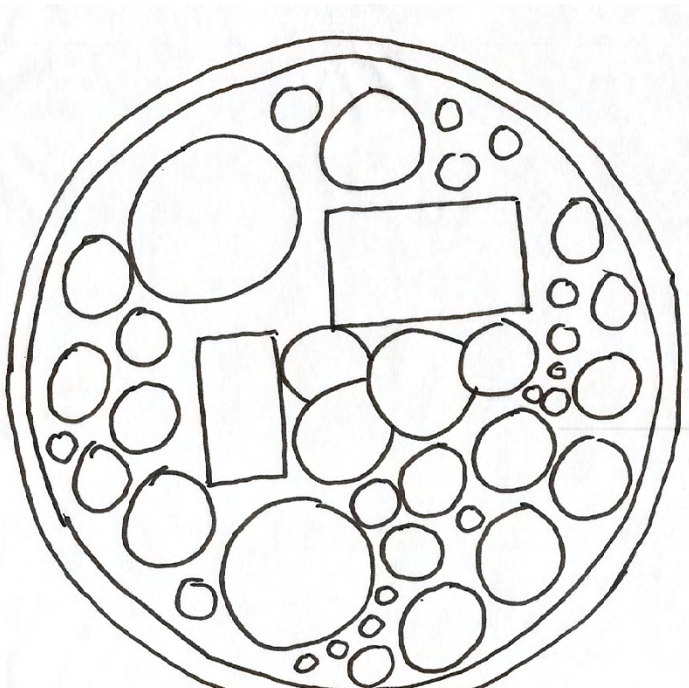
Illu 298: Outdoor space 6



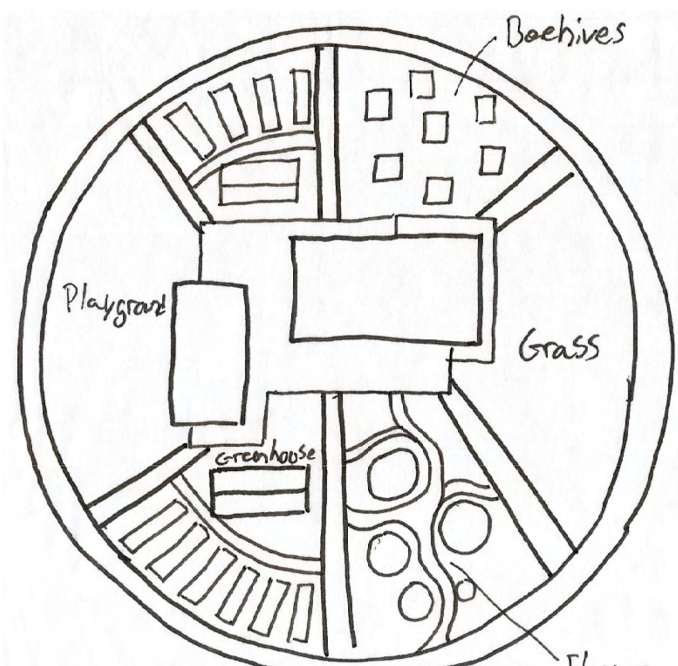
Illu 299: Common area around common house 1



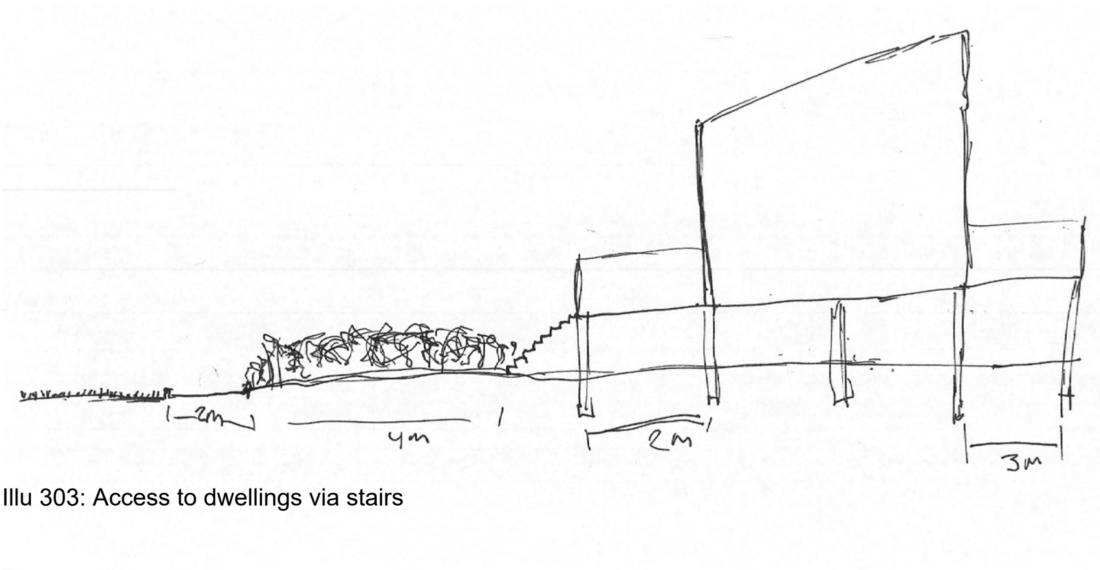
Illu 300: Common area around common house 2



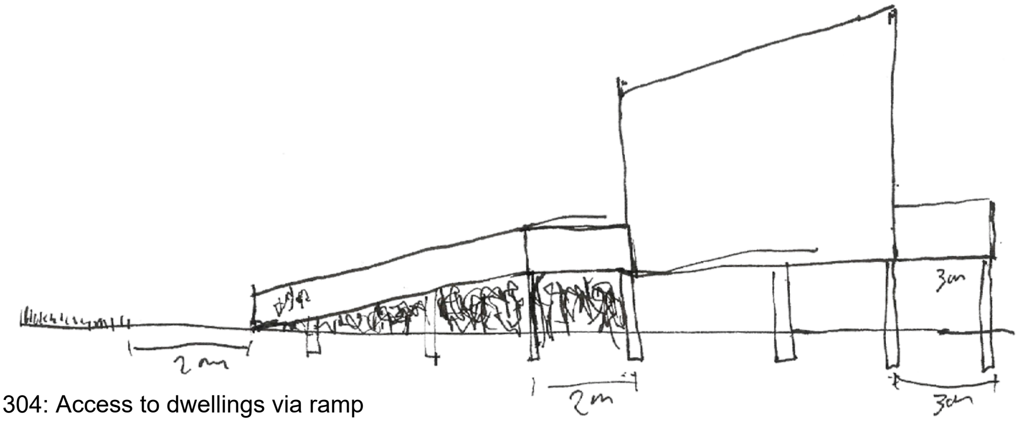
Illu 301: Common area around common house 3



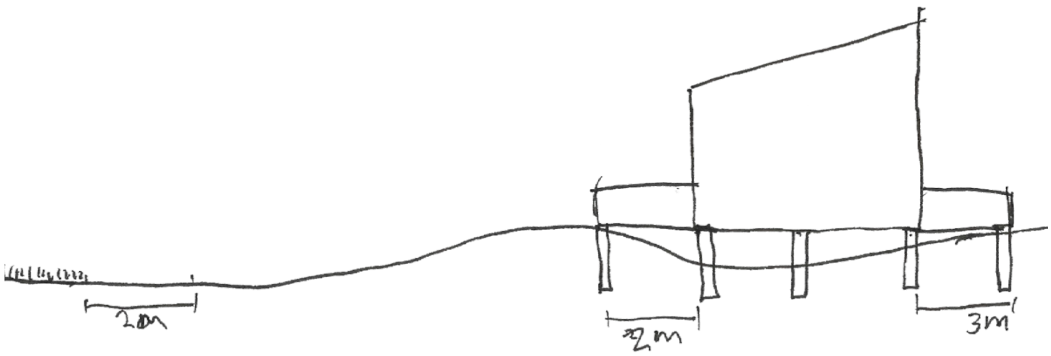
Illu 302: Common area around common house 4



Illu 303: Access to dwellings via stairs



Illu 304: Access to dwellings via ramp



Illu 305: Access to dwellings via modified landscape

PRESENTATION

MASTERPLAN

Illu 306: Masterplan

0 m 30 m

The masterplan for the site shows that the buildings are placed in a circle around common facilities situated in the middle. The circular shape provides equal access and views to the common facilities for all dwellings. A circular path leads around the site, connecting all dwellings with each other and the common facilities. The car - and bicycle parking happens outside the circular shape, resulting in an area where pedestrians are prioritized.

OUTDOOR COMMON SPACE

Illu 307: Common outdoor space

Around the common houses are social facilities such as an outdoor fireplace, a communal garden, a shared terrace, and a playground for kids situated. These outdoor common areas are designed to give all the qualities found in a single-family homes garden. By being situated in the middle of the site, the common areas are shielded from the strong western winds prone on the site.

SITE FACADES

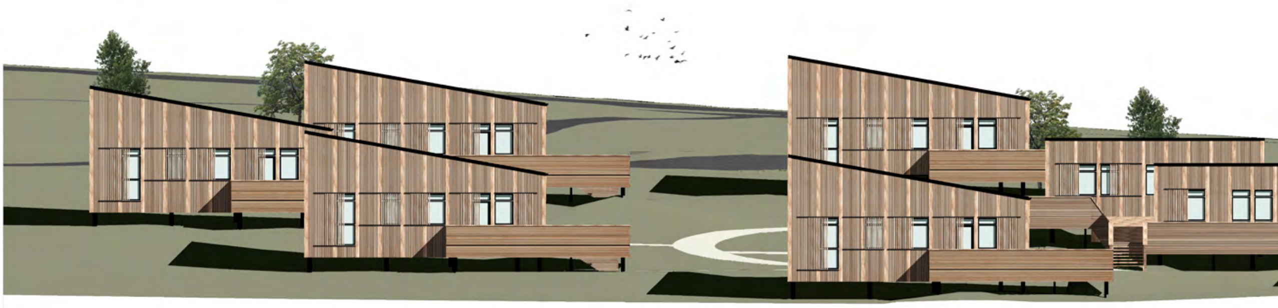
Illu 308: North facade

0 m 15 m

Illu 309: South facade

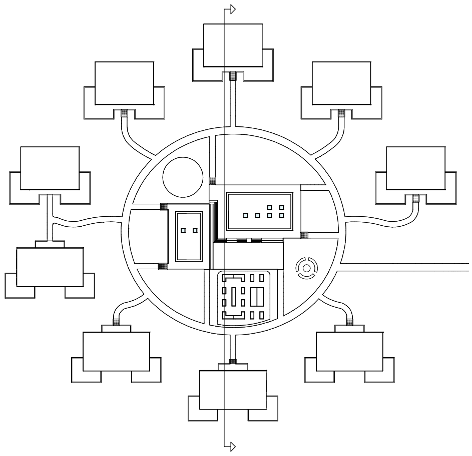
0 m 15 m

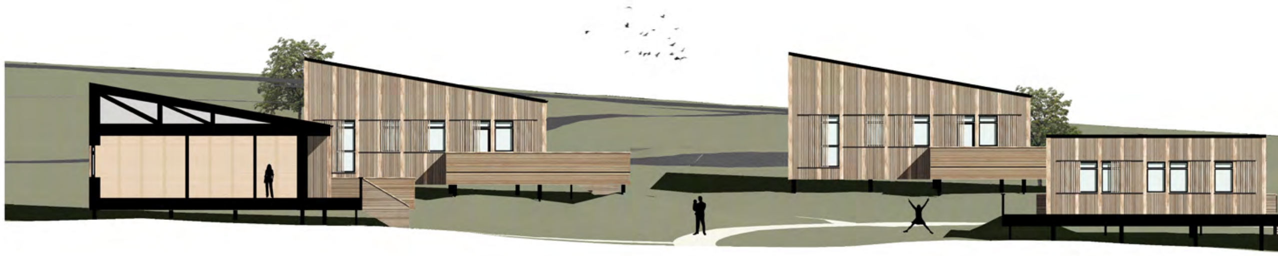
Illu 310: East facade



Illu 311: West facade

SITE SECTION

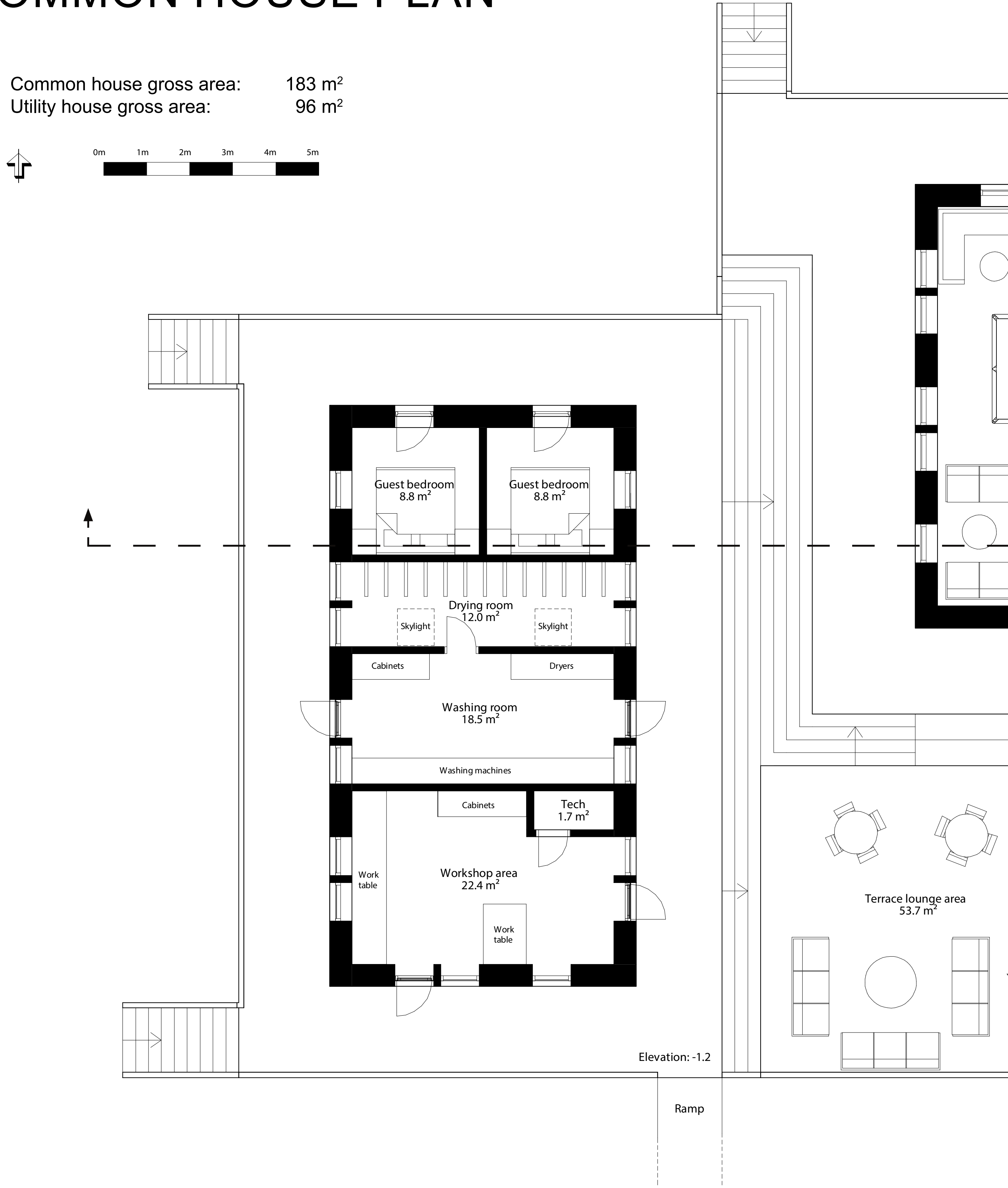


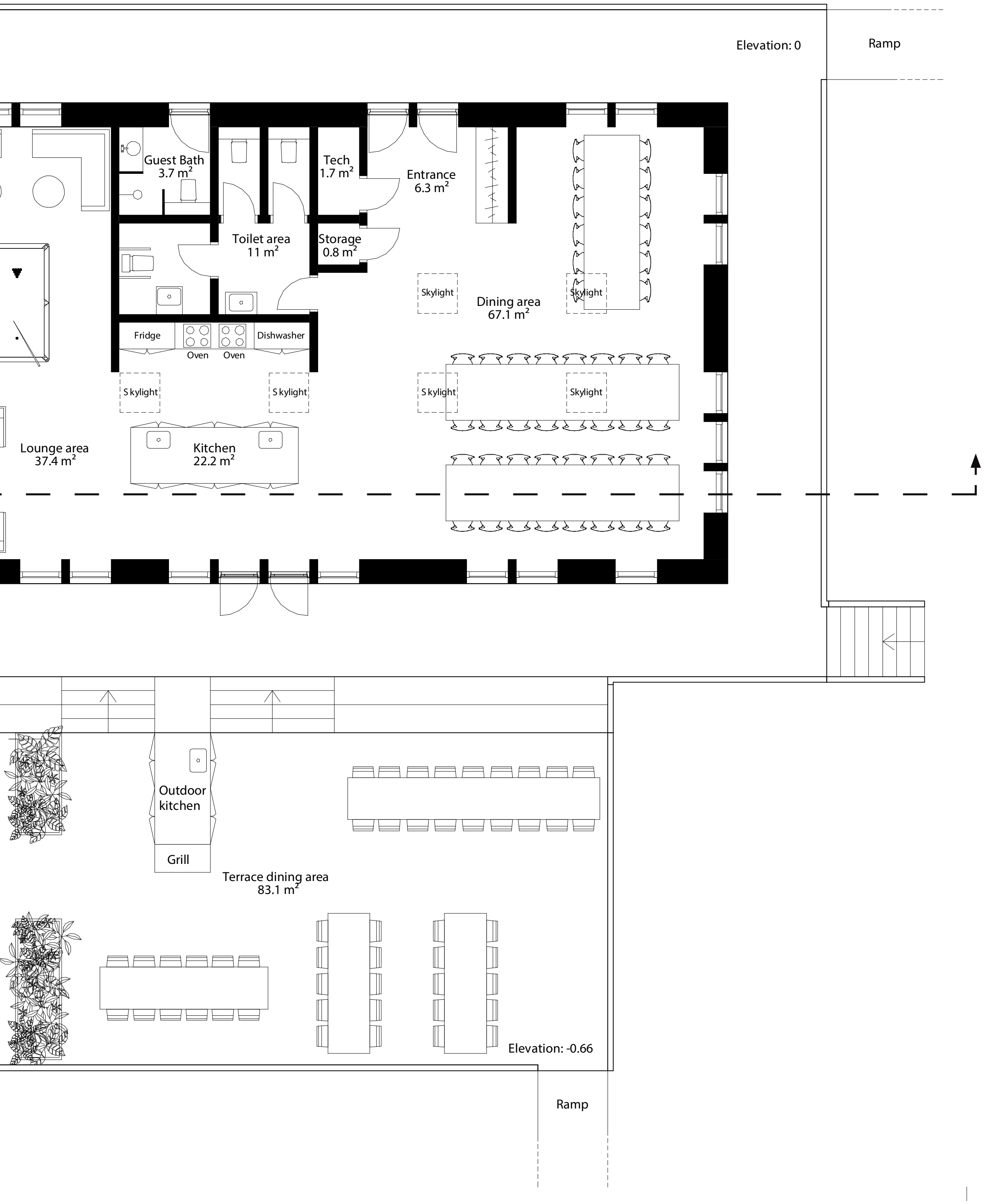


Illu 312: Site section

COMMON HOUSE PLAN

Common house gross area: 183 m²
Utility house gross area: 96 m²




Elevation: 0
Ramp
Guest Bath 3.7 m^2
Tech 1.7 m^2
Entrance 6.3 m^2
Toilet area 11 m^2
Storage 0.8 m^2
Skylight
Dining area 67.1 m^2
Skylight
Fridge
Oven
Oven
Dishwasher
Skylight
Skylight
Skylight
Skylight
Lounge area 37.4 m^2
Kitchen 22.2 m^2
Outdoor kitchen
Grill
Terrace dining area 83.1 m^2
Elevation: -0.66
Ramp

COMMON HOUSE

Illu 313: Common house

The common house space is designed for social interaction, with a direct connection between indoor and outdoor, and a centrally placed communal kitchen, that allows people to gather, cook and dine. The lounge creates a laid-back area, where people can sit down for a board game, a drink after dinner, or the kids can play.

COMMON HOUSE FACADES

Illu 314: North facade

0 m 5 m

Illu 315: South facade

0 m 5 m

Illu 316: East facade

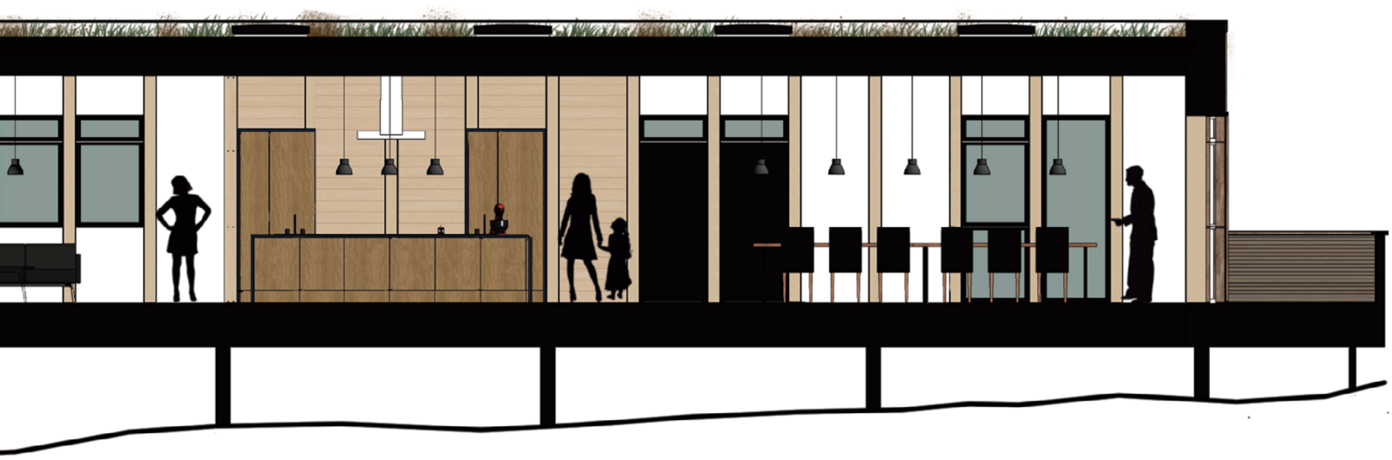
0 m 5 m

Illu 317: West facade

0 m 5 m

COMMON HOUSE SECTION

Illu 318: Section common house

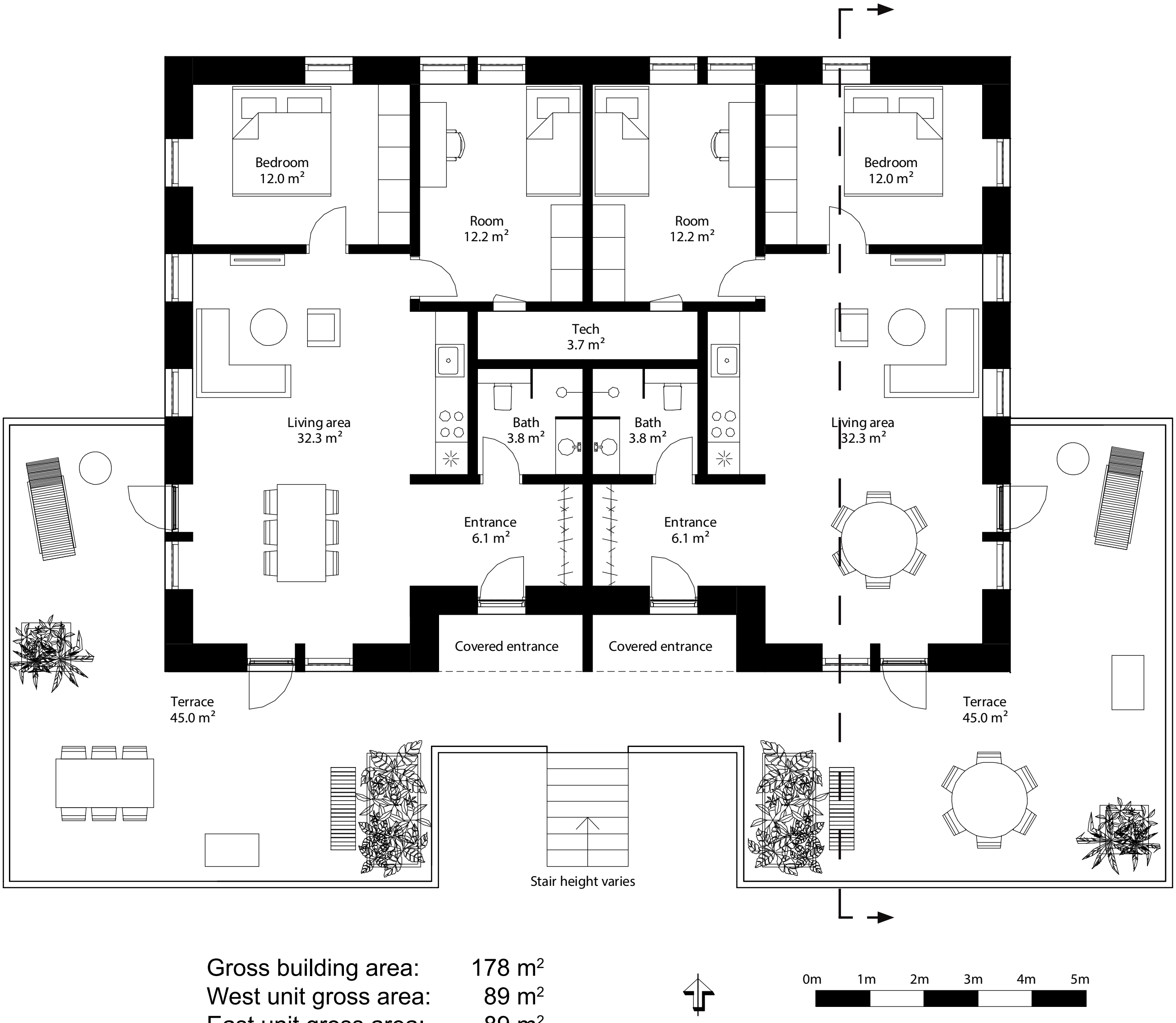


TERRACES

Illu 319: Terraces

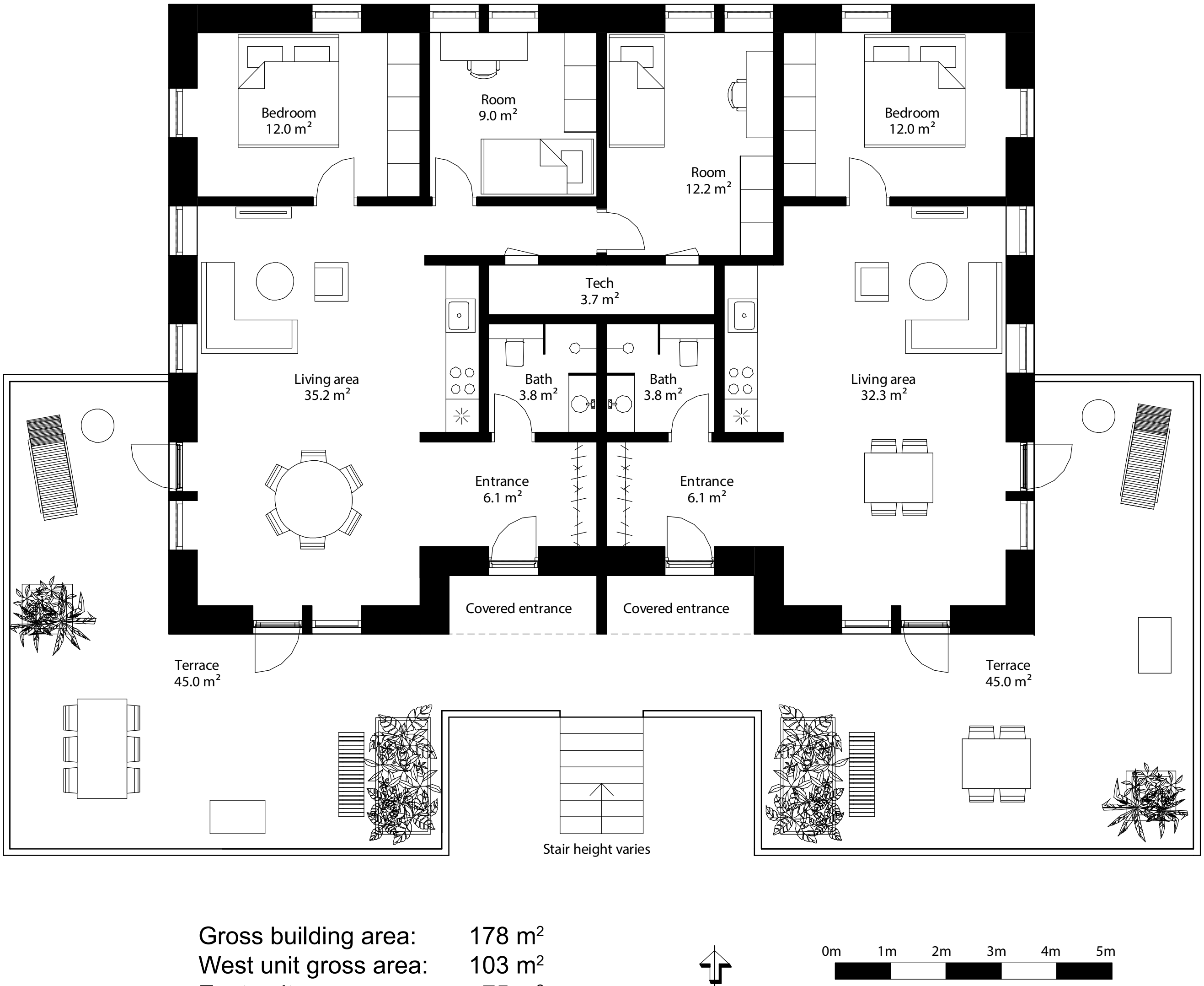
The terraces act as the private outdoor space for each dwelling, where the inhabitants can place their specific outdoor needs, be it outdoor dining, plants or sunbathing. The distance between the path around the site and the terrace allows for interaction between inhabitants while still maintaining a distance to create a feeling of privacy.

NORTH DWELLING PLANS



Gross building area:	178 m^2
West unit gross area:	89 m^2
East unit gross area:	89 m^2

Illu 320: North building
plan 2 3-room dwellings



Gross building area: 178 m^2
West unit gross area: 103 m^2
East unit gross area: 75 m^2

Illu 321: North building plan 1 4-room dwelling and 1 2-room dwelling

NORTH DWELLING

Illu 322: North dwelling

In this dwelling, there is a fully open connection in the main living spaces, all covered in wood to give a warm and calm atmosphere. The gridlines in floor and ceiling give a clear visual for the inhabitants, what possibilities there are for altering their interior space.

NORTH DWELLING FACADES

Illu 323: North facade

Illu 324: South facade

Illu 325: East facade

0 m 5 m

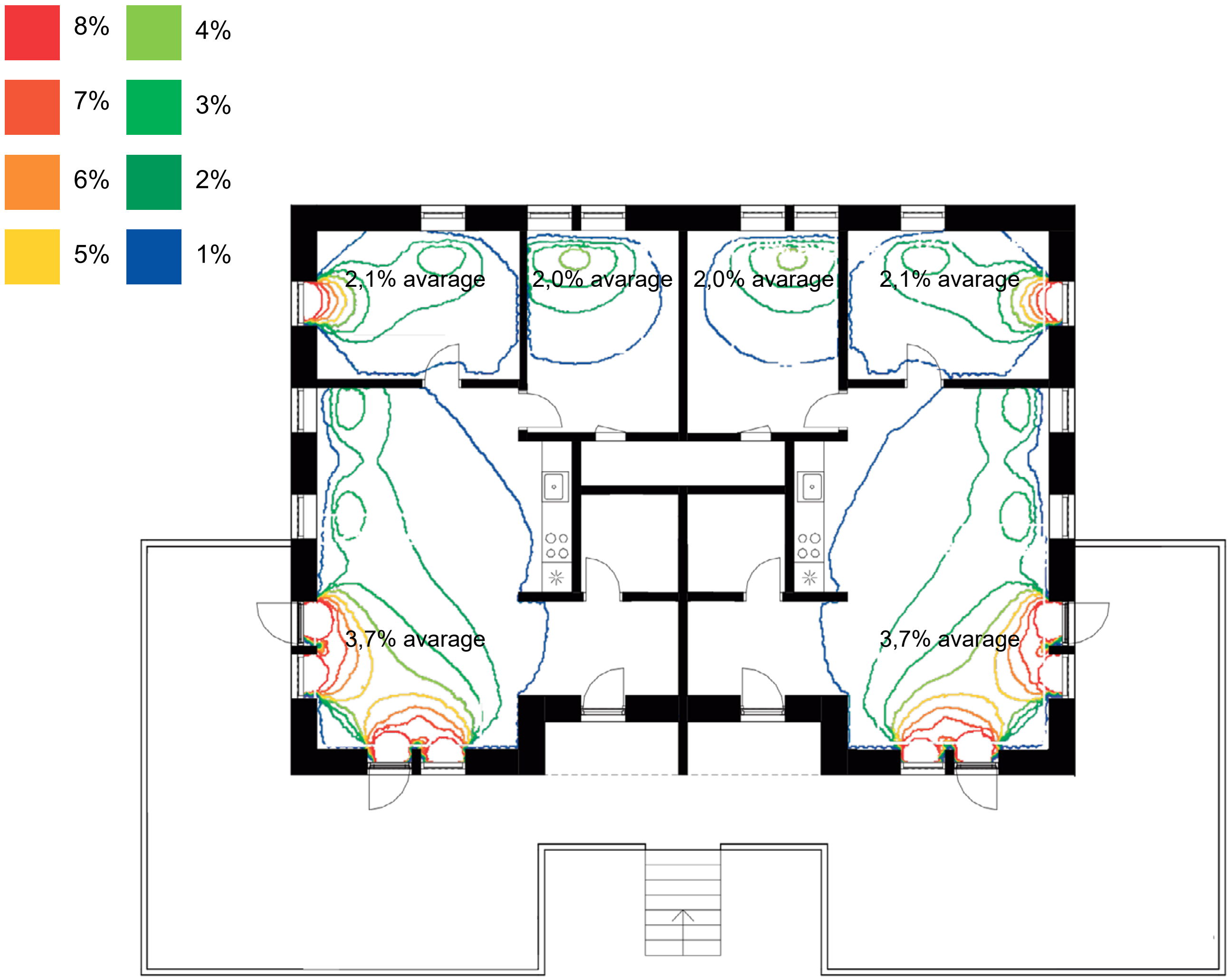
Illu 326: West facade

0 m 5 m

NORTH DWELLING SECTION

Illu 327: North dwelling section

NORTH DWELLING DAYLIGHT



Illu 328: North dwelling section

NORTH DWELLING ENERGY FRAME

Heating	23,2	kWh/m² pr year
Electricity	10,1	kWh/m² pr year
Overheating	0	kWh/m² pr year

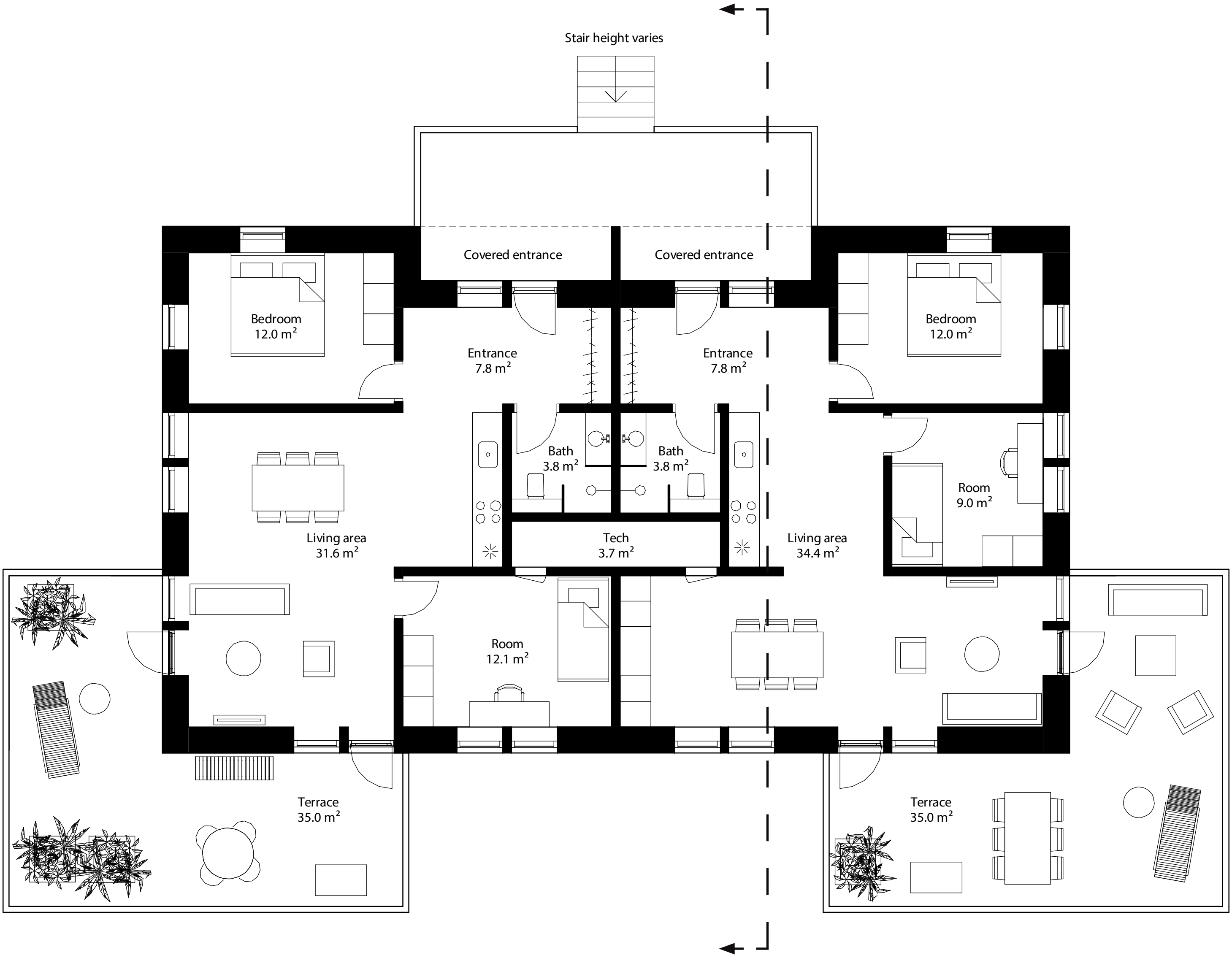
Illu 329: Final energy frame for north dwelling.
See Appendix 7 for all measures.

LANDSCAPE

Illu 330: Landscape seen from southwest

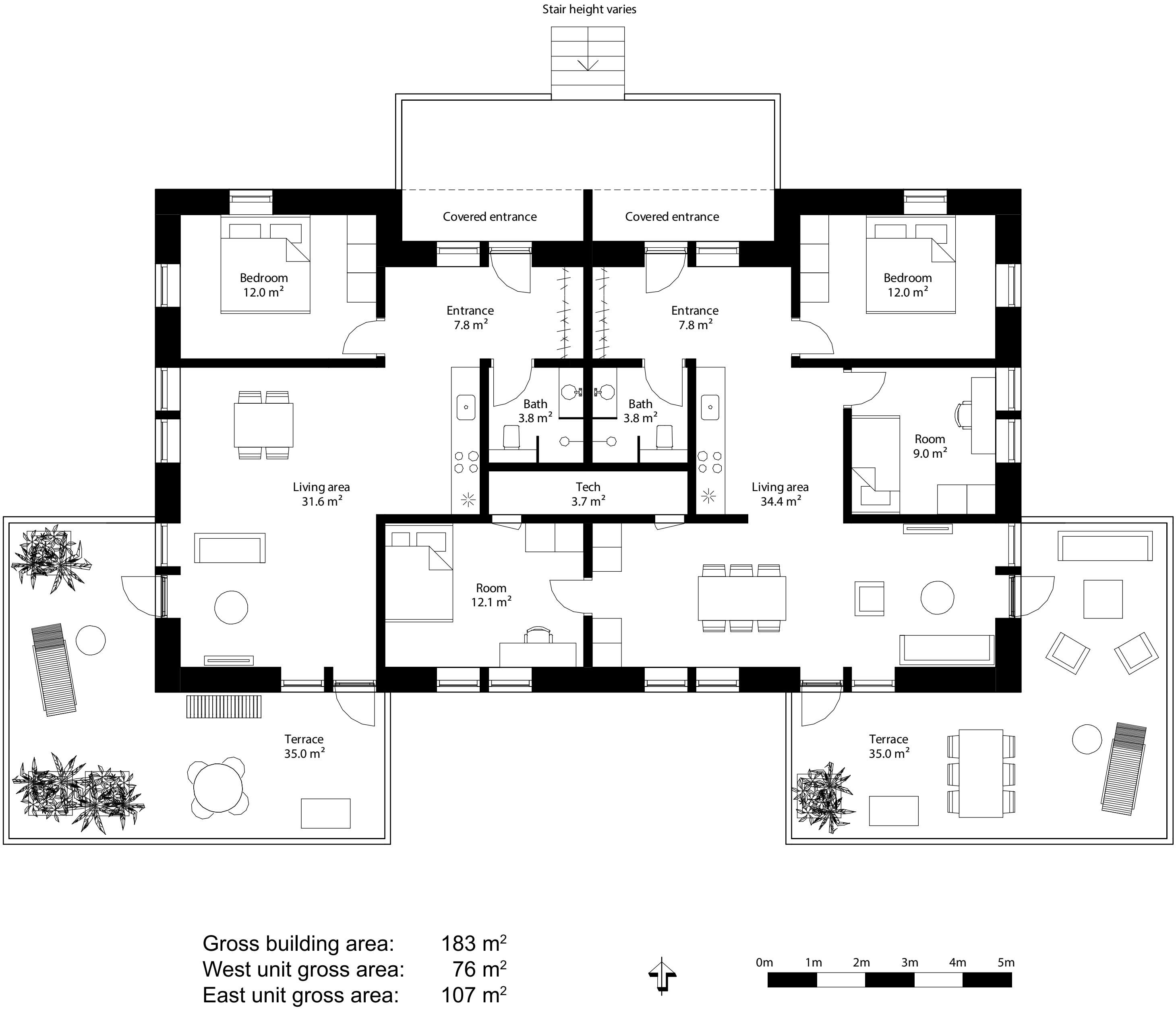
The dwellings are placed in the wild nature found on the site, appearing as if growing out of the sea of grass. The sloped green roofs play into the wild nature of the site, while allowing the grass that disappears under the building, to instead appear on the roof surface.

SOUTH DWELLING PLANS



Gross building area: 183 m²
West unit gross area: 91,5 m²
East unit gross area: 91,5 m²

Illu 331: South building plan
2 3-room dwellings



Gross building area: 183 m²
West unit gross area: 76 m²
East unit gross area: 107 m²

Illu 332: South building plan 1 4-room dwelling and 1 2-room dwelling

SOUTH DWELLING

Illu 333: South dwelling

In this dwelling the main living spaces are placed towards the south, in a larger apartment configuration with 3 bedrooms. It allows for a bright and sunny interior space with the white walls and provides open unobstructed views towards the south.

SOUTH DWELLING FACADES

Illu 334: North facade

0 m 5 m

Illu 335: South facade

0 m 5 m

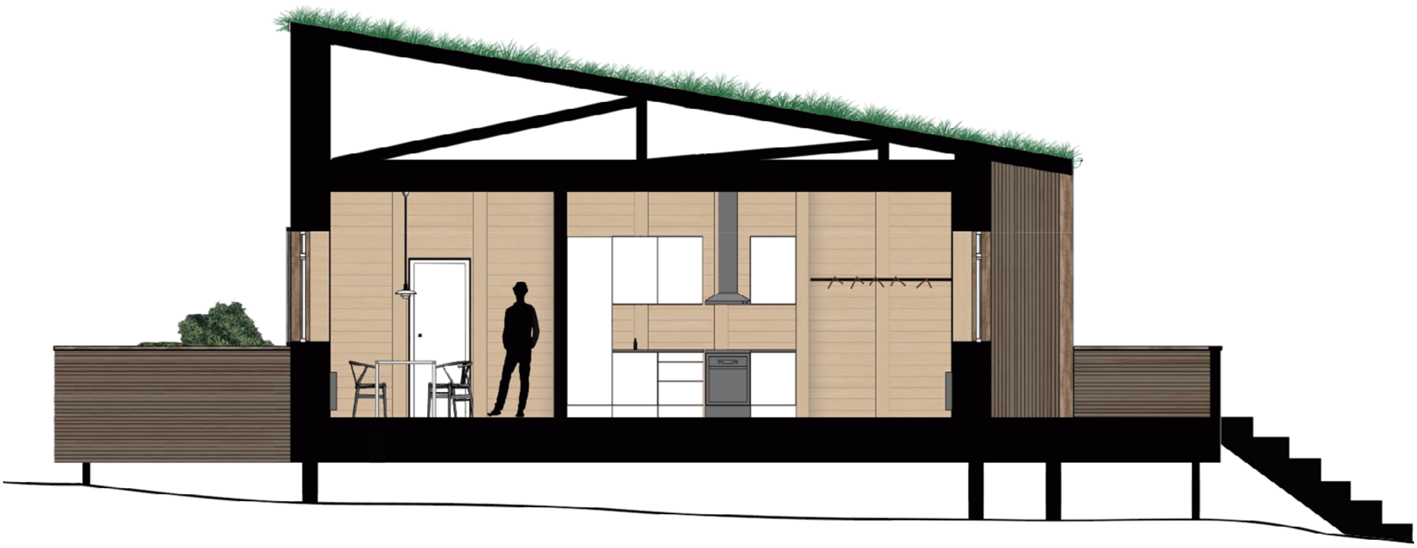
Illu 336: East facade

0 m 5 m

Illu 337: West facade

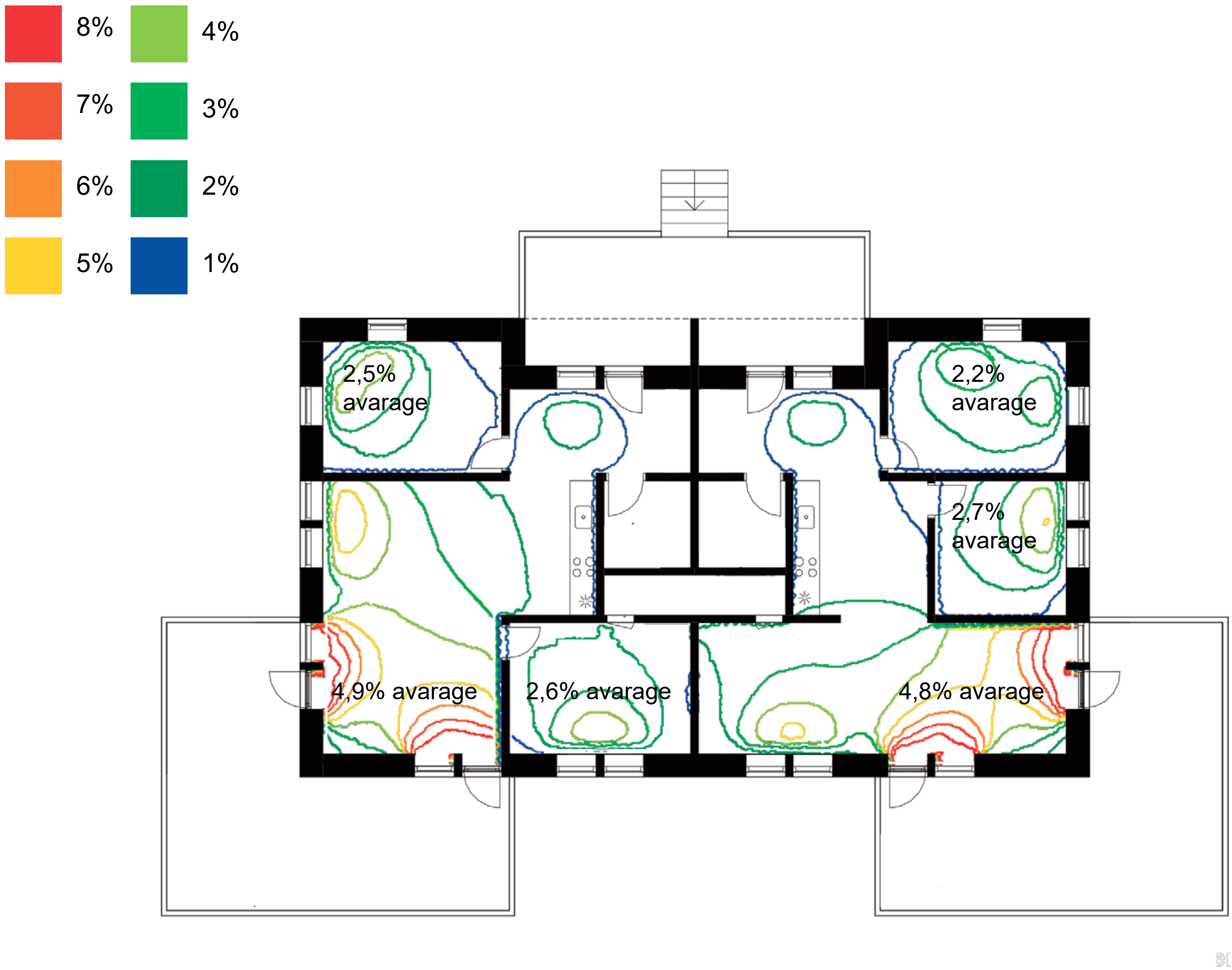
0 m 5 m

SOUTH DWELLING SECTION



Illu 338: South building section

SOUTH DWELLING DAYLIGHT



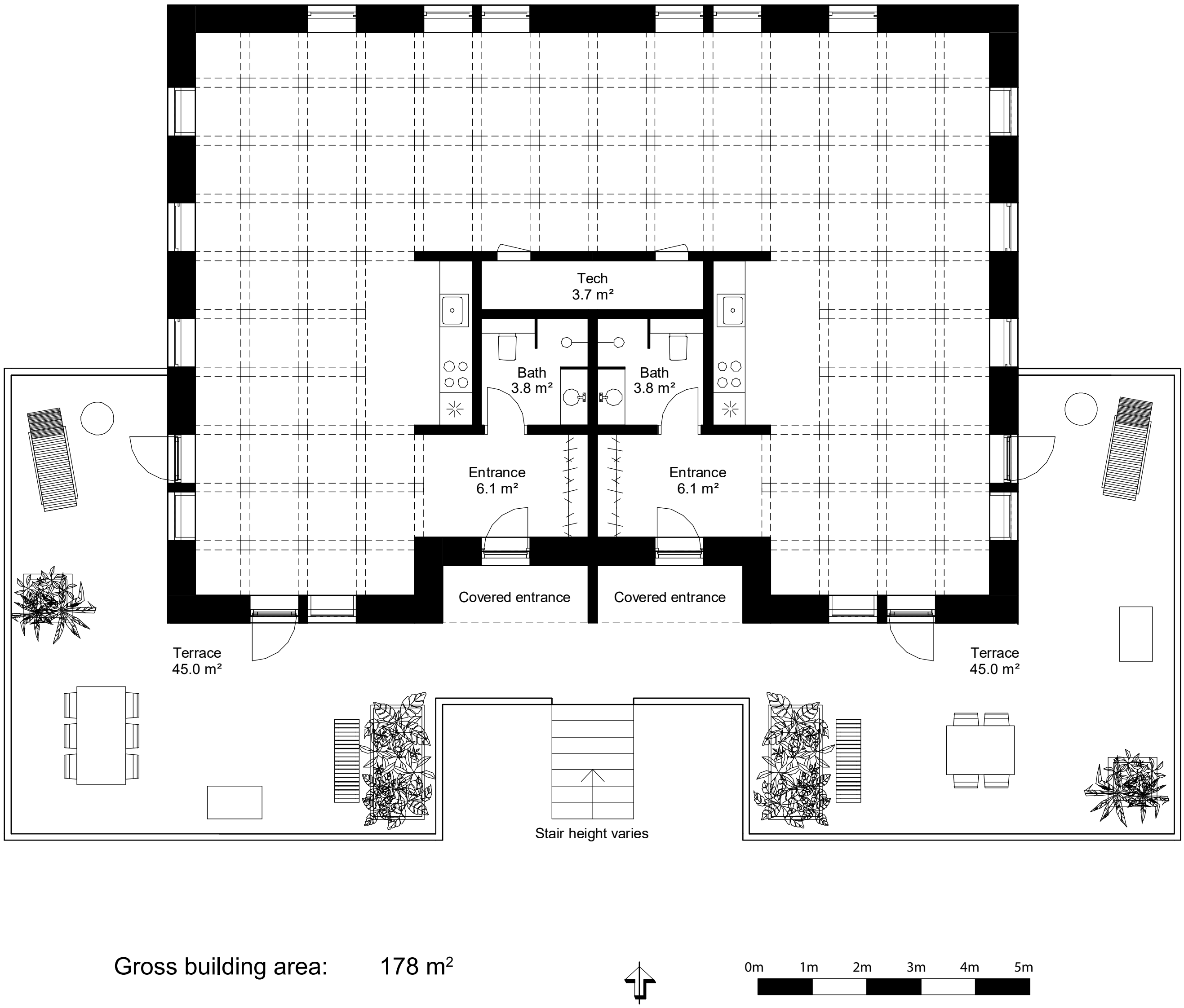
SOUTH DWELLING ENERGY FRAME

Heating	22,4	kWh/m² pr year
Electricity	10,0	kWh/m² pr year
Overheating	0	kWh/m² pr year

Illu 339: Final energy frame for south dwelling.
See Appendix 7 for all measures.

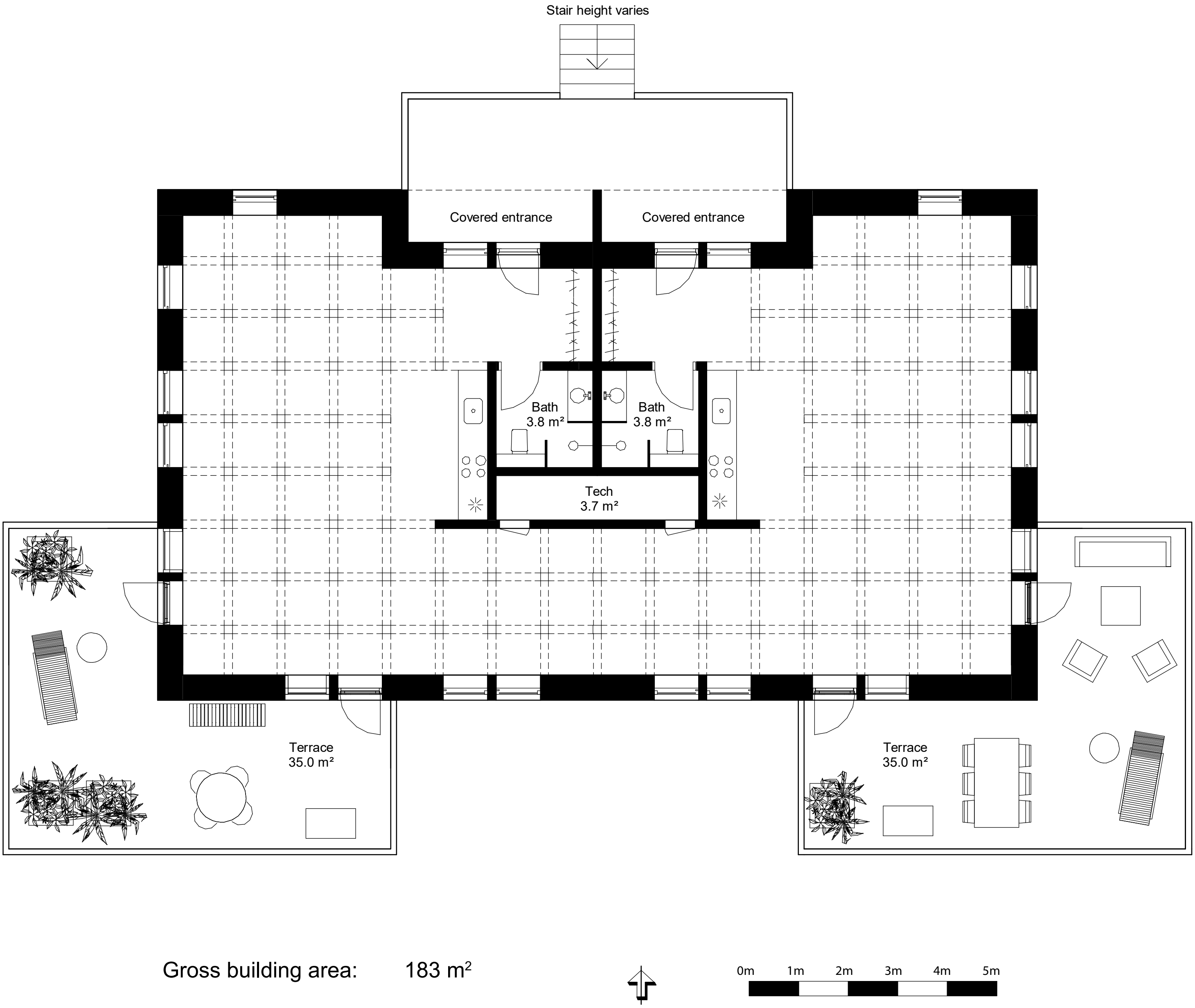
GENERIC PLAN NORTH

The generic plans show the grid system in the floor, and thus the many possibilities for flexibility and how to place the inner walls in different configurations. The large floor squares are not to be removed, whereas the narrow grid lines can be removed and interior walls can be installed instead. The earlier presented plans are thereby examples of how the inner walls can be placed, but there are many other options as well.



Illu 340: Generic plan North

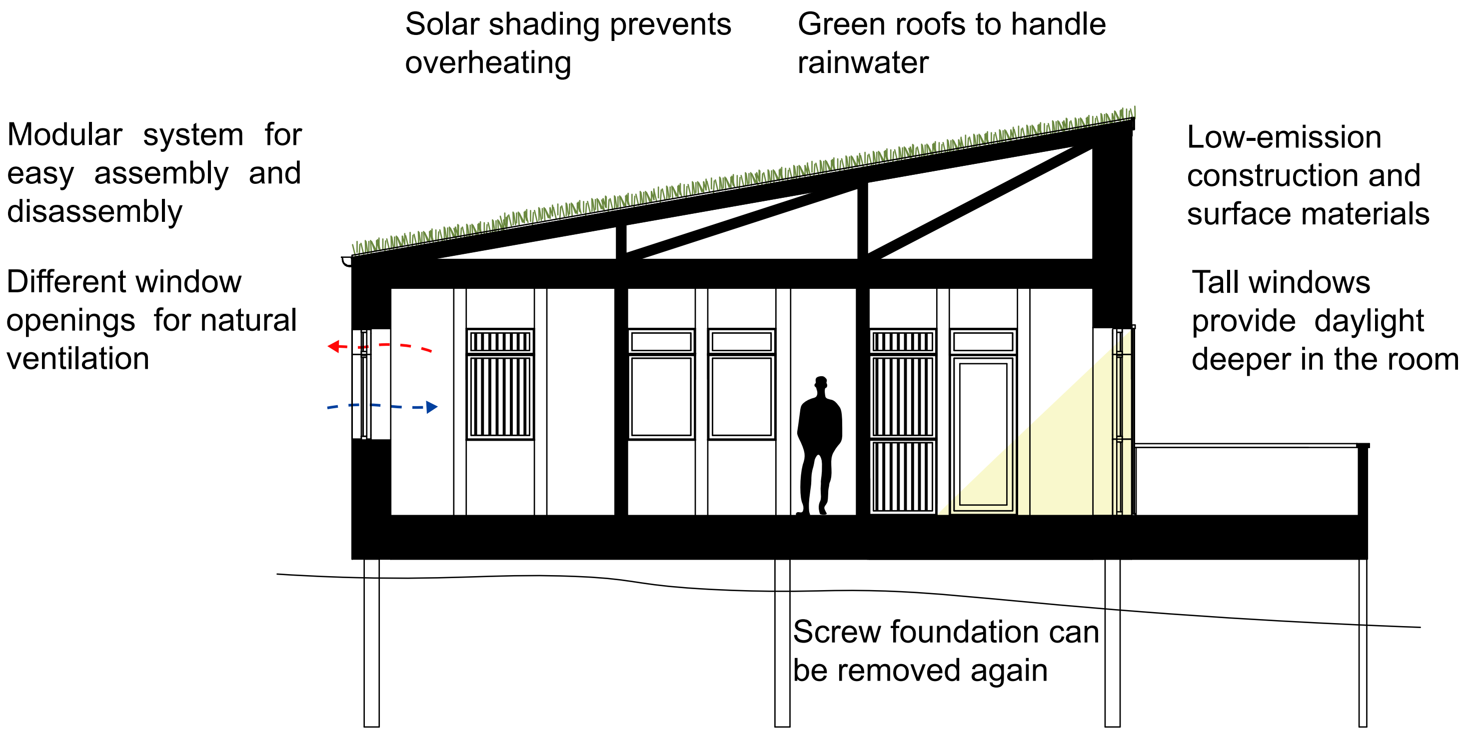
GENERIC PLAN SOUTH



Illu 341: Generic plan South

SUSTAINABILITY STRATEGIES

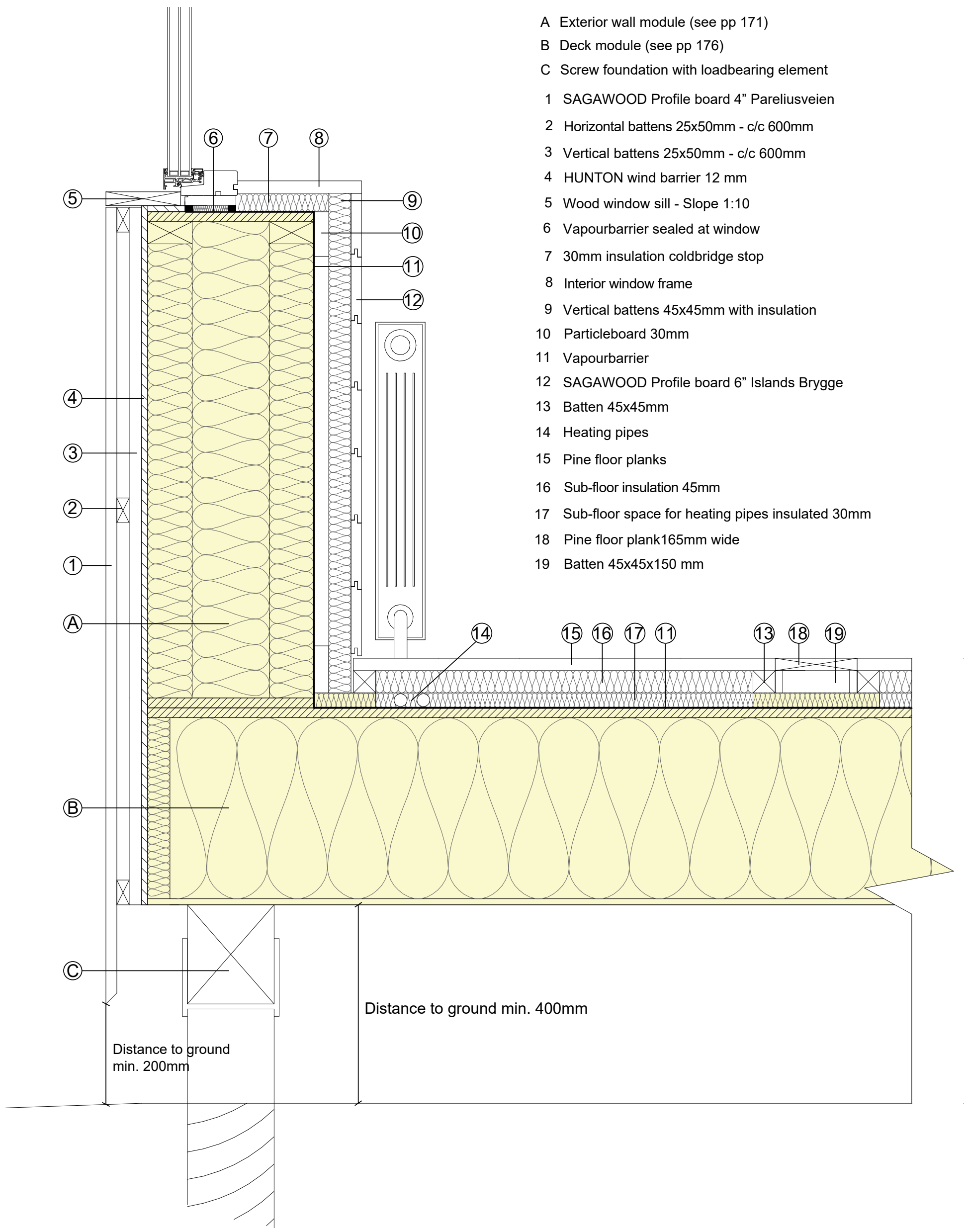
This section presents some of the sustainable approaches taken to the design of the building. The green roof, solar shading, and wooden facades help promote a visually sustainable building. The modular system ensures that the building can be disassembled and reused on another site, along with the screw foundation. The different window openings and heights give variety to the facade's expression, along with the modular wooden cladding. The windows also provide good control of the indoor environment for the users, ensuring good indoor environment year-round.



Illu 342: Sustainability strategies

DETAIL DRAWING 1

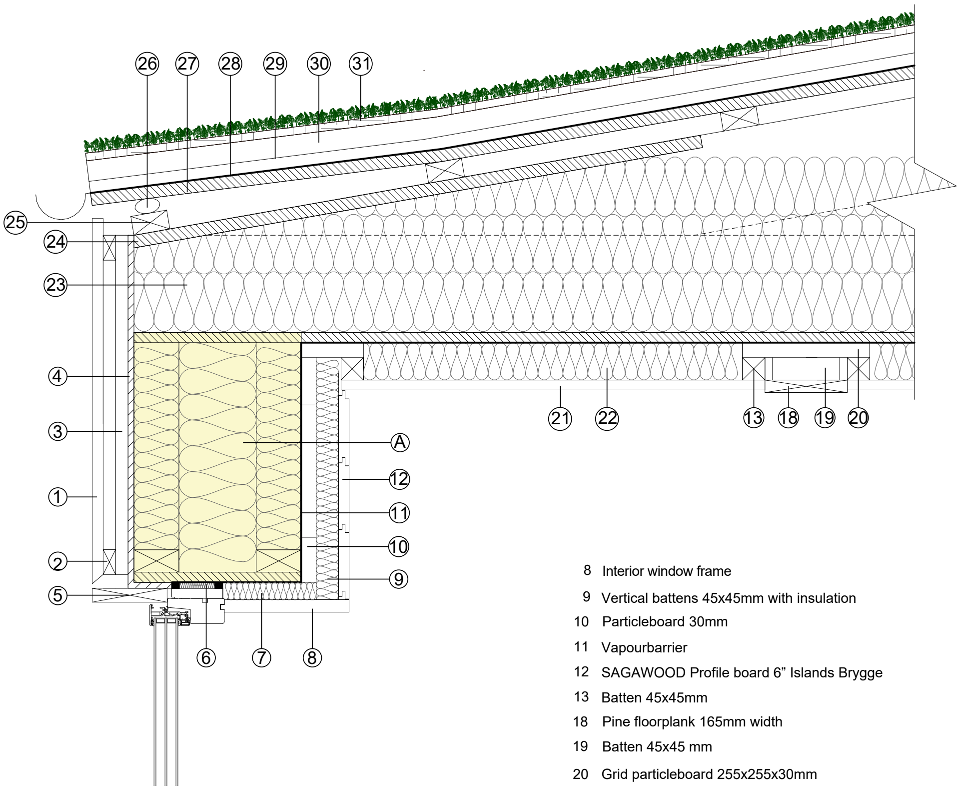
Foundation, outer wall and window



Illu 343: Detail drawing 1 - foundation, deck, outer wall and window 1:15

DETAIL DRAWING 2

Roof, outer wall and window



8 Interior window frame
9 Vertical battens 45x45mm with insulation
10 Particleboard 30mm
11 Vapourbarrier
12 SAGAWOOD Profile board 6” Islands Brygge
13 Batten 45x45mm
18 Pine floorplank 165mm width
19 Batten 45x45 mm
20 Grid particleboard 255x255x30mm
21 Perforated gypsum board 20mm
22 Insulation and installation layer 45mm + 30mm
23 Raft construction with 360mm insulation
24 Particleboard to prevent wind on insulation
25 Batten 38x73mm
26 Ventilation opening with insect net
27 Particleboard 25mm
28 Urbanscape vapour membrane and root defense
29 Urbanscape drainage layer
30 Urbanscape roll substrate layer
31 Urbanscape sedum-mix

A Exterior wall module (see pp 171)

1 SAGAWOOD Profile board 4” Pareliusveien
2 Horizontal battens 25x50mm - c/c 600mm
3 Vertical battens 25x50mm - c/c 600mm
4 HUNTON wind barrier 12 mm
5 Wood window sill - Slope 1:10
6 Vapourbarrier sealed at window
7 Insulation coldbridge stop 30mm

Illu 344: Detail drawing 2 - Window, outer wall and roof 1:15

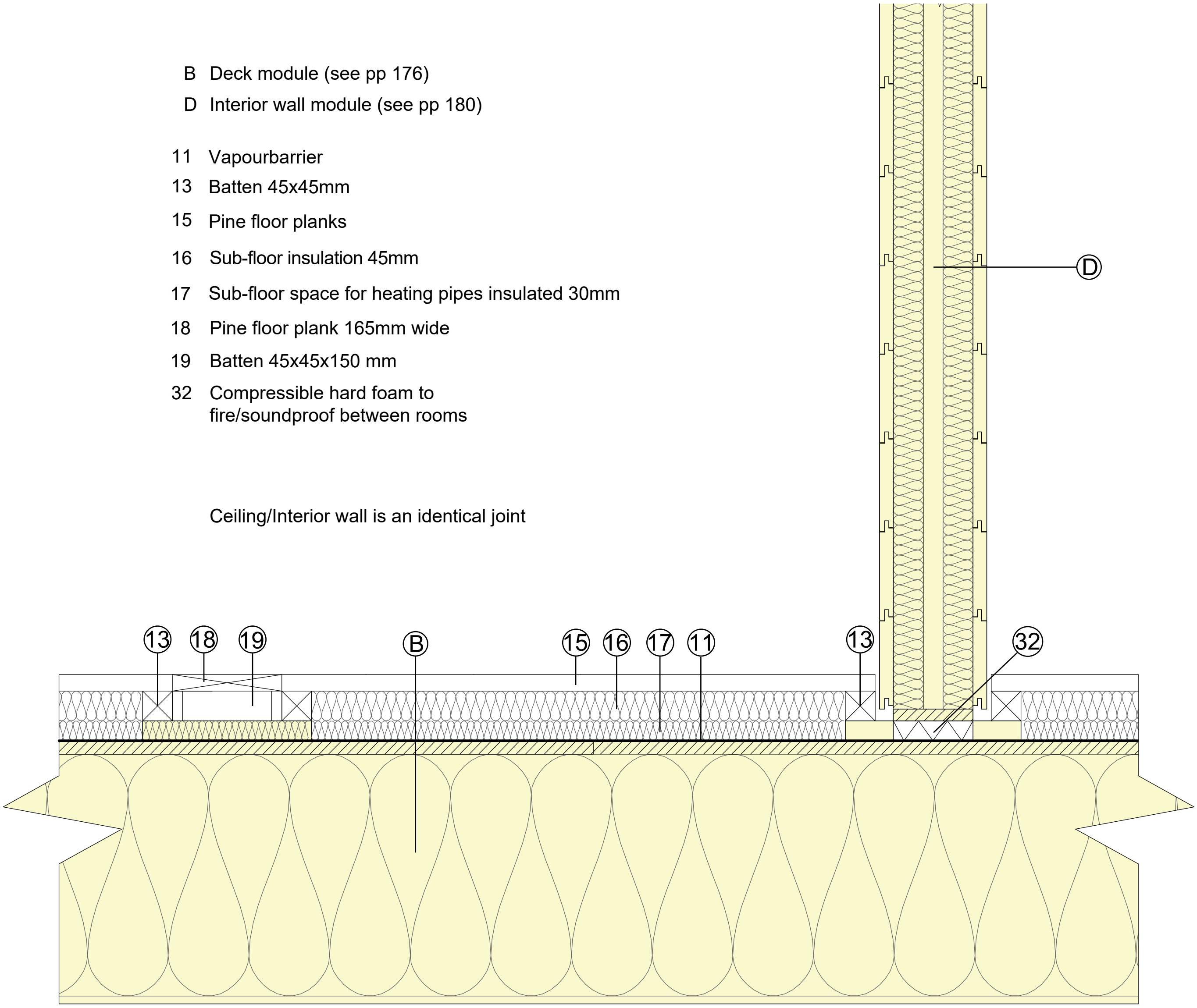
DETAIL DRAWING 3

Deck and interior wall

B Deck module (see pp 176)
D Interior wall module (see pp 180)

11 Vapourbarrier
13 Batten 45x45mm
15 Pine floor planks
16 Sub-floor insulation 45mm
17 Sub-floor space for heating pipes insulated 30mm
18 Pine floor plank 165mm wide
19 Batten 45x45x150 mm
32 Compressible hard foam to fire/soundproof between rooms

Ceiling/Interior wall is an identical joint



Illu 345: Detail drawing 3 - Deck and interior wall 1:15

ASSEMBLY PROCESS

The assembly process is important for this project, as proper assembly is what ensures the possibility of disassembly. This page presents each step of the process, and the modules used in each step. The process described below is also disassembly process if read in reverse.

1. The screw foundation is added and levelled out

2. The deck module is added

3. The exterior wall modules are added on the deck

4. The wind barrier is added which also joins and stabilises the walls. The vapour barrier is installed on the walls and is joined with the vapour barrier in the floor

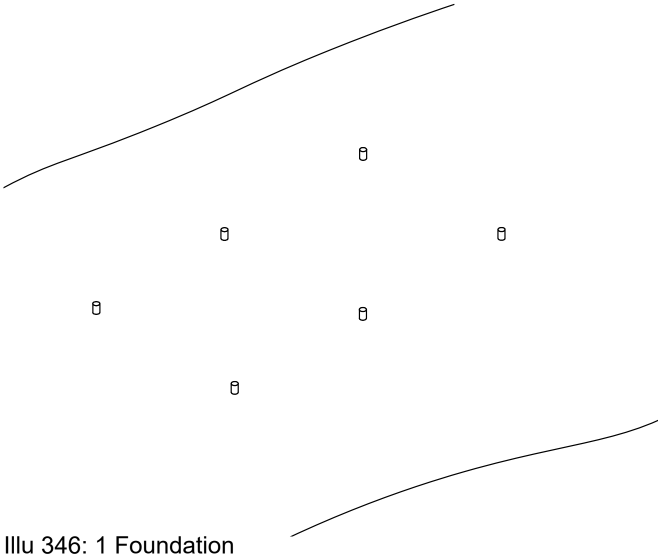
5. The roof construction is added, and the vapour barrier is joined with the wall

6. The interior wall columns are bolted to the pre mounted boards on the floor and ceiling

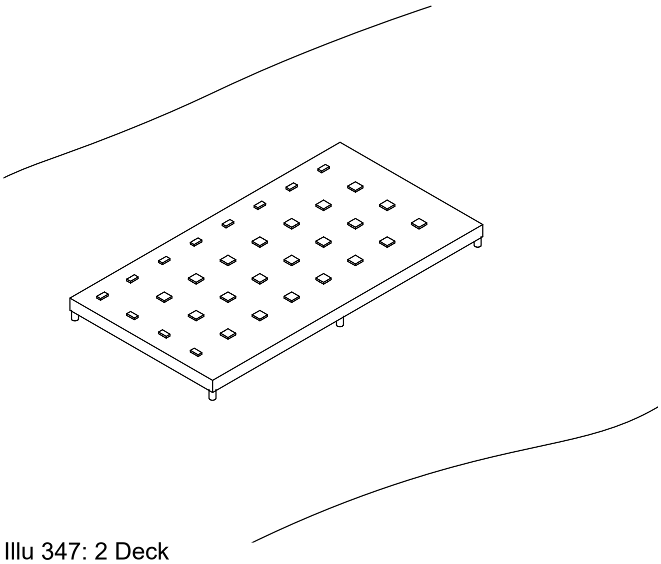
7. The interior walls are attached to the columns and sealed with compressible foam between the deck and ceiling

8. The flooring is added to each modular square

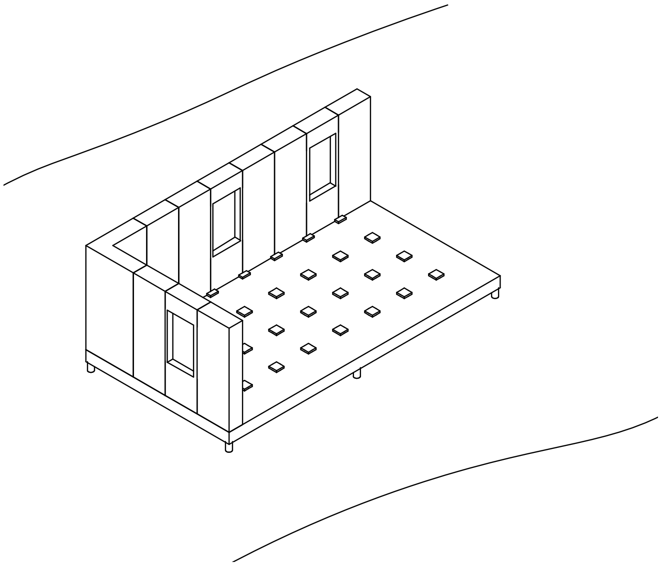
9. Interior/Exterior cladding is added as the final layer



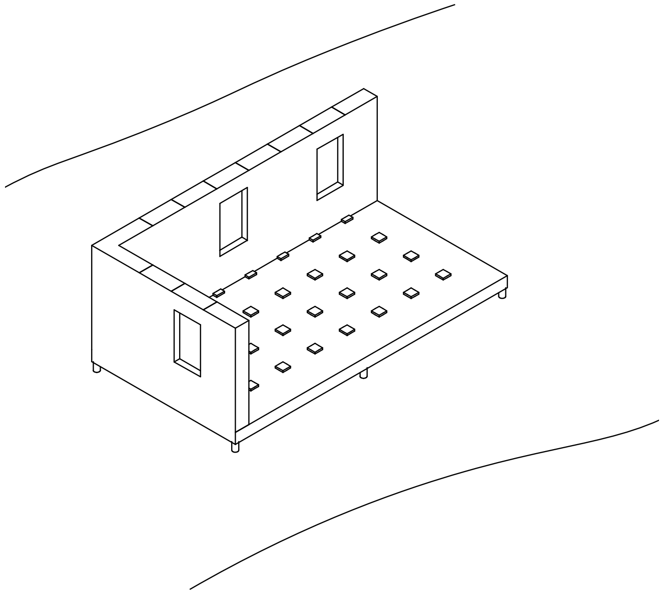
Illu 346: 1 Foundation



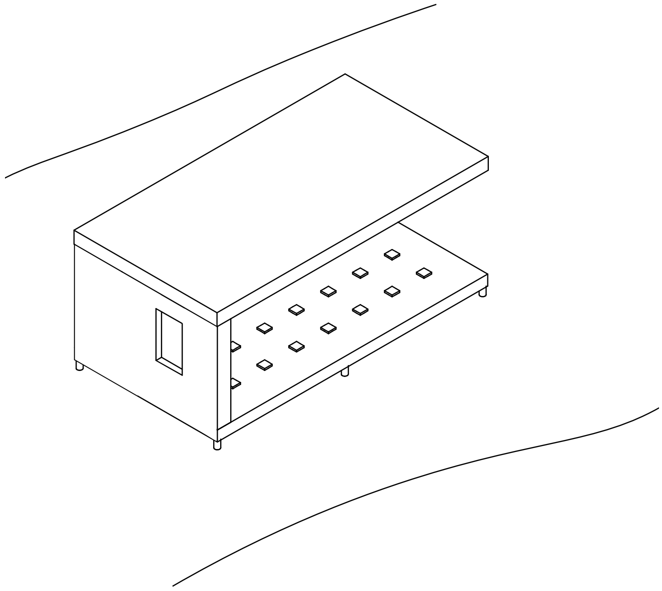
Illu 347: 2 Deck



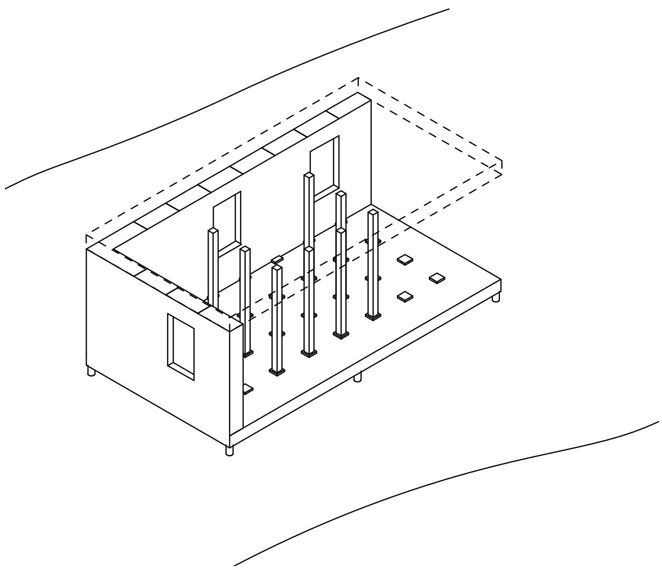
Illu 348: 3 Modular outer walls



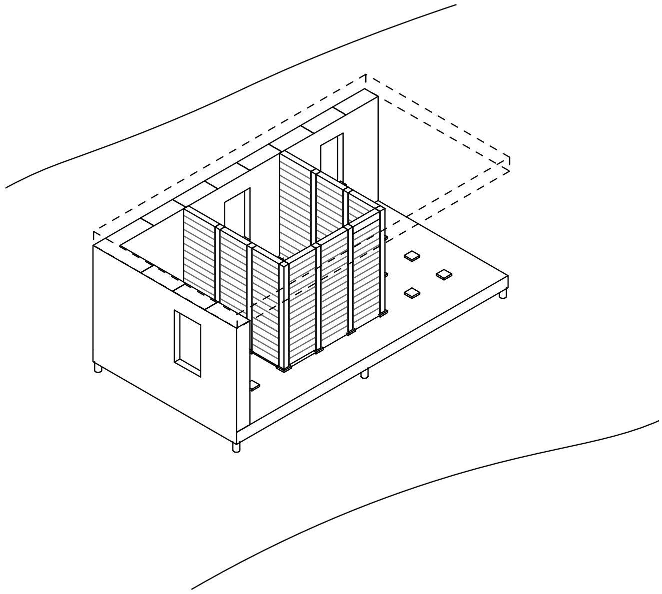
Illu 349: 4 Vapour barrier and wind barrier



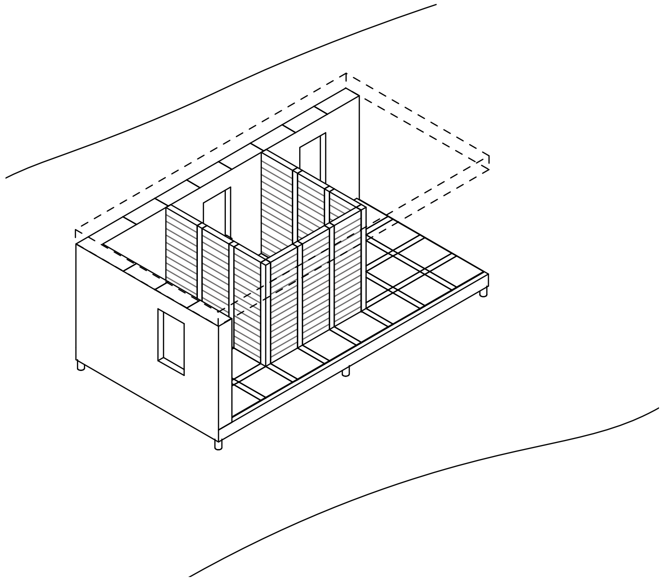
Illu 350: 5 Roof



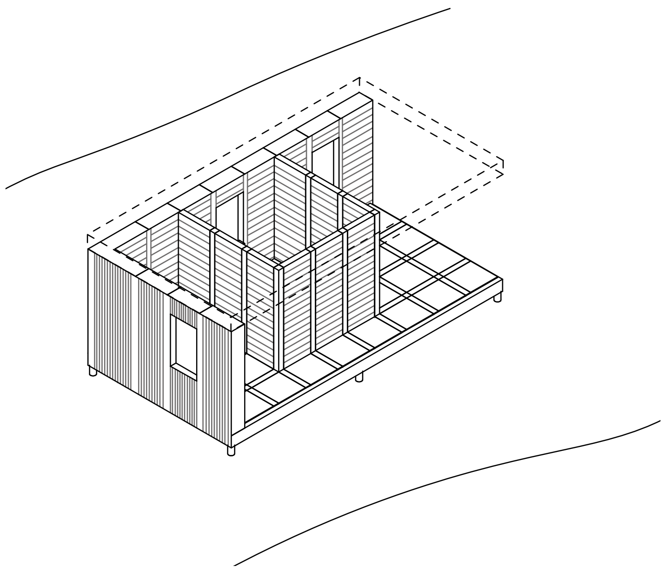
Illu 351: 6 Column interior walls



Illu 352: 7 Interior walls



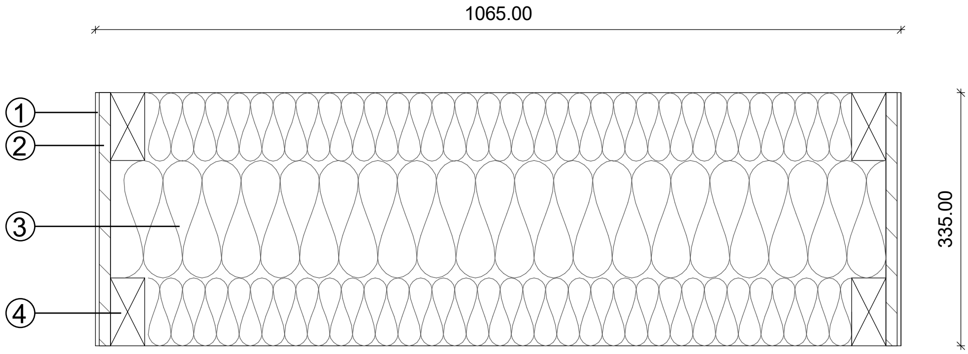
Illu 353: 8 Flooring



Illu 354: 9 Facade and interior cladding

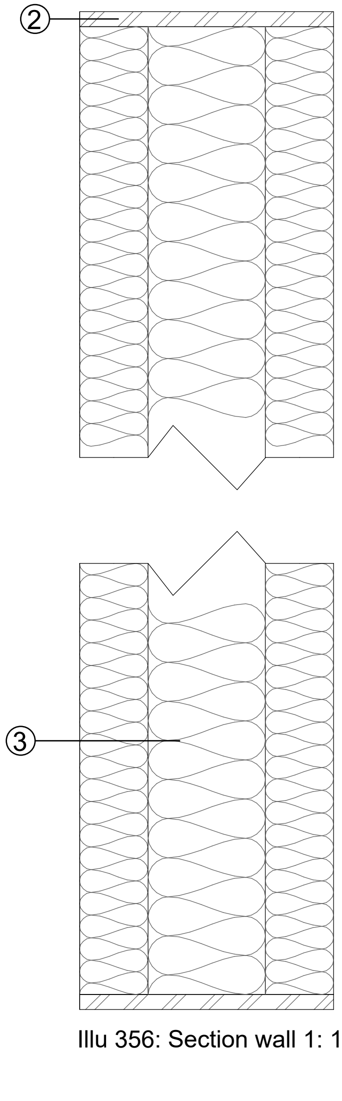
OUTER WALL MODULE

The outer layer of the wall module consists of cork-boards, which is a little flexible and thus ensures tightness between two modules. A particleboard along with the wooden columns are the loadbearing part of the module, functioning as an i-column. The walls are isolated with wooden fibre insulation.

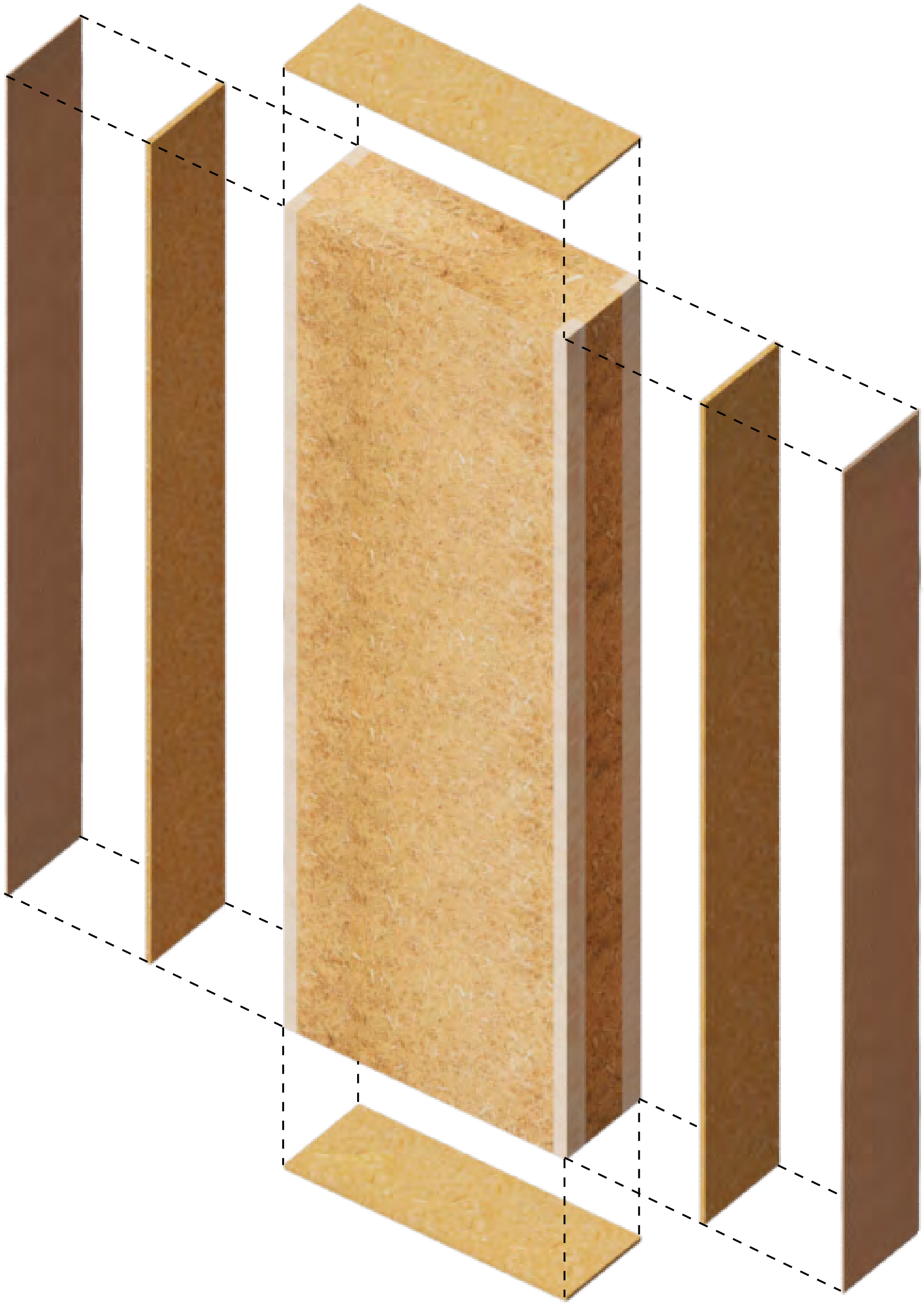


Illu 355: Plan wall module 1: 10

① Cork board 5 mm
② Particleboard 18 mm
③ Wooden fibre insulation 335 mm
④ Loadbearing columns 90 mm x 45 mm



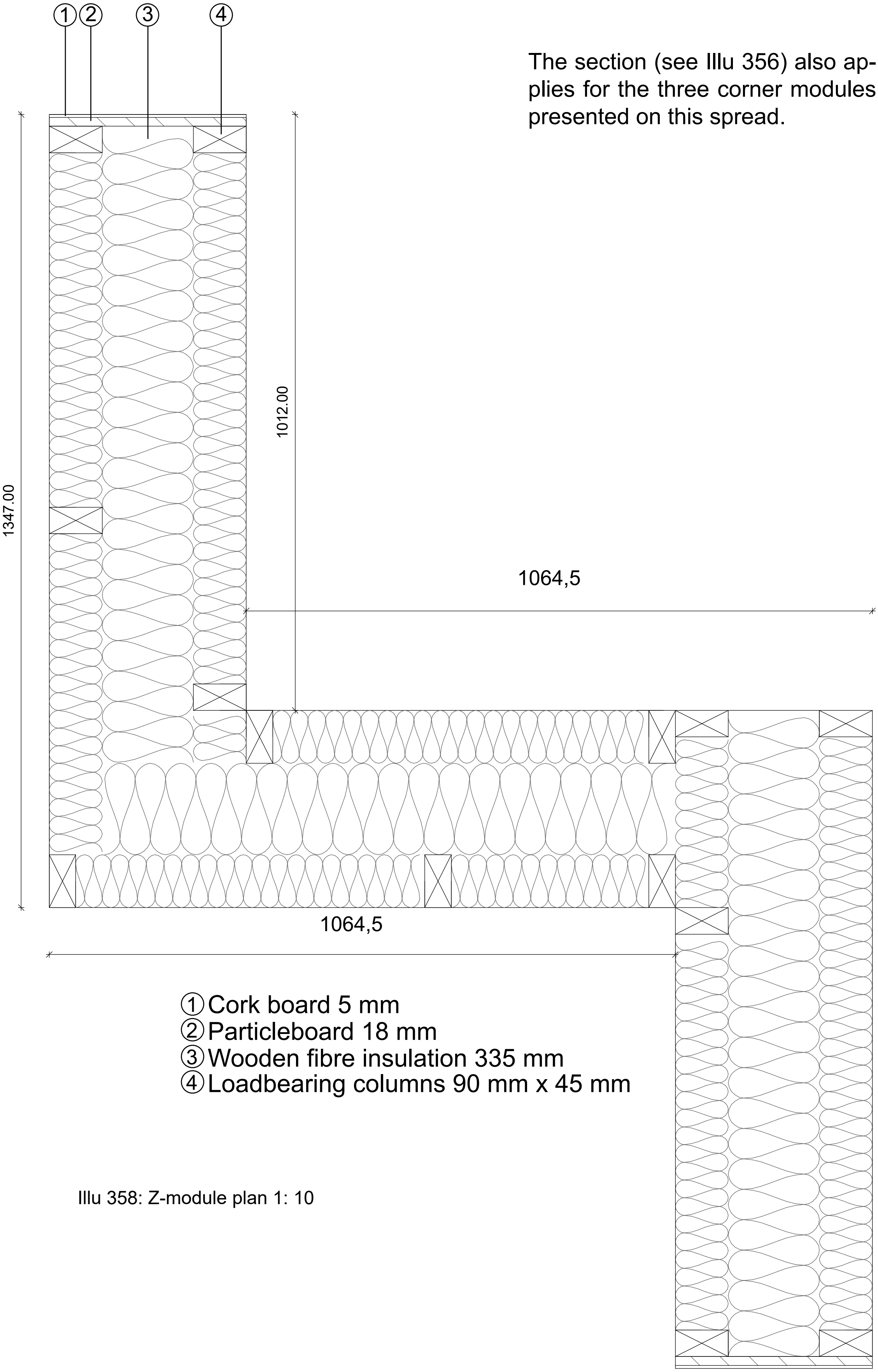
Illu 356: Section wall 1: 10



Illu 357: Exploded view wall module

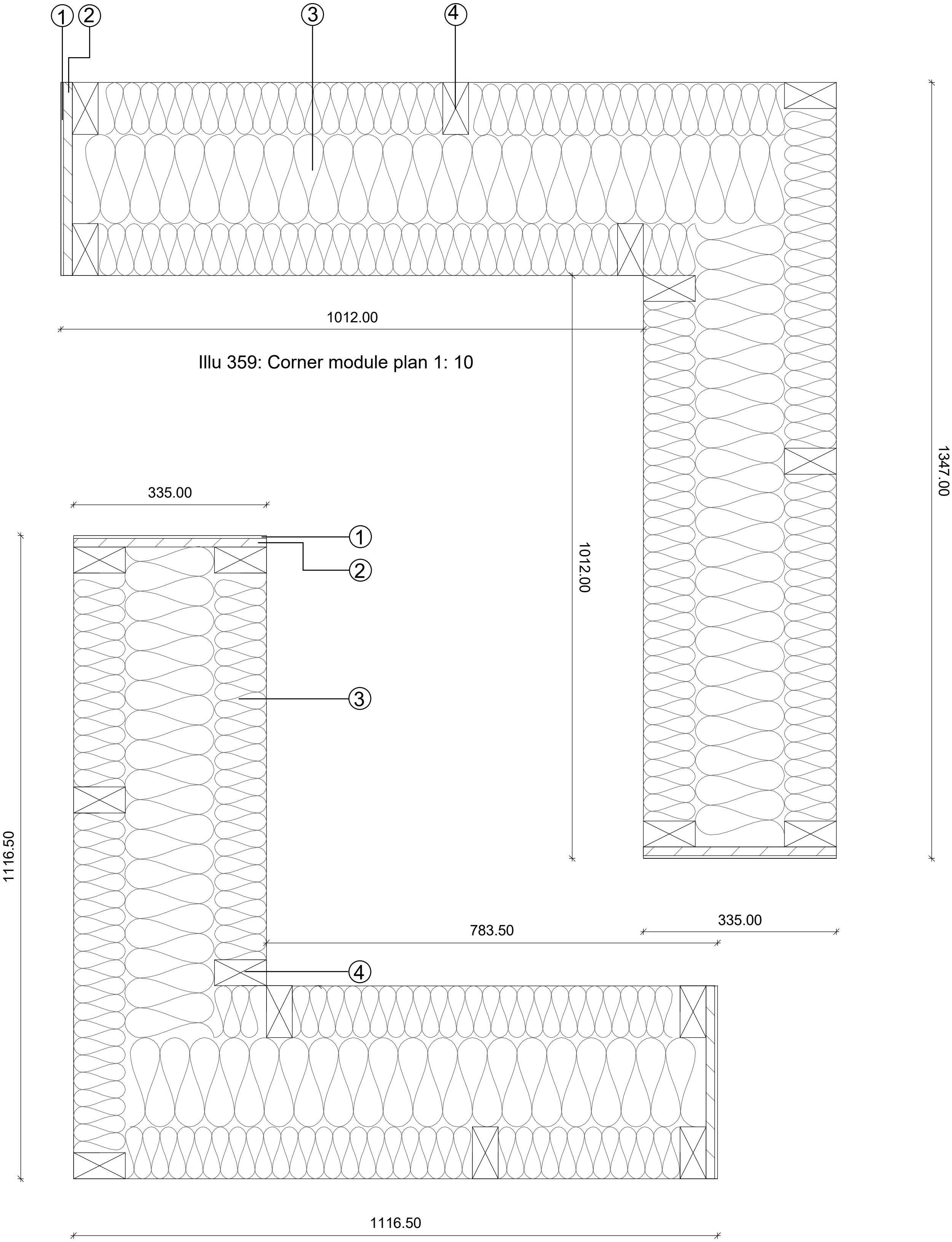
CORNER MODULES

The section (see Illu 356) also applies for the three corner modules presented on this spread.



① Cork board 5 mm
② Particleboard 18 mm
③ Wooden fibre insulation 335 mm
④ Loadbearing columns 90 mm x 45 mm

Illu 358: Z-module plan 1: 10



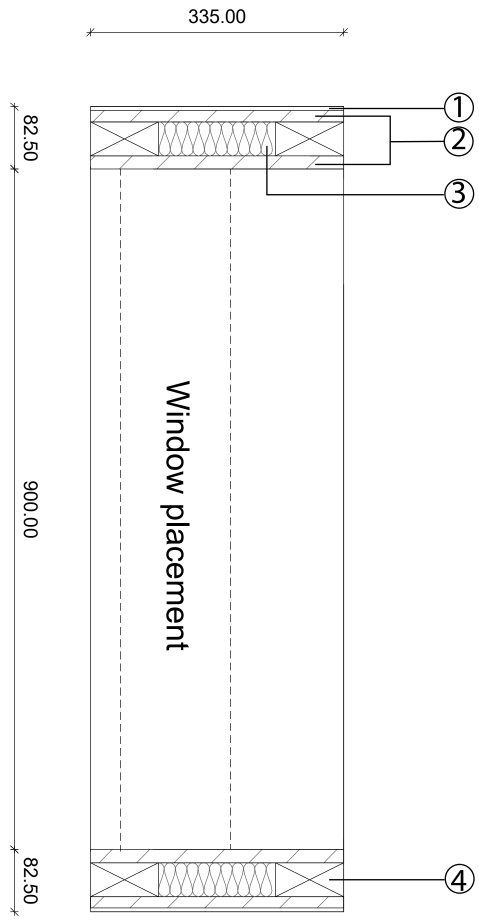
Illu 359: Corner module plan 1: 10

Illu 360: Inner module plan 1: 10

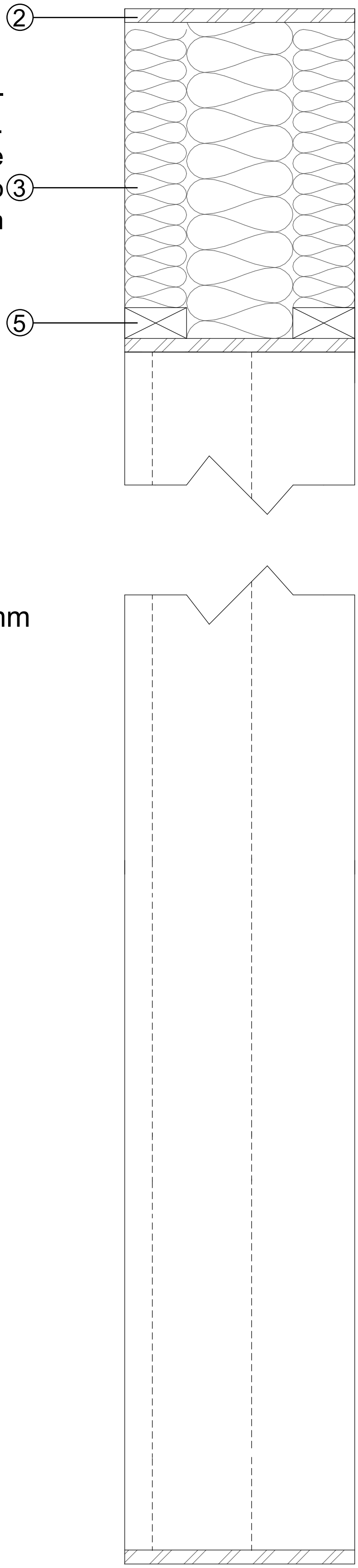
WINDOWS MODULE

The window modules consist of 2 x 82,5mm construction and then a 900 mm window in the plan. The windows can vary in height as seen on the sections (see Illu 362 and Illu 363), both going to the floor being 2500 mm and starting in 1000 mm height and being 1500 mm high.

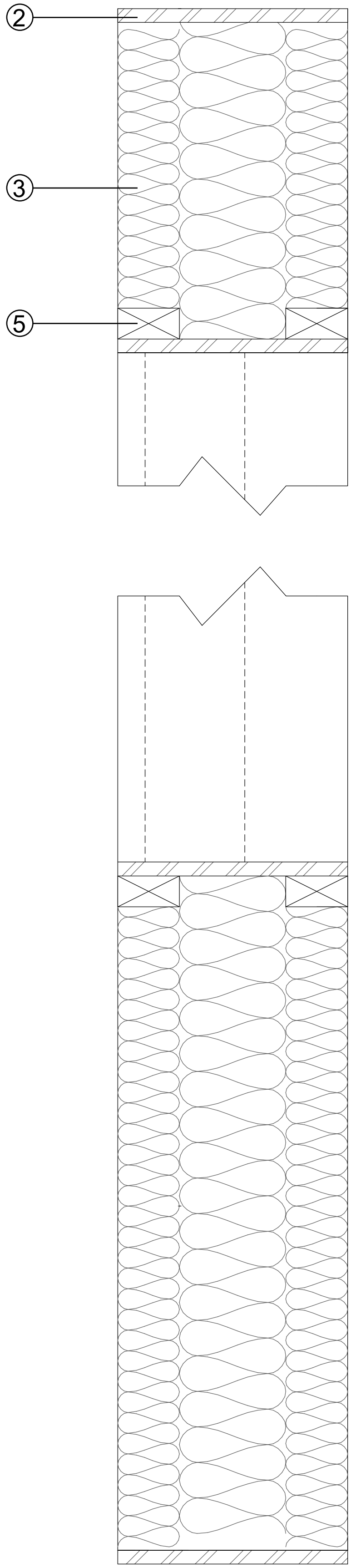
1. Cork board 5 mm
2. Particleboard 20 mm
3. Wooden fibre insulation 45 mm
4. Columns 90 mm x 45 mm x 3000 mm
5. Beams 45 mm x 90 mm x 900 mm



Illu 361: Window wall module plan 1: 10



Illu 362: Room height window wall module section 1: 10

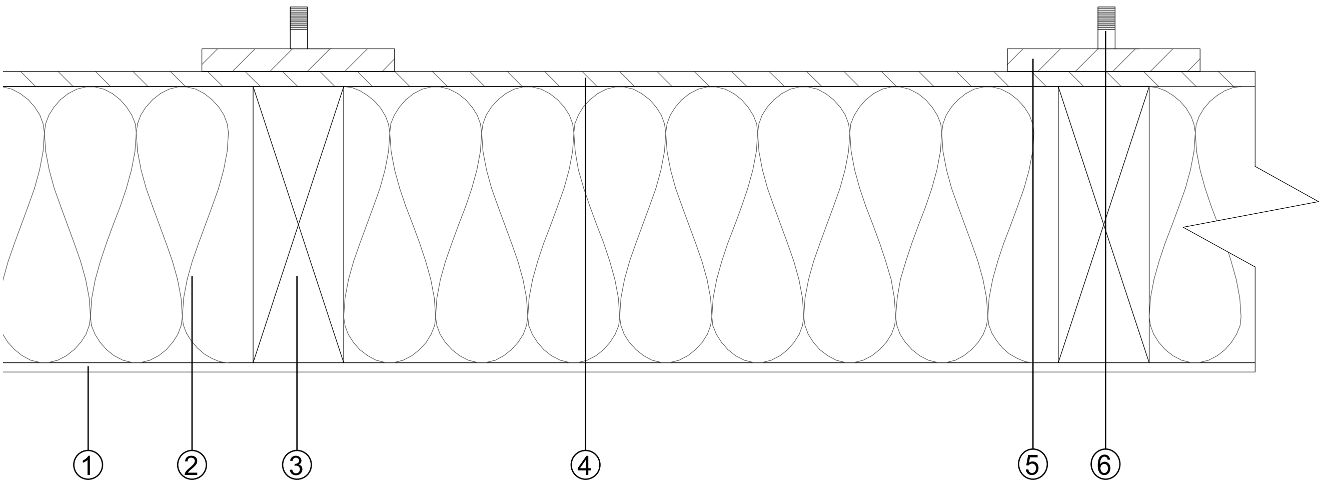


Illu 363: 1500 mm window wall module section 1: 10

Illu 364: Window wall module exploded view

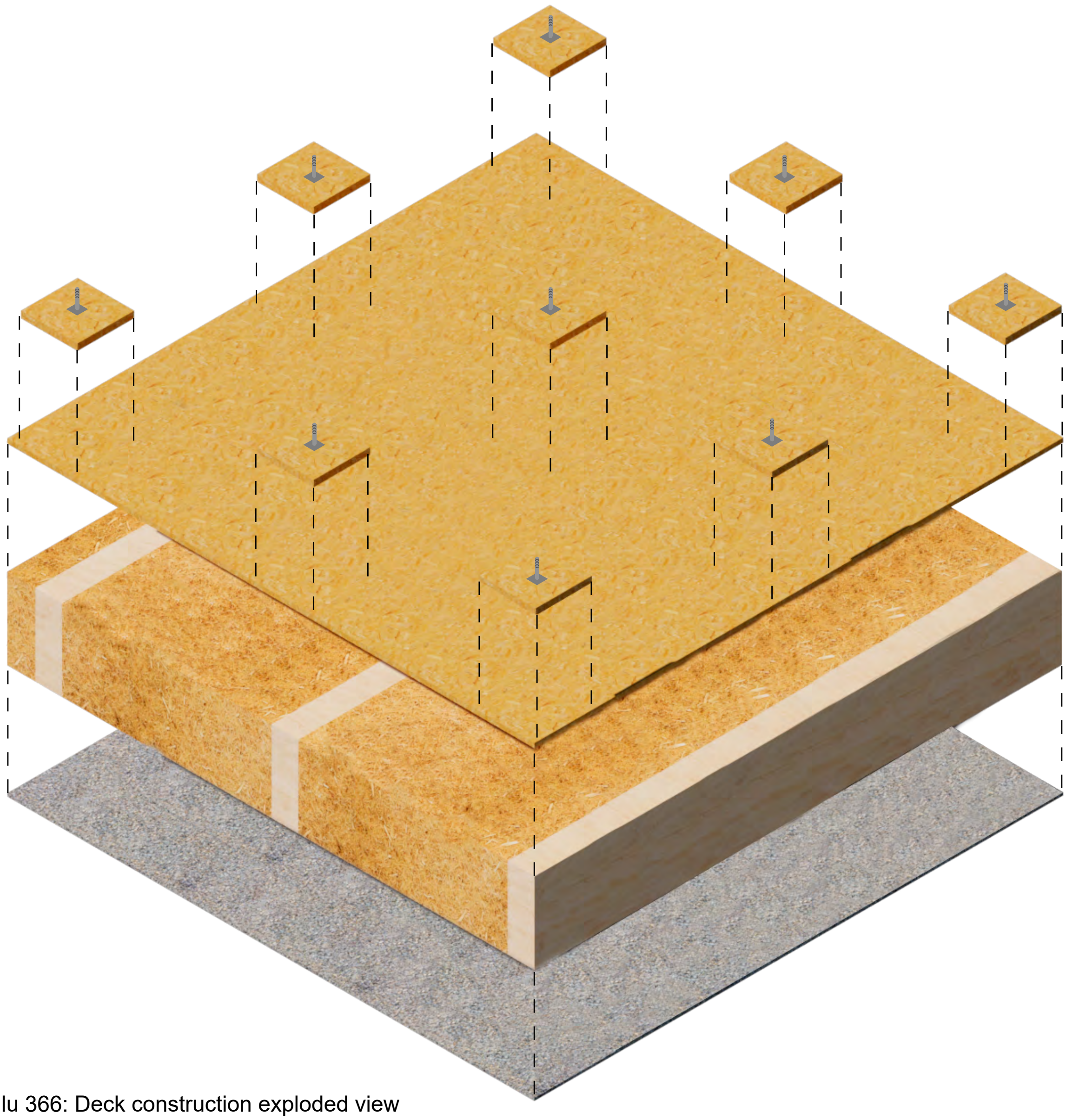
DECK MODULE

The deck consist of a loadbearing construction c/c 1065 mm with wooden fibre insulation in between. Underneath, a windbarrier is placed, blocking wind and moisture from getting into the construction. A subfloor along with premounted squared boards with bolts is placed above the construction. The bolts allow for the interior column to be bolted to the deck and unbolted again when they need to be moved. The same structure can be used for the floor separating decks, by removing the wind barrier and instead adding a particleboard and the grids and bolts.



Illu 365: Deck construction section 1: 10

① HUNTON wind barrier 12 mm
② Wooden fibre insulation 365 mm
③ Loadbearing beams 365 x 120 mm
④ Subflooring particleboard 20 mm
⑤ Floor grid board 255 mm x 255 x 30 mm
⑥ Bracket to fasten walls to floor with bolts

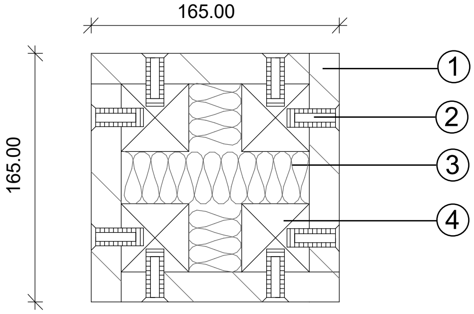


Illu 366: Deck construction exploded view

INTERIOR COLUMN MODULE

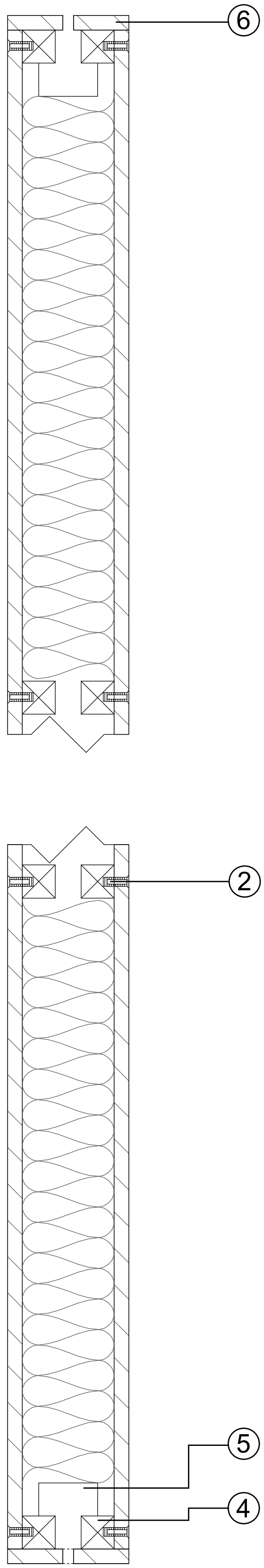
The interior column module consists of four pine planks where one of them has a hole in the top and bottom, enabling access to the bolts placed on the deck, and thereby the columns can be joined to the floor and ceiling.

Each plank is mounted with threaded screws to eight 45 mm x 45 mm x 45 mm battens.

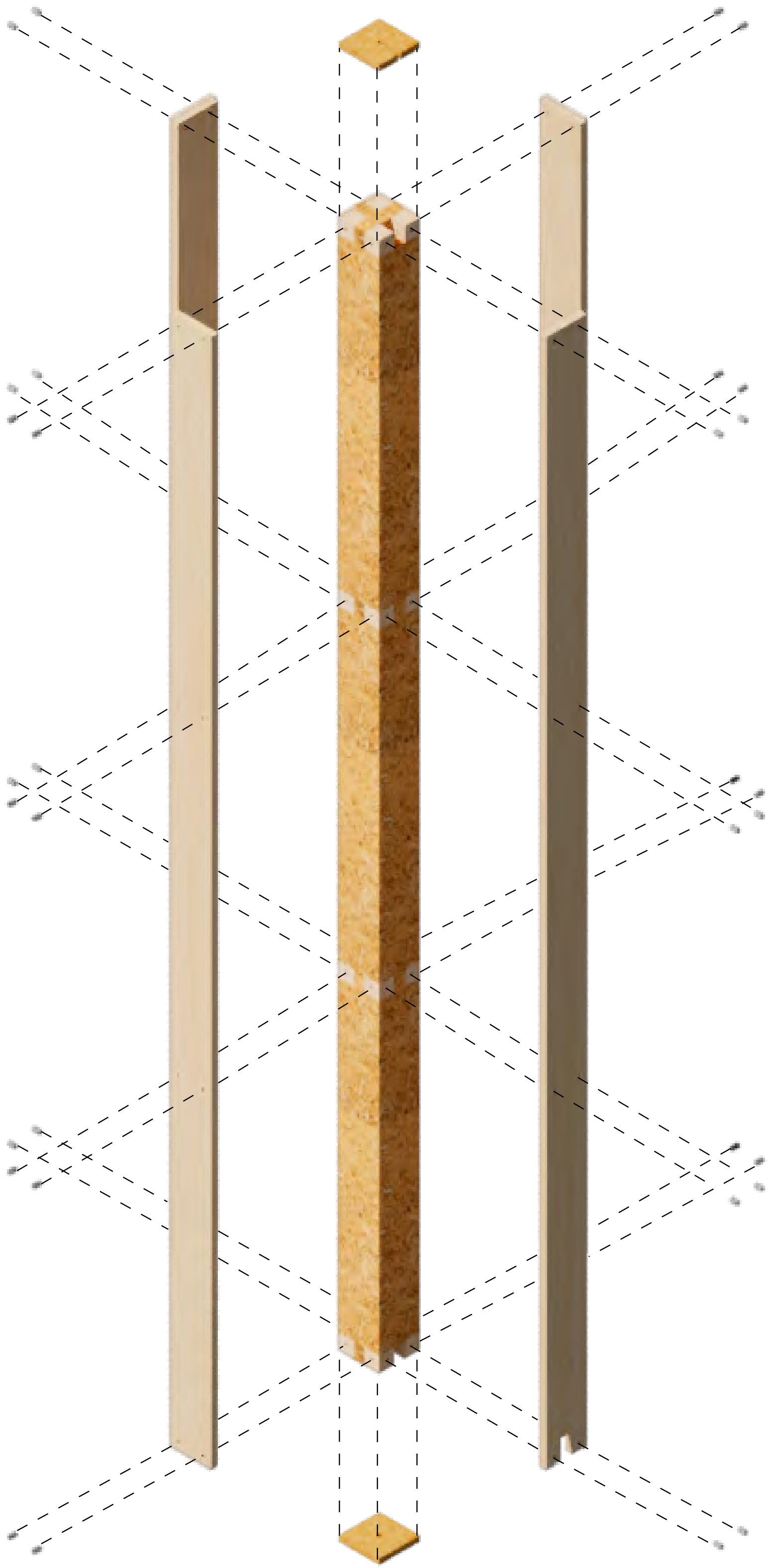


Illu 367: Column interior wall plan 1: 5

① Vertical pine plank 145 mm x 3000 mm x 20 mm
② Threaded screws d 12 mm
③ Wooden fibre insulation 125 mm
④ Battens 45 mm x 45 mm x 45 mm cc 1000
⑤ Hole in pine plank to allow access to bolt and assembly with the floor
⑥ Particleboard 18 mm
⑦ Battens 45 mm x 45 mm x 3000 mm
⑧ Horizontal pine plank 900 mm x 100 mm x 20 mm
⑨ Wooden fibre insulation 45 mm
⑩ Airgap 35 mm
⑪ Cork board 5 mm



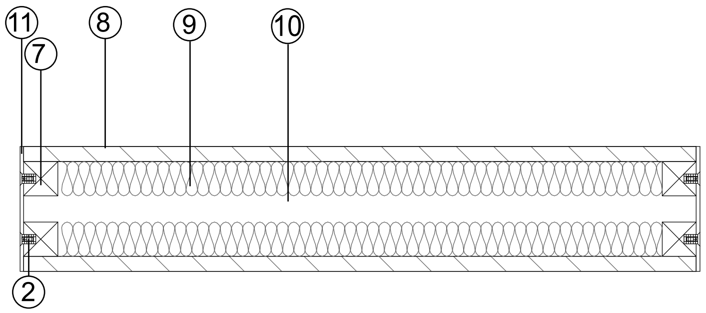
Illu 368: Column interior wall section 1: 10



Illu 369: Column interior wall exploded view

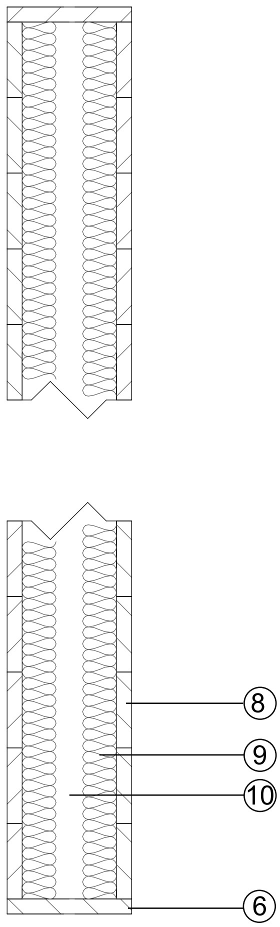
INTERIOR WALL MODULE

The interior wall module is connected to the interior column by the magnetic screws and are sealed with cork on both sides.



Illu 371: Interior wall plan 1: 10

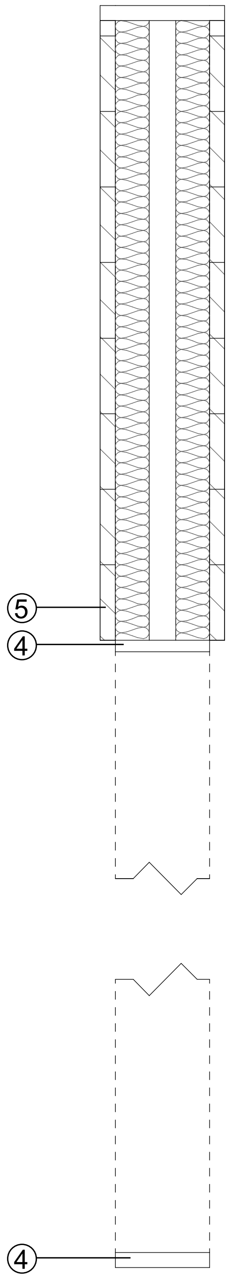
① Vertical pine plank 145 mm x 3000 mm x 20 mm
② Threaded screws d 12 mm
③ Wooden fibre insulation 125 mm
④ Battens 45 mm x 45 mm x 45 mm cc 1000
⑤ Hole in pine plank to allow access to bolt and assembly with the floor
⑥ Particleboard 18 mm
⑦ Battens 45 mm x 45 mm x 3000 mm
⑧ Horizontal pine plank 900 mm x 100 mm x 20 mm
⑨ Wooden fibre insulation 45 mm
⑩ Airgap 35 mm
⑪ Cork board 5 mm



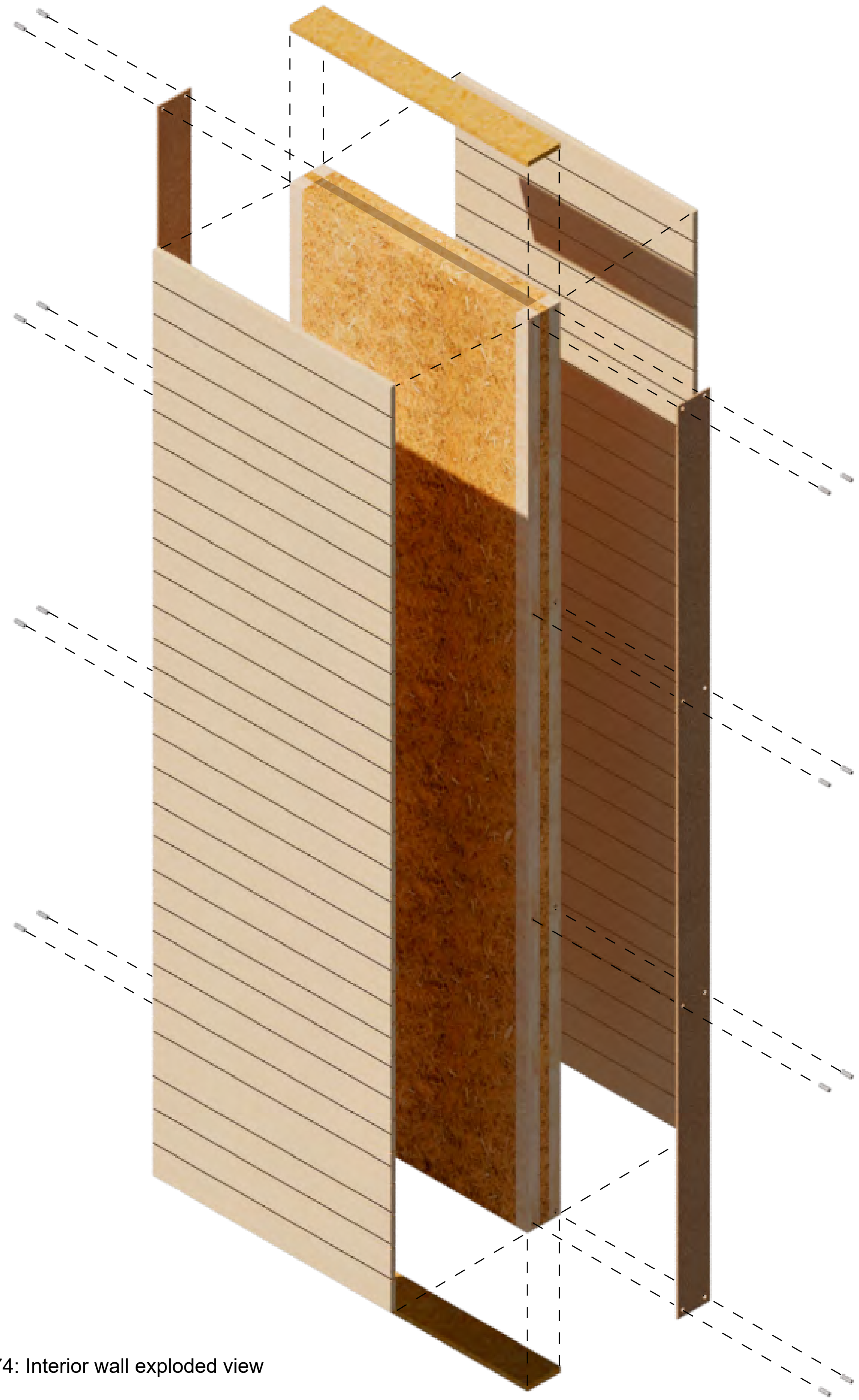
Illu 370: Interior wall section 1: 10

Illu 372: Interior wall with door plan 1: 10

① Columns 45 mm x 45 mm x 3000 mm
② Door frame
③ Threaded screws d 12 mm
④ Particleboard 20 mm
⑤ Horizontal cladding 20 mm x 100 mm x 900 mm



Illu 373: Interior wall with door section1: 10



Illu 374: Interior wall exploded view

OUTRO

CONCLUSION

The goal of this project was to introduce the concept of circular economy into architecture, building on existing knowledge from state-of-the-art research and literature. The approach was based on the design of a modular system, that had the purpose of providing flexibility for the users and ensure that the building could be recused in several lifecycles.

This was achieved in this project, by designing a system of interior and exterior walls that fit together in a grid system, pre-mounted to the floor and ceiling. Short-term flexibility is achieved with an interior wall system, which can be moved around at the desire of the users. Long-term flexibility is achieved in the exterior wall system, through it being able to be disassembled, relocated, and reconfigured to design new buildings. The exterior wall system is designed flexibly so that it provides many possibilities for design in relation to the shape of the building, thereby ensuring that the system can be used without the architecture becoming stale.

From a circular economy perspective, this means that the main construction elements can function in multiple lifecycles, ensuring that there is less resource waste. With the use of wood for the construction materials, either new or recycled types, it is ensured that each module can be disassembled again, and either go to the production of new modules or be recycled into new lifecycles. The buildings utilize a screw foundation that negates the use of concrete in the building, ensuring that the building is as easy to disassembly and remove from the site, leaving behind as small a footprint as possible.

The concept of cohousing was incorporated into the project on a functional level, and it proved to mesh well with circular economic ideas. Especially, the idea of a sharing platform, which in this project is both achieved through the utility house were functions such as washing, and workshop is shared between users; and through the common house were kitchen and dining space is available for all users. This results in better equipment and space for each user, providing an overall better quality to everyday life.

The exterior of the site has been designed as a circular path, in the centre of which the common houses are placed, along with many outdoor activities that allow for socialisation between inhabitants. Placed around the exterior of the circular path is the dwellings, designed as double houses to allow for the best possibilities in the flexibility of the interior, due to 3 facades being available for each unit within the double house.

Each unit is designed as its own functional dwelling with a small kitchen, living and dining space, bath, and 1-3 bedrooms, depending on the desired configuration of the floorplan. A configuration which can be constantly changing to fit different demands, due to the flexibility provided in the interior wall system. Each dwelling is provided with a large private outdoor terrace that allows for withdrawn relaxation while being low maintenance.

The windows of the dwellings are designed to provide the best user control of the indoor environment, ensuring different openings for different natural ventilation requirements, both for night and day. Combined with shutter solar shading that is individually controllable, help prevents overheating on warm days.

The focus on lowering the built floor area was achieved by designing smaller dwellings, and instead placing infrequently used functions up for sharing between all inhabitants. This has resulted in a reduction of 20-30% floor area for the combined masterplan. The exact number depends on how many inhabitants live in each dwelling, which is again something that can be constantly changing due to flexible room configurations.

The materials on the exterior of the buildings is a locally produced wood cladding, that provides a long lifespan and good contrast on the facades. This way the modular system is also expressed in the final buildings, by the design of cladding that expresses each joint of the exterior wall. The roof is covered in sedum to help retain rainwater on the site, along with the green roof providing beautiful aesthetics and sustainable notions. The materials help provide the overall architecture with a warm and welcoming aesthetic, that communicates the sustainable living on the site.

DISCUSSION

The intention of this discussion is to provide reflection and perspective to the conclusion of this project, to help acknowledge points of interest for discussion regarding the project. The reflection is both related to project work, the experiences gained when working with circular economy in architecture in general, and specific problems that have arisen in this project.

Digital project work during corona virus

To begin, the group would like to acknowledge the Covid-19 virus situation, that has been in effect during this project. Due to the lockdown of the country, and following the guidelines of Aalborg University, it has meant that 2/3 of this project has been digital, with the group members separated from each other. The separation and digital work have had a profound impact on the process at large, and likewise on the outcome of the project.

Architecture is a creative process that requires iterative processing to obtain a great result. This iterative process bases itself in being able to discuss and “shoot” ideas between collaborators on a project. In a way it can be said, that just as many ideas are created in the discussion of sketches, as they are in the sketching itself. However, due to the lockdown, such informal discussions have been difficult to carry out, both due to the digital nature of communication, but also with the lack of pen and paper sketching between collaborators during the discussion.

This has resulted in a split-up workflow for this project, where each collaborator has had a task to carry out, and then the product of this task has been presented to each other. Sometimes requiring discussion during the process itself, but as mentioned, these discussions were not as useful as one is used to with physical presence. The project group has noticed that the largest impact has been on the iterative process itself, with ideas and changes being hard to communicate effectively, this has resulted in misunderstandings that then require time to correct.

Another critical part to a project is the entire creative environment that exists in a physical studio surrounded by fellow students. In such a setting, creative ideas between projects can be discussed and outside feedback can be achieved fast by asking other groups. The lack of this environment has without a doubt had a negative influence on the project, by finding it hard to be inspired during sketching.

The experience has, however, also been rewarding in some ways, as it has provided a lot of perspective on the way information is communicated within a project group. Along with gaining new skills and competencies within digital project work. Despite the situation, the group feels that the final project is close to what was desired from the beginning and that under the circumstances, a satisfying result has been achieved.

Process and iterations

With the previously discussed situation, and its impact on the iterative process it is, therefore, no surprise that the project group feels that there is a lack of iterations of some elements of the project. This especially relates to the interior wall system, which by far was the most challenging part of the project.

Designing such a system, and going deep into the construction aspects, has been something new and challenging for this project. But due to the lockdown situation, the lack of proper discussion possibilities in the project, and the general knowledge, this has proven a great challenge. Combined with the fact, that the entire project springs out from decision made to the interior wall system, namely the sizes and grid system, it has been difficult to iterate and improve on this system, as it would result in a major change to the entire project.

This project has had a broad focus on the circular economy, resulting in trying to solve all aspects such as interior walls, exterior walls, foundation, decks, foundation, and all the materials used. Another way to deal with this project could have been to focus more in-depth on one or two of the aspects, which could have resulted in more detailing and iterations of these.

Modularity and circular economy

With all the previous being said, it has still been an interesting experience to work with circular economy, co-housing, and other sustainable perspectives. And the discussion will now focus on the experience gained from this project, in relation to designing with circular economy in mind.

From the beginning of the project, the decision was made to work with a modular system, as it could help provide a framework for working with the circular economic aspects. Through the exploration of the modular system, it has become apparent that developing a modular system that truly works within circular economy is an extreme challenge.

Such a modular system must at least be able to: Fit within a wide range of architectural styles and provide enough freedom in designing with the system, that it does not impose limitations on the architecture and functionality be completely disassembled after use, and to be disassembled into new configurations throughout its life.

In this project, there is a clear imposition on functionality, as the modules and their sizes make it difficult to design precise spaces, as an example: hallways risk becoming too narrow or too wide, and rooms often became a bit too narrow (under 2m) or wider than desired (above 3m) without any possibility of achieving sizes in between.

Is modularity then the future of circular economy in architecture? It is hard to say. For a modular system to be viable, it must be used widely enough, that elements of the system are always available, and in the future, that enough “reuse” elements are available for reconfigurations. Therefore, it must be concluded, that the best modular system, is one that blurs the lines the most between being a rigid system and a tailormade solution. Because it imposes the least design restrictions, making it more probable that it will be used widely enough.

This project decided to work with future reuse of modules in relation to circular economy, as it is manageable for this type of project. But reusing and recycling materials in buildings being built now, is another approach to circular economy more widely seen in some architectural practices such as the Danish firm Lendager Group. However, this type of practice requires a large number of resources, time, and knowledge just to pull off a few projects, as each one is different.

This was learned from a webinar held by Lendager group during the lockdown period, that the project group decided to attend. It then is perhaps not surprising, that it was difficult to work with new types of materials and recycling in this project, as Lendager employs an entire side-company just focusing on this.

Level-free access

In this project, there also occurred a very real problem, caused by the desire to work with the screw foundation. This problem ties into the lack of iterative work, and spreading the focus too thin in the project, as the foundation became a side thought rather than something that was fully explored. Had it been fully explored, it would have been realised early on, that problems would arise with the level-free access for the dwellings.

As mentioned in the project, this could not be solved due to the slope of the site itself. But the issue does not only lie with this specific project but will become a general problem if raised foundations begin to see more use. There are many great concepts that prove that screw foundations are much better for the environment, it would, therefore, be great if it was utilised more in the coming years.

The issue then is that raised foundations would result in all buildings requiring ramps for level-free access. In many cases, the ramps would be at least 10-12m long, which is quite significant if one is to relate it to single-family houses. Ramps are almost never a desirable element in architecture, but rather one that exists out of the necessity of level-free access. These ramps then might cause screw foundations to be underutilised, which is a shame as it is a much better solution seen from an environmental and circular economy perspective.

The discussion then lies deeper in whether level-free access should always be accessible, or if it should just be possible to integrate it at a later stage if it becomes necessary for the inhabitant of the specific house. It is still important to provide access for common facilities or areas, as these, of course, accommodate more people. So, excluding the requirement of level-free access in dwellings, and instead just requiring preplanning for this, it might be a solution, that allows more use of screw foundations, which would be a benefit to the overall environmental footprint of architecture.

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ILLUSTRATION LIST

Illustrations not listed here are own production

Illu 1: Increase in floor area, emissions, and energy consumption, compared to population growth from 2010-2018. Presented in (GABC, 2019). Data derived from IEA (2019a; 2019b)

Illu 3: Vitruvius Triangle: Rowland, I.D and Howe, T.N. (2001). Vitruvius ten books on architecture. Cambridge: Cambridge University Press.

Illu 6: K1 Orchard Park common house: inhabitat.com, (2019). Cambridge's first co-housing development fosters sustainable living. [online]. Available at: https://inhabitat.com/cambridges-first-co-housing-development-fosters-sustainable-living/ [Accessed 14.02.2020]

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Illu 8: K1 Orchard Park mixture between houses and apartments: inhabitat.com, (2019). Cambridge's first co-housing development fosters sustainable living. [online]. Available at: https://inhabitat.com/cambridges-first-co-housing-development-fosters-sustainable-living/ [Accessed 14.02.2020]

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Illu 12: Lange Eng Plan: Langeeng.dk. (2020). Langeeng fakta. [online] available at: https://www.langeeng.dk/fakta/den-groenne-gard/ [Accessed 23.03.2020]

Illu 13: Tinggaarden outside: Vandkunsten.com. (2020). Tinggaarden. [online]. Available at: https://vandkunsten.com/projects/tinggaarden [Accessed 24.03.2020]

Illu 14: Common outdoor area in a cluster: Vandkunsten.com. (2020). Tinggaarden. [online]. Available at: https://vandkunsten.com/projects/tinggaarden [Accessed 24.03.2020]

Illu 15: Tinggaarden private dwelling, view of basic room and bedrooms: Vandkunsten.com. (2020). Tinggaarden. [online]. Available at: https://vandkunsten.com/projects/tinggaarden [Accessed 24.03.2020

Illu 20: Cubeflex by Arne Jacobsen at Trapholt. Exterior photo by Andreas Trier Mørch

Illu 21: Espansiva by Jørn Utzon, principle drawing of components by Utzon. Utzon Archives / Aalborg University & Utzon Center.

Illu 22: Cubeflex by Arne Jacobsen at Trapholt. Interior photo by Andreas Trier Mørch

Illu 23: Espansiva by Jørn Utzon, exterior photo of original building. Utzon Archives / Aalborg University & Utzon Center.

Illu 30: Noise map of the site: Miljoegis.mim.dk, (2018). Noise. [online]. Available at: http://miljoegis.mim.dk/spatialmap?&profile=noise [Accessed 03.02.2020]

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Illu 230: Sedum roof: urbanscape-architecture.com (2020). green roof system. Available at: https://www.urbanscape-architecture.com/projects/huf-haus-model-house/ [Accessed 26.05.2020]

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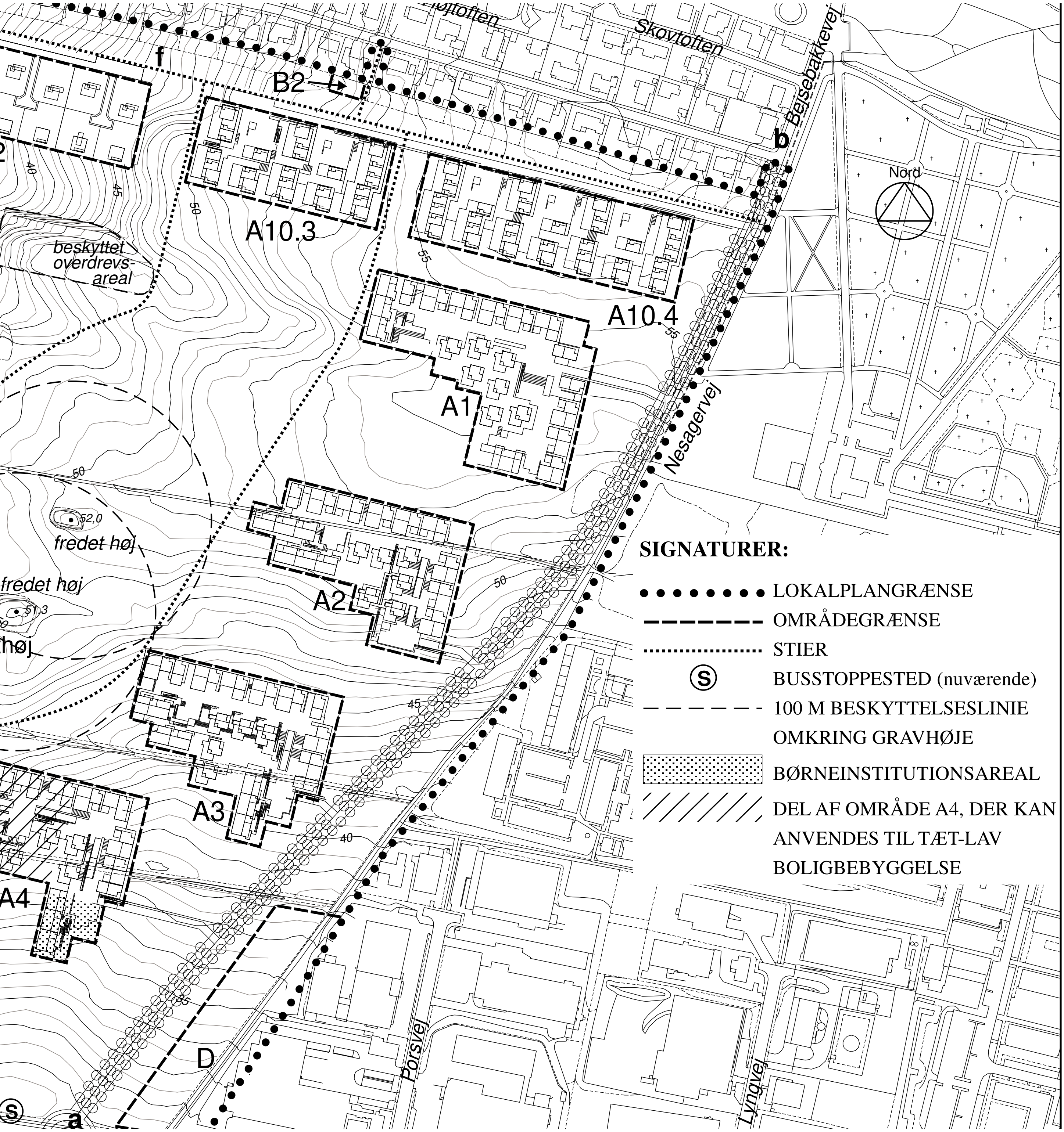
APPENDIX

APPENDIX 1: LEVELS ON SITE

Appendix 1: Levels of the site


Skovtoften
Bejsebakkevej
Nord
B2
f
b
A10.3
A10.4
beskyttet
overdrevs-
areal
A1
A2
A3
A4
D
a
Nesagervej
fredet høj
fredet høj
52,0
51,3
Porsvej
Lyngvej
50
55
45
40
35
SIGNATURER:
LOKALPLANGRÆNSE
OMRÅDEGRÆNSE
STIER
S
BUSSTOPPESTED (nuværende)
100 M BESKYTTELSESLINIE
OMKRING GRAVHØJE
BØRNEINSTITUTIONSAREAL
DEL AF OMRÅDE A4, DER KAN
ANVENDES TIL TÆT-LAV
BOLIGBEBYGGELSE

APPENDIX 2: U-VALUE

material	Thickness (d)	Thermal conductivity (λ)	Thermal insulation (R = d/λ)	Uvalue (U=1/R)
	m	W/mK	m^2K/W	W/m^2K
mineral wool	0,28	0,034	8,33	0,12
paper wool	0,32	0,038	8,33	0,12
Wooden fibre	0,32	0,038	8,33	0,12
Straw	0,50	0,06	8,33	0,12

This appendix shows the four insulation materials, which are analysed in LCA on page 69. The U-value is kept the same on 0,12 W/m^{2}K, and as the thermal conductivity varies, so does the thickness. It shows that mineral wool, paper wool and wooden fibre nearly has the same thermal cunductivity, whereas the straw is much worse, resulting in a thicker construction than the three others.

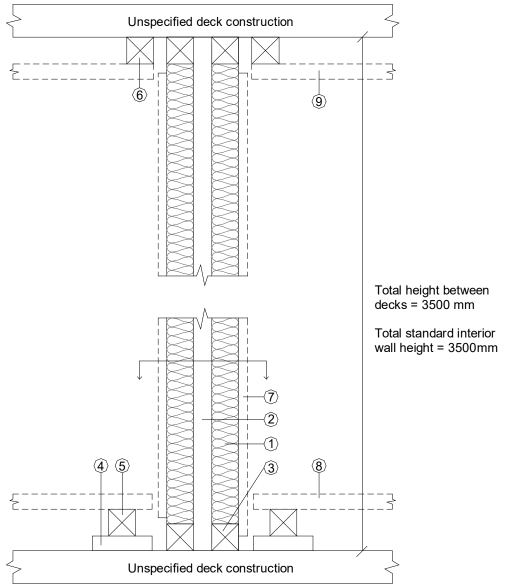
APPENDIX 3 - INTERIOR COMPARISON

Standard interior wall

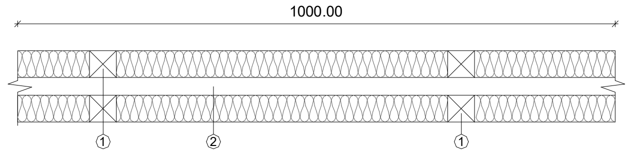
Below is listed the suggested interior separating wall construction. The construction is based on Construction 6 - Wall - Non Load-bearing (Rockwool.dk. Skillevægge af træ og stål. 2020c). The floor construction is based on principles from traegulvet.dk (2020). The ceiling construction is based on principles from ”tag og lofter” on Rockwool.dk (2020b).

The sections are cutouts of a larger construction, and the material amounts given are the average materials pr m wall or m² for floor/ceiling construction.

Cross section

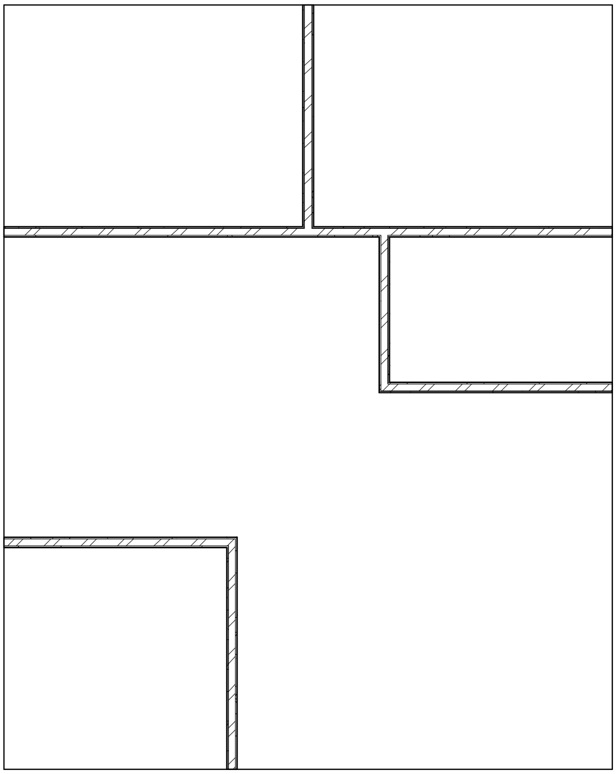


Plan section



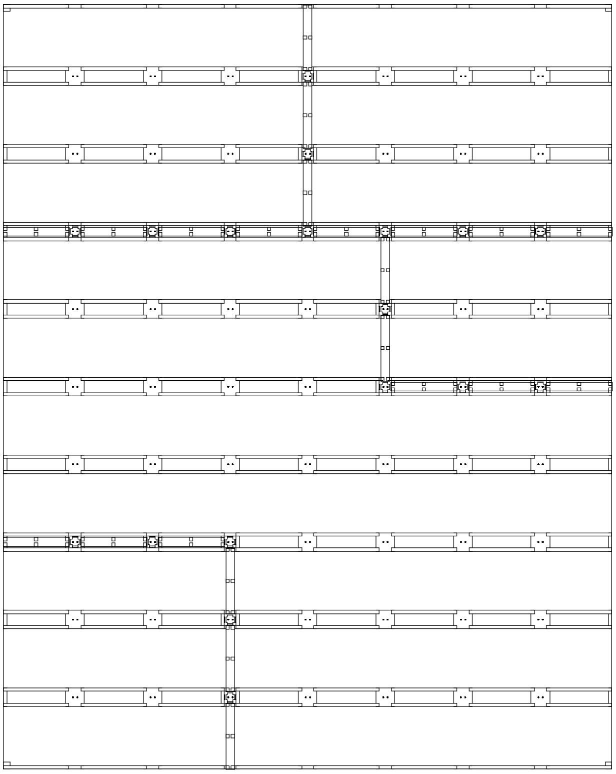
1. 45 x 45 mm Wood latching c/c 600 mm. 45 mm insulation between latching. (Latching 0.024 m³ pr m wall + 0.028 m³ pr corner joint) (Insulation 0.27 m³ pr m wall)
2. 30 mm Air gap
3. 45 x 45 mm Wood Latching (0.0081 m³ pr m wall)
4. 100 x 100 x 20 mm Plywood board piece c/c 600 mm. (0.0017 m³ pr m² floor) + (0.00067 m³ pr m along all walls)
5. 45 x 45 mm Wood latching c/c 600 mm + (0.0023 m³ pr m along all walls)
6. 45 x 45 mm Wood latching c/c 600 mm (0.0035 m³ pr m² ceiling)
7. Potential interior wall cladding
8. Potential floor cladding
9. Potential ceiling cladding

Floorplan- Standard interior wall



- Total wall length: 23.5 m
- Total free floor area: 85 m²
- Total free ceiling area: 85 m²
- Total length along walls: 65.8 m
- Total corner wall joints: 4 joints

Floorplan - Modular interior wall



- Total wall modules: 22 modules
- Total column modules: 18 columns
- Total floor squares: 80 squares
- Total ceiling squares: 80 squares
- Total 255x255 boards: 63 pieces
- Total 255x45 boards: 32 pieces
- Total 90x90 boards: 4 pieces

Material descriptions

Below is a material description for each type of material in each wall. Either its material in LCAByg, or the EPD used for the material. The numbers refer to the number seen on each detail drawing for a specific member.

Standard interior wall

1) 3) 5) 6) Wood battens
- Wood, Constructionwood (Posts and beams) (LCAByg)
Total amount walls: 0.866 m³
Total amount floor/ceiling: 0.745 m³

1) Insulation
- Cellulosefibreplates (LCAByg)
Total amount: 6.345 m³

4) Plywood board
- Plywood (LCAByg)
Total amount: 0.1885 m³

Modular interior column

1) Grid boards. 3) Column board
- Plywood (LCAByg)
Total amount grid board: 0.276 m³
Total amount column board: 0.028 m³

2) 4) Wood battens
- Wood, Constructionwood (Posts and beams) (LCAByg)
Total amount column: 5 m³
Total amount floor/ceiling: 0.576 m³

5) Wood cladding attachment
- Wood, Construction (LCAByg)
Total amount: 0.15 m³

8) Compressible foam
- Rubbersealer, siliconerubber
Total amount: 0.0048 m³

Modular interior wall

3) Top/bottom board
- Plywood (LCAByg)
Total amount: 0.143 m³

4) Wood battens
- Wood, Constructionwood (Posts and beams) (LCAByg)
Total amount: 0.836 m³

4) Insulation
- Cellulosefibreplates (LCAByg)
Total amount: 5.06 m³

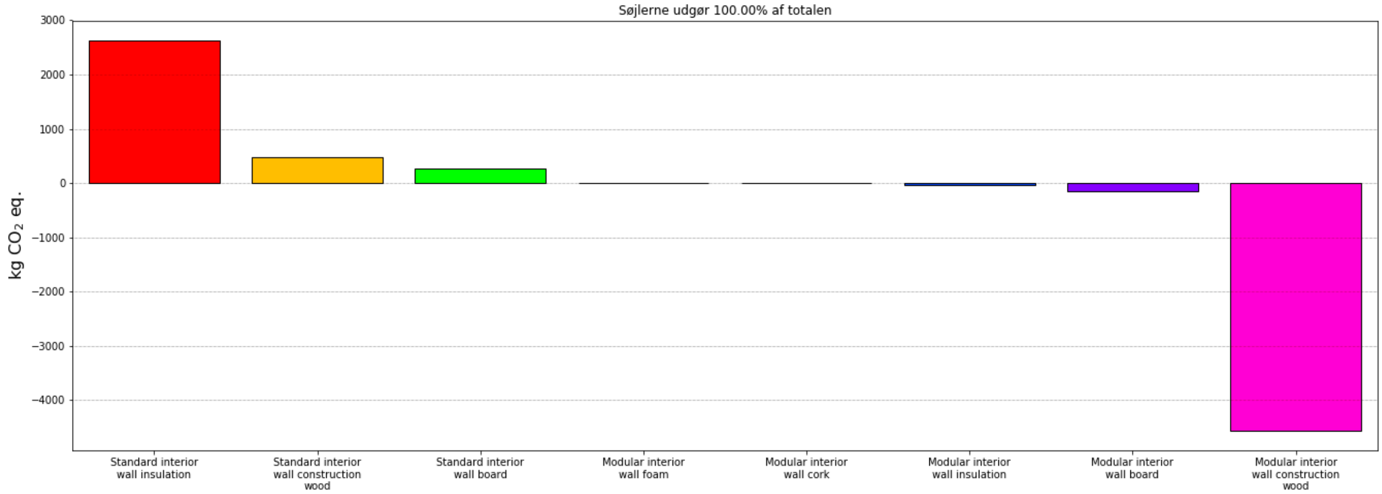
6) Compressible foam
- Rubbersealer, siliconerubber
Total amount: 0.0242 m³

7) Cork board
- Expanded cork (LCAByg)
Total amount: 0.055 m³

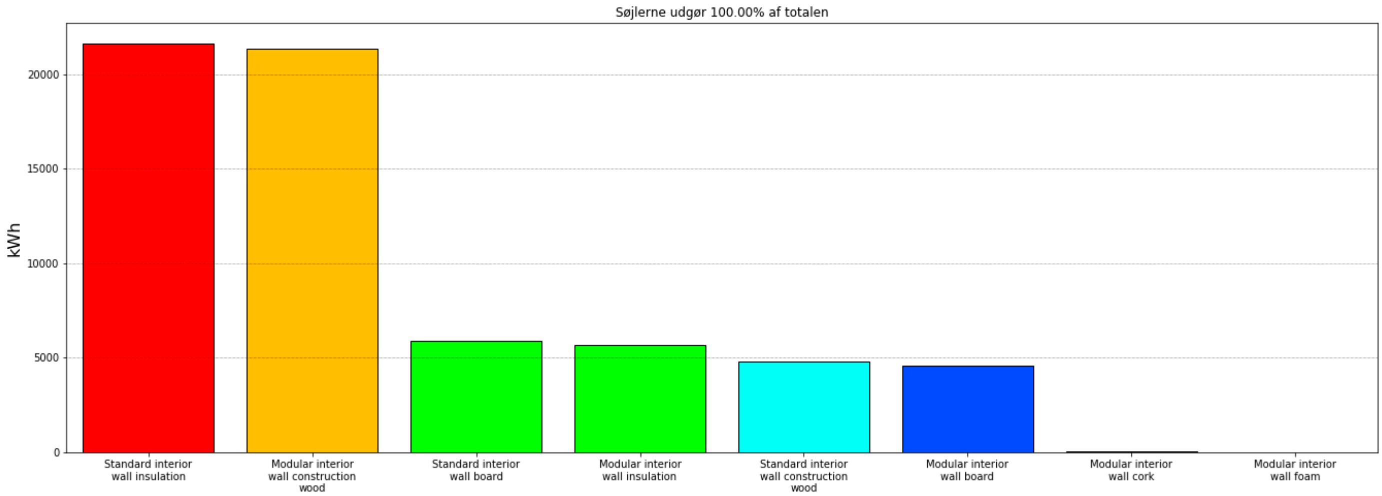
LCA Calculations

On the next page the calculations from LCAByg can be seen. Both for GWP (CO_2) and Embedded nergy (kWh). This information is used on Illu 131

There is also a table showing the increase for the standard interior wall, for each replacement. This is information is used in the Illu 377.



Illu 375: LCA showing GWP for both standard and modular wall and each different construction element.



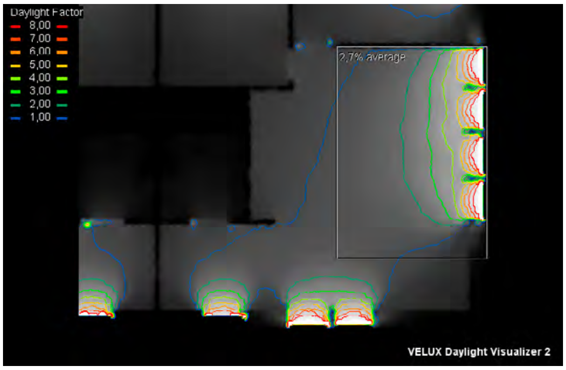
Illu 376: LCA showing PETot for both standard and modular wall and each different construction element.

A	G	Q	AF	AY
	2020	**2030**	**2045**	**2064**
Total GWP (kg CO2 eq)	-1247.78	-120.32	1007.15	3382.39

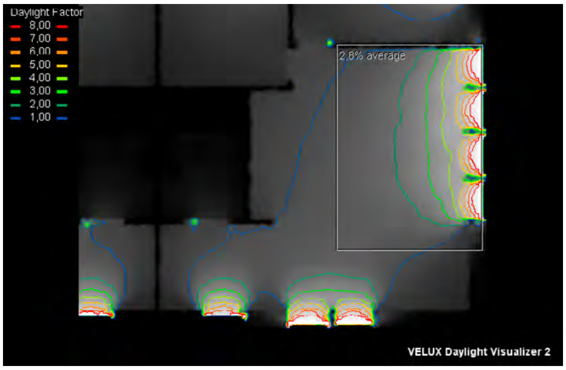
A	G	Q	AF	AY
	2020	**2030**	**2045**	**2064**
Total PeTot (kWh)	14445.36	25218.38	35991.4	32319.06

Illu 377: Tables showing the increasing environmental impact of the standard interior wall for each replacement cycle.

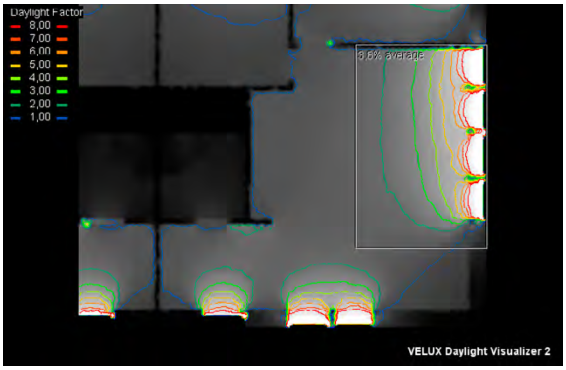
APPENDIX 4 - DAYLIGHT DIFFERENT MATERIALS



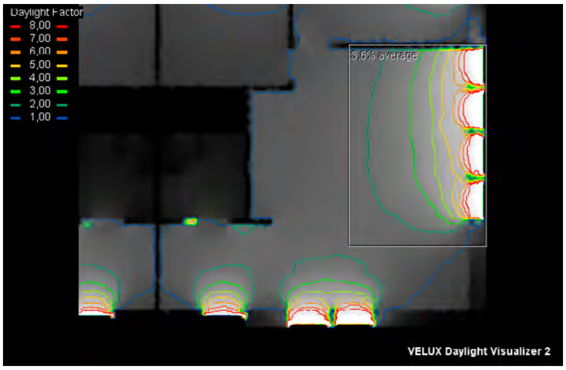
Illu 378: Daylight - Clay, pine, pine and gypsum



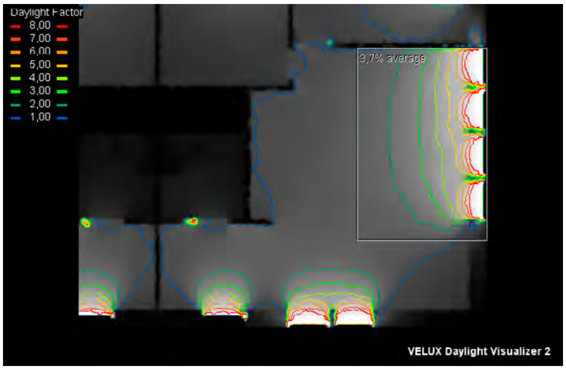
Illu 379: Daylight - Clay, particle board, bamboo and gypsum



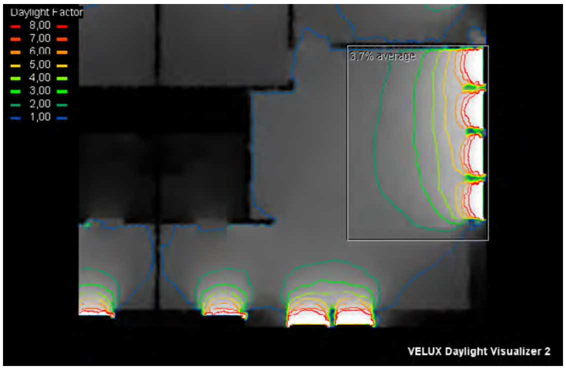
Illu 380: Daylight - Gypsum, pine, pine and pine



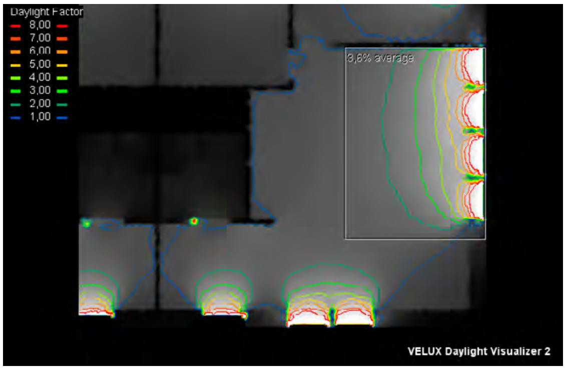
Illu 381: Daylight - Gypsum, particle board, bamboo and gypsum



Illu 382: Daylight - Pine, pine, pine and gypsum



Illu 383: Daylight - Pine, particle board, bamboo and gypsum



Illu 384: Daylight - Pine, pine, pine and pine

APPENDIX 5 - ACOUSTICS DIFFERENT MATERIALS

Reveberation time														
Equivalent absorption area	**Material**	**Areal**	**125 Hz**		**250 Hz**		**500Hz**		**1000Hz**		**2000Hz**		**4000 Hz**	
		S(m^2)	α	Sα	α	Sα	α	Sα	α	Sα	α	Sα	α	Sα
Floor	Bamboo	35	0,15	5,25	0,11	3,85	0,1	3,5	0,07	2,45	0,06	2,1	0,07	2,45
Ceiling	Gypsum	35	0,45	15,75	0,7	24,5	0,8	28	0,8	28	0,65	22,75	0,45	15,75
Big wall elements	clay	53,91	0,13	7,0083	0,39	21,025	0,32	17,251	0,32	17,251	0,36	19,408	0,39	21,025
Squared wall elements	Particle board	12,375	0,2	2,475	0,18	2,2275	0,15	1,8563	0,12	1,485	0,1	1,2375	0,1	1,2375
windows	glass	13,59	0,04	0,5436	0,04	0,5436	0,03	0,4077	0,03	0,4077	0,02	0,2718	0,02	0,2718
Absorption from persons		**Antal**	**Sα/stk**	**Sα**	**Sα/stk**	**Sα**	**Sα/stk**	**Sα**	**Sα/stk**	**Sα**	**Sα/stk**	**Sα**	**Sa/stk**	**Sα**
Persons		0	0	0	0	0	0	0	0	0	0	0	0	0
chairs		0	0	0	0	0	0	0	0	0	0	0	0	0
Absorption in air														
v/ 50% RF		**Volumen**	**125 Hz**		**250 Hz**		**500Hz**		**1000Hz**		**2000Hz**		**4000 Hz**	
		[m3]	m	mV	m	mV	4mV pe	4mV	4mV per	4mV	4mV per	4mV	4mV per	4mV
		105					1,6	0,168	4	0,42	9,6	1,008	24,4000	2,562
Total absorption				31,0		52,1		51,2		50,0		46,8		43,3
Efterklangstid	T=(0,16*V)/((Σα*s)+(Σn*A)+(4*m*V))			0,5		0,3		0,3		0,3		0,4		0,4

Illu 385: Acoustics - Clay, particle board, bamboo and gypsum

Reveberation time														
Equivalent absorption area	**Material**	**Areal**	**125 Hz**		**250 Hz**		**500Hz**		**1000Hz**		**2000Hz**		**4000 Hz**	
		S(m^2)	α	Sα	α	Sα	α	Sα	α	Sα	α	Sα	α	Sα
Floor	Pine	35	0,2	7	0,18	6,3	0,15	5,25	0,12	4,2	0,1	3,5	0,1	3,5
Ceiling	Gypsum	35	0,45	15,75	0,7	24,5	0,8	28	0,8	28	0,65	22,75	0,45	15,75
Big wall elements	Clay	53,91	0,13	7,0083	0,39	21,025	0,32	17,251	0,32	17,251	0,36	19,408	0,39	21,025
Squared wall elements	Pine	12,375	0,2	2,475	0,18	2,2275	0,15	1,8563	0,12	1,485	0,1	1,2375	0,1	1,2375
windows	glass	13,59	0,04	0,5436	0,04	0,5436	0,03	0,4077	0,03	0,4077	0,02	0,2718	0,02	0,2718
Absorption from persons		**Antal**	**Sα/stk**	**Sα**	**Sα/stk**	**Sα**	**Sα/stk**	**Sα**	**Sα/stk**	**Sα**	**Sα/stk**	**Sα**	**Sa/stk**	**Sα**
Persons		0	0	0	0	0	0	0	0	0	0	0	0	0
chairs		0	0	0	0	0	0	0	0	0	0	0	0	0
Absorption in air														
v/ 50% RF		**Volumen**	**125 Hz**		**250 Hz**		**500Hz**		**1000Hz**		**2000Hz**		**4000 Hz**	
		[m3]	m	mV	m	mV	4mV pe	4mV	4mV per	4mV	4mV per	4mV	4mV per	4mV
		105					1,6	0,168	4	0,42	9,6	1,008	24,4000	2,562
Total absorption				32,8		54,6		52,9		51,8		48,2		44,3
Efterklangstid	T=(0,16*V)/((Σα*s)+(Σn*A)+(4*m*V))			0,5		0,3		0,3		0,3		0,3		0,4

Illu 386: Acoustics - Clay, pine, pine and gypsum

Reveberation time														
Equivalent absorption area	**Material**	**Areal**	**125 Hz**		**250 Hz**		**500Hz**		**1000Hz**		**2000Hz**		**4000 Hz**	
		S(m^2)	α	Sα	α	Sα	α	Sα	α	Sα	α	Sα	α	Sα
Floor	Bamboo	35	0,15	5,25	0,11	3,85	0,1	3,5	0,07	2,45	0,06	2,1	0,07	2,45
Ceiling	Gypsum	35	0,45	15,75	0,7	24,5	0,8	28	0,8	28	0,65	22,75	0,45	15,75
Big wall elements	Gypsum	53,91	0,14	7,5474	0,1	5,391	0,06	3,2346	0,05	2,6955	0,04	2,1564	0,04	2,1564
Squared wall elements	Particle board	12,375	0,2	2,475	0,18	2,2275	0,15	1,8563	0,12	1,485	0,1	1,2375	0,1	1,2375
windows	glass	13,59	0,04	0,5436	0,04	0,5436	0,03	0,4077	0,03	0,4077	0,02	0,2718	0,02	0,2718
Absorption from persons		**Antal**	**Sα/stk**	**Sα**	**Sα/stk**	**Sα**	**Sα/stk**	**Sα**	**Sα/stk**	**Sα**	**Sα/stk**	**Sα**	**Sa/stk**	**Sα**
Persons		0	0	0	0	0	0	0	0	0	0	0	0	0
chairs		0	0	0	0	0	0	0	0	0	0	0	0	0
Absorption in air														
v/ 50% RF		**Volumen**	**125 Hz**		**250 Hz**		**500Hz**		**1000Hz**		**2000Hz**		**4000 Hz**	
		[m3]	m	mV	m	mV	4mV pe	4mV	4mV per	4mV	4mV per	4mV	4mV per	4mV
		105					1,6	0,168	4	0,42	9,6	1,008	24,4000	2,562
Total absorption				31,6		36,5		37,2		35,5		29,5		24,4
Efterklangstid	T=(0,16*V)/((Σα*s)+(Σn*A)+(4*m*V))			0,5		0,5		0,5		0,5		0,6		0,7

Illu 387: Acoustics - Gypsum, particle board, bamboo and gypsum

Reveberation time														
Equivalent absorption area	**Material**	**Areal**	**125 Hz**		**250 Hz**		**500Hz**		**1000Hz**		**2000Hz**		**4000 Hz**	
		S(m^2)	α	Sα	α	Sα	α	Sα	α	Sα	α	Sα	α	Sα
Floor	Pine	35	0,2	7	0,18	6,3	0,15	5,25	0,12	4,2	0,1	3,5	0,1	3,5
Ceiling	Pine	35	0,2	7	0,18	6,3	0,15	5,25	0,12	4,2	0,1	3,5	0,1	3,5
Big wall modules	Gypsum	53,91	0,14	7,5474	0,1	5,391	0,06	3,2346	0,05	2,6955	0,04	2,1564	0,04	2,1564
Squared wall elements	Pine	12,375	0,2	2,475	0,18	2,2275	0,15	1,8563	0,12	1,485	0,1	1,2375	0,1	1,2375
windows	glass	13,59	0,04	0,5436	0,04	0,5436	0,03	0,4077	0,03	0,4077	0,02	0,2718	0,02	0,2718
Absorption from persons		**Antal**	**Sα/stk**	**Sα**	**Sα/stk**	**Sα**	**Sα/stk**	**Sα**	**Sα/stk**	**Sα**	**Sα/stk**	**Sα**	**Sa/stk**	**Sα**
Persons		0	0	0	0	0	0	0	0	0	0	0	0	0
chairs		0	0	0	0	0	0	0	0	0	0	0	0	0
Absorption in air														
v/ 50% RF		**Volumen**	**125 Hz**		**250 Hz**		**500Hz**		**1000Hz**		**2000Hz**		**4000 Hz**	
		[m3]	m	mV	m	mV	4mV pe	4mV	4mV per	4mV	4mV per	4mV	4mV per	4mV
		105					1,6	0,168	4	0,42	9,6	1,008	24,4000	2,562
Total absorption				24,6		20,8		16,2		13,4		11,7		13,2
Efterklangstid	T=(0,16*V)/((Σα*s)+(Σn*A)+(4*m*V))			0,7		0,8		1,0		1,3		1,4		1,3

Illu 388: Acoustics - Gypsum, pine, pine and pine

Reveberation time														
Equivalent absorption area	**Material**	**Areal**	**125 Hz**		**250 Hz**		**500Hz**		**1000Hz**		**2000Hz**		**4000 Hz**	
		S(m^2)	α	Sα	α	Sα	α	Sα	α	Sα	α	Sα	α	Sα
Floor	Bamboo	35	0,15	5,25	0,11	3,85	0,1	3,5	0,07	2,45	0,06	2,1	0,07	2,45
Ceiling	Gypsum	35	0,45	15,75	0,7	24,5	0,8	28	0,8	28	0,65	22,75	0,45	15,75
Big wall elements	Pine	53,91	0,28	15,095	0,22	11,86	0,17	9,1647	0,09	4,8519	0,1	5,391	0,11	5,9301
Squared wall elements	Particle board	12,375	0,2	2,475	0,18	2,2275	0,15	1,8563	0,12	1,485	0,1	1,2375	0,1	1,2375
windows	glass	13,59	0,04	0,5436	0,04	0,5436	0,03	0,4077	0,03	0,4077	0,02	0,2718	0,02	0,2718
Absorption from persons		**Antal**	**Sα/stk**	**Sα**	**Sα/stk**	**Sα**	**Sα/stk**	**Sα**	**Sα/stk**	**Sα**	**Sα/stk**	**Sα**	**Sa/stk**	**Sα**
Persons		0	0	0	0	0	0	0	0	0	0	0	0	0
chairs		0	0	0	0	0	0	0	0	0	0	0	0	0
Absorption in air														
v/ 50% RF		**Volumen**	**125 Hz**		**250 Hz**		**500Hz**		**1000Hz**		**2000Hz**		**4000 Hz**	
		[m3]	m	mV	m	mV	4mV pe	4mV	4mV per	4mV	4mV per	4mV	4mV per	4mV
		105					1,6	0,168	4	0,42	9,6	1,008	24,4000	2,562
Total absorption				39,1		43,0		43,1		37,6		32,8		28,2
Efterklangstid	T=(0,16*V)/((Σα*s)+(Σn*A)+(4*m*V))			0,4		0,4		0,4		0,4		0,5		0,6

Illu 389: Acoustics - Pine, particle board, bamboo and gypsum

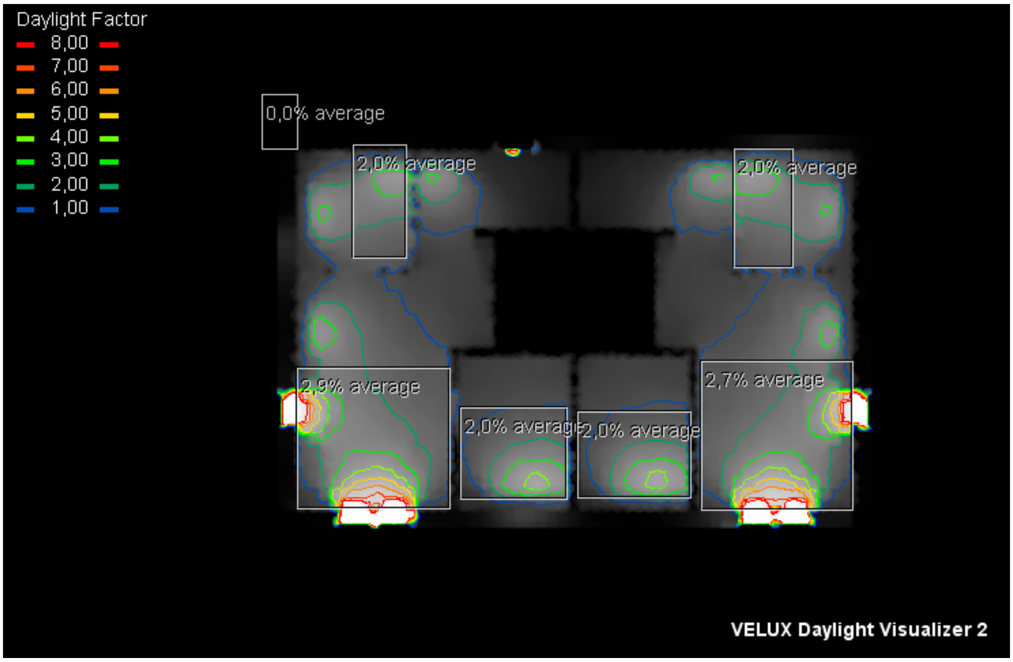
Reveberation time														
Equivalent absorption area	**Material**	**Areal**	**125 Hz**		**250 Hz**		**500Hz**		**1000Hz**		**2000Hz**		**4000 Hz**	
		S(m^2)	α	Sα	α	Sα	α	Sα	α	Sα	α	Sα	α	Sα
Floor	Pine	35	0,2	7	0,18	6,3	0,15	5,25	0,12	4,2	0,1	3,5	0,1	3,5
Ceiling	Pine	35	0,2	7	0,18	6,3	0,15	5,25	0,12	4,2	0,1	3,5	0,1	3,5
Big wall elements	Pine	53,91	0,2	10,782	0,18	9,7038	0,15	8,0865	0,12	6,4692	0,1	5,391	0,1	5,391
Squared wall elements	Pine	12,375	0,2	2,475	0,18	2,2275	0,15	1,8563	0,12	1,485	0,1	1,2375	0,1	1,2375
windows	glass	13,59	0,04	0,5436	0,04	0,5436	0,03	0,4077	0,03	0,4077	0,02	0,2718	0,02	0,2718
Absorption from persons		**Antal**	**Sα/stk**	**Sα**	**Sα/stk**	**Sα**	**Sα/stk**	**Sα**	**Sα/stk**	**Sα**	**Sα/stk**	**Sα**	**Sa/stk**	**Sα**
Persons		0	0	0	0	0	0	0	0	0	0	0	0	0
chairs		0	0	0	0	0	0	0	0	0	0	0	0	0
Absorption in air														
v/ 50% RF		**Volumen**	**125 Hz**		**250 Hz**		**500Hz**		**1000Hz**		**2000Hz**		**4000 Hz**	
		[m3]	m	mV	m	mV	4mV pe	4mV	4mV per	4mV	4mV per	4mV	4mV per	4mV
		105					1,6	0,168	4	0,42	9,6	1,008	24,4000	2,562
Total absorption				27,8		25,1		21,0		17,2		14,9		16,5
Efterklangstid	T=(0,16*V)/((Σα*s)+(Σn*A)+(4*m*V))			0,6		0,7		0,8		1,0		1,1		1,0

Illu 390: Acoustics - Pine, pine, pine and pine

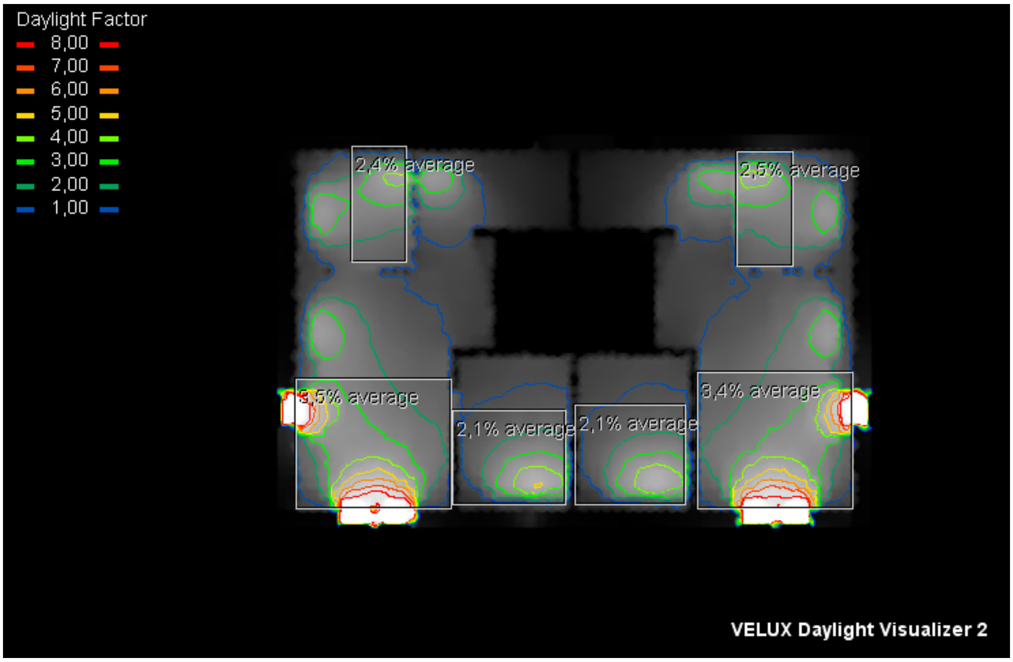
APPENDIX 6 - ENERGY AND THERMAL

Daylight

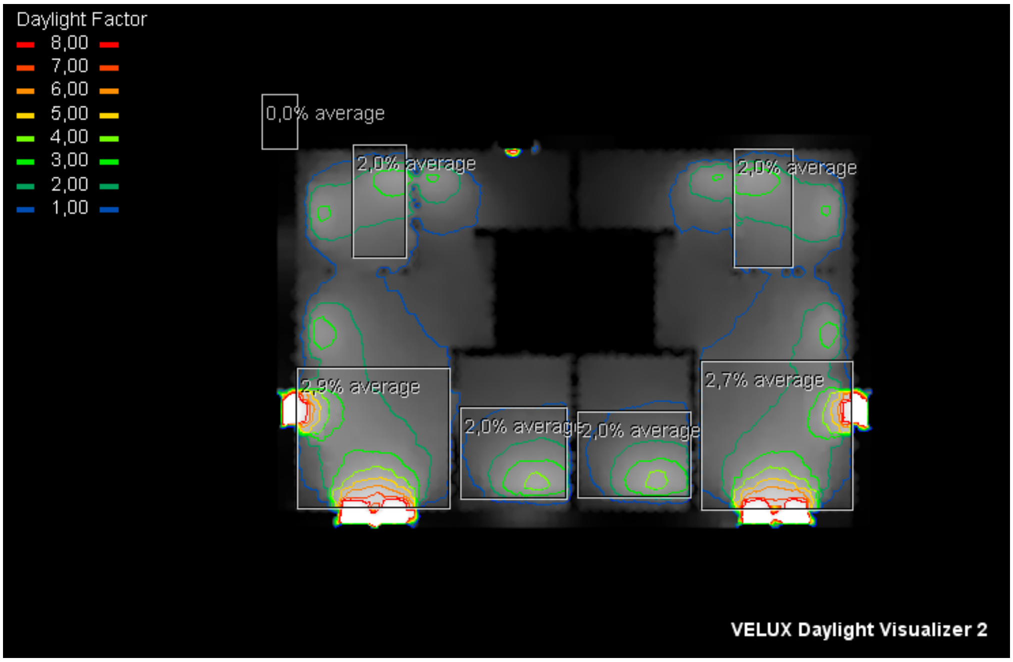
Below is listed the mentioned daylight simulations under refered to for this appendix number.



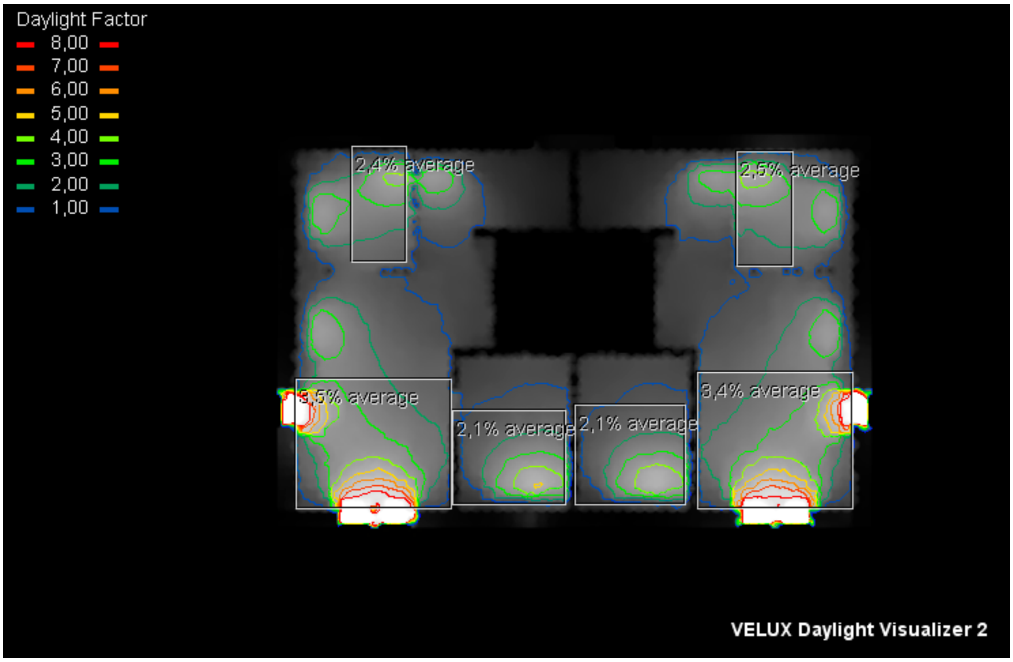
Illu 391: Daylight factor in apartment with windows G-value: 0.53



Illu 392: Daylight factor in apartment with windows G-value: 0.61



Illu 393: Daylight factor in apartment with windows G-value: 0.53



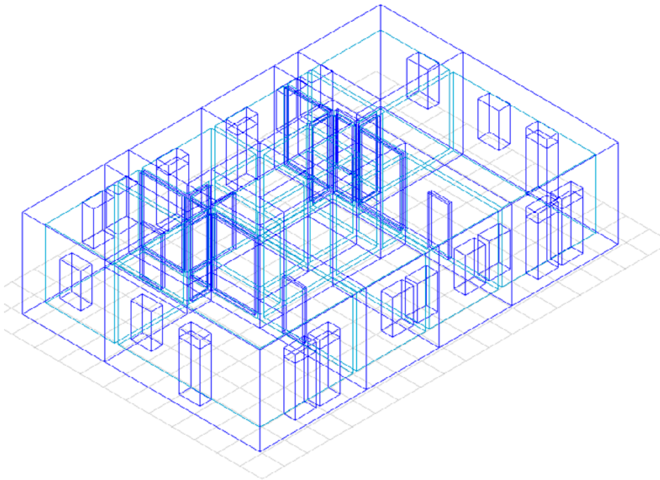
Illu 394: Daylight factor in apartment with windows G-value: 0.61

BSim

The following is to introduce the BSim model and inputs. The model is built as the an entire building, separated into two thermal zones, one for each apartment. Because of the buildings relatively small siz, it is determined that such an evaluation basis is realistic.

The night ventilation is calculated as a factor from the full natural ventilation seen as a factor 1, the factor is then calculated as the relative opening area for windows that can open at night, compared to the entire opening area of all windows. Example given below for a single apartment:

Area of side hung windows: 13.12 m²
Opening area factor for side hung windows: 0.6
Area of top hung windows: 1.278 m²
Opening area factor for top hung windows: 0.4
Full opening area: 8.4 m²
Night opening area: 0.5 m²
Night opening factor: 0.06 = 6%



Illu 395: BSim model

The follow table shows the initial inputs to the BSim model. The main changes will occur in the Solar shading and natural ventilation sections. And these changes will be described further down for each iteration.

System	Description	Regulation/Profile	Time schedule
Equipment	Heatload: 0.24 kW Part to air: 0.7	Usage schedule according to DS/EN 16798-1:2019. Occupancy profile "Apartment residential"	All year
Heating	MaxPow: 5 kW FixedPart: 0	HeatCoolControl Factor: 1 Set Point: 22C Design Temp: -12C MinPow: 0.5 kW Te Min: 17 C Sensor Zone: Apartment	Heating Season January-April September-December
Infiltration	Basic Airchange: 0.13 H-1 TmpFactor: 0.1 (/h/K) TmpPower: 0.5 WindFactor: 0.05 (s/m/h)	100% 1-24	Always

Peopleload	Number of people 3 Activity: 1.2 met	Usage schedule according to DS/EN 16798-1:2019. Occpancy profile "Apartment residential"	All year Weekday schedule Weekend Schedule
Ventilation	Input: Supply: 0.0466 m3/s Pressure Rise: 600 Pa Total Eff: 0.5 Part to Air: 0.5 Output: Return: 0.0466 m3/s Pressure Rise: 600 Pa Total Eff: 0.5 Part to Air: 0.5 Recovery Unit: MaxHeat Rec: 0.9 MinHeat Rec: 0 MaxCool Rec: 0 MaxMoist Rec: 0 HeatCoil: 5 kW Air Source: Outdoor	InletControl: Part of nom. Flow: 1 Point 1 Te1: -12C Tinl on line: 18C Point2 Te2: 8C Tinl2 on line: 18C Slope before 1: 0 Slope after 2: 0 Air hum: 0.07 (kg/kg)	Always
Lighting	Task lightening: 0.02 kW General Lighting: 0.2 kW General lighting level: 200 Lux Lighting type: Incandescent Solar limit: 0.15 kW Exhaust Part: 0	Light Control: Factor: 1 Lower Limit: 0.1 kW Temp. Max: 25 C Solar Limit: 0.2 kW	Usage schedule according to DS/EN 16798-1:2019. Occupancy profile "Apartment residential"
Natural venting	Max Airchange: 0.5 H-1 Max Wind: 14 m/s Control: Automatic	Venting Control: Setpoint: 26 C Setpoint CO2: 850 PPM Day time Factor: 1 Night time Factor: 0.06	Summer: April-September Day: 7-24 Night 0-7
Solarshading	Type: Simple Shading Coeff: 0.8 Max Sun: 150 W/m2 Reflec: 0.5 Transmission: 0.5 Position: Internal	Shading coeff: 0.8 Max Sun: 150 W/m2 Delta Sun: 50 W/m2 Temp. max: 24 C Sun limit: 0.4 kW Sf4 shading: 0.05 Control form: Continuous	Summer: April-September Day: 7-24

Baseline

2002	1489(17)	1401(16)	1314(15)	1226(14)	1138(13)	1051(12)	963(11)	876(10)	788(9)	700(8)	613(7)	525(6)	438(5)	350(4)	262(3)	175(2)	87(1)	0(0)
Ti(Apartment East)°C	23.63	23.76	23.93	24.06	24.18	24.31	24.46	24.60	24.78	24.94	25.15	25.43	25.68	25.95	26.18	26.70	27.36	29.48
Ti(Apartment West)°C	23.64	23.79	23.93	24.06	24.21	24.38	24.51	24.67	24.82	24.98	25.17	25.40	25.67	25.94	26.17	26.61	27.43	29.71
ExtTmp([Outdoor])°C	16.38	16.71	17.13	17.31	17.66	18.02	18.40	18.66	18.95	19.33	19.76	20.21	20.73	21.45	22.30	23.48	24.84	27.70

Illu 396: Thermal Environment temperatures measured in hours above a certain temperature

2002	Min	Mean	Max	1	2	3	4	5	6	7	8	9	10	11	12
VentIn(Apartment East)m³/s	0.0000	0.0028	0.0303				0.0000	0.0000	0.0017	0.0080	0.0064	0.0003			
VentIn(Apartment West)m³/s	0.0000	0.0026	0.0303				0.0000	0.0000	0.0018	0.0075	0.0060	0.0005			
AirChange(Apartment East)/h	1.11	1.47	2.08				1.52	1.48	1.42	1.48	1.49	1.43			
AirChange(Apartment West)/h	1.08	1.47	2.09				1.52	1.48	1.43	1.47	1.47	1.43			

Illu 397: Natural ventilation rates for daytime

2002	Min	Mean	Max	1	2	3	4	5	6	7	8	9	10	11	12
VentIn(Apartment East)m³/s	0.0000	0.0000	0.0018				0.0000	0.0000	0.0000	0.0002	0.0001	0.0000			
VentIn(Apartment West)m³/s	0.0000	0.0000	0.0018				0.0000	0.0000	0.0000	0.0002	0.0001	0.0000			
AirChange(Apartment East)/h	1.19	1.40	1.79				1.49	1.46	1.39	1.34	1.36	1.39			
AirChange(Apartment West)/h	1.19	1.40	1.79				1.49	1.46	1.39	1.34	1.36	1.39			

Illu 398: Natural ventilation rates for nighttime

Natural ventilation - Iteration 1

2002	1489(17)	1401(16)	1314(15)	1226(14)	1138(13)	1051(12)	963(11)	876(10)	788(9)	700(8)	613(7)	525(6)	438(5)	350(4)	262(3)	175(2)	87(1)	0(0)
Ti(Apartment East)°C	23.64	23.78	23.92	24.06	24.19	24.30	24.43	24.57	24.72	24.88	25.06	25.27	25.52	25.76	25.92	26.02	26.33	28.34
Ti(Apartment West)°C	23.63	23.78	23.91	24.05	24.19	24.33	24.44	24.58	24.73	24.88	25.05	25.21	25.42	25.68	25.90	25.99	26.28	28.46
ExtTmp([Outdoor])°C	16.38	16.71	17.13	17.31	17.66	18.02	18.40	18.66	18.95	19.33	19.76	20.21	20.73	21.45	22.30	23.48	24.84	27.70

Illu 399: Thermal Environment temperatures measured in hours above a certain temperature

2002	Min	Mean	Max	1	2	3	4	5	6	7	8	9	10	11	12
VentIn(Apartment East)m³/s	0.0000	0.0121	0.2592				0.0000	0.0000	0.0077	0.0349	0.0276	0.0018			
VentIn(Apartment West)m³/s	0.0000	0.0113	0.2592				0.0000	0.0000	0.0086	0.0314	0.0248	0.0022			
AirChange(Apartment East)/h	1.24	1.79	6.57				1.65	1.61	1.68	2.15	2.07	1.60			
AirChange(Apartment West)/h	1.17	1.78	6.59				1.65	1.61	1.70	2.11	2.02	1.61			

Illu 400: Natural ventilation rates for daytime

2002	Min	Mean	Max	1	2	3	4	5	6	7	8	9	10	11	12
VentIn(Apartment East)m³/s	0.0000	0.0000	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			
VentIn(Apartment West)m³/s	0.0000	0.0000	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			
AirChange(Apartment East)/h	1.31	1.53	1.92				1.61	1.59	1.52	1.46	1.49	1.52			
AirChange(Apartment West)/h	1.31	1.53	1.92				1.61	1.59	1.52	1.46	1.49	1.52			

Illu 401: Natural ventilation rates for nighttime

Natural ventilation - Iteration 2

2002	1489(17)	1401(16)	1314(15)	1226(14)	1138(13)	1051(12)	963(11)	876(10)	788(9)	700(8)	613(7)	525(6)	438(5)	350(4)	262(3)	175(2)	87(1)	0(0)
Ti(Apartment East)°C	23.60	23.75	23.88	24.01	24.14	24.26	24.38	24.53	24.68	24.84	25.03	25.23	25.48	25.73	25.93	26.00	26.18	28.30
Ti(Apartment West)°C	23.59	23.74	23.88	24.01	24.15	24.29	24.40	24.54	24.68	24.85	25.01	25.18	25.38	25.65	25.88	25.98	26.13	28.41
ExtTmp([Outdoor])°C	16.38	16.71	17.13	17.31	17.66	18.02	18.40	18.66	18.95	19.33	19.76	20.21	20.73	21.45	22.30	23.48	24.84	27.70

Illu 402: Thermal Environment temperatures measured in hours above a certain temperature

2002	Min	Mean	Max	1	2	3	4	5	6	7	8	9	10	11	12
VentIn(Apartment East)m³/s	0.0000	0.0117	0.2592				0.0000	0.0000	0.0074	0.0339	0.0263	0.0016			
VentIn(Apartment West)m³/s	0.0000	0.0107	0.2592				0.0000	0.0000	0.0082	0.0303	0.0232	0.0020			
AirChange(Apartment East)/h	1.24	1.78	6.57				1.65	1.61	1.67	2.14	2.04	1.59			
AirChange(Apartment West)/h	1.14	1.78	6.59				1.65	1.61	1.70	2.08	2.00	1.61			

Illu 403: Natural ventilation rates for daytime

2002	Min	Mean	Max	1	2	3	4	5	6	7	8	9	10	11	12
VentIn(Apartment East)m³/s	0.0000	0.0000	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			
VentIn(Apartment West)m³/s	0.0000	0.0000	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			
AirChange(Apartment East)/h	1.31	1.53	1.92				1.61	1.59	1.52	1.46	1.49	1.52			
AirChange(Apartment West)/h	1.31	1.53	1.92				1.61	1.59	1.52	1.46	1.49	1.52			

Illu 404: Natural ventilation rates for nighttime

Natural ventilation - Iteration 3

2002	1576(18)	1489(17)	1401(16)	1314(15)	1226(14)	1138(13)	1051(12)	963(11)	876(10)	788(9)	700(8)	613(7)	525(6)	438(5)	350(4)	262(3)	175(2)	87(1)	0(0)
Ti(Apartmer	23.51	23.64	23.78	23.92	24.06	24.18	24.30	24.43	24.57	24.72	24.88	25.06	25.26	25.51	25.75	25.92	26.01	26.24	28.34
Ti(Apartmer	23.49	23.63	23.78	23.91	24.05	24.19	24.33	24.44	24.58	24.73	24.88	25.05	25.21	25.41	25.67	25.89	25.98	26.17	28.46
ExtTmp([Ou	16.29	16.38	16.71	17.13	17.31	17.66	18.02	18.40	18.66	18.95	19.33	19.76	20.21	20.73	21.45	22.30	23.48	24.84	27.70

Illu 405: Thermal Environment temperatures measured in hours above a certain temperature

2002	Min	Mean	Max	1	2	3	4	5	6	7	8	9	10	11	12
VentIn(Apartment East)m³/s	0.0000	0.0121	0.2592				0.0000	0.0000	0.0077	0.0349	0.0276	0.0018			
VentIn(Apartment West)m³/s	0.0000	0.0113	0.2592				0.0000	0.0000	0.0086	0.0314	0.0248	0.0022			
AirChange(Apartment East)/h	1.24	1.79	6.57				1.65	1.61	1.68	2.15	2.07	1.60			
AirChange(Apartment West)/h	1.17	1.78	6.59				1.65	1.61	1.70	2.11	2.02	1.61			

Illu 406: Natural ventilation rates for daytime

2002	Min	Mean	Max	1	2	3	4	5	6	7	8	9	10	11	12
VentIn(Apartment East)m³/s	0.0000	0.0000	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			
VentIn(Apartment West)m³/s	0.0000	0.0000	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			
AirChange(Apartment East)/h	1.31	1.53	1.92				1.61	1.59	1.52	1.46	1.49	1.52			
AirChange(Apartment West)/h	1.31	1.53	1.92				1.61	1.59	1.52	1.46	1.49	1.52			

Illu 407: Natural ventilation rates for nighttime

Natural ventilation - Iteration 4

2002	186(17)	175(16)	164(15)	153(14)	142(13)	131(12)	120(11)	109(10)	98(9)	87(8)	76(7)	65(6)	54(5)	43(4)	32(3)	21(2)	10(1)	0(0)
Ti(Apartment East)°C	23.90	24.01	24.08	24.20	24.30	24.36	24.46	24.53	24.59	24.70	24.78	24.85	24.95	25.04	25.14	25.26	25.42	25.81
Ti(Apartment West)°C	23.91	24.00	24.10	24.22	24.29	24.35	24.42	24.50	24.58	24.64	24.78	24.84	24.91	25.03	25.13	25.24	25.42	25.81
ExtTmp([Outdoor])°C	14.94	15.10	15.17	15.30	15.39	15.55	15.73	15.92	16.11	16.41	16.70	17.02	17.19	17.34	17.60	18.23	18.51	20.20

Illu 408: Thermal Environment temperatures measured in hours above a certain temperature

2002	Min	Mean	Max	1	2	3	4	5	6	7	8	9	10	11	12
VentIn(Apartment East)m³/s	0.0000	0.0108	0.2592				0.0000	0.0000	0.0066	0.0318	0.0240	0.0015			
VentIn(Apartment West)m³/s	0.0000	0.0099	0.2592				0.0000	0.0000	0.0075	0.0284	0.0209	0.0017			
AirChange(Apartment East)/h	1.23	1.77	6.57				1.65	1.60	1.66	2.11	2.00	1.58			
AirChange(Apartment West)/h	1.14	1.76	6.57				1.65	1.61	1.68	2.06	1.97	1.59			

Illu 409: Natural ventilation rates for daytime

2002	Min	Mean	Max	1	2	3	4	5	6	7	8	9	10	11	12
VentIn(Apartment East)m³/s	0.0000	0.0000	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			
VentIn(Apartment West)m³/s	0.0000	0.0000	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			
AirChange(Apartment East)/h	1.31	1.53	1.92				1.61	1.59	1.52	1.46	1.48	1.52			
AirChange(Apartment West)/h	1.31	1.53	1.92				1.61	1.59	1.52	1.46	1.49	1.52			

Illu 410: Natural ventilation rates for nighttime

Natural ventilation - Iteration 5

2002	1489(17)	1401(16)	1314(15)	1226(14)	1138(13)	1051(12)	963(11)	876(10)	788(9)	700(8)	613(7)	525(6)	438(5)	350(4)	262(3)	175(2)	87(1)	0(0)
Ti(Apartment East)°C	23.53	23.67	23.81	23.94	24.06	24.20	24.33	24.47	24.61	24.79	24.97	25.17	25.43	25.69	25.91	26.01	26.16	28.27
Ti(Apartment West)°C	23.53	23.67	23.82	23.94	24.09	24.22	24.35	24.48	24.61	24.79	24.95	25.13	25.33	25.61	25.88	25.96	26.09	28.37
ExtTmp([Outdoor])°C	16.38	16.71	17.13	17.31	17.66	18.02	18.40	18.66	18.95	19.33	19.76	20.21	20.73	21.45	22.30	23.48	24.84	27.70

Illu 411: Thermal Environment temperatures measured in hours above a certain temperature

2002	Min	Mean	Max	1	2	3	4	5	6	7	8	9	10	11	12
VentIn(Apartment East)m³/s	0.0000	0.0111	0.2592				0.0000	0.0000	0.0069	0.0326	0.0251	0.0015			
VentIn(Apartment West)m³/s	0.0000	0.0102	0.2592				0.0000	0.0000	0.0077	0.0290	0.0221	0.0018			
AirChange(Apartment East)/h	1.23	1.77	6.57				1.65	1.60	1.66	2.12	2.01	1.58			
AirChange(Apartment West)/h	1.14	1.77	6.57				1.65	1.61	1.69	2.06	1.99	1.59			

Illu 412: Natural ventilation rates for daytime

2002	Min	Mean	Max	1	2	3	4	5	6	7	8	9	10	11	12
VentIn(Apartment East)m³/s	0.0000	0.0000	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			
VentIn(Apartment West)m³/s	0.0000	0.0000	0.0000				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			
AirChange(Apartment East)/h	1.31	1.53	1.92				1.61	1.59	1.52	1.46	1.49	1.52			
AirChange(Apartment West)/h	1.31	1.53	1.92				1.61	1.59	1.52	1.46	1.49	1.52			

Illu 413: Natural ventilation rates for nighttime

Solarshading - Iteration 1

Solarshading	Type: Venetian Shading Coeff: 0.3 Max Sun: 150 W/m2 Reflec: 0.3 Transmission: 0.1 Position: External Slat width: 0.05m Slat distance: 0.042m	Shading coeff: 0.3 Max Sun: 150 W/m2 Delta Sun: 50 W/m2 Temp. max: 26C Sun limit: 0.4 kW Sf4 shading: 0.05 Control form: Continuous	Summer: April-September Day: 7-24

2002	1489(17)	1401(16)	1314(15)	1226(14)	1138(13)	1051(12)	963(11)	876(10)	788(9)	700(8)	613(7)	525(6)	438(5)	350(4)	262(3)	175(2)	87(1)	0(0)
Ti(Apartment East)°C	23.57	23.72	23.86	24.01	24.14	24.26	24.41	24.56	24.72	24.90	25.09	25.35	25.62	25.90	26.08	26.43	27.06	28.96
Ti(Apartment West)°C	23.58	23.72	23.87	24.00	24.14	24.28	24.44	24.57	24.72	24.89	25.08	25.28	25.53	25.82	26.04	26.35	26.98	28.94
ExtTmp([Outdoor])°C	16.38	16.71	17.13	17.31	17.66	18.02	18.40	18.66	18.95	19.33	19.76	20.21	20.73	21.45	22.30	23.48	24.84	27.70

Illu 414: Thermal Environment temperatures measured in hours above a certain temperature

Solarshading - Iteration 2 - 1.7m overhang

Solarshading	Type: Overhang Modelled directly into model	Always in use	Always

2002	1489(17)	1401(16)	1314(15)	1226(14)	1138(13)	1051(12)	963(11)	876(10)	788(9)	700(8)	613(7)	525(6)	438(5)	350(4)	262(3)	175(2)	87(1)	0(0)
Ti(Apartment East)°C	23.32	23.44	23.56	23.69	23.86	24.01	24.16	24.31	24.49	24.66	24.86	25.11	25.40	25.70	25.94	26.23	26.85	28.72
Ti(Apartment West)°C	23.33	23.48	23.61	23.73	23.88	24.02	24.17	24.32	24.49	24.64	24.83	25.05	25.31	25.61	25.89	26.11	26.73	28.73
ExtTmp([Outdoor])°C	16.38	16.71	17.13	17.31	17.66	18.02	18.40	18.66	18.95	19.33	19.76	20.21	20.73	21.45	22.30	23.48	24.84	27.70

Illu 415: Thermal Environment temperatures measured in hours above a certain temperature

Solarshading - Iteration 2 - 0.85m overhang

2002	1489(17)	1401(16)	1314(15)	1226(14)	1138(13)	1051(12)	963(11)	876(10)	788(9)	700(8)	613(7)	525(6)	438(5)	350(4)	262(3)	175(2)	87(1)	0(0)
Ti(Apartment East)°C	23.55	23.69	23.82	23.96	24.09	24.23	24.36	24.51	24.69	24.87	25.06	25.33	25.62	25.89	26.09	26.53	27.15	29.04
Ti(Apartment West)°C	23.55	23.70	23.83	23.96	24.10	24.24	24.39	24.54	24.68	24.84	25.02	25.25	25.50	25.78	26.03	26.35	27.02	29.01
ExtTmp([Outdoor])°C	16.38	16.71	17.13	17.31	17.66	18.02	18.40	18.66	18.95	19.33	19.76	20.21	20.73	21.45	22.30	23.48	24.84	27.70

Illu 416: Thermal Environment temperatures measured in hours above a certain temperature

Solarshading - Iteration 3

Solarshading	Type: Screen Shading Coeff: 0.2 Max Sun: 150 W/m2 Reflec: 0.3 Transmission: 0.1 Position: External	Shading coeff: 0.2 Max Sun: 150 W/m2 Delta Sun: 50 W/m2 Temp. max: 26C Sun limit: 0.4 kW Sf4 shading: 0.05 Control form: Continuous	Summer: April-September Day: 7-24

2002	1489(17)	1401(16)	1314(15)	1226(14)	1138(13)	1051(12)	963(11)	876(10)	788(9)	700(8)	613(7)	525(6)	438(5)	350(4)	262(3)	175(2)	87(1)	0(0)
Ti(Apartment East)°C	23.58	23.71	23.86	24.01	24.14	24.27	24.40	24.55	24.72	24.90	25.09	25.35	25.62	25.90	26.08	26.38	27.01	28.86
Ti(Apartment West)°C	23.59	23.73	23.87	24.01	24.15	24.29	24.45	24.58	24.73	24.89	25.08	25.28	25.52	25.82	26.03	26.30	26.94	28.78
ExtTmp([Outdoor])°C	16.38	16.71	17.13	17.31	17.66	18.02	18.40	18.66	18.95	19.33	19.76	20.21	20.73	21.45	22.30	23.48	24.84	27.70

Illu 417: Thermal Environment temperatures measured in hours above a certain temperature

Energy Frame

Below is listed the screenshots from BE18 for each iteration refered to in this appendix.

Iøgletal, kWh/m² år

Renoveringsklasse 2

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
97.5	0.0	97.5
Samlet energibehov		57.7

Renoveringsklasse 1

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
73.1	0.0	73.1
Samlet energibehov		57.7

Energiramme BR 2018

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
42.5	0.0	42.5
Samlet energibehov		57.7

Energiramme lavenergi

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
27.0	0.0	27.0
Samlet energibehov		57.7

Bidrag til energibehovet		Netto behov	
Varme	23.1	Rumopvarmning	20.2
El til bygningsdrift	10.5	Varmt brugsvand	5.7
Overtemp. i rum	18.1	Køling	0.0

Udvalgte elbehov		Varmetab fra installationer	
Belysning	0.0	Rumopvarmning	2.9
Opvarmning af rum	0.0	Varmt brugsvand	5.7
Opvarmning af vbv	5.7	**Ydelse fra særlige kilder**	
Varmepumpe	0.0		
Ventilatorer	4.7	Solvarme	0.0
Pumper	0.0	Varmepumpe	0.0
Køling	0.0	Solceller	0.0
Totalt elforbrug	41.1	Vindmøller	0.0

Illu 418: Energy Frame - Baseline building

Heating: 23.1 kWh/m² pr year

Electricity for building: 10.5 kWh/m² pr year

Overheating: 18.1 kWh/m² pr year

Nøgletal, kWh/m² år

Renoveringsklasse 2

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
97.5	0.0	97.5
Samlet energibehov		39.5

Renoveringsklasse 1

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
73.1	0.0	73.1
Samlet energibehov		39.5

Energiramme BR 2018

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
42.5	0.0	42.5
Samlet energibehov		39.5

Energiramme lavenergi

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
27.0	0.0	27.0
Samlet energibehov		39.5

Bidrag til energibehovet		Netto behov	
Varme	23.1	Rumopvarmning	20.2
El til bygningsdrift	10.5	Varmt brugsvand	5.7
Overtemp. i rum	0.0	Køling	0.0

Udvalgte elbehov		Varmetab fra installationer	
Belysning	0.0	Rumopvarmning	2.9
Opvarmning af rum	0.0	Varmt brugsvand	5.7
Opvarmning af vbv	5.7	**Ydelse fra særlige kilder**	
Varmepumpe	0.0		
Ventilatorer	4.7	Solvarme	0.0
Pumper	0.0	Varmepumpe	0.0
Køling	0.0	Solceller	0.0
Totalt elforbrug	41.1	Vindmøller	0.0

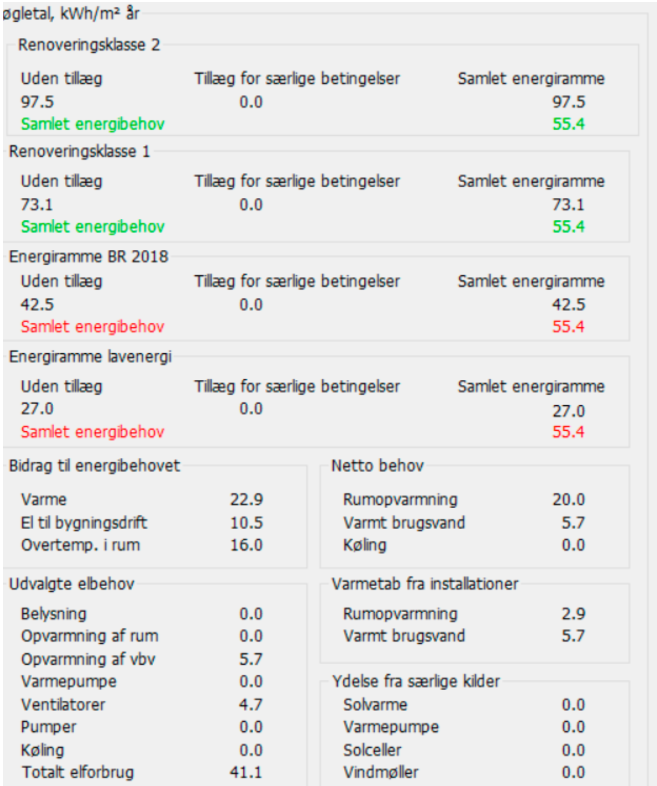
Illu 419: Energy Frame - All iterations for natural ventilation

Heating: 23.1 kWh/m² pr year

Electricity for building: 10.5 kWh/m² pr year

Overheating: 0 kWh/m² pr year

Notice that all iterations for natural ventilation have identical energy frames, as they all allow for enough natural ventilation such that overheating is combated in the simplistic calculation that BE18 performs with regards to overheating.



øgletal, kWh/m² år

Renoveringsklasse 2		
Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
97.5	0.0	97.5
Samlet energibehov		55.4

Renoveringsklasse 1		
Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
73.1	0.0	73.1
Samlet energibehov		55.4

Energiramme BR 2018		
Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
42.5	0.0	42.5
Samlet energibehov		55.4

Energiramme lavenergi		
Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
27.0	0.0	27.0
Samlet energibehov		55.4

Bidrag til energibehovet		Netto behov	
Varme	22.9	Rumopvarmning	20.0
El til bygningsdrift	10.5	Varmt brugsvand	5.7
Overtemp. i rum	16.0	Køling	0.0

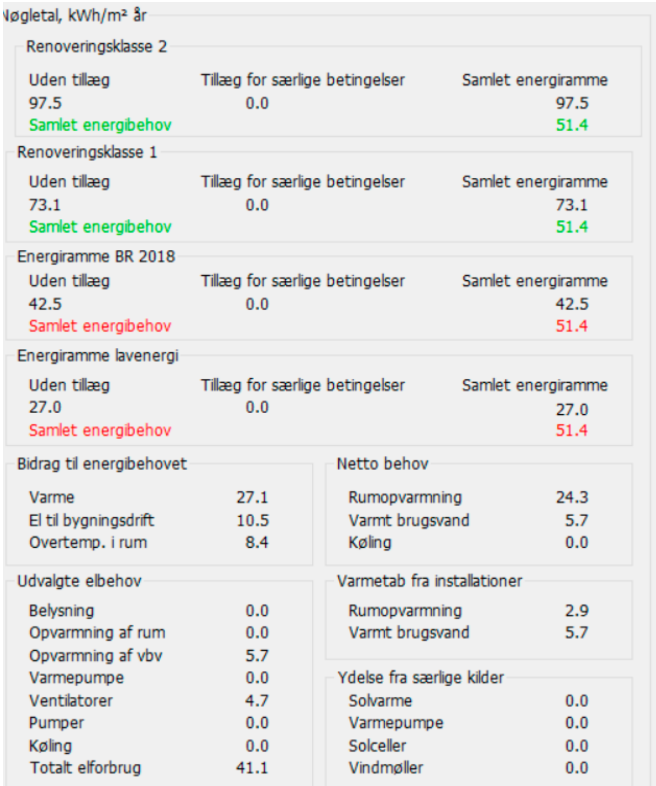
Udvalgte elbehov		Varmetab fra installationer	
Belysning	0.0	Rumopvarmning	2.9
Opvarmning af rum	0.0	Varmt brugsvand	5.7
Opvarmning af vbv	5.7	Ydelse fra særlige kilder	
Varmepumpe	0.0		
Ventilatorer	4.7	Solvarme	0.0
Pumper	0.0	Varmepumpe	0.0
Køling	0.0	Solceller	0.0
Totalt elforbrug	41.1	Vindmøller	0.0

Illu 420: Energy Frame - Solarshading - Slat solars-hading

Heating: 22.9 kWh/m² pr year

Electricity for building: 10.5 kWh/m² pr year

Overheating: 16 kWh/m² pr year



Nøgletal, kWh/m² år

Renoveringsklasse 2		
Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
97.5	0.0	97.5
Samlet energibehov		51.4

Renoveringsklasse 1		
Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
73.1	0.0	73.1
Samlet energibehov		51.4

Energiramme BR 2018		
Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
42.5	0.0	42.5
Samlet energibehov		51.4

Energiramme lavenergi		
Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
27.0	0.0	27.0
Samlet energibehov		51.4

Bidrag til energibehovet		Netto behov	
Varme	27.1	Rumopvarmning	24.3
El til bygningsdrift	10.5	Varmt brugsvand	5.7
Overtemp. i rum	8.4	Køling	0.0

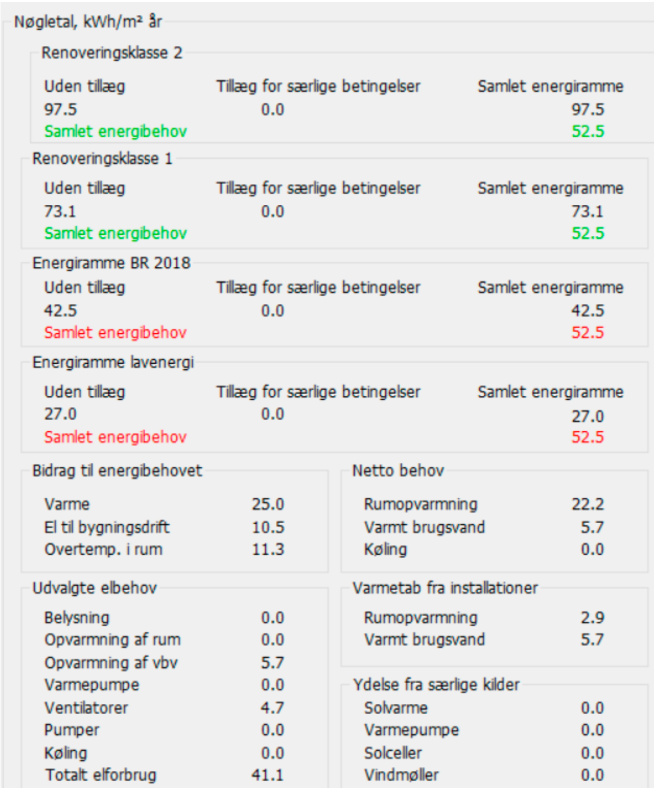
Udvalgte elbehov		Varmetab fra installationer	
Belysning	0.0	Rumopvarmning	2.9
Opvarmning af rum	0.0	Varmt brugsvand	5.7
Opvarmning af vbv	5.7	Ydelse fra særlige kilder	
Varmepumpe	0.0		
Ventilatorer	4.7	Solvarme	0.0
Pumper	0.0	Varmepumpe	0.0
Køling	0.0	Solceller	0.0
Totalt elforbrug	41.1	Vindmøller	0.0

Illu 421: Energy Frame - Solarshading - South facing overhang 1.7m

Heating: 27.1 kWh/m² pr year

Electricity for building: 10.5 kWh/m² pr year

Overheating: 8.4 kWh/m² pr year



Nøgletal, kWh/m² år

Renoveringsklasse 2

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
97.5	0.0	97.5
Samlet energibehov		52.5

Renoveringsklasse 1

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
73.1	0.0	73.1
Samlet energibehov		52.5

Energiramme BR 2018

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
42.5	0.0	42.5
Samlet energibehov		52.5

Energiramme lavenergi

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
27.0	0.0	27.0
Samlet energibehov		52.5

Bidrag til energibehovet

Varme	25.0
El til bygningsdrift	10.5
Overtemp. i rum	11.3

Netto behov

Rumopvarmning	22.2
Varmt brugsvand	5.7
Køling	0.0

Udvalgte elbehov

Belysning	0.0
Opvarmning af rum	0.0
Opvarmning af vbv	5.7
Varmepumpe	0.0
Ventilatorer	4.7
Pumper	0.0
Køling	0.0
Totalt elforbrug	41.1

Varmetab fra installationer

Rumopvarmning	2.9
Varmt brugsvand	5.7

Ydelse fra særlige kilder

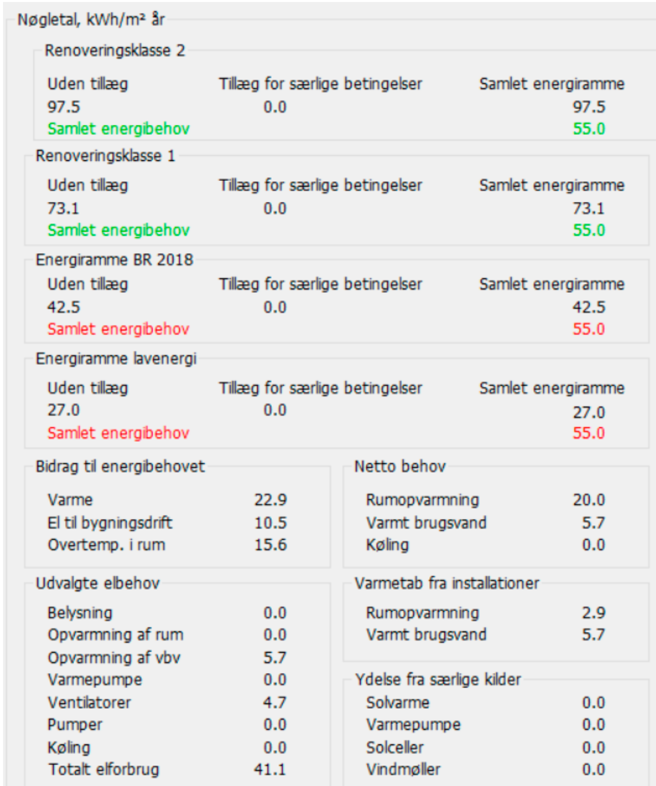
Solvarme	0.0
Varmepumpe	0.0
Solceller	0.0
Vindmøller	0.0

Illu 422: Energy Frame - Solarshading - South facing overhang 0.85m

Heating: 25 kWh/m² pr year

Electricity for building: 10.5 kWh/m² pr year

Overheating: 11.3 kWh/m² pr year



Nøgletal, kWh/m² år

Renoveringsklasse 2

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
97.5	0.0	97.5
Samlet energibehov		55.0

Renoveringsklasse 1

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
73.1	0.0	73.1
Samlet energibehov		55.0

Energiramme BR 2018

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
42.5	0.0	42.5
Samlet energibehov		55.0

Energiramme lavenergi

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
27.0	0.0	27.0
Samlet energibehov		55.0

Bidrag til energibehovet

Varme	22.9
El til bygningsdrift	10.5
Overtemp. i rum	15.6

Netto behov

Rumopvarmning	20.0
Varmt brugsvand	5.7
Køling	0.0

Udvalgte elbehov

Belysning	0.0
Opvarmning af rum	0.0
Opvarmning af vbv	5.7
Varmepumpe	0.0
Ventilatorer	4.7
Pumper	0.0
Køling	0.0
Totalt elforbrug	41.1

Varmetab fra installationer

Rumopvarmning	2.9
Varmt brugsvand	5.7

Ydelse fra særlige kilder

Solvarme	0.0
Varmepumpe	0.0
Solceller	0.0
Vindmøller	0.0

Illu 423: Energy Frame - Solarshading - Exterior screen

Heating: 22.9 kWh/m² pr year

Electricity for building: 10.5 kWh/m² pr year

Overheating: 15.6 kWh/m² pr year

Combination

Below is listed the values for the combination of natural ventilation iteration 4, and solar shading iteration 1.

2002	1489(17)	1401(16)	1314(15)	1226(14)	1138(13)	1051(12)	963(11)	876(10)	788(9)	700(8)	613(7)	525(6)	438(5)	350(4)	262(3)	175(2)	87(1)	0(0)
Ti(Apartment East)°C	23.41	23.53	23.65	23.77	23.87	23.98	24.07	24.20	24.35	24.48	24.63	24.78	24.88	24.96	25.01	25.07	25.76	27.95
Ti(Apartment West)°C	23.38	23.50	23.63	23.75	23.86	23.97	24.08	24.21	24.33	24.46	24.61	24.75	24.86	24.94	24.99	25.05	25.70	27.91
ExtTmp([Outdoor])°C	16.38	16.71	17.13	17.31	17.66	18.02	18.40	18.66	18.95	19.33	19.76	20.21	20.73	21.45	22.30	23.48	24.84	27.70

Illu 424: Thermal Environment temperatures measured in hours above a certain temperature

2002	Min	Mean	Max	1	2	3	4	5	6	7	8	9	10	11	12
VentIn(Apartment East)m³/s	0.0000	0.0177	0.2592				0.0000	0.0000	0.0140	0.0487	0.0388	0.0035			
VentIn(Apartment West)m³/s	0.0000	0.0156	0.2592				0.0000	0.0000	0.0134	0.0418	0.0337	0.0035			
AirChange(Apartment East)/h	1.14	1.91	6.59				1.65	1.60	1.80	2.46	2.28	1.62			
AirChange(Apartment West)/h	1.12	1.86	6.59				1.65	1.60	1.80	2.32	2.17	1.62			

Illu 425: Natural ventilation rates for daytime

2002	Min	Mean	Max	1	2	3	4	5	6	7	8	9	10	11	12
VentIn(Apartment East)m³/s	0.0000	0.0000	0.0039				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			
VentIn(Apartment West)m³/s	0.0000	0.0000	0.0066				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			
AirChange(Apartment East)/h	1.30	1.53	1.92				1.61	1.59	1.52	1.46	1.48	1.52			
AirChange(Apartment West)/h	1.30	1.53	1.92				1.61	1.59	1.52	1.45	1.48	1.52			

Illu 426: Natural ventilation rates for nighttime

øgletal, kWh/m² år

Renoveringsklasse 2

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
97.5	0.0	97.5
Samlet energibehov		55.4

Renoveringsklasse 1

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
73.1	0.0	73.1
Samlet energibehov		55.4

Energiramme BR 2018

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
42.5	0.0	42.5
Samlet energibehov		55.4

Energiramme lavenergi

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
27.0	0.0	27.0
Samlet energibehov		55.4

Bidrag til energibehovet

Varme	22.9
El til bygningsdrift	10.5
Overtemp. i rum	16.0

Netto behov

Rumopvarmning	20.0
Varmt brugsvand	5.7
Køling	0.0

Udvalgte elbehov

Belysning	0.0
Opvarmning af rum	0.0
Opvarmning af vbv	5.7
Varmepumpe	0.0
Ventilatorer	4.7
Pumper	0.0
Køling	0.0
Totalt elforbrug	41.1

Varmetab fra installationer

Rumopvarmning	2.9
Varmt brugsvand	5.7

Ydelse fra særlige kilder

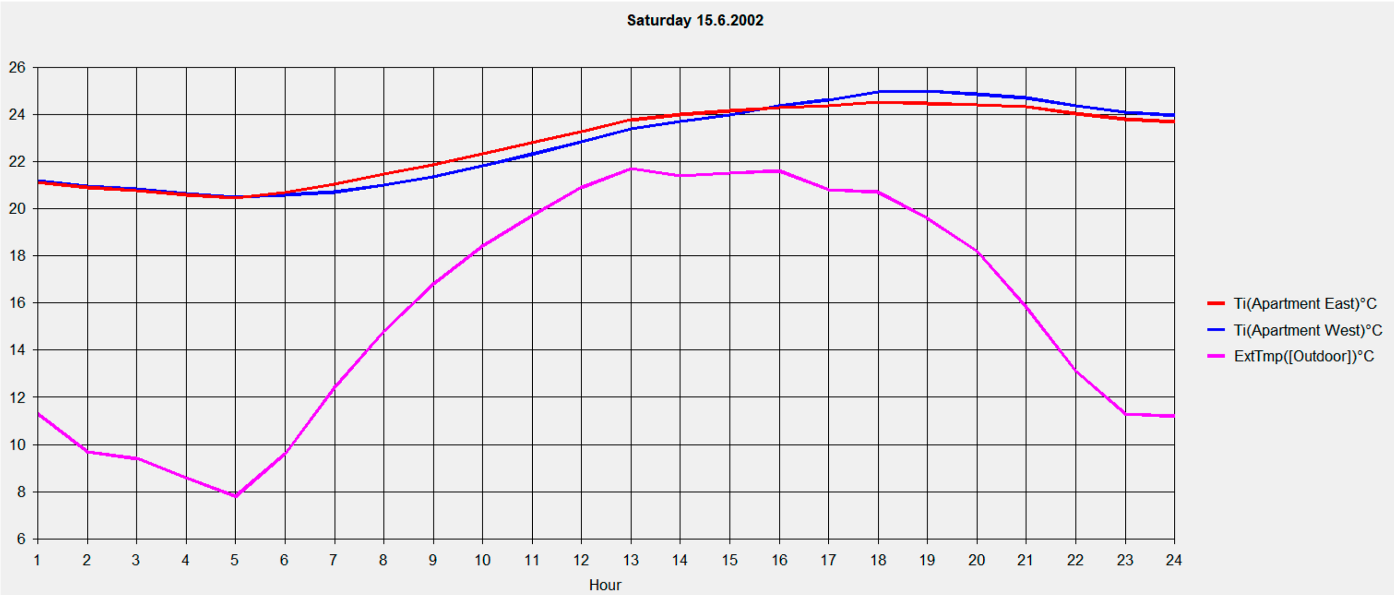
Solvarme	0.0
Varmepumpe	0.0
Solceller	0.0
Vindmøller	0.0

Illu 427: Energy Frame - Solarshading - Slat solarshading

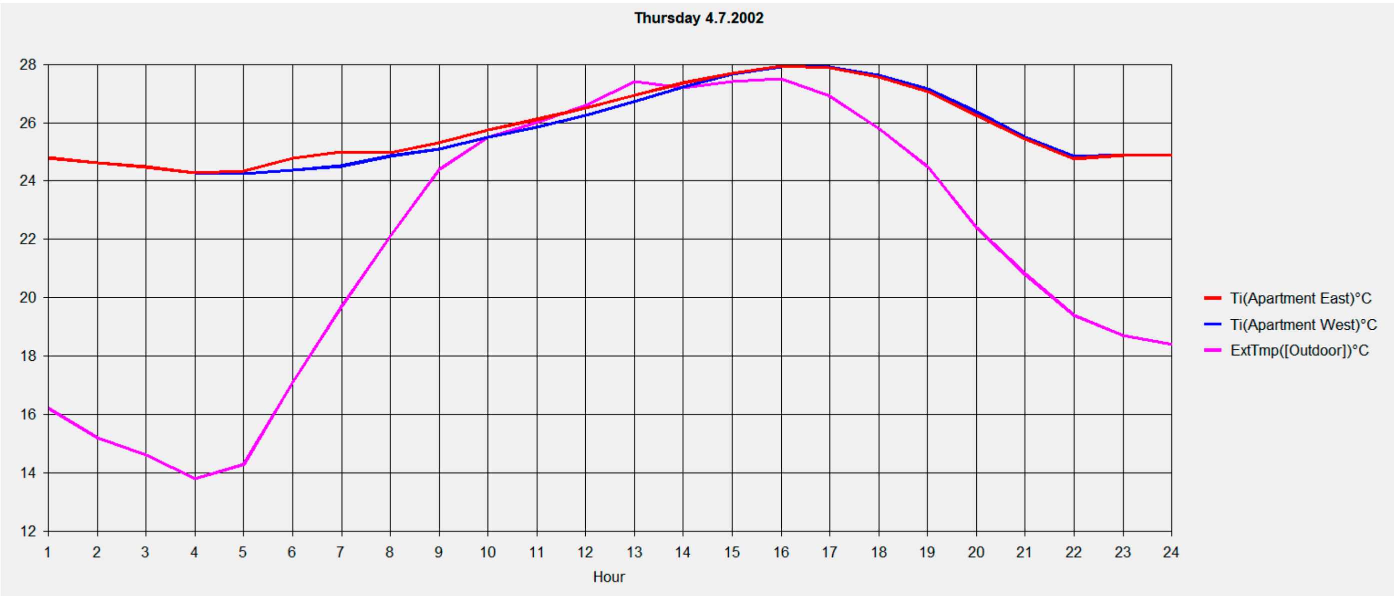
Heating: 22.9 kWh/m² pr year

Electricity for building: 10.5 kWh/m² pr year

Overheating: 0 kWh/m² pr year



Illu 428: Graph showing the outdoor temperature on the 15th of June. It is clear that heat is building up in the apartment during the day, despite the outdoor temperature dropping. A proof that the building indeed is low in thermal mass, but also that natural ventilation at night is useful.



Illu 429: Graph showing the outdoor temperature on the 4th of July. Though the outdoor temperature is high on this day, the corresponding interior temperature is not much higher. This shows that good natural ventilation is happening, and the temperature exceeding 27 degrees inside, is explained by the outdoor temperature being comparably as high.

APPENDIX 7 - FINAL ENERGY FRAME

Nøgletal, kWh/m² år

Renoveringsklasse 2

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
95.6	0.0	95.6
Samlet energibehov		38.9

Renoveringsklasse 1

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
71.7	0.0	71.7
Samlet energibehov		38.9

Energiramme BR 2018

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
41.6	0.0	41.6
Samlet energibehov		38.9

Energiramme lavenergi

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
27.0	0.0	27.0
Samlet energibehov		38.9

Bidrag til energibehovet		Netto behov	
Varme	23.2	Rumopvarmning	23.2
El til bygningsdrift	10.1	Varmt brugsvand	5.3
Overtemp. i rum	0.0	Køling	0.0

Udvalgte elbehov			
Belysning	0.0	**Varmetab fra installationer**	
Opvarmning af rum	0.0	Rumopvarmning	0.0
Opvarmning af vbv	5.3	Varmt brugsvand	5.3
Varmepumpe	0.0	**Ydelse fra særlige kilder**	
Ventilatorer	4.7	Solvarme	0.0
Pumper	0.0	Varmepumpe	0.0
Køling	0.0	Solceller	0.0
Totalt elforbrug	40.7	Vindmøller	0.0

Illu 439: North dwelling final energy frame

Nøgletal, kWh/m² år

Renoveringsklasse 2

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
95.1	0.0	95.1
Samlet energibehov		38.0

Renoveringsklasse 1

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
71.4	0.0	71.4
Samlet energibehov		38.0

Energiramme BR 2018

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
41.4	0.0	41.4
Samlet energibehov		38.0

Energiramme lavenergi

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
27.0	0.0	27.0
Samlet energibehov		38.0

Bidrag til energibehovet		Netto behov	
Varme	22.4	Rumopvarmning	22.4
El til bygningsdrift	10.0	Varmt brugsvand	5.3
Overtemp. i rum	0.0	Køling	0.0

Udvalgte elbehov			
Belysning	0.0	**Varmetab fra installationer**	
Opvarmning af rum	0.0	Rumopvarmning	0.0
Opvarmning af vbv	5.3	Varmt brugsvand	5.3
Varmepumpe	0.0	**Ydelse fra særlige kilder**	
Ventilatorer	4.7	Solvarme	0.0
Pumper	0.0	Varmepumpe	0.0
Køling	0.0	Solceller	0.0
Totalt elforbrug	40.6	Vindmøller	0.0

Illu 440: South dwelling final energy frame