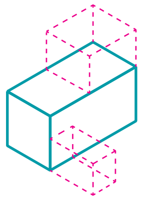
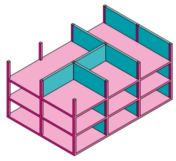
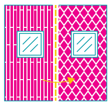
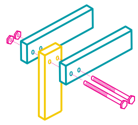
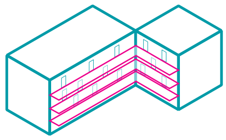
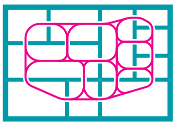
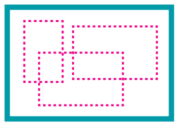
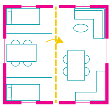
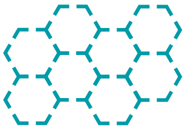
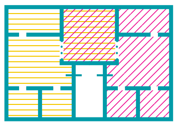
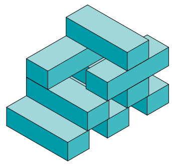
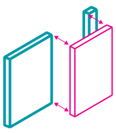



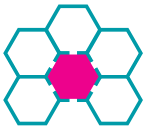


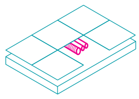
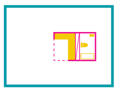
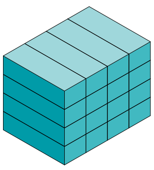
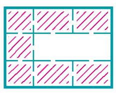
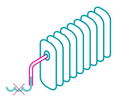
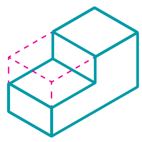





The Futureproof House

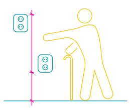
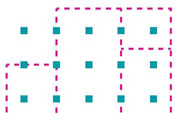
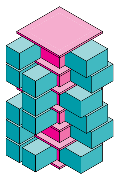
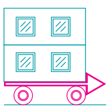
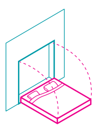







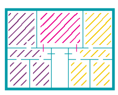
- backcasting architecture for flexible housing



Master thesis by Kaj Norberg
Department of Architecture
Chalmers University of Technology
Supervisor: Jan Larsson
Examiner: Ola Nylander



The Futureproof House
- backcasting architecture for flexible housing

Gothenburg, 2019

Chalmers University of Technology
Department of Architecture and Civil Engineering
Master's programme of Architecture and Planning
Beyond Sustainability

Examiner: Ola Nylander
Supervisor: Jan Larsson

CHALMERS

Student background

A personal interest in environmental issues, a penchant for clever solutions and future adaptations as well as the enjoyment in putting puzzle pieces together all led me to this project.

Taking master courses veered toward social sustainability, introduced the notion that users of apartment housing come from a broader spectrum than what is usually designed for. A competition course in sustainable building design let me work more in-depth with concepts such as Design for Disassembly and Cradle-to-Cradle™. These thoughts combined sparked the idea of a flexible apartment building, and after being introduced to the research project Beyond GDP-growth, I found a tool that could steer the project toward a place I found interesting. Working with prefabricated wood made sense due to, among other things, environmental performance.

Bachelor's degree
Umeå School of Architecture
2011-2014

Master's degree
Chalmers University of Technology
2017-2019

Acknowledgements

Thanks to Jan Larsson and Ola Nylander.
Thanks to Ingrid.
Thanks to Anna Braide Eriksson, Kaj Granath, Pernilla Hagbert, Robert Jockwer, Saga Karlsson, Joao Pereira, Staffan Schartner.
Thanks to Anders, Felicia, Gustav, Josefin, Lovisa, Sandra.

Abstract

With an increasingly urgent climate crisis going on, the need for environmentally sustainable architecture is bigger than ever. The building and property sector use 37% of all energy produced in Sweden and produce 31% of all Swedish waste, a clear message that the way we build needs to change.

The Futureproof House is a thesis exploring ways of reaching a more sustainable architecture through three interconnected approaches, flexibility, prefabrication and backcasting scenarios.

Due to climate change, our way of living and the way we build will have to change, either as a proactive measure to mitigate adverse effects to the climate or as a result forced upon us if we do nothing. This thesis' aim is to design a flexible building that can adapt to the pre-emptive changes. The adaptations necessary can be made with minimal energy and material waste, awarding a society that decides to be more sustainable.

The Futureproof House is constructed with prefabrication methods, which also can reduce material waste and energy use. If constructed with flexibility in mind, prefabrication can also facilitate future alterations.

The proactive changes used in the thesis are from the research project 'Beyond GDP-growth', where four backcasting scenarios, four different roads to reaching a Sweden without carbon emissions in 2050, was established – Collaborative economy, Local self-sufficiency, Automation and Circular economy. The thesis will explore how these kinds of scenarios can be a guiding light in the design process of a flexible building, leading to a building that can adapt to any of these sustainable futures, a Futureproof House.

Keywords: flexibility, future-proofing, backcasting scenarios, prefabrication, sustainability, clt

Table of contents

1. Introduction

1.1 Problem statement

We live in a non-sustainable society, using more resources than we have. The building and property sector use 37% of all energy produced in Sweden and produce 31% of all Swedish waste (Boverket, 2019). Globally, 10 per cent of the material used in the same sector is wasted (Goodbun & Jaschke, 2012).

Change is not only necessary, it's inevitable. Either we perform a pre-emptive change in the way we live, the way we build and the way we reside, or all these changes will be forced upon us, without us having any say in it.

In whatever form these changes arrive, as a choice or as a forced result, the building sector will be affected heavily. This thesis suggests the design of a house which will be able to adapt to the changes that will come, a Futureproof House.

1.2 Research questions

How can backcasting scenarios influence a design process toward flexible housing?

How can prefabricated housing be flexible?

1.3 Aim & Purpose

The Futureproof House is a thesis exploring ways of reaching environmentally sustainable architecture, through three interconnected approaches; Flexibility, Prefabrication and Backcasting scenarios. The aim is to design a apartment block in Gamlestaden in Gothenburg.

Flexibility
To reduce the amount of material and energy used over time, flexible buildings can be important, as they can be adapted rather than torn down when the use needs to change. However, designing for flexibility needs certain parameters, since all-encompassing flexibility is wasteful in cost, space and material use (Finch, 2009). This is where the backcasting scenarios come in.

Prefabrication
With less material waste, safer work environments, higher quality control and reduced time and cost, prefabrication methods can be very useful in sustainable architecture. The modularity often used in prefabrication can also be of good use when designing for adaptability.

Backcasting scenarios
Backcasting is a method, where a goal future is set up, and different ways of reaching this goal are researched and theorized. The four scenarios used in this thesis are from the research project 'Beyond GDP-growth', the goal being a socially and environmentally sustainable Sweden without carbon emissions in 2050. Design decisions are taken by trying them against the four scenarios, to determine what decision makes the building most able to adapt to all four scenarios.

1.4 Glossary

Backcasting
Backcasting is a tool for planning. The method starts with defining a desirable future, and then working backwards, finding different ways to reach this goal from present day.

Flatpack / Volume
The word flatpack, as used in this thesis, means a construction element which arrives to the site in a flat package. It can be a floor cassette or a preassembled wall element. Volume modules are prefabricated, load-bearing modules which are assembled in a factory before being delivered to the site.

Flexibility / Adaptability
The terms adaptability and flexibility can often be confusing and are used in different ways by different authors. Steven Groak (1990, p. 15) offers the distinction that adaptable buildings are "capable of different social uses" and flexible ones are "capable of different physical arrangements". This differentiation is also recommended by Schneider and Till in their seminal book 'Flexible Housing' (2007) and will be used in this thesis. The thesis will focus on flexible architecture; a building which can change. Within this flexibility, adaptable architecture (spaces for varying activities and uses) can occur.

Future-proofing
In the words of Brian D. Rich (2016), "future-proofing is the process of anticipating future events and developing methods of adaptation".

1.5 Method

The thesis has a three-legged approach, adaptability, prefabrication and backcasting.

As a starting point for this thesis, structures, principles, technologies, papers, materials and inventions for prefabricated buildings, and strategies for flexibility is researched, to form an understanding of existing possibilities.

Parallel with this research, exploration is made into future scenarios through a reading of existing literature. Four backcasting scenarios are used as a foundation; Circular economy, Local self-sufficiency, Automation and Collaborative economy. These scenarios were proposed by the Swedish research project 'Beyond GDP-growth'. All four scenarios are prospective ways that Sweden could develop and transform to reach a sustainable future by 2050. (Hagbert et al., 2018)

Based on the research, a design is made. The design decisions are taken by testing possibilities against the different scenarios, either through a more formal tryout - where each option is tried against each scenario in a pro-and-con matrix - or a more informal sketching with the scenarios in mind.

1.6 Theory

Flexibility theories used in this thesis mainly comes from books and papers. Main authors are Schmidt III & Austin (2016), Schneider & Till (2007), Tarpio (2016) and Kim (2013). In the prefabrication field, the authors used most prominently are Albus (2018), Knaack (2012) and Bergdoll et al. (2008). In both these fields, additional authors, papers and projects have been used, as referenced in the text. The backcasting scenarios all come from the same Swedish research project, 'Beyond GDP-growth'. (Hagbert et al., 2018) To these scenarios some information has been added, which is then mentioned.

1.7 Delimitations

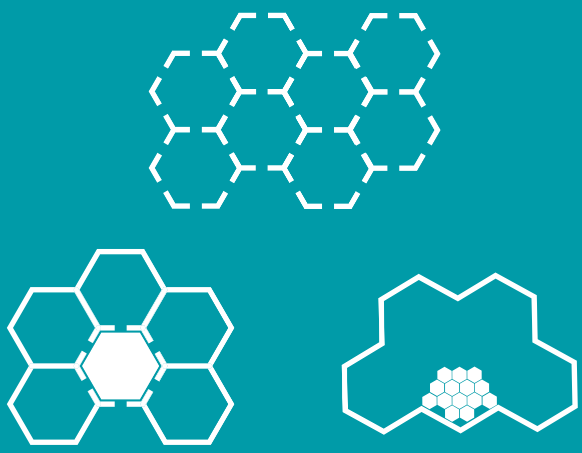
The question of who will implement the changes and adapt the building is not answered in this thesis, as important is it may be. This thesis rather focuses on the systematic approach in the design of a building.

In the design, the site, ground floor, courtyard, staircases and surroundings have all stepped back to leave the focus on the dwelling units on storeys 2 and above.

1.8 Reading instructions

This thesis report is split into two main parts, research and process (chapters 2-5) and result (chapter 6). Each of the three research approaches has its own chapter. Within these chapters are markings which refer to reference projects and case studies available in the appendix, such as this:
A5 iValla

2. Flexibility



2.1 Background

Fig. 1. Mongolian ger. (Tkn20, 2007)

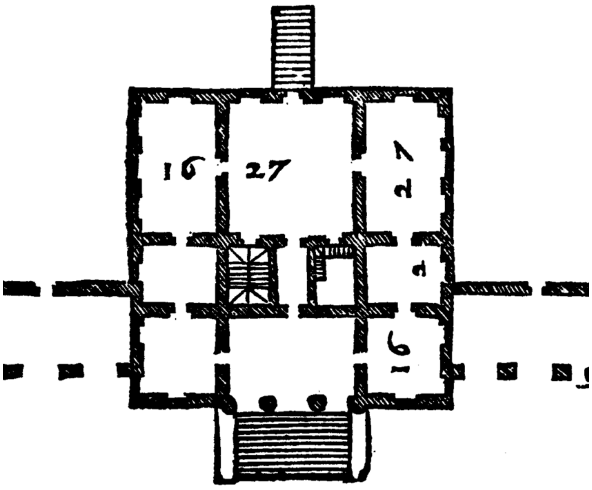


Fig. 2. Villa Emo, Fanzolo di Vedelago by Andrea Palladio, 1558.

Flexibility and adaptability within architecture is not a new idea. Habitable spaces have always had different activities going on within them. The first cave-dwellers probably didn't have one cave for sleeping, one for gathering and another for eating, but rather used their cave for all possible tasks. Alas, a flexible space was used. Over the centuries and millennia, dwellings have evolved, and new types of adaptable architecture have emerged. The Central Asian yurt or ger, formed by a latticework of lightweight bamboo or wood covered with skins or felt provided families with a home suitable for a nomadic lifestyle. This adaptable architecture provides the user with the possibility to move their home to different locations and create different configurations of houses.

Schmidt III and Austin (2016) argues that historically (before the arrival of modernism) one can divide western and eastern adaptable housing into two strategies. The western way of thinking promoted robust buildings, meant to last the wear and tear of time. Materials were durable, and the rooms were generous and similarly sized so that different activities could take place in every room. An example is Palladio's Villa Emo, one of many renaissance villas still standing, where sizable rooms are interconnected, providing ample possibility for program change.

In eastern architectural traditions, non-permanence has been the leading strand of thought. Japanese houses were traditionally based on the measurement ken (180 cm, with some regional variation). The size of a tatami mat would be 1x0,5 ken, and the measurement would also exist in the structure of the house. Loads would be transferred through posts and beams, leaving lightweight movable partitions to divide the indoor space into different room configurations. Using these lightweight materials, together with non-permanent connections and standardized measurements such as the ken permeates the eastern pre-modern architecture. This non-permanent way of thinking can be exemplified in the Ise Jingū shrine complex, which is rebuilt every twenty years. This calls for extreme flexibility in the architecture.

One of modernism's key principles was flexibility. Schneider and Till go as far as stating that "variable and flexible plan forms, for architects and clients alike, signified the true beginning of modernism" (2007, p. 17). A famed example is Le Corbusier's building system Maison Dom-Ino, which used slabs held up by pillars in its construction. This idea of the 'Open Space', to leave the architect (or the user) with the possibility to freely place interior walls and plan the room layout without the restrictions of load-bearing walls, was ground-breaking and opened up a new world within flexible architecture. (Bergdoll et al., 2008)

Fig. 3. Youkoukan Garden, Fukui, Japan. (663highland, 2008)

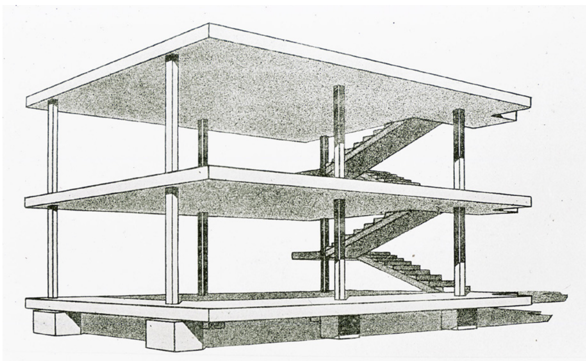


Fig. 4. Maison Dom-Ino by Le Corbusier, 1915.

2.2 Strategies

Several architectural theorists have tried to categorize flexibility within architecture. Different approaches have been tried, from the famous layers concept by Brand (1994) to the very practical and pragmatic book Flexible Housing by Schneider & Till (2007). Some of these theories, strategies and categorizations have been used in the thesis as inspiration for different ways to create a flexible building and is presented on the coming pages.

Diagrams of the different flexibility strategies are presented with short texts explaining them. Some of these categories also have corresponding reference projects in the appendix which have implemented these strategies.

2.2.1 Shearing layers

During the '70s, British architect Frank Duffy brought forward the idea of a building as "several layers of longevity of built components" (Brand, 1994, p. 12). He divided the building into four layers, *Shell*, *Services*, *Scenery* and *Set*. Stewart Brand (1994) continued this concept, adding and changing a bit to these layers, as shown in Fig. 5. This diagram with its set of layers has become widespread, being reused and adapted. The layers all have different lifespans, and a building should be designed with this in mind. Separating the layers makes change easier, as, for example, alterations to the space plan usually happen more often than the ventilation needs to be replaced, and these changes should be doable without affecting the services.

One development of the model is done by Schmidt III and Austin (2016), who added two more layers, *Social* and *Surroundings*, which deal with the activities going on around and within a building. This adds depth to the diagram, as the use of a building, and how that use varies, becomes more apparent.

The shearing layers concept occur a lot within flexible architecture and informs other theories on flexibility and adaptability.

A1 Cellophane House

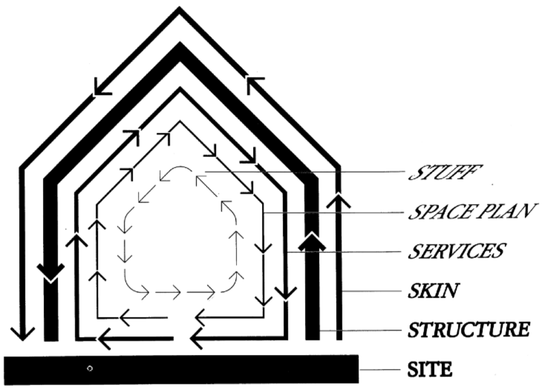


Fig. 5. Shearing layers of change (Brand, 1994)

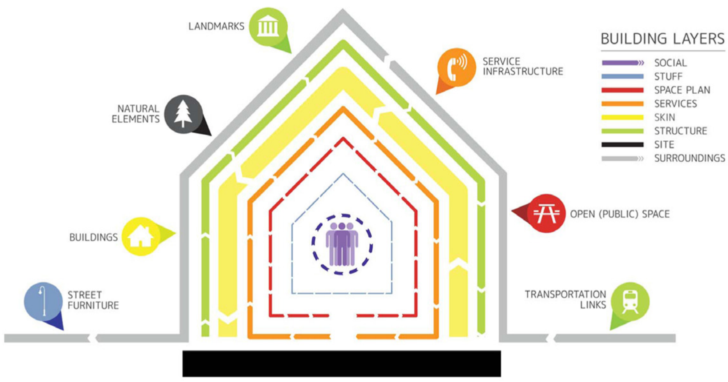


Fig. 6. Building layers model (Schmidt III & Austin, 2016)

2.2.2 Types of change

Schmidt III and Austin (2016) use the word adaptability rather than flexibility, but the basic idea is the same. In their extensive book Adaptable Architecture many categorizations, characteristics, typologies and design strands are mentioned. They list six ways that a building can adapt, six types of change: *Adjustable*, *Versatile*, *Refitable*, *Scalable*, *Convertible* and *Movable*.

An **Adjustable** house concerns itself with the *changing of task or user*, which may happen with rather high frequency in some buildings. Movable equipment, furniture and fixtures are some ways that this change might be catered for.

A **Versatile** building is one where the layout can be altered in a quick and easy way, a *change of space*. Partitions may be movable, and installations and water pipes could change place as well.

Refitable design is based on future physical changes, a *change of performance*. The building is planned to be refitted with for example a new façade or better insulation.

Convertible design is about the *change of use*. It's similar to the adjustable design, but with a longer perspective and larger changes, such as the conversion from office to housing. This makes demands on the building's service capabilities, floor capacity and storey height to mention a few.

A **Scalable** house is simply one that may grow when the need arises. Adding an extra floor or an additional wing might help execute this *change of size*.

The **Movable** building is a less common occurrence in our non-nomadic society. When society change, some places may lose their importance, and so the building may be moved rather than torn down, accommodating the *change of location*. A8 Snabba Hus

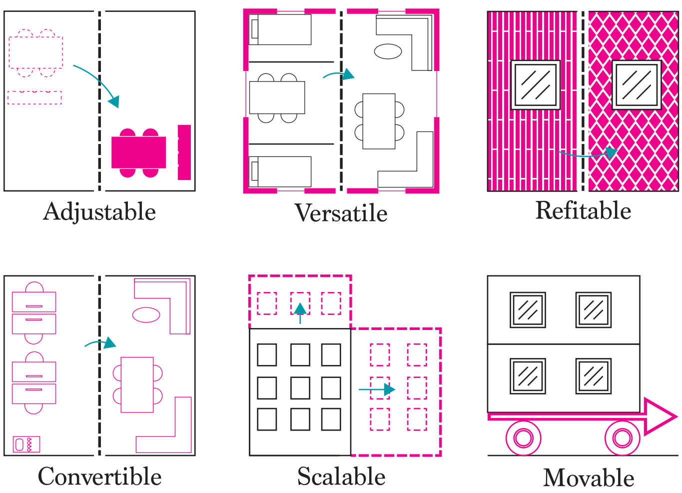


Fig. 7. Based on Schmidt III & Austin (2016)

2.2.3 Flexibility archetypes

Kim Young-Ju (2013) bases his arguments on flexible architecture on the writings of Herman Hertzberger and Aldo Rossi, reasoning that flexible architecture is to be found in the way a house is planned, within its form. These forms of flexibility can according to Kim be divided into three different types of floorplans: *Centripetal*, *Condensed/Released* and *Non-hierarchical*.

The **Centripetal** type of flexible architecture is based on a centrally located, multifunctional room or courtyard. The central space can generally be reached from most rooms of the house, providing the inhabitant with the possibility to use the centripetal room in different combinations with other rooms. This type has similarities to Tarpio's *Access through a hall* (Ch. 2.2.4), but the importance of this room is much more than just an entrance hall, and not necessarily the first room one reaches when entering a home.

Condensed/Released is a type of architecture where necessary functions such as bathroom, kitchen, stairs etc. are intentionally compacted to take up a minimal amount of space, leaving more released space which can be used for multifunctional spaces.

A7 Modulatorsgatan 15

Non-hierarchical plans have no hierarchy between rooms, and they can thus be used for different activities. The rooms will, when in use, always be on different levels of hierarchy, but this may change over time due to the non-hierarchical base plan. This type is closely tied to Tarpio's idea of *Route variation* (Ch. 2.2.4), as the spaces need to have various route opportunities to provide for hierarchical changes.

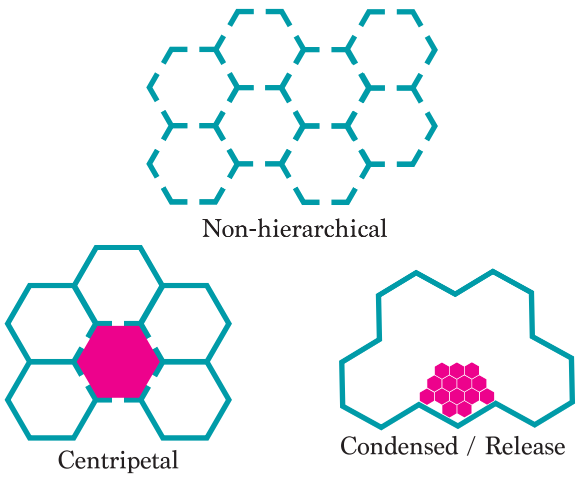


Fig. 8. Based on Kim (2013)

2.2.4 Spatial principles & logics

Jyrki Tarpio (2016) suggests different ways of categorising flexible architecture. In his work, he divides existing flexible architecture into four spatial principles; *Preform*, *Room series*, *Initial mass & places for growth* and *Volume*.

Preform is the idea of a space that may be used in several different ways, by dividing and subdividing the space to create rooms in different sizes and for various uses. This principle consists of two logics. *Flexibly dividable areas* entails an enclosed room which may be divided by interior partitions. A7 Modulatorsgatan 15 *Structural modularity* came to life with the emergence of load-bearing pillars holding up floor slabs. On these floor slabs, both interior and exterior walls may be placed as preferred. A6 Maison Dom-Ino

Room series consists of three logics concerning the movement within a dwelling, and how this affects the flexible use of rooms. *Route variation* gives the inhabitant the possibility to swap room functions, without having to take illogical or unnecessary routes through the dwelling. The same thinking is behind the *Access through a hall*, where a central space is used to reach all rooms. *Switchable rooms* is the idea of placing a room between two dwellings, and with minimal carpentry work changing which household the room belongs to.

Core and growth, a logic within the **Initial mass & places for growth** principle, is a way of constructing a building. A core, usually small but usable on its own, is constructed but with the possibility to expand the house over time. A11 Quinta Monroy

The principle of **Volume** holds the last logic, *Open plan*. Here, the division of a dwelling is divided in other ways than with walls. Examples of other kinds of demarcation used are furniture, character difference due to the placement of windows and ceiling height.

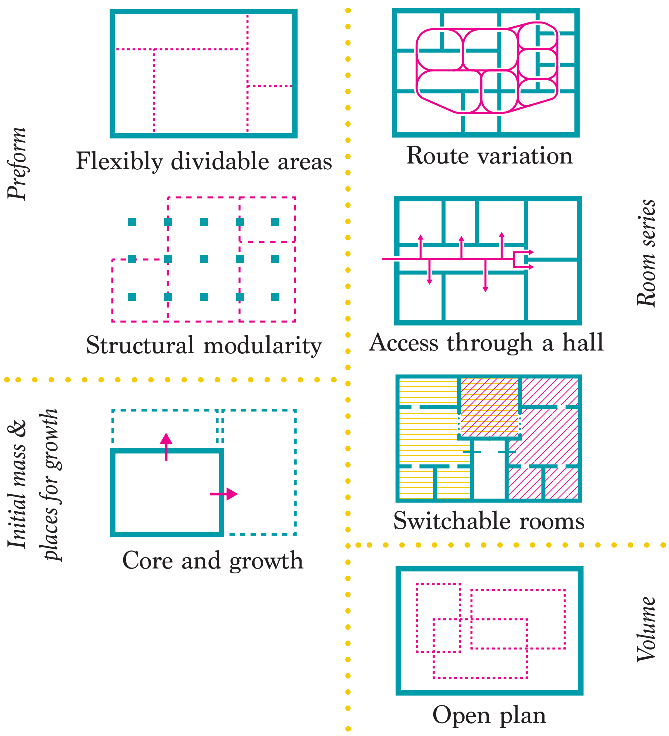


Fig. 9. Based on Tarpio (2016)

2.2.5 A manual for flexible housing
Schneider and Till (2007) set up several ways in which a building can be made flexible, categorised into different focuses and scales. The manual is straightforward and contains strategies of how a house can be made more flexible. It's divided into three categories, *Plan* (with sublevels *Building*, *Unit* and *Room*), *Construction* (sublevels *Principles* and *Building*) and *Services*.

Plan – Building concerns larger scale planning, how a building as a whole can be flexible. It includes *Additions - horizontal and vertical*, where possible extensions are included into the planning, both add-ons on top of the roof, new rooms in an attic or extensions to the side, front or back. *Communal circulation* can be important for flexible housing. A generous circulation space can make it possible with more people in the building without it becoming crowded. This can also provide the possibility to add more entrances or move existing ones around if the unit layout changes. *Slack space* is a way of constructing that leaves a certain amount of the building volume as an empty void. This can in the future be filled in by the inhabitant or the building owner. A11 Quinta Monroy

Plan – Unit is about the planning of the units within a building. *Functionally neutral rooms* are closely related to Kim's Non-hierarchical spaces. Having rooms in similar sizes, where the route is not set, leaves the user with the possibility to change the function of the rooms. Widening *Circulation* – corridors and passageways – is a great way to create useful space rather than just wasting it. *Joining* and *Dividing up* are opposites of each other. Planning dwellings with so-called soft sections in partitioning walls as well as thoughtful placement of services, kitchen and bathroom can make it possible to change apartment sizes with few alterations. The idea of a *Shared room*, identical to Tarpio's *Switchable rooms*, is a room that can be swapped between two different units, creating the option of adding or taking away one room from the dwelling with little work. The *Service core* is based on the same idea as Kim's *Condensed/released*, where necessary dwelling functions such as kitchen and bathroom are compressed, to make open space for other functions. A7 Modulatorsgatan 15 Lastly, *Raw space* is the idea of leaving the dwelling unfinished. The occupants can then finish on their own, making the space just as they want it. When a new occupant takes over the space, it can be returned to its original raw state.

Plan – Room goes into even further detail in the design. *Connections between rooms* are important as they can provide the user with the opportunity to use two rooms simultaneously, or close them off, for example, a studio and a bedroom. *Foldable furniture*, commonly a bed, can be a great way to create space free for use. *Movable and sliding walls* can similarly provide the user with new spaces, quickly adding an extra room for guests, or enlarging the kitchen. A3 Drömlägenheten *The divisible room* can, for example, be a master bedroom that can be turned into two smaller rooms. The placement of entrance and windows is important for this to work.

Construction – Principles is as important as the plan design. *The frame* can be a way to construct a building so that infills can be used in different ways. The frame could be a post-and-slab construction or perhaps a bearing core one. *Layers* are based on Brand's idea of shearing layers, which is discussed earlier (Ch. 2.2.1). *Simplicity & legibility* is important in the long-term perspective, as the overuse of specific solutions such as specialized joints might impair the possibility to do changes in the future if these joints no longer exist on the market, or if the skills needed for certain details are lost. Easy *Disassembly & exchangeability* is also important. Using screws and nuts rather than nails makes it easier to separate later and does not do any damage to materials. Having the joints visible or at least easily accessible is also good for easy disassembly. A1 Cellophane House

Construction – Building set up a few parameters that make the building more flexible. *Clear spans* make non-loadbearing internal partitions possible, which can then be moved around within the span.

A8 Snabba Hus Making the *foundations* extra bearable for future additions as well as allowing forces to go down into the foundation in different places can help future changes and additions to the building. *Partitions* should not be load-bearing and preferably not have water or electricity running through them, so they easily can be moved. *External walls* are more seldom changed than internal partitions but may still have to undergo renovation. Having the possibility of moving doors and windows can make the building more flexible. A5 iValla The *Roof construction* is important when it comes to vertical additions and should be designed with this in mind. Flat roofs are generally easier to add to than pitched. *Over-capacity* ensures that the building can withstand built additions and increases in load.

Services are very important but easily forgotten. They can become a hindrance if done incorrectly. *Vertical distribution* and the placement of shafts defines where kitchen and bathroom will be places and must, therefore, be thought through. Planning for *Horizontal distribution* is also a vital aspect. Avoiding placing installations in walls (which will obstruct moving said walls) but rather adding a raised floor adds flexibility to a project. A5 iValla Providing *Heating* without using radiators with water in them will also make changes easier, as pipes will not have to be moved. *Lifetime considerations* of the services include the placement of electrical sockets, switches and ventilation control, so everyone, regardless of age or mobility constraints can access them easily.

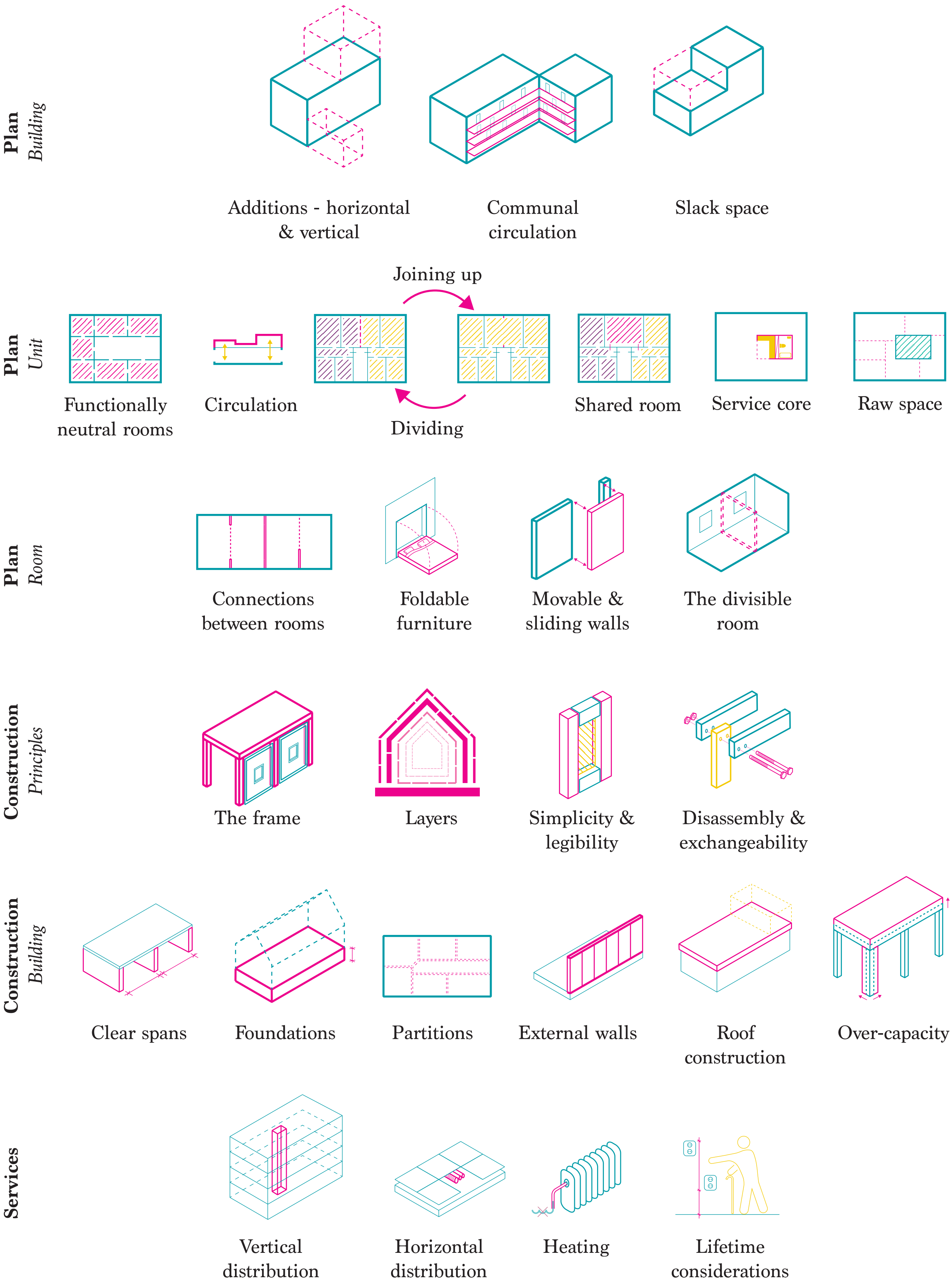
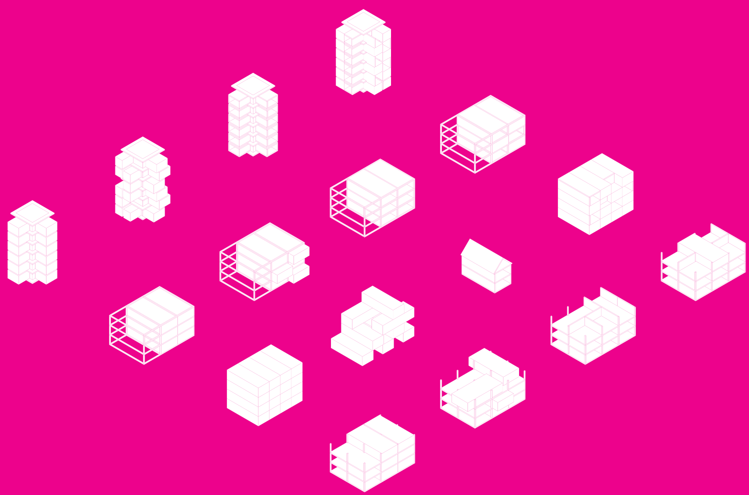


Fig. 10. Based on Schneider & Till (2007)

3. Prefabrication



3.1 Background

Building houses without any level of prefabrication is all but impossible. A wooden beam is prefabricated as it is cut from a log, a brick is shaped and burnt, even a screw goes through a long process before arriving at the building site. Steinhardt et al. (2013) have sorted prefabricated construction by defining the level of prefabrication of the material arriving at the building site, as shown in Fig. 11. This thesis will mainly be focused on the levels of *Modular, Pods* and *Panels.*

Prefabricated construction can be very useful if incorporated into the building process correctly. Li et al. (2014) list benefits such as improved quality control, less waste when building, noise and dust reduction on site, higher standards for health and safety and savings in both time, cost and material. As on-site building has been the common way of building for hundreds or even thousands of years, the processes has been honed to a speed sometimes even greater than the one of prefabrication (Knaack et al., 2012). This is not necessarily an argument against construction through prefabrication, as this technique still has lots of improvement potential.

A higher level of prefabrication may collide with the main focus of this thesis, flexibility. Volumetric modules equipped with everything from the start and constructed to fit into one type of building may prevent future changes to take place, as walls may be loadbearing and services unmovable. However, the pros of cheap, efficient construction may outweigh the cons named as a low-cost construction can make up for raised costs due to added flexible strategies. Schneider & Till (2007) warn against the use of volumetric modules as they can be hard to adapt but point out that simple, clear and modular construction also can help a project reach flexibility. They argue that many successful flexible projects use few, similar parts in their construction.

Level of prefabrication	Type	Definition
High	Complete	Box-form, volumetric, completed buildings delivered to a building site
	Modular	Structural, volumetric, potentially fitted-out units delivered to site and joined together
	Pods	Volumetric pre-assembly. Fully fitted-out units connected to an existing structural frame such as bathroom or kitchen pods
	Panels	Structural, non-volumetric frame elements which can be used to create space, such as Structural Insulated Panels (SIPs), precast concrete panels and structural wooden panels
	Component sub-assembly	Precut, preassembled components such as doors, and trusses not feasible to produce on site
Low	Materials	Standard building materials used in onsite construction

Fig. 11. (Based on Steinhardt et al., 2013)

3.2 Methods

Prefabrication methods are, just as flexibility strategies, subject to various attempts of categorization as a way of better understanding the possibilities. Based on Albus (2018), Knaack et al. (2012) and Bergdoll et al. (2008) a categorization suitable for this thesis was created. Prefabrication techniques were divided into two distinguishers: **Bearing structure** and **Partition typology**. These distinguishers were then subdivided.

Common and existing **bearing structures** found in literature and projects can be divided into *Core*, *Post-and-beam*, *Self-bearing* and *Slab construction. Core* is a load-bearing centre with services, elevator and staircases. Outside of this, additional elements are added. *Post-and-beam* consists of, as the name implies, posts and beams in between which infill elements are placed. Under this category, load-bearing walls instead of posts are included. *Self-bearing* buildings are ones where the partitioning elements are also the ones which take the load. Slab construction consists of posts (or load-bearing walls) holding up slabs on top of which partitioning elements may be placed.

The **Partition typology** is divided depending on the level of prefabrication of the partitioning elements, and the way that they are placed. It's divided into *Volume modules (regular stacking), Volume modules (irregular stacking), Flatpack* elements and *Combined (volume & flatpack). Volume modules* are fully furnished volumetric modules preassembled in a factory and delivered to the building site, where they can be placed in a *regular* or *irregular* fashion. *Flatpack* elements can be wall panels or floor cassettes which are added to the structure on site. These can also be *combined* to form a fourth option.

These two distinguishers and their subdivisions were placed into a matrix (see Fig. 12), generating 16 possible prefabrication typologies. Through a reading of earlier mentioned literature 10 of these were found to have corresponding projects, some of which are shown on the coming pages and some that occur in the appendix. A further analysis of these prefabrication typologies in regards to the project can be found in the process chapter (Ch. 5.2).

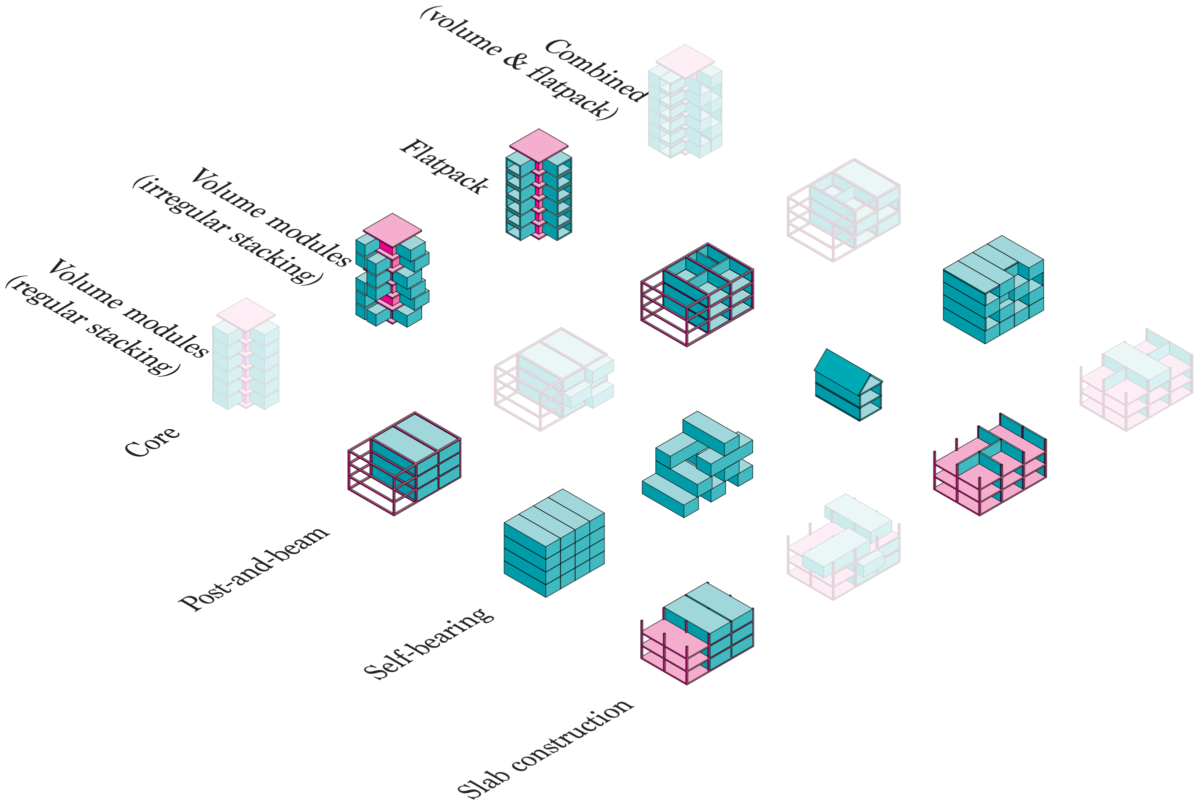
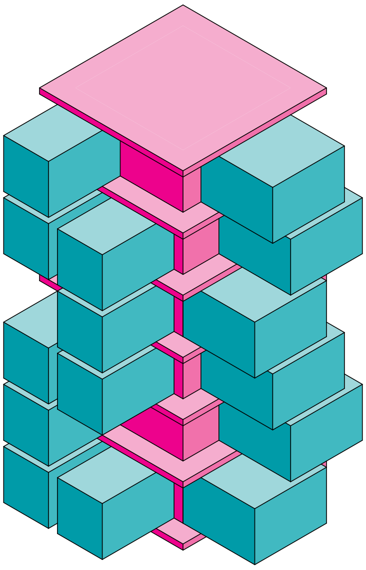


Fig. 12. Matrix of prefabrication techniques.

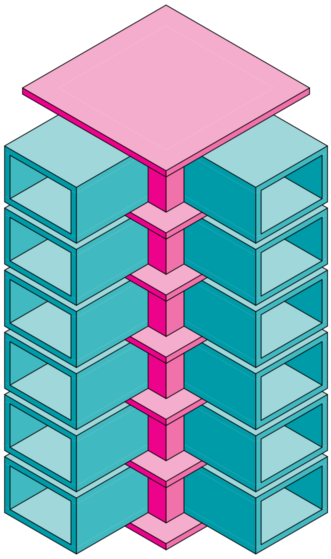
3.2.1 Core / Volume modules (irregular)
Load-bearing core as a first structure. Volume modules are added in an irregular pattern.



Nakagin Capsule Tower, Tokyo - Kisho Kurokawa
A central structural core, 14 stories high, with identical modules or pods plugged into it, in varying angles. Despite the pods being replaceable, nothing has changed since its inauguration in 1972.

Fig. 13. Nakagin Capsule Tower (Kakidai, 2018)

3.2.2 Core / Flatpack
Load-bearing core as a first structure. Flatpacked floors, façade elements and inner walls are added.

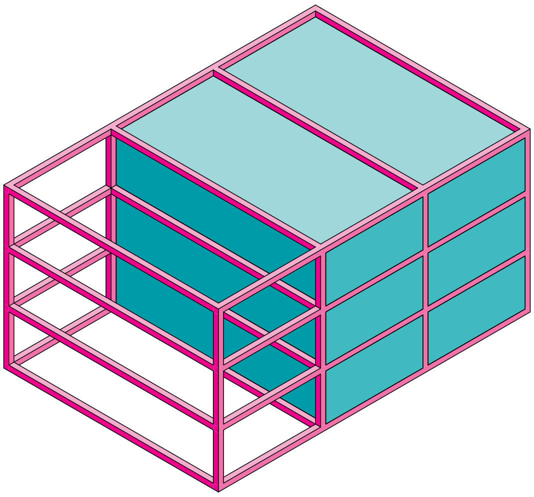


Norra Tornen, Stockholm - OMA
A core, with services, stairs and elevators. On the outside, flatpack elements form the rooms and façades.

Fig. 14. Norra Tornen (Ellgaard, 2019)

3.2.3 Post-and-beam / Volume modules (regular)

Load-bearing posts and beam as a first structure. Volume modules added within.



Takara Beautilion Pavilion, Osaka - Kisho Kurokawa

For the Expo ‘70, Kurokawa created a Metabolist pavilion. The bearing structure is made up of identical steel elements, bolted together. Modules are placed into the structure.

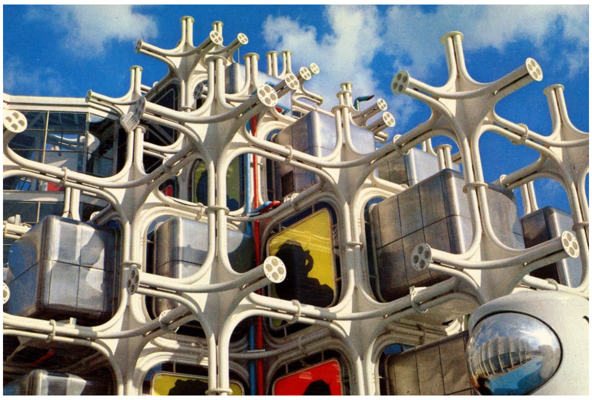
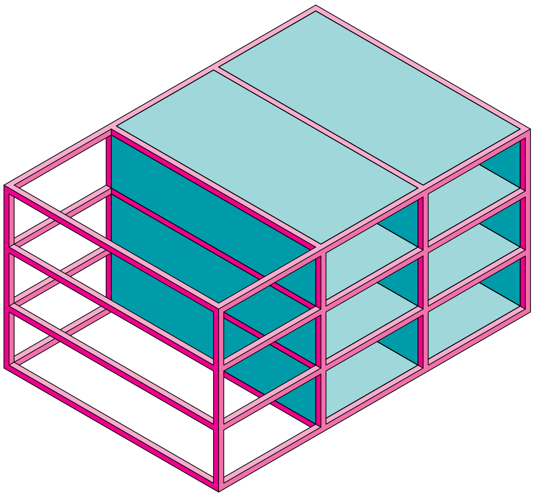


Fig. 15. Takara Beautilion Pavilion (1970)

3.2.4 Post-and-beam / Flatpack

Load-bearing posts and beam as a first structure. Flatpacked floors, façade elements and inner walls are added.



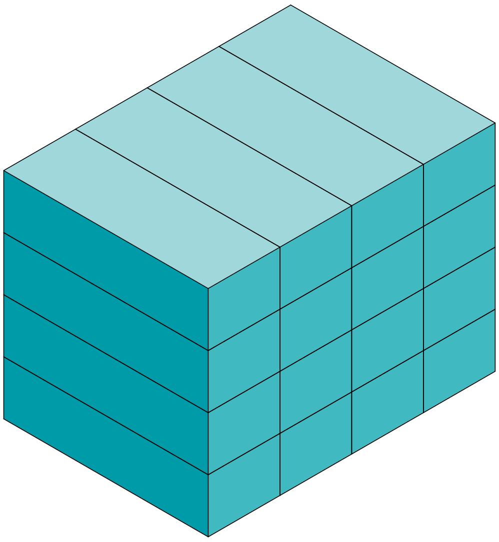
Mini Sky City, Changsha - Broad Sustainable Building

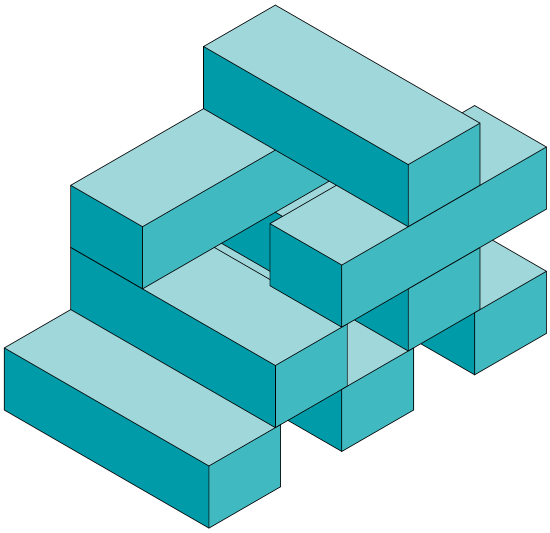
A 57-storey skyscraper built with flatpack construction, both in the post-and-beam and the floor and wall elements. The two key components are the bearing steel components and the prefabricated floor slabs (12x2m) with preinstalled air ducts, electric wiring and plumbing. Outer walls are added afterwards, also as panel elements.

Fig. 16. Mini Sky City (World Economic Forum, 2016)

3.2.5 Self-bearing / Volume modules (regular)
Prefabricated volume modules, stacked on top of each other in regular patterns.

3.2.6 Self-bearing / Volume modules (irregular)
Prefabricated volume modules, stacked on top of eachother in irregular patterns, leaving the gaps empty.





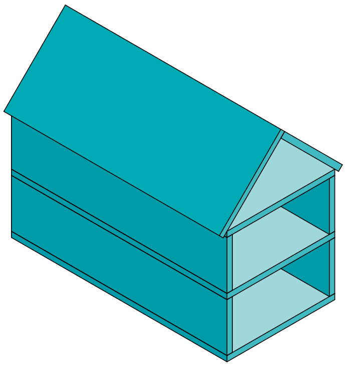
Flexator building modules
Simple modules, stacked on top of each other, with load-bearing walls on the short sides and within the modules.

Fig. 17. Loftgångshus, Åsa (Flexator AB, 2017)

A4 Habitat '67

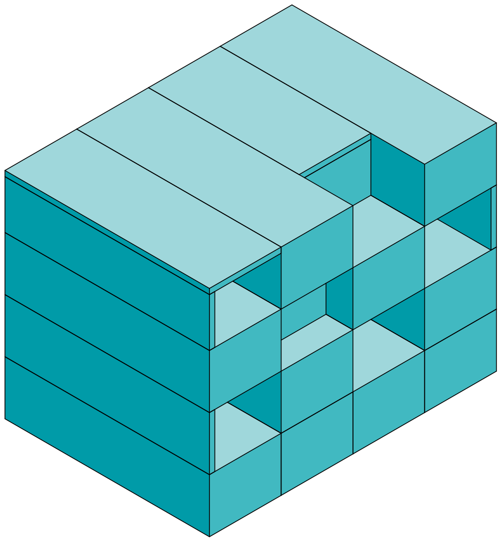
3.2.7 Self-bearing / Flatpack

Prefabricated flatpacked elements, put together on site to a building.



3.2.8 Self-bearing / Combined (volume & flatpack)

Prefabricated volume modules, stacked on top of each other in irregular patterns, combined with flatpack elements to fill up the gaps.



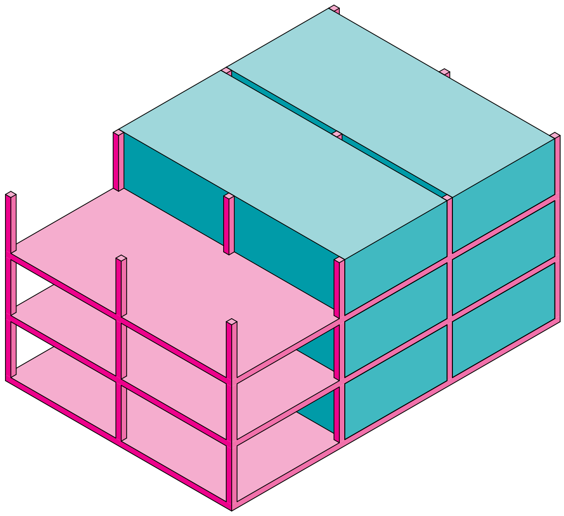
Balloon frame systems

Old, well spread system, with simple, wooden stud-and-beam walls, floors and roofs.

Fig. 18. Balloon frame in Katy, Texas (Jaksmata, 2008)

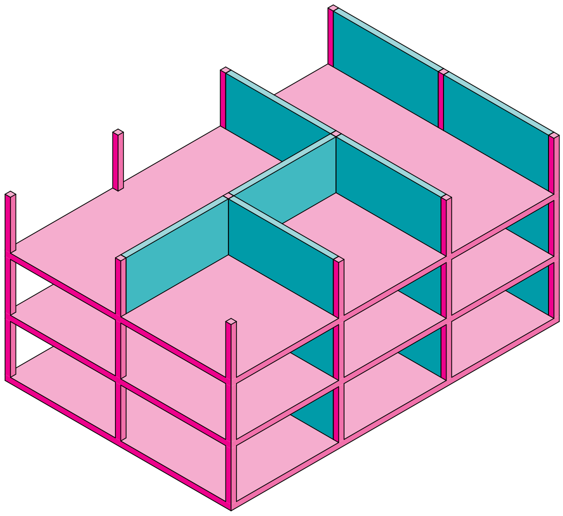
A2 Dortheavej Residence
A9 STACK II
A10 Stadtgemeinde Hallein

3.2.9 Slab / Volume modules (regular)
Prefabricated volume modules, placed onto a floor slab held up by pillars/bearing walls.



A8 Snabba Hus

3.2.10 Slab / Flatpack
Large slabs supported by pillars/bearing walls. Prefabricated panels are used for outer and inner walls.



A5 iValla
A6 Maison Dom-Ino

4. Scenarios

4.1 Background

These four scenarios were described in the research project "Bortom BNP-tillväxt: Scenarier för hållbart samhällsbyggande" [Beyond GDP-growth: Scenarios for sustainable building and planning]. Information has been taken from the final report of the project as well as podcasts, interviews and reports connected to the project. More information can be found at the website of the project: http://www.bortombnptillvaxt.se/

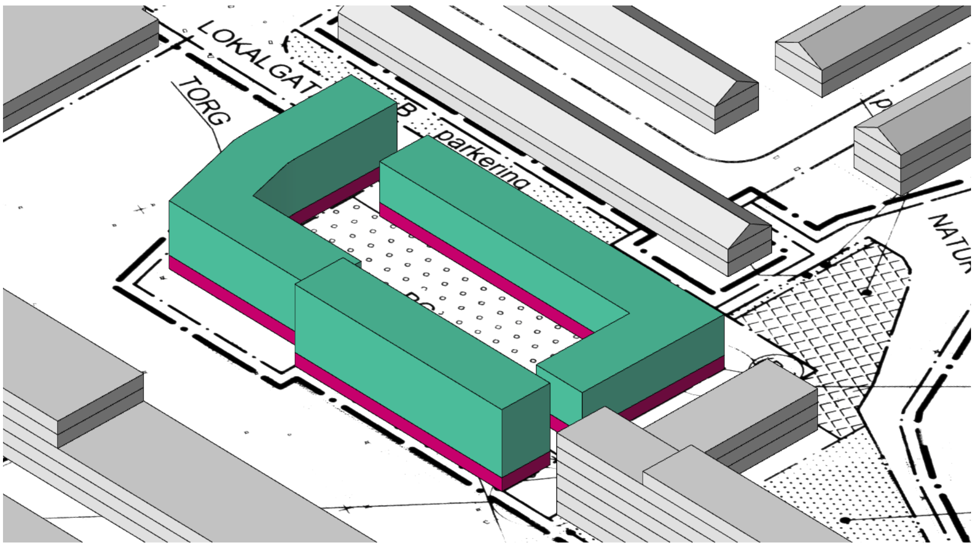
The information under the subtitles *Background*, *The built environment* and *Materials & techniques* as well as the subchapter *Scenario comparison* is taken from the sources mentioned above. The stories exemplifying the scenarios and the information under the subtitle *Program* are products of the thesis work. The *Present day* program is from the detailed development plan from the municipality of Gothenburg.

4.2 Present day

Program
Appr. 140 apartments, mix of apartments for singles, couples and families.

2800 m^2 footprint
10600 m^2 gross floor area for apartments
2800 m^2 gross floor area for services etc.

The site consists of an almost closed block, with two accesses from the street. The west façade faces a square to be and will have public premises on the ground floor, shops, cafés and similar. The south façade faces Artillerigatan, which is planned to become a street with more city life, rather than the transport road it is today, dominated by the closed-off tram tracks. The buildings will be 4-6 storeys.



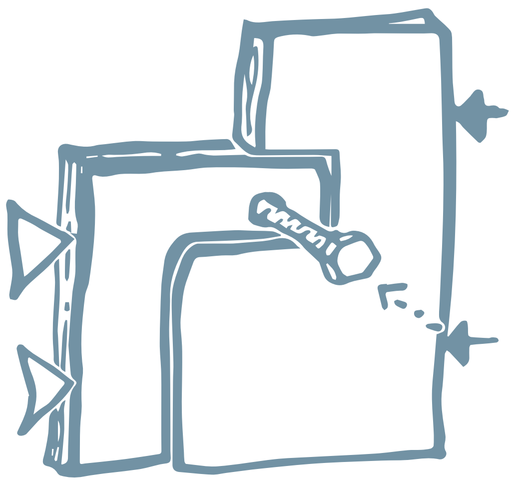
4.3 Collaborative economy

Coming home after a day's work, you walk into your house. You're met by the bustle of people in the open spaces you're walking through towards your staircase. The activity is high, and the machines are running full speed. The air is filled with sawdust, and the smell of glue, garlic and machine oil. A woman from the apartment building down the street is cutting out pieces for a kitchen table in the CNC-milling machine, and your next-door neighbour is cutting out pieces for a new shirt. One of the open kitchens is already full of activity, a group of friends are cooking dinner, and a few people from the building has decided to join.

On one of the common computers, your craft-skilled friend is discussing the construction of a hand-powered drill with some unknown person from Indonesia, connected over the web by their common interest and goal. You wave, but he's engulfed in the details of some kind of connecting piece, so you continue on.

You walk up the stairs two steps at a time, before entering your two-storey apartment which you share with two families with children, a young couple, and a woman your age. Both of the families are already eating, the last months they've been taking turns in cooking for all the kids, leaving time for other things. You greet them and say hi to the couple on one of the couches, before heading up the open staircase to your room.

You have one room that is just your own, with a bed that turns into a sofa daytime, and a big, ornate desk that you let the laser cutter downstairs cut out the pieces to, and which your neighbours helped you assemble. You know that other people have more bigger private spaces, but you are fine with the little you have. You don't have use for much storage, since you share most things with your flat mates or the rest of the house. On the clothing rack hangs the most recent finds from this month's visit at the clothes library.



Background

In the “Collaborative economy” scenario, people have become increasingly aware of the dark side of consumption, with resources being depleted and the bad conditions for workers abroad. This has resulted in lowered consumption and a sharing society, where products are borrowed, shared and rented between individuals. These types of interactions occur between private persons rather than with companies, what once was competition is now cooperation. Many people are *prosumers*, both producers and consumers at the same time.

Digitalisation has an important role in society, collaborations aren’t necessarily local, but can span the globe. Time banks are used to control the higher amount of voluntary work put into collectives and production units, that has replaced some formerly paid services. These units work as an extended family, looking after children and helping the elderly. (Hagbert et al., 2018)

The built environment

Since society is further digitalized, location is not as important as previously. Creative clusters form, so that the sharing of physical objects and tools can be done, and the city has been densified. Each individual has less personal space, and cohousing is a common occurrence (Francart et al., 2018). Collective spaces are shared by residents in the same building or the same part of the city, depending on how the function of the spaces.

Materials & techniques

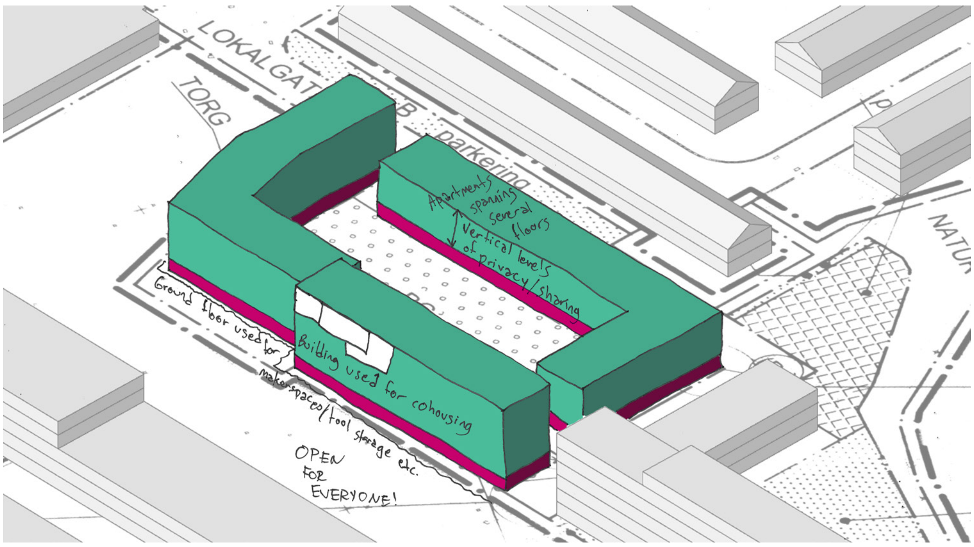
Wood is the most used material, even though most construction processes and materials are still in use. Materials are rarely moved longer distances and differ from region to region.

Program

Appr. 60 apartments, different sizes of cohousing with 14m^2/person on average.

2800 m^2 footprint
10600 m^2 gross floor area for apartments
2800 m^2 gross floor area for services etc.

A building with cohousing. Different sizes of cohousing will be available throughout the plot. Housing units will be both apartments on one floor, as well as several storeys connected, for different levels of cohabitation. The ground floor will be used for open/public maker spaces, storage for common tools and machines and collective living areas. The building will be open for members of the community, to some extent.



4.4 Local self-sufficiency

The last sun of the day shines through the glass panes of the rooftop greenhouse. This particular section of the greenhouses is your favourite, the smell of the ripening tomatoes is intense this time of year. You're happy to be home after a week at your cousin's place, helping them harvest a third of this year's crops. His house is very similar to your apartment, since it's constructed by parts moved from the city. It's been added on over the years, with verandas and workspaces stretching over the plot.

Tired after long days outside, you're happy to be home with plenty of corn, courgette and beans. You're picking tomatoes so you have something to swap and sell at the market on the square below your kitchen window this weekend.

Back in your apartment you're helping your brother with the dinner. The courgette is already coming handy. Almost all you eat is from the area, even though you do treat yourself to some coffee and olive oil. During the evenings you gather in the living room, talking to your family and your friends before they each retire to their own bedrooms. You usually stay up the latest, enjoying the calm that settles in your shared apartment, but tonight you go to bed first of all. Before that however, you walk through the apartment, taking stock on the chillies growing, picking of a few that you could sell together with your tomatoes.

Background
Globalisation and urbanisation have come to a halt. The municipalities and citizens are the decision-makers, and most decisions are made locally. Import is very small, diets are based on what's grown locally and people rarely travel. People made the decision to live this life to live within the boundaries of nature and the eco-systems. Open source knowledge, DIY and self-organisation within the local community are key elements in the configuration of society. (Hagbert et al., 2018)

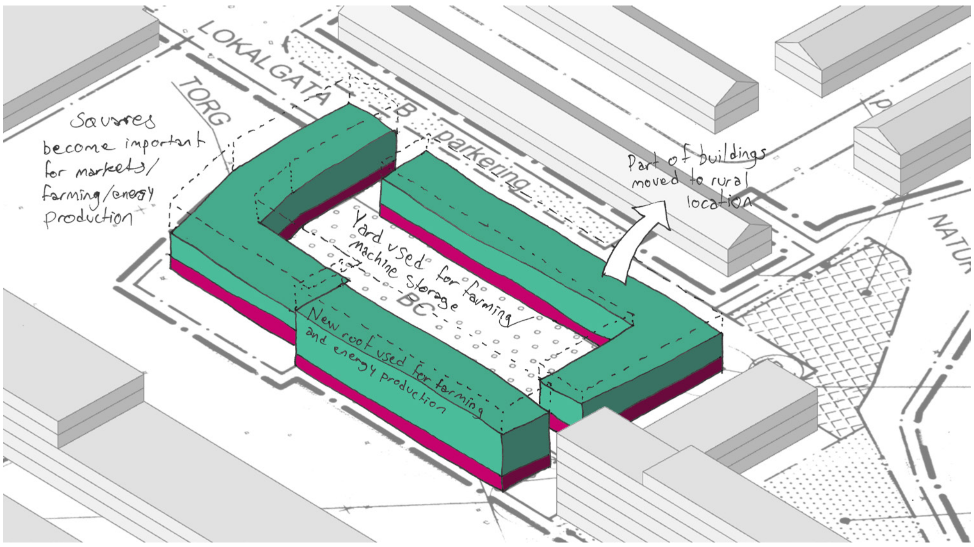
The built environment
The family has grown, with relatives, parent, grandparents and friends living together. They collect in smaller clusters, with living spaces being quite large compared to the other three scenarios. The big cities are less populated, with people moving to the countryside where food and materials may be produced. Existing infrastructure is being maintained, but improvements are local and done when the need arises. (Hagbert et al., 2018)

Materials & techniques
Local materials are almost exclusively used. Examples are wood, straw bale and clay. PV panels and solar heating are used, and other technological innovations may be reused or repurposed. Few new technologies are being developed. Construction processes are simple. (Francart et al., 2018)

Program
Approximately 30 apartments, mostly for families together with extended family or friends, on average 20m^2/person.

2800 m^2 footprint
5000 m^2 gross floor area for apartments
2800 m^2 gross floor area for services etc.

The two top floors or its equivalent in volume will be removed from the buildings. These will be moved to the countryside to be used as extended family dwellings and should work as such. The apartments will mostly be for larger groups of people. What area is still available (roofs, yards, part of squares and green areas) will be used for the production of food and energy. The bottom floor will become places for production and some co-living spaces.

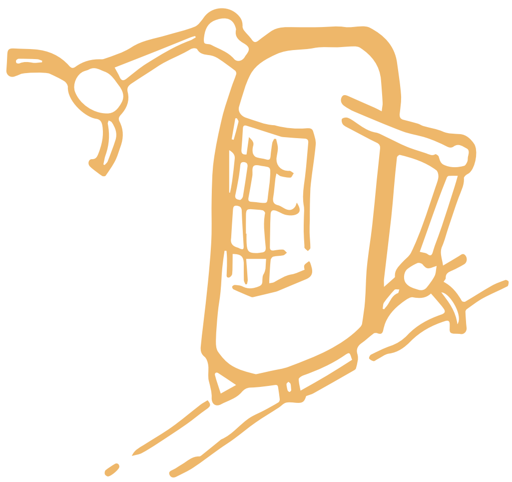


4.5 Automation

You climb out of the PRT (Personal Rapid Transit) rail car as it stops next to your house. Today has been one of your two official work days this week, so you feel you've contributed to society. You oversee the automated hydroponic farming systems on the outskirts of the dense central core of Gothenburg.

The two bottom floors of your house are unsparingly decorated with 3D-printed ornaments made of wooden composites, bioplastic polymers and microbial materials, technology that used to be far beyond your level of comprehension. Now, however, you're taking online classes in your spare time, in the manufacturing of such materials. Many people use their spare time on art projects or physical activities, but you've always fancied technology. In the common areas, there are several multi-purpose rooms, where both kids and adults can play digital VR games or use for other activities.

Your rooms stand in stark contrast to the homely and ornate common rooms downstairs. It's small, one multifunctional space, with smart technology incorporated in every detail. Many days you order food, nutritious, cheap and quick, which comes by automated delivery. Today however, you'll be using one of the downstairs kitchens, since you don't have one in your apartment and your friends are coming over for dinner.



Background

Robots, computers and digital technology have replaced humans in many work areas. Political decisions have led to people having more free time and enough wealth, rather than having to worry about being out of a job. People spend more time with friends and family, often in nature and the parks of the city. Most aspects of life have a degree of automation in them, and objects are connected in networks. Materialistic consumption is low, and most production is automated, with services and products being imported and exported. (Hagbert et al., 2018, p. 23)

The built environment

Due to digitalization and automation, people can spread out over the country, even though most people live in bigger cities. The built environment is very dense, and people have small but highly efficient dwellings with automated functions. (Hagbert et al., 2018, p. 23) Household varies in size and structure (Francart et al., 2018, p. 7). In combination with these dense housing areas, there are several green areas, parks and playgrounds, where the residents can spend their free time close to their homes. The border between home and spaces for recreation is loose, with lots of flexible spaces for common activities. Infrastructure is based on public transport, biking and walking. (Hagbert et al., 2018, p. 23)

Materials & techniques

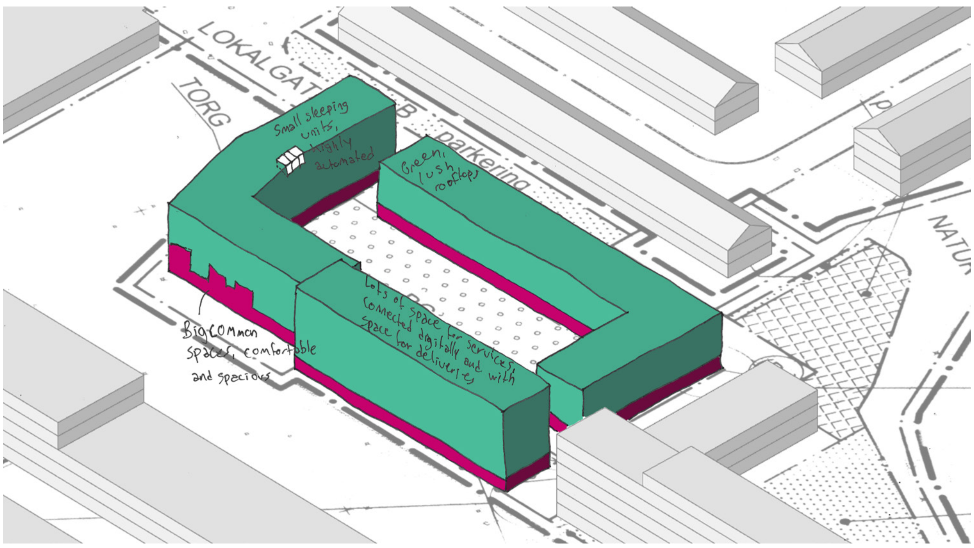
Construction processes are highly innovative, with complex techniques such as 3D-printing coupled with new materials. According to Francart et al. (2018, p. 7), "savings are mostly due to improvements in process efficiencies, not necessarily improved recycling".

Program

Appr. 190 apartments, mostly very small, some cohousing, all sharing large common areas.

2800 m^2 footprint
10600 m^2 gross floor area for apartments
2800 m^2 gross floor area for services etc.

The house will become densified, with small living units, perhaps just for sleep/rest and hygiene. The bottom floor, or even the bottom two floors, will become spacious common areas, where people can spend their free time. Since digital activities will be common, rooms for this should be available. Many things will be automated, and the services for this should be thought of. "Smart" solutions will be bountiful.



4.6 Circular economy

Before cooking dinner, you bring down the broken kitchen chair to Circulation, scan its bar code and attach the newly printed sticker to it. The system then sends a message to the manufacturer, who will pick it up the morning after and return it as good as new in the evening.

The concept of ownership hardly exists anymore. The chair belongs to its manufacturer, who runs the rental service, providing your kitchen with furniture. The clothes on your body you did buy, but they will be returned to the circular system once you no longer need them. Most likely they'll become someone else's clothes until they're eventually threadbare, the fabric then continuing its life in some other useful way.

Circulation is filled with interesting objects and materials. Some are free to take, to reuse and upcycle into something else. If no one takes it, the state recycling programs will eventually take care of it and put it to good use.

After dinner it's time for your weekly dance class, a nice hour where you can meet people and enjoy your time together, and then return the calm of your own apartment. It's small, but you like it anyways. Apart from dance, you go swimming and outdoor rock climbing every week, as well as take classes in how to cook with algae.

Background
This scenario is the one closest to what our society looks like today (IVL Svenska Miljöinstitutet, 2018). Waste does no longer exist, everything is being reused, repurposed or, as a last resort, recycled. Materialistic consumption is low, green, sustainable services and activities are status markers in the circular society. The state has an important role, promoting and rewarding sustainable innovation and resource efficiency, as well as introducing laws to prohibit non-sustainable activities and production. (Hagbert et al., 2018, p. 25)

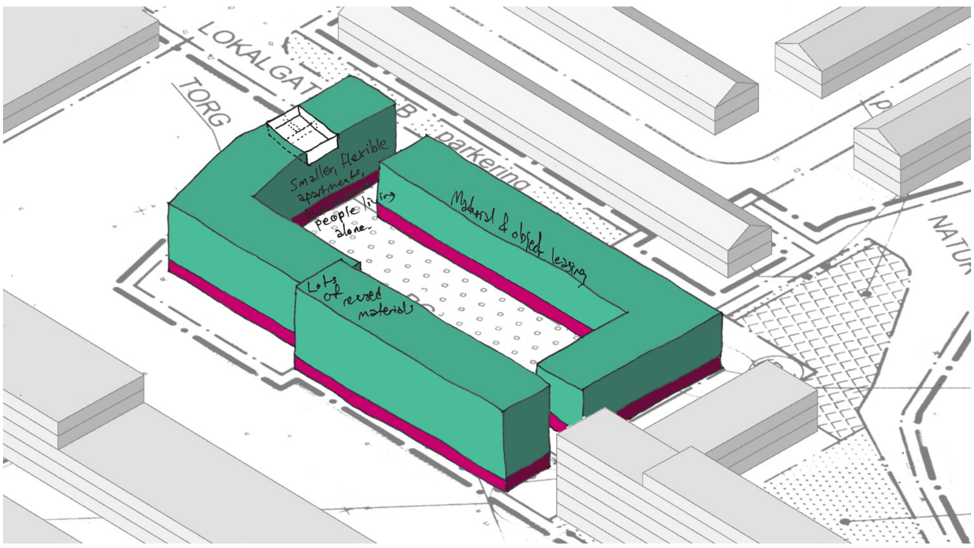
The built environment
Most people live in the big city regions. The connection between urban and rural is important. The cities are densified, and the countryside provides crucial ecosystem services, food and other goods. (Hagbert et al., 2018, p. 25) Overcrowding norms are changed to decide the lowest level of heated residential area per person, to stimulate a more efficient use of housing. Household sizes follow current developments towards more people living alone. (Gunnarsson-Östling et al., 2017)

Materials & techniques
Concrete continues to be prevailing. Materials are recycled and reused to a very high degree, and some technological improvements are made. (Francart et al., 2018, p. 7)

Program
Appr. 180 apartments, many single, on average $26m^2$/person.

2800 m^2 footprint
10600 m^2 gross floor area for apartments
2800 m^2 gross floor area for services etc.

Apartments are similar to today, although smaller in both household size and area. Everything should be able to be reused. Recycling will take up more of the ground floor, both for the residents to use themselves and for the state-run recycling programs to use. Activities rather than shops will take up space on the ground floor.



4.7 Scenario comparison

	Collaborative economy	Local self-sufficiency
Materials	Mostly wood, but most other materials are still used to some extent.	Local materials; wood, straw bales and clay.
Building techniques	Some more technical construction techniques available, but mostly locally sourced. Ideas for low-tech construction are spread quickly online, with makerspaces providing help and knowledge for all.	Simple on-site, construction methods, without high-tech tools. Knowledge will be available online, but few experts will be around.
Urban/rural	People cluster together for production, often in medium-sized cities, even though the bigger ones still attract people. The clusters are connected in networks.	People move to the countryside to be closer to means of production and farming. In the city, which are becoming less populated, empty areas are used for food and energy production.
Living constellations	Co-housing is very common, and a lot of spaces are shared, in houses or neighbourhoods.	Groups of friends and extended family live together, taking care of production as a group.
House types	Single-family: 22,25% Multi-family: 30,75% Cohousing: 47%	Single-family: 74% Multi-family: 7% Cohousing: 19%
Household sizes	Single person: 15% Two persons: 30% Family/group: 55%	Single person: 5% Two persons: 15% Family/group: 80%
Floor area per person	Single-family: 50m^2 Multi-family: 26m^2 Cohousing: 14m^2	Single-family: 43m^2 Multi-family: 30m^2 Cohousing: 20m^2
Location of time spent	Regular work week, but a lot of it voluntary for different organisations and collectives. Time banks are used.	Long work week, and other time spent in or close to home.
Production	Close to housing, in collaborative spaces, with many actors involved. Usually for the local market.	Close to housing, fitted to what the community needs.
Consumption	People rent, borrow, lend, swap and share, rather than buying for themselves. Less material consumption, but more digital, and same level as today of activities.	The little consumption happening is local, but often people create what they need on their own, or together in the local community.

Automation for quality of life	Circular economy in the welfare state	Present day
Materials that can be used by machines: CNC wood, 3D-printed polymers, metals, bioplastics and high-tech materials. (Reichental, 2018)	Concrete is still used a lot. All materials are reused or recycled.	
Automated processes, 3D-printing, highly innovative technologies. Construction and upkeep can also be robotized. Housing is smart and small.	Similar construction methods to today, renovations for energy performance are common and often state-driven. Technological improvements, especially in reuse and recycling processes. Apartments are flexible, and material and object leasing is common.	
The bigger cities are mostly populated, where the highly automated centres exist.	Mostly in the bigger cities.	
Smaller living conditions with common spaces for an abundance of free time.	Following the trends of today, people often live alone.	
Single-family: 8,5% Multi-family: 73,75% Cohousing: 17,75%	Single-family: 16,5% Multi-family: 83,5% Cohousing: 0%	Single-family: 42% Multi-family: 58% Cohousing: 0%
Single person: 30% Two persons: 30% Family/group: 35%	Single person: 45% Two persons: 35% Family/group: 20%	Single person: 17% Two persons: 25% Family/group: 58%
Single-family: 38m² Multi-family: 20m² Cohousing: 14m²	Single-family: 53m² Multi-family: 26m² Cohousing: None	Average: 42m²
Very short work week, lots of time spent in common areas in house and outside. High-tech travel possible.	Regular work week, free time spent on activities in the region and home.	
Separated from housing, with the state and experts doing most work.	The state, in close collaboration with producers, decides how and what to produce, with reused resources.	
Less material consumption, but a lot more digital consumption, as well as digital equipment. Since lots of time is spent in and around the home, people spend energy in creating a comfortable home.	Consumption is mostly connected with services and activities rather than material consumption, with the sustainable choices giving the highest status.	

5. Process

5.1 Method

The backcasting scenarios are the guiding light of the design process, influencing all design decisions, either through more formal tryouts or through sketching with the scenarios in mind. One of these tryouts are shown here as an example.

Early on, the use of prefabricated modules made from cross laminated timber slabs was decided. The CLT modules have the upside of being able to act as load-bearing elements as well as rooms.

5.2 Tryout #1 / Prefabrication strategies

Input
10 possible strategies in prefabrication building, concerning load-bearing elements and room-construction.

Tryout
Each scenario provided a few key factors, which will affect the structure and room partitioning of the building. The prefabrication was then tried against the scenarios and their key factors, to assess how well they can perform.

Key factors
Present day
Since the building is a lamella of sorts, this removed two of the strategies straight away. The number of storeys also made one of the strategies impossible.

Collaborative economy
The possibility to connect spaces to bigger shared apartments, partly horizontally, but mostly vertically became the big deciding factor in this scenario.

Local self-sufficiency
Storey removal is a key factor in this scenario, and the simplicity of reusing these living spaces in a rural location. The possibility to expand the dwelling units horizontally also affected the grade.

Automation
Making dwelling units smaller or dividing them in different ways was the most important factor in the scenario during this test. It didn't disqualify any strategy completely.

Circular economy
The reduction of unit sizes was the main aspect looked at in this scenario. The possibility to disassemble and reuse materials will be important as well but will be looked into further at a later stage.

Output
Four strategies scored extra good in the tryout.

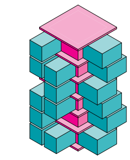
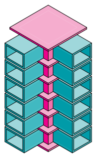
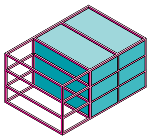
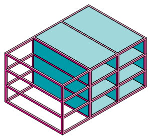
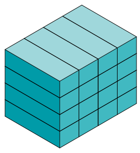
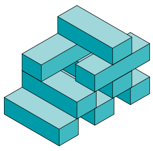
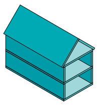
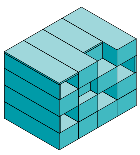
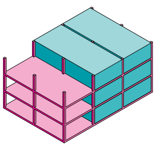
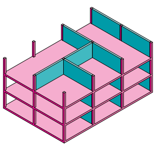
Both the two strategies ('Post-and-beam / Flatpack' and 'Slab / Flatpack') proved interesting. However, they offer quite similar opportunities, but the former creates bigger possibilities of expanding vertically between floors.

Two other ('Self-bearing / Volume modules (irregular)' and 'Self-bearing / Combined (volume & flatpack)') can be combined into one: 'Self-bearing / Irregular combined'.

The ease of reusing the living spaces in a rural location led to 'Self-bearing / Irregular combined' being selected as the continuing prefabrication strategy.

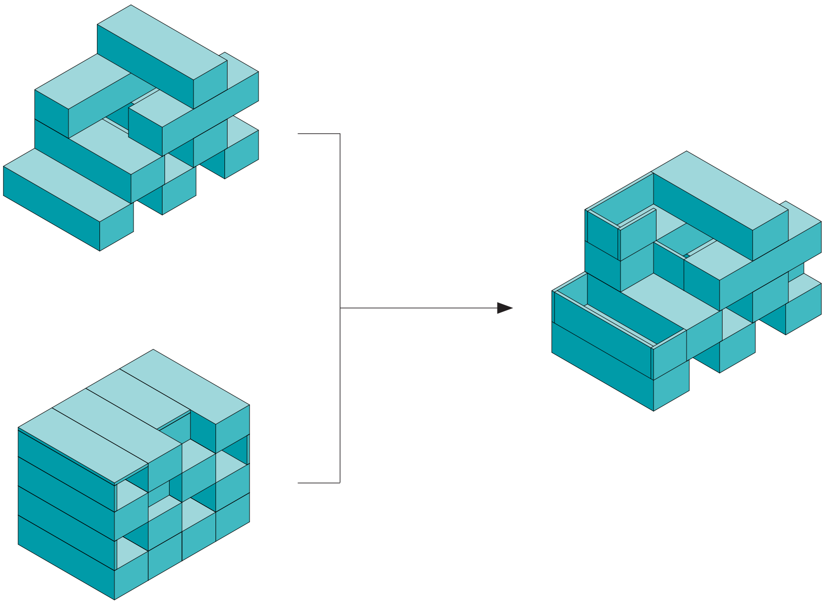
Conclusions
Scenario tryout proved very useful in tryout number 2. It gave a quick an overview of what abilities the structure needed to have to work with the building and its program.

The depth of the tryout was quite superficial, which was enough for this stage in the design process. The need to further the project resulted in going back after the tryout and pushing it a bit extra, resulting in a single strategy being chosen.

Input		Tryout	
Prefabrication strategy		Present day	Collaborative economy
	Core / Volume modules (irregular)	Material inefficient when not used in high-rise. Does not fit site.	
	Core / Flatpack	Material inefficient when not used in high-rise. Does not fit site.	
	Post-and-beam / Volume modules (regular)	Might work, insulation and services might be in issue because of gaps between modules, but that can probably be solved in some way.	Being based on inserted pods, connecting apartments of several floors makes this strategy hard.
	Post-and-beam / Flatpack	Common way of constructing in current prefabrication building, can be very open for future changes.	Due to the bearing structure being beams, it leaves both inner and outer walls interchangeable, with spaces expandable in both horizontally and vertically.
	Self-bearing / Volume modules (regular)	Fast, cheap, energy efficient way to construct. However, sizes are very fixed, and varying plans might be difficult.	Fast, cheap, energy efficient way to construct. However, sizes are very fixed, and varying plans might be difficult.
	Self-bearing / Volume modules (irregular)	Can be very beautiful, and spaces can become multifunctional and varied. However, not too well suited for Swedish climate.	The irregular stacking creates interesting spaces which can be used interchangeably, if used with the 'Self-bearing / Combined' strategy.
	Self-bearing / Flatpack	Not good for making a building of the size proposed.	
	Self-bearing / Combined (volume & flatpack)	The combination of efficient modules and flatpack elements in irregular patterns can create both efficient and varied rooms.	Can work very well if combined with the 'Self-bearing/Irregular modules' approach, as spaces can be opened both vertically and horizontally.
	Slab / Volume modules (regular)	Fast, cheap, energy efficient way to construct. However, sizes are very fixed, and varying plans might be difficult. Easy to remove volumes though.	Due to both modules and slabs being used, vertical openness is not a possibility.
	Slab / Flatpack	Common way for disassemblable buildings, as not walls are load-bearing. Moving entire floors might prove difficult however.	Since slabs are used, vertical openness is problematic. Slabs can be cut, but 'Post-and-Beam / Flatpack' seems like a similar and better solution.

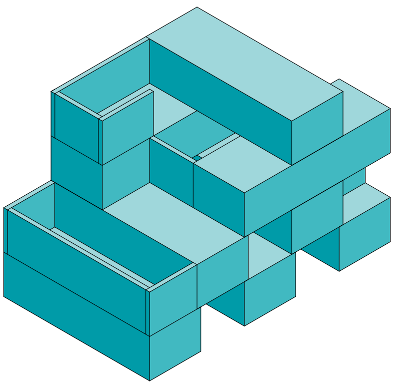
			Output
Local self-sufficiency	**Automation**	**Circular economy**	**Results**
If constructing the post-and-beam as separable elements, removing two storeys could be easy. Connecting apartments horizontally is possible.	Could work well, since pods/modules can be switched or rebuilt. The post-and-beam does limit sizes.	The possibility to reduce unit sizes could argue against this strategy. The further adding of bathrooms could be tricky in this module strategy.	
If constructing the post-and-beam as several elements connected, storeys could be removed. Dwelling units can quite easily increase in size. However, lacks ease to reuse in rural areas.	Since inner walls can be moved, the unit sizes can change without big problems.	Changing of unit sizes is easy. The possibility to disassemble has proven to be high in other projects.	
The fixed sizes of volumes, make the vertical space changes limited. Horizontally, connecting modules into an open space is next to impossible without big interventions.	Removing storeys would be easiest with this strategy. Making bigger dwelling units is a struggle, but not impossible.	Fixed module sizes makes the amount of different unit sizes few, which poses a problem.	
Removing storeys is possible. And changing unit sizes should be a problem if planned to ensure load-bearing modules in key places after storey removal.	Fixed module sizes makes the amount of different unit sizes few, even though the spaces around could be used.	Fixed module sizes makes reducing the unit sizes harder, even though the spaces around could be used.	
Storey removal not an issue due to self-bearing nature. Combining volume and flatpack makes unit size expansion possible.	Open spaces made up of flatpack elements between fixed modules can be flexible, allowing for different unit sizes.	Open spaces made up of flatpack elements between fixed modules can be flexible, allowing for smaller units.	
If constructed with each storey slab being removable, this strategy can work. Units can be expanded, although the fixed size makes it trickier.	Modules can be pulled out of the load-bearing slab and replaced with different sizes, but that would require a lot of work and energy.	Fixed module sizes makes the reduction of unit sizes problematic.	
If constructed with each storey slab being removable, this strategy can work. Units can change size easily.	Very flexible in unit sizes due to non-bearing inner and outer walls.	Very flexible in unit sizes due to non-bearing inner and outer walls.	

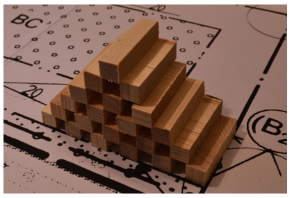
After the tryout, the two “winning” prefabrication methods were combined into one: *Self-bearing / Irregular combined.*

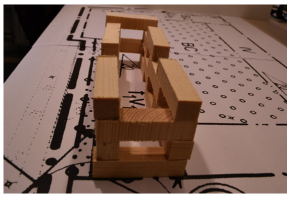


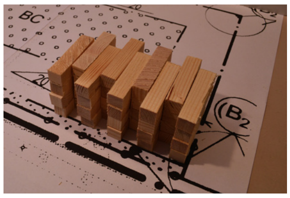
5.3 Volume sketches

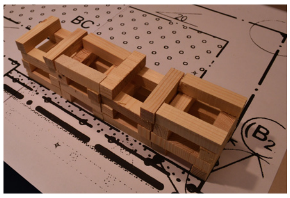
Volume sketches on how construction could work. The model is based on modules of 12x3x3 metres. Spaces in between modules are imagined to be filled by flatpack elements. The volume modules could be “wet modules”, containing kitchen and bathrooms.

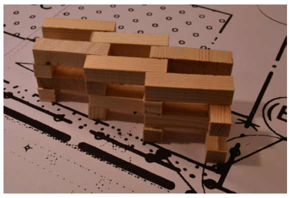


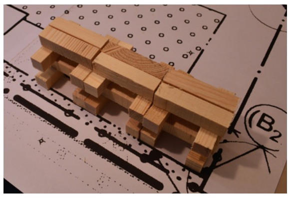


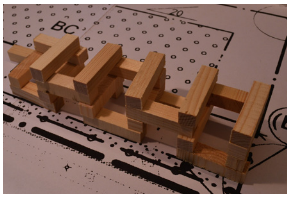


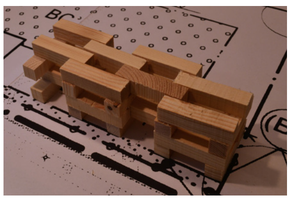


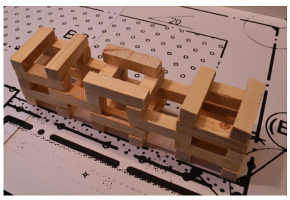




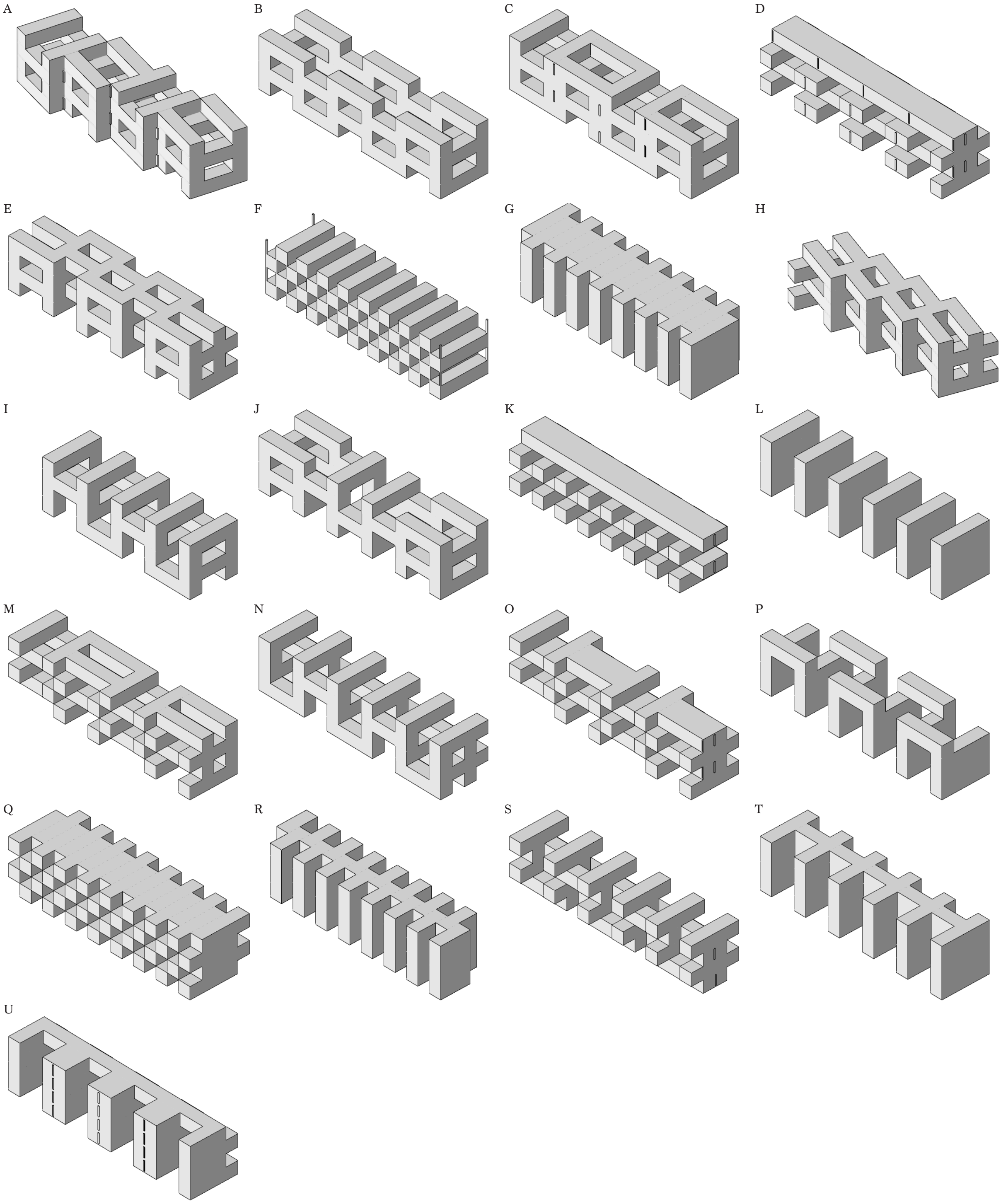




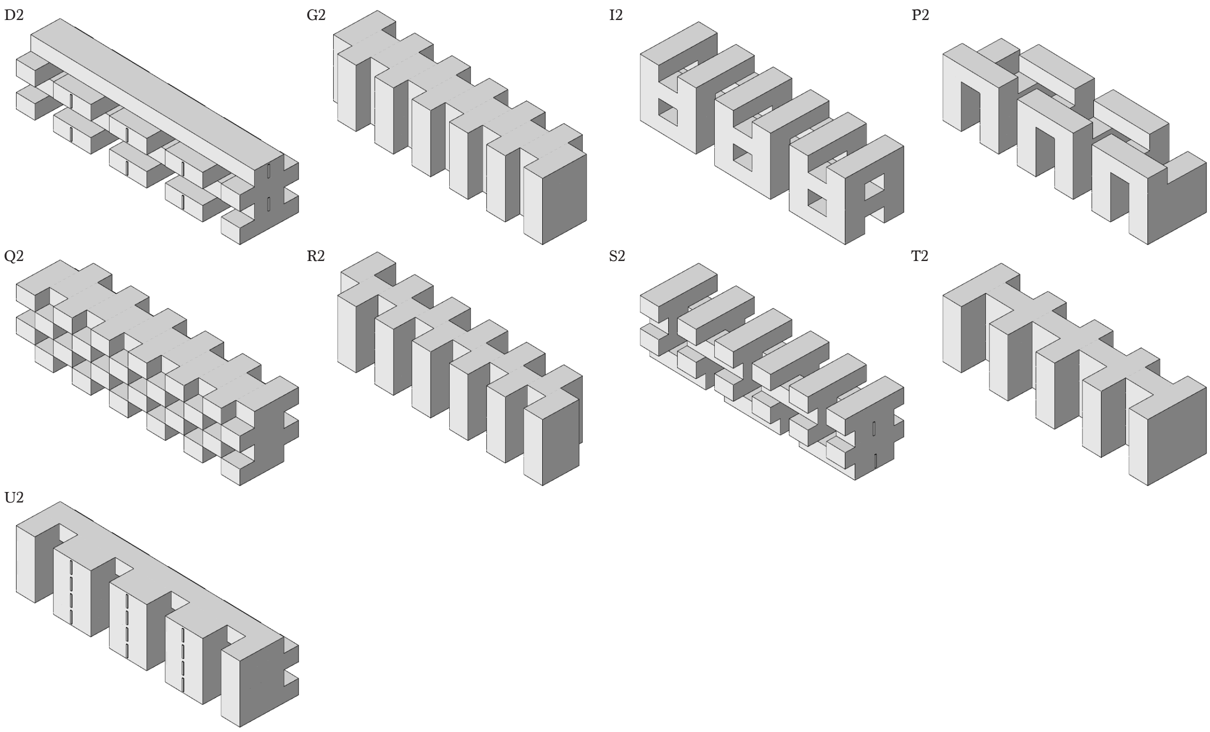




Based on the physical model sketches, 21 possible configurations were developed digitally, and recorded in 3D (shown below), plans and façade for further analysis.



After starting a fourth tryout, reducing the 21 configurations to 12, the need for modules with a width of approximately four metres became apparent. Of the 12 configurations, 9 were considered suitable for four-metre variants. These were recorded in isometric views (shown below), plans and façade for further analysis.



6. The Futureproof House

<u>6.1 Location</u>

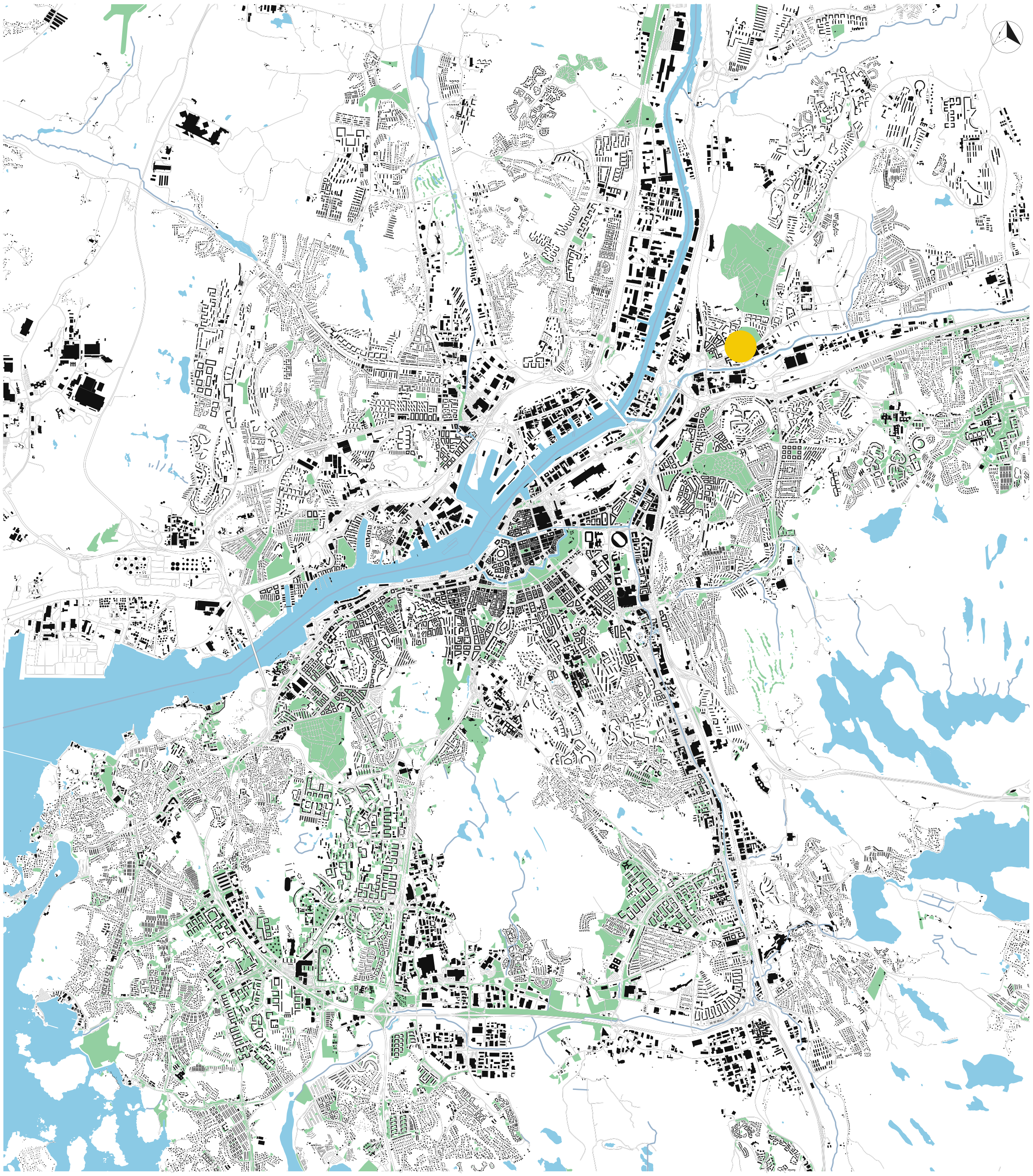


Fig. 19. Map of Gothenburg - 1:100 000

Fig. 20. Site map - 1:4000

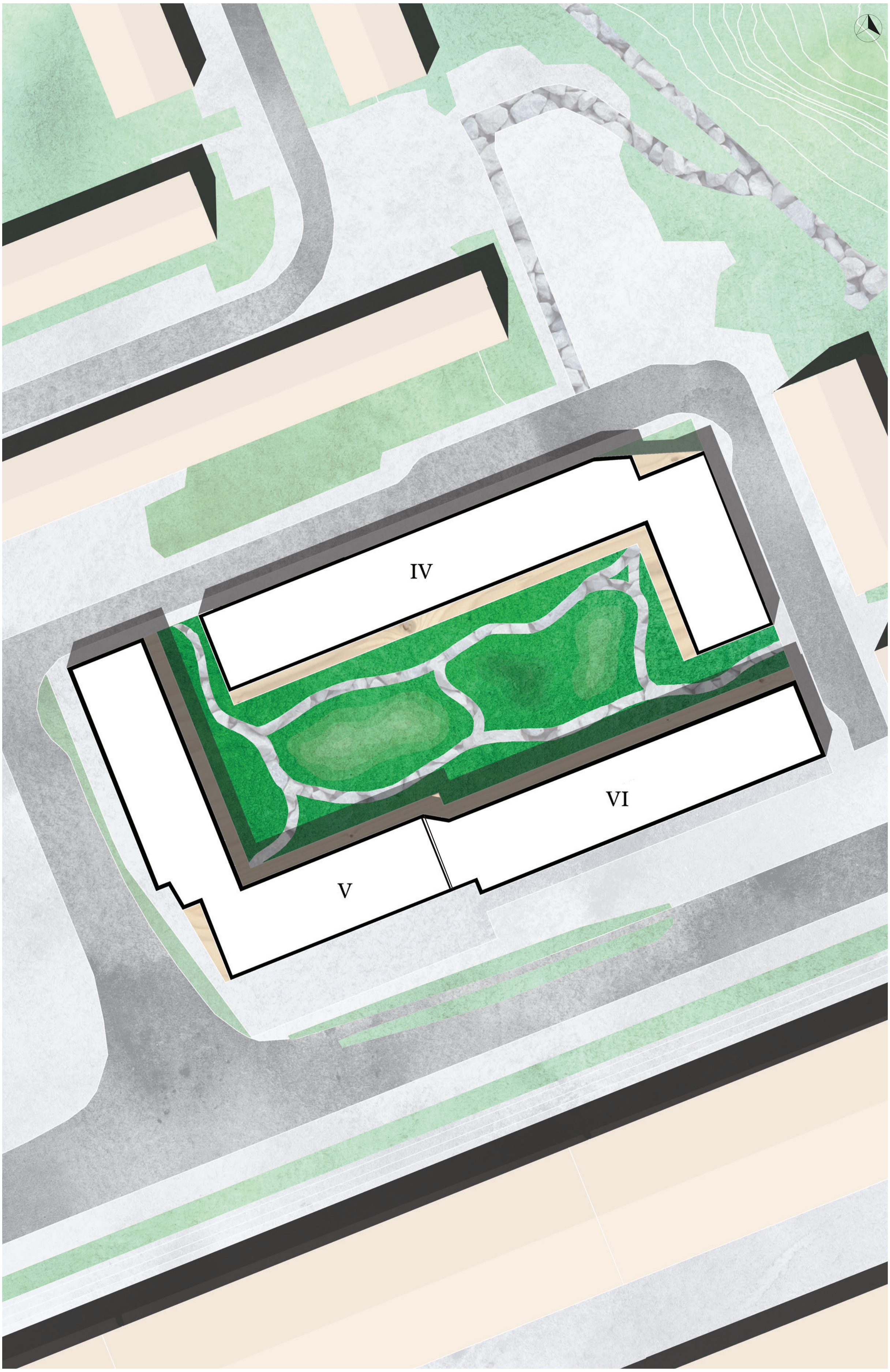


Fig. 21. Site plan - 1:800

Fig. 22. Photo of model, scale 1:500, north view

Fig. 23. Photo of model, scale 1:500, south view

6.2 Construction

As mentioned earlier, the construction method is a combination of prefabricated volumetric modules and prefabricated flatpack elements. These are put together as shown in Fig. 28. Two different volumetric modules are used, shown here.

Module A (approximately 4 times 8 metres) is used in the center of the apartments, never reaching the façade. It can have two walk-through kitchens, two bathrooms and one or two small rooms that can act as one extra bathroom or two closets. The shafts are added on the short ends to align with the shafts of module B, with piping going under the raised floor. Module A is used on storeys 2, 4 and 6.

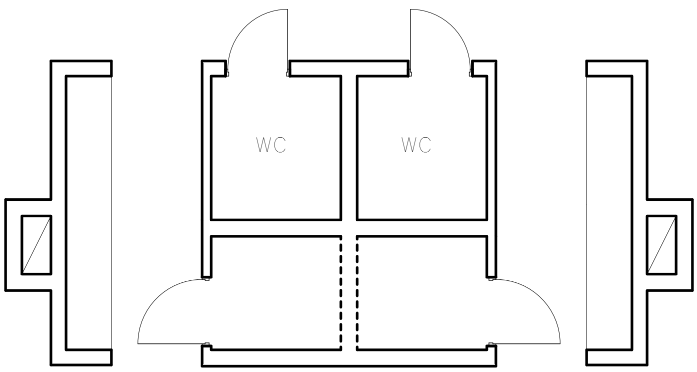


Fig. 24. Module A - 1:100

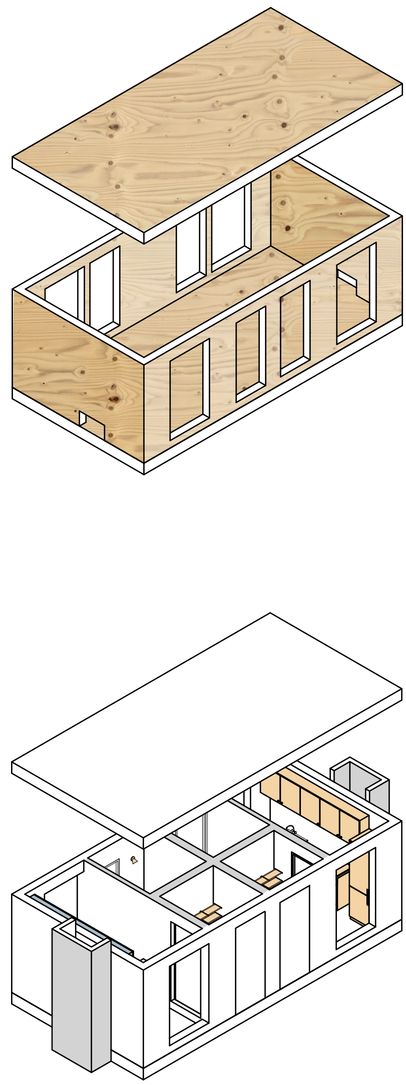


Fig. 25. Construction of module A

Module B (approximately 4x12 metres) spans the entire width of the apartment building, with its short ends covered in ceramic shingles as part of the façade. It contains two entrances with accompanying hallways and bathrooms, two installation walls where kitchens may be placed, as well as a central room with connections to both sides of the module and which can be either kitchen, bedroom or work room. Module B is used on storeys 3 and 5.

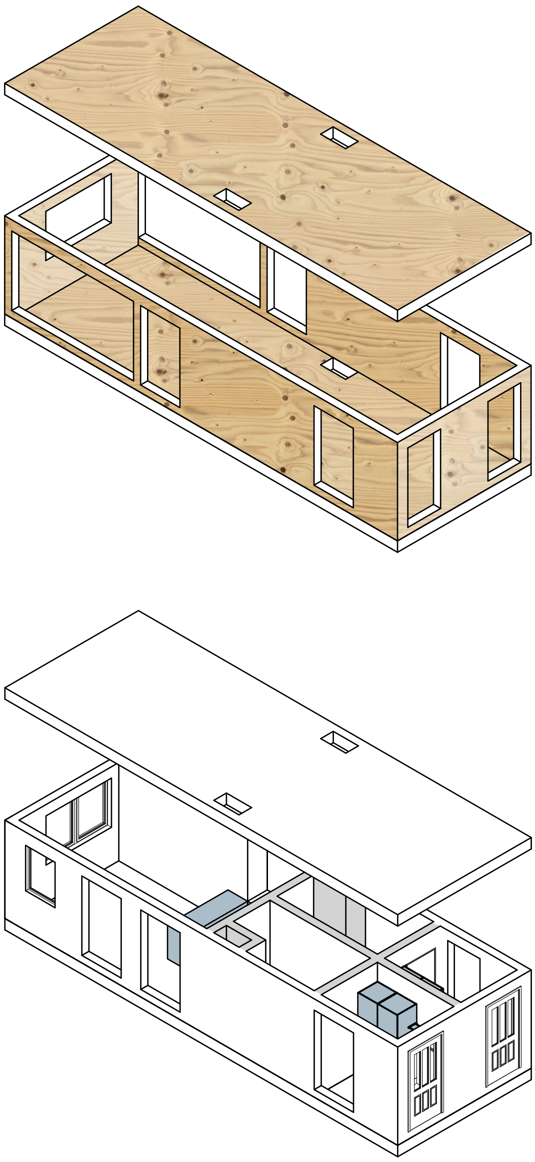


Fig. 26. Construction of module B

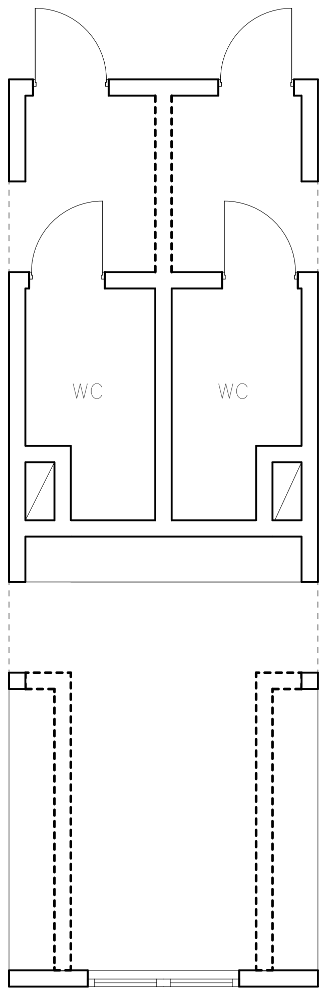


Fig. 27. Module B - 1:100

Step 1 The ground floor is constructed with CLT pillars and slabs.

Step 2 Modules type A are placed on the slabs at a regular interval. Additonal pillars and beams are added.

Step 3 Modules type B are placed orthogonally on top of modules A, balancing on the wall edges. Insulated CLT floor cassettes are mounted between module and beam.

Step 4 Modules A are placed again, in the exact same location as two storeys below. Extra beams are placed between modules to allow for floor cassettes to be added.

Step 5 The same system is used to construct all the storeys, ensuring that shafts align.

Step 6 A flat roof is placed on top of the building, providing space for a roof terrace, urban gardening or solar panels, and if necessary future expansion.

Step 7 The flexible exterior wall is added, raised floor is mounted to level height differences and interior partitions not in the modules are constructed. A freestanding access balcony is constructed on the courtyard side.

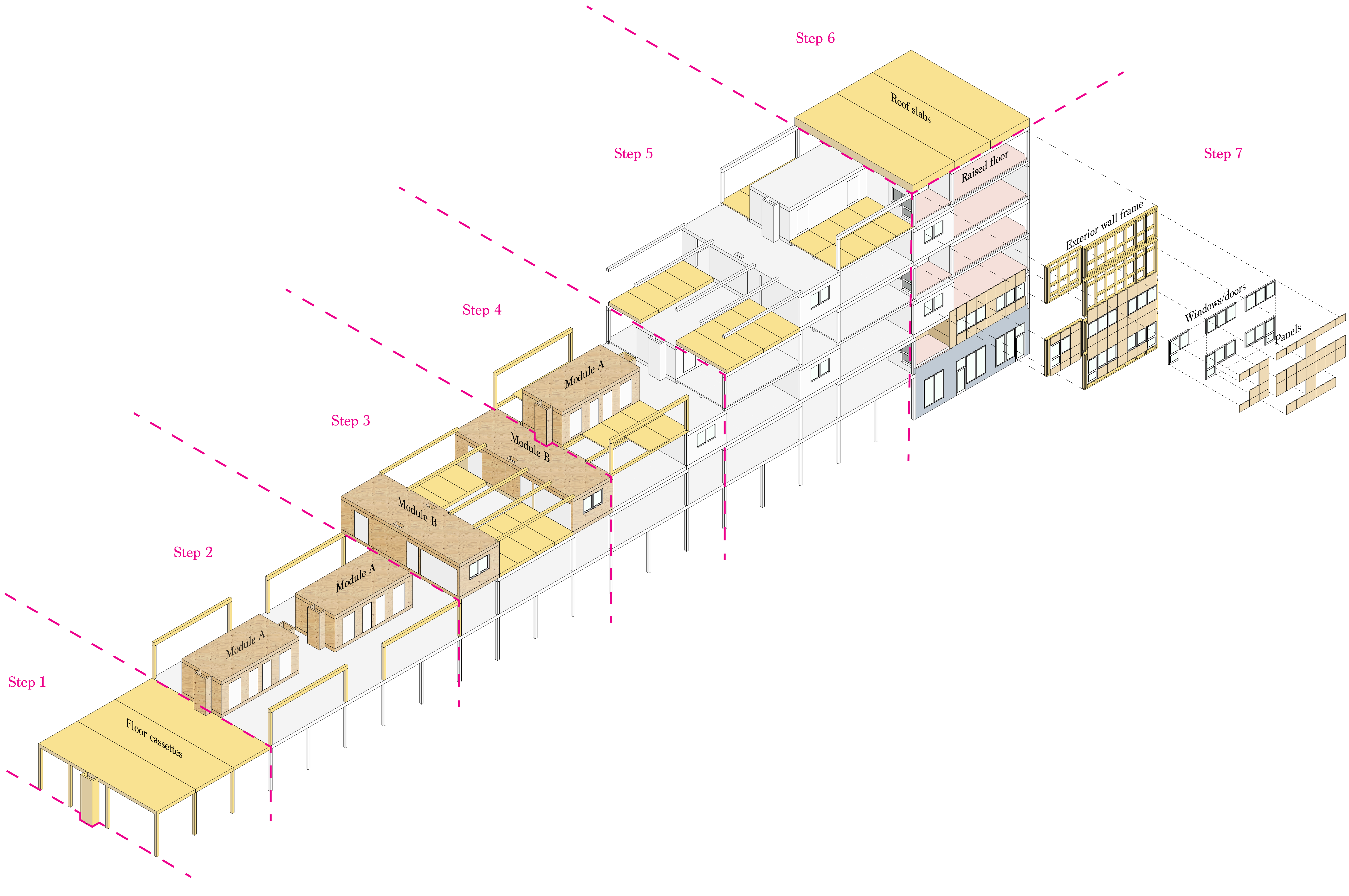


Fig. 28. Construction diagram, modular system

6.3 Plans

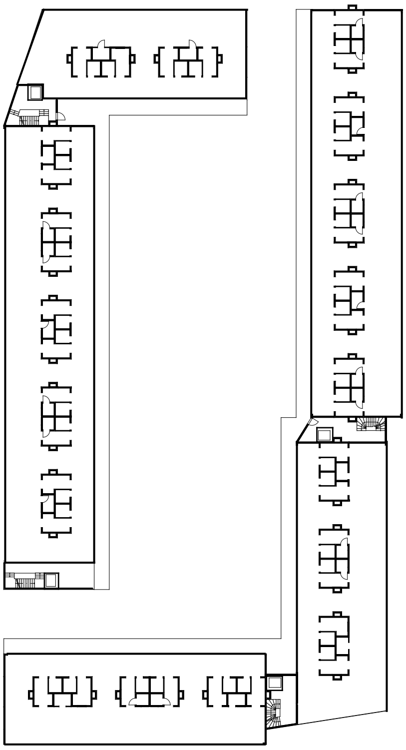


Fig. 29. Raw space plan, type A - 1:1000

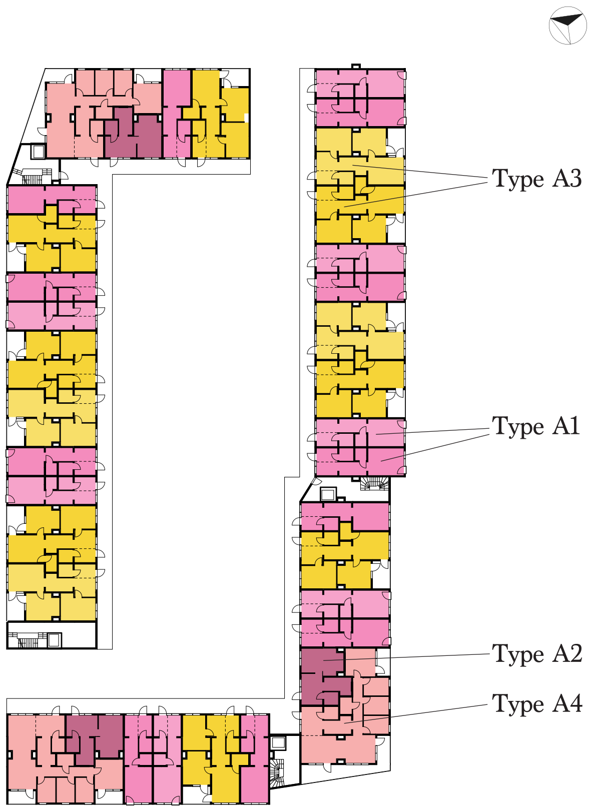


Fig. 30. Apartment distribution, type A - 1:1000

The construction shown in the previous section creates two different raw space plans, depending on the module used. Module A gives raw plan type A (Fig. 29) which is used on storeys 2, 4 and 6. Module B gives raw plan type B (Fig. 31), used on storeys 3 and 5.

By partitioning them with interior and exterior walls, both of these two plans can be divided into apartments with different sizes. (Fig. 30 & Fig. 32) For each raw plan, four apartment types have been produced. Of these, one per plan has been worked with more intensely.

The ground floor is constructed with a different system of pillars and slabs (Fig. 33). Shops and offices are placed facing the street, and services such as laundry, bike storage and overnight rooms are placed facing the courtyard. There are four staircases feeding the access balcony and giving stability to the modular system.

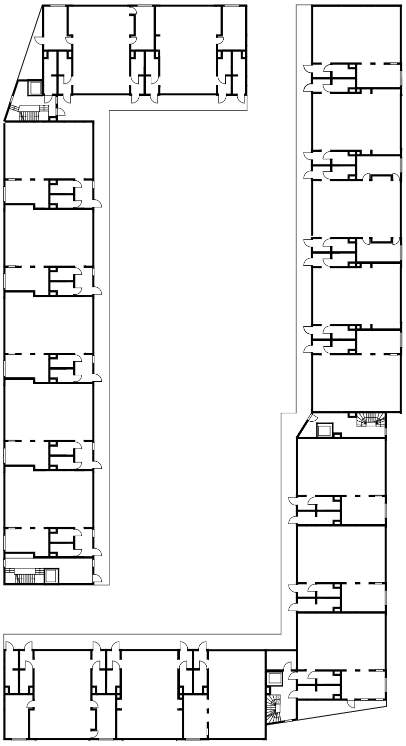


Fig. 31. Raw space plan, type B - 1:1000

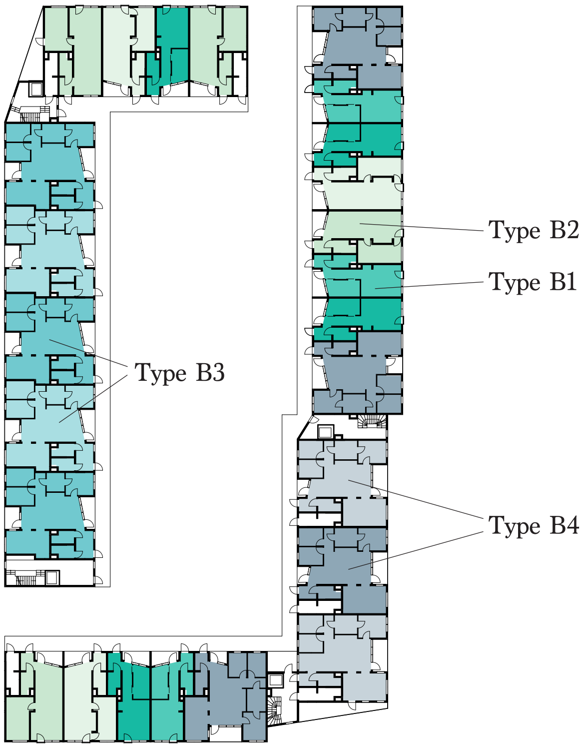


Fig. 32. Apartment distribution, type B - 1:1000

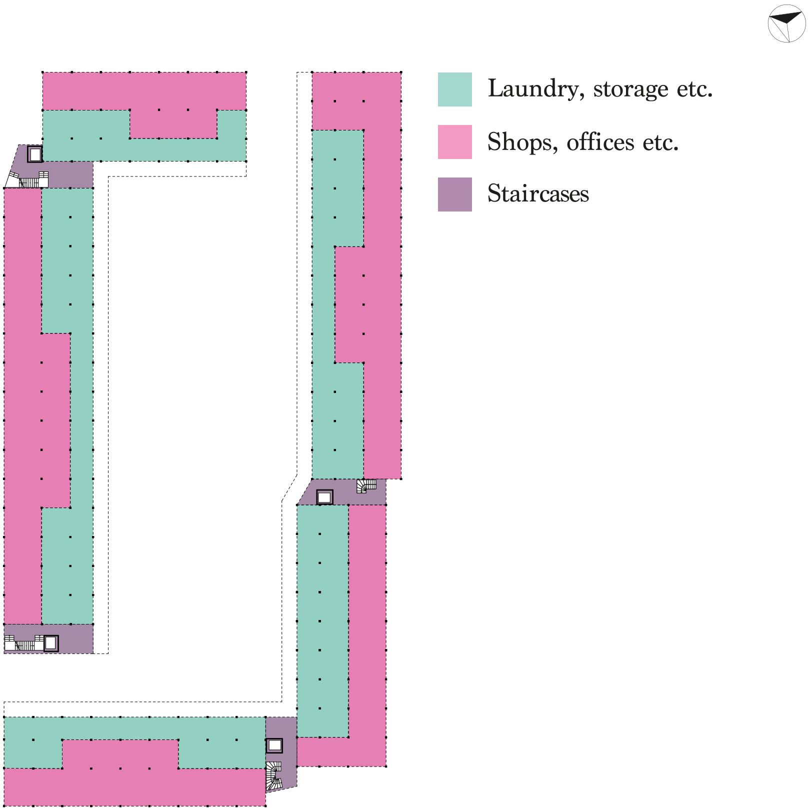
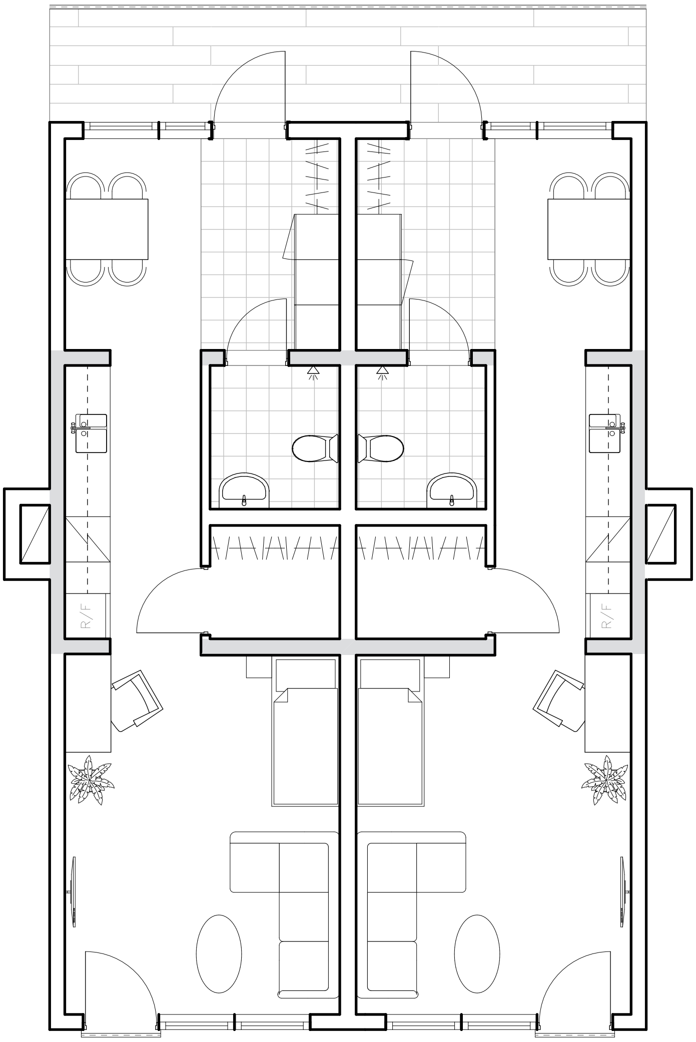


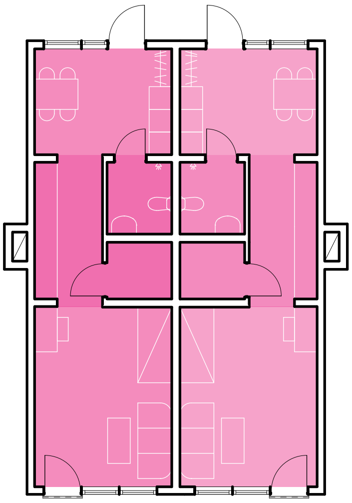
Fig. 33. Ground floor, zoned - 1:1000



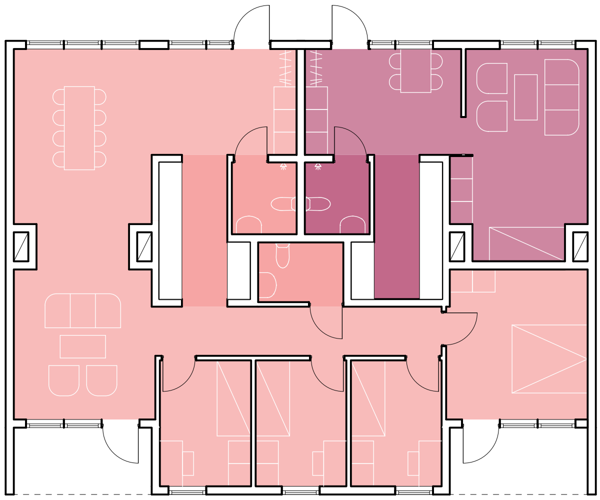
Module A
Type A1
1 ROK
42 m²

Fig. 34. Apartment A1 - 1:100

Apartment A1 (based on module A) is a two-sided one-room apartment with a central walk-through kitchen lit from both sides, with a light axis going through the apartment. One module serves two apartments, consisting of two kitchens, two bathrooms and two closets. The shafts are placed on the short ends of the module, to align with the shafts on the other storeys. Piping and wiring can be placed under the raised floor to reach the shafts.



A1
1 ROK
42 m²

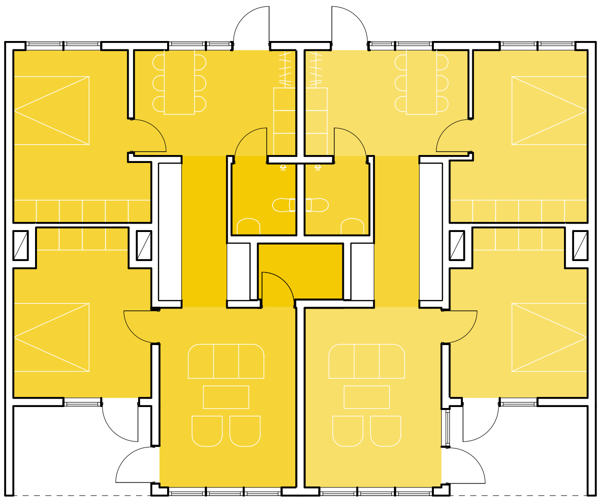


A4
5 ROK
113 m²

A2
1 ROK
39 m²

Of the other type A apartments, all but the smallest one (A2) has an axiality of light going through them. The largest one (A4) has the possibility to circulate, with a large dining room/living room that can be divided into two rooms if the need arises.

The distribution of the apartments on the type plan can be seen in Fig. 30.



A3
3 ROK
73-77 m²

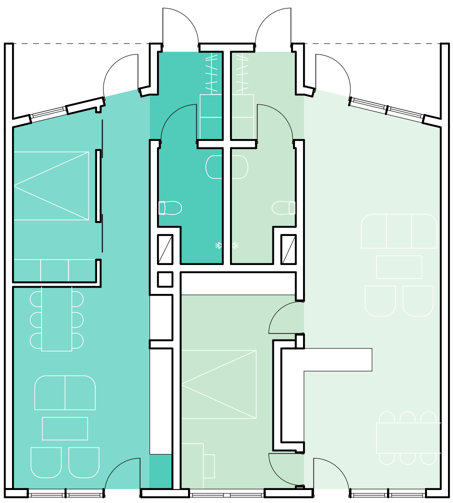
Fig. 35. All apartment types deriving from module type A - 1:200

Fig. 36. Apartment B3 - 1:100

Apartment B3 is a large apartment with 3 bedrooms. a private laundry room and a spacious walk-in closet. The living room is large to ensure the possibility to provide living space in for example the Collaborative economy scenario, where cohousing will be prevalent. The possibility to add an extra room by replacing one of the balconies also exist.

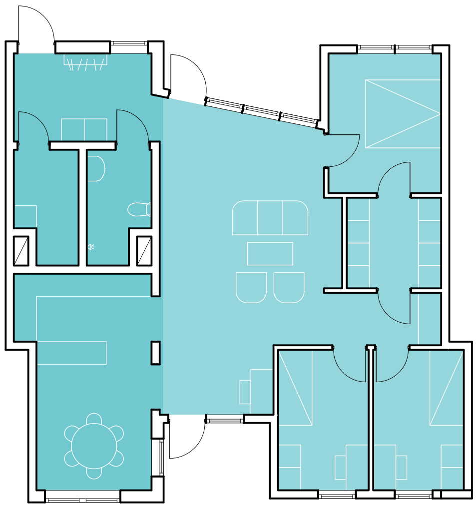
Similar to the apartment type A, apartment B3 has an axis going through the living room, providing light from both sides.

On the side of the access balcony, the apartment has a balcony split by the walkway, where both sides can be used.



B1
1 ROK
49 m²

B2
2 ROK
65 m²

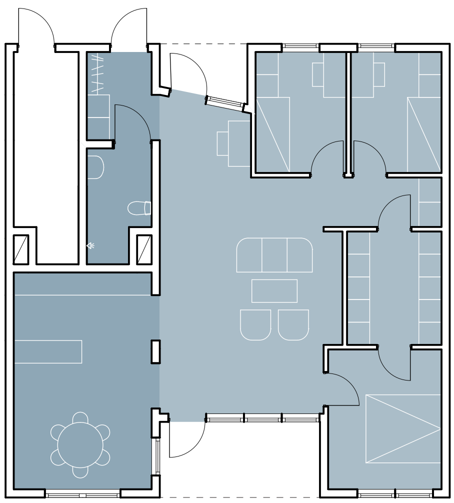


B3
4 ROK
112 m²

The other apartments of type B all have a similar light axis through the apartment. Apartment B3 is a mirroring of B4, which can be used depending on which side faces south.

Apartment B2 can be used open plan, or be closed off between kitchen and living room.

The distribution of the apartments on the type plan can be seen in Fig. 32.



B4
4 ROK
105 m²

Fig. 37. All apartment types deriving from module type B - 1:200

6.4 Elevations & sections

The façade is made up of two main materials, panels made from wood planks and ceramic tiles. The wood panel is part of a flexible exterior wall system explained more in detail on the upcoming page. The ceramic tiles are used to create a heavier feeling in the base of the building, despite them being easily demountable. The tiles also occur on the staircases and the short ends of module B, which reach all the way to the façade.

Fig. 38. Martial Cottle Park (Hansen, 2016)

Fig. 39. Ceramic tiles, Circle House (Eliasson, 2018)

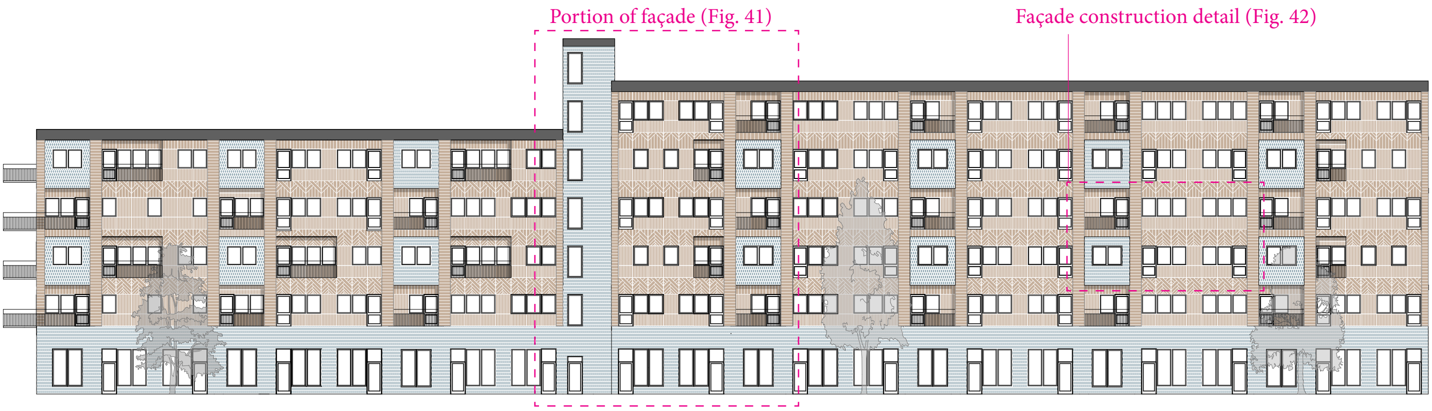


Fig. 40. South elevation - 1:500

Fig. 41. Portion of façade - 1:100

Once all modules and floor cassettes has been placed, the exterior wall is attached. It's constructed through a stud-and-beam system, made up by three or seven 1-metre horizontal gaps. On the outside of these gaps, two panels, a panel and a window or a door (removing one horizontal stud) can be placed, depending on which apartment type they will be used for.

Once filled with panels, windows and doors, the walls are delivered to the building site, and mounted in their designated spot. Additional panels are then attached over the slabs. These panels have a higher ornamental detail, as they are less likely to be changed. The panels on the lower storeys have higher complexity, getting simpler higher up (left to right in Fig. 42).

The sides are also covered with pilasters made from preassembled wooden planks. Each panel can be replaced without removing the wall.

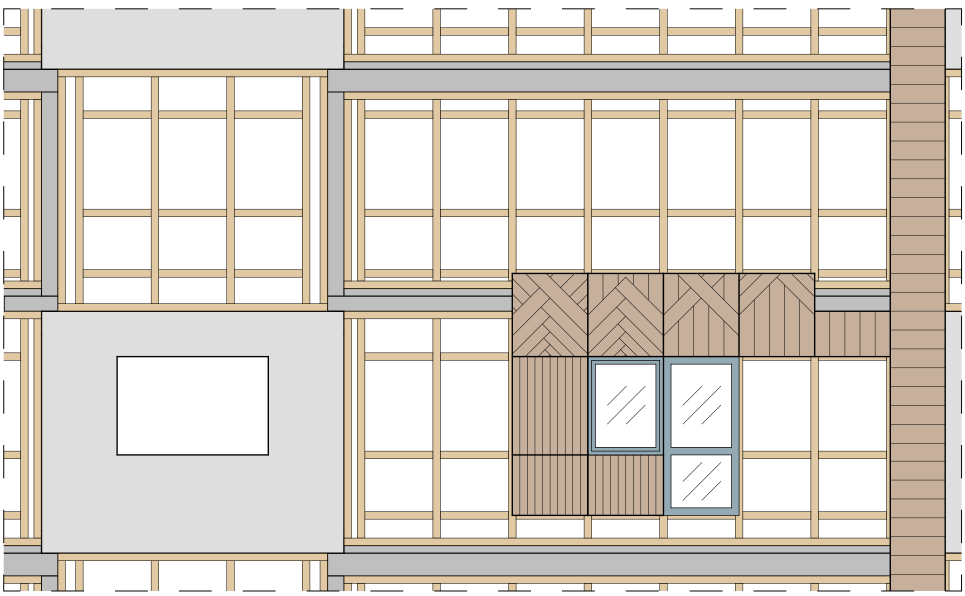


Fig. 42. Façade construction detail - 1:100

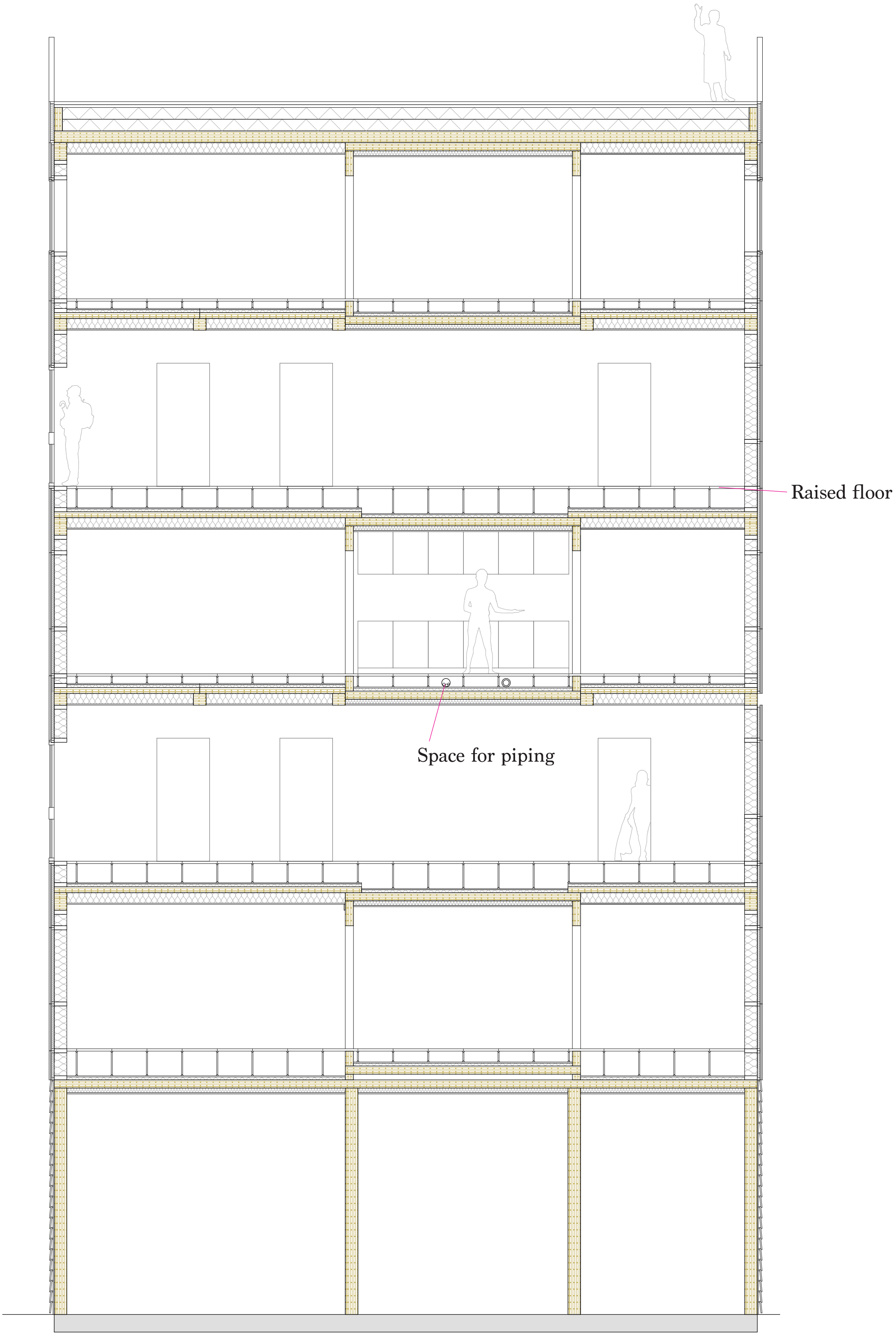


Fig. 43. Section - 1:100

6.5 Flexibility strategies

Flexibility strategies derived from the research as used in the design. *Horizontal distribution* is solved by applying a raised floor, which also deals with the *versatility* in changing recessed balconies to rooms and adding flexibility to interior walls. This in turn facilitates the *joining up and dividing* of rooms. The flexible exterior wall ticks the boxes of *external walls* by the use of *disassembly and exchangeability* as well as *structural modularity*, and together with the communal circulation in shape of an access balcony, which provides the adding and removing of units. To every strategy a legend shows which scenarios benefits from the implementation.

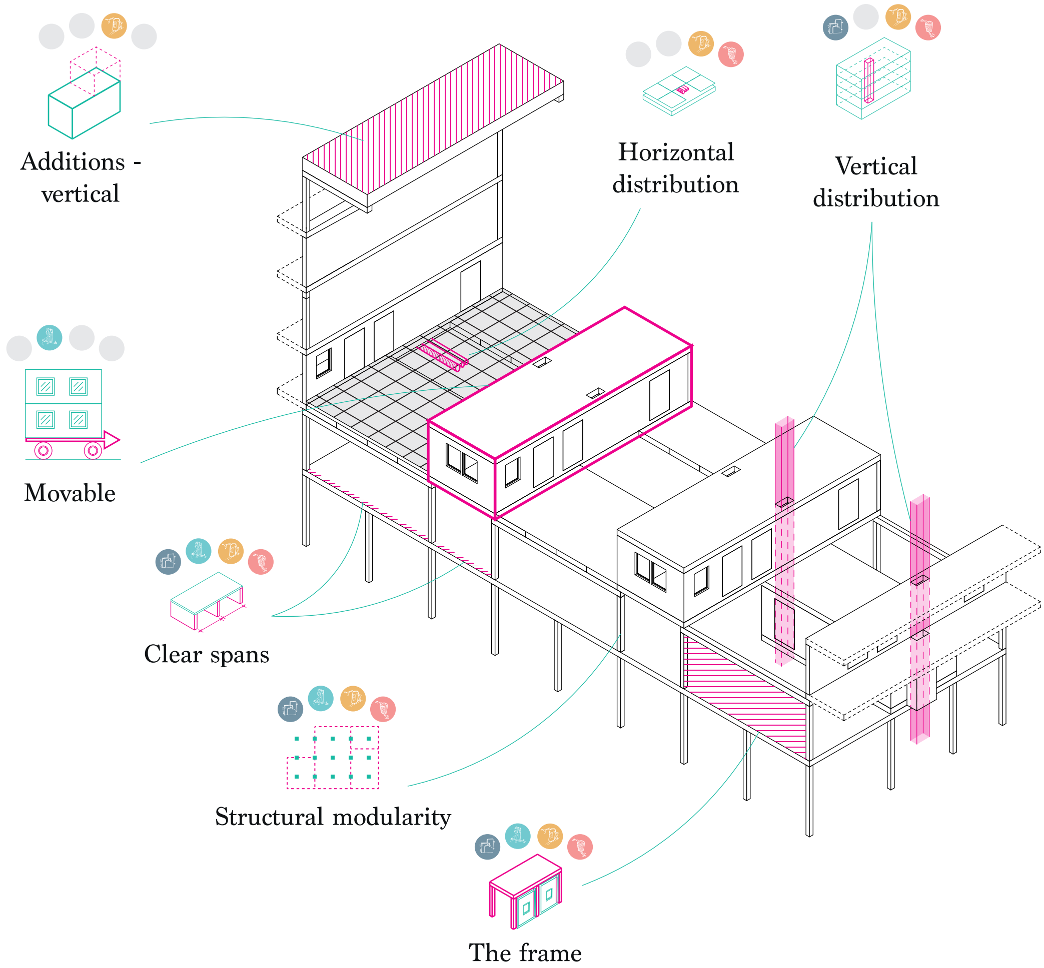


Fig. 44. Used flexibility strategies

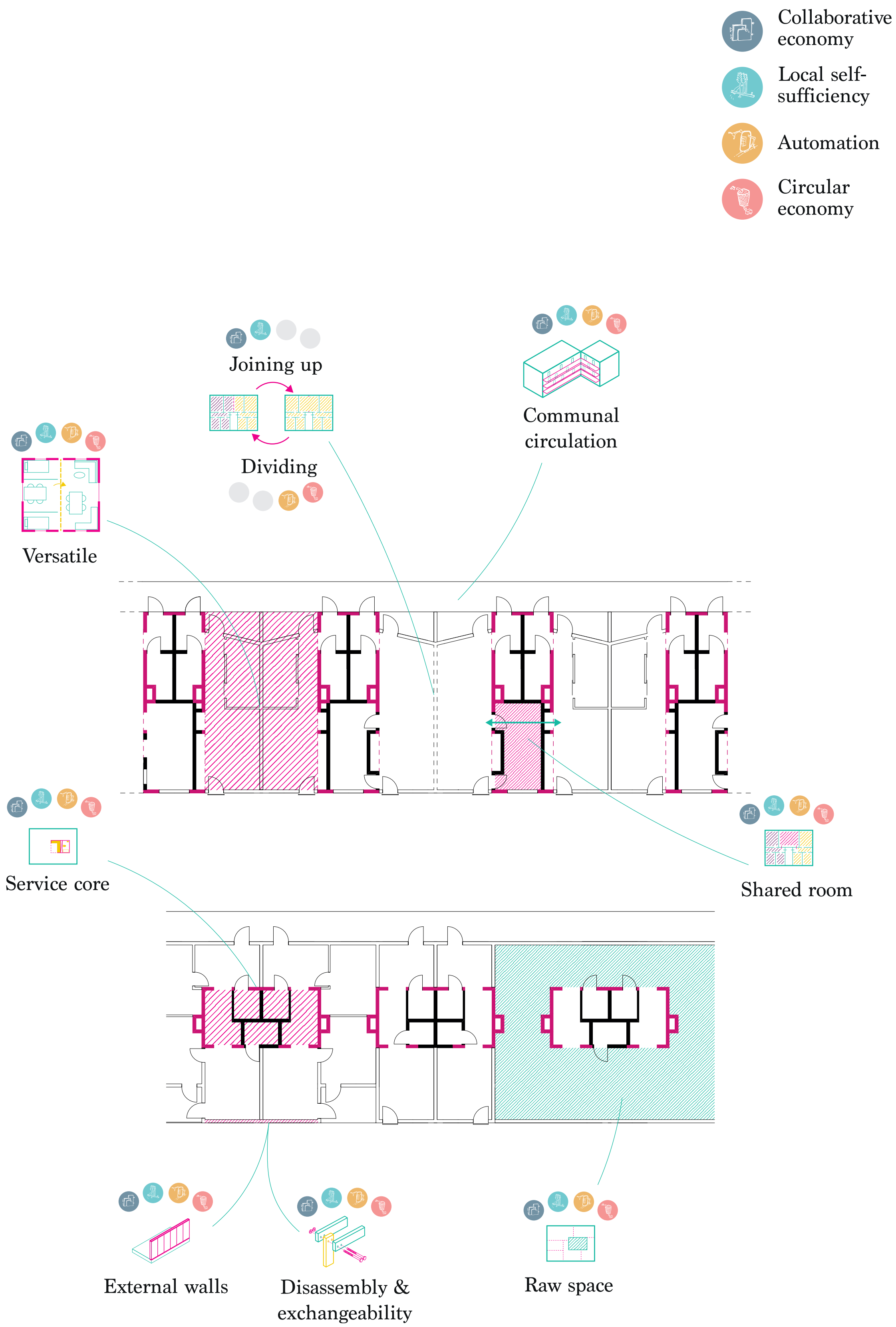


Fig. 45. Used flexibility strategies

6.6 Scenario adaptations

Collaborative economy

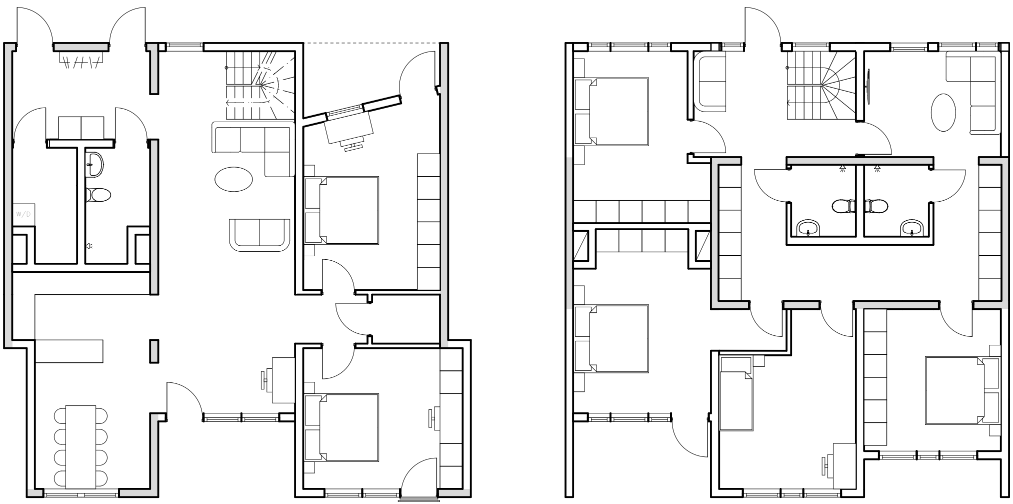


Fig. 46. Cohousing apartment - 1:100

The flexibility built into the house make the following sketched suggestions possible. Removing a single floor cassette provides the adding of a staircase. Together with the moving of few interior walls, it provides a collective in the Collaborative economy scenario with six bedrooms, a shared living room and a smaller living room for common or private use. The raised floor makes it possible to change the placement of recess balconies.

Local self-sufficiency

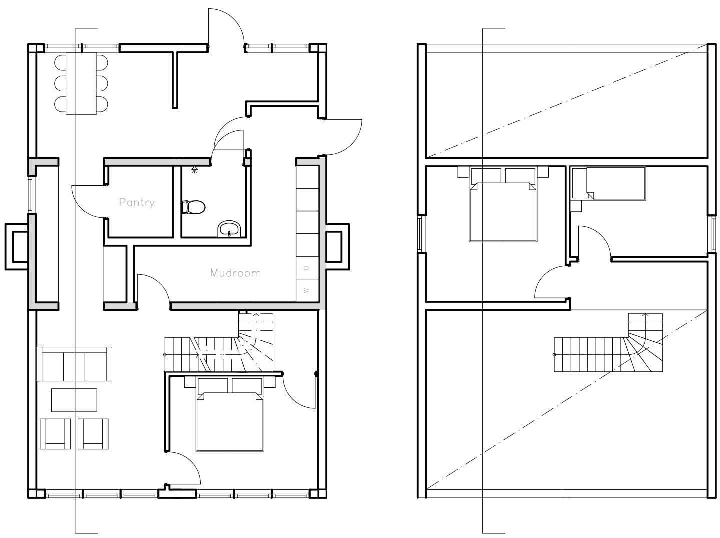
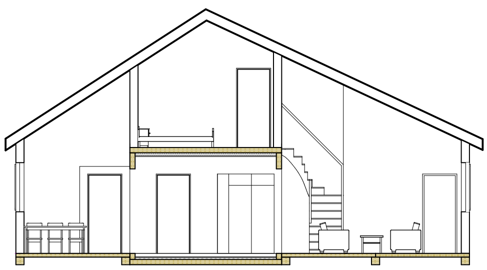


Fig. 47. Rural villa - 1:100

The possibility to move an entire module is used in the Local self-sufficiency scenario, where people move to the countryside to farm their own food. The module, it's adjoining floor cassettes and two flexible exterior walls are all reused here. The bearing of the module makes a small second story possible, and the villa can be extended in the future if the need arises.



Automation

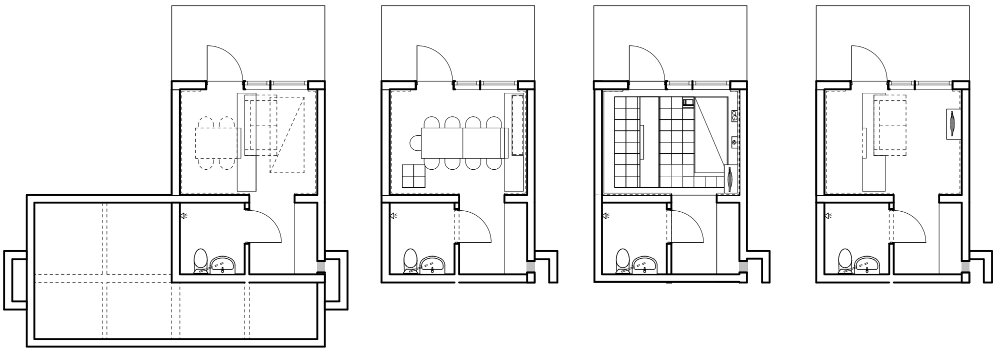


Fig. 48. Automated configurations - 1:100

In the automation scenario, the raised floor can hide a bed and a bedside table during daytime, as well as provide space for the wiring of an intelligent sliding wall, as is becoming more common in flexible housing (Pereira, 2019). Different configurations are possible in a small space, and the doors and windows can be moved thanks to the flexible exterior wall.

Circular economy

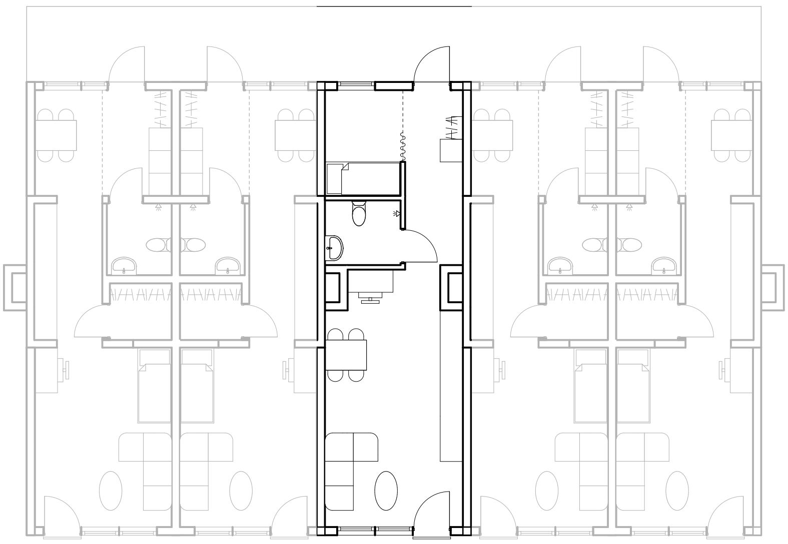


Fig. 49. Added one-room apartment - 1:100

The circular economy scenario demands more smaller apartments, which can be achieved by adding an infill apartment between existing ones. The raised floor and the placement of shafts provide the option of adding bathroom and kitchen, and the flexible exterior wall facilitates the adding of extra entrances.

6.7 Discussion

The use of backcasting scenarios helps with the flexible solutions, even if some discrepancies has been discovered. In the research project 'Beyond GDP-growth', smaller heated spaces are called for in all scenarios. However, for flexibility reasons the size of the living room is key for expansion and alteration. The solution has been to use the recessed balconies as a way to minimize the heated space. These spaces do not need to be heated but can be added to the indoor space at a later date to make the apartments larger.

Some strategies have proved to be more useful than others, when checking against the scenarios. The use of a raised floor combined with the placement of shafts provides many of the scenarios the possibility to add extra bathrooms or kitchens, as well as the adding and removal of recessed balconies with the needed extra space for insulation and waterproofing. This also has the added positive outcome of drawing all electrical wiring beneath the floor, thus highly adding flexibility to the interior walls.

Another strategy that proved to be successful in the scenario adaptations is the flexible exterior wall. Changing the number of units means adding doors and often moving windows, and the flexible wall makes this a lot easier. Several flexibility strategies mentioned in the research chapter provided the background for the wall, such as *clear spans*, *disassembly & exchangeability* and of course *external walls.*

Many flexibility theorists also mentioned some form of service core. Whilst not necessarily clearly visible in the scenario adaptations, it's the foundation of the raw plan, and provides the possibility to use both the raised floor and flexible interior and exterior walls.

The choice of prefabrication method, and the irregular placement of bearing modules which was chosen by trying prefabrication methods against the scenarios also made this service core possible. The scenario tryout used to determine this method and the subsequent sketching was also the moment when the three approaches - flexibility, prefabrication and backcasting scenarios - were closest intertwined, resulting what may be the project's biggest strength.

Modular building can often make a project very rigid, but the need to meet the demands of the scenarios pushed the project towards a point where the prefabrication was beneficial to the flexibility.

The added possibilities and thus the extended lifespan of the building outweigh the added complexity, making this a futureproof house.

Appendix A:
Reference projects

A1 Cellophane House

Kieran Timberlake Associates, exhibition house in New York, 2008.

A highly technological house, but at the same time simple. A frame made out of off-the-shelf structural steel is connected into both volumes and flat packs. Floor cartridges, wall panels and windows are attached to the frame system, and a thin plastic film is wrapped around the structure. The film contains photovoltaic cells which can gather solar energy. All parts of the house may be disassembled and can be reused in another way.

During the work with the project, the architects worked extensively with the layers of the building, making sure that there would be as few connections as possible between the layers to facilitate the building's disassembly.

Cellophane House shows an interesting way to combine volume modules with flat prefabricated parts such as floor cartridges and wall panels. The use of the thin energy generating façade film is also an interesting way to add value to a building. (Schmidt III & Austin, 2016)

2.2.1 Shearing layers
2.2.5 A manual for flexible housing

Fig. 50. Exhibition at MoMA (Aaron, 2008)

A2 Dortheavej Residence

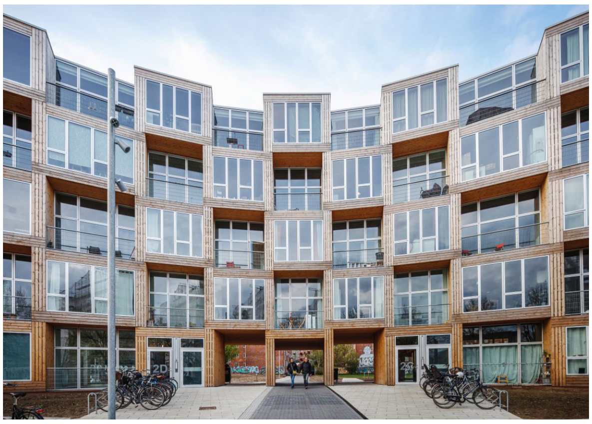


Fig. 51. Dortheavej, exterior (Hjortshøj, 2018a)

Fig. 52. Dortheavej, interior (Hjortshøj, 2018b)

Bjarke Ingels Group, social housing in Copenhagen, 2018.

A five-story apartment building, constructed of modules stacked in a chess-like pattern, with apartments between 61-115 square metres. Every module stands on the edges of the two modules below. The space created in between is enclosed with glazed walls, creating a big open room and a terrace towards the south. The stacking also results in the floor being sunk down two steps. (ArchDaily, 2018) This solves the otherwise common problem of modular building having double walling and flooring.

3.2.8 Self-bearing / Combined (volume & flatpack)

A3 Drömlägenheten

White Arkitekter, apartment interior in Linköping, 2017. (Study visit)

White created a very flexible apartment, which can go from a one-room apartment to a four-room through the use of movable walls and foldable furniture (Fig. 54). Storage exists underneath the flooring, and the kitchen can grow if necessary. When visiting the apartment, about a year and a half after it's inauguration, it became evident that flexible solutions also need to be sturdy. Some pieces of the solutions were starting to come lose, and some had had to be removed entirely.

Fig. 53. Storage in Drömlägenheten (Own photo, 2019)

2.2.5 A manual for flexible housing

Fig. 54. Movable walls in Drömlägenheten (Own photo, 2019)

A4 Habitat '67

Fig. 55. Habitat '67, Montréal (Ziko, 2017)

Moshe Safdie, housing in Montreal, 1967.

Constructed from 354 identical prefabricated modules for the 1967 World Fair, this housing seems to be growing organically despite its rigid building parts and orthogonal stacking. Interesting pathways, balconies and private terraces are created by the weaving and interlocking of the "boxes". Safdie was inspired by the Metabolists but moved away from the megastructure with add-in modules to a stacked construction. (Bergdoll et al., 2008)

3.2.6 Self-bearing / Volume modules (irregular)

A5 iValla

Omniplan, apartment housing in Linköping, 2017. (Study visit)

A house built on Cradle-to-Cradle principles, this apartment building has many interesting features. The floor is raised 60cm over the loadbearing floor slab, with easily removable floor plates resting on a metal grid. All installations are placed underneath the plates, creating the possibility to move both bathrooms and kitchen with relative ease. The flooring system also provides ample storage space.

The outer walls are divided with 60 and 100 cm spacing, leaving the owner with the possibility to move doors, windows and walls along the wall. Inside the apartments, the walls can be moved, and the bathroom door can quite simply be moved into another position.

2.2.5 A manual for flexible housing
3.2.10 Slab / Flatpack

Fig. 56. iValla, Linköping (Omniplan, 2017)

Fig. 57. Raised floor with installations beneath (Own photo, 2019).

Fig. 58. Exchangeable exterior wall (Own photo, 2019).

A6 Maison Dom-Ino

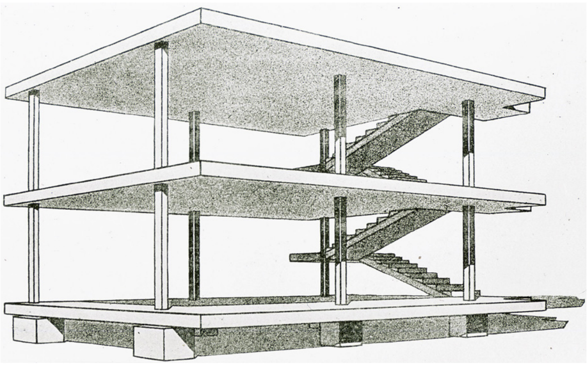


Fig. 59. Maison Dom-Ino by Le Corbusier, 1915.

Le Corbusier, building concept, 1915

Le Corbusiers concept of concrete floor slabs held up by concrete pillars revolutionized modernist architecture. Both interior and exterior walls could be placed in whichever way the architect wanted to as it is completely separated from the structure. (Schneider & Till, 2007)

2.2.4 Spatial principles & logics
3.2.10 Slab / Flatpack

A7 Modulatorsgatan 15

Tage & Anders William-Olsson, apartment housing in Gothenburg, 1953.

Experimental flexible housing, making use of the raw space type of flexible design. A large space only interrupted by one pillar can be adapted to several different kinds of apartments. Bathroom and kitchen have their predetermined places, all other rooms can be placed in whatever way the user wants. This flexibility is no longer in use. (Schneider & Till, 2007)

2.2.4 Spatial principles & logics

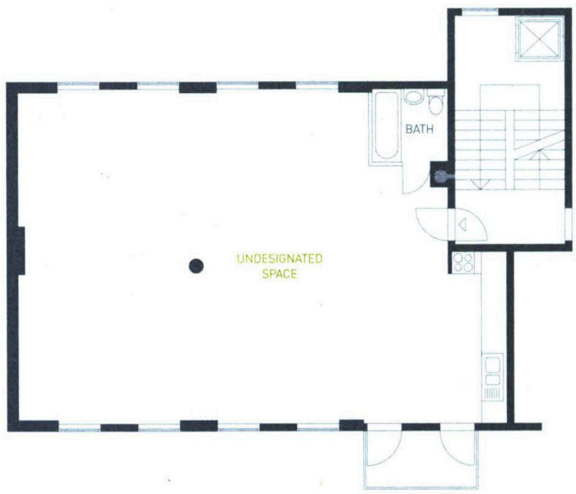


Fig. 60. Empty shell (Schneider & Till, 2007)

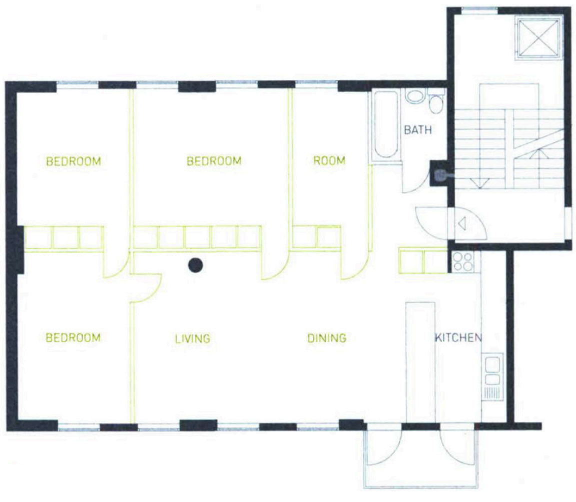


Fig. 61. 3-room apartment (Schneider & Till, 2007)

A8 Snabba Hus

Fig. 62. Snabba Hus (E:son Lindman, 2016)

Andreas Martin-Löf, apartment housing in Västberga, 2016.

A very quick and cheap build, and an award-winning building. Identical modules were built, with one apartment per module. These were placed on a concrete slab, held up by concrete walls. The modules can be removed and reused in another place. (ArchDaily, 2017)

This is a good example of one type of flexibility (movable) making other types of flexibility (versatile, adjustable) impossible.

2.2.2 Types of change
3.2.9 Slab / Volume modules (regular)

A9 STACK II

Arcgency, office building in Copenhagen, 2015.
(Study visit)

Made from recycled shipping containers stacked in irregular patterns, with façade elements filling up the spaces in between. This type of construction creates spaces that can be used differently over time, as well as using the bearing structure (the containers) for rooms as well.

3.2.8 Self-bearing / Combined (volume & flatpack)

Fig. 64. Stack I, staircase (Hjortshøj, 2015b)

Fig. 63. Stack I, interior (Hjortshøj, 2015a)

A10 Stadtgemeinde Hallein

Fig. 65. Stadtgemeinde Hallein, exterior (Tollerian, 2013b)

sps-architekten, elderly care in Hallein, Austria, 2013.

The rooms in this elderly housing is constructed with volumetric CLT modules, and they act as the load-bearing elements of this construction. In between these modules however, CLT floor slabs are placed, to act as corridor and common spaces. This kind of construction is similar to the one suggested in this thesis. The biggest difference is the module stacking, which in this project is regular, one on top of the other. (sps-architekten, 2013)

3.2.8 Self-bearing / Combined (volume & flatpack)

Fig. 66. Stadtgemeinde Hallein, common space (Tollerian, 2013a)

A11 Quinta Monroy

ELEMENTAL, social housing in Iquique, Chile

ELEMENTAL's idea of half a house is implemented here. Instead of building the entire house straight away, and thus raising the prices, they are built smaller but with the inherent possibility to grow. This growth can happen whenever the inhabitant has the money, need or opportunity to build extra.

This half house idea sets some demands on the building. Circulation, installations and structure need to be dimensioned to handle the added load when the house is bigger. (ArchDaily, 2008)

2.2.4 Spatial principles & logics
2.2.5 A manual for flexible housing

Fig. 67. Quinta Monroy, newly built (Palma, 2003)

Fig. 68. Quinta Monroy, after 5 years (ELEMENTAL, 2008)

References & figures

References

Albus, J. (2018). *Construction and design manual : Prefabricated housing* (Vol. Vol. 1: Technologies and methods): DOM publishers.

ArchDaily. (2008). Quinta Monroy / ELEMENTAL.

ArchDaily. (2017). Snabba Hus Västberga / Andreas Martin-Löf Arkitekter. Retrieved from https://www.archdaily.com/875086/snabba-hus-vastberga-andreas-martin-lof-arkitekter

ArchDaily. (2018). Homes for All - Dortheavej Residence / Bjarke Ingels Group. Retrieved from https://www.archdaily.com/903495/homes-for-all-dortheavej-residence-bjarke-ingels-group

Bergdoll, B., Christensen, P., Broadhurst, R., & Museum of Modern Art. (2008). *Home delivery: fabricating the modern dwelling*. Basel; Boston; Berlin: Birkhäuser.

Boverket. (2019). Bygg- och fastighetssektorns energianvändning uppdelat på förnybar energi, fossil energi och kärnkraft. Retrieved from https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/miljoindikatorer---aktuell-status/energianvandning/

Brand, S. (1994). *How Buildings Learn: What Happens After They're Built*: Phoenix Illustrated.

Finch, E. (2009). Flexibility as a design aspiration: the facilities management perspective. *Ambiente Construído, Vol. 9* (No. 2), 7-15.

Francart, N., Malmqvist, T., & Hagbert, P. (2018). Climate target fulfilment in scenarios for a sustainable Swedish built environment beyond growth. *Futures, 98*, 1-18. doi:10.1016/j.futures.2017.12.001

Goodbun, J., & Jaschke, K. (2012). Architecture and Relational Resources: Towards a New Materialist Practice. *Architectural Design, 82* (4), 28-33. doi:10.1002/ad.1424

Groak, S. (1990). *The Idea of Building: Thought and Action in the Design and Production of Buildings*: Taylor & Francis Group.

Guldager Jensen, K., & Sommer, J. (2016). *Building a circular future*: GXN Innovation.

Gunnarsson-Östling, U., Svenfelt, Å., Alfredsson, E., Aretun, Å., Bradley, K., Fauré, E., Fuehrer, P., Hagbert, P., Isaksson, K., Malmaéus, M., Malmqvist, T., Buhr, K., Finnveden, G., Francart, N., Hornborg, A., Stigson, P., & Öhlund, E. (2017). *Scenarier för hållbart samhällsbyggande bortom BNP-tillväxt*.

Hagbert, P., Finnveden, G., Fuehrer, P., Svenfelt, Å., Alfredsson, E., Aretun, Å., Bradley, K., Callmer, Å., Fauré, E., Gunnarsson-Östling, U., Hedberg, M., Hornborg, A., Isaksson, K., Malmaéus, M., Malmqvist, T., Nyblom, Å., Skånberg, K., & Öhlund, E. (2018). *Framtider bortom BNP-tillväxt: Slutrapport från forskningsprogrammet 'Bortom BNP-tillväxt: Scenarier för hållbart samhällsbyggande'*.

IVL Svenska Miljöinstitutet. (2018). Hur skulle ett samhälle som inte bygger på tillväxt kunna se ut? [Video file]. Retrieved from https://www.youtube.com/watch?time_continue=132&v=JjdP0o7Fd20

Kim, Y.-J. (2013). On Flexibility in Architecture: Focused on the Contradiction in Designing Flexible Space and Its Design Proposition. *Architectural Research, Vol, 15* (No. 4), 191-200.

Knaack, U., Chung-Klatte, S., & Hasselbach, R. (2012). *Prefabricated Systems : Principles of Construction*. Basel: Birkhäuser.

Li, Z., Shen, G. Q., & Xue, X. (2014). Critical review of the research on the management of prefabricated construction. *Habitat International* (No. 43), 240-249.

Pereira, J. (2019). Personal communication.

Pons, O. (2014). Assessing the sustainability of prefabricated buildings *Eco-Efficient Construction and Building Materials* (pp. 434-456): Woodhead Publishing Limited.

Reichental, A. (2018). The Future Of 3-D Printing. *Forbes*. Retrieved from https://www.forbes.com/sites/forbestechcouncil/2018/01/23/the-future-of-3-d-printing/#5e11c2c965f6

Rich, B. D. (2016). *Future-Proofing: Seeking Resilience in the Historic Built Environment*.

Schartner, S. (2019). Personal communication.

Schmidt III, R., & Austin, S. (2016). *Adaptable Architecture*: Routledge.

Schneider, T., & Till, J. (2007). *Flexible Housing*: Architectural Press.

sps-architekten. (2013). *Stadtgemeinde Hallein*.

Steinhardt, D. A., Manley, K., & Miller, W. (2013). *Reshaping housing - the role of prefabricated systems*.

Tarpio, J. (2016). Monenlaista joustavuutta. *Arkkitehti* (No. 4), 12-21.

Figures

663highland. (2008). Youkoukan Garden, Fukui, Fukui prefecture, Japan [Online image]. Retrieved from https://en.wikipedia.org/wiki/Tatami#/media/File:Youkoukan06n4592.jpg. CC BY 2.5.

Aaron, P. (2008). Cellophane House [Online image]. Retrieved from https://kierantimberlake.com/files/pages/14/cellophane.jpg?1548845049673.

Brand, S. (1994). *How Buildings Learn: What Happens After They're Built*: Phoenix Illustrated, p. 13, illus.

E:son Lindman, Å. (2016). Snabba Hus Västberga [Online image]. Retrieved from https://images.adsttc.com/media/images/595b/56c7/b22e/386b/ae00/00d0/large_jpg/9042_005.jpg?1499158208.

ELEMENTAL. (2008). Quinta Monroy, 5 years later [Online image]. Retrieved from https://images.adsttc.com/media/images/5010/2dd8/28ba/0d42/2200/0ff3/large_jpg/stringio.jpg?1414338617.

Eliasson, J. (2018). Ceramic tiles, Circle House

Ellgaard, H. (2019). Norra tornen [Online image]. Retrieved from https://commons.wikimedia.org/wiki/File:Norra_tornen,_april_2019.jpg.

Flexator AB. (2017). Loftgångshus, Åsa [Online image]. Retrieved from https://www.flexator.se/globalassets/referenser/boende/loftgangshus-asa/flexator-loftganshus-asa-1.jpg.

Hansen, R. (2016). Martial Cottle Park [Online image]. Retrieved from https://kebony.com/sites/default/files/wood_siding_ideas_01.jpg.

Hjortshøj, R. (2015a). Stack I, interior space [Online image]. Retrieved from https://arcgency.com/unionkul-stack-i.

Hjortshøj, R. (2015b). Stack I, staircase [Online image]. Retrieved from https://arcgency.com/unionkul-stack-i.

Hjortshøj, R. (2018a). Dortheavej, exterior [Online image]. Retrieved from https://big.dk/wp-content/uploads/2018/09/01_BIG_DONG_Dortheavej_Image20by20Rasmus20Hjortshoj-1125x900.jpg.

Hjortshøj, R. (2018b). Dortheavej, interior [Online image]. Retrieved from https://big.dk/wp-content/uploads/2018/09/06_BIG_DONG_Dortheavej_Image20by20Rasmus20Hjortshoj-1125x900.jpg.

Jaksmata. (2008). Balloon frame in Katy, Texas [Online image]. Retrieved from https://commons.wikimedia.org/wiki/File:Wood-framed_house.jpg.

Kakidai. (2018). Nakagin Capsule Tower [Online image]. Retrieved from https://commons.wikimedia.org/wiki/File:2018_Nakagin_Capsule_Tower_02.jpg.

Omniplan. (2017). iValla [Online image]. Retrieved from http://omniplan.se/wp-content/uploads/2017/09/Vallastaden-avslutningehelgen-0793-1150x768.jpg.

Palma, C. (2003). Quinta Monroy, newly built [Online image]. Retrieved from https://images.adsttc.com/media/images/5010/2df1/28ba/0d42/2200/0ff7/large_jpg/stringio.jpg?1414338615.

Schneider, T., & Till, J. (2007). *Flexible Housing*: Architectural Press, p. 70, illus.

Schmidt III, R., & Austin, S. (2016). *Adaptable Architecture*: Routledge, p. 56, illus.

Tkn20. (2007). Mongolian ger: wooden framework covered with one layer of felt. [Online image]. Retrieved from https://commons.wikimedia.org/wiki/File:Yurt-construction-4.JPG.

Tollerian, D. (2013a). Stadtgemeinde Hallein, common space [Online image]. Retrieved from

Tollerian, D. (2013b). Stadtgemeinde Hallein, exterior [Online image]. Retrieved from

World Economic Forum. (2016). Mini Sky City [Online image]. Retrieved from http://www.broad.com/Storage/article/01ec0cbb498348f2a8bf1fe909afbbf8.pdf.

Ziko. (2017). Habitat 67, Montréal [Online image]. Retrieved from https://commons.wikimedia.org/w/index.php?curid=61993924. CC BY-SA 4.0.