Master thesis

Developing a computational method for including a client's input in a mass customizable 3D module building industry.

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Mentors

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Preface

This thesis is done as the final part of the Building Technology Master Track at the Technical University in Delft.

This paper, which took about three-fourths of a year has helped me in many ways to learn more about the building industry and has helped me to look at it from a different perspective.

Prefabrication and industrialization with computational tools have been an interest of mine and was my key learning goal when I enlisted myself for the master track. For this reason, most of my work during the master's track can be related to these learning objectives. I am interested in these objectives because I understand that these tools can aid the building industry in building with higher quality while being more and more sustainable. This thesis focuses more on industrialization and prefabrication and allows room for creating computational methods of working.

I would like to thank my mentors Prof.ir. Thijs Asselbergs and Dr.ir. Pirouz Nourian for their support and insight into relevant research for my thesis. They have smoothened the process of creating methodology and executing on in it to be able

Abstract

This thesis focuses on mass customization using user input in the building environment.

During recent years the need for more housing has only been increasing, while there are also more and more vacant buildings that no longer serve their intended function.

The current building stock is hard to adapt to the changing needs of the inhabitants, which does not promote a sustainable and optimal living condition.

It is in the best interest for everyone to focus more on the optimal living conditions, to make the building industry more efficient in their spending on raw materials and emitting harmful gasses, and to use the limited space optimally.

Industrialization and standardization will be researched to propose a solution for this problem, by developing a method of adaptable and modular buildings using a degree of user input to generate new buildings.

The goal is to use standardization to be able to adapt to the needs of the current market demand, and also to anticipate the changing needs of the future market.

Keywords:
Mass customization, Building industry, user input based design, Adaptability, Flexibility, Architecture

1. Methodology

The building industry is facing a bilateral problem. On the one side, there is the continuous increase of the world's population, with it space becomes more and more of a premium as urban areas continue to be the most popular place to live. On the other side, there is increasing pressure to make the building industry more efficient. This has to do with the pressing need to spent recourses more and more efficiently. The goal of the thesis is to present a literature survey to research industrialization and mass customization and to determine whether or not these methods can improve the current issues. The second goal is to design a proposal for a method that incorporates the theory from the literature survey into a building method that allows for industrialization.

1.1. Problem statement

The building industry needs to comply with more and more demands from both governments and the user base. Material depletion and emissions need to be registered and reduced progressively, while the erection of buildings needs to increase over time to comply with the growing demand for housing. These problems will be addressed.

The goal for the Netherlands is for it to have a circular economy by 2050 that is energy neutral. Similar regulations as in the Netherlands are globally recognizable. This is an enormous task that will require a lot of change and optimization in the current process.

The current building stock will require a lot of adaptation to comply with these regulations. Oftentimes these buildings are not considered to be changed during the design process or prepared for the end-of-life scenario. Therefore, it is a costly job in time and materials to adapt or deconstruct these.

The building industry is one of the largest industries in the world. However, it is not as optimized as other industries in terms of industrialization. Industrialization can offer multiple new options for a sector. Such as mass production and mass customization. Depending on the implementation of these options, they can assist in more customized buildings that can function longer due to adjustments in the building stock that allow for the changing needs of the users. With these options, it is possible to design a framework for the building industry where the use of material and space are considered more carefully and the demands of the user are easier to fulfill.

1.2. Phase 1 - research

The first phase is the research phase. This phase will provide an overview of the relevant literature and will provide the necessary knowledge for the design phase.

Objective

The objective of this research is to provide an overview of the current knowledge on industrialization and prefabrication, and if it can aid the building industry to move towards mass customization. The focus will be on relevant theories, methods, and gaps in existing research.

Research question

The goal of the research is to offer an overview of the components that are needed to enable mass customization in the building industry. Therefore the main research question for this thesis is as follows:

How can a computational method be designed in order to include a client's input in a mass customizable 3D module building industry?

Terminology

- Computational method: A process that makes use of computational power. It is a process with a predetermined procedure to transfer constrained input to the desired output.
- Client: The client can be any citizen, user, or consumer.
- Input: Constrained data provided by the client that serves as input for the computational method.
- Mass customizable: An adaptable and flexible building method with the goal of mass production.
- Module: A three-dimensional volume that when placed in an array creates a grid for a dimensional coordination system.

The literature survey will serve to provide research components for this design objective. In order to do so, the following sub questions have been formulated:

What is industrialization & prefabrication?
Literature points to industrialization and prefabrication as a possible method to achieve mass customization. The benefits and disadvantaged of this method need to be researched in order to provide a solid basis for the thesis.

Why adaptable & flexible?
Adaptability and flexibility are components of sustainability. The degree of adaptability and flexibility can determine how sustainable a building will be. How can these be incorporated in an industrialized building process?

How to incorporation user input?
The last research question will be research by performing a case study. This case study will focus on projects within the scope of the research where either mass customization or prefabrication has been applied together with user input.

Research method

The research method for this survey will be composed of qualitative research methods. The main data will be retrieved by literature reviews of academic papers. Secondly, case studies will be conducted to research computational methods.

Research scope

The scope of the research is based on literature regarding industrialization in the building industry that is focused on mass customization and modularization using user input to guide the process.

Regarding the user input: The scope of the survey is on research and case studies of where user input has been researched or applied to serve mass customization or the adaptability in a project. Other social studies are not inside the scope of this research.

Regarding the modules: The focus of the research will not be on the details of how to manufacture or engineer such a modular system, but rather provide a basis of information that can be added onto in additional research. Table 1 displays the levels of a modular system, and those that are, and are not within the scope.

Table 1. *Terminology of modules to define scope*

	Level	Term	Explanation
	1	Configuration	A Building composed of units
	2	Modular Units	Prefabricated units
↑ Inside scope	3	Modular Rooms	Spatial elements that are types of rooms
↓ Outside scope	4	Assembly of modules of rooms	Linear and planar elements
	5	Parts of modules	Equipment
	6	Pieces of parts	Layers of elements

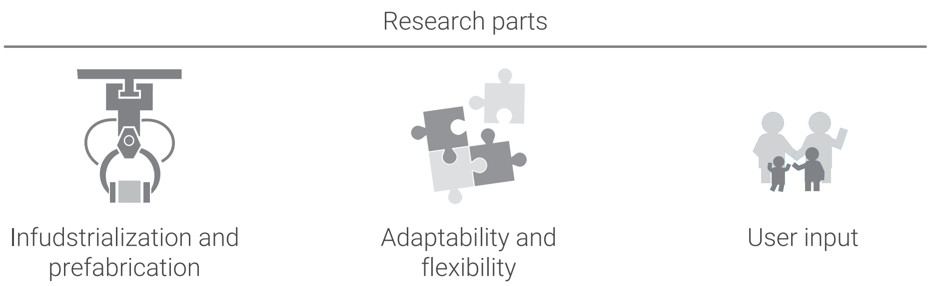


Figure 1. *Phase 1: research components and parts (by Author)*

1.3. Phase 2 - Design

The design phase is followed by the research phase. The goal is to use the relevant theory to create a methodology for designing a building method that is focused on mass customization.

Objective

The objective of the design is to provide a method for applying the theory in practice. The focus of this design will be on the infill level and on how the end-user can adapt this space to their needs. Figure 2 shows how the infill is inserted into the support.

Design objective

The design objective consists out of two phases: The first goal is to offer an overview of the components that are needed to enable mass customization in the building industry. The second goal is to design a suggestion for these components as to how these components can function in practice.

Based on the research phase the following design components and parts have been devised:

1. The infill system
    1. The dimensional coordination system
    2. The volumetric unit
    3. The catalog of modular rooms
2. The open building parts
    1. User interaction
    2. The kit of parts
3. The case study
    1. Example units
    2. The existing building

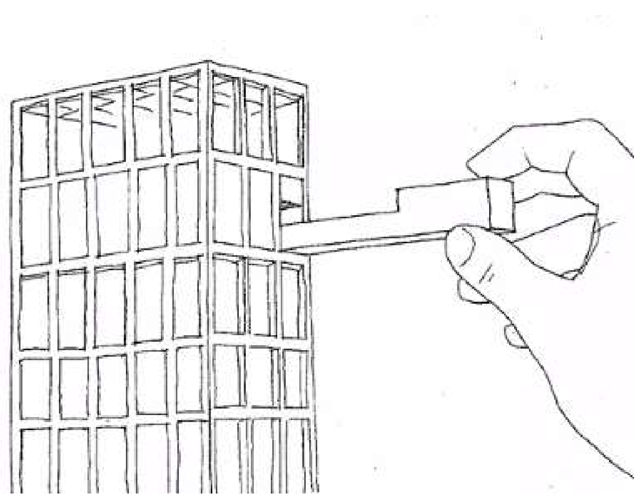


Figure 2. *Depiction of the open building (from open building lecture)*

These design components and parts are graphically summarized in figure 3.

1. The infill system

The infill system will be the method that allows for mass customization. It is the key component of the design phase. Three separate design studies are done to design this infill system based on the literature.

The dimensional coordination system

The dimension coordination system is a three-dimensional system based on rules that allow for mass customization. The system will determine the grid in which components can be designed.

The volumetric unit

The volumetric unit will be the so-called infill component. It is a prefabricated structure that will focus on the usability of the end-user while applying the rules from the previous design component.

The catalog of modular pods

The catalog of modular pods will provide a design study on the components that are placed inside the volumetric unit. To achieve mass customization, the user has to be presented with many, but specific options. The focus is on providing a system of how these options can be designed, and on providing a set of example components to use later on in the design process.

2. The open building parts

The open building parts consist mainly out of the support and the infill. The previous design component is focused on the infill part. This design component is focused on how this infill system can be integrated into the support. Therefore two design parts have been devised.

The user interaction
The user interaction is a key component of the integration of the infill system. It determines how the end-user can configure the unit. This design part focuses on the different design flows that an end-user can choose

The kit of parts
The kit of parts is an overview of all the components that are used in the infill system, and all the components that are necessary to be able to implement this system into the building industry. To function these components are designed together with a set of rules to which these need to comply.

3. The case study

The case study will provide an example of the previous theoretical design components. The example takes all the parts into account and focuses on the accuracy of the created rules for the system.

Example units
Example units are designed that comply to the rules designed in: 'the infill system' design component.

The existing building
The existing building is a case study that focuses on the rules designed in: 'the open building parts'. The goal is to retrofit an existing building to fit the open building system.

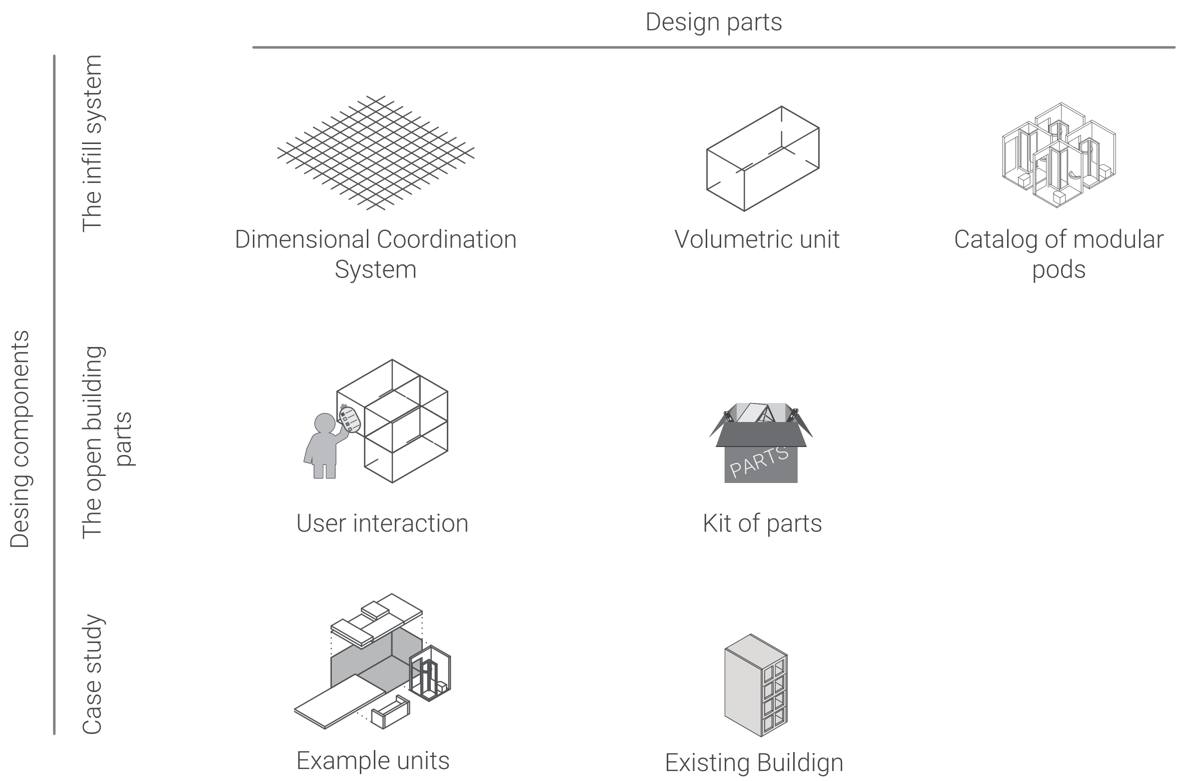
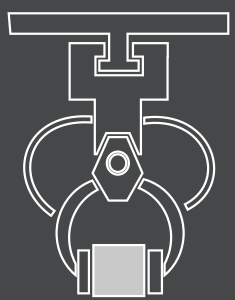
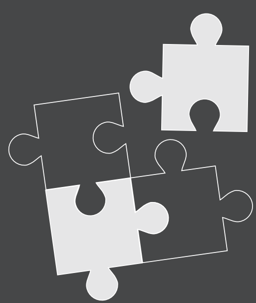


Figure 3. *Phase 2: design components and parts (by Author)*

Phase I: Research





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2. What is industrialization & prefabrication

Today, multiple different industries profit from mass production using industrialization techniques, to name a few: the shipbuilding industry, the aerospace industry, and the automotive industry, starting with Henry Ford who adapted the conveyor belt for the mass production of cars in 1913. According to Delsing, in general, these methods benefit from an accelerated building process due to: rationalization, mechanization, prefabrication, series production, continuity, and systemization (Delsing, 1989, p. 67).

2.1. History of industrialization

Through the years there have been multiple attempts to industrialize the building industry. Most of these attempts were pushed by architects or manufacturers that believed in a new approach for the building industry that would allow for i.e. rapid deployment of urban housing, mass customization, or more affordable housing. In the case of Le Corbusier it was the goal to mass-produce houses:

“We must create the mass-production spirit. The spirit of living in mass-production houses. The spirit of conceiving mass-production houses“ (Vogler & Eekhout, 2016, p. 11)

Literature provides plenty of reasoning as to why to adopt Le Corbusier’s proposed methodology. Bertram et al (2019) state that offsite production can benefit the process because of: a controlled environment, the ability to repeat activities increasing the level of automation, three possible work shifts, parallel with substructure, and quality control. This topic is covered in more detail in chapter 2.2.

However, many of these attempts failed. A. Vogler states it is the Henry Ford Syndrome: “Why can’t we mass-produce houses-standard, well-designed at low cost - in the same way, Ford mass-produces cars?“ (Vogler & Eekhout, 2016, p-1). It is not clear why at this point there is still no answer to this question. Throughout the times there have been plenty of start-ups and entrepreneurs who pushed the idea of converting the building sector to the industry as well. When looking at individual cases in the literature patterns can be seen as to why these case studies have failed to reach the ambitious goal of sustainable mass production. In the case of Pessac (1923), by Le Corbusier, there was a lot of negative publicity. Vogler states: “The local architects made such bad press against the houses, that nobody wanted to take the risk to buy one“ (Vogler & Eekhout, 2016, p. 11).

Gunnison housing corp (1935) is another example of an attempt to push to mash production using prefabricated elements. Gunnison used, as a first in the building industry a conveyor belt to assemble products. The factory reached a point of producing 600 units in a month (Vogler & Eekhout, 2016, p. 15).

Wachsmann, chief designer at Christoph & Unmakck pushed for industrialization using components. He was able to set up the: General Panel factory, located in California (1947), using funding from the government. The factory would be able to produce 30.000 houses a year. However, by 1951 no more than 200 houses were produced, and due to financial problems, the factory had to shut down. According to A. Vogler, the company failed due to mismanagement, lack of funds, and a missed time-to-market window.

Other mentionable startups are:
1947 - General Panel Factory - USA - 30.000 houses per year - 200 total produced.

1946 - Beech Aircraft Corporation - 60.000 houses per year - USA - 1 total produced (Vogler & Eekhout, 2016, p. 18).

1947 - Aluminium Bungalow - 12400 houses per year - UK - 8462 total produced.

However, all these projects have failed, most commonly it is always a problem of finance. But the reasons as to why there is not enough recurring revenue vary more widely:

- Local social environment
- Cultural environment
- Economic environment
- Poor-man’s house image

- Low end touch image

However this time around, as G. Staib puts it: “with the continuously growing ecological and economical challenges facing the construction industry today, structures based on building systems and prefabricated production techniques are becoming increasingly important” (Staib, 2008, p. 5). As seen in different industries, such as automotive, different governments may aid more and more in pushing for more responsible building solutions. Therefore it is more likely that a next: large-scale industrial module start-up will have less trouble financing its endeavors. Some of these start-ups are already present in the Netherlands. A few of these are mentioned in a Webinar hosted by ING (ING Sector Banking, 2020) by T van de Kolk from KolkGroep, T. Opdam from Plegt-Vos Bouwgroup and S. van den Brink from Lister Buildings, H Meurs from VORM and M. Uildriks from MBS Groep. Were serious steps are taken to build factories for prefabricating housing units. Secondly, Bertram et al.(2019), mentions that digitalization and automated design manufacturers can reduce the negative stigma around prefabricated housing by producing high-end homes with a modern look and an emphasis on sustainability.

2.2. Industrialization in the building industry

As can be read in paragraph 2.1, there is no shortage of industrialization projects. However, most of them have yielded no large successes. To the question of: “Why do these innovations come about now?”, R. Krulak from Full Stack Modular mentions that:

> *“The technology really didn’t exist to really affect building a floor at a time, a piece at a time until right now. So the convergence of that technology, the willingness to take risk, and the fact that we understand a lot about it more… is really why… it is a convergence of the willingness and the technology at this point in time that didn’t exist previously.” (Forbes Tech, 2013, 03:25-03:46)*

Cinark Research (2010, p.12) notes that industrialization is a way of bringing the architect and the end-user back in control through the use of new tools that can optimize tasks, and therefore allow for more room for creativity and personalization. They define sustainable architecture as: “Buildings of high architectural quality taking into consideration people, environment and resources – both concerning genesis, use, and maintenance.” (Cinark Research, 2010, p.12). Therefore by utilizing industrialization it is possible to focus on improving sustainability.

To achieve industrialization in the building industry, Delsing (1989, p75) cites six actions that need to be performed by the building industry to achieve an industrial building process: rationalizing, mechanization, prefabricating, serial production, continuity, and systemization. Delsing proposes an addition to this list by Franssens which is automation.

Rationalization is to guide the building process from the start to finish more into a systematic approach that can be repeated

Mechanization, prefabrication, and Automation are defined by Cinark Research (2010, p58-59) as components for the five degrees of industrialization. Prefabrication is described as the first degree of industrialization and it implies building in a factory with a focus on mass production. Mechanization is described as whenever machinery is employed to ease the work of the laborers. It is described as the second degree of industrialization. The last addition from Delsing: Automation, is the third degree and this is when tooling takes over certain tasks from the laborers. In this case, there would only be a supervisor in place to keep a check over the performed actions. The chronological order of the list for the five degrees of industrialization by R.-B. Richard is as follows:

1. Prefabrication
2. Mechanization
3. Automation
4. Robotics: The same as automation with the addition of robotic arms with multiple axis of flexibility to preform the job.
5. Reproduction: A technology that can simplify the fabrication of products.

If a level of industrialization higher than mechanization is also achievable for the building industry, it would be possible to add it to the list to benefit from a better performing industry.

Serial production is when products are produced according to a fixed catalog with similar constraints and measurements system. For an industry to benefit from this type of product all elements must be created according to the same constraints and grid system. Paragraph 3.3 will cover more about these grid and module systems.
Systemization is when every partner has a specific role in the industrialization process.

2.3. The modular building methods of prefabrication

Modular building or construction systems are defined by Staib (2008, p.43) as: "Closed systems in which the elements are prefabricated by the manufacturers independent of a particular building". Multiple different elements are produced that can be assembled to fit a predetermined entity. These methods can be designed in such a way that multiple entities can be combined in different variations. In general, there are four different methods of modular prefabrication. The main difference between them is the size of prefabricated elements and the amount of work that is left to do on the building site once the elements leave the factory. They are named after the primary shape that the elements have (Staib, 2008, p.42, Bertram et al., 2019):

- Linear elements
- Planar elements
- Spatial elements
- Hybrid elements

The methods are graphically shown in figure 4. The methods can increase in scale and complexity. The scale can increase from single individual units to complete structures and fully furnished housing. And the complexity can change from single units and complete structures to fully serviced and finished units, and fully serviced and finished housing. In general, the more the scale and the complexity increase, the less labor is needed on-site and more complete elements are shipped to the building site.

Linear elements

This method is already widely adopted in the building industry. For example, most structural beams are prefabricated as linear elements. However, these elements are often not complex as they are mainly concrete, steel, or wooden beams or pillars and lack finishings. Fully serviced and finished single units are less often used. In general, this system requires the most amount of work on-site. Linear elements are often not complex and easy to connect, but there are often more of them to connect and finishings still

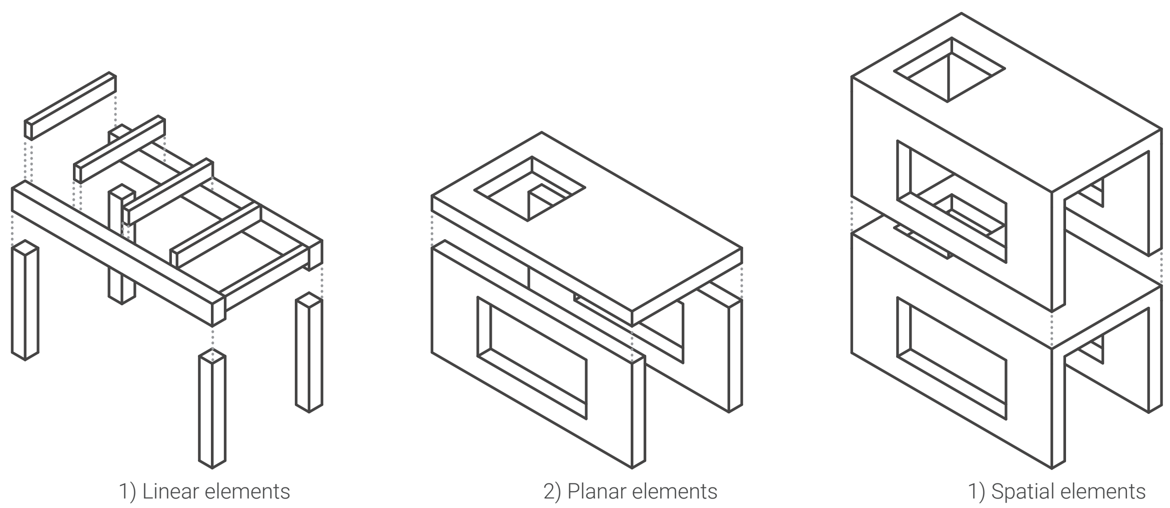

Figure 4. *Prefabrication methods (by author)*

need to be applied.

Planar elements

Planar elements are also referred to as two-dimensional panels (2D elements). These panels perform better on design flexibility and optimized logistics. Therefore they are more used in high-quality single-family housing projects. Complex planar elements contain all the necessary ducts for building services such as HVAC systems, plumbing, and electricity systems. The planar elements are easier to connect than traditional buildings and do not necessarily require more space for transportation.

Spatial elements

Spatial elements also referred to as 3D volumetric elements, are volumetric elements that can represent, a part of, or an entire room. These are blocks are connected on site. Compared to 2D panels they are less flexible and require much more (five to six times) space for transportation. For this reason, they are less suited for single housing units and more optimal for larger suburban housing projects than high-rise units for residential or commercial purposes. The size of spatial elements is often limited by the maximum with, length, and height that is allowed to transport on local roads. Spatial elements become much more expensive when special transport is needed and roads need to be blocked to get the elements to the building site. Once on-site, this method is the fastest for constructing and requires the least amount of time and workers to be applied properly. The benefit of fully serviced and finished rooms (high complexity and large scale units) is that most of the work can be done in the factory. Therefore there is often no need for scaffolding. R. Krulak mentions that another benefit of having modules completely fitted with stairs increase execution, as there is no need for ladders or lifts for a trade to move from one level to another (Forbes Tech, 2013, 03:07-03:16).

Hybrid elements

Most construction is done with not just one method but is executed with mixed-use of the different approaches. Mixed-use of 2D and 3D elements can result, according to Bertram et al. (2019), can be cheaper (3%) than just using 2D elements.

2.4. The effect of modular construction

Regardless of the method, they are all required to be built off-site. When building off-site unlocks multiple advantages according to Bertram et al. (2019) and Cinark Research (2010, p.58). Off-site production is often faster due to a controlled environment, the ability to repeat activities, rationalization of the tasks, increasing level of automation, multiple possible shifts (with a limit of 3), increase quality control, and bulk purchasing. It is also possible to construct the modules while the substructure is still being created, executing these two processes at the same time will decrease the total time needed when comparing to traditional building systems. Also, the modules are often optimized on weight due to transportation, therefore the total building will often weigh less. This directly affects the amount of material that is needed for the substructure. According to R. Krulak, it is also safer because most of the construction is performed close to the ground and in a controlled environment (DisruptCRE, 2019, 02:49). According to their findings, there is also a greater time and cost predictability (98%), less construction waste (<5%) and it requires fewer onsite workers (70%).

The phase where off-site production generally requires more time than traditional building systems is during the design phase. For complex 2D and 3D elements to be created a lot of thought is needed in the design process. However, as projects have been repeated this process is also reduced in time. The true benefit in time can be achieved with the offsite manufacturing and the onsite installation. According to Bertram et al. (2019), This is consistently 20-50% faster than traditional building methods.

3. Why adaptability and flexibility

Dwellings often inhabit different users with changing needs during their user phase. It is often the case that building stock is created based on the temporal needs of market research, with the limited insight of the individual. It is because of this that buildings contentiously change to keep the buildings exploitable. These changes are often expensive processes in the life-cycle of a building. Adaptability and flexibility of buildings are therefore important.

Adaptability implies the ability to change space as fundamental living circumstances change, and flexibility implies the ability of objects to be moved or changed on demand (Demchak, 2000, p.89). By keeping adaptability and flexibility in mind it is possible to design for renovations that allow for better use of space. Renovations are expensive and time-consuming to perform in buildings where these concepts have not been part of the design process. Whereas buildings that have been designed with these concepts in mind can adapt and adjust and therefore can outperform other buildings.

3.1. The effect of adaptability and flexibility

To build adaptable and flexible implies building using user input and customization. Combining these terms with the potential of industrialization results in a definition of mass customization. Marchesi and Matt (2017, p. 2) provide a clear definition of this term:

> *"Mass customization is a mix between mass production and customization. Mass production consists of the creation of large amounts of identical products, such as ready-built homes, to reduce costs significantly, but it results in limited individual choice. Conversely, customization provides a personalized product, such as a custom home built according to the customer's specific requirements, but costs are typically high. A mix of these two strategies can provide product variants and keep costs reduced." (Marchesi & Matt, 2017, p. 2)*

Enabling mass customization allows for industrialization in the building industry. This enables offsite production of building components

Offsite production for mass customization

Offsite production is when elements are created on an offsite location, separate from where the final project will be located. Compared to traditional building systems many activities are shifted to these offsite locations. According to studies by Bertram et al. (2019), Bock & Linner (2015), and Cinark Research (2010, p.58), offsite production has a lot of influence on the time, cost, and quality of a project.

A faster production is one of the benefits of offsite production. Bertram et al. (2019) mention a 20-50% time decrease compared to traditional building systems. Gaining efficiency in the time to market is one of the most important elements to be able to provide a large enough building stock for the increasing population. The faster production can be achieved by a multiplicity of factors.

The first one is a controlled environment. Having a building location where weather changes do not impact the operating environment can increase productivity by the workforce. A driving factor of a traditional building method is to achieve water- and airtight structure as soon as possible. Working offsite removes this constrain for the building sequence and allows for optimization on different, more important, parts. Secondly, certain weather conditions lead to delays in activities. Having a controlled environment will make sure of the right weather conditions for all required actions. The ability to repeat activities and the rationalization of tasks also allow for optimization in the timeline. The repetition of activities allows for a specialized workforce for specific tasks, and also for the increase of automation. Having a fixed location also allows for multiple shifts. With onsite production, there are often only single shifts possible due to noise constraints during different periods of time. With offsite fabrication, a location can be picked where this would not be a constrain. Then it will be possible to have up to three different shifts that will keep production running around the clock.

Another gain in time can be achieved with parallel construction. It is possible for the substructure to be created at the same time as the modules at the offsite

location.
Due to the controlled environment and the repeatability of tasks, it is possible to optimize actions. This gains a time advantage by reducing both the time to perform an action and the total amount of required reworks. The change for a defect not being noticed onsite is higher which increases the risk for reworks later on in the process which is often both harder to fix and more expensive.
Having an offsite location allows for bulk purchasing and storing of materials. Because of economies of scale, this ultimately drives down the costs for the project.
Projects build offsite often weigh less than projects build onsite. This is because prefabricated elements usually are optimized on weight for transportation. A weight reduction will decrease the amount of material that is needed for the substructure.

There are also multiple hazards to consider when opting for offsite construction. Some of these are transportation, duplicate use of materials, and an increase in the time to design.
The size of offsite elements is always limited to the maximum size that can be transported on the roads. The cost will go up if special transport is necessary. Also, spatial elements will cause a lot of air to be transported due to the inability of stacking that is possible with linear or planar elements.
Duplicate use of materials is often needed because elements need to be brought into place. Elements that wouldn't require structural properties in traditional onsite building methods, might need to be on offsite production because they are required to be lifted into place.
Lastly, the planning and design phase takes longer and is more expensive. The very first project requires a lot of design and also an initial investment in the factory. Designing and optimizing a factory is considered to be extremely difficult and requires much time. However, as with materials, economies of scale come into play. When a functioning design is created, the next iterations of it will become increasingly improved and faster to produce.

3.2. Open building system

When mentioning Open Building, it is important to also mention J. Habraken. Who devoted a lot of research to this concept. Habraken defines Open Building as follows: "The idea of distinct Levels of intervention in the built environment, such as those represented by 'support' and 'infill', or by urban design and architecture. The idea that users/inhabitants may make design decisions as well. "(Habraken, n.d.)

Dwellings often inhabit different users with changing needs during their user phase. It is often the case that building stock is created based on the temporal needs of market research, with the limited insight of the individual. It is because of this that buildings contentiously change to keep the buildings exploitable. These changes are often expensive processes in the life-cycle of a building.

Open Building (Open bouwen) was founded in the Netherlands in 1984. During that time the Dutch government stated that: The open building is seen, also by the Dutch government, as the best method towards innovation in the housing construction.
The Open Building method takes three points into account:
1. Dimensional coordination
2. Separation of the support and the infill
3. Building metrology

Dimensional coordination
Dimensional coordination is a system of agreements regarding measurements and placement agreements. The goal of creating this set of rules is to be able to connect all different elements to each other in a single system which is followed by all materials. This will ensure that there will be as few as possible custom parts that need to be created for an individual case. On this basis, a single rectangular module (M) is created. Stacking these modules across the x and y direction will create a design grid. The M contains a single value in the x and y direction, after which a multiplication of this module is referred to as n * M. Modules will be more carefully explained in chapter 3.3.

Some barriers have to be overcome to successfully integrate dimensional coordination (Delsing, 1989, p. 143)

- Most elements available today are not based on a shared dimensional system, they rather created their own standardized system that are accepted based on local expectations or manufacturing standards.
- Tolerances are a second barrier. Different material elements have different expansion rates/ connections which will result in custom connections even if elements share the same dimensional coordination.

Due to the fragmentation of the many different suppliers it is difficult adapt this dimensional coordination on a large enough scale.

Separation of the support and the infill

For the separation between the support and the infill, it can be explained as the parts that are collective and the parts that are individual. In this, the support acts as an open system that can be used for the infill. The purpose of the support is to serve the needs of the infill. The infill can change over time, depending on the needs of the individual. This approach of building design connects with the need for adaptability. Delsing states that three suggestions can be recommended to increase the quality of the support and the infill: “1. Enlarge the influence of the user throughout the entire building process. 2, Keep future exploitation possibilities into account. 3, differentiate pars of objects in life-cycles.“ (Delsing, 1989, p. 88). The last note connects well with the idea of separating building elements by Steward Brand. He suggests that there are different layers in a building with different lifespans:

the site: forever, the structure: 30-300 years, the skin: 30-50 years, services: 7-20 years, spatial plan 5-7 years, and the stuff, like furniture, can change within a year.

Adapting a building so that the different layers can be changed separately from each other can help to lower the previously mentioned exploitation costs. In this system, by Brand, the structure can not directly be compared to the separation of the support and the infill

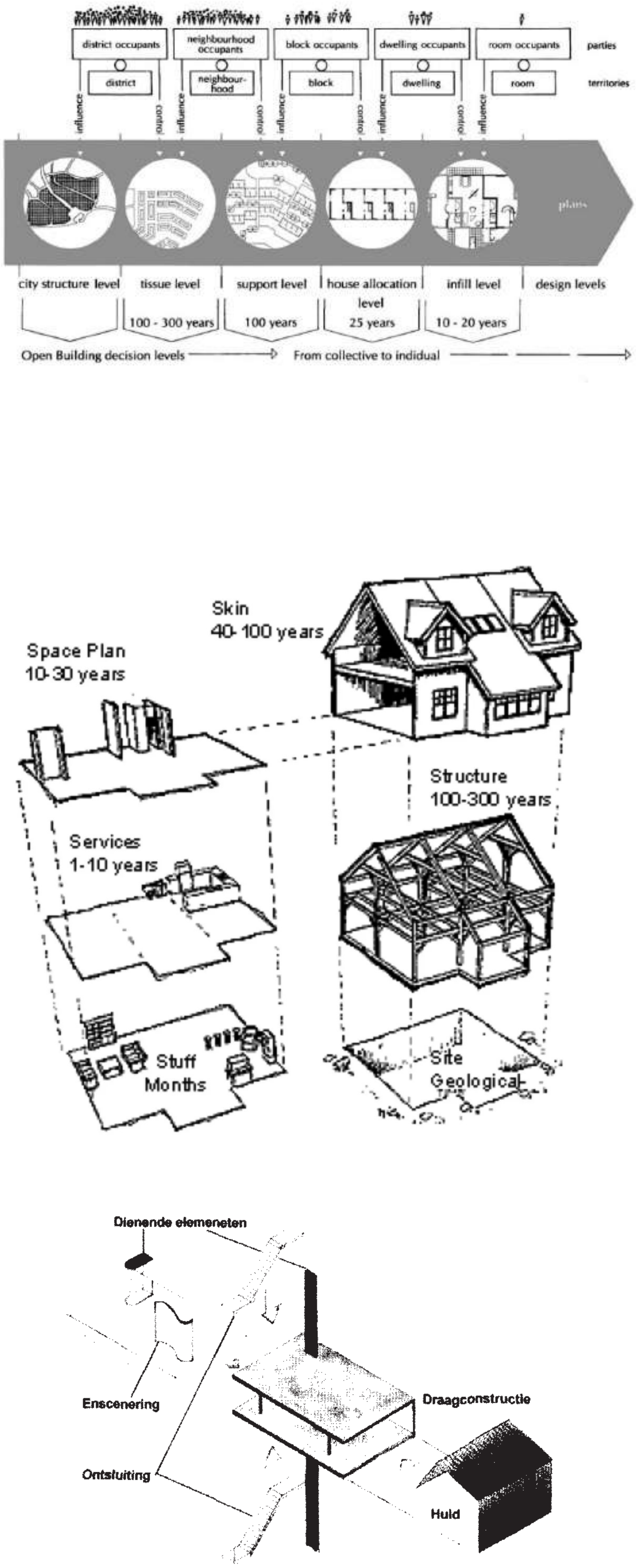

Figure 5. *Habraken (Lo, Schnabel, & Gao, 2015), Brand (Staib, 2008), Leupen (Leupen, 2002), Delsing*

of Habraken. To increase the adaptability of a building the structure can be separated into the foundation and the structure above the ground. The foundation has a longer timespan and can be harder to change than the support.

A third method is proposed by Leupen (2002, p31). He proposes a separation by functions, rather than by elements. The system is composed out of five functions: Structure, skin, access elements, dividing elements, serving elements, and access elements.

The last system is mentioned by Delsing (1989, p124) This system divides the building into seven parts: the foundation, the structure, the skin, the division in space, the connection climate, the control of climate, and the services.

These different systems proposed by Habraken, Brand, Leupen, and Delsing serve the same goal: 'To separate the building in different elements.' Separating these elements will increase the adaptability and change the end-of-life strategy. The end-of-life strategy is especially important because this approach would allow for dismantled elements to be reused or recycled, which could make up for the use of extra materials that are needed to create such a system. By separating elements with different functions, and different lifespans, it is possible to introduce subsystems in a building. These subsystems can be removed and changed separately from different systems.

This allows the systems to be changed when either new systems are available, systems are worn out, or when the user preferences change. To be able to change these subsystems will make the buildings flexible and adaptable which is necessary to achieve open building according to F. Bijdendijk (2015, p26). For these systems to work, elements in a building only need to fulfill one function. For example, if an element has both a structural and a skin purpose, it cannot be separated individually. This approach could introduce more elements in a system than would otherwise be necessary for more traditional building systems where the end-of-life scenario is less incorporated.

How flexible these systems are can be measured using three different indicators that are listed by Delsing (1989, pp 127-128): demountable connections, the last-in-first-out principle, and the degree of freedom.

The demountability has to do about the connections of the subsystems, and whether they can be removed without damaging other subsystems or connections.

Last-in-first-out has to do with the order of assembly. Subsystems with shorter lifespans are optimally placed after systems with longer lifespans. This makes it possible to access the systems better without having to remove more durable systems.

The last flexibility indicator is the degree of freedom. If a structure is designed with future expansions in mind, it is possible to make more changes.

Combining these indicators and systems of separating building elements is possible to achieve a flexible and adaptable infill and support.

3.3. How to achieve adaptability and flexibility

The previous chapter went into different methods and systems that can define adaptability and flexibility in a building. However, to anticipate it , Delsing, (1989, p.88) proposes three pointers to take into account during the design phase of the project:

- Enlarge the influence of the user during the entire building process.
- Keep future exploitation possibilities of the building process in mind.
- Define objects according to their "life cycle".

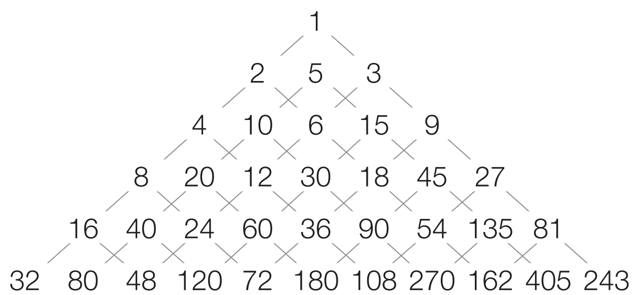

Figure 6. *Preferred multiples (Staib, 2008, p.45)*

In order to achieve this level of adaptability, it is necessary to work on a common grid. The grid is best explained by Staib:

> *The grid is a geometrical system that determines the position and dimensions of modular building elements. The basis is provided by a spatial network of dimensional lines generally based on a square or rectangular system... The planning, manufacture and assembly of the building elements are based on this system. (staib, 2008 p.44)*

Delsing (1989, p76) notes that standardization of measurements is one of the most important steps to reach a industrial system. The grid can be used as a common language among subsystems to provide this standardization.

It is unlikely that there is one grid system that can serve the needs of all subsystems and functions that need to be created in a modular industry. Different spaces, functions, and requirements call for different measurement systems. Therefore a distinction between different groups of spaces needs to be established. Habraken (1976) mentions that access- and vertical service elements play a large role in the layout of the support and infill. These modules are described as M. The general basic module unit in Europe is M = 100mm. All measurements are multiples of the module so they fit in the same grid. Krippner, Lang, and Herzog (2004, p.49) describe that there are preferred multiples of modules to be able to achieve multi-modular sizes of elements (figure 6). In an industrial system, it is important to limit the number of multiples for the modules to be able to achieve serial production. For these systems, a more broad planning grid can be introduced, which is based on the multiples of the single module. An example of a planning grid is introduced by MACE (Russell, 1981, p. 566). The system consists out of a 100mm basic module (M). The planning grid is created as 9Mx9M with 1Mx1M bands creating a tartan grid-like pattern. Later on, Russell (1981, p. 581) notes that a one-by-one-meter planning grid is too coarse because it produces useless space for toilets, corridors, and smaller rooms. Habraken proposes a system of four zones that separate space and to be able to introduce multiple planning grids in the same building. The α-zones, β-zone, γ-zone, and the δ-zone:

- α-zones: Inside and adjacent to an external wall
- β-zone: Inside and not adjacent to an external wall
- δ-zone: Private outdoor space
- γ-zone: Internal or external space for public use

Distinguishing functions and zones within a project could help to define a measurement system that works on each level.

A Grid is needed to start creating such a measurement system. In general, there are two types of grid systems (Krippner, Lang, & Herzog, 2004, pp. 48–51) the axial grid and the modular grid.

The axial grid is commonly used nowadays in most construction projects. This grid type references the center of a building element. Therefore, the thickness of building elements is not taken into account.

The second, less commonly used is the modular system. The biggest difference with the axial grid is that this system does take the thicknesses of elements into account. This means that less overlapping of elements can occur. This system is most suited for building elements that are regularly laid out within a modular system. A single unit of measure is taken for creating this module. This module can be based on the human body (Delsing, 1989 p.104), for example on tatami mats or the feet. Within these systems, it is possible to have multiple grids of different functions. For example, pipework for MEP systems can be placed according to their own grid system, a services grid, that functions in the modular grid.

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4. How to incorporate user input in the building industry

The goal of this chapter is to present an overview of case studies were user input has been used to apply mass customization. The first two paragraphs will go over the practical qualities of Open building: Flexibility and adaptability and mass customization. The third paragraph will present the case study. This chapter contains two topics for case studies. The first topic is regarding adaptability and flexibility and how it is applied in multiple different projects. The focus of the second case study is regarding mass customization and building with user input.

4.1. Flexible and adaptable buildings

So far flexibility and adaptability have been discussed in previous chapters. However, how to achieve these qualities in a project has not been discussed. In Three ways of assembling a house, Cinark Research (2010, p.26) introduces a model named: the model of flexibility (figure 7). The model describes the qualities of building systems with the level of few to many possibilities on the y-axis and open to fixed possibilities on the x-axis. Herein mass customization is defined as a building system with many but specific possibilities. To determine the adaptability T. Frantzen proposes a model to classify buildings to determine their level of the open building ("Open Building NOW! Lecture by Tom Frantzen," 2020, 20:05-24:45). A total of nine classifications are ranked from non-flexible as the lowest to max-flexible as the highest rank. This table (Table 2) can be used to classify multiple different buildings in terms of their flexibility. The grayed-out cells determine the level of flexibility for a class. For example, if a building has fully integrated installations in the load-bearing structure, it is graded as non-flexible. These models can aid in the design and grading of buildings to determine whether their design is according to Open-Building standards.

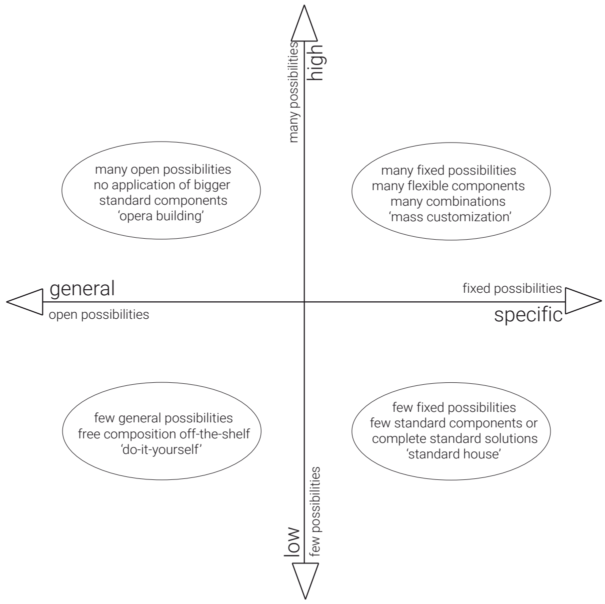

Figure 7. *Model of flexibility (Cinark Research, 2010)*

Table 2. *Classification system by T. Frantzen ("Open Building NOW! Lecture by Tom Frantzen," 2020, 20:05-24:45)*

	Installations fully integrated in load bearing and apartment-dividing structure	**Installations partly independent of load bearing and apartment-dividing structure**	**Installations fully independent of load bearing and aprartment-dividing structure**	**Division walls coincide with load bearing structure**	**Division walls independent of load bearing structure**	**Facade independent from load bearing structure**	**Extra floor height**	**Free function zoing (to allow programmatic transformation)**	**Number of arartment-rights > number of apartments**
Non-flexible / one time flexible									
Slightly flexible									
Flexible									
Very flexible									
Max-flexible									

4.2. Mass customization and user input

As Cinark Research (2010, p. 43) states: "Mass customization is proclaimed as the overall answer to ... integrate the user in creating higher quality industrialized products." There are multiple methods of how to introduce user input to mass customization. The level of flexibility can range from, for example, only being able to select a few custom colors for paint, to being able to determine the complete layout and size of the users' apartment. According to the research, there seems to be no consensus on how much flexibility the user needs to be able to reach a sustainable housing market that is able to efficiently adapt to new needs. Cinark Research (2010, p. 31) states on the topic that it is most important that the user has the feeling that he has a choice or influence on the appearance of the personal living space. In this, the user demands this flexibility in order to be able to reflect personal identity to space. However, full flexibility would increase the complexity of this platform and it would be necessary to introduce an expert user i.e. an architect or engineer to the process to aid the user. This complex level of flexibility would also imply that an industrialized system would not be able to profit from a simplified building process, or from the rationalization of the tasks. M. Koehler's mentions the topic of user influences: "The funny thing is, that most people are very happy just to choose from a catalog, between 3, 4, 5 configurations. And maybe 20% really wants to design their own loft." ("WAF 2019 - Marc Koehler's Talk," 2020, 33:37-33:52). In addition (Cinark Research, 2010, p. 32) research shows that the number of options does not directly influence the sense of flexibility. Even if all options are available and there are no constraints, people still have the tendency towards a limited few options. According to this research, it is possible to propose a system created by expert users that is optimized in terms of the complex building system and industrialization, with the flexibility for the user input in mind. This method would allow for not only flexibility for the anticipated end-user but also, maybe more importantly, still for the unanticipated end user that will follow after a move. This is described as a limited solution space where a production system can automatically handle variations of a successive product. This limited solution space can be created using constraints. These constraints create the solution space for the operator, which is based on standards or parameters, creating a modular system. A modular system is a closed system that functions with a catalog of prefabricated elements that can be organized in different ways to create complete entities.

4.3. Case study: Modular systems

A case study is conducted in order to provide a better overview of a modular system that profits from mass customization. Cinark Research (2010, pp.54-55) concludes that the more end-user orientated and the more product integrated a project is, the more complex it becomes. More integration requires more embedded intelligence or computation power but is also able to provide more complete or more complex data that can benefit the industrialization process.

The goal of the case study is to research how user input can be incorporated and to what extent it incorporates the end-user and the product integration.

The following projects are researched in the case study:

- Towards a post industrial architecture case study.
- Bumblebeespace
- Molenvliet
- Patch 22
- Superlofts Houthavens
- Creatomus
- The New Makers

Towards a post industrial architecture case study

Demchak (2000, pp. 110-121) provides a case study where to potential clients get to design their house using a web interface design. This case study provides an example of how user input can be incorporated into a mass customization system. At the start of the design, process information is collected about the clients. This information is then used to present multiple visualizations of design options. These visualizations can be adjusted on specific areas such as room materials, spacial character, and geometry. The information is stored and collected on the website. This information is translated into simple data for the client. A budget is displayed so that if a client exceeds the budget, he is able to selectively go through the design and change options according to their priorities. Giving this flexibility it is possible for the client to put value into what is most important to them.

During the design phase the program checks for conflicting parameters. These conflicts can either be adjusted by the software or it can present the user with options in order to generate a design that complies with the constraints.

In the case study clients are able to add rooms such as bedrooms and kitchens in the sizes: S, M, L, and XL. Secondly, clients are able to provide a preference of connections between rooms and spaces.

After the preferences have been selected, the client is presented with multiple layout options that suit their selected design parameters. The client is then asked to select the layout that suits their needs best.

After this phase, the second transformation phase can start. In this, it is possible for the client to change the geometric composition, wall openings, materials, module definition, and lighting. During all phases, it is possible for the client to go back and make changes to add rooms or select different layouts.

User integration in this case is done through a highly-optimized web interface. No additional input from expert users is needed. The basic layout is generated based on simple user parameters and is later fine-tuned according to the clients wishes. In this case, both the focus of the project is end-user oriented. No details on project integration are shared. However, based on the standardized process that clients are guided through, it can be imagined that the production process can be integrated into this flow.

Figure 8. *Bumblelbeespace bed module (Bumblebeespace, n.d.)*

Bumblebeespaces

Bumblebee is a company located in America, San Fransico. The goal of the company is to utilize the volume of a room better by also enabling the ceiling as a place for storage. By applying this system it is possible to give a single room multiple functions. The ceiling modules can be configured by the user in any pattern or configuration they prefer. The main modules would function as a place to store items. But it is also possible to incorporate tables, desks, and beds in the modules. This system could function well within the Open Building concept. As seen in Table 1 extra floor height increases the flexibility of a building. The extra height of a module grants the potential flexibility for it to be a spacious living room, a functional bedroom, or an office space. In this manner, extra floor height can increase the usability at locations where square meters come at a premium.

User integration for this system can work seamlessly with the previous proposal. It can function as another layer of options to present to a client. For example, it can offer a layout that has been optimized based on square meters and integrate pairs of rooms inside the same space.

Molenvliet project

The Molenvliet project (1970) was designed by Frans van der Werf (Geldermans, Tenpierik, & Luscuere, 2019, p.8), and incorporated the proposed typology by Habraken of the infill and the support. In total 80 rental spaces were designed. User integration was done with the help of an expert user. Each user was scheduled for two one-hour infill consults. The first meeting concerned spaces and functions, but also the ages, hobbies, and preferences of the client. The second meeting conducted two weeks later concerned details regarding the previously proposed plan.

In this case, user integration is high because the expert user sat down with the clients to come up with a combinatorial solution based on the knowledge of the expert user and the wishes of the clients. However, due to a large amount of manual labor and the intensive involvement of the expert user, project integration is relatively low.

Patch 22

The building Patch 22, designed by T. Frantzen is a high-rise building 30 meters tall, mostly from wood, and is located in Amsterdam, the Netherlands ("Open Building NOW! lecture by Tom Frantzen," 2020). Together with C. Oussoren they initiated the project. Having the architect as a designer and developer allowed them to achieve what they had never been able to manage when working on commission.
Their goal was to develop a flexible building that allowed for clients to design their floorplans, while also keeping the building convertible.
The building was designed to be able to have multiple locations for front doors. This was because during the design phase it is still unclear what the building's infill will look like, and therefore multiple options need to be taken into account. For the project, it was important to keep the floorplan as empty as possible. Therefore, meters and fuse boxes are moved to an independent separate location. This method connects with Brand's proposal of repeating layers in a building system.
With a 3.5-meter free height space and a 0.5-meter hollow floor, it is possible to house multiple different functions inside the building, which makes it possible to convert

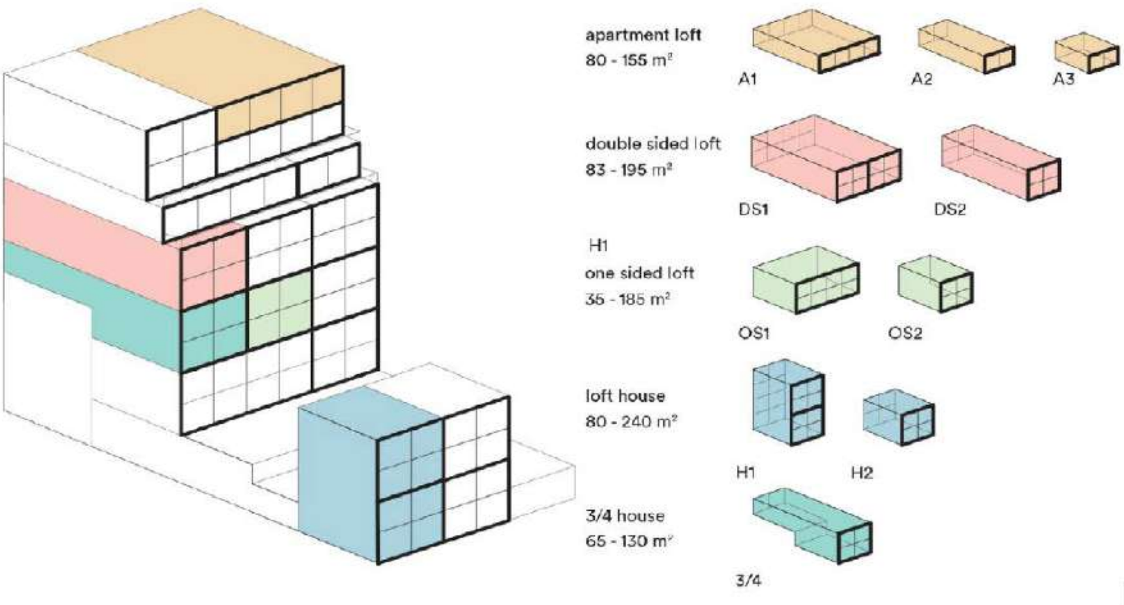

Figure 9. *Superlofts arrangement types by MKA (MKA, 2016)*

homes into offices.

As an example, 24 layouts were designed by the architect, but none of them were picked by the clients. All users opted to change the floorplans to their preferences.

Superlofts Houthavens

The firm MKA designed multiple: Superlofts projects. Houthavens is one of these projects. The goal of the Superlofts is to make the buildings according to the open building system proposed by Habraken and to thereby give users more control over their own space ("WAF 2019 - Marc Koehler's Talk," 2020). Different from Patch 22, vertical control of apartment design is introduced. With this design, it was possible to create multiple different configurations as can be seen in figure 9. The development of the support and the infill is done separately. It is possible for clients to design their own infill with multiple different architects. To allow for this system to work MKA developed a process that allows for different kinds of clients to take different routes in this design phase. For most clients, it is enough to be able to choose from a catalog of designs, but some prefer a more creative route. To allow for this level of flexibility it was again, as with Patch 22, needed to separate the service elements from the floorplans. The adaptable floorplan allows for changes over time and for the building to adapt to the changing needs of clients.

Creatomus

Creatomus is a company that offers a online configurator to aid a client in configuring a house to their needs. The designs are based of 369 Pattern Building industrial construction system. This is a system of parts that allows for a modular construction system based of volumetric units. They offer stakeholders their design services to aid the process of developing a mass customizable project and creating a configurator for the end-user alongside. With this service they have created multiple different tailored configurators that function for different housing concepts.

Figure 10 displays a still image of the configuration for a Tube House. It is possible to select various options (5) throughout three steps (2). When making changes in the design the data of cost estimation (11) and floorplan area (12) change accordingly. The fixed amount of options presents the user with a limited solution space that guides them in the decision making process.

Fabfield

Fabfield is a company that offers an open infill system based on 2D milled parts. They offer flat pack planar elements that can be build by the clients themselves. Projects are based on mass customization and are created entirely through the use of digital production. The client is able to design their project using online tools (figure 11). Basic elements can be chosen from a catalog and moved on a fixed grid system in order to build a custom design. With this tool the client is able to design a custom project that is not fixed in a limited solution space. However due to the high amount of customization an expert user needs to be involved in the process to check the design options.

Figure 10. *Tube house configurator by Creatomus (Creatomus, n.d.)*

Figure 11. *Fabfield builder tool by The New Makers (The New Makers, n.d.)*

5. Research conclusion

The goal of this paper was to provide an overview of current literature on industrialization in the building industry that was focused on modularization using user input to guide the process. The following question was devised to research this topic: *How can a computational method be designed in order to include a client's input in a mass customizable 3D module building industry?* In order to answer this research question, three subquestions are devised:

What is industrialization and prefabrication?

Industrialization is a way of bringing the architect and the end-user back in control through the use of new tools that can optimize tasks, and therefore allow for more room for creativity and personalization. To apply industrialization is to move a large portion of the building process to offsite manufacturing. This offsite construction has the potential to decrease: the time to market and the use of materials, while also being able to increase quality control and cost predictability. The challenge to make industrialization work for the building industry is to restructure the current fractured building process where a lot of different parties add different elements to the process.

Why adaptable and flexible?

Mass customization is achieved through flexibility and adaptability. It combines industrialization and customization to apply it on a large scale. Key components that need to be taken into account when building adaptable and flexible are: separating building elements, separating zones, dimensional coordination mass customization, and offsite production. The open building method combines these elements and divides a building into the collective support and the individual infill. This method allows introducing user input to a building system.

Why incorporate user input?

When introducing user input to a building system, a balance needs to be struck between customization and prefabrication to allow for mass customization, this is achieved when the user is presented with many, but specific possibilities. Integrating the user in the process can result in a higher quality industrialized product.

Based on the research a computational method for including a client's input in a mass customizable 3D module building industry can be designed with the following key components:

- A Dimensional coordination grid system
- A volumetric unit
- A catalog of modular rooms
- A method for user interaction
- A kit of parts for the open building method

According to the literature survey research, these elements combined are a computational method for a user input-based mass customizable open building system.

The next phase will focus on the design part. In this phase, the above-listed design elements will be researched by design.

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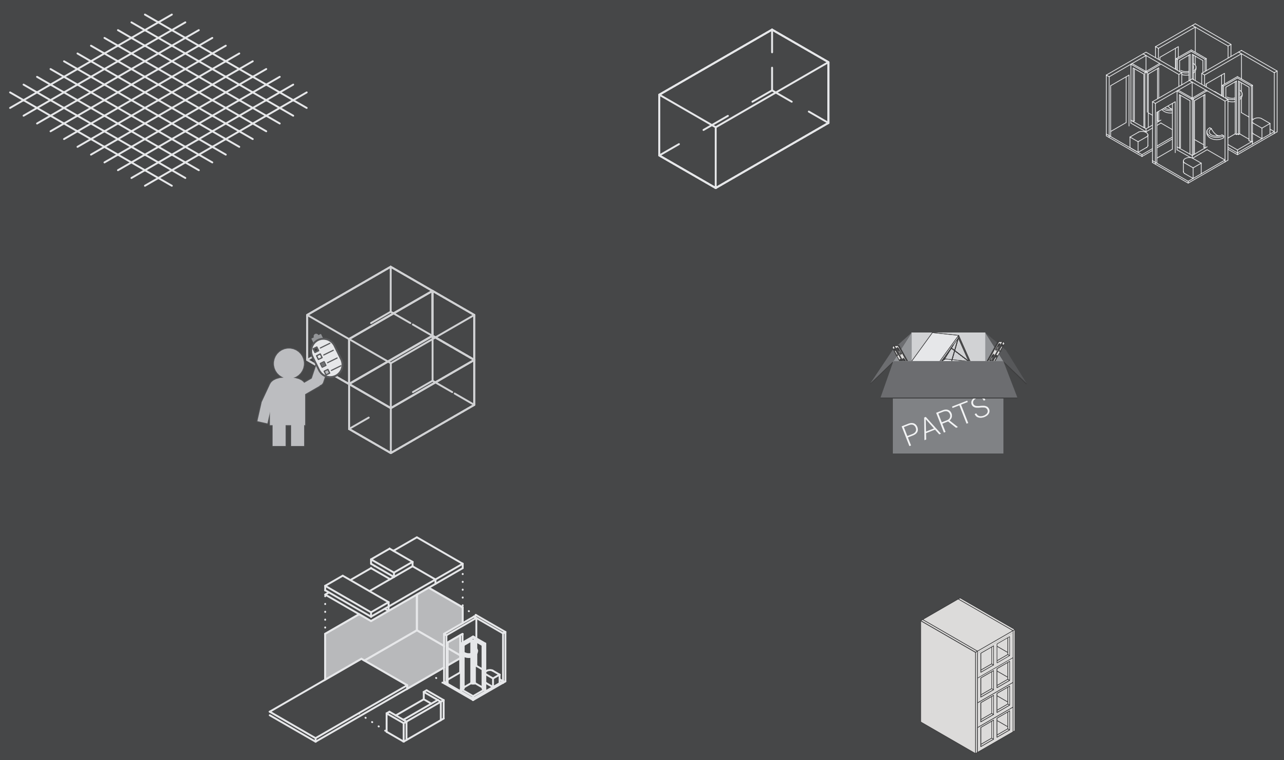
Phase I: Design



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6. Dimensional coordination sytem

This chapter marks the first step of the design process for the development of an open building system. A functioning grid might be the most important part of the successful execution of the open building concept. It needs to be able to adapt to new needs or sub-systems in order to function. For example, one of the most well-known grids is the one used by LEGO. The grid of extrusions on each block ensures a certain proportion and connection among all pieces. Part of the success of LEGO is the backward compatibility of new and old pieces, they still fit the same pattern. This backward compatibility is a key requirement for mass production and the end-of-life strategy for the sub-systems.

Of a grid, the most important component is the module. The module, as explained in paragraph 3.3., is a tridimensional shape that represents the smallest size of a grid. Each measurement is a multiple of this module.

With these modules, a planning grid, or tartan grid can be created. The purpose of such a modular grid is to be able to take thicknesses of elements into account. Literature suggests multiple different module sizes. A European standard is 100mm in the x and y space. Habraken in the 1988 Shell Infill House suggests a band grid with bands of 100 and 200mm.

For this design by research, a module will be proposed that is based on human dimensions. The concept of basing measurements on the human body is very old and can be traced back ca 3000 B.C. to the Egyptians (Haak, Burgh, & der Burgh, 1980, p.1; Neufert & Neufert, 2012, p.27), who devised a decimal system based on parts of the human body. Other well-known systems that are based on the human body are the tatami mat or the feet (Delsing, 1989, pp.104-156).

In order to determine the size of a module, the decision has been made to choose an object that a user uses in the x,y, and z space. The most common object that comes to mind is the stair. Of all building elements, the stair is most connected to the human scale (Haak et al., 1980, p.29). Therefore the assumption is made that if a module can fit a stair, it will fit other elements as well.

The length of a stride is one of the most important measurements for designing a stair. This is because one stride should span two risers (R in mm) and one tread (T in mm). The length of a stride is 600 to 630mm (Haak, Burgh, & der Burgh, 1980, p.30). Therefore: (2xR+T=600 to 630mm).

Secondly, the incline determines the type of stair. If the incline is too steep it will result in a ladder rather than a stair, and if it is too shallow it will result in a ramp. Figure 12 shows the incline of various stair types (Haak et al., 1980, p.29). From this figure, it can be determined that a stair should have an incline between 30° and 45°.

Within the constraints of a stride between 600 to 630mm and an incline between 30° and 45°, there are a lot of combinations that could result in an optimal stair that can be the basis for a module. To limit the number of options a third constrain is added to the list: the module has to be a multiple of the European standard size of 100mm in x and y-direction. Adding this constrain makes sense for the incorporation with most existing building elements. To guide the decision, even more, Haak et al describe the

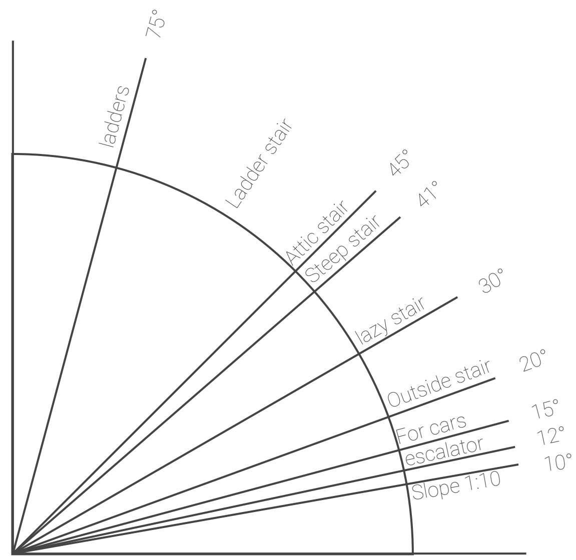


Figure 12. *Incline of various riser types (by Author)*

preferred physiologically stairs are (R-T): 250-190 (38°), 290-170 (30°), and 410/110 (16°) (Haak et al., 1980, p.32).

Between these, 250-190 fits the constraints the most. It allows for an x and y dimension of 50mm. The Z dimension would need to be a multiple of, or 190mm exactly. This results in the following module proposal (x,y,z): 50x50x47,5 mm (figure 13). So for the x- and the y-direction of this module the dimensions are primarily based on research from the SAR, the European standard, and suggestions from J. Habraken. (NEN, 1986; 1988 Shell Infill House). The dimension for the z-direction are based on research from: de menselijke maat and Neufert (Haak et al., 1980; Neufert & Neufert, 2012). Together they form the Micro voxel of 150x150x190mm.

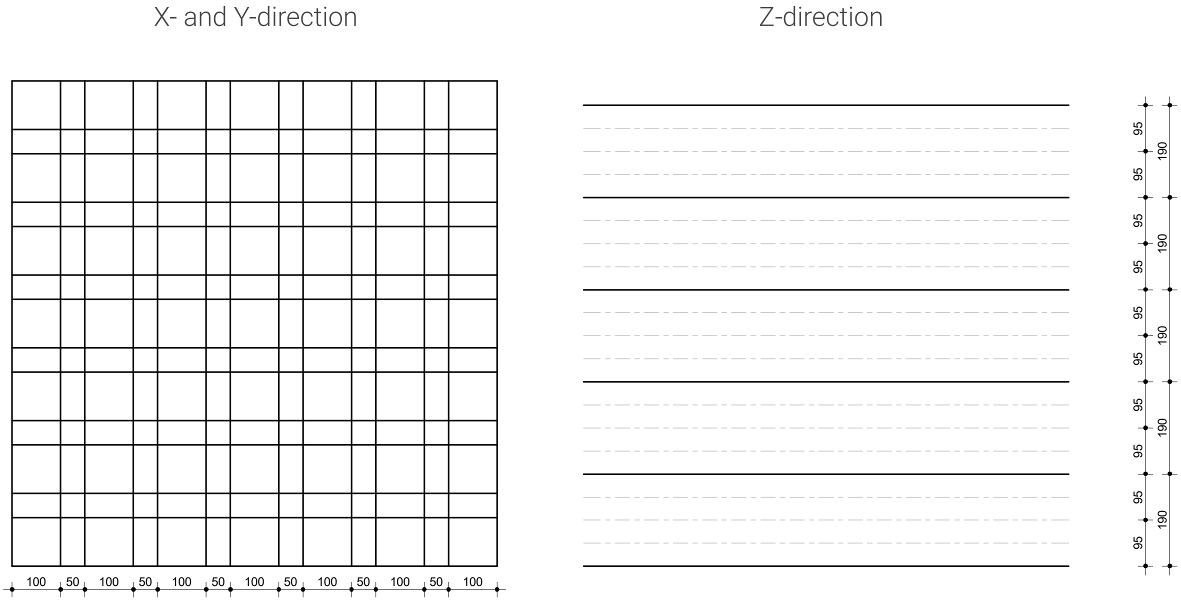


Figure 13. *Module and grid proposal (by Author)*

7. Volumetric unit

The size of 1one unit needs to be determined. One unit represents one volumetric prefabricated structure, that can be used as the shell of the infill system. For this unit the following requirements are set:

- One unit should fit a studio apartment
- Two units should fit a one bedroom apartment
- Three units should fit a two bedroom apartment

These guidelines match the volumetric modular apartment building in New York ("2018 Innovation Conference - 461 Dean 'Delivering the Tallest Volumetric Modular Apartment Building,'" 2019, 04:59-05:21).

Additional requirements for the unit the unit are to make the infill more multi functional as it should also be able to change the function of (a part of) the building. Housing should, for example, be able to be exchanged for office space when the local needs change. For the changing of function it is easier to change residential space to office space. Changing the other way around will result in the need of placing a lot of additional service systems and shafts to provide for the extra bathrooms, sinks and toilets. For this reason the main design goal is focused on the residential function. However, extra demands for office space, such as extra free height and space for electrical systems should be taken into account.

The strategy for designing this unit is to first determine the maximum size of a unit, then the minimum size of a unit, and use the data from those studies to design the final unit.

7.1. Infill and support

As stated in the scope, this research only regards the infill of a mass customizable system. For it, it is assumed that support can be designed that fulfills all the requirements of the infill system. However, for designing the infill it is needed to define more closely what is part of it, and what is part of the support. As explained in chapter 3.2 of the research: The infill is the individual part of the building, and the support is the collective. For this study, the infill is defined as the volumetric unit. Therefore, it does not need to contain complete separating walls to the outside or to other apartments, but it does need to be able to carry itself to be able to be moved are hoisted into place. It will also contain basic walls, floors, and ceilings for service systems and finishings. Therefore, separation of all zones: α-, β-, γ- and the δ-zone (chapter 3.3. of the research) will be done with a layer of 100mm fitting the dimensional coordination system.

7.2. Maximum size of the volumetric unit

When deciding on a volume for the unit, the biggest constrain is the transportation limit. For a system to function in mass production, it should be able to ship units on public roads without having to obtain special shipping permits. For this research, only Dutch regulations are taken into account. The limits of transportable volumetric units are (L x W x H): 18,00x3,50x4,35m.

7.3. Minimum size of the volumetric unit

The minimum size regards a few more constraints than for the biggest unit. A unit should be able to house a studio apartment containing all the necessities. To be able to

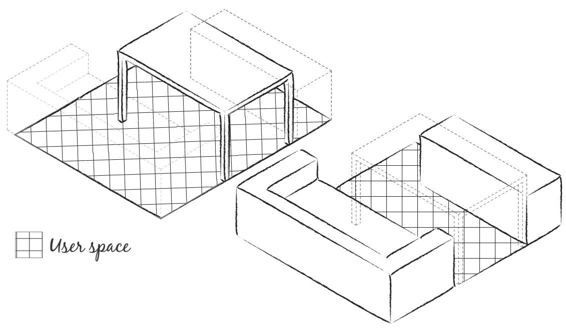


Figure 14. Configuration of user- and physical space (by Author)

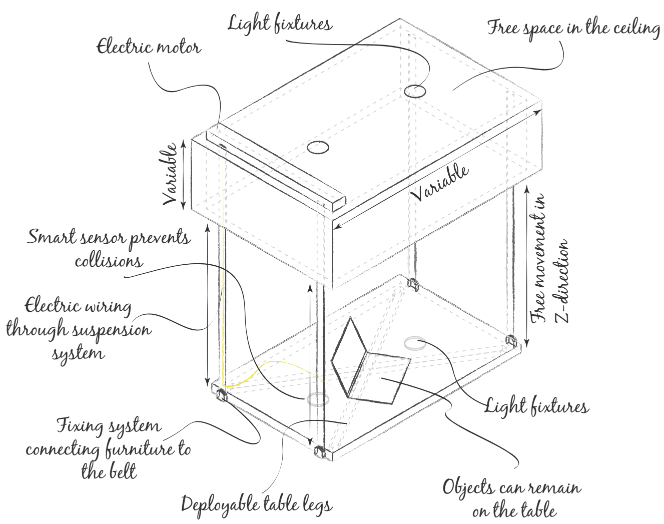


Figure 15. Ceiling box concept (by Author)

design for the smallest footprint space has to be used in all dimensions. Therefore, the concepts presented in chapter 4.3 of the research will be applied to be able to also use the space in three dimensions. Applying this strategy allows for a multifunction use of the space. Space can be occupied in two different ways: it can contain a physical object, or it can contain a user space/ corridor. With the option to move furniture in the z-axis it is possible to change a user space to a physical space and vice versa. Figure 14 depicts a configuration where it is possible to occupy the same space with a table or with a couch and a side table. Figure 15 depicts an example of a tabletop system that can be moved in the z-direction into the ceiling. The concept of switching user and physical spaces will be used to design a unit with the smallest footprint.

Requirements smallest unit

The smallest unit can be configured in a seemingly endless amount of ways. For example, Terzidis provides a list of 384 possible arrangements of a small bathroom with four objects: a door, a shower, a toilet, and a washbasin (2014, p. 84). Therefore, for designing the most compact unit there is most likely no one answer there will always be multiple solutions. This design study aims to achieve one of these solutions as an example to serve the rest. It will be designed using objects that are designed for the human scale (Haak et al., 1980; Neufert & Neufert, 2012).

Vertical space

The vertical space should be able to be used in different ways. For now, there are three types of functions that require different use of vertical space:

- Apartments
- Loft apartments
- Office

Figure 16 shows the different height requirements and the use of the space for the different types of spaces that can be accommodated in the unit.

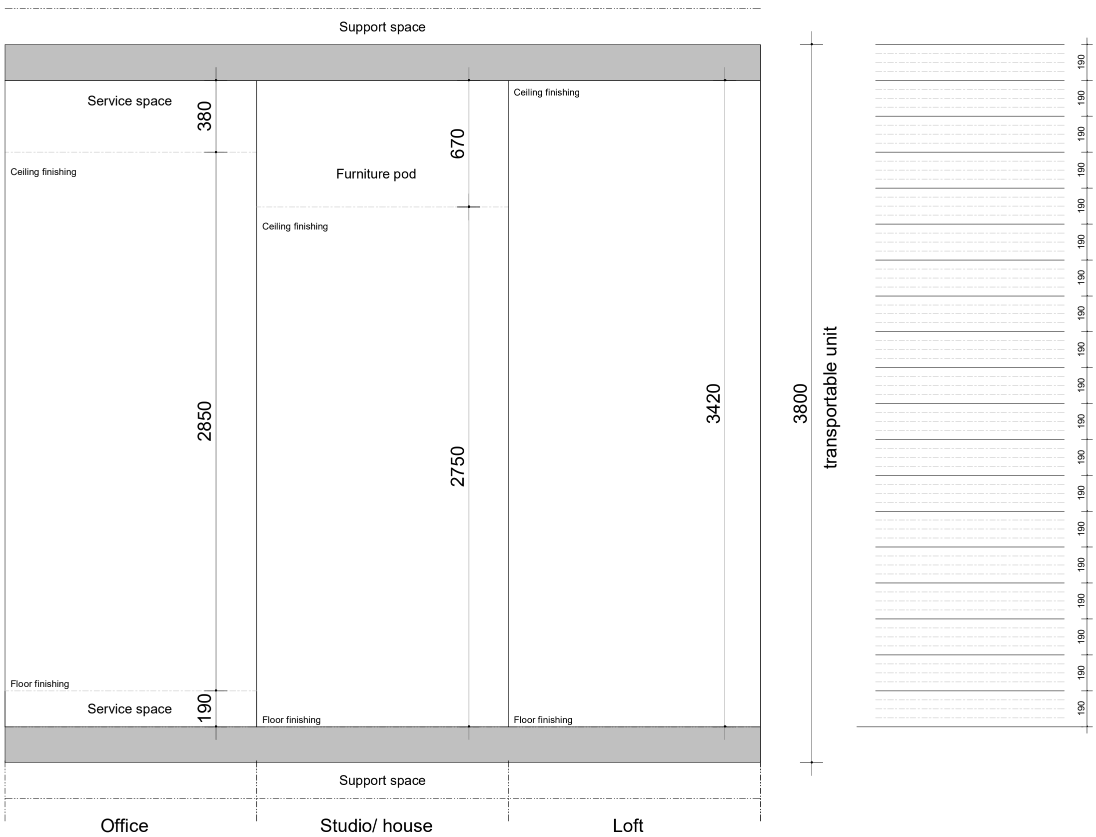


Figure 16. *User of vertical space (by Author)*

Case study

For the case study, a corridor flat is considered. This type has been chosen because it allows for the least amount of options for configuration. This is because there is only one facade that allows for the placement of windows, and as a result, all the living spaces have to be adjacent to this wall.

Figure 17 shows a design of the three different floorplans. The design incorporates all the previously listed requirements and is designed using building Dutch codes and sizes of rooms. Furniture is used that is based on research by Haak and Neufert. The use of vertical furniture allowed for smaller spaces.

Figure 18 shows the different room configurations that are possible due to the vertical movement of furniture.

4.4. Final size of the volumetric units

With the design studies the maximum and minimum sizes are established:

Maximum: 18,00x 3,50x 4,35m,

Minimum: 5,05x 3,40x 3,62m.

For continuing the design process some decisions have to be made in order to choose the final size.

Multiple arguments are in favor of going with the maximum size. Having a bigger size would require fewer units to fill the entire space. It would therefore also require fewer actions to complete a building with larger units because there are fewer crane movements and fewer connections to be made. With regards to the number of connections, in general, it can be stated that the fewer connections there are, the better quality can be guaranteed. Also, fewer connections will also mean less material used.

However, there are also arguments in favor of choosing a smaller size. In order for placing units, smaller size is easier to (re)place and install. It would also allow for a greater amount of flexibility in the division of space since smaller units are able to be placed in a greater variety than a large unit. This would allow users to have more impact on their final design.

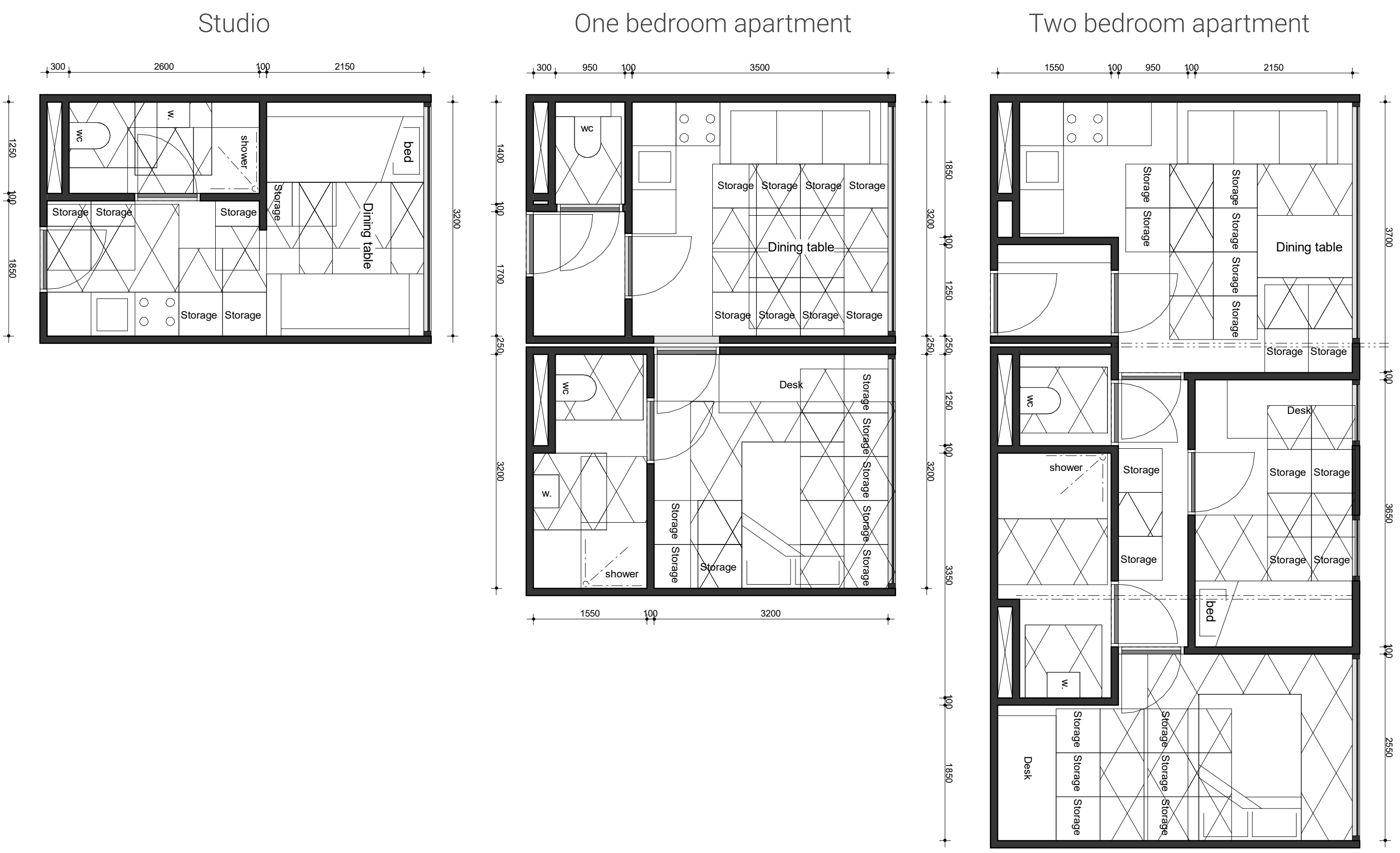


Figure 17. *Floorplan: smallest unit (by Author)*

The final decision for this design research is to go with the smaller size. This is because this would allow for better incorporation with the open building philosophy of the infill and the support. And although arguably it will use more material, it will also be easier to design strategies of separating them by following strategies of separating that are proposed by Habraken, Brand, and Leupen (chapter 3.2 of the literature survey).

For the final size, a scaled voxel based on the micro voxel is designed that it will still fit in the same system. Leading in this is the maximum allowable width of transport and the dimensional coordination system. This results in a width of 3,4 meters and a Mezo voxel of 3,4 x 3,4 x 3,8 meters.

The final size of the unit is the two Mezo voxels combined. This results in a unit of 3,4x 6,8x 3,8 meters that fits the smallest unit and the dimensional coordination system. According to the design study (figure 8 & 9), one unit can fit a single studio, two units are able to fit a one-bedroom apartment, and three units can fit a two-bedroom apartment:

- Studio: 21 m^2
- One bedroom apartment: 42 m^2
- Two bedroom apartment: 63 m^2

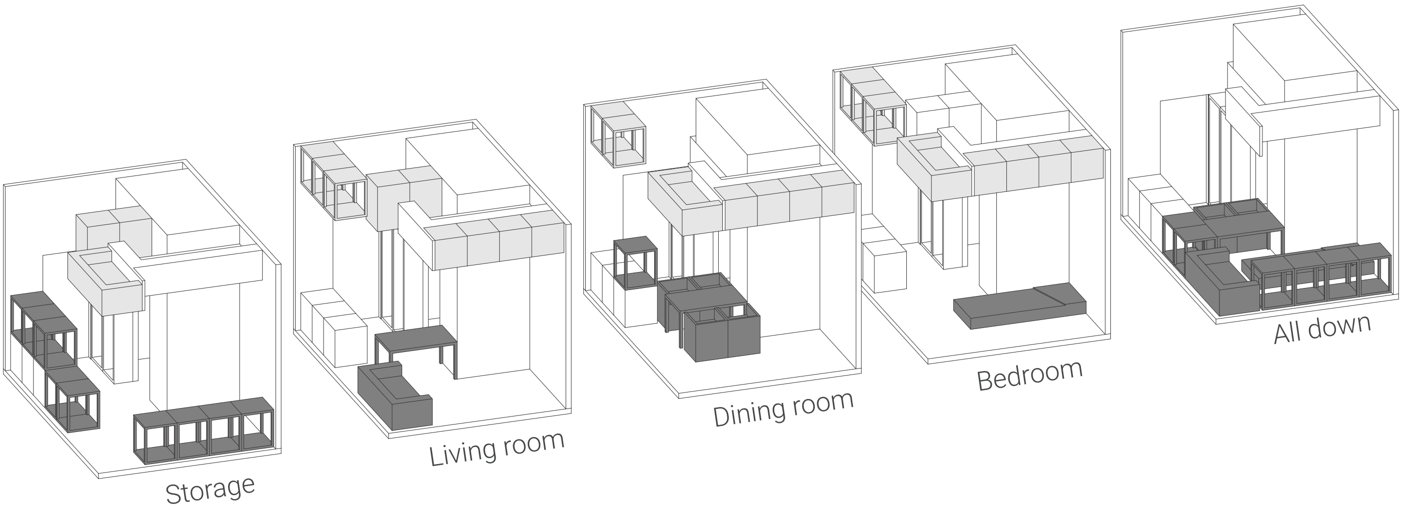


Figure 18. *Configuration of furniture for the smallest unit (by Author)*

8. Catalog of modular pods

The catalog of modular pods is the last part of the proposal for an open building system. The catalog needs to contain many but specific options for clients to be able to achieve mass customization. The goal for the first version of the catalog is to make it with high accuracy and low precision, therefore it has to function in a large percentage of the design cases.

A modular pod is a prefabricated room/ area that can be assembled offsite and installed in the unit before shipping it to the building site. Examples of a modular pod can be a toilet, bathroom but also a configuration of the z-furniture system. The first goal of this design part is to determine which types of pods are needed. To increase the scope the design task will again be limited to the smallest unit. The second goal is to design a select number of pods to serve the case study.

The catalog will be presented in a data tree that contains different levels. The levels are based on naming from Dutch legislation for spaces. For this design, the focus is on the residential function. In this, the first most broad level is the function type of the rooms, of which there are only two categories: Living spaces and functional spaces. Secondly, the different rooms are listed.

- Living spaces
    - Kitchen
    - Living room
    - Bedroom
    - Study room
- Functional spaces
    - Water closet
    - Bathroom

For this design study, only the spaces for the smallest unit will be designed. These are the kitchen, bedroom, study room, and bathroom.

What is designed

The pods contain fixed furniture and appliances that can not be moved around. The majority of these appliances can normally be found in wet rooms such as the bathroom and the water closets, but also the kitchens. The reason for these appliances to be fixed is that they are connected to ducts and shafts that are not designed for movement.

Due to the challenge of designing the smallest unit, there are also other pieces of furniture that can not be considered to be stationary. All the Z-furniture is fixed to the ceiling and can therefore also be moved in the Z-direction. Therefore, the Z-furniture will also be taken into account for designing the pods.

For designing these pods the human scale will be leading. Minimal heights and widths of elements will be taken into account, as well as the userspace that is needed to interact with the elements (figure 14).

Naming structure

A code is introduced in order to structure the pods and the subsystems in the pods:
(1) Pod name - (2) Subsystem - (3) Tree number - (4) System number (5) Z furniture

1. First three letters of the full pod name
2. Letter from A to Z naming the subsystem in a pod
3. Tree structure. The depth of the three can vary among elements
4. System number. Multiple variations of the same component.
5. Use as Z-furniture. 0 = no, 1= yes

Example:
KIT-A-1-1-0
X1 - #1.#2.#3... - #1/0
X = host that can fit elements that contain this code
#1 = first host element
#2 = second host element
#3... = third host element

8.1. The Kitchen

Of all room types, the kitchen might be the most complex space for a pod. Due to a large number of different elements, it can contain. Some elements are optional but some are mandatory for a functioning apartment.

Figure 19 displays the available elements and their names. For the kitchen mandatory elements are:

- A.1.2 or A.2.3
- A.1.5 or A.2.4
- B.1.2.1 or B.1.2.2
- B.1.1
- B.1.2.3

Restricted collisions (elements that can not be next to or underneath each other:

- If host B = B.1.2.2/B.1.2.1 then next host B ≠ next to B.1.1
- If host B contains B.1.1 then Host A ≠ A.1.1/A.1.2/A.1.4/A.1.5
- If host B contains B.1.1 and Host A contains A.2 then Host A2.1 ≠ A.1.x.1/A.1.x.3/A.1.x.4

Figure 20 shows example configurations that meet the constrains.

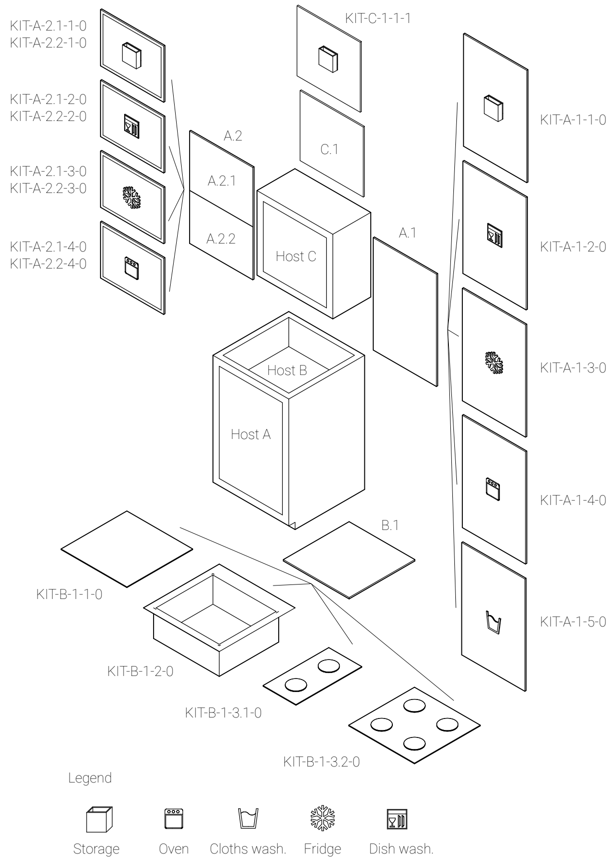


Figure 19. *Available kitchen elements*

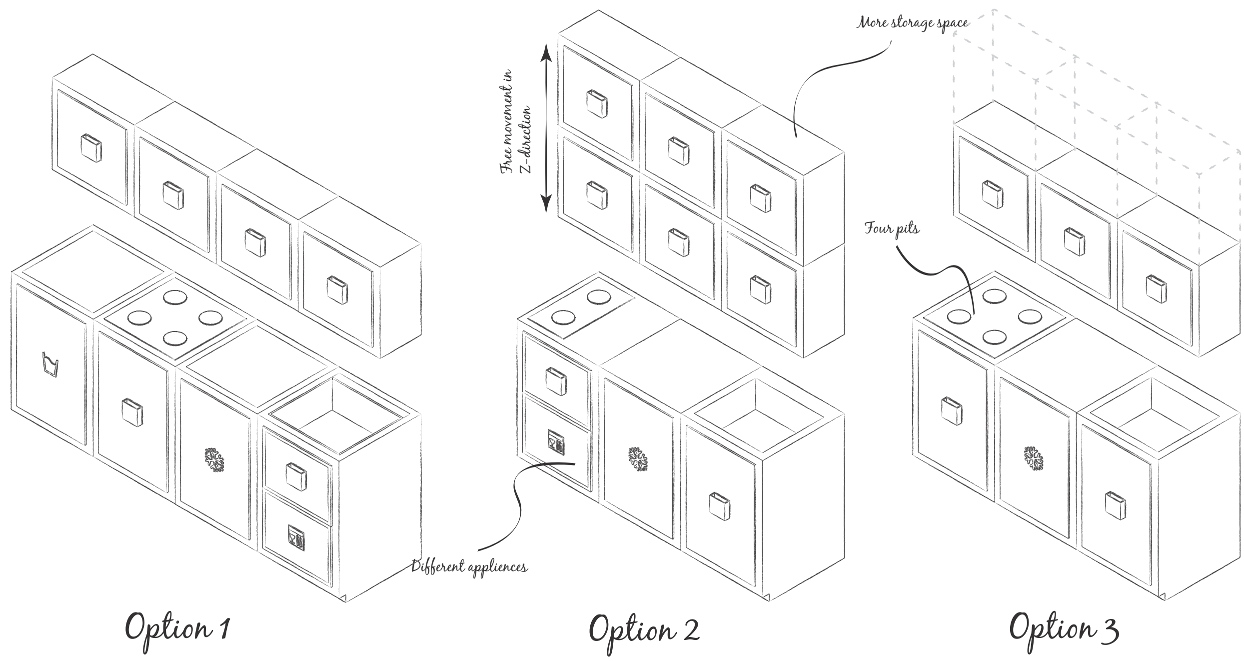


Figure 20. *Possible kitchen configurations*

8.2. The Living room

The living room of the smallest unit only contains Z-furniture. The furniture used in figure 21 and a few common pieces of furniture are designed to serve as an example for the case study.

Since the Z-furniture is considered to be fixed, it has to align with the module (figure 22). In this case, it is important that the furniture aligns with all the other prefabricated components to the sub-systems and the open building principles.

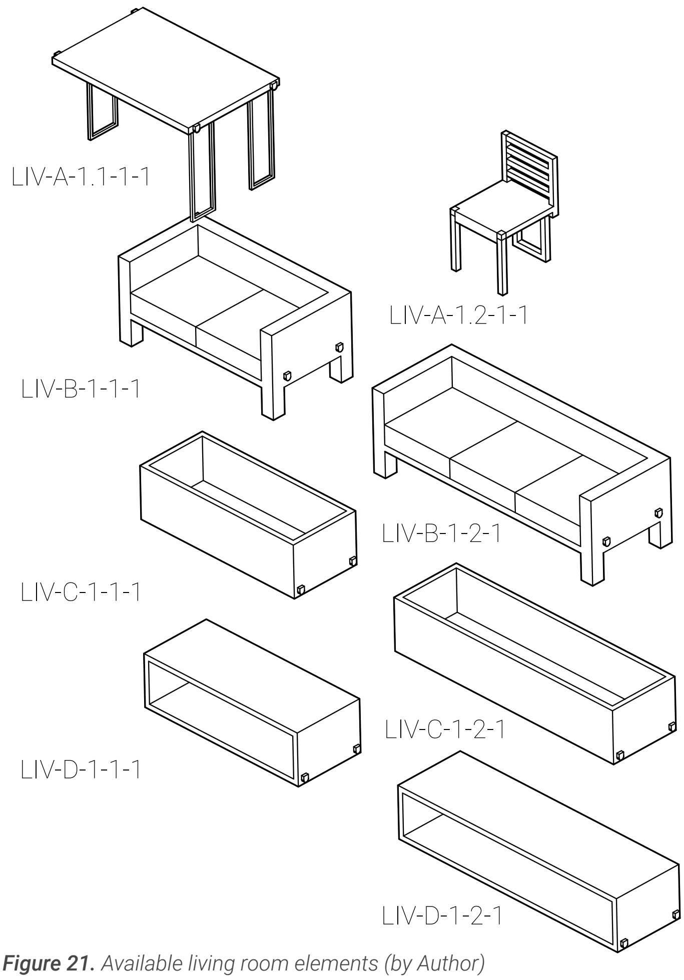


Figure 21. *Available living room elements (by Author)*

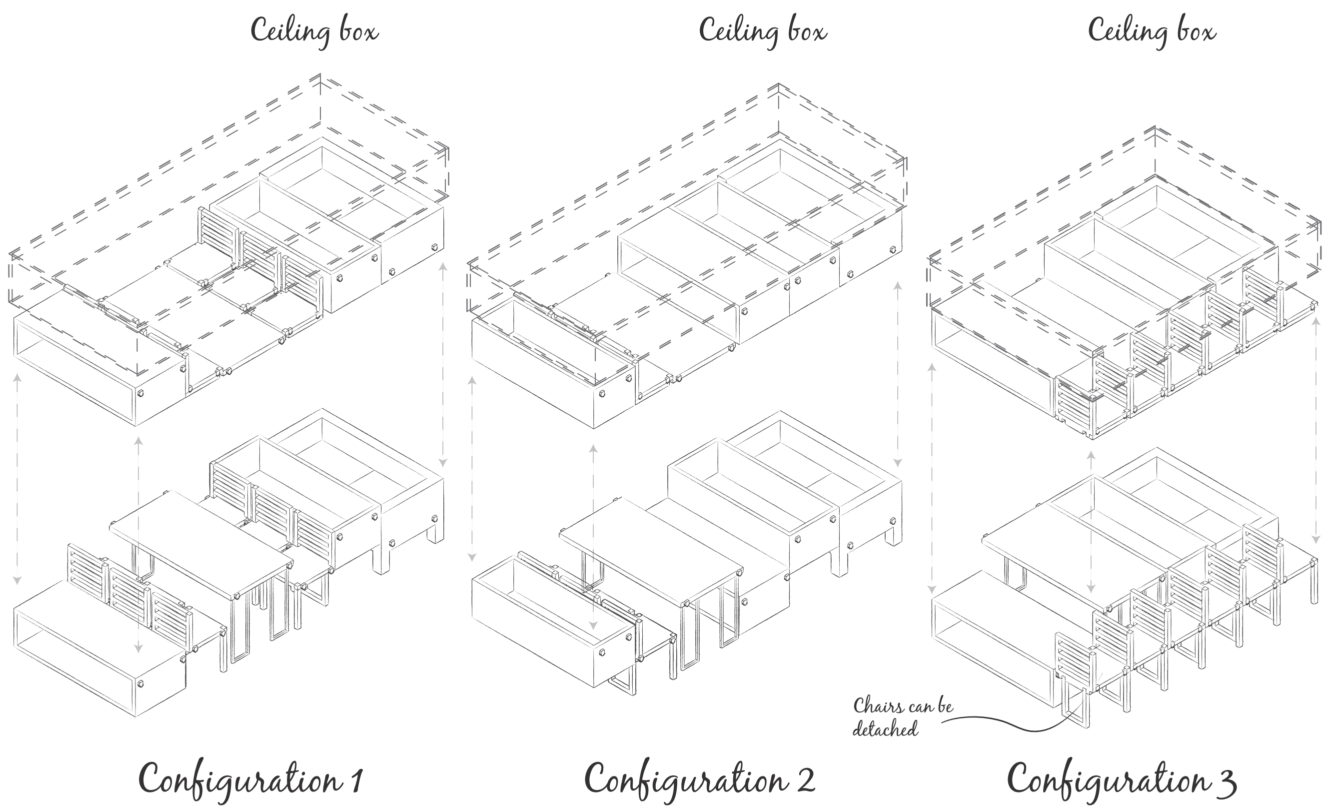


Figure 22. *Possible living room configurations (by Author)*

8.3. The bedroom & study room

The most prominent component of the bedroom is the bed. When considering Z-furniture as an option for possible configurations the bed has the most impact. A small bedroom can be filled completely with a two-person bed. When removing the bed it is possible to use the room for a secondary function during the day, such as a study room.

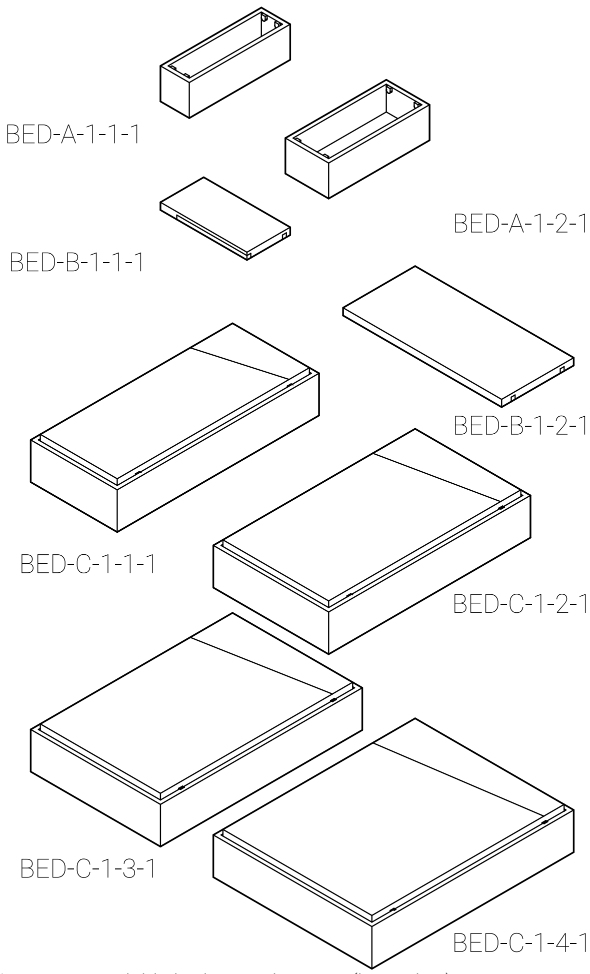


Figure 23. *Available bedroom elements (by Author)*

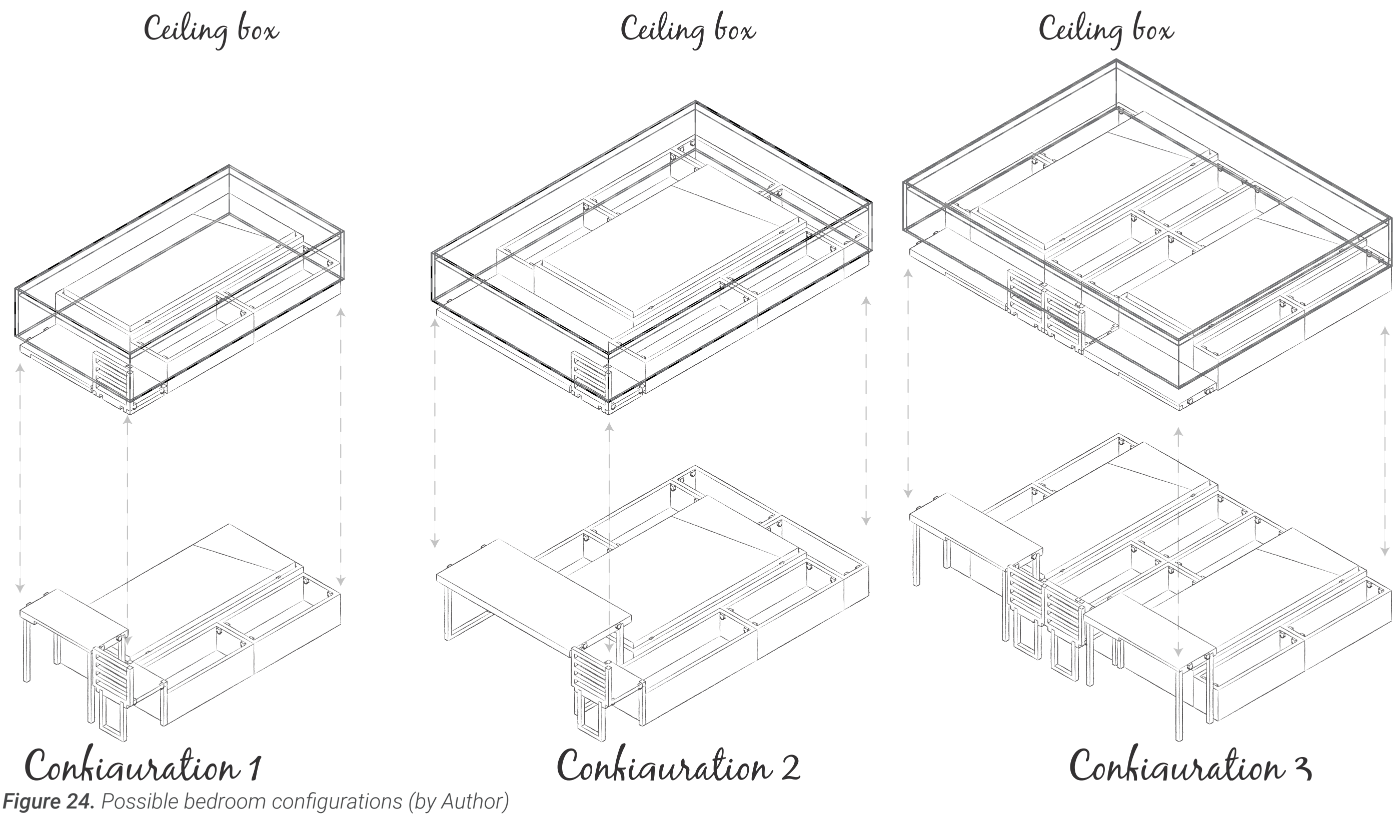
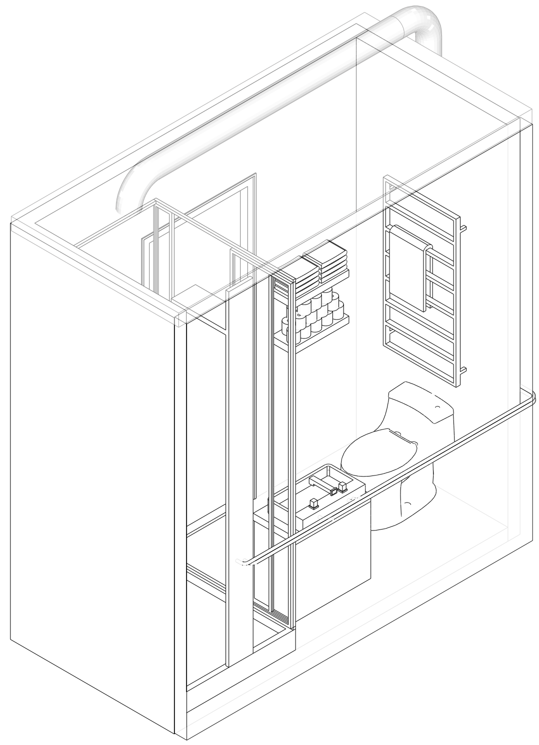


Figure 24. *Possible bedroom configurations (by Author)*

8.4. The wet rooms

The wet rooms are the shower a sink and the water closet combined into one pod. Configuring these elements can result in a seemingly endless amount of options, as illustrated in permutation design (Terzidis, 2014, pp. 82–85). For this design part, a pod is designed that fits the smallest unit and is based on the design studies from chapter 7.

The wetroom has the largest amount of service systems connected to it. The drainage for the toilet is the most limiting factor. It needs to be a pipe with a diameter of 110mm and it needs to be on an incline. It is possible for it to run underneath the unit, however when the distance to the shaft becomes too large an additional pump needs to be installed.



WET-A-1.1-1-0

Figure 25. *Wetroom pod (by Author)*

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9. The user interaction

The goal of this chapter is to design a process for the end-user of how they can interact with the open building method. The user interaction is an important part of the open building concept because the user wants to reflect their personal identity to the space. This in turn will increase the quality of the building and decrease the amount of rebuilding that will take place.

9.1. The user interaction

The user interaction for the open building system is determined by the type of mass customization. The goal is to create an orderly process for the end-user, hereinafter referred to as the client. This order process has to be intuitive and clear to present the client with a process that is able to serve most of the market. This design will describe how this tool should function in order for it to connect with the open building method.

The order process starts with a personal survey. The goal of this survey is to provide information for the home configurator for it to be able to pick a suggestion for a floorplan. In an ideal scenario, the configurator is able to generate an option for the client, only based on this information.

After the suggestions for floorplans are made, multiple different process flows of options are possible. They differ from default options (C1) to completely custom options(C4). In the case of C4, the unit is taken out of the default process. This means that a unit can be obtained without any finishings or modular pods.

9.2. The design process

This paragraph will focus on a graphical representation of the design process for the end user. For it a configurator will be designed that aims to serve the client. The case study

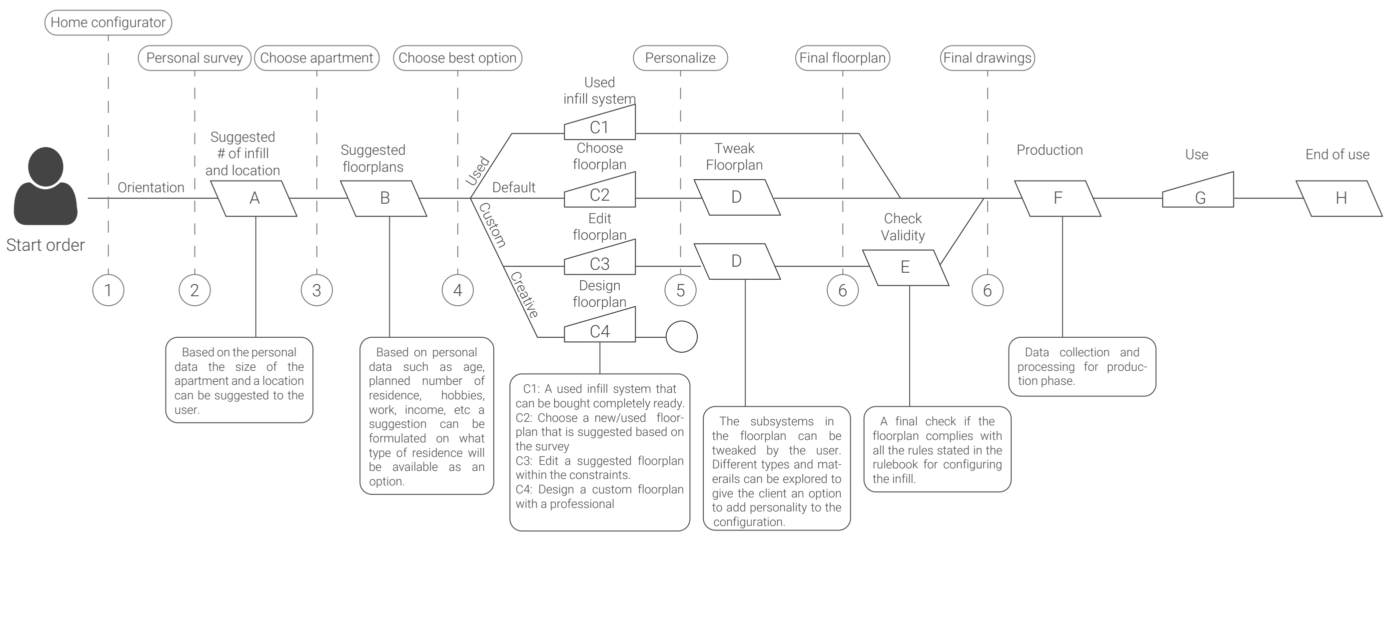

Figure 26. *System of user interaction with the open building concpet (by Author)*

from paragraph 4.3. will be used as a source for designing the configurator. The design and the content of the actual user interface is outside the scope of this research, instead this design study focuses on the functionality of what the configurator needs to contain in order for it to function.
For designing the different stages figure 26 is used. It contains the general stages of the process that the client will go through. Figure 28 depicts the process for a client that opts for option C3 (edit floorplan) displayed in the user interaction flowchart. The first step is a client survey (A). The goal for this survey is to pin point the size of the apartment that is needed and the location in the building that it can have. The tool will take this input and present the client with available options in the building. Next the client is presented with a set of suited floorplans (B). He can choose on of them based on design and functionality and continue. Thirdly the client can change the unit to his personal taste through swapping of elements (C3). The user can choose from a catalogue and change the look of elements. Lastly the unit is finalized (E).

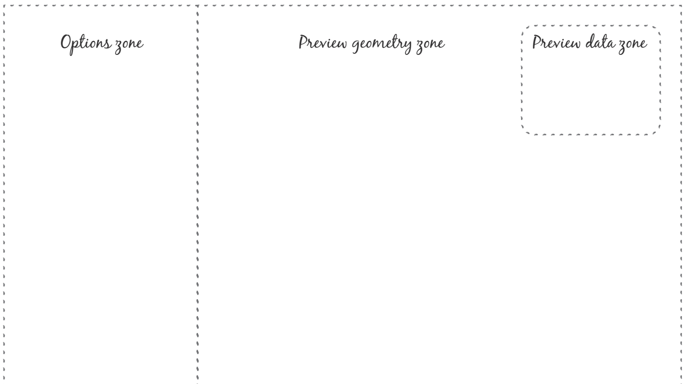

Figure 27. *Configuration tool layout (by author)*

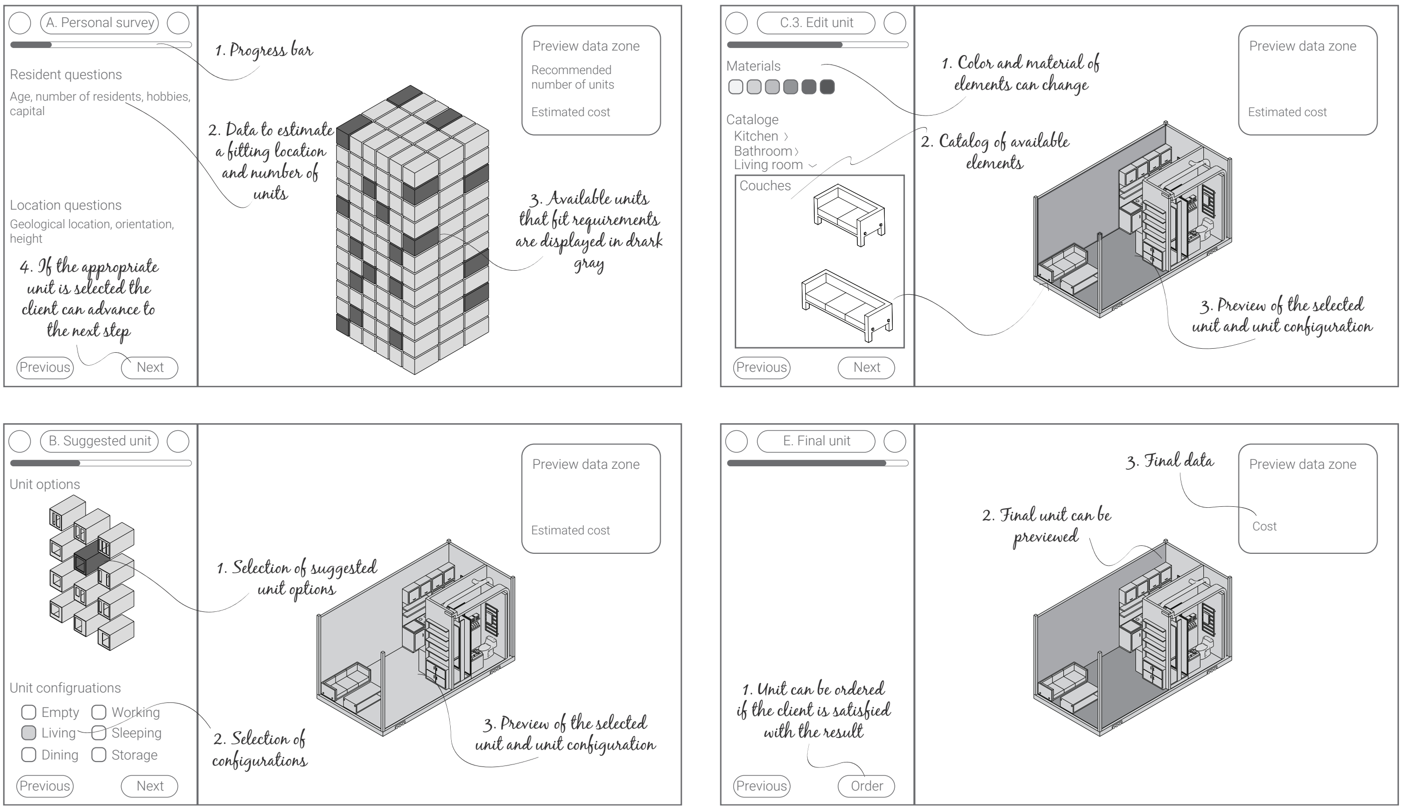

Figure 28. *C3 concept for configuration tool (by Author)*

Table 3 displays all the inputs, outputs and goals per step for figure 26. It aims to provide an overview of the individual steps of user interaction that the client is guided through the entire user phase of the housing. Most input is either based on the client. The first steps are based on the user survey. In this survey the computational process should provide the client with the best option possible in the limited solution space. Next most input is from the client and the catalog of subcomponents that the user can choose from the further personalize the configuration.

Table 3. *Input and output table for configuration process*

Step	Operation	Comment	Parameters			
			Input	source	Output	Goal
A	Data gathering	Determine number of units and location	User survey	Client	Generalized data of the client	Provide client with a infill solition
B	Choose floorplan	Provide client with selection of fitting infill solutions	User selection	Client/ limited solution space	Selected floorplan	Provide client with a floorplan within the solution space that fits the clients needs the best
C	Determine level of flexibility	Determine the level of flexiblity for the client	User selection	Limited solution space	Suggestion to continue to: C1,C2,C3 or C4	Provide the client with a infill unit
C1	Infill marketplace	Provide client with options in the infill marketplace that offer the best fit	User survey	Client	Final unit to order for the client	Provide the client with a pre-owned unit that fits their need
C2	Infill default space	Provide client with a set of options of default configurations	User survey	Default catalog	Final unit to order for the client	Provide the client with a option to enhance mass production
C3	Infill custom space	Provide client with a set of options of default configurations that can be adjusted	User survey + user input	Default catalog	Final unit to order for the client	Provide the client with a option to allow them to create a custom space
C4	Infill only	Provide the client with just the unit and no subsystems	User input	Default catalog	Final unit	Provide the client with the option to just order the unit and have full controll to edit onto it
D	Tweak unit	The configuration can be tweaked based on personal taste	User input	Default catalog	Final personalised unit	Allow the client to be able to add personal taste to the configuration
E	Check	Depending on the deviations from the limited solution space the unit is checked	Final unit configuration	Manual/ computational	Checked unit final for production	Check if the configuration is up to code
F	Production	Unit is taken into production	Computational method	Configurator	Physical unit ready to take order	-
G	Use	Unit is used by the client	-	-	-	-
H	End of use	The end of use is either when the user sells the unit, or when the lifespan of the unit is reached	Client	-	-	Either resell the unit or deconstruct it for re-use of subsystems

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10. The kit of parts

10.1 Implementation

Chapters 3, 4, and 5 have focused on the development of the open building system. This chapter concludes the proposed open building system on how it can be implemented in the building industry.

To do this a suggestion is done for materialization. This suggestion is based on desk research for similar volumetric units. Multiple different material options are able to achieve the same open building principle. The main decision in choosing a material has to do with price, availability, and sustainability. For example, the units fabricated by Blumer Lehmann or the Pattern Buildings are constructed primarily out of wood. While the units created by FullStack Modular are created primarily from steel. These units have in common that they ought to be made from lightweight materials since the transportation and lifting of heavy elements can cause more troubles. The proposal for this design component will apply a basis of wood such as CLT and wooden columns, but it is important to realize that this could be any other material that allows the same amount of flexibility.

There are two viable user cases for the open building system. The first is for the existing building stock, the second for new building projects.

Existing building stock

For the existing building stock industrialization is less optimal, because the percentage of custom elements will increase. This has to do with the large variety of typologies of buildings. Not all existing buildings can be retrofitted to fit the system, and a higher amount of oversize will likely need to be accepted. Oversize is not an issue but it should be taken into account. There are also some constraints for an existing building to comply with for it to be able to fit the open building concept. The main constrain is for the free height to be over 3620mm. This height will allow a full height unit to fit. It is possible to use less high units but that would decrease the flexibility. The width of the grid system will be less of a constrain. It does not need to fit the dimensional coordinate system of the tartan grid completely, some oversize in this case is acceptable.

New building projects

The open building system exists out of three sizes of

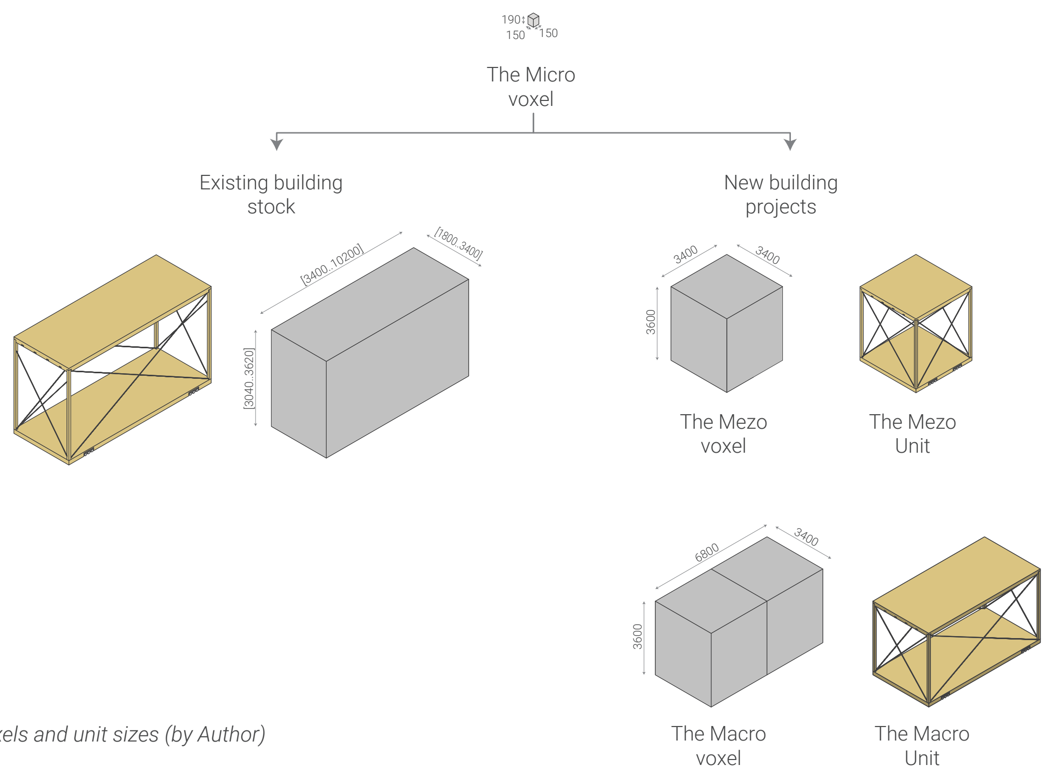

Figure 29. *The Voxels and unit sizes (by Author)*

units, composed of the same voxel. The smallest voxel is the micro voxel: 150x150x190mm. The second is the Mezo Voxel: 3400x3400x3600mm. These fixed larger scales of voxels will enhance the industrial nature of the system greatly. With it, it is possible to mass-produce fewer parts that fit in more circumstances. Sub-systems can be swapped or repaired more easily. The Mezo Voxel can be placed in a row to create one, two, and three sizes Voxel units.

10.2 The parts

For the design process most of the focus is placed on the unit and the parts that it contains. This paragraph will provide an global overview of the necessary parts of the concept. They are listed in the figure below:

1. The Unit
2. The infill subsystems
3. The connector
4. The Support system
5. The Service systems
6. The Skin

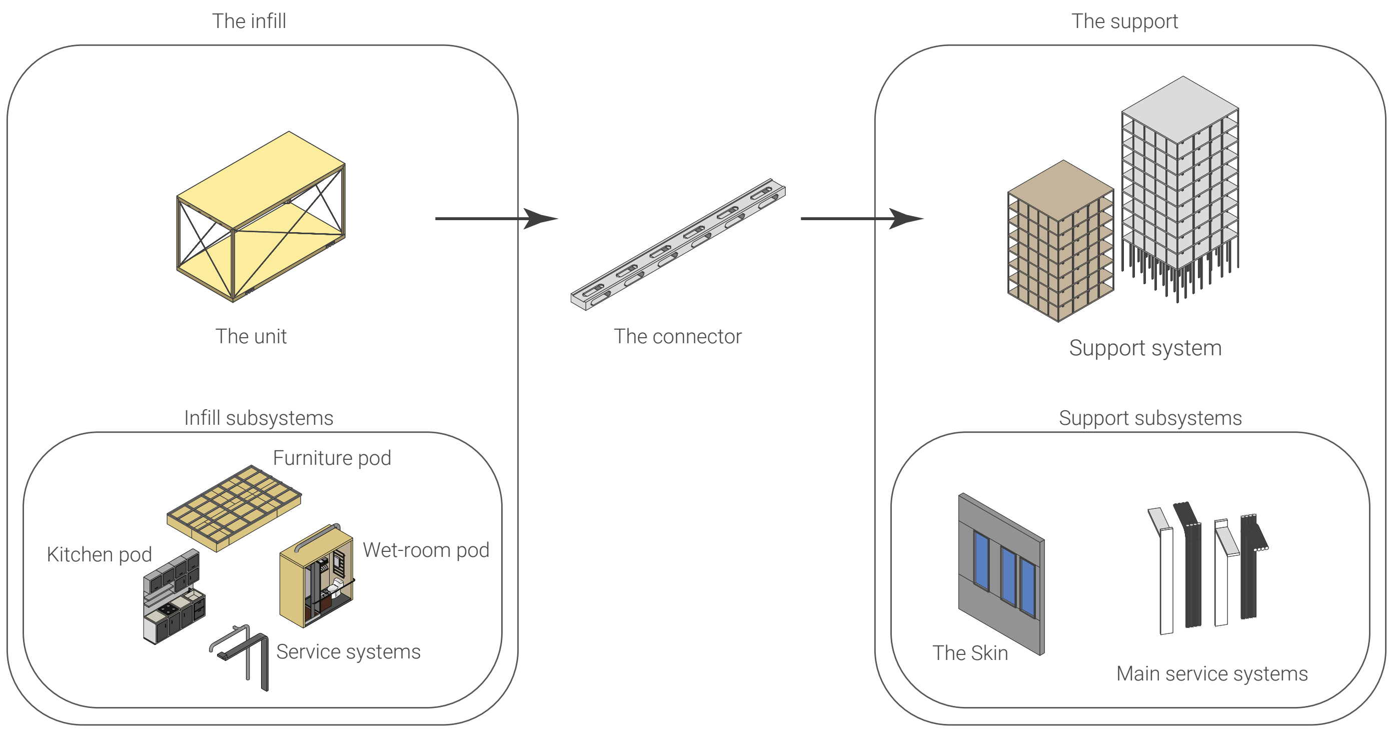

Figure 30. *The kit of parts (by Author)*

10.3.1. The unit

The unit is the key part of the infill system. The trick of the unit is for it to be able to serve multiple different functions. It should be able to house a single unit studio but connected to multiple, it should also be able to serve as an office.

The module is composed out of CLT floor and ceiling parts and four columns. This volume is able to carry its own weight for transportation and placement. The floor system is equipped with a wheel system that allows the unit to slide into place. This ensures that it can be installed separately from the support and that it can, later on, be moved or switched out with a different unit.

All the subsystems, such as walls, finishings utility systems, and furniture are added to the factory. In this way, most work is done in a controlled environment.

Depending on the project the module can be produced in a number of fixed sizes: S, M, and L.

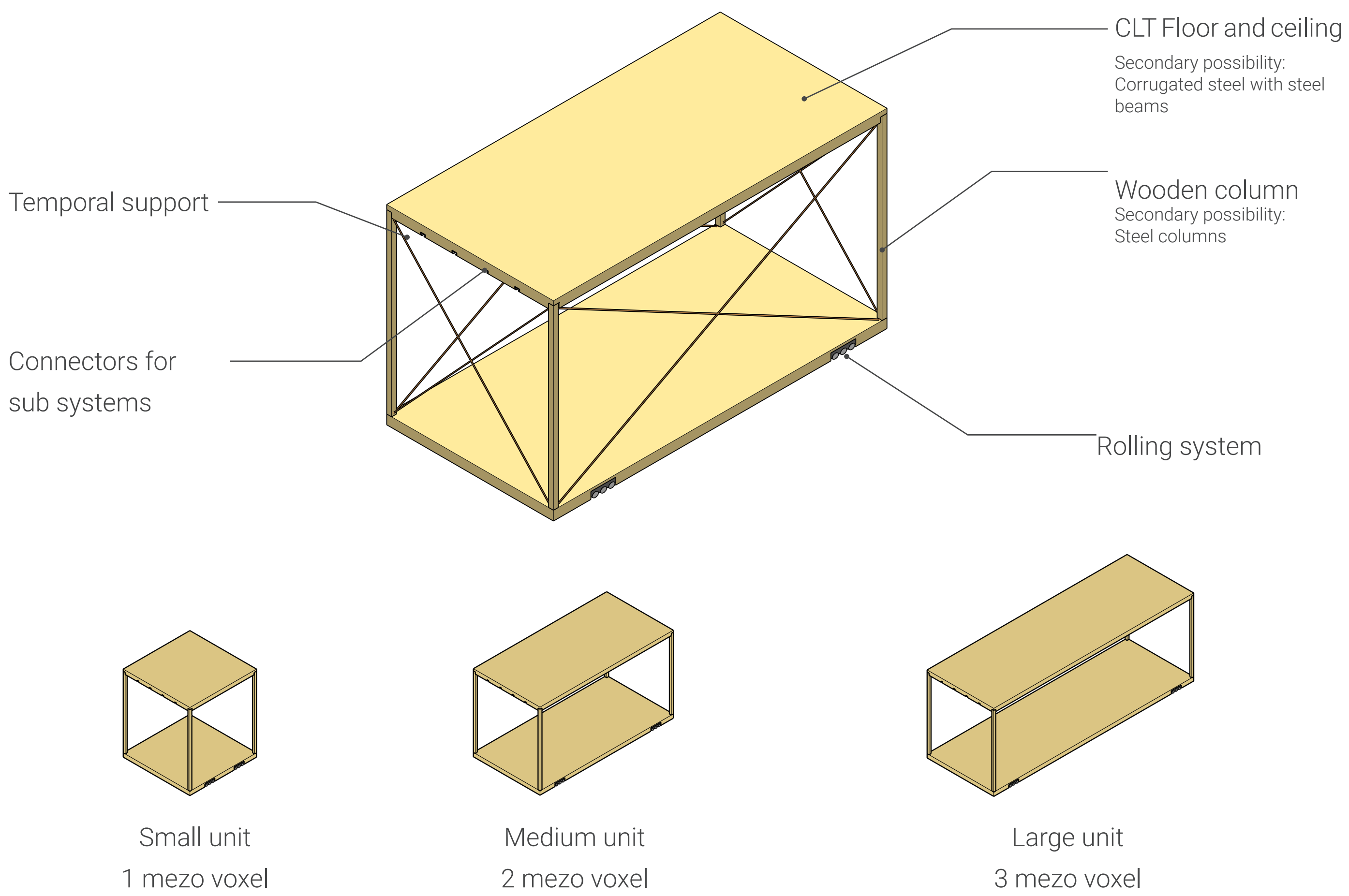

Figure 31. *The unit (by Author)*

10.3.2. The infill subsystems

The unit can be equipped with several subsystems to make it into a casco or a completely finished product. The subsystems are complete pods that can be installed in the factory.

Most notable is the furniture unit, it is a ceiling-mounted pod that is attached to the base unit. It partially covers the ceiling of a unit. In it, a large range of different furniture elements can be stored and brought up and down using a suspension system.

Depending on the client the ceiling unit can take many different configurations of different components and sizes. The frame allows for components to change over time once new components become available or old ones fail.

Other pods that can be installed are kitchen- and wetroom-pods. All the pods are complete with all the necessary service systems. Ventilation and electricity are integrated into the furniture pod, and water management is integrated both in the kitchen and wetroom pods.

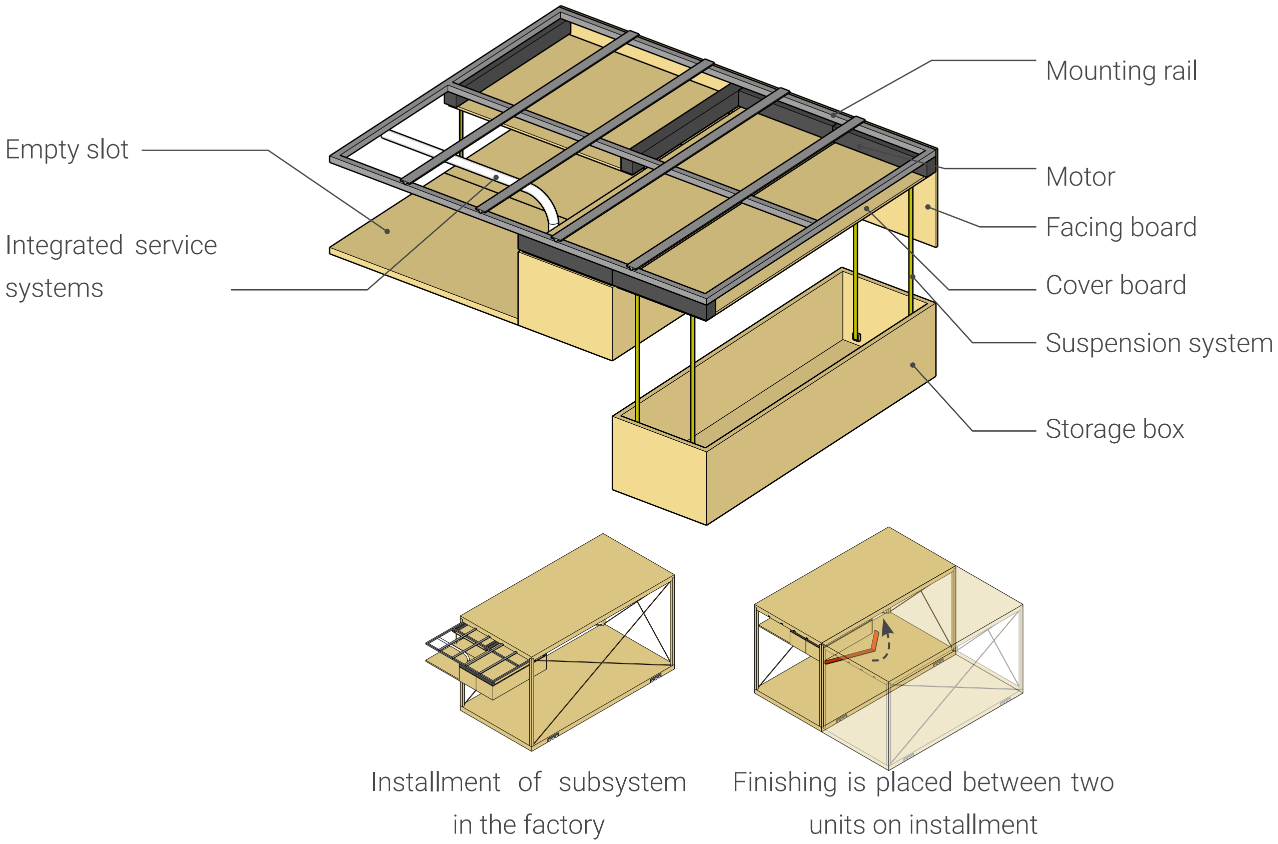

Figure 32. *The infill subsystem: the furniture pod (by Author)*

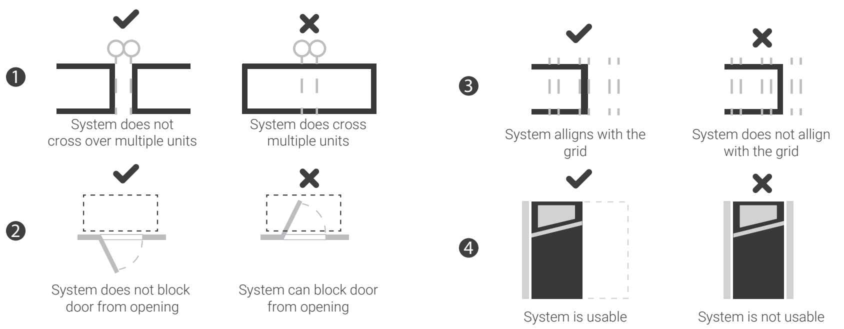

Figure 33. *The subsystem principles (by Author)*

10.3.3. The Connector

The connector is a structural element that connects the support and the infill in such a way that they can always be separated from each other. It serves as a rail to guide the unit into place. In this design case, the separator is made from steel with pressure-resistant insulation strips on top. After the placement of the unit, it is rested into these strips to allow for sound insulation between units. This makes that the infill and the support system do not have to really on mass for sound insulation.

The shafts in the connector allow for the main service systems to run horizontally below the units or vertically between units. When these are in place the secondary service system from the units can be connected to the grid.

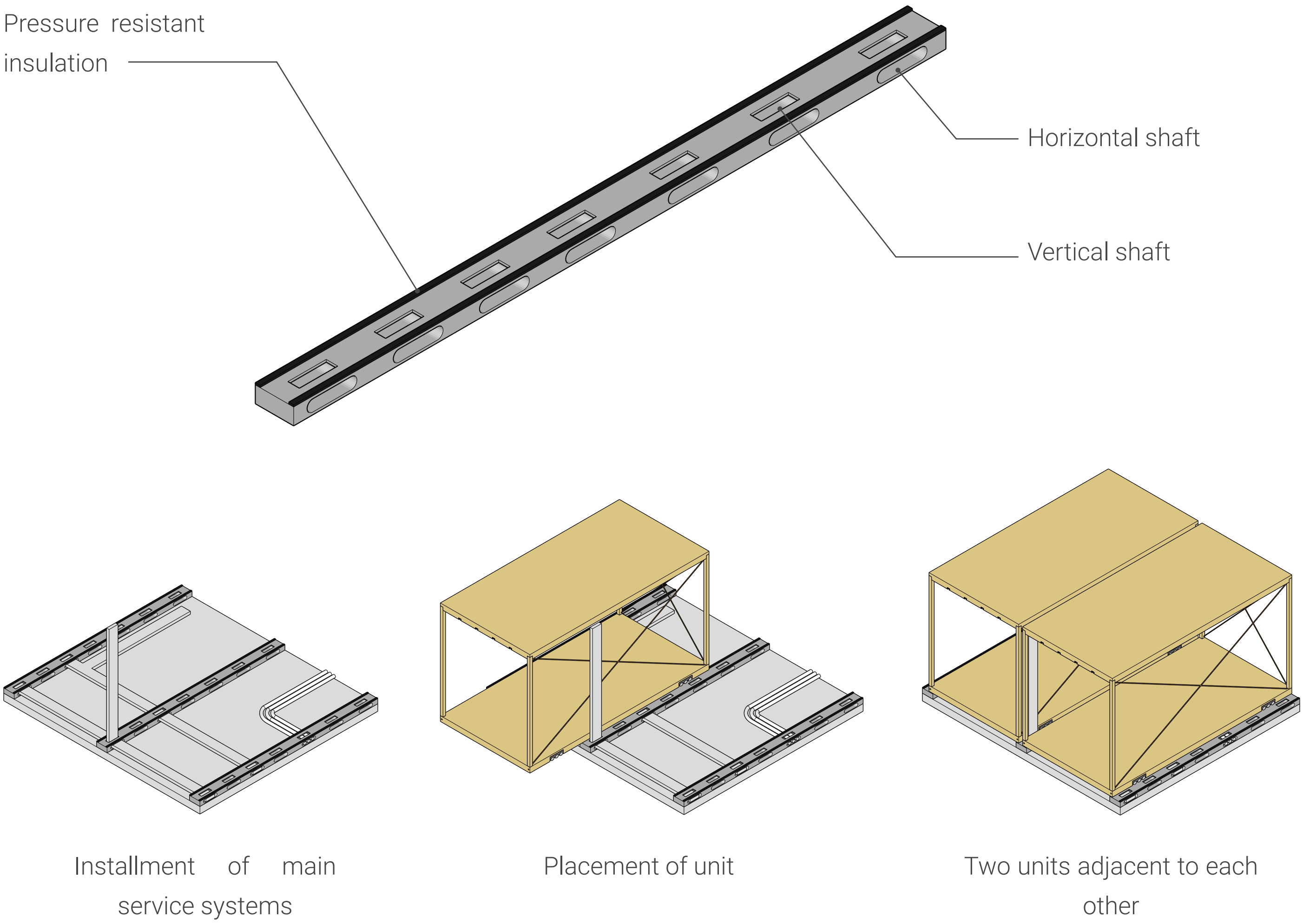

Figure 34. *The connector (by Author)*

10.3.4. The support

The goal of the support is to serve every need of the infill. This is easier to achieve for new buildings but harder for the existing building stock. However, as long as the support fits the listed guidelines it is able to fit the infill. The benefit of a better fit is less oversize and more optimal use of space. Guidelines are created for new buildings and for support systems from existing buildings. The main difference between new and existing supports is that existing support options can always be adjusted to fit the openbuilding principle. It is more a question of if it is a valuable option if a lot of parts need to be changed.

New buildings

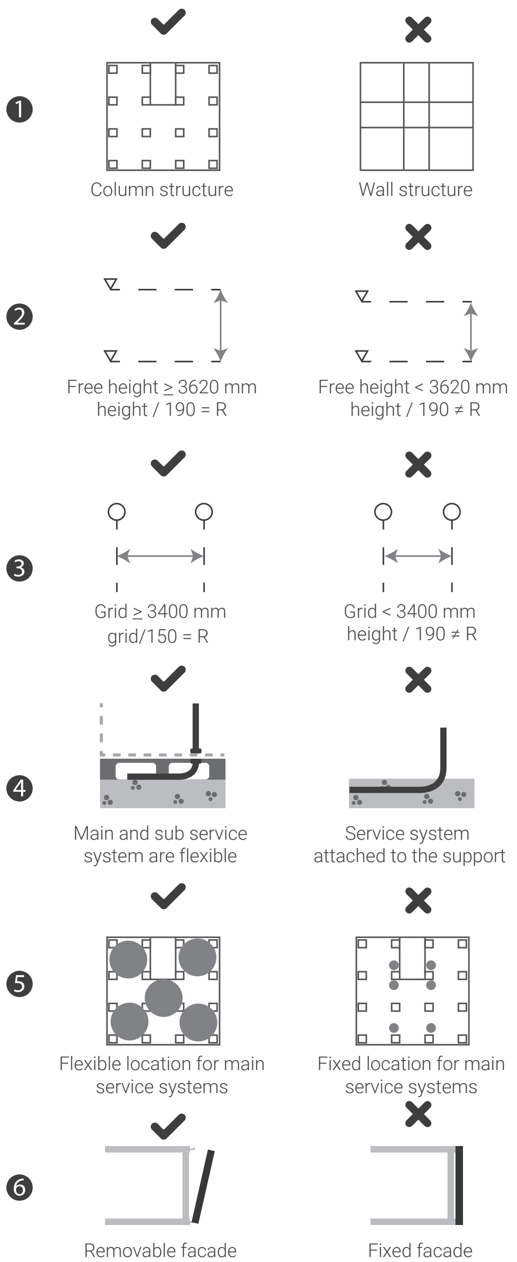

Figure 35. *The for a new building support principle (by Author)*

Existing building stock

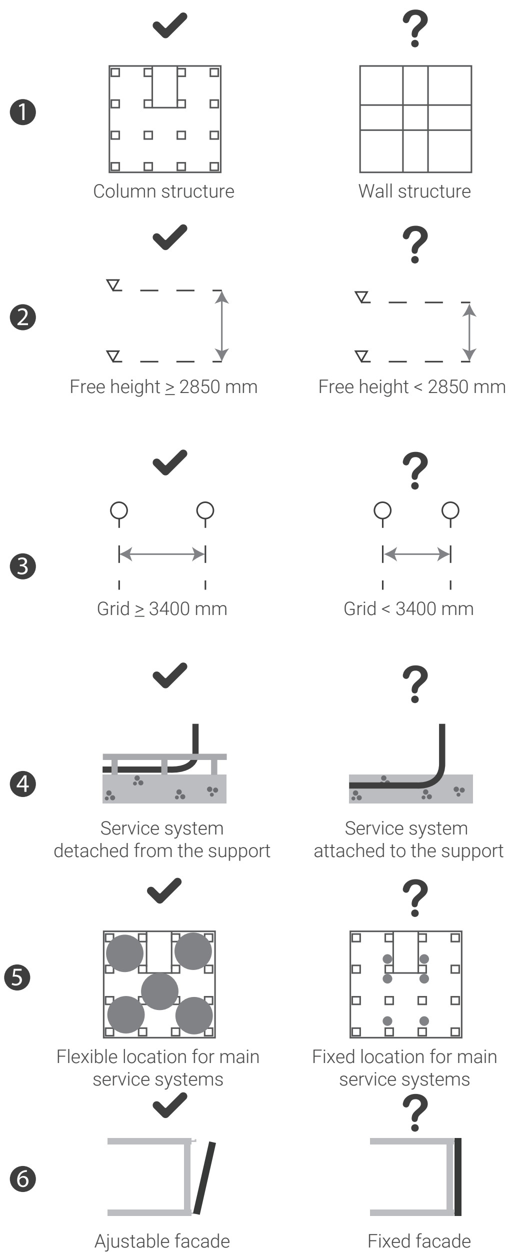

Figure 36. *The for a existing building support principle (by Author)*

10.3.5. The skin

The skin of the open building system is vague in terms of whether it is part of the collective like the support, or it is part of the individual, as the infill. On the one side, it is preferred if the facade is unified on the entire face of the building. On the other hand, it has to fit the infill system perfectly. To make a decision the alignment of openings is the most important factor for the facade, it has to fit the infill unit. Therefore, for new buildings, the facade is a part of the individual. The support system as part of the collective has to be able to fit this facade type. For the existing building stock, it will differ per scenario and it is more likely that a custom facade will be more beneficial.

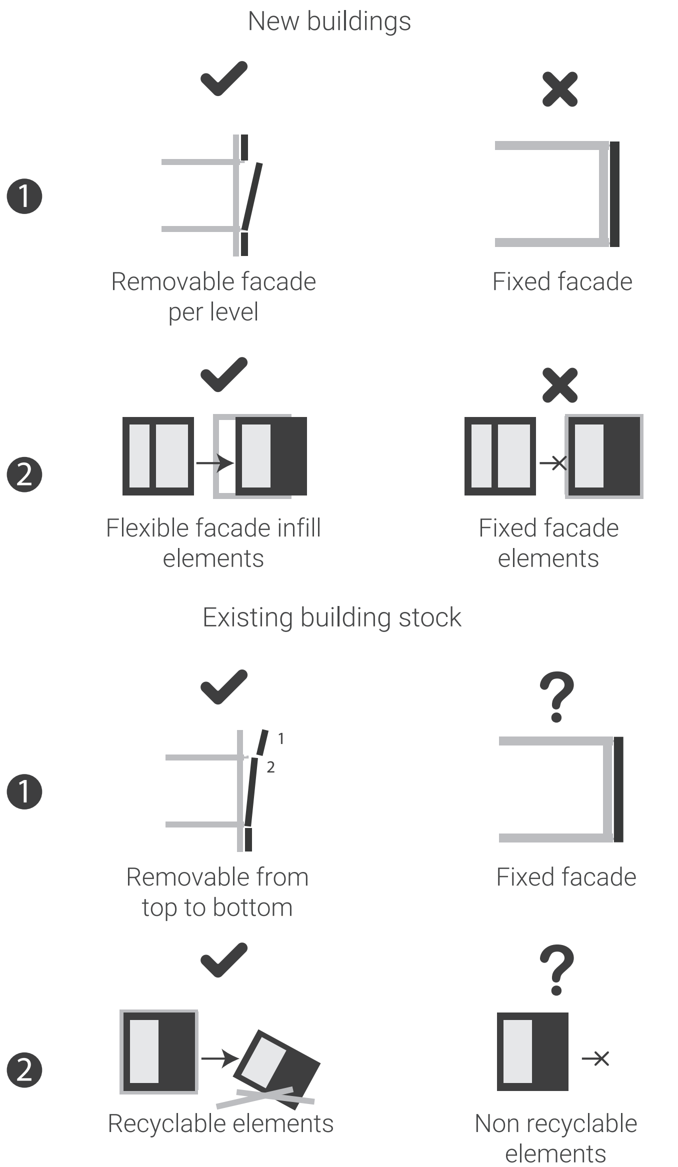

Figure 37. *The skin principles (by Author)*

10.3.6. The service systems

Service systems can be the most limiting factor in creating an open building. If a building has limited flexibility for these systems it is costly to fit new systems in place. For the method for new buildings, the service systems are divided into two parts, the collective and the individual. The collective service systems have to connect to the individual and depend on the support. The individual service systems depend on the infill unit.

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11. Example units

This chapter will provide a example units with all the components and subsystems that have been designed in the previous chapters. These examples are created in order to test and add onto the rulebook from the kit of parts.

The configuration for a one unit studio apartment consists out of the following parts:

- Furniture pod 1 with:
    - Sleeping
    - Living
    - Eating
    - Working
    - Storage
- Four cabinet kitchen pod
- Bathroom pod

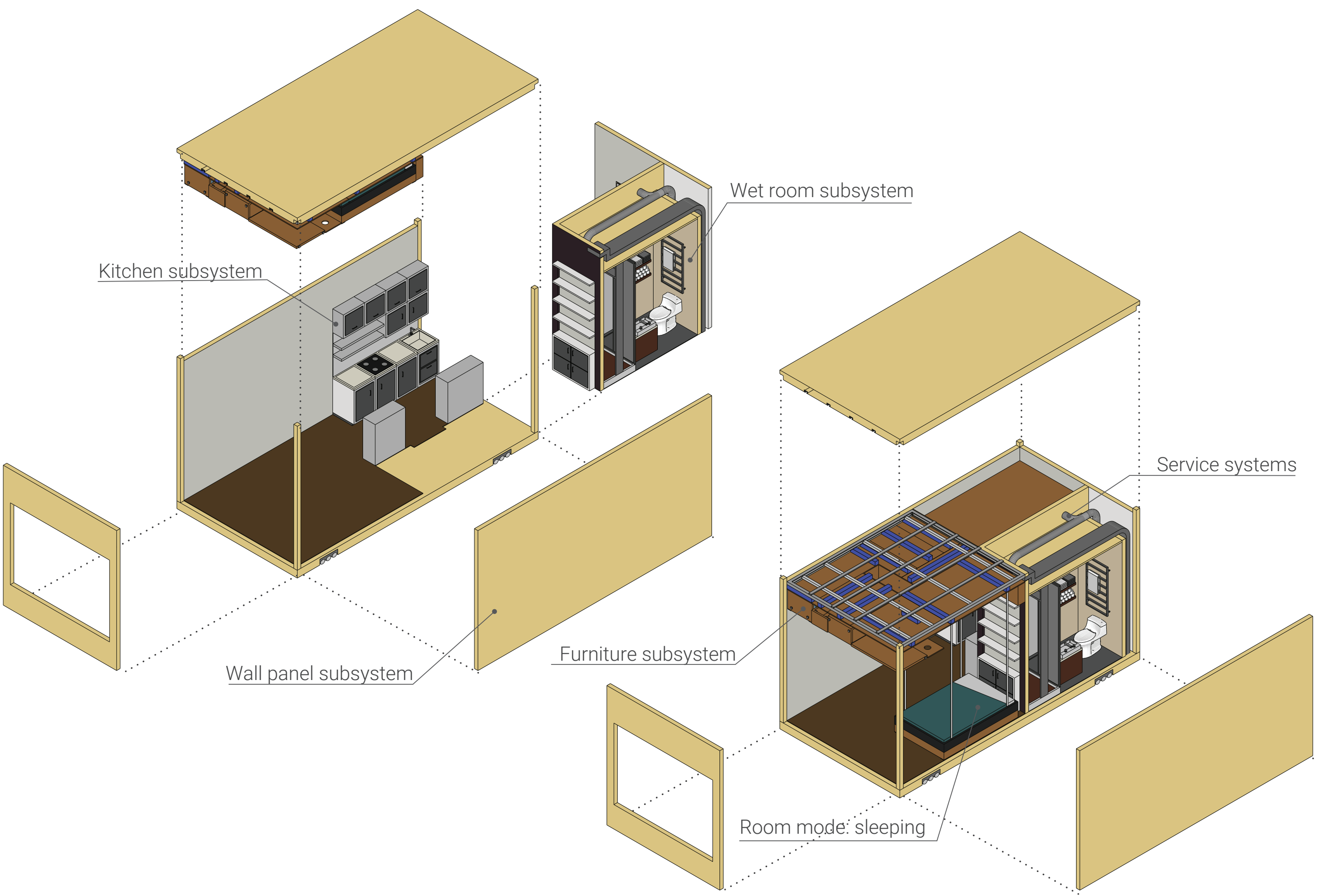


Figure 38. *Example unit 1 (by Author)*

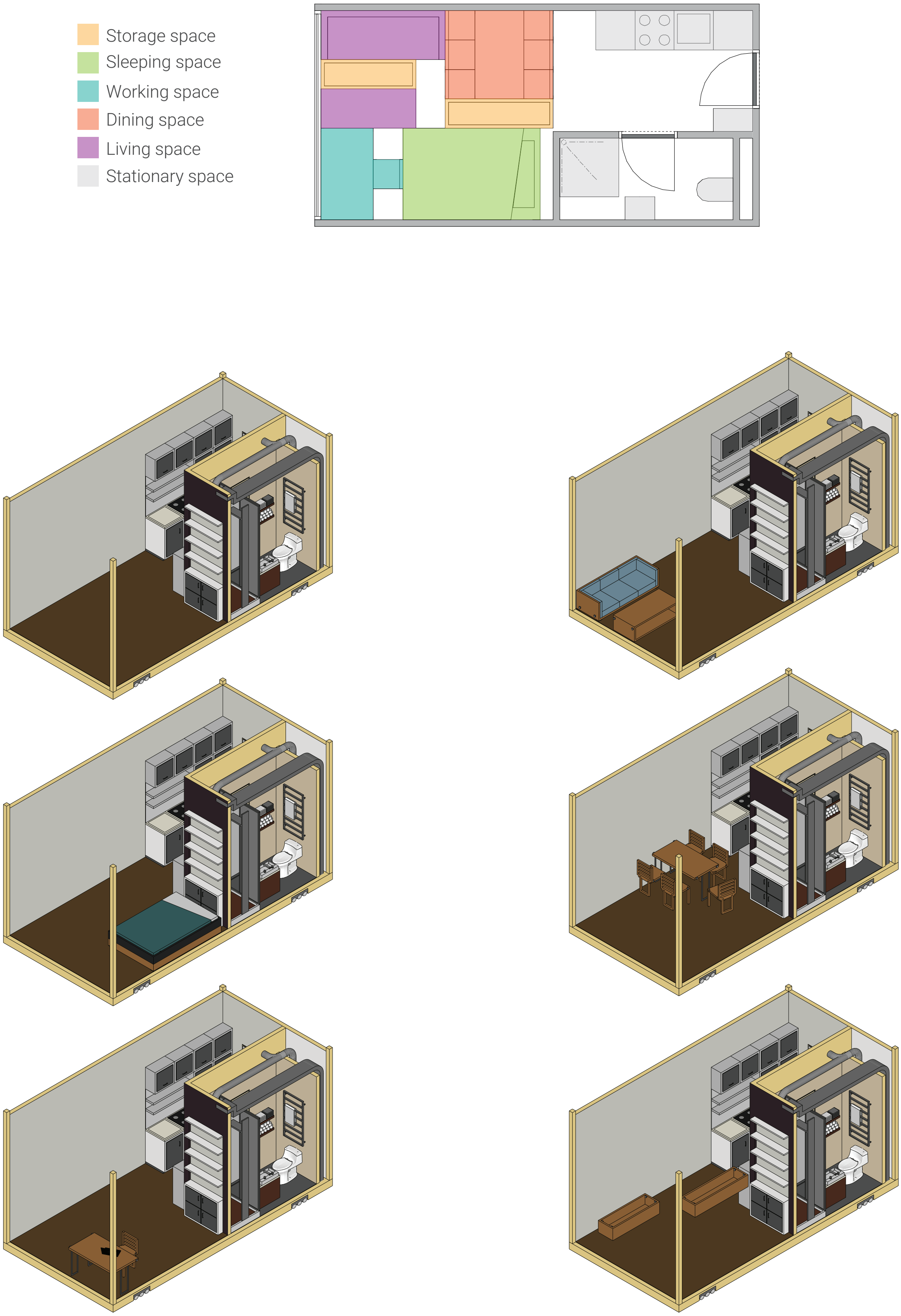


Figure 39. *Example unit 1 example pod configurations (by Author)*

12. The case study

This chapter will provide a design case for a building that will fit the designed open building method. It will act as an example as to how the open building method can work in practice, and the design will test the rulebook from the kit of parts.

For this case study, it is the goal to retrofit an existing building and fit twice as many apartments in it as before. This would be a practical example of an area that undergoes densification and would need more places for people to house.

For the case study the project: Superlofts Houthavens by MK Architects has been selected, this project has been analyzed in chapter 4. The project is located in Amsterdam, the Netherlands.

The first step is to check if the building complies with the rules formulated in chapter 10.

After this analysis, a procedure is designed of how the open building method will fit inside the existing support structure.

Thirdly the units can be configured by users and are manufactured offsite.

The fourth step is to place the units inside the prepared support structure and to apply the finishings.

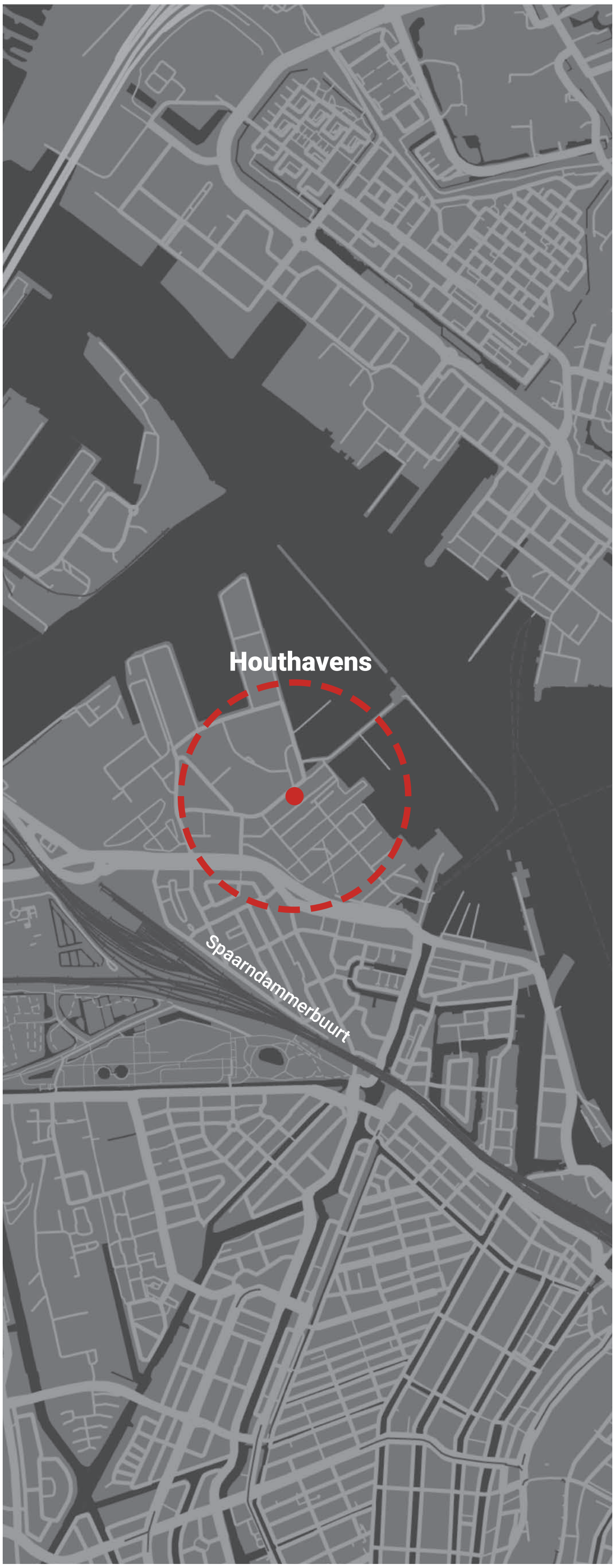


Figure 40. *Houthavens site (by Author)*

***Figure 41.** Houthavens site: superlofts (by Author)*

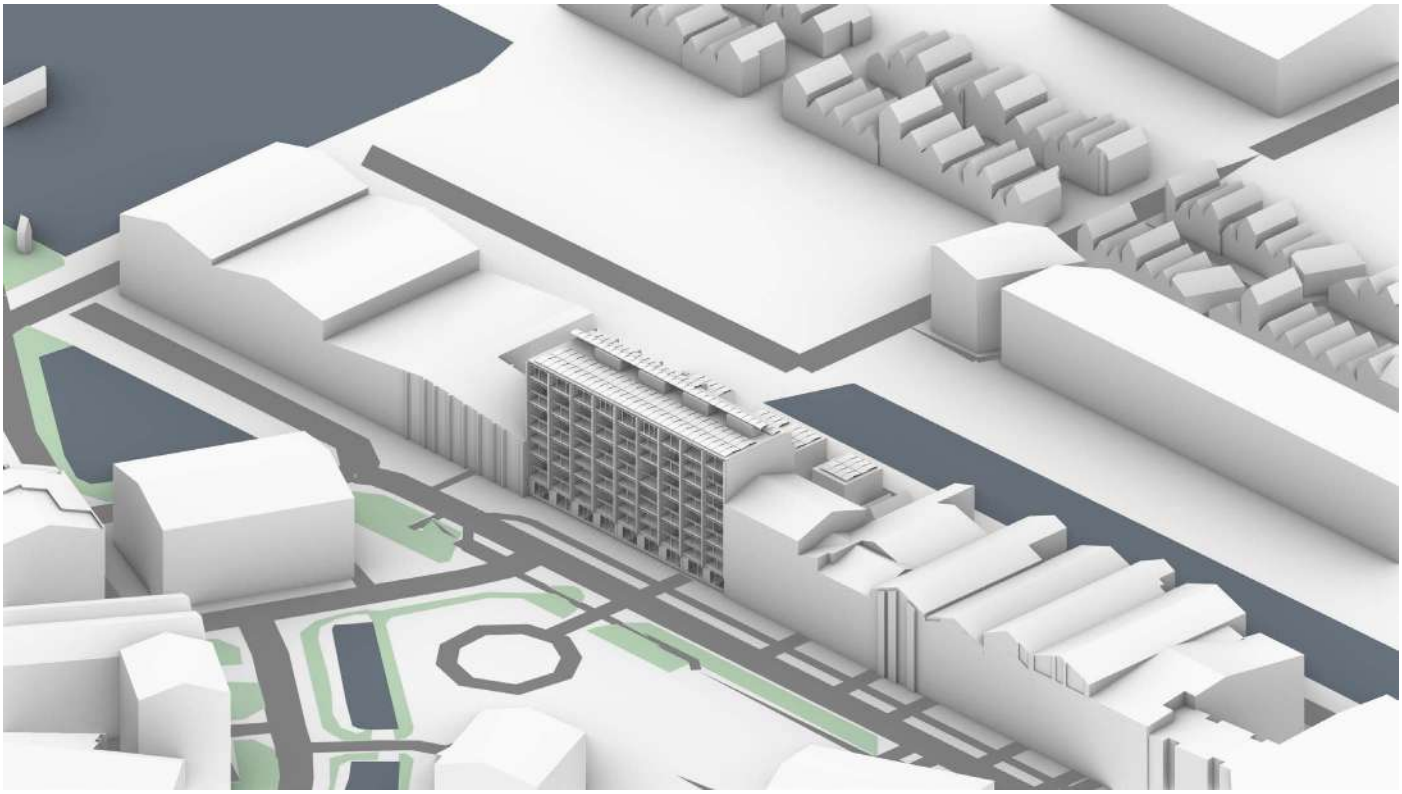


***Figure 42.** Houthavens perspective: superlofts (by Author)*

12.1. Building analysis

To determine if the building is suitable for the open building concept the rule system from chapter 10 is used.

1. Structure

The main structure of the building is based on a wall structure. This is less favorable than a column structure because this will make the building less suitable for different arrangement of units since there are load bearing walls in between them.

2. Free height

The free height of an apartment is 5000mm. Is more than exceeds the required 2950mm which means that the units can be designed with oversize in the height.

3. The grid

The grid of the building from the one load bearing wall to the other is 5750mm and thereby fits the required minimum width.

4. The service systems

Most of the service systems are reachable. Some are integrated the concrete and are reached less well. The floor heating and cooling is cast inside the concrete floor.

5. Shaft location

For each apartment there are two shafts that are placed against the core of the building. The allows for a flexible placement of main service systems.

6. Facade

The facade is placed inside a concrete framework and can be detached separate from different levels.

Conclusion

The building meets most design requirements for the retrofit. Some of the points, such as the service systems and the load baring walls will require more attention for the design process.

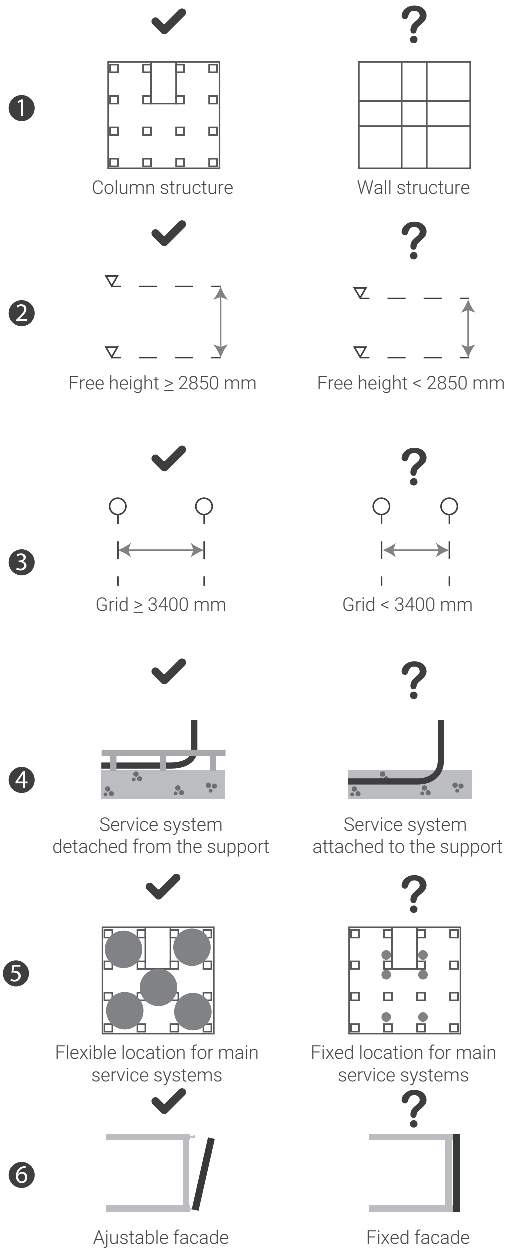


Figure 43. *Principles existing support structure (by Author)*

12.2. Unit placement

The placement of the units depends on the available space and the grid size. To design the placement of the units first a single support part of the building was isolated in order to analyze it.

Secondly the new finished floor height of the unit is determined. This is different from the current structure because the height of the connector and the unit have to be taken into account. The new finished floor height will therefore be +380mm

Thirdly the arrangement of units is designed. In this design the apartment is split into two sections, this way it is possible to have two small apartments or one large apartment.

Fourthly a new section for the core is designed that makes the transition form the current core to the new floor heights.

The fifth step is to design the sizes of the new units. They have to be based on the dimensional coordination system and allow for tolerances from the infill system and the support system.

The second to last step is to place the connector elements. These allow for a accurate placement of the units onsite and allow for service systems to be guided below the units to the right place.

The last step is to place the units themselves. Each apartment will house two large units of 7150x 3100x 4560, and two small units of 2350x 4450x 4560.

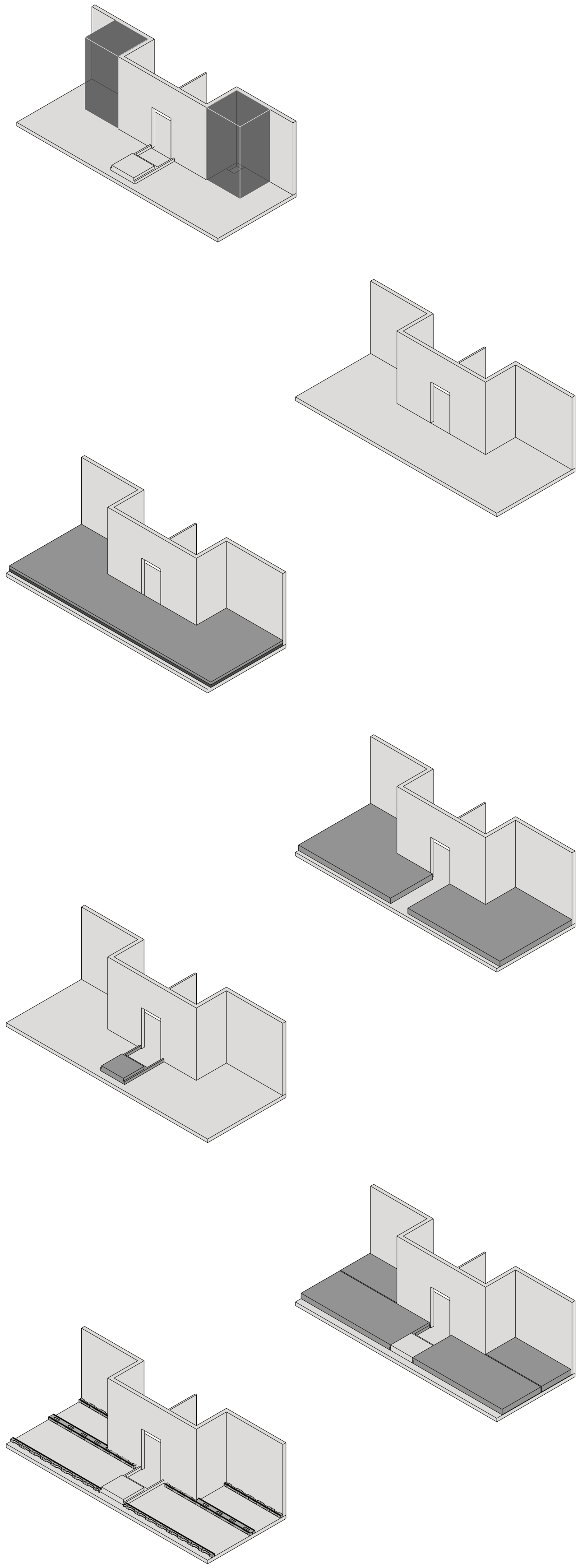


Figure 44. *Unit placement (by Author)*

12.3. Unit configuration

The unit procedure for unit configuration is done according to chapter 9. For this paragraph a single apartment is designed in order to serve as an example of the possibilities.

As determined in the previous paragraph the apartment will consist out of two prefabricated units. They are designed using the rules from chapter 10 to most importantly guarantee the usability of the space and secondly to make sure the units can be manufactured according to the dimensional coordination system.

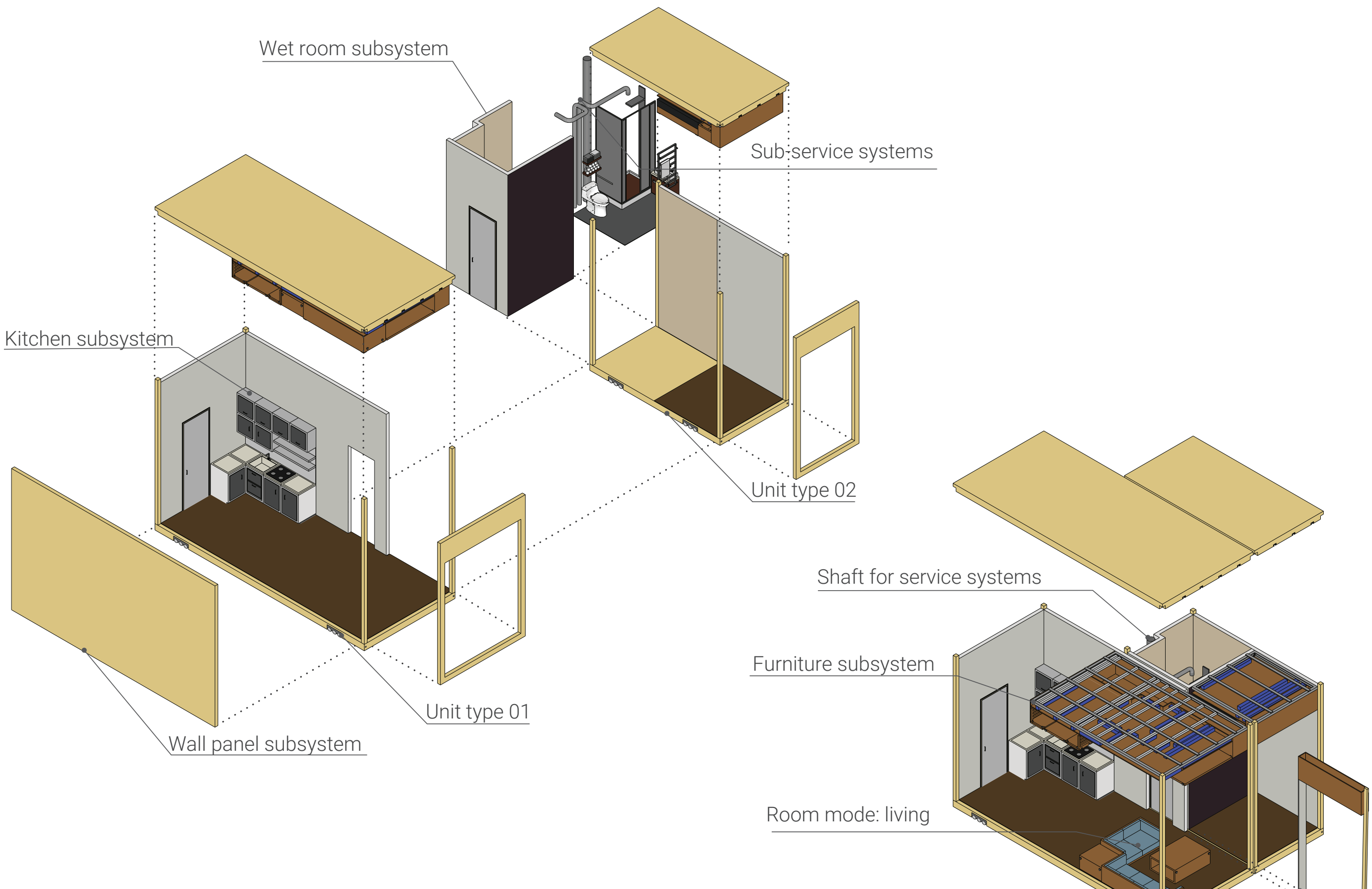


Figure 45. *Example unit existing building 1 (by Author)*

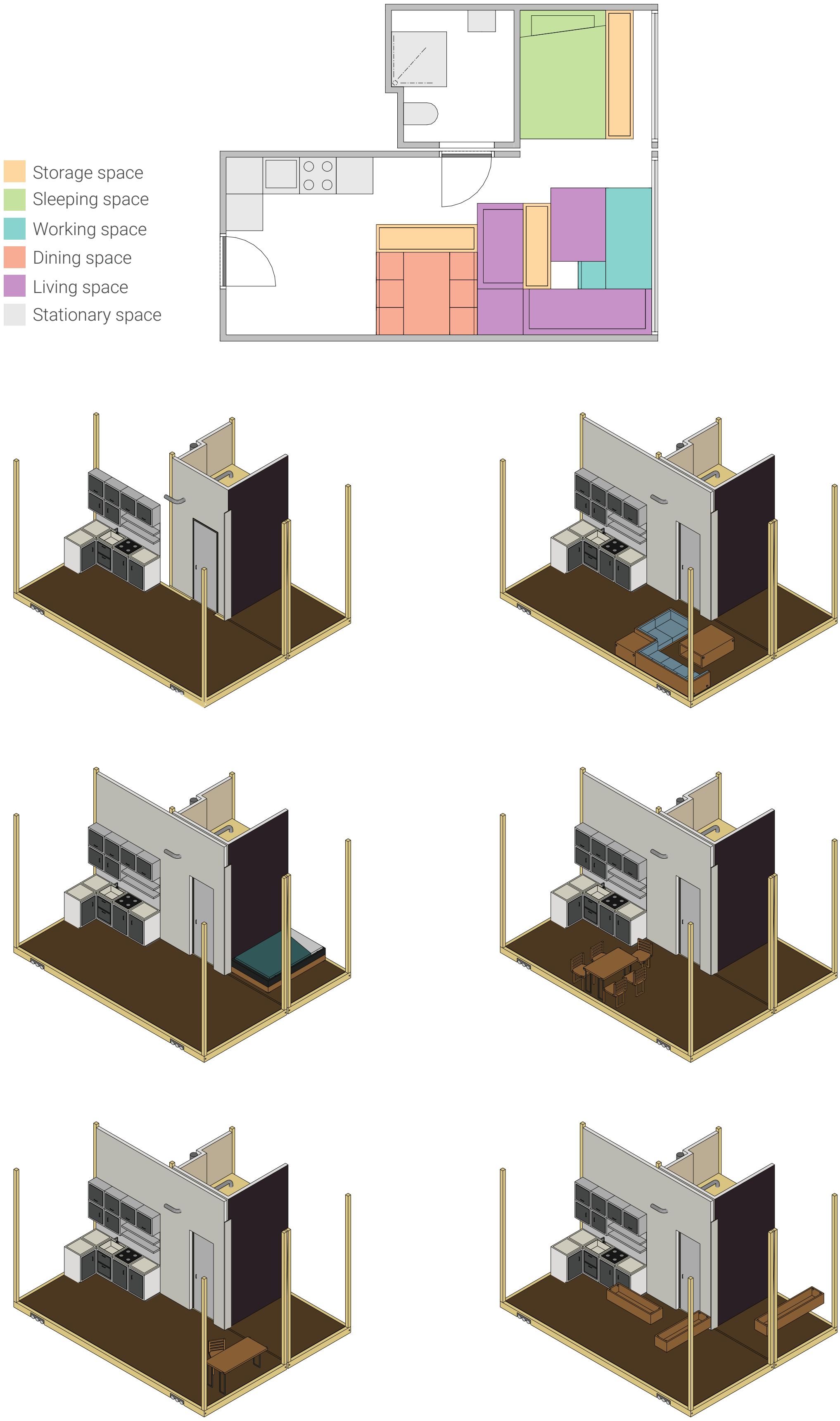


Figure 46. *Example pod configuration existing building 1 (by Author)*

12.4. Construction

The retrofitting of the building happens simultaneously to the units being configured and produced.

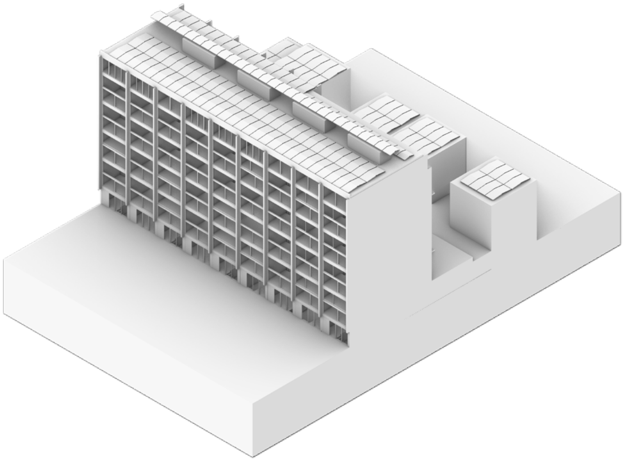
The first step is to remove the facade of the building. In this case it can be reused for later so they are put in storage.

The second step is to strip the building further to the casco state. For this to happen the extra floors, walls, finishings and current services systems need to be removed.

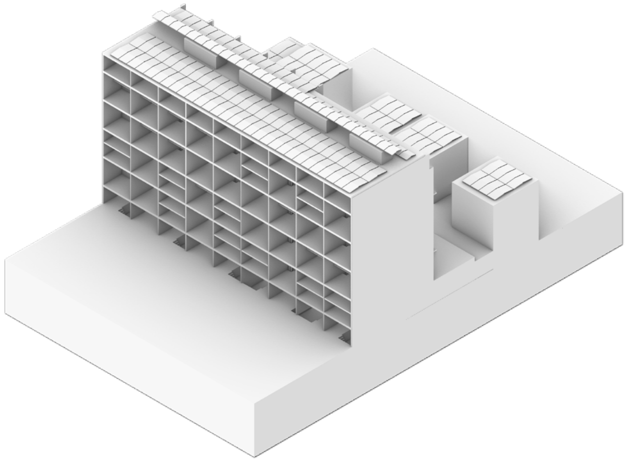
After the building is striped down to the support level the connectors are brought into place, together with possible adjustments to the main service systems. Then the infill units can be rolled into place and connected to the main grid.

The last step is to apply the finishings and the reapply the facade. This concludes the retrofitting of the houthavens superlofts building. It contains 70 more apartments now then it did before.

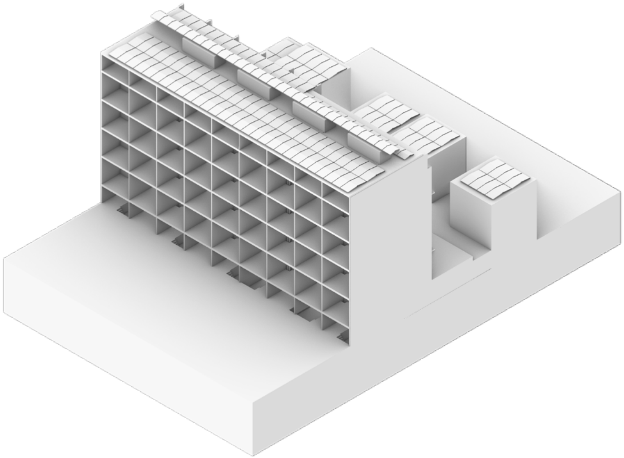
Figure 47. *Superloft perspective with infill unit (by Author)*



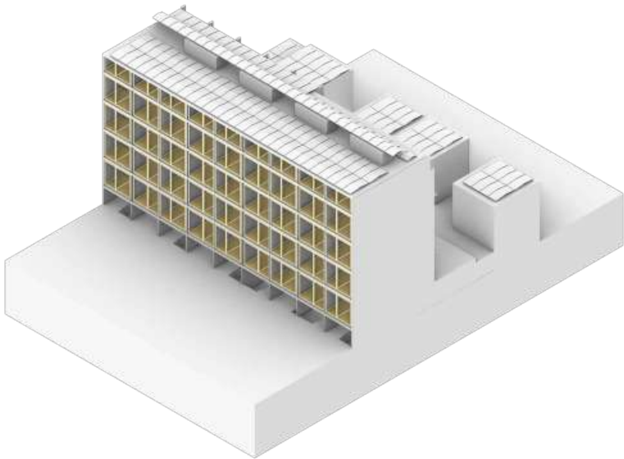
1. Remove facade



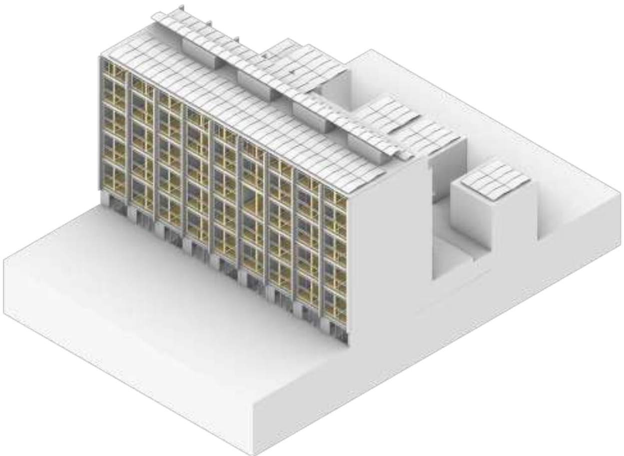
2. Casco building



3. Adjust support to fit the infill system



4. Insert and connect infill system



5. Place the facade

Figure 48. *Superloft retrofit process (by Author)*

13. Discussion

The discussion will focus on the legitimacy of the proposed open building method. This is done using a SWOT analysis. For it, the strengths weaknesses, opportunities, and threads are listed. The four categories are examined with the information obtained from the literature survey and the design study.

Strengths

The strengths are considered to be the helpful elements for an organization. The designed method for open building can allow organizations to adapt industrialization and prefabrication to their company. It can allow them to build in a new way and offer different products to their clients. As of now, there are multiple startups that aim to achieve the same goals. However the market is large, and the first company to successfully apply this method and achieve mass production will take most of the demand and can become the new standard.

Weaknesses

The weaknesses are considered to be the points that are damaging for the organization. The main reason why most start-ups who tried to apply industrialization in the building industry were not successful has to do about financial issues. Underlaying of this weakness is the change of how time is spent with regards to the current building industry. For a startup, the proposed open building method, relative to the current building industry is fast during the design phase, and slow during the building phase. The startup will need to switch to an approach more similar to the automotive industry, where, at the start phase, it is normal to take about five years to produce a product that can reach mass production.

Opportunities

The opportunities are the elements that are helpful for the client. The opportunity for a client during the design phase is to experience the ability of choice and to express personal identity to it. During the use phase of the dwelling, the client is able to swap sub-systems and to scale up, or down if their life changes. After the client is looking for a new location he is able to either take the dwelling with them, or to sell the unit and all its sub-components back to the company, or to a different client.

Threads

The threats are the components that can be damaging for the client. Previous mass-produced housing has left a regional bad sentiment towards this type of dwelling. Also, the cultural environment can change per region or country, therefore one configuration(tool) is not guaranteed to function in a different part of the world. Venucalair architecture can also be different per region of the world, this provides a risk that it will be less suitable to place the same configuration in different locations.

Table 4. *SWOT Analysis (by Author)*

		For the goal	
		Helpful	**Damaging**
		Strengths	**Weaknesses**
For the organisation	Intern	-Winner takes most	-Financial investements
		-All the benefits of industrialization	-Time investment
		-Can be adapted to work with multiple producers	-Execution is difficult
		-Durable and re-useable	
		Opportunities	**Threaths**
	Extern	-Offers the abillity of choice	-Bad setiment towards mass production
		-Can be scaled up or down	-Cultural environment
		-Can be maintained or upgraded	-Climatic environment

SWOT analysis conclusion

The proposed method for open building is able to take the input of a client and turn it into a unit that can be produced in a mass production process. The method provides helpful elements both for the organization and the client that makes use of it.

However, the SWOT analysis also provides insight into the most prominent feature as to why there are threads and weaknesses for this method to be implemented today into the building industry, which is the lack of a roadmap. As mentioned, the designed open building method is more a final goal than something that can be applied today. Achieving a method of producing like this will take many years of development that needs to be done as efficiently as possible. The main goal of this design research is to provide a suggestion of a final result that is key in order to aid the creation of a successful roadmap.

Future research

This thesis aims to provide a first basis for a proposal for a building industry that can make use of mass customization through the methods of an open building. The focus of this research is mainly on the infill level, and how it can be connected to a support structure. Future research can take the proposed infill system and research for a method of creating a support structure that is able to fit all the needs of the infill. The second topic of further research would be to look into the equally important roadmap of integrating such a system into the building industry. The suggestion is to create this roadmap for a company that performs most work on-site, and on how they would be able to make the transition to a mass customizable production process in a limited amount of time.

14. Conclusion

This thesis tries to provide part of the solution for the rising need for dwellings around the world. The forecast for the Netherlands alone is that before 2030 there will be a need for one million extra dwellings while the use of space needs to be considered more and more carefully. All of this while the needs of the end-user should not be forgotten. Mass customization can provide a solution to this problem, therefore the following research question is composed: *How can a computational method be designed in order to include a client's input in a mass customizable 3D module building industry?*

In order to provide an answer to this question, a methodology is devised that exists out of two parts, a part of the research, and a part of the design. The goal of the research section is to provide a solid basis of relevant literature to understand the design components that are needed for creating this method. The method that best fits this idea of mass customization is the open building method, wherein a building can be divided between the infill and the support. The infill and the support are described as the parts that are individual and the parts that are collective, wherein it is the purpose of the support to serve the needs for the infill.

For this reason, it is determined that the first most important component is the infill part of the open building method. The main components stemming from the research that is needed to design it are a dimensional coordination system, a volumetric unit, and a catalog of modular pods. To be able to make it function a method for user interaction is designed and an overview of the kit of parts that are needed is created.

These design studies result in a set of suggested rules to which an infill system has to comply in order to achieve mass customization. These rules and principles are then tested in two ways. The first test is to design an infill unit that complies with the rulebook. The second test is to adapt an existing building to be able to function as the support for the infill unit. These tests are used to add on to where is needed for the design studies.

The components and the tests above describe the answer to the research question and provide a range of principles of how to design it. The test studies are used to check the principles and to provide an example of how they can be implemented in practice.

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