HOW CAN WE DESIGN FOR A REMOUNTABLE AND FLEXIBLE OPEN BUILDING?

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ABSTRACT

The Dutch economy is in a transition from a linear- to a circular economy, with a goal to reach full circularity by 2050. These circularity goals are also applicable in the built environment. One of the goals is re-using elements or components with the highest intrinsic value, according to the Ellen MacArthur foundation and the holistic design approach of design for disassembly. Although the generic ideas and framework are available, there is no usable evaluation method for the re-use or remountability of elements or components, which is an important part of design for disassembly. Via a cross relational research in product design, these available evaluation methods have been altered and made applicable within the built environment. Another important aspect of design for disassembly is the flexibility of a building, which one can design for. This aspect is explored and can be further divided and understood with the use of certain available frameworks. These theoretical frameworks have been found in literature and are related to the philosophy of open buildings, which has regained interest in the last year by a group of Dutch architects. Case studies were conducted in order to gain knowledge of the typology and research requirements for a flexible building. Although it is evidently clear to design for flexibility, more research has to be done in order to define the level of flexibility within a certain project. This is due to the fact that it becomes more expensive and it takes more materials to design with higher levels of flexibility and so the relevancy within each project's contextual characteristics and perspectives needs to be determined. Remountability and flexibility are important aspects of design for disassembly which already can be implemented within the built environment. However, defining a certain minimal level within both themes is necessary, presumably imposed by laws- and regulations, in order to make the transition achievable.

KEYWORDS: *ADAPTABILITY, FLEXIBILITY, OPEN BUILDING, STRATEGIES, MEASURING REMOUNTABILITY, DESIGN FOR DISASSEMBLY (DFD)*

I. INTRODUCTION

The Dutch economy is in a transition from a linear- to a circular economy, with a goal to reach full circularity by 2050. This transformation, among other things, is a strategy to reduce raw material consumption and waste to a minimum, in turn drastically reducing the negative impact on the environment. Within a circular economy, keeping the highest intrinsic values of resources needs to become the main focus, illustratively shown in figure 1 of the Ellen MacArthur foundation: a charity dedicated to promoting the transition to the circular economy. These circularity goals are also applicable in the built environment. As one of the most polluting fields, major changes of several processes are necessary in order to accomplish this transition. For instance: more reuse (with higher quality) of materials, products and elements and a different view on producing, tendering, designing and building of projects in the built environment. As displayed in the document of Platform CB'23 (2019), we stand before a major transition which is still not completely defined and organized. Still a lot of research is necessary within the several topics towards a circular built environment, although some general frameworks and guidelines are already available. Additionally, laws- and regulations are required, which several organizations and companies are currently working on. A lot of initiatives are set up to guide the transformation and it becomes clear that this is one of the most important societal themes at this moment, within the built environment and beyond.

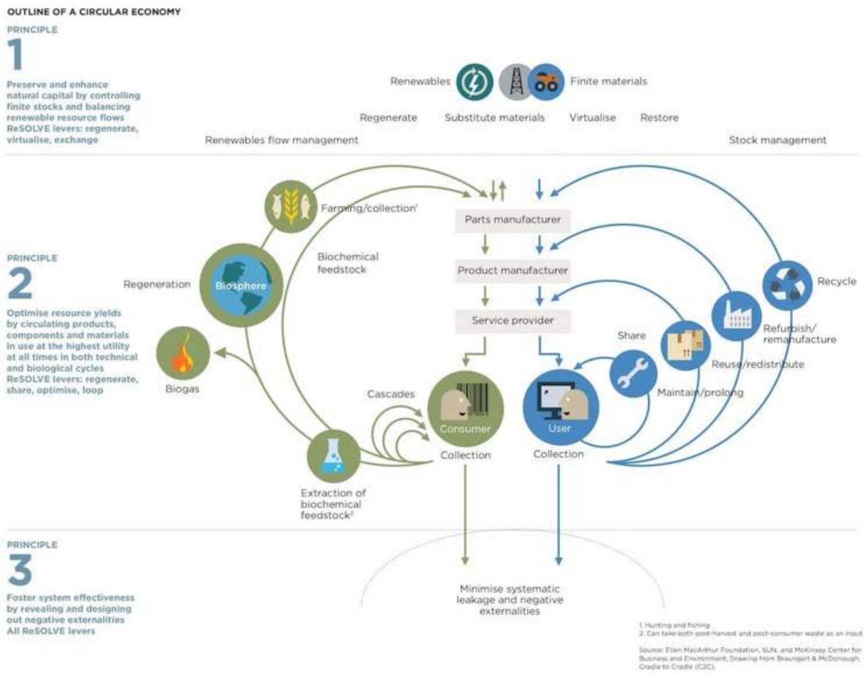

Figure 1: Circular Economy System Diagram (Ellen MacArthur Foundation 2017)

Specifically looking at the strategies to design and built in a circular way, some preliminary strategies can already be found in the work of Platform CB'23. Also, in the study of GXN (2018), the research part of the architectural office 3XN, one finds interesting guidelines in order to achieve a circular building future. Within this, the holistic design approach called 'Design for Disassembly'(DfD) is explained. The main aim of this approach is "to let all buildings become material banks, wherein circular business models can be implemented" (GXN/3XN 2018, p. 40). DfD can be divided into 5 main principles according to this research: 'materials', 'service life', 'standards', 'connections' and 'deconstruction'. Acknowledging all these generic terms and strategies to make the transformation feasible, there is a demand to further research specific aspects within this realm. As we can see in the document of Platform CB'23 (2019) where the necessity of a measuring system for circularity in general becomes clear, further specific research is required in order to practically implement these main principles. Companies like Arup (2016) are also concluding in their research that there are overall frameworks available, yet not enough specific practical application methods can be found.

The aim of this paper is to conduct research into the theme of design for disassembly and to compose useable and practical frameworks and exploratory examples which can be used as design methods for a circular building. This paper is divided into two parts, where the first part is a correlational group research into the aspects of measuring remountability. The document of platform CB'23 (2019) is referring to this term as an important aspect of the future built environment in terms of a circular approach. Interestingly, in other fields (e.g. product design) there was already the necessity of designing for disassembly. With that, certain measuring methods within the realm of product design were researched and transferred into the built environment because no fitting framework was found within this branch.

The second part of the paper is an exploratory case-study based research within the notion of flexibility of buildings. An important asset in order to achieve circularity, according to Platform CB'23(2019) and GXN/3XN (2018). By conducting case studies, examples of flexibility can be found and discussed. Within the theoretical framework of GXN, this subject is placed within the sub-theme of 'service life', see figure 2. In order to research certain projects, a fitting framework was found in the 'open building' typology, legacy of architect John Habraken. Which in short is a design strategy to achieve flexible and adaptable buildings. Interestingly, platform CB'23 and GXN/3XN are referring to 'open buildings' in order to achieve a strategy for designing circular buildings. The renewed interest of this typology is evident in the architectural discussion in the Netherlands, showcased by various contemporary projects. These topics and projects will be researched in order to get a framework that can be applied by designers in order to achieve flexible buildings. By combining the research of measuring remountability with the case studies of flexibility of open buildings, the main research question can be answered in order to require design principles for a research-based remountable and flexible open building:

How can we design a remountable and flexible contemporary open building?

- *How can we assess the remountability in the building industry? (*groupwork)*
- *What is the theoretical framework of flexibility and its relation to open building typology?*
- *What can we learn about flexibility of open buildings from certain case studies?*

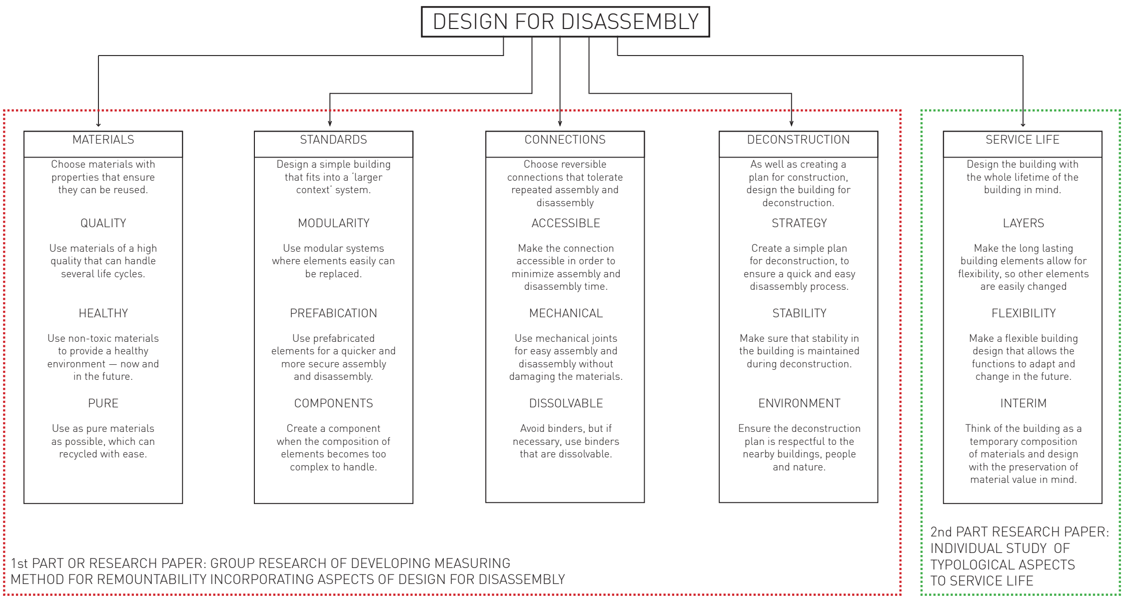

Figure 2: Redrawn scheme (GXN/3XN 2018) – 5 principles to consider when designing for disassembly.

II. MEASURING REMOUNTABILITY

To select the most suitable design solution for remountability, an evaluation method has been developed. The goal of the evaluation method is to create a tool that can be used for decision making in the design process and is intended for the comparison of elements or products in the field of the built environment.

The remountability evaluation method is inspired by a design tool developed by Devdas Shetty. This tool is based on rating factors and consist out of six criteria that can be evaluated using lists with several options (Shetty & Ali, 2015). The method can be improved and altered by prioritizing certain criteria and need to be made more suitable for the field of the built environment. This optimization will be explained in the next paragraphs.

2.1. Type Of The Evaluation Method

These types of evaluation methods are often based on a system called Analytical Hierarchy Process (AHP), which is invented by Thomas L. Saaty (Güngör, 2006). This multi-criteria decision making (MCDM) method uses a hierarchy which compares the relation between all criteria and alternatives.

Another widely used MCDM method is the Analytic Network Process (ANP) which is also invented by Saaty. This method is focused on a network of relations and can be used when alternatives can influence the weighting of criteria this method can be used. Special calculation software and programming knowledge is required for using this method. This is why the remountability evaluation method is based on the ANP method. Different profiles can be made by using a pair comparison to translate a specific vision or goal into a set of weighted criteria, which can be used to calculate a score for every alternative.

2.2. Criteria

There are many criteria related to remountability with different levels of priority. Several criteria from existing measure tools were selected by eliminating irrelevant criteria. Criteria like motion complexity and internal dirt traps were eliminated because they are specifically used in the product industry. Some of the terms found in literature show many similarities and are therefore combined to reduce the amount of criteria. Because of the origin within another field (i.e. product design), there are also new criteria thinkable when transformed into the built environment. For instance, the ability for elements to cope with vandalism in public spaces. For this research however, only scientific criteria were used that already existed within the realm of design for disassembly and which focused on the technical characteristics.

Tool complexity, accessibility, the number of fasteners and the connector types are criteria which are widely used in design for disassembly related work. The number of parts and the amount of fasteners have a huge impact on the efficiency of disassembly processes, whereby the fastener type is crucial according to Askiner Güngör (2006). Other researchers like Fernanda Cruz Rios claim that the accessibility of connections and the separation of systems is highly important for disassembly. Simple structures and forms, which allow standardization, are therefore desirable (Rios, Chong and Grou, 2015).

2.3. Descriptive rating (rating scale)

The rating scale uses descriptions of varied options (with a score from 1 to 9) that have influence on the grade of remountability. Score 9 can be seen as the best case scenario to stimulate remountability, where score 1 is the worst possible scenario. The range is therefore depending on its context and can be changed.

The use of numbers in the options have been avoided because a sentence (which is familiar) is more sufficient than a numerical judgement according to researchers (Ishizaka & Labib, 2011). The method is moreover more user-friendly because the options are recognizable for people involved in the field of the built environment and no additional time calculations are needed.

2.4. Evaluation method

A clear vision or goal and some construction knowledge is needed to use the evaluation method. Specific properties like lifespan, connector type and end of cycle potential of materials or products are also necessary. The first step of using the evaluation method is to define the general ‘profile’ of the building by looking at for instance the function and the intended use of the system. This profile should address all different criteria in order to be able to make use of the evaluation method. It is important, for example, to clarify the intended lifespan and how many times it will be reassembled in this time.

The second step of using the remountability evaluation method is to determine the priority of certain criteria by using a Pair Comparison Chart (PCC). All criteria are compared in pairs and rated from a scale 1-9, which result in *profile factors*. The scale, which is invented by Thomas L. Saaty ranges between equal importance (1) to extreme importance (9). The alternatives which will be compared are rated using lists with several options with a scale from 1 to 9. The scores for each criteria are then multiplied by the *profile factors* generated with the pair comparison to form a final score for every alternative. The final scores can then be compared, and a decision can be made.

III. FLEXIBILITY OF THE OPEN BUILDING TYPOLOGY

In the previous chapter the research focused on the dismantling of the building in order to keep a high value of each component, however considering the butterfly diagram by the Ellen MacArthur foundation, more strategies in different phases can be researched. For instance, before the disassembly phase there is the renewal phase, as shown in the application of a circular building in the diagram of ARUP, figure 3. Within the renewal phase, the notion of flexibility is making buildings enlarge its lifecycle with the re-use of space, preventing it from the necessity for disassembly and presumably delaying the required energy demand. Thus, keeping the highest utility value within a technical or biological, circular loop.

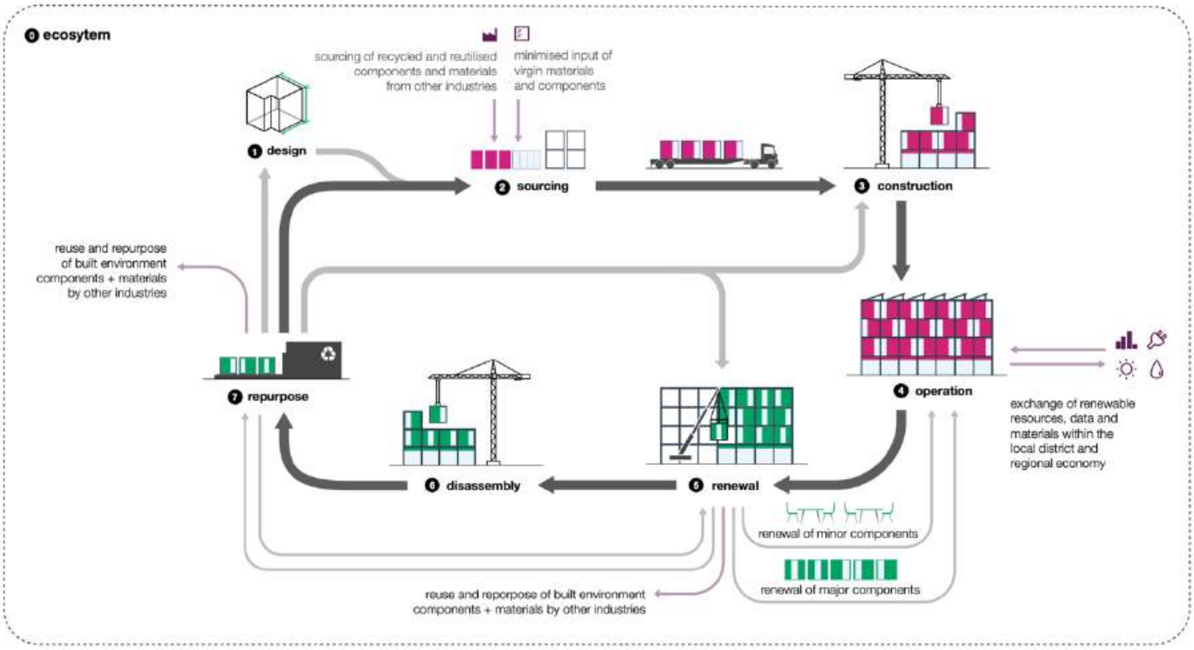

Figure 3: Application of Circular Economy Principles to Commercial Property (Arup 2014)

Within the school of thought of the linear built environment, it becomes evident that designers were mostly concerned with the fitting in of a specific program in a technical, functional and aesthetic way. The essence of time within a lifecycle of a building was often neglected, as studies show (Schmidt, Eguchi, Austin & Gibb, 2016). However, it is inevitable that change would not happen and so the crux becomes visible.

In a sustainable world, where the transition towards circularity is a major contributor of, the essence of change over time becomes thus of high importance. As seen in the phrase of Croxton (2003) “If a building doesn’t support change and reuse, you have only an illusion of sustainability”. As we can see in the paper of Schmidt et al. (2016) a design approach, which incorporates adaptability, is addressing the issue of change over time. Where a building should embody spatial, structural and service strategies in order to respond to changing operational parameters over time. To understand the definition of the word adaptability, literature has multiple definitions (Schmidt et al., 2016), where the conclusion is that it is ‘the capacity of a building to accommodate effectively the evolving demands of its context, thus maximizing value through life’. For this further research, the definition of adaptability is equal to what ANA architects (2014) defined as ways to incorporate forms of flexibility. What is defined as: “the ability of a building to accommodate (functional) change, with limited technical interventions”. Which can be subdivided into 5 applicable methods: fill-ins, changeability, polyvalence, demountable & modular and expandable, schematically exemplified in figure 4.

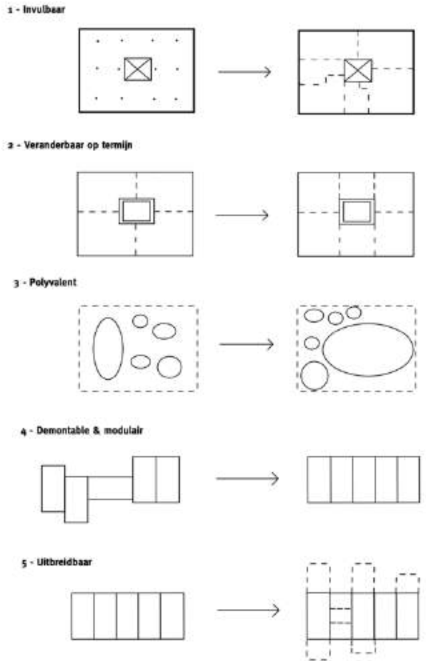

Figure 4: Types of flexibility (ANA 2014)

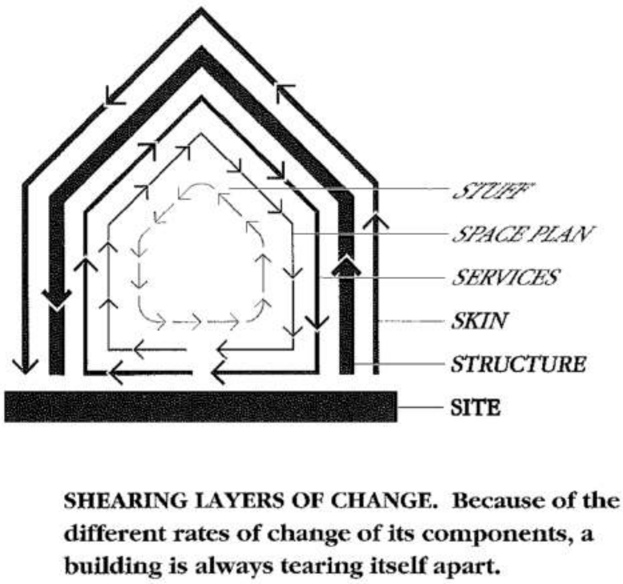

Figure 5: Shearing layers of change (Brand 1995)

However, the changes within a building can be further explored via acknowledging and separating the several layers a building exists of. This is where the philosophy of John Habraken started, with his book: De dragers en de mensen (1985), where there was a division between the permanent carrier and the changeable infill. This philosophy continued along other architects, for instance with Frans van der Werf (1993). Historically, this separation was presumably a start to consciously divide layers within a building, acknowledging several life cycles within it, thus implementing the aspect of time. Later, Steward Brand (1995) broadened the philosophy with the further division into 6 layers, as can be seen in figure 5, which is according to platform CB’23 (2019) now mainly used in the discussion.

Nowadays certain Dutch architects regained interest in the design philosophies of open buildings, exemplified with the lecture from key note speaker Mark Koehler at 2019’s World Architecture Forum about this theme. This renewed interest resulted in a proclaimed movement, the open building academy, where the research and development of the open building typology is conducted. This resulted already in various projects in the Netherlands, highlighted on the website of the architectural like-minded. In order to understand and explore these projects, case studies have been conducted. Within the scope of flexibility, combining the framework of ANA (2014) and Brand (1995), these case studies have been researched in order to define the practical applications and possibilities within this typology. Conclusions and recommendations can be made in relation to flexibility within the open building typology.

IV. CASE STUDIES OF CONTEMPORARY OPEN BUILDINGS

The conducted case studies are chosen from the website of the open building academy (Openbuilding.co 2019). These three contemporary projects are all located in the regenerated Buiksloterham terrain in the city of Amsterdam. Next to the model of ANA (2014) and Brand (1995), the evaluation method developed in chapter 2 is also used to assess certain aspects of remountability. However, the measuring system is in this case more experimentally used on a different scale, not diving into the actual connections but more to explore whether it can be applied to a bigger scale (i.e. building scale). With this assessment, future developments within this typology can learn how to the implement circular 'design for disassembly' strategies on a building scale.

4.1 Patch 22

Designed by architectural office Tom Frantzen et al., this multifunctional building provides mainly housing. In terms of fill-in, the architect designed a general lay-out of a typical floorplan which can be divided into six individual units. Adjacent units can be linked in order to achieve a bigger apartment, resulting in a maximum of up to 48 residential or office spaces on the six typical floorplans. Every unit has the ability to change the service layer, due to the incorporated cavities within each floor. The circulation hub of the building is a concrete core which provides stability for the mainly column-beam structure. This concrete core defines for each floor the number of individual units it can facilitate. The free height of 3500 mm is claimed by the architect to make a functional change towards an office function possible (Frantzen et al, 2017). This feature has to be paid for by the first residential users, which legally can suffice with 2600 mm. Right now, some residential occupants claim this space and turning it into mezzanines: exemplifying the philosophy of Habraken (1995). There are however downsides involved in this strategy, where the initial costs and materials used in the building are generally higher. Thus, it is important to decide which investments are reasonable when looking at changing lifecycles within a building, concluded by platform CB'23 (2019). No data or information could be found on the modularity and expandability of the building, recognizing the flexibility cannot be addressed in these subthemes. For more flexibility and remountability specifics and case study research references, see appendix.

4.2 Blackjack

BNB architects designed this multifunctional building in collaboration with BO6, located next to Patch 22. This omni-directional structure has, in terms of flexibility, equal characteristics in relation to Patch 22. Again, a concrete circulation core provides stability for the overall column-beam structure and defines the number of individual units that can be made due to the number of openings within the concrete core. Every unit contains an own front door, fuse box and shaft. Although not the most cost-efficient strategy, it does result in enormous flexibility, according to the architects (Architectenweb, 2017). The users are more restricted in the placement of plumbing services because the piping is poured into the concrete floor. The end user, who is responsible for the floating screed, has a range of two meters from a certain point wherein the connection can be made. Resulting in a required demolition of the screed flooring when future users want to change certain services. Here, the services are intertwined with the structure thus resulting in problematic characteristics in relation to Brand's model (1995). The modularity and expandability of the building could also in this case, not fully be assessed due to a lack of information. For more flexibility and remountability specifics and case study research references, see appendix.

4.3 CiWoCo

This multifunctional building, designed by GAAGA architects, consist of mainly housing. Integrated car-parking with a collective elevated courtyard on top, defines the programmatic differences with the other cases. Moreover, in this building the circulation shafts are placed separated from the main building structure and connected via a gallery. The adjacent façade defines the number of dwellings with incorporated entrances for polyvalent spaces. In terms of remountability, the prefab concrete columns are provided with a screw thread, making a mechanical connection possible. The service layer, which is placed in lowered ceilings and retention walls, and the partitioning walls are separated from the structure. The modularity aspect of flexibility can thus be found here, whereas the level of expandability remains unknown. More specifics on flexibility can be found in the appendix.

V. Conclusions

The overarching philosophy of design for disassembly is perspicuous within the transition towards a circular future. Research within the field of design for disassembly with applicable methods and examples as outcome, are necessary to guide designers towards the practical implementation of a circular built environment. Although there are many frameworks for what a circular built environment entails, there are not yet strict applicable guidelines to follow. To make the transition possible, especially within the design for disassembly discourse, this requires attention and further research. The measuring method for remountability is a first step towards a usable guideline, testing, adjusting and deepening of the evaluation method is however necessary. The criteria within the measuring method, which can be further expanded, provides a solid core for the essence of measuring remountability. Currently, the user of the evaluation model determines whether certain scores are too low in order to be used as an optional, remountable connection. The logical first improvement of the measuring method would thus be implementing a required minimum of each criteria in order to still count as 'remountable' within the circular school of thoughts. However, the evaluation method can already be used to measure remountability, which is one of the key aspects within the design for disassembly framework.

Another important element within the framework of a circular future, is the flexibility of buildings. The open building typology convinces to implement certain philosophies that are improving 'design for disassembly' and thus the circularity goals, especially within the term of flexibility. Various strategies within the lifecycle of a building can be designed in order to improve its DfD, when placed in the mentioned theoretical frameworks of GXN/3XN (2018). Flexibility is still an umbrella concept with various definitions and frameworks. Due to its relevancy for a circular future, a generic model of flexibility can be helpful to keep the discussion within one model. More case studies are desirable in order to acquire more applications of these definitions and to work towards a research-based evaluation model. An interesting starting point is the framework of the division of ANA architects (2014) of the ways to implement flexibility and the shear layers by Brand (1995). These models could already be used in order to explore certain case studies of the open building typology.

Considering not every case study enforced the complete framework of for instance ANA architect and because there are multiple understandings of flexibility, the implementation of flexibility can be conducted in various ways. It does however, for a circular future envisioned by the Ellen MacArthur foundation, make sense to incorporate the ability to change within the lifecycle of a building. The elaboration on the subject should be critically assessed and be decided on by developing parties (e.g. architect, end-user and developer). If we would incorporate the maximum level of adaptability within each building, it becomes questionable if the redundant use of material will be beneficial from a circular perspective. Apart from that, the costs of developing, buying and renting these buildings will only be more increasing. It thus becomes highly important to research the contextual characteristics of a project's site, in order to implement the required perspective level on the long term. This research can be a leading guideline for designers to understand the level of flexibility that is required within a certain context. Next to a fixed starting point of a building, various scenarios and the added value of flexibility and remountability should be explored with all the parties involved in the design phase. Moreover, in the use-phase the characteristics of flexibility and remountability needs to be available for later users, so the lifecycle of the building can be maximally made use of with a minimal energy demand.

For now, however, it is evident that the ideological point of views of certain architects (and other parties involved in the design phase) was the leading cause to explore the implementation of flexibility and remountability. Flexibility, as well as remountability will need laws- and regulations to construct a certain base level for flexibility and remountability, i.e. what can still be called design for disassembly within the circular school of thoughts. The method to design a 'remountable' and flexible open building is however elaborated upon, although there are for now still considered limitations. The practical use of the evaluation method and its scientific background, together with certain frameworks and examples of flexibility, can guide designers in exploring flexibility and remountability for themselves.

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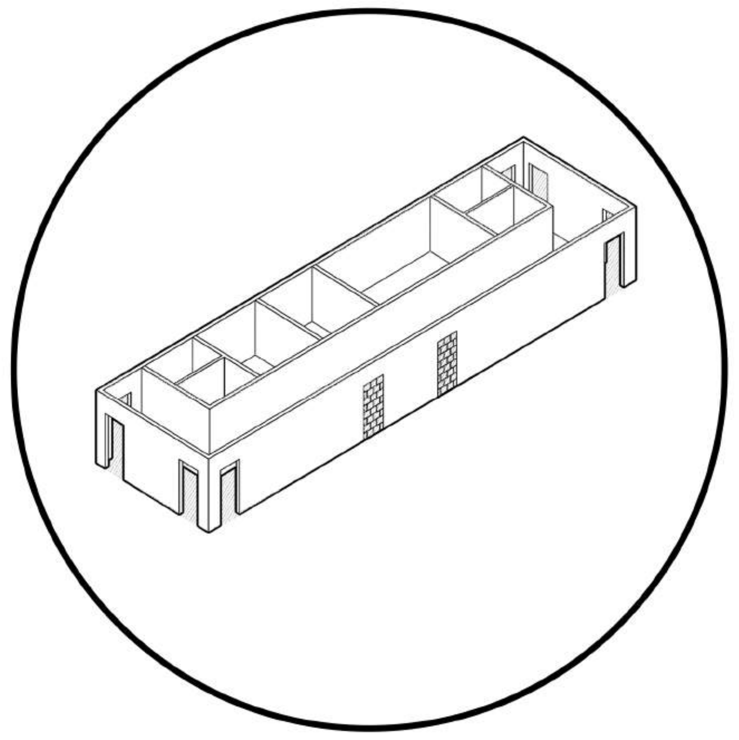
APPENDIX

- CASE STUDIES
  - Patch 22
  - Blackjack
  - CiWoCo
- OVERVIEW PROCESS OF DEVELOPMENT
- OVERVIEW USE OF EVALUATION MODEL
- DEVELOPMENT LOG (FOR EVALUATION MODEL)
- CRITERIA DEFINITIONS FOR EVALUATION MODEL
- DEFINITIONS

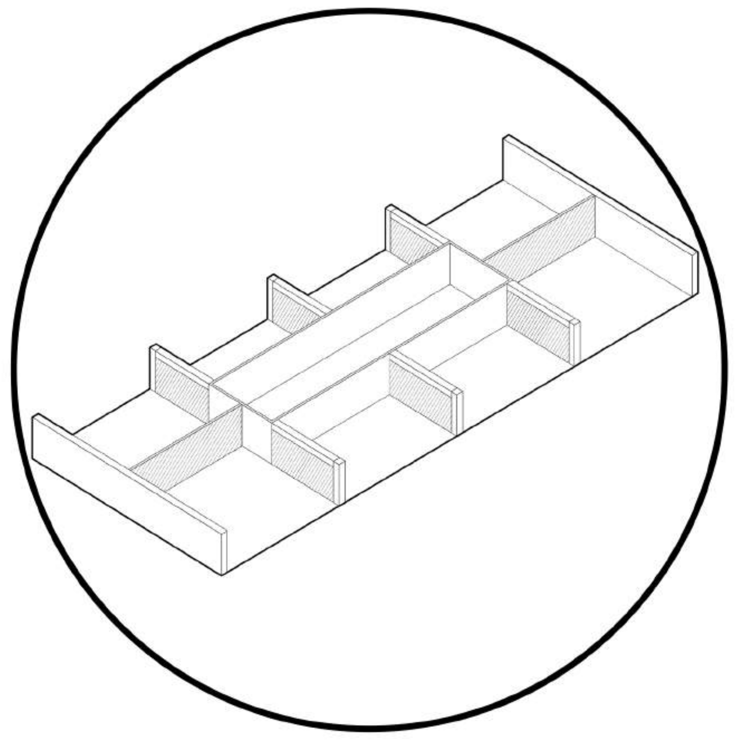
CASE STUDIES // PATCH22

flexibility of contemporary open buildings // Steven Lammersen



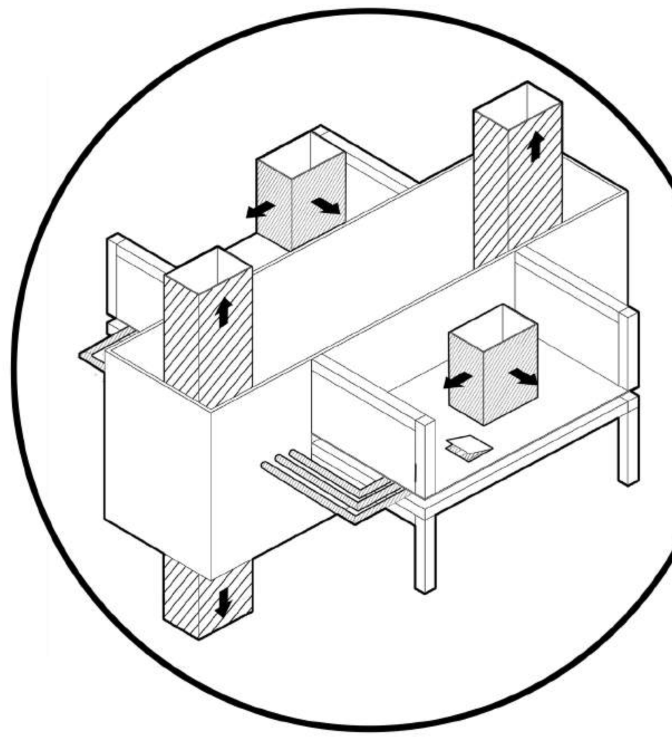
CIRCULATION HUB

The concrete core of the high-part of the building is a collective part which facilitates the transport of different flows. The stairs, elevators, sewage systems, (rain)water, electricity and heat is organized via this part. Although it is in the beginning identical on each floor, this aspect can change. As the diagram shows, there are 10 openings possible from the collective to the private part. This is assigned by the architect as the maximum number of entrances to each (individual) commercial or residential unit. Although they can be hidden by a plastered wall, they are included from the beginning.



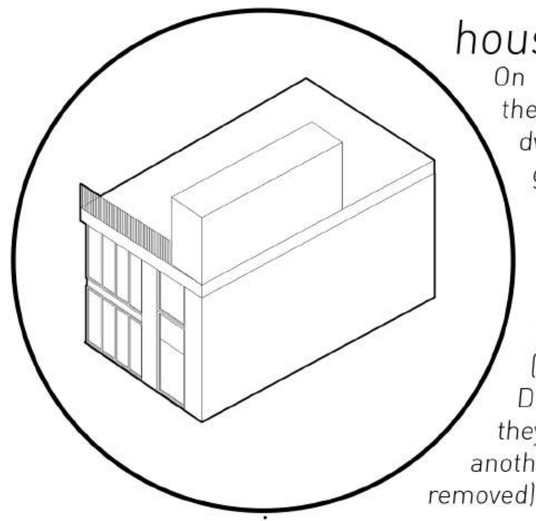
DESIGNED DIVIDING ELEMENTS

As can be seen in the diagram, the structural column-and beam elements are in a direct relation with the functional divisions of the individual private spaces. The architect shows here that the division between individual units can be made exactly under the beams and on the shorter facades exaclty in the middle. Every contiguous option of floorplans is however possible. The building also consist out of one maisonette, so a vertical link is also made possible.



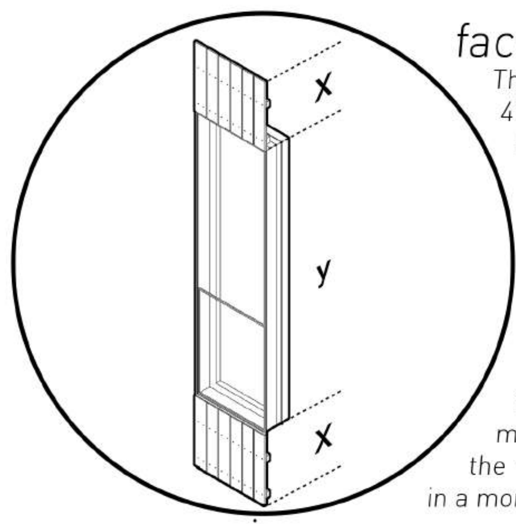
TRANSPORT FLEXIBILITY

Within each individual private area, the end-user has flexibility in terms of how to organize the floorplan. The different pipes(e.g. sewage and hot-/cold water) are accessible via panels in the floor which makes it possible to (re-)place the kitchen and bathroom in different locations. Each individual unit is connected to the vertical shafts which are placed in the collective core of the building, distributing the various flows.



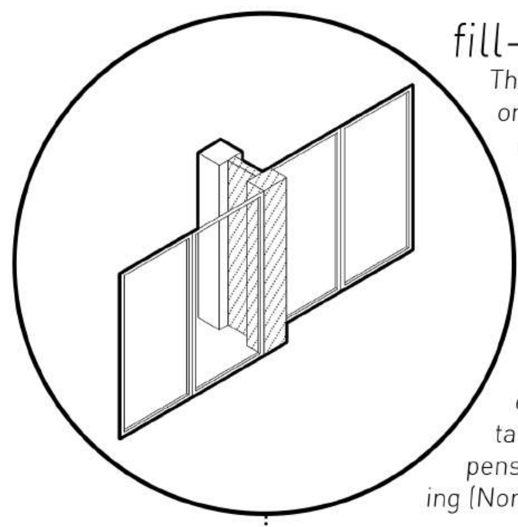
housing element

On the north-east side of the building are 5 identical dwellings placed on the ground floor. Economically, the repetition makes the construction costs more affordable. Functionally, these houses have the minimal height (2,60meter) of a standard Dutch dwelling. Technically they can be transformed into another function (if the floor is removed). Compared with the high-



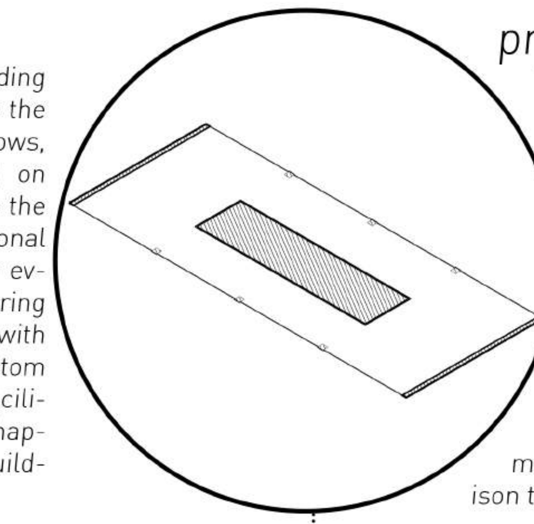
facade element

This windowframe is used 47 times on the north-east facade. Economically this is an interesting approach, where the architect probably tried to play with the configuration to not make it look 'standardized'. The wooden facade has the same dimensions under- as above the window. Thus, resulting in a more standardized facade.



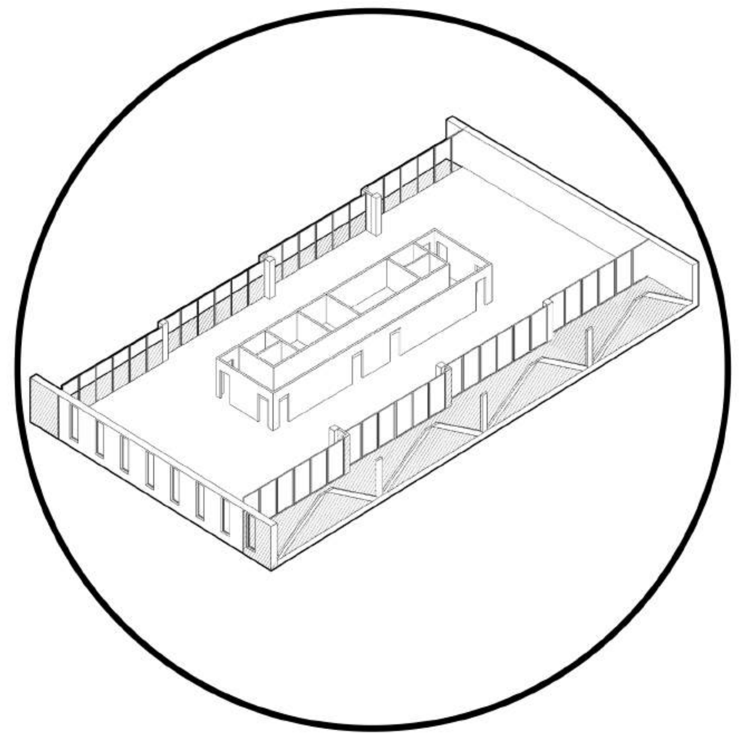
fill-pieces

The facade of the building on the south-side is, as the diagram below shows, shifted and stacked on every level. Because the construction is rational and standardized on every floor, the staggering aspects are filled up with piers, which are custom elements needed to facilitate these jumps. This happens on two sides of the building (North- and South).



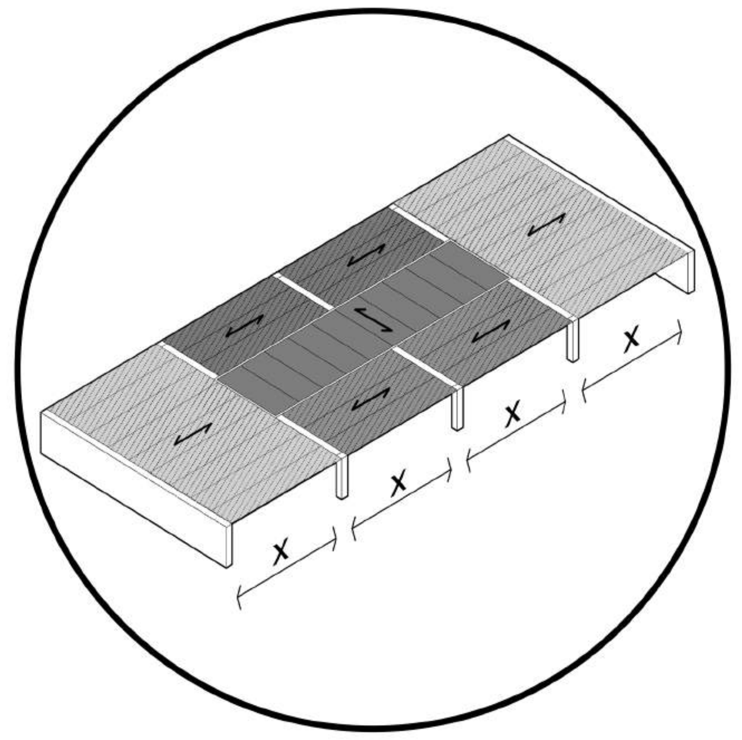
private/collective

The functionallity of the program in the higher part of the building is organized in a way that the 'private' part is surrounding the collective area where the stairs and elevators are situated. Within the private parts divisions can be made to facilitate different users. The collective part consist of full-walls, making it inflexible, in comparison to the flexible private part.



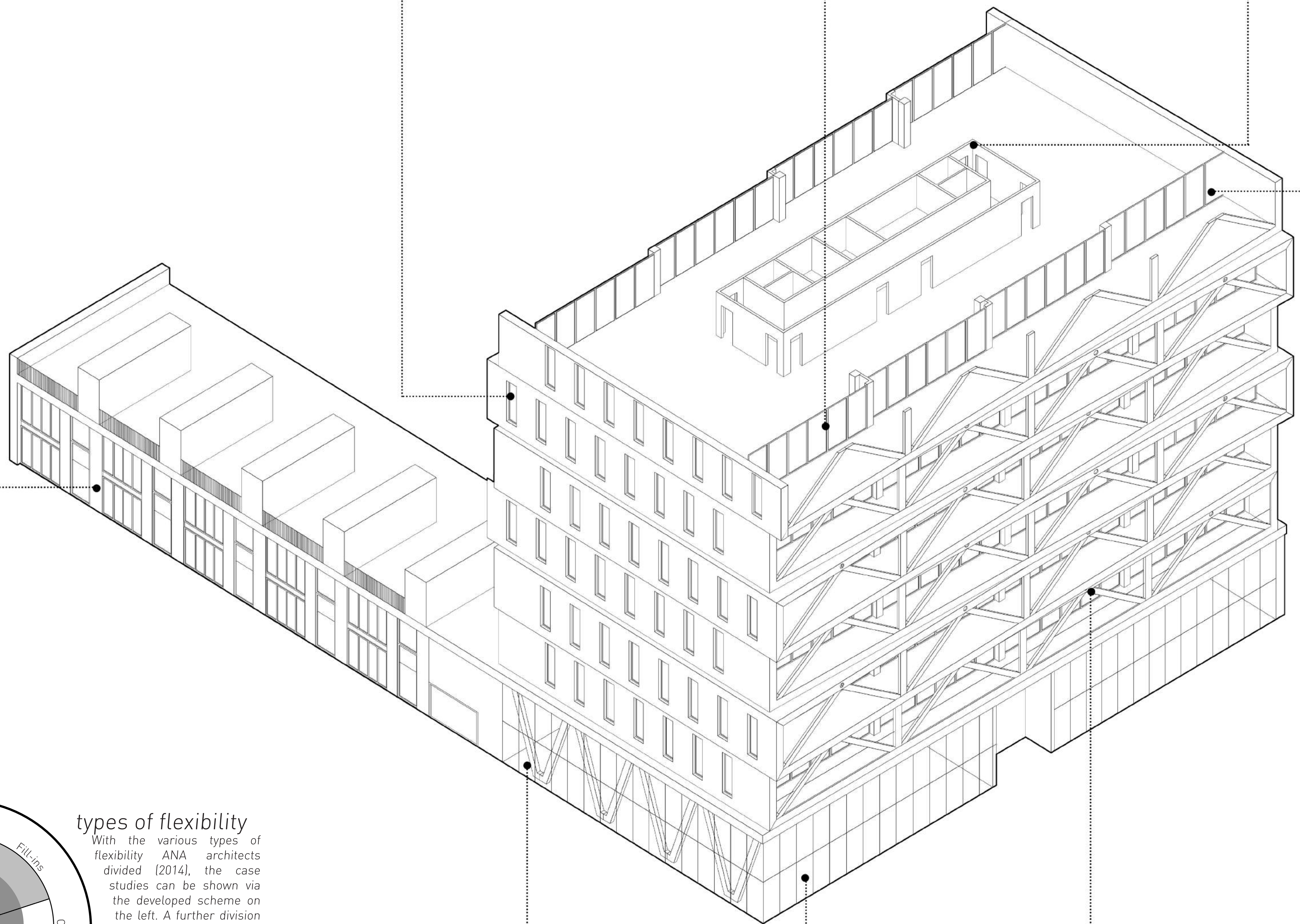
STANDARDIZED/CUSTOMIZED

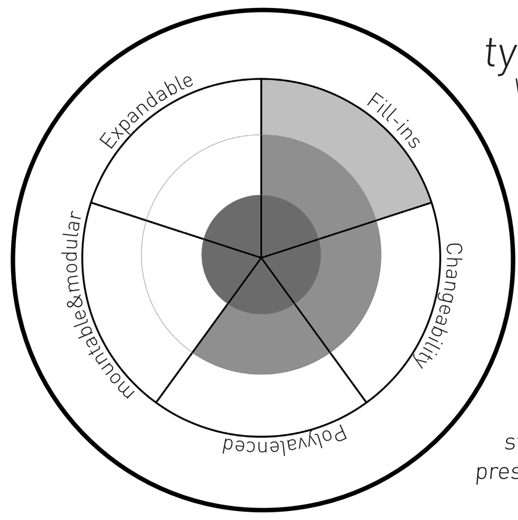
The higher part of the building consist of horizontal blocks (or one story) which are placed slightly shifted on top of each other to make the facade more dynamic. Although the main load-bearing stucture is placed precisely above each other, the variation of floors is causing the building to have some parts that are custom as the diagram above shows. These custom floors are placed, mirrored, on the level above which causes them to also have an element of standardisation. Which expands the overall remountability of the building.



FLOORSPANS/FLOORWIDTHS

The main part of the building, the higher tower, consists of 4 identical floorspans. These spans are 9.5 meter. The 'core' of the building has a different floorspan. Interestingly the areas where the 9,5 meter floor span is applied the architect could have made use of one standard floorwidth. 3 different floorwidths are assumed for now, which is already quite standardized. This is not containing the balconies(see diagram above).





types of flexibility

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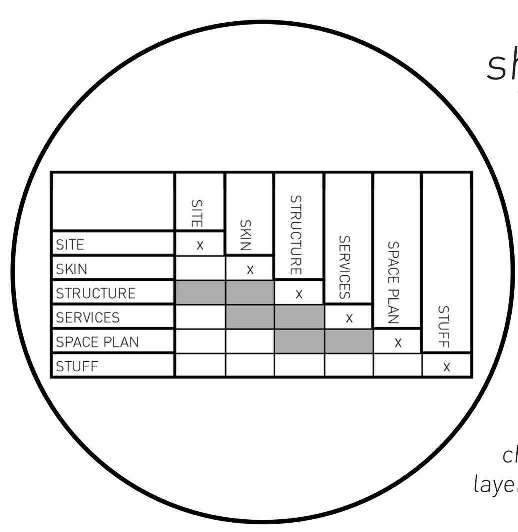

shearing layers

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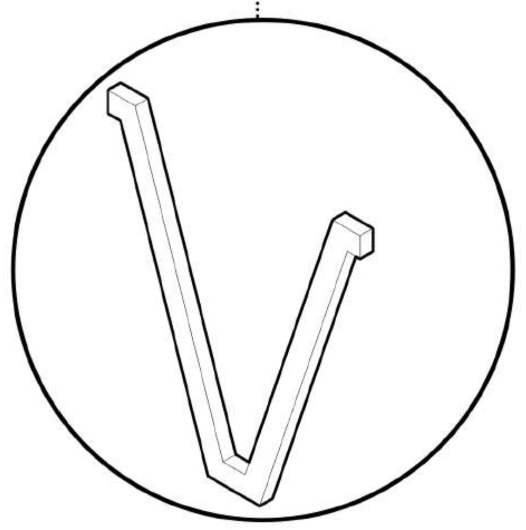
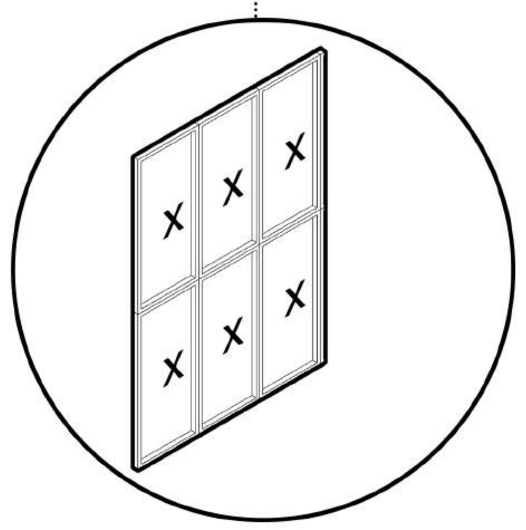


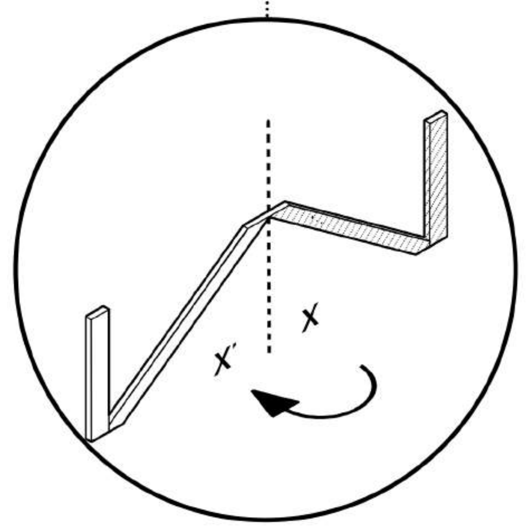
structural element

On the ground floor these V-shape concrete elements are placed 4 times. This element is only applied on this part of the building. Although it is highly visible and bringing a certain dynamic to this part: it is a custom element(placed 4 times).



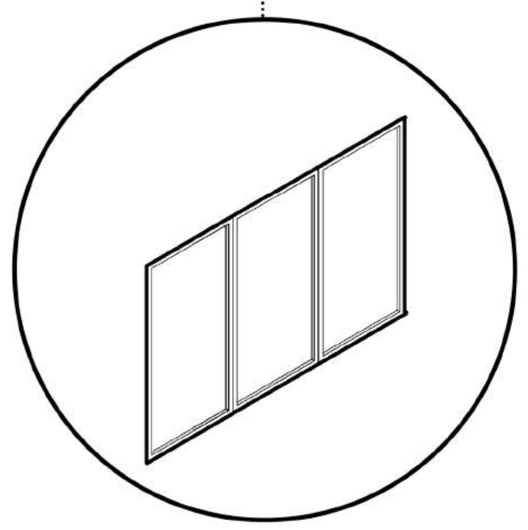
plinth element

The plinth of the building has a double height and is mainly commercial or collective (circulation) space. These functions have a high transparancy and are made out of full-height window frames, repeated on 3 sides of the building.



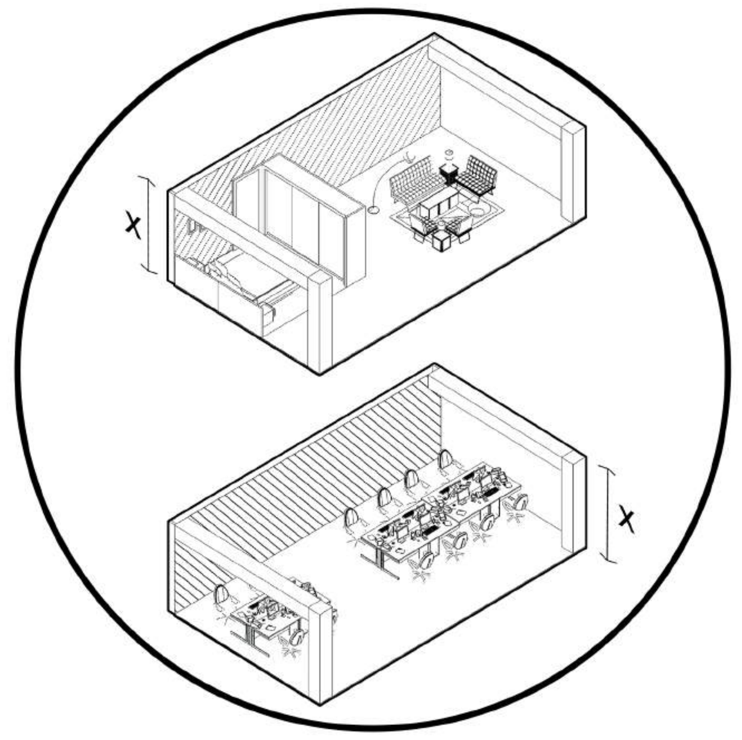
balcony element

The balcony elements consists of wooden columns and beams with steel connections. These are mirrored and highly repeated along the facade. By mirroring the beams more variation is added while using standard elements.



glazing element

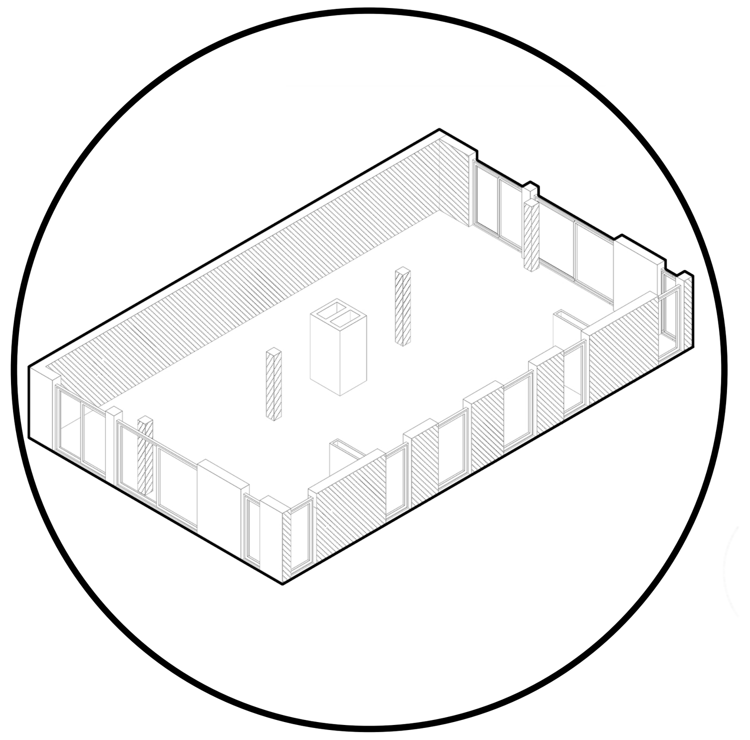
The full glazing on the south- and north facade of patch22 is facilitated by sliding doors. As the diagram shows, the elements are placed shifted next to each other, however the same standard element is used.



FUNCTIONAL CHANGES

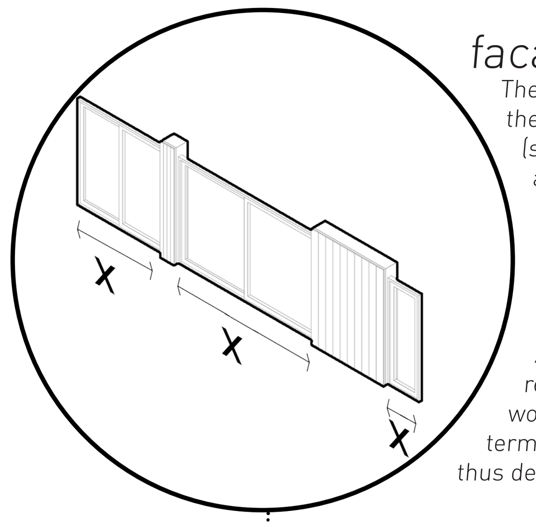
The ability of functional changes of the higher part of the building are facilitated by the design of the architect. The floors are 3,5 meters high which can facilitate the building to be transformed into an office-building. In total this part of the building could be used for 48 commercial or residential units, however the current number is 27 residential units. Although the users had to commit themselves to at least 10% of their units as workspace (municipality stipulated a mixed-use building). The plinth of the building consist of commercial program. The reusability of the building is expanded by ability to make functional changes (from residential to commercial).

CASE STUDIES // CiWoCo



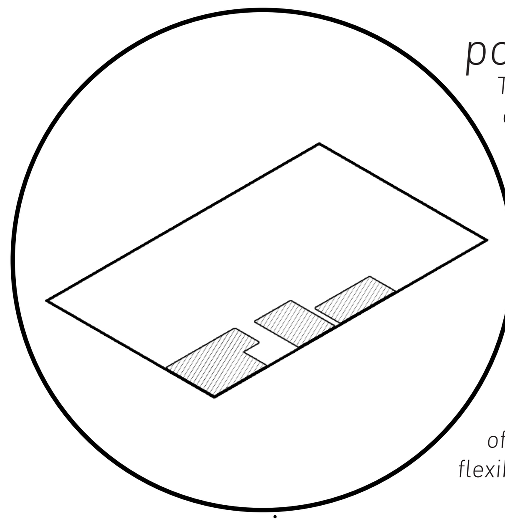
STRUCTURAL BUILD UP

The structure of the higher part of the building can be schematically shown as in the scheme above. The outer walls on two sides are load bearing, with a row of columns between them to divide the floor span. The other two facades are not load bearing and could be changed during it's lifecycle. The entrances, as shown above, are already in the load bearing wall, which can be seen from the starting point (i.e. they are not hidden/plastered like for instance with patch22.



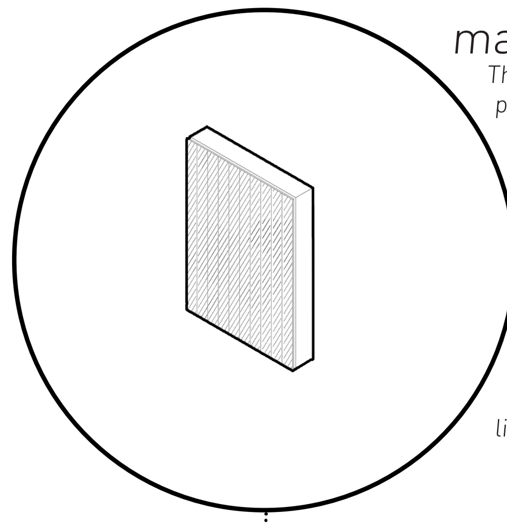
facade elements

The facade of the building on the not load bearing sides (street and courtyard side), as the diagram shows, are playfully divided on the facade. Different measurements have been found, with a minimal amount of repetition. Although this looks playfull, repetition in measurement would give higher scores in terms of standardization (and thus design for disassembly).



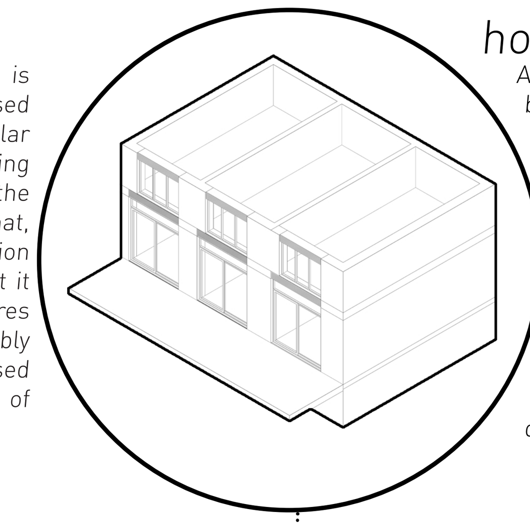
polyvalence

The gallery of the building on the inner side (a load bearing wall) allows the various entrances to the main building. The architect designed fixed areas where optionally office spaces can appear. Although this also had to do with municipality regulations with a minimal area for offices spaces, it does provide flexibility.



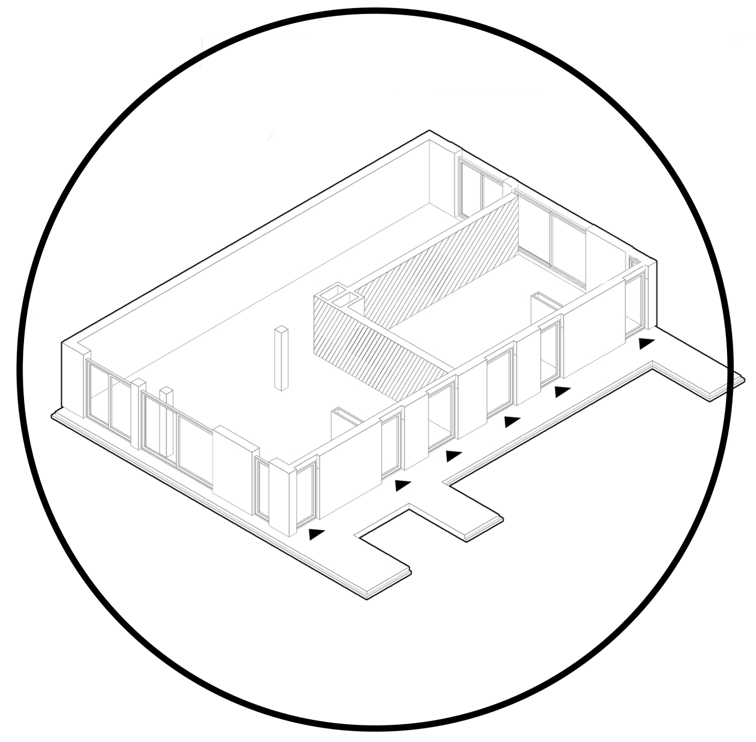
material

The facade of the building is partly made out of re-used wood. This is, from a circular perspective, an interesting approach to materialize the building. Apart from that, in the developed evaluation model one can see that it does provide higher scores for design for disassembly when materials are used that can be re-used (end of life potential - criteria)



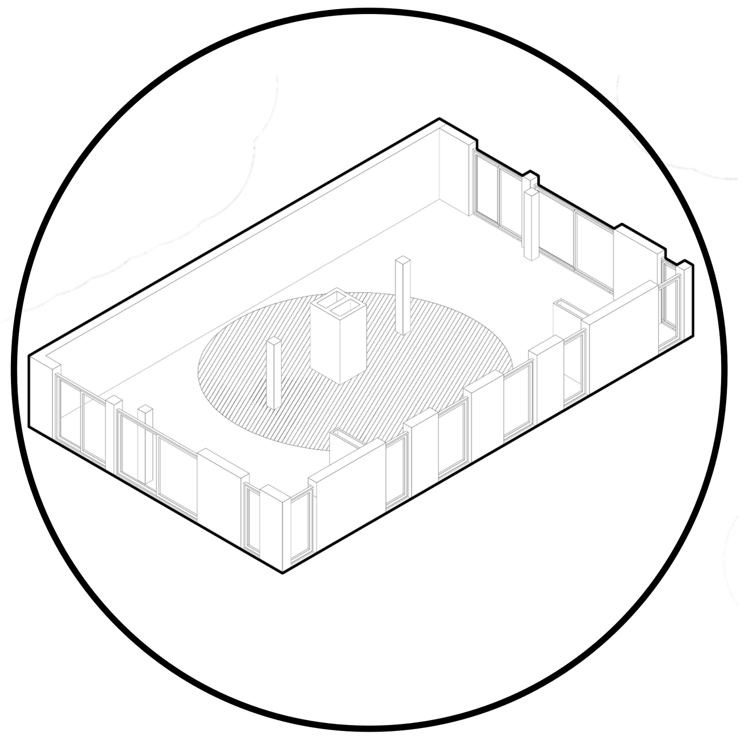
housing element

As well as in patch22 and blackjack, ciwoco has a more conventional part of development. Enclosing the collective courtyard, this part of the building is more traditional and has less flexibility aspects in comparison with the higher part of the building. The load bearing structure is mainly preventing the dwellings to grow or shrink.



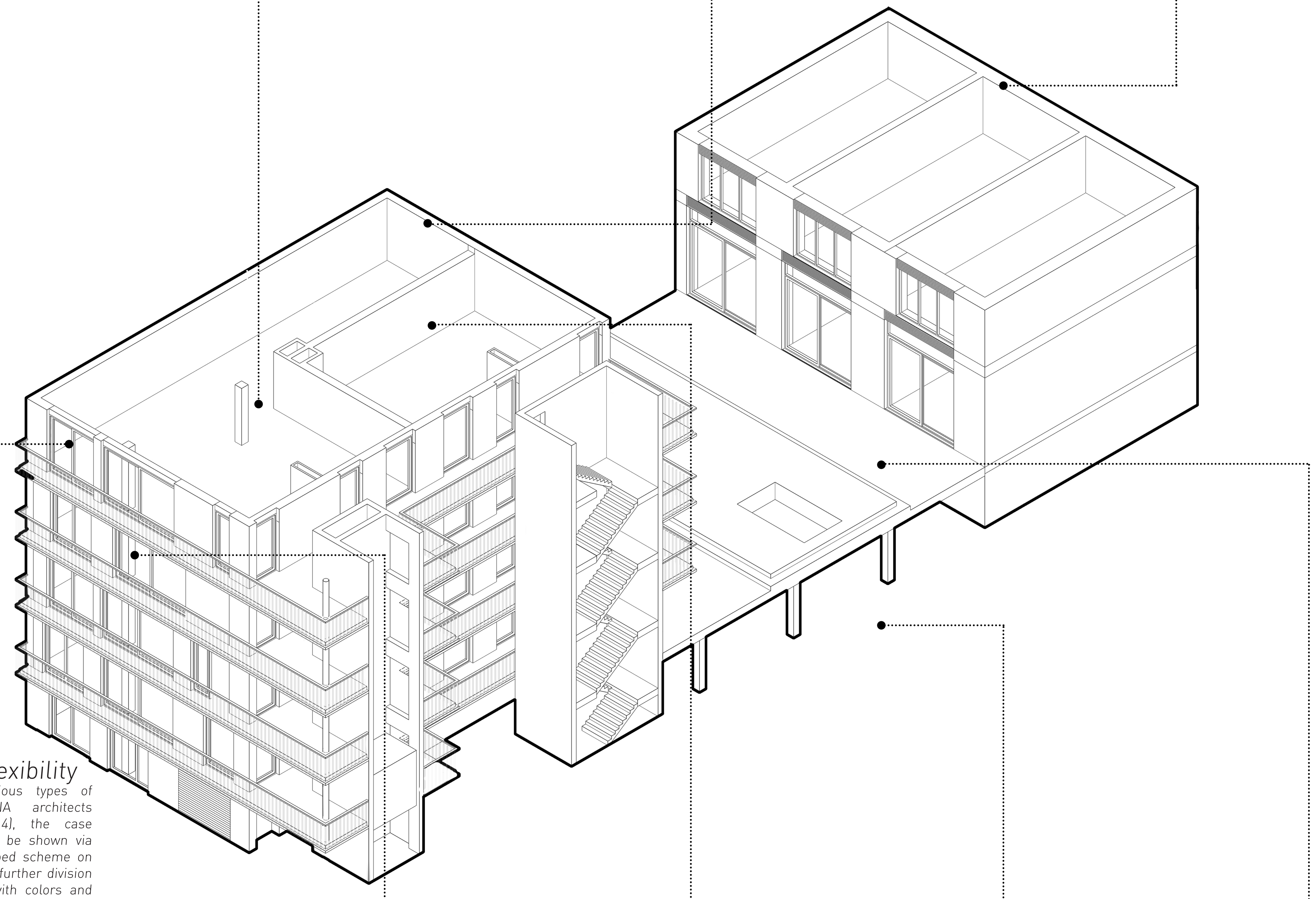
ENTRANCES/INDIVIDUAL SPACES

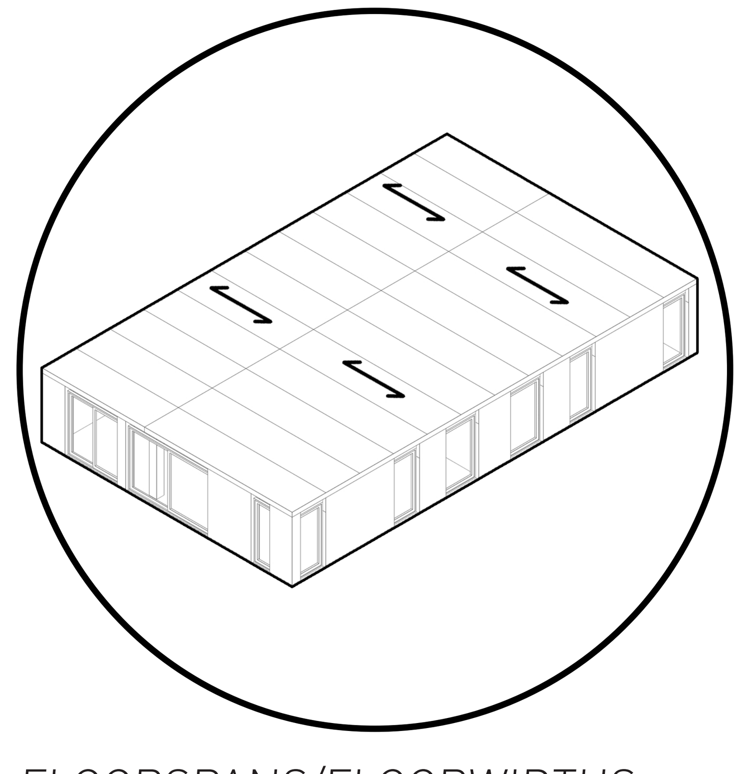
The higher part of the building consist of galleries that make the entrances possible to the various functions . As can be seen in the diagram, the structural beam elements are making a functional division of the individual private spaces possible. The architect shows here that the division between individual units can be made in different locations, although the pre-designed entrances should be considered. Every contiguous option of floorplans is however possible.



WET CELL PLACEMENT

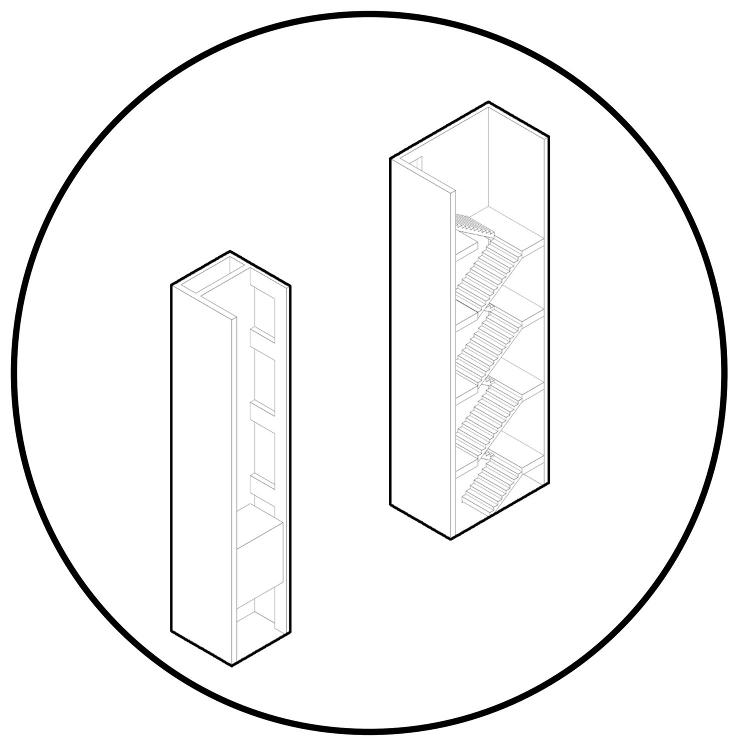
As can be seen in the diagram, the drainaige for kitchen and toilets are designed in a way that they have a certain radius from the shafts. Within each individual private area, the end-user has flexibility in terms of how to organize the floorplan. The different pipes(e.g. sewage and hot-/cold water) are accessible via lowered ceilings and retention walls which makes it possible to (re-)place the kitchen and bathroom in different locations. Each individual unit is connected to the vertical shafts which are placed in the collective shaft of the building, distributing the various flows





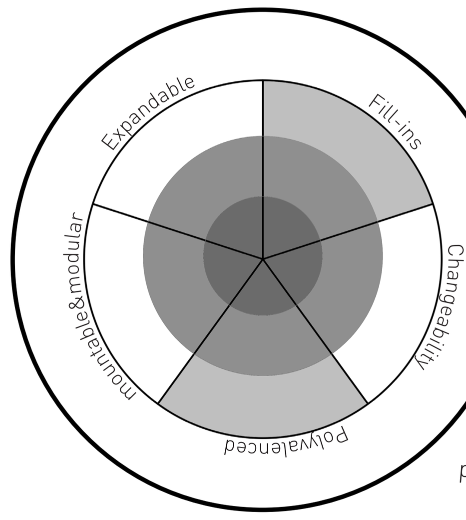
FLOORSPANS/FLOORWIDTHS

The main part of the building, the higher tower, consists of 2 different floorspans. These spans are approximately 7 and 5 meters. There is thus a standardization found in the types of floors.



TRANSPORT FLEXIBILITY

Interestingly, the architect decided to place the collective stairway and elevator not within the main building. There is a seperation between the main building and the circulation area, connected via an outside gallery. This makes the main building assumingly more flexible in use, if it is compared with the fixed location within the main building of patch22 or blackjack.



types of flexibility

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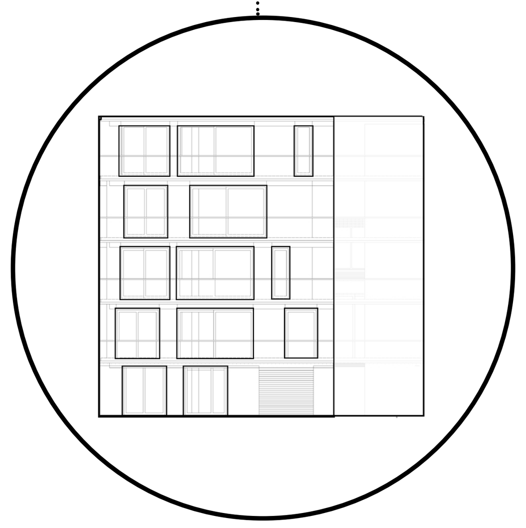
	SITE	SKIN	STRUCTURE	SERVICES	SPACE PLAN	STUFF
SITE	x					
SKIN		x				
STRUCTURE			x			
SERVICES				x		
SPACE PLAN					x	
STUFF						x

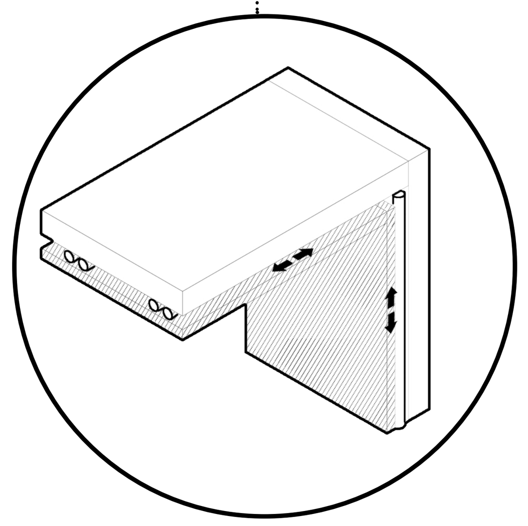
shearing layers

Within the scheme of Brand (1995), the various layers within a building can be determined. The developed scheme on the left shows the relation between each layer. White: no relation, so positive seperation. Grey: almost no relation, some minor mixes of the layers are found. Dark grey: not seperated, problematic characteristics of the various layers found.



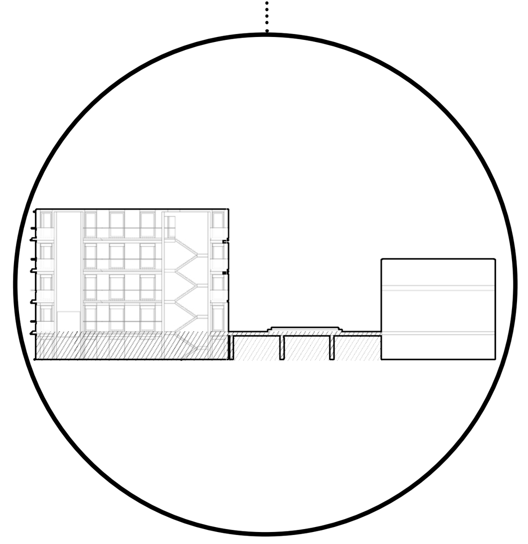
playfull facade

Although there are windowframes and enclosed facada panels that have the same dimension, a bigger standardization could have been realized within this project. The playfull facade brings architectural qualities perhaps, but in terms of design for disassembly this could have scored higher.



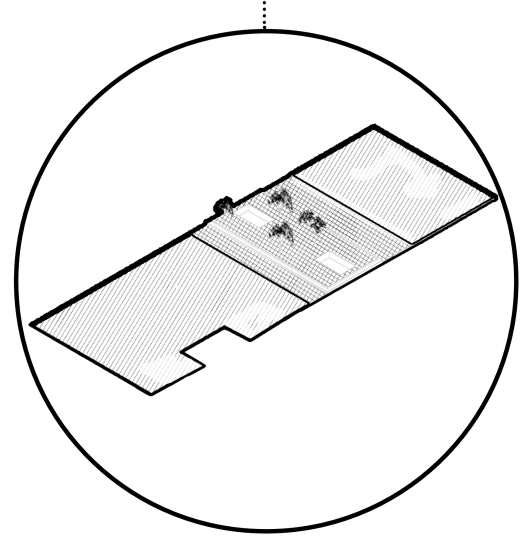
flexibility of service

The lowered ceilings and retention walls in this project make it possible to change the services. It is a strategy to divide the various layers as described in the shearing layers of Brand (1995). This makes the building more flexible than strategies where the services are within the (structural) floor, although it presumably costs more material.



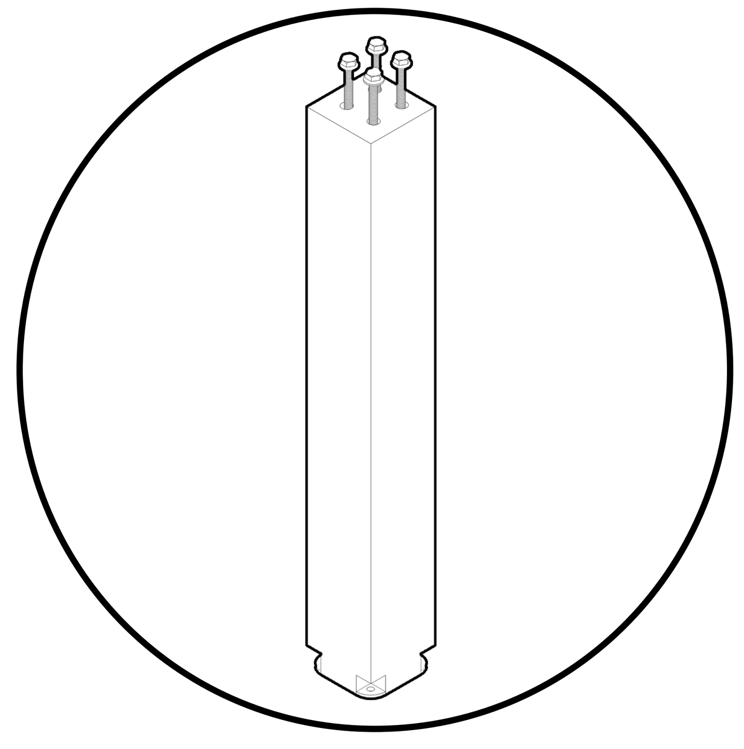
integrated parking

The enclosed collective courtyard is defined as the roof of the integrated parking. In comparison to patch22 and blackjack, this allows the building to have a green connection on the first floor.



collective courtyard

The higher, flexible part of the project and the more traditional lower part, are enclosing a collective courtyard. In comparison with patch22 and blackjack, the two parts of the building are physically connected with a collective courtyard.

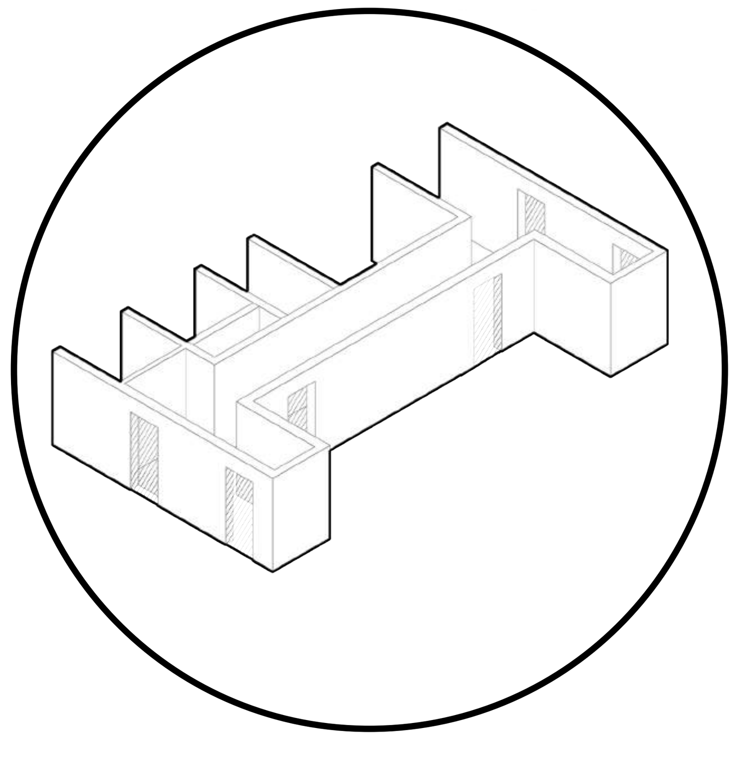


REMOUNTABLE STRUCTURE

The interesting part of this project is the remountable column structure. In terms of remountability, the prefab concrete columns are provided with a screw thread, making a mechanical connection possible with the floors. This obviously scores higher at design for disassembly than the more traditional prefab column-beam structure (where they are later connected with concrete).

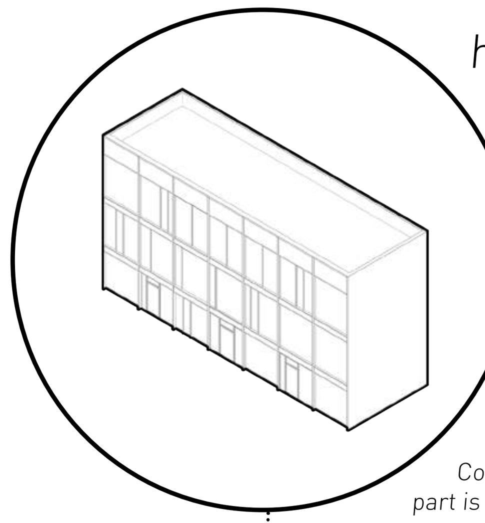
CASE STUDIES // BLACKJACK

flexibility of contemporary open buildings // Steven Lammersen



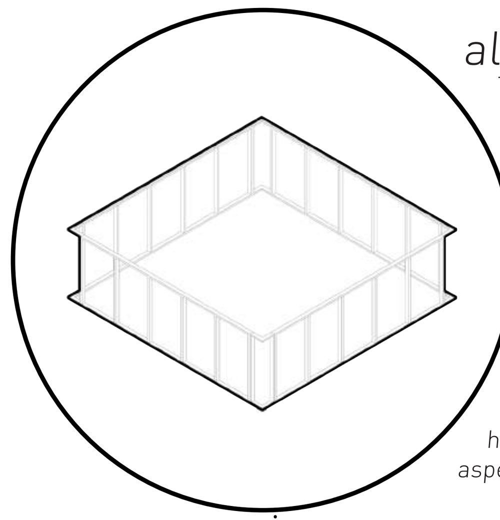
CIRCULATION HUB

The concrete core of the high-part of the building is a collective part which facilitates the transport of different flows. The stairs, elevator, sewage systems, (rain)water, electricity and heat is (partly) organized via this part. This part is identical on each floor and can not be changes in the lay out of the building. As the diagram shows, there are 6 openings possible from the collective to the private part. This is assigned by the architect as the maximum number of entrances to each (individual) commercial or residential unit. Although they can be hidden by a plastered wall, they are included from the beginning.



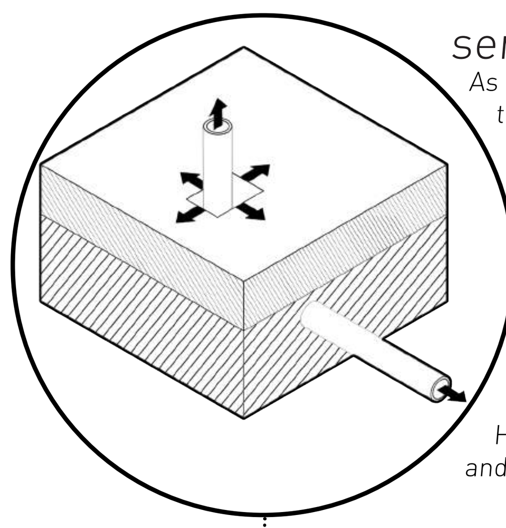
housing element

On the north-east side of the building are identical dwellings placed on the ground floor. Economically, the repetition makes the construction costs more affordable. These houses have the minimal height (2,60meter). Technically they can be transformed into another function, although it is questionable if it is high enough for offices. Compared with the high-rise, this part is rather conventional.



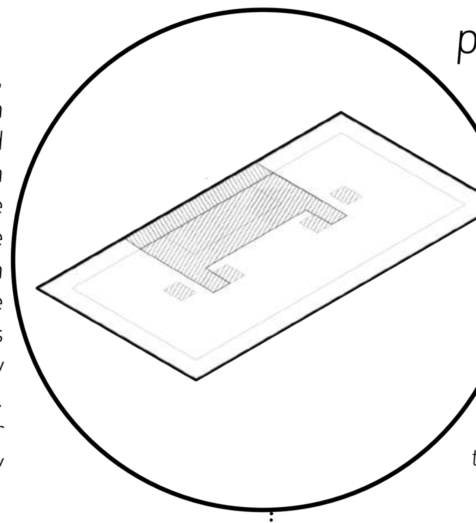
all sided building

The facade of the building consist of a repetetive design, as the diagram shows. Because the construction is rational and standardized on every floor, the complete facade is no exception within this characteristics. It consists of highly repetetive elements and thus scores high on the standardization aspects.



service flexibility

As can be seen in the diagram, the drainage for kitchen and toilets are designed in a way that they have a certain radius from the point where it leaves the structural floor. Within each individual private area, the end-user has flexibility in terms of how to organize the floorplan. However, the service layer and structure are seriously intertwined.



private/collective

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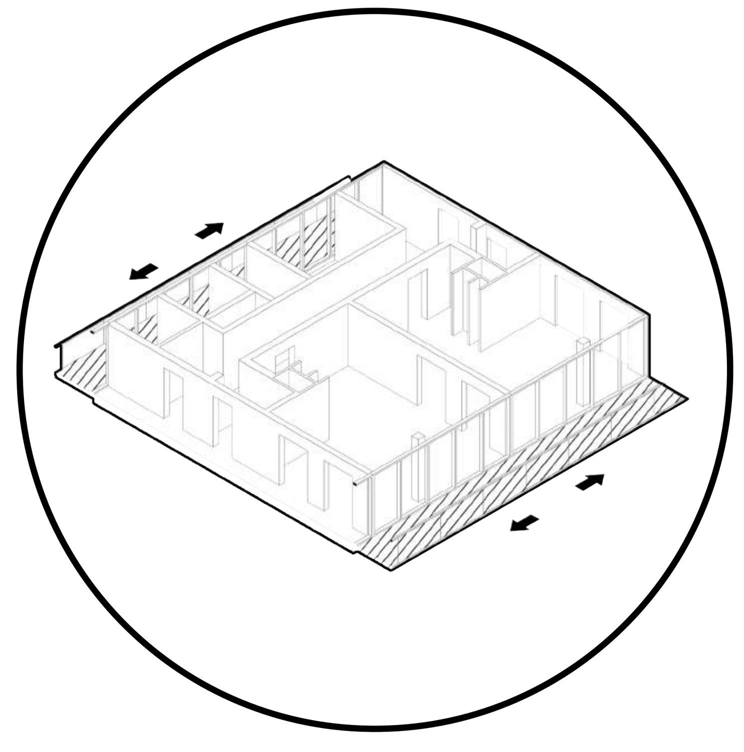
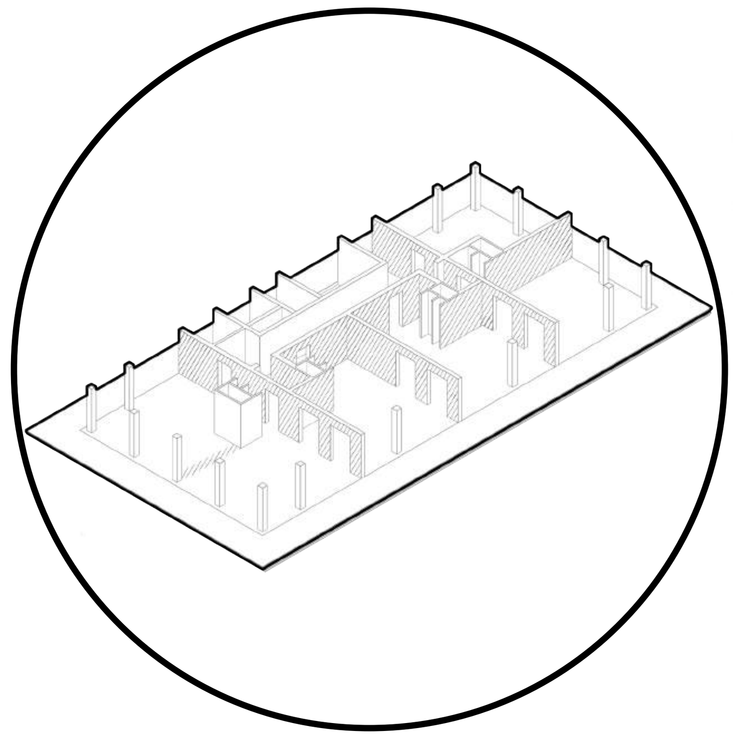


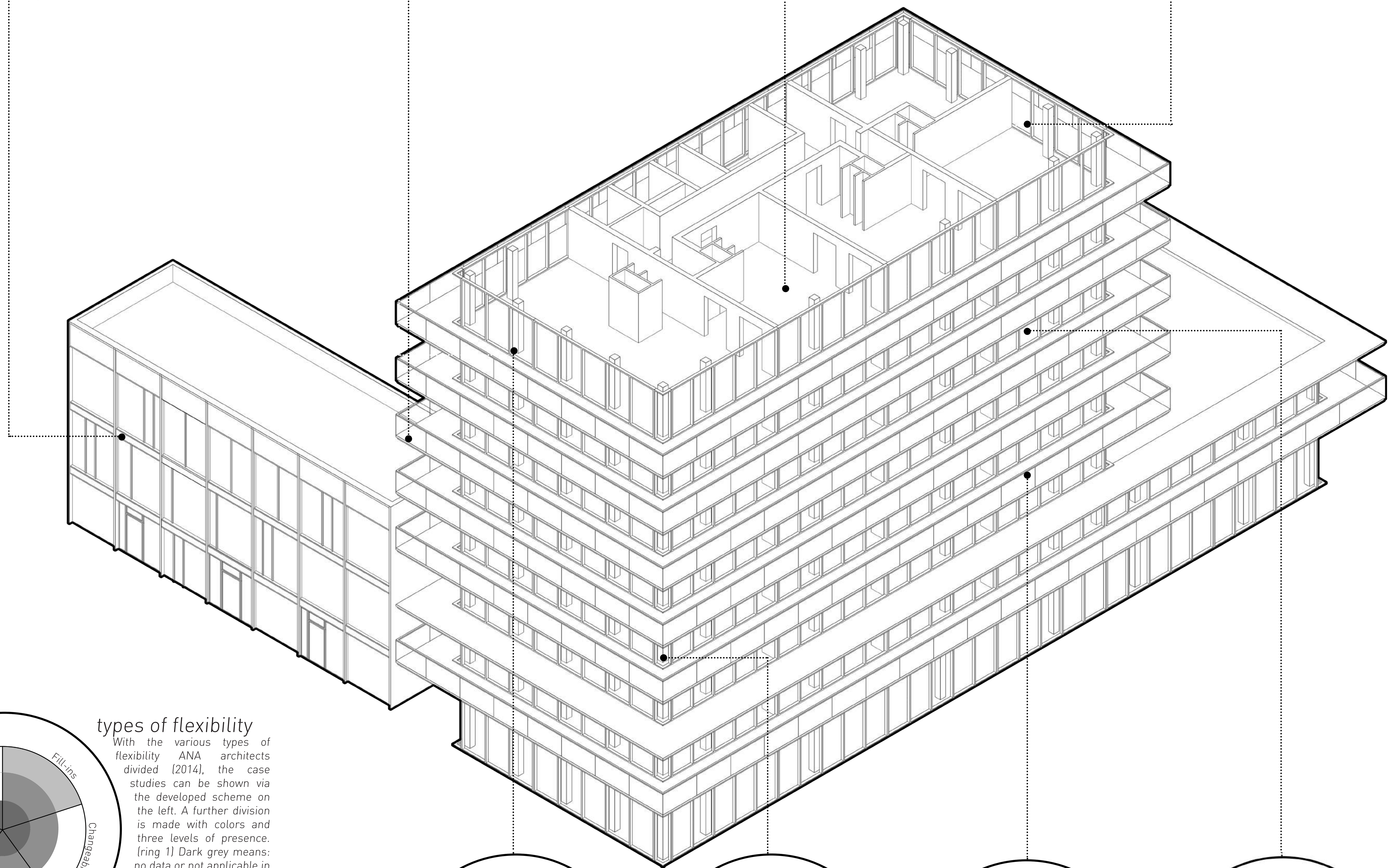
OUTSIDE SPACES

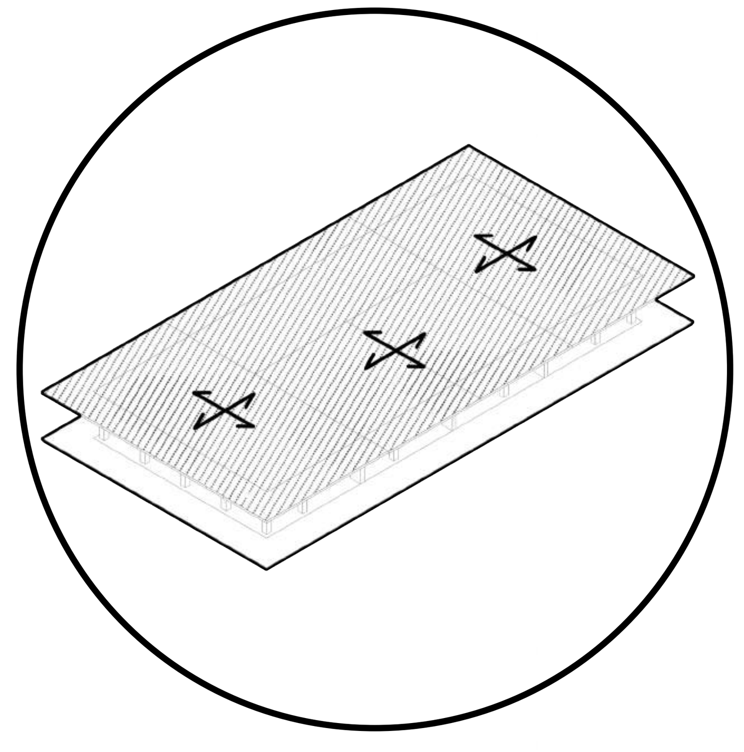
The higher part of the building consist of four facades that are almost entirely made out of glass and have continuous balconies around the building. In terms of flexibility it is interesting that the balconies are continuous, which makes it possible to make connections of units possible however also acquiring more (private) outside space. Only adjacent to the collective part of the building is a collective outside balcony, which is used in the fire plan strategy of the building.



DESIGNED DIVIDING ELEMENTS

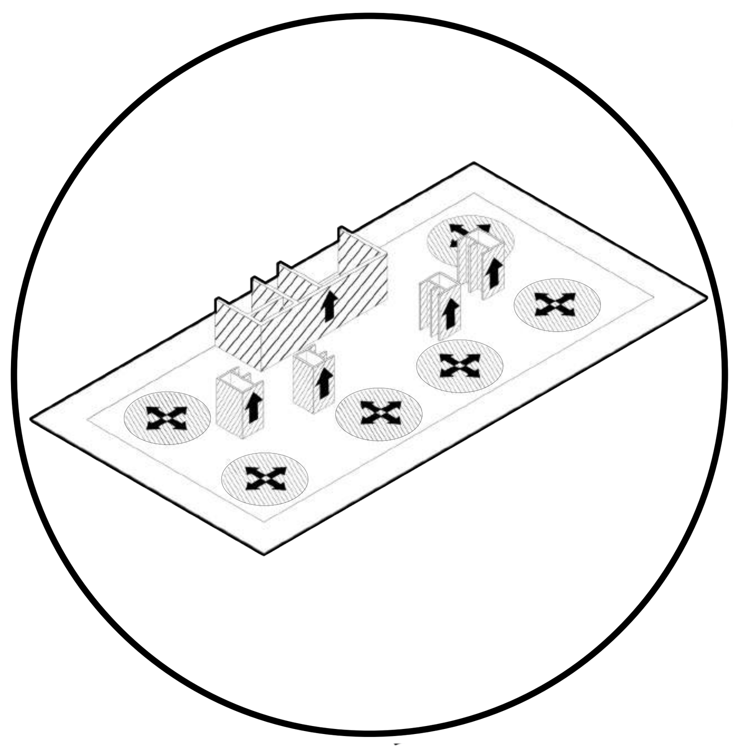
As can be seen in the diagram, the structural column elements are not in a direct relation with the functional divisions of the individual private spaces. The architect shows here that the division between individual units can be made in certain areas, with a maximimum of 6 units per floor (2 x 3 different units). Every contiguous option of floorplans is however possible. The units can thus be connected to form a bigger space.





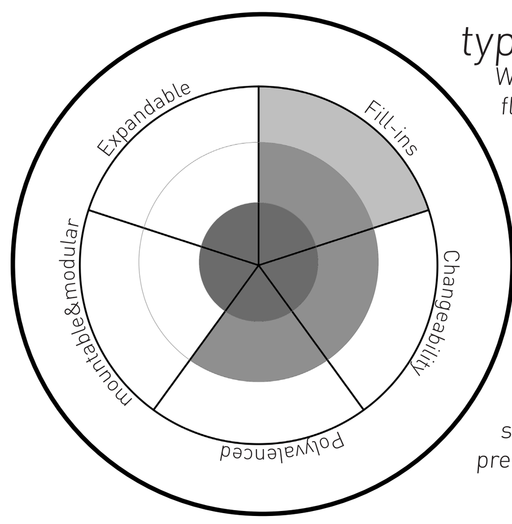
FLOORSPANS/FLOORWIDTHS

The main part of the building, the higher tower, is assumed to be a floor that spans in both directions. This assumption is made because of the overhanging balconies, that probably are divided (inside and outside part) and connected with IsoKorf (or equal) on all 4 sides. This is not feasible with a hollow-core floor. In terms of remountability, if it is a monolithic floor, this floor scores very low in this aspect.



TRANSPORT FLEXIBILITY

Within each individual private area, the end-user has flexibility in terms of how to organize the floorplan. The different pipes(e.g. sewage and hot-/cold water) are accessible via panels in the floor which makes it possible to (re-)place the kitchen and bathroom in different locations. The top layer of the floor need to be demolished for this. Each individual unit is connected to the vertical shafts which are placed in the building, distributing the various flows. There is however a certain radius where the pipes can connect to, not all locations are optional.



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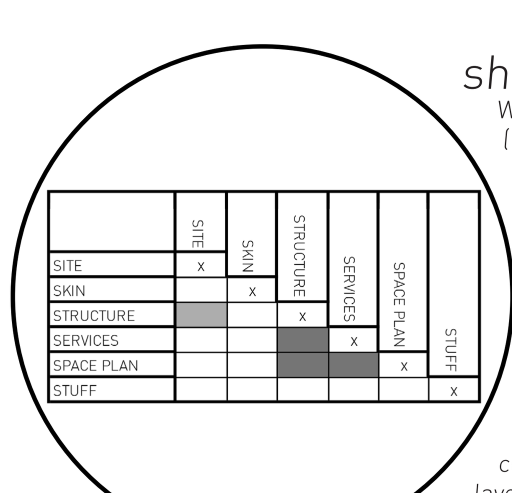

shearing layers

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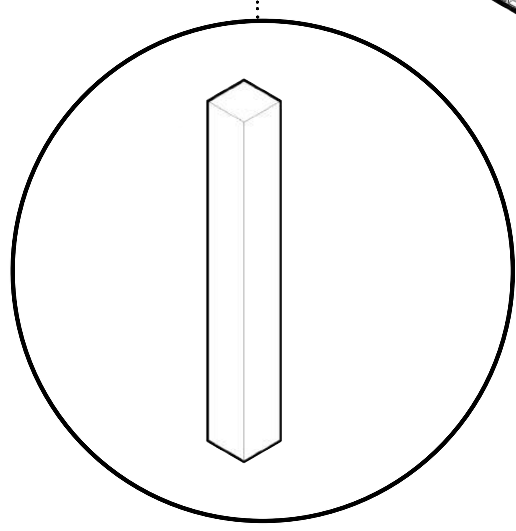
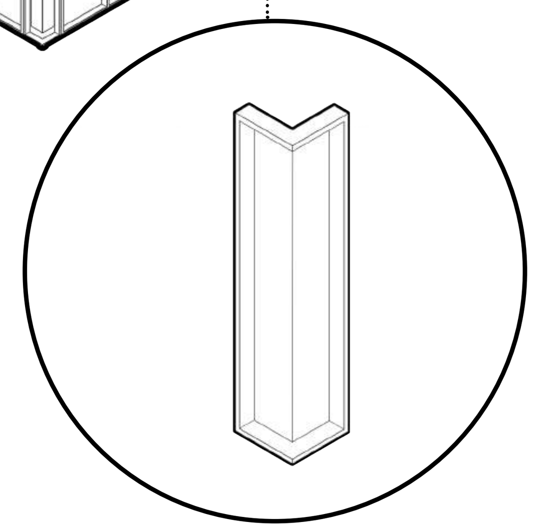


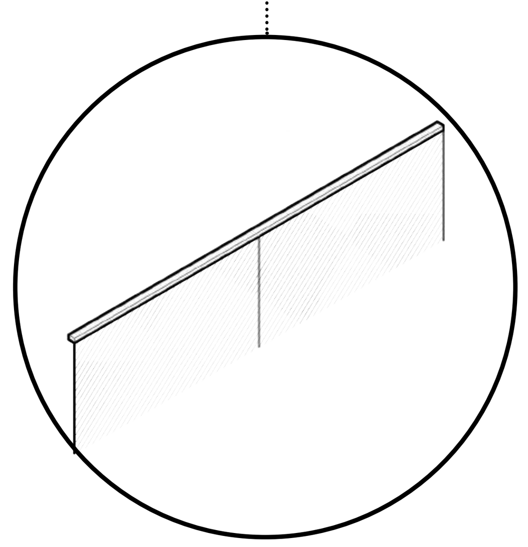
structural element

On each floor, concrete beam elements are placed 16 times. This element is applied in every part of the building. Although it is highly repeated and thus scores high on standardization, it has a 'wet' connection with the floors and can not be mechanically disconnected.



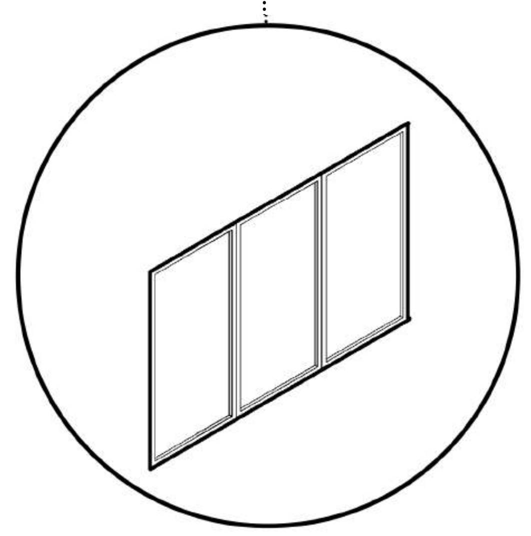
corner solution

Because of the continuous glazed elements on all four facades, each corner consists of a fill in piece, which is used on every corner. This scores high in terms of standardization and thus design for disassembly.



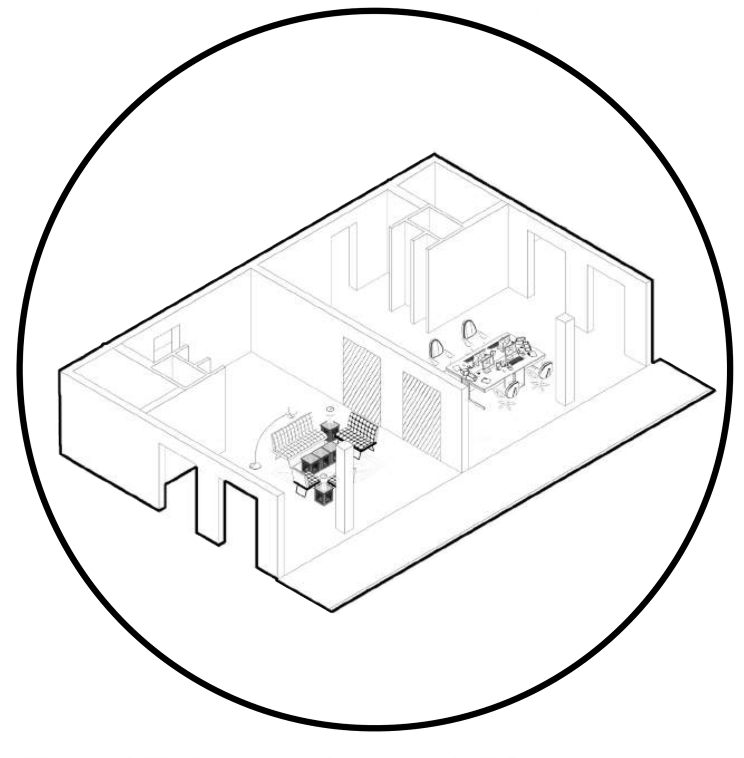
balcony element

The balcony elements consists of glazed panels and steel frames. These are highly repeated along all four of the facades. To protect the balconies from wind and sound, they are a bit higher than strictly is necessary. This scores high in terms of standardization and thus design for disassembly.



glazing element

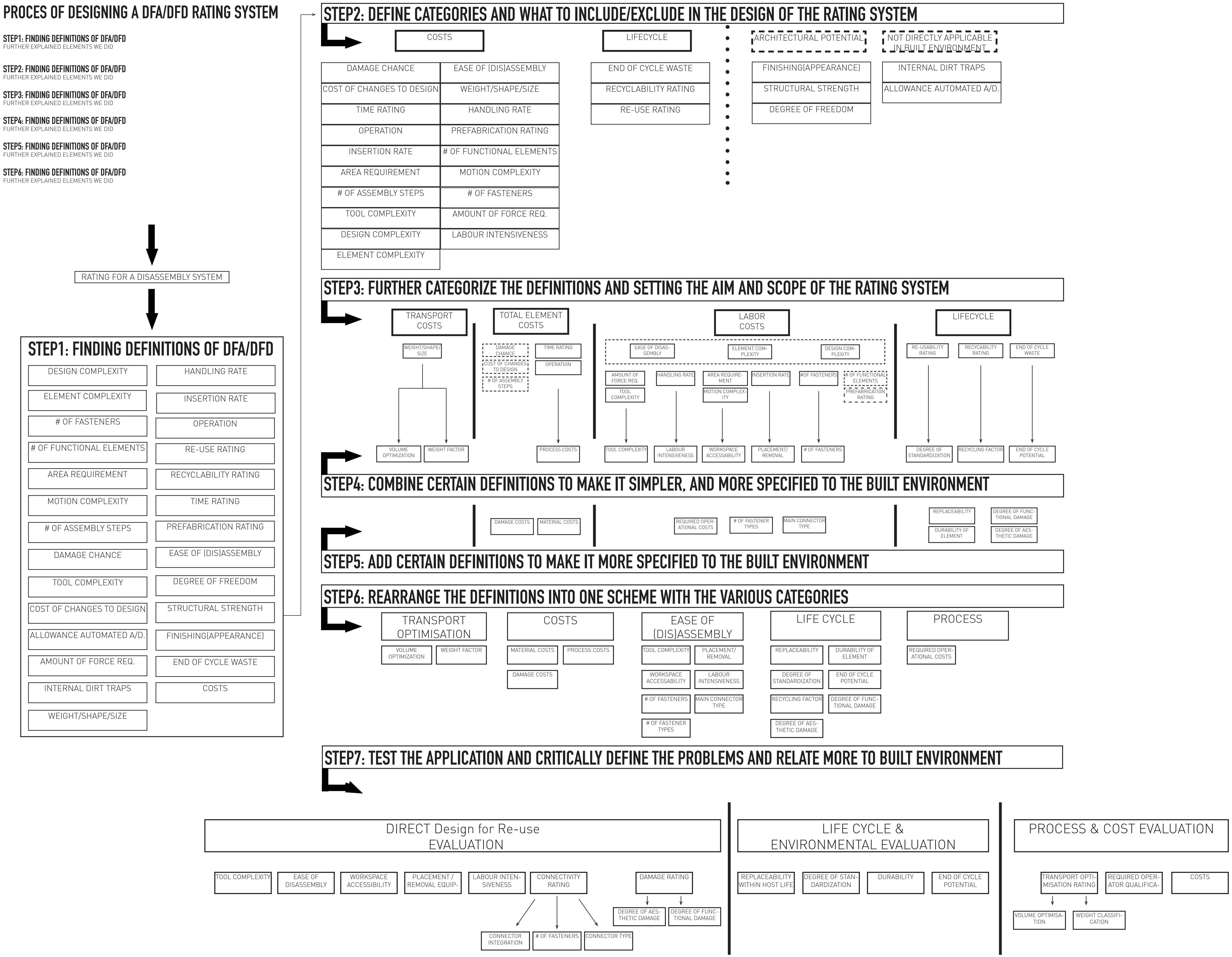
The full glazing on the all the facades of blackjack is facilitated by sliding doors and window frames. As the diagram shows, the elements are placed next to each other, however the same standard element is used. This scores high in terms of standardization and thus design for disassembly.



FUNCTIONAL CHANGES

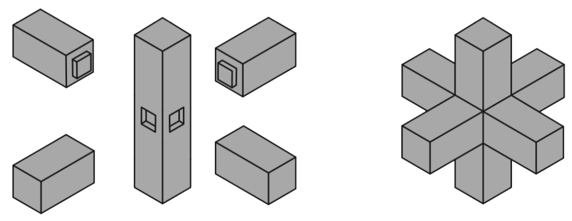
The ability of functional changes of the higher part of the building are facilitated by the design of the architect. The floors are 2,6 meters high which make it difficult to facilitate the building to be transformed into an office-building. Although the users had to commit themselves to at least 10% of their units as workspace (municipality stipulated a mixed-use building). The plinth of the building consist of commercial program. Because of strict regulations for ventilation, it becomes questionable whether 2,6 meters is enough to transform it into office spaces.

PROCES OF DEVELOPING A EVALUATION METHOD FOR DfD



RATING FOR A DISASSEMBLY SYSTEM

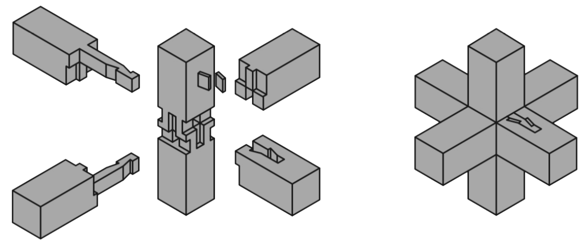
STEP1: DEFINE THE OPTIONS WHICH NEED TO BE RATED AND THE PROFILE OF THE INTENDED USAGE



OPTION 1

STRUCTURAL BEAMS OF A TENT. NEEDS TO BE ASSEMBLED/ DISASSEMBLED QUICKLY AND A LOT OF TIMES (APP. 100x/year) WITH A LIFECYCLE OF AT LEAST 50 YEARS. WILL BE USED OUTSIDE IN VARIOUS CLIMATES. NEED TO BE WORKED WITH BY UNSKILLED PEOPLE. PREFERABLY NO/MINIMAL AMOUNT OF TOOLS NEEDED.

PROFILE



OPTION 2

STEP2: RATE THE VARIOUS OPTIONS WITH THE VARIOUS ASPECTS IN DIFFERENT CATEGORIES

TRANSPORT OPTIMISATION

WEIGHT FACTOR	How well are the elements optimized to be transported.
VOLUME OPTIMIZATION	How well are the elements optimized to be transported.

COSTS

MATERIAL COSTS	The amount of raw material costs to producing one element of its type in comparison to the average for a functionally similar
DAMAGE COSTS	The costs of the repairing to the original state when an element is damaged, in relation to the total element costs.
PROCESS COSTS	The total process costs to produce on element in comparison to the generally accepted average for a functionally similar element.

EASE OF (DIS)ASSEMBLY

TOOL COMPLEXITY	The type and amount of speciality of the tools that are used for amounting.
WORKSPACE ACCESSABILITY	The amount of access that is available to perform assembly or disassembly work.
# OF FASTENERS	The amount of connectors used to connect two components to each other.
# OF FASTENER TYPES	The amount of different connectors that are used to connect two components to each other.
PLACEMENT/ REMOVAL	The required scale of equipment that is needed to place/remove an element from storage to place of assembly/disassembly
LABOUR INTENSIVENESS	The amount of work that is needed to handle the element.
MAIN CONNECTOR TYPE	The typology of the physical connection between the elements.

LIFE CYCLE

REPLACEABILITY	The grade of the complexity to replace independent elements.
DEGREE OF STANDARDIZATION	The grade of standard measurements and other typology within the element in relation to regular market standards.
RECYCLING FACTOR	The amount of hazardousness and recyclability of the material.
DEGREE OF AESTHETIC DAMAGE	The amount of visual damage during assembly/disassembly.
DURABILITY OF ELEMENT	The lifespan of an element in relation to the requested lifespan of the overarching system.
END OF CYCLE POTENTIAL	The amount of ability to reuse an element after the lifecycle of the total building.
DEGREE OF FUNCTIONAL DAMAGE	The amount of damage to the element during (dis)assembly. Damage Chance Rating: Functional damage

PROCESS

REQUIRED OPERATIONAL COSTS	The specific qualifications workers need to work with the system/element.

STEP3: TRANSLATE THE PROFILE IN A CHART

Pairwise Comparison Chart (PCC)

	Number of fasteners & types	Tool complexity	Main connector type	Transport optimisation	Accessibility	Labour intensiveness	Ease of disassembly	End of life potential	Durability	Degree of standardization	Replaceability	Degree of damage	Costs
Number of fasteners & types		1	1/2	1/2	1/2	1/5	1/7	1	1/3	1	1/2	1/3	3
Tool complexity	1		1	1	1	1/2	1/2	1	1/2	1/3	1	1/2	2
Main connector type	2	1		1	2	1/5	1/3	1	1/4	1/5	6	1	3
Transport optimisation	2	1	1		1	1/6	1/2	1	1	1/5	1	1/2	2
Accessibility	2	1	1/2	1		1/4	1/3	1	1	1/5	5	1	3
Labour intensiveness	5	2	5	6	4		1/3	4	1	1	1	4	2
Ease of disassembly	7	2	3	2	3	3		3	3	4	4	3	5
End of life potential	1	1	1	1	1	1/4	1/3		1/5	1/6	1/4	1/2	4
Durability	3	2	4	1	1	1	1/3	5		1	4	3	5
Degree of standardization	1	3	5	5	5	1	1/4	6	1		6	2	2
Replaceability	2	1	1/6	1	1/5	1	1/4	4	1/4	1/6		1/2	3
Degree of damage	3	2	1	2	1	1/4	1/3	2	1/3	1/2	2		4
Costs	1/3	1/2	1/3	1/2	1/3	1/2	1/5	1/4	1/5	1/2	1/3	1/4	

STEP 4: ASSESS THE RATING (R)

CONNECTION 1		CONNECTION 2	
R	S	R	S
5	45	9	81
7	63	9	81
5	52	9	93
5	90	9	162
9	102	9	102
9	147	9	147
8	283	8	283
7	294	5	210
2	21	2	21
9	273	9	273
9	335	4	149
8	108	7	95
6	111	9	166
8	34	3	13

STEP 5: READ THE TOTAL SCORE

	Factor	%	Perfect example		CONNECTION 1		CONNECTION 2	
			Rating	Score	R	S	R	S
ber of fasteners & types	9,0	3,5%	9	81,1	5	45	9	81
mber of fastener types	9,0		9	81,1	7	63	9	81
Tool complexity	10,3	4,0%	9	93,0	5	52	9	93
Main connector type	18,0	7,0%	9	161,9	5	90	9	162
Transport optimisation	11,4	4,4%	9	102,3	9	102	9	102
Accessibility	16,3	6,3%	9	146,6	9	147	9	147
Labour intensiveness	35,3	13,8%	9	318,0	8	283	8	283
Ease of disassembly	42,0	16,4%	9	378,0	7	294	5	210
End of life potential	10,7	4,2%	9	96,3	2	21	2	21
Durability	30,3	11,8%	9	273,0	9	273	9	273
gree of standardization	37,3	14,5%	9	335,3	9	335	4	149
Replaceability	13,5	5,3%	9	121,8	8	108	7	95
Degree of damage	18,4	7,2%	9	165,8	6	111	9	166
Costs	4,2	1,6%	9	38,1	8	34	3	13
DISASSEMBLY								
Space needed				2392,1		####		####
			Maximum	100		81,8		78,4

Development log:
Substantion behind all rating factors

For the DfR rating method prototype developed by Veldhuis, L., van der Kooij, J., Lammersen, P.S., and Beem, A.

I. Factors that were removed during development

As described in the main paper, in early development of the DfR rating method, a complete list of rating factors gathered from various different DfA/DfD rating methods was created. From this list, several factors have been removed, for various reasons. In chapter one of the development log these rating factors are described, as well as the reasons for their non-inclusion.

Motion Complexity

Motion complexity is a rating factor used by Güngör (2006) in evaluating DfD. In product design, for which his method is developed, motions to assemble or disassemble products are done countless in a time frame that is as little as possible. This is different in building construction. In close similarity, the ease with which building elements are handled is an important factor for building construction. However, this is handled seperately by the factors Ease of Mounting and Labour intensiveness.

Allowance to automated assembly(/disassembly)

Allowance to automated assembly is a rating factor used by Güngör (2006) to measure the degree in which a product can be automatically assembled. In product design this is very relevant, and has been relevant for decades, since the industrial revolution. However, automated assembly in building construction is still taking its first baby steps, and is no where near main stream usage or financial viability. While automated assembly and disassembly will likely be very important factors for the building industry in the future, in the present they are left out of this rating method.

Identification of internal dirt traps

Identification of internal dirt traps is a rating factor used by Mital et al.(2014), in a method developed for product design. It is quoted as '…important for obvious reasons. A product that has been in regular use is bound to accumulate internal dirt over a period of time. From a disassembly perspective, components that accumulate dirt need to be cleaned and degreased before disassembly and therefore involve prior preparation'. These problems are obvious at the scale of product design. However, in building construction, where most hidden-away cravices never come in contact with the outside world and therefore do not accumulate dirt, this factor loses its relevance. When reassembling in building construction, dirt is also much less of a problem due to the large scale difference compared to product design.

Structural Strength

This is a rating factor used by Pozzi (2019) to compare the structural strength of connectors evaluated by the system. His rating method is specifically designed to help architects in choosing the right connector type for their needs. Structural strength is an important part of that. However, the rating method prototype developed in this cooperation is made in the image of the method by Shetty & Ali (2015), and is meant to guide the design process of reusable building elements, rather than to guide product choices of architects. Proper structural strength is a given requirement for any element, but the exact structural performance is only important in relation to the function of the building element. In addition, structural strength is not directly related to either DfA, DfD or DfR, and was therefore not used in any way in this rating method.

Finishing (effect on appearance)

This rating factor is also used by Pozzi (2019), to measure the degree in which the connectors evaluated by his system have an effect on the appeareance of the building, or rather the degree in which they can be hidden. This is important information for an architect when choosing the right type of connector for his architectural design, for which Pozzi's method was developed. However, when considering the reusability of building elements, it has no direct correlation and is therefore not used in any way in this rating method. However, as suggested in the main paper, if the method would be expanded in a way to include architectural aspects, a factor measuring this could be a valuable addition.

II. Rating factors directly related to DfA and DfD

Chapter two of the development log contains the description of all rating factors directly related to DfA or DfD, as well as substantiation behind their inclusion and their structure.

Process Description: Tool Complexity Rating

Tool Complexity is a rating factor found in both Güngör (2006) and Shetty & Ali (2015), as respectively Tool Complexity and Tool Rating, but is in both cases used only for the disassembly phase of products. While assembly in product design is mostly automated, in architecture tools are almost always used both in assembly and disassembly. Tool Complexity rating in this method evaluates the complexity of tools used during both the mounting and demounting of the rated the element, and therefore important to the evaluation of elements in the light of DfR. Theoretical best- and worst-case scenarios are used as extremes in the rating list, with practical intermediate steps.

Process Description: Workspace Accessibility Rating

The method introduced by Shetty & Ali (2015) uses an Access Rating to evaluate how well parts can be approached and subsequently removed. It relates this accesibility to the potential to remove or disassemble the element without damaging it. Deviating from this, Workspace Accessibility Rating is relevant to the amount of time the workspace accessibility of an element adds or subtracts from the process of mounting or demounting an element, as this can be significant to the assembly or disassembly process in extreme cases (both negative and positive). In this method, potential damage to the element during the mounting or demounting process is handled seperately in a damage rating, and therefore left out of this rating.

Process Description: Element Placement/Removal Rating

The method developed by Shetty & Ali (2015) uses an Insertion rating to determine how easy it is to insert parts into their proper place during assembly. Like in product design, the effort it takes to move an element from on-site storage to its proper placement in a building, or in reverse, has a big influence on the assembly or disassembly process respectively. A potential difference of scale, from wooden elements carriable by hand to concrete walls that need a crane, complicates the translation of this concept from product design to architecture.

To solve this, two different ratings are created: Insertion/Extraction Rating and Labour Intensiveness Rating. When a crane or other heavy equipment is needed, the rating is based on the size and power of this equipment. Less heavy equipment equates a higher rating. When the element is handled manually, the Insertion Rating automatically receives the highest score, and the Labour Intensiveness Rating is activated. The Labour intensiveness rating then evaluates the intensity of the manual labour required to get the element in place. Less labour intensiveness equates a higher rating.

Process Description: Labour Intensiveness Rating

Labour Intensiveness is not a rating factor used in existing DfA or DfD methods for product design. However, in the light of a DfR assessment method, it makes sense to include this as a rating factor. Building elements or systems can be either light and easy to work with or heavy and hard, which should be reflected in a complete DfR assessment. In this method, the Labour Intensiveness Rating is split in two factors: Element Weight and Element graspability. These are two different element properties that separately influence how intense the labour is. The element graspability category is based on the Handling Rate factor from Shetty & Ali (2015). The element weight category is based on the Dutch Arbo law from 2019, and could be adjusted internationally according to national law.

Process Description: Connectivity Rating

A rating factor that evaluates the degree of pre-fabrication is something that is missing from current DfA or DfD methods in the field of product design. However, measuring in some form the degree of prefabrication of elements makes sense as part of evaluating how well an element or system functions when dis- and re-assembling for buildings. Pozzi (2019) uses a rating factor called "Prefabrication Degree", stating that more pre-fabrication leads to less assembly steps and thus quicker assembly times. As Pozzi aimed to create a simplified method that is easy to use for architects, in his method determining the actual degree of pre-fabrication for en element is not based on a factual list of properties. Instead it is based on a quick and subjective study of the element entered in the system. To give this evaluation more depth and make it more scientifically measurable, instead of manually determining a prefabrication degree this method measures a variety of related properties, which together tell roughly the same story. These factors are connector integration, connector type and number of connectors used. These factors are combined into the Connectivity Rating. Firstly, the degree of connector integrated is determined. Integrated connectors lead to significantly less assembly time, as an important part of the assembly work is moved to an automated factory. Secondly, the type of connector is determined. Fixed connections such as poured concrete or welded steel are rated as very low and have a negative impact on the rest of the score. If more than 1 type of connector is used, the worst scoring type is used for measurement.
Lastly, the average amount of connectors required to connect two elements is measured. A lower amount of connectors is desirable because it leads to less assembly time.

Process Description: Damage Rating

Of the currently existing DfA/DfD rating methods, Güngör (2006) is the only one that includes a rating factor that directly measures damage, in the form of a damage chance rating. The more recent method developed in Shetty & Ali (2015) lightly integrates damage related issues into its other ratings, for example in its Access rating. In the building industry there are many more opportunities for building elements to be damaged compared to the product industry. In the product industry product elements are mostly handled automatically, and elements are in general much smaller, lighter, and less prone to accidents. In the building industry elements are mostly transported non-automatically, sometimes manually, and due to bigger weight and size wrong movements can more quickly result in damage. Additionally, when an element is damaged, repair costs can range from almost nothing to replacing the entire element, depending on numerous factors. In a DfR rating method it therefore makes sense to evaluate how easily a building element can be damaged, and how expensive this is on average.
When looking at damage to building elements, an important division can be made between functional damage and aesthethic damage. Constructional damage always impacts an elements performance, while aesthethic damage is only relevant when the element in question has some aesthethic function. By splitting the damage rating in this way, both aesthethic (e.g. a part of the facade)and purely functional (e.g. a constructional wall slab) elements can be evaluated correctly in this method. The functional damage rating is always used and counted, but the aesthethic rating is only used when the element in question has an aesthethic funcion.

Process Description: Required Operator Qualifications

In current literature, no precedents can be found in DfA/DfD rating methods that evaluate required operator qualifications. However, in the building industry this can have tremendous impact, especially when considering the use of an element or system in less prosperous countries, where skilled labour might be hard to come by. It is therefore considered an important part of the evaluation of a building element in regards to DfR, and included in this method. For the Operator Qualifications Rating theoretical but realistic best- and worst- case scenarios were used as extremes, with practical steps in between.

III. Rating factors related to DfR

Chapter three of the development log contains the description of the novel rating factors that look at Design for Reuse as a whole, as opposed to solely DfA or DfD. These factors are not based on precedents and should be seen as suggestions or sketches for rating factors that should be included in a fully developed DfR rating method.

Process Description: Transport Optimisation

In no current existing DfA/DfD rating methods, neither in product design and architecture, transport is considered as a rating factor. As seen in the flowchart of figure 1, transport optimisation relates to both the economic and climatic values of a building element or system. If a building element or the system it is part of is properly optimised for transport, both the amount of trips required and the fuel per trip can be reduced. Both have a direct impact on the economic costs of operating with the element or system, as well as a direct impact on its climatic performance. Because this method aims to capture a broad scope of values in its assessment, Transport Optimisation is therefore included as a factor in this method. As previously mentioned there are two important values that influence how well an element is transport optimised. Firstly, the amount of empty volume in an average cargo transport for the element, which influences the amount of trips required to bring all elements to the building site, and where less empty volume equates better climatic and economic performance. Secondly, the weight classification of the element, which influences fuel usage and where a lower weight classification equates better climatic and economic performance. The weight class is determined by the standards in the fields of the element in question. In case of a lack of such standards, the weight class is determined on the basis of percentile deviation from the normal weight of a functionally similar element, according to figure 2. A lower weight classification results in a higher score in this method.

Process Description: Functional Reusability

When designing for reuse, one of the most important factors to consider is wether or not the designed element can be easily reused in new designs. An element that is very easy to assemble and disassemble, but cannot be applied in new context has very little reusability value. Existing DfA and DfD rating methods do not measure this, as it does not belong to either.

Process Description: Replacability within Host Building Lifecycle

Güngör (2006) uses the factor 'Cost of changes in design' in his rating method for DfD. This factor relates to how easily the design can accommodate changes without drastic increases in cost. In building construction a similar concept is important when designing for disassembly and reuse. Sometimes elements have to be replaced or changed in a building design, either due to technical (broken elements) or functional reasons (changing floor plans due to changing needs). Designing in a way where such replacement is accomodated and does not require the removal of many surrounding elements is desirable, and is therefore rewarded by a high score in this rating factor. This factor is specified as Replacability within the Host Building Lifecycle, and not related to removal or replacement after the host buildings lifecycle is at its end.

Process Description: Standardization of measurements and connections

Current DfA and DfD rating methods focus mostly on the assembly and disassembly process of products. However, when considering the end goal of reusing building elements, it makes sense to award higher scores to an element or system that can be more easily and/or flexibly applied in new situations. This creates the need of a factor that evaluates this. One simple variable that has a big impact on whether or not building elements can be easily applied in new situations is if they are dimensioned according to market standards. If an element has market standard measurements, it is much easier to reuse than when it does not, and should be rewarded for this in an assessment. Therefore, this method includes a factor that tries to determine the degree of standardization of dimensions and connections of an element.

Measuring this proves difficult, but theoretical best- and worst-case scenarios can be determined. However, as market standard dimensions vary per function and per region, measuring this inherently requires user knowledge about the relevant field. This factor also includes terms such as ‘can be easily used alongside’, which is not a hard measurement but something that has to be subjectively determined by a person. This rating factor is subsequently one of the less scientific ones, but due to its large impact on DfR product performance it is still included in the method.

Process Description: Element Durability

In existing DfA and DfD rating methods nothing resembling an Element Durability rating factor can be found. However, when evaluating a building element in the light of design for reuse, it makes sense to incorporate element durability in some way. If an element lasts only one year, that makes it a lot less fit for reuse compared to an element that lasts for five hundred years. It is important that this is reflected in a DfR assessment method, to reward smart design with high economic and climatic value.

Element durability is one of the few scale-sensitive aspects when evaluating DfR in this method. When relating the lifespan to absolute values (years), the problem arises that for some elements 50 years might be a great performance while for others it is a poor performance. It therefore makes sense to relate the lifespan of the element to the average lifespan of the building type it will be used in. Setting up the rating factor like this relates the rating to the goal of the element or system, making it flexible and allowing a broad variety of elements, with a big range of lifespans, to be assessed in a fair way. It further increases the knowledge requirement and input of the user as a potential downside.

An element lasting less than the lifespan of the building it is intended for is determined as worst-case scenario for an element that is made for reuse, as this would not allow these elements to be reused at all. The best-case scenario is somewhat of an extreme, but still possible value, where a building element can be used more than ten times in its intended function before it reaches its end of life.

IV. Additional Rating factors

Güngör (2006) states there are many factors not directly related to DfA or DfD that are still important in the evaluation of an elements performance and can have large influence on design decisions. Therefore, some external factors, not directly related to DfA, DfD or DfR, are included in the scope of this method. The factors are not meant as elaborate measurement systems, but rather as a quick way to provide guidance in the design process, much like the rest of the method.

Process Description: End of Cycle Potential Rating

When designing for Reuse, it makes sense to consider all influential factors of a products total lifecycle. However, considering true circularity and as substantiated by Circle Economy (2014), it is also important to look at what happens after an element's lifecycle, evaluating the elements so called End of Cycle Potential. In relevant literature, a variety of 3 to 10 so called 'R-words' are often used to describe potential post-life processes for products as guidelines towards reaching a circular economy, ranging from Refuse (choosing not to buy new products) to Recover (recovering embodied energy from a product by combustion). The Outline of a Circular Economy from the EllenMacArthur Foundation is a good example where these concepts are part of the bigger picture that is a circular economy.

In the building industry determining the distinction between for example reusing and recycling is important because there is a large difference in economic and climatic value if an element can be reused directly compared to when it can only be refined into low-value recycled material, or when it has no end of cycle potential at all. An element or system that does well in this regard should be rewarded for this in its DfR assessment, creating the need of a rating factor that measures the End of Cycle Potential.

Many different definitions and mixes of these R-words are used in literature and even by government organisations such as the EU or the UN. Vermeulen et al. (2018) created a clear overview of all different End of cycle potential R-words used and what they stand for, reducing a total of 38 different words to a list of 9. Out of these 9 words, two (Refuse and Remine) have no meaning looking at a product or element that is already bought and that is not a landfill. This leaves 8 possible end of cycle scenarios for products, including a scenario for no recovery potential. These scenarios are used to determine an elements score in this method, ranging from the highest score for the best-case scenario (direct reuse) to the lowest score for the worst-case scenario (no recovery potential).

Process Description: Element Costs

While material or process cost ratings have no direct precedent in rating methods for DfA or DfD in Product Design, Güngör (2006) does mention the importance of including all aspects of the life cycle of a product even if the objective is to design the product for disassembly. In architecture, material costs are a very important factor in the early decision-making process of any design. Pozzi (2019) uses a Cost Rating in his method to compare structural timber connections, focussed on helping architects choose the overall best option.

A challenge while introducing a Cost Rating is its relativity. Using absolute values alienates any product or element that does not fit within that price range. By weighing the price of the element against what in this method is called the generally accepted average for a functionally similar element, any product or element can theoretically be rated in this method. This garantuees the broad application of the method that it aims for.However, by doing so, the method requires the user to produce the relevant data to substantiate this.

CRITERIA FOR EVALUTION MODEL

Tool Complexity Rating
Tool Complexity Rating evaluates the complexity of mechanical tools required to mount or demount the element.

Tool Complexity (Assembly)	Rating
Tools are not required; task is accomplished by hand	9
Common hand tools are required	7
Power tools are required	5
Special tools are required	3
Significant time delay (due to the tool complexity)	-2
Special care/techniques are needed	-1

Ease of disassembly
The complexity regarding the disassembly task.

Ease of disassembly	Rating
Elements can be disassembled without tools (unclipping, lifting or similar)	9
Elements can be disassembled by removing nuts and bolts	8
Elements can be unscrewed	7
Hand tools are required	6
Powered tools are required	5
Special tools are required	3
The elements can't be separated without severe damage (sawing, breaking etc.)	1
Significant time delay	-2
Special care/techniques are needed	-1

Workspace Accessibility Rating
The amount of access that is required to perform assembly or disassembly work.

Workspace accessibility	Rating
The task can be done with hardly any space required (< 5 cm)	9
The task requires some space for hands or small hand tools (< 20 cm)	7
The task requires space for hand or powered tools	5
Special care/tools/techniques are needed	-1
Blind assembly/disassembly	-1
Significant time delay	-1
One element have to be removed to access the area	-1
Multiple elements have to be removed to access the area	-2

Element Placement/Removal Rating
The required scale of equipment that is needed to place/remove an element from storage to place of assembly/disassembly

Element Placement/Removal Rating	Rating
Elements are movable by hand	9
A wheelbarrow is needed to place/remove the elements	8
A pump truck is needed to place/remove the elements	7
A forklift truck is needed to place/remove the elements	5
A crane with 2t power is needed to insert/extract the elements	3
A crane with 10t power is needed to insert/extract the elements	2
Integrated handles or lifting facilities	+1

Labour intensiveness
The physical intensity of work that is needed to handle the element.

Labour intensiveness	Rating
The element is manageable with one hand (<7.5kg)	9
The element is manageable with two hands (7.5-15kg)	8
The element is liftable in accordance with working conditions (15-25kg)	7
The element requires two people to manage (25-50kg)	5
The element requires more than two people to manage (50-100kg)	3
The element is hard to grasp or manage (tool needed, flexible, slippery, long or similar)	-1
Placement above head, sitting or squatted while lifting	-1

Connectivity Rating: Connector Integration
The degree in which connectors are integrated into the element.

Connector Integration	Rating
Connectors are fully integrated into the element	9
Connectors are partly integrated into the element, but separate connecting elements are needed	7
Connectors are not integrated into the element, but design allows for aided affixing of connectors	5
Connectors are not integrated into the element, and design does not allow for aided affixing of connectors	1

Connectivity Rating: Connector type
The type of connector used between the elements.

Connector type	Rating
Elements are connected without dedicated fasteners (friction fit, puzzle joints)	9
Elements are connected with bolts or clips (or similar)	7
Elements are connected with screws (or similar)	5
Elements are connected with nails (or similar)	3
Elements are connected with a fixed connection, but can be detached with some difficulty	2
Elements are connected with a fixed connection, and cannot be detached without heavy damage	1

Connectivity Rating: Number of fasteners
The average amount of connectors used to connect two elements to each other.

Number of fasteners	Rating
No fasteners are needed to connect two components	9
One fastener is needed to connect two component	7
Two fasteners are needed to connect two components	5
Three fasteners are needed to connect two components	4
Four or more fasteners are needed to connect two components	1

(The range depend on application of measure method and can therefore be changed!)

Damage Rating: Functional Damage
The amount of functional damage to the element during (dis)assembly. Constructional damage is defined as damage that reduces the structural integrity of the element.

Damage Rating: Functional Damage	Ratin g
No noticeable damage when assembled or disassembled multiple times	9
Small scratches or dents (or similar) which have hardly any impact on the performance	8
Deep scratches or dents (or similar) which have some small impact on the performance	7
Light damage such as screw holes or rust formation during (dis)assembly	6
Constructional performance is reduced when disassembled, repair is desirable	5
Repair is always necessary when after disassembly	3
Replacement is needed after disassembly (one time use)	1

Damage Rating: Aesthetic Damage
The amount of aesthetical damage to the element during (dis)assembly. Aesthetical damage is defined as damage that reduces the aesthethic quality of the element.

Damage Rating: Aesthetic Damage	Ratin g
No noticeable aesthetic damage when assembled or disassembled multiple times	9
Small scratches and/or dents (or similar) which have hardly any effect on the appearance of the building/element	7
Deep scratches and/or dents (or similar) which have significant impact on the appearance of the building/element	5
Repair is desirable due to significant impact on the appearance of the building/element	3
Replacement is desirable due to the severe effect on the appearance of the building/element	1

Life Cycle & Environmental Evaluation

Replaceability within Host Building Lifecycle
The degree of complexity in replacing an element within the host building's functional life.

Replaceability within Host Building Lifecycle	Ratin g
Elements can be replaced without removing an adjacent element	9
Elements can be replaced by removing one adjacent obstructive element	7
Elements can be replaced by removing two adjacent obstructive elements	5
Elements can be replaced by removing several adjacent obstructive elements	3
Elements can't be replaced	1
Special care/tools/equipment/techniques are needed	-1
Significant time delay	-1
Damage to adjacent elements are probable	-2

Degree of standardization
The grade of conformity of measurements of the element compared to market standards.

Degree of standardization	Ratin g
Element has market standard dimensions and connection-system	9
Element can be easily altered to market standard dimensions and connection-system, or can be easily used along-side market-standard elements	7
The element can be further dismantled and individually altered to market standard dimensions and connection-system	4
Element cannot be standardized in dimensions and connections and cannot be easily used along-side market-standard elements.	1

Element Durability
The lifespan of an element in relation to the expected lifespan of a building of the intended type.

Durability of element	Ratin g
Lifespan of ≥ 300% in relation to the expected lifespan of the intended building	9
Lifespan of ≥ 200% in relation to the expected lifespan of the intended building	8
Lifespan of ≥ 100% in relation to the expected lifespan of the intended building	7
Lifespan of < 100% in relation to the expected lifespan of the intended building	6
Lifespan of < 50% in relation to the expected lifespan of the intended building	3
Lifespan of < 50% in relation to the expected lifespan of the intended building	1

End of cycle potential

The circularity potential of an element at the end of its total lifecycle. Definitions of the words used in the rating list (reuse, repair, etc.) are according to Vermeulen et al. (2018).

End of Cycle Potential Rating	Rating
Element can be directly re-used	9
Element can be repaired	8
Element can be refurbished	7
Element can be remanufactured	6
Element can be repurposed	5
Element can be recycled	4
Element can be recovered (combustion)	2
Element has no recovery potential	1

Process & Costs Evaluation

Transport Optimisation Rating
The Transport Optimisation Rating evaluates how well the element is optimised for efficient transport of the building element to the building site.
Transport Optimisation: Volume Optimisation
The Volume Optimisation measures how much empty volume is left over when a relevant cargo transport (truck, freight train) is filled with the element.

Volume Optimisation	Rating
Can fill relevant cargo space with less than 15% empty volume	9
Can fill relevant cargo space with less than 20% empty volume	7
Can fill relevant cargo space with less than 30% empty volume	5
Can fill relevant cargo space with less than 40% empty volume	3
Cannot fill cargo space with less than 40% volume.	1

Transport Optimisation: Weight Classification
The Weight Classification determines the weight class of the element, according to market standards of its type and function. If such standards do not exist, figure 2 is used to determine the weight class.

Weight Classification	Rating
Elements are considered Heavy Weight	9
Elements are considered Mid Weight	5
Elements are considered Light Weight	1

Required Operator Qualifications
The Operator Qualifications rating is based on the type and amount of qualifications a worker needs to work with the element / system.

Required operator qualifications	Rating
Does not require operator to have any official qualifications	9
Requires operators to acquire a single certificate	8
Requires operators to acquire multiple certificates	7
Requires operators to have completed the equivalent of a three year long full-time education, but no additional qualifications	5
Requires operators to have completed the equivalent of a three year long full-time education, and acquire an additional certificate	3

Element Costs

The total costs to produce one element of its type, in relation to the generally accepted average costs for a functionally similar element.

Element Costs	Rating
Less than 50% of the generally accepted average for a functionally similar element	9
Between 50 - 75% of the generally accepted average for a functionally similar element	8
Between 75 - 100% of the generally accepted average for a functionally similar element	7
Roughly 100% of the generally accepted average for a functionally similar element	6
Between 100 - 125% of the generally accepted average for a functionally similar element	5
Between 125 - 150% of the generally accepted average for a functionally similar element	4
Between 150 - 175% of the generally accepted average for a functionally similar element	3
Between 175 - 200% of the generally accepted average for a functionally similar element	2
More than 200% of the generally accepted average for a functionally similar element	1

Definitions

In order to give definitions of the used terms next to the rating factors, the definitions of several sources are compared, and used to define a definition. Sometimes the definition of the source is directly used. The definitions that are used in the rating factors can be found at each independent rating factor.

A (building) component is described as followed by Harris:

‘’**Component**: *1. A building element which uses industrial products that are manufactured as independent units capable of being joined with other elements.*

2. According to the NEC, any subsystem, subassembly, or other system designed for use in (or integral with) a structure or part of a structure, which can include electrical, fire protection, mechanical, plumbing, and structural systems and other systems affecting health and safety.’’ (Harris, 2006)

Another definition of a (building) component is given by Masters & Brandt:

’’Component: *A building element using industrial products that are manufactured as independent units capable of being joined with other elements.’’* (Masters, 1989)

The definition that is used in this research is as followed:

Component: *Composition of elements that can be joined together, forming the subassembly of a total building.*

’’Connector: A mechanical device for fastening together two or more pieces, members, or parts, including anchors, fasteners, or wall ties.‘’ (Harris, 2006)

The definition of a connector is in this research the same as Harris used.

‘’Design for deconstruction: *The process of designing a building to facilitate its deconstruction or disassembly. The same idea is sometimes conveyed as ‘design for disassembly’, and both are often abbreviated as DfD.’’ (Addis, 2012)*

’’Disassembly: *a synonym for dismantling; an antonym of assembly’’ (Addis, 2012)*

’’Durability factor: *A measure of the change (with time) in the property of a material as a result of exposure to an influence which has the potential of causing deterioration; usually expressed as a percentage of the property before exposure.’’ (Harris, 2006)*

‘’Durability: *The capability of a building, assembly, component, product or construction to maintain serviceability over at least a specified time’’* (Masters, 1989)

The dictionary of architecture and construction (Harris, 2006) defines an building element as followed:

‘’**Element**: *An architectural component of a building, facility, or site.’’ (Harris, 2006).*

The definition that is used in this research is as followed:

Element: *Composition of building materials that form together one functional and/or architectural unit, which is part of a component and/or total building.*

’’Fastener: *A mechanical device, weld, or rivet for holding together two or more pieces, parts, members, or the like.’’ (Harris, 2006)*

Insert: Relocating the element from the storage on-site to the desired placement in the building structure.

Extract: Relocating the disassembled element from the building structure to storage on-site or transport.

''Labor cost: *On a construction project, the cost of all labor necessary to produce the construction required by the contract documents'' (Harris, 2006)*

Harris gives a definition of a building material:

''Material: *Any material used in construction, such as steel, concrete, brick, masonry, glass, wood, etc.'' (Harris, 2006)*

Masters also give a definition for a building material:

''Material: *An identifiable material, such as brick, concrete, metal or timber, that may be used in a building component.''* (Masters, 1989).

The definition that is used in this research is as followed:

Material: the physical identifiable material that is used to form elements and so components

''Prefabricate: To fabricate components or units prior to their installation at the site, usually at a mill or plant away from the site.'' (Harris, 2006)

''Recycle: *collect and separate usable materials from waste and process them to produce marketable products.'' (Addis, 2012)*

''Service life *(of a building material or component)* *The period of time after installation during which all essential properties meet or exceed minimum acceptable values, when routinely maintained.''* (Masters, 1989)

''Work: *All labor necessary to produce the construction required by the contract documents, and all materials and equipment incorporated or to be incorporated in such construction.''(Harris, 2006)*

Addis, B. (2012). *Building with reclaimed components and materials: a design handbook for reuse and recycling*. Routledge.

Harris, C. M. (2006). *Dictionary of Architecture and Construction*. McGraw-Hill.

Masters, L. W., & Brandt, E. (1989). Systematic methodology for service life prediction of building materials and components. *Materials and Structures*, *22*(5), 385-392.