BOTTOM-UP REDEVELOPMENT OF VACANT OFFICE SPACE IN MASS-CUSTOMIZED HOUSING SOLUTIONS UTILIZING DIGITAL WOOD PROCESSING TECHNIQUES

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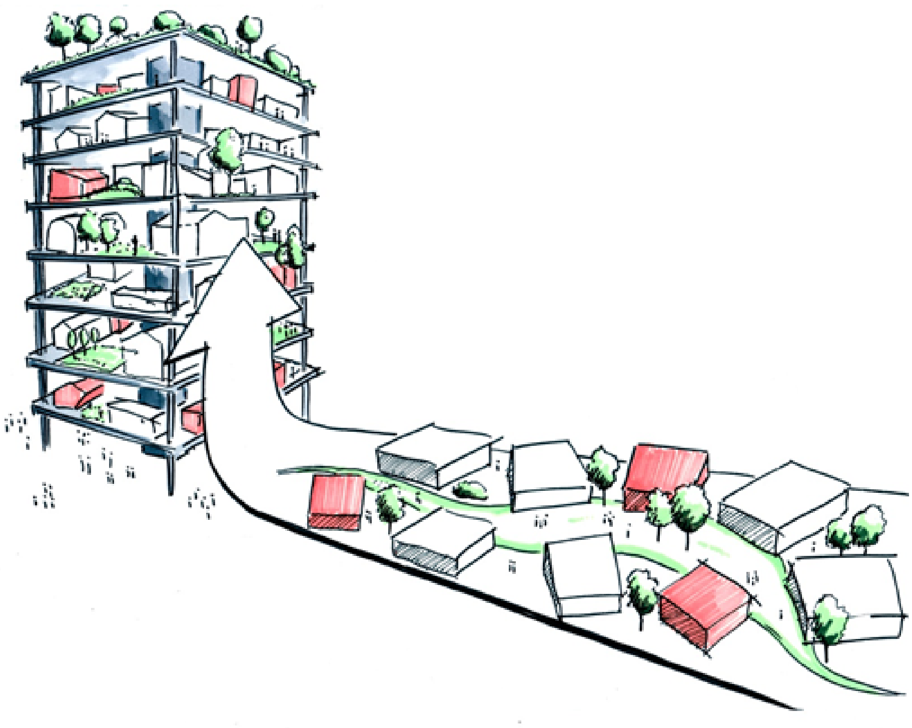


KEYWORDS
Mass customization, CNC, digital fabrication, office redevelopment, vacancy, open building, supports, fit-out, chassis + infill, housing, Design For Manufacturing and (Dis)Assembly, DFMA

ABSTRACT
This research consists of 3 parts/scales, combined in a single methodology:

1. The regeneration and redevelopment of (structurally) vacant office buildings, preparing a base 'support' building for
2. A customized housing solution, answering the diverse requirements households have regarding their living conditions by giving them the opportunity to spatially design their own home – with constraints – as the current post-war housing stock doesn't provide a viable answer and;
3. A given set of reference points for a technical construction system that facilitates the spatial mass customization of a single dwelling, taking into account design for manufacturing and (dis) assembly strategies for a durable system with relatively low life-cycle embodied energy due to the minimisation of the recurring embodied energy.

The 3 different scale levels combine in an open building approach, where a generic top-down structural frame is being designed and facilitates a bottom-up redevelopment of an office building ensuring individual customization and requirements. The research concludes with a proposal for a generic design methodology combining the 3 research aspects, to be followed in redeveloping specific office buildings.

1. INTRODUCTION & PROBLEM STATEMENT

1.1 PROBLEM STATEMENT

The housing shortage after the Second World War resulted in an extreme demand for dwellings, resulting in government driven mass-produced housing projects. All of these housing projects have the appearance of uniformity, excluding the individual influence and the action of the individual it houses. The Bijlmermeer is one of the most exemplary projects that failed in their attempt to rationalize housing, excluding the individual from the equation. That being said, the challenge that has been given to us as a result of the war and the way it has been solved is impressive. After the booming housing market came to a hold and the demand decreased, the same attitude remained in regards to housing projects, where individuality was neglected. In the '90s the Dutch government introduced the VINEX motion where the trend of mass production and the accompanied generalisation and standardisation of houses continued (VROM, 1991). This way of thinking in the Dutch housing market has been present up till now, although Dutch housing policy has rapidly changed over the last decade focusing on decentralisation reducing the influence of the national government (Halman, Voordijk, & Reymen, 2008). The opportunities this decentralisation offers the building sector are being neglected. The rehabilitating way of providing a place to live is as prominent in the minds of the spatial planners as it was right after the war. It can be stated that this way of building indicates that uniformity is a characteristic of modern society (Habraken, 1972), what would it mean for the individual expression if that is true? At present, the demand for mass production has dried up and shifts towards innovative and custom solutions, giving the individual more influence on the end result. While the market screams for solutions like this, the real estate sector stays rigid in its proposals and limits itself to 'what is known' (Dalhuisen, 2013a).

Ofcourse, there have been alternatives offered during the years where attempts have been made to individualise the house as a unique product. These offered alternatives were conceptual in nature, proposing a methodology or vision on how to change the housing market and were not project specific or attempting to actually revising the process as such. As early as in 1933, Le Corbusier – already turning away from his machine-age ideology – presented his plan Obus on Algiers where he envisioned a gigantic support structure where individual and unique houses are drawn in his illustrations (Pouliot, 2011). Habraken continued working on this conceptual idea with the SAR research group from Eindhoven, developing a theoretical and philosophical background on support structures and their infill, coming to a chassis + infill method of building where he emphasizes on the social and philosophical aspect of living. In a more manifesto way, Carel Weeber (1998) wrote his publication 'het Wilde Wonen' (Wild living) about the individualisation of the single dwelling turning away from the petrified housing blocks he also used to build himself, as the Peperklip complex in Rotterdam is at present still the biggest housing block in the Netherlands.

Over the course of last years, more initiatives around the customization of buildings and dwelling emerged. House configurators, where people can set-up their own house by using an interface on the internet, are a way of utilizing this customization feature. Other projects use a more individual architect-to-client basis to design individual dwellings in bigger housing projects to meet the demands of the user, for example the Fenixlofts in Rotterdam and De Hoofden in Amsterdam. These type of projects are in fact a variation on the support and infill Habraken proposed. One of the first of its kind was the Tetterode complex in Amsterdam, followed up by the Solids concept constructed several years ago. The urge for a structured methodology on mass customized future housing projects is evident, as more and more initiatives can be found. The challenge is to search for the right balance between the ultimate freedom for the end user and the boundaries, circumstances and limits a specific project is faced with, next to the influence of the architect. Therefore these projects mentioned, among a few others, are subject to an analysis of the potential of mass customization.

Another problem the real estate sector is facing is the high vacancy rate of the office stock; a problem that is becoming a structural one. Currently more than 7 million m2 (15%) of office space is vacant, where a percentage of 3 to 5% is regarded as 'normal'. Around half of the vacant space is defined as structural[1] (Remøy & van der Voordt, 2014), giving need for new solutions in redevelopment of these buildings. In larger cities the structural vacancy rate is even higher. In Amsterdam more than 2/3 of the total vacancy has been recorded as being structural (Bak, 2009). Out of a few options possible – consolidation, renovation, demolition or conversion – the conversion is the most feasible option for redevelopment. Conversion to new use sustains a beneficial and durable use of the location and the building, implies less income disruption and has high social and financial benefits (Remøy & van der Voordt, 2014). This research focuses on the office space where the technical lifespan of the façade and

1 Structural vacancy is defined according to Remoy and van der Voordt (2014) as vacancy of the same office space for three or more consecutive years and with no perspective on future tenancy.

FIGURE 1 & 2 – INFORMAL VERTICAL CITIES. LEFT THE TORRE DAVID, RIGHT THE KOWLOON WALLED CITY

installations is outdated. In general, the lifespan of these building services do not exceed 30 years (Wamelink, Geraedts, Hobma, Lousberg, & de Jong, 2007) thereby this research is emphasizing on offices constructed before 1990, elaboration on this emphasis is done in the first chapter. The structural frame is the durable part of the building in this aspect and can generally exceed the lifespan of several centuries, allowing for a different infill and program during time with the right methods applied. More elaboration on the scope of offices is done in the first chapter of this research.

At first, there doesn't seem to be a connection between the two presented problems. However, an initial fascination for informal vertical communities like the Torre David and the Kowloon Walled City[2] triggered the idea to combine the two in trying to offer a methodology to bridge the existing gap in the housing market and to offer an alternative in bringing a solution where the current market falls short. This way, two problems the real estate market is facing can be solved by offering one solution. With the façade stripped and the technical installations removed, the building can be interpreted as a support structure as proposed by Habraken (1972) in the '60s, providing the structural framework in where individualised dwellings can be situated. A new typology emerges in the city, where people can accommodate according to their own living conditions thereby extending the street in a vertical way.

New developments, by some described as the new digital industrial revolution, can play a key role in the customization of housing solutions. Where in the past custom architecture applied to the wealthy ones of our society – using an architect to create their 'dream-villas' – digital fabrication techniques now make it possible to, within a set of predetermined boundaries, give freedom to every individual that wants to build their dream house for an affordable price (Bliek, 2012; van Bleiswijk, 2013). Digital fabrication techniques make it possible to produce 1000 custom houses or 1000 identical houses with the same effort, cost and material (Kolarevic, 2003).

1.2 RESEARCH QUESTION

The different aspects discussed before can be enclosed in the following research question:

How can the mass customization potential of digital wood processing techniques be used in the bottom-up re-development of (structurally) vacant office space into custom housing solutions?

Regarding the office vacancy, a scope is being set by means of a target group. The mass customization aims primarily on the mass customization of the housing market in relation to conventional housing projects. The focus within the digital fabrication part will be on the several wood processing techniques that exist and their potential in facilitating a construction language for mass customization.

2. RESEARCH METHODOLOGY

The research is split in 3 categories, from where a generic design methodology can be deducted:

1. **Office regeneration. Preparing the base building.**
   A literature study is performed to study the parameters affecting the regeneration of an office building to provide a structural framework for the fit-out construction of customized dwellings. Before the analysis of the different conditional and spatial aspects, the scope of the office blocks is being set at a specific target

2 Literature and documentaries regarding these informal vertical cities are given in a next chapter in this research.

FIGURE 3 – RESEARCH METHODOLOGY OUTLINE

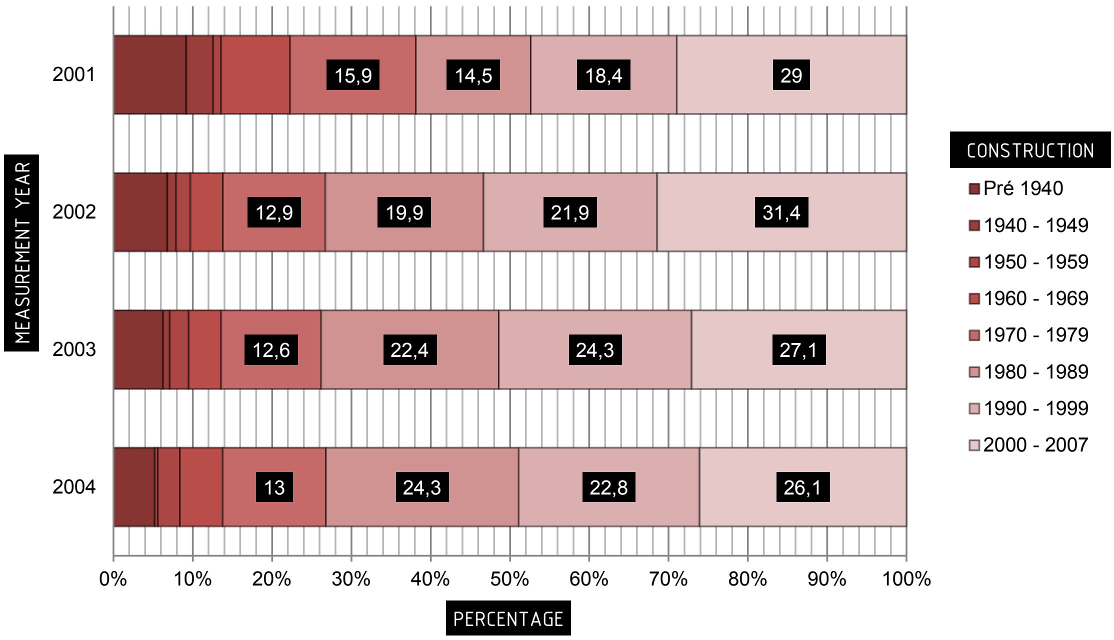
group. At the end of the chapter, a general methodology is proposed in preparing a top-down framework facilitating the bottom-up redevelopment process utilizing mass customization potentials of digital fabrication techniques.

2. **Mass customized housing solutions in reaction to the anonymous mass production**
A literature study on the application of mass customization in housing solutions brings insight into the desires of the individual in the contemporary housing market. These requirements form the basis for a case study analysis on several finished and historical projects with a customization aspect, categorised for ease of analysis on their mass customization potential. Out of this analysis, general requirements for a good strategy regarding the implementation of mass customization in the realization of housing solutions can be found.

3. **Digital fabrication and Design for Manufacturing and (Dis)Assembly strategies**
A short literature overview on the aspects of design for manufacturing and (dis)assembly is given in combination with the growing demand for self-build projects. These guidelines are then used as parameters in analysing several case studies on their DFMA potential. The pros and cons out of this analysis serve as reference points for the research by design process of a construction logic serving the customization and (dis)assembly aspects lined out in the previous chapters.

These 3 categories of research can then be formulated in a generic design methodology, where the different stages of a redevelopment is made insightful and the different scale levels and the influence of the different actors becomes clear. This methodology can then serve as a generic framework assessing specific redevelopment projects.
The other outcome of the research is a set of reference points from where a constructional logic can be built by performing a research by design process, facilitating the open building method as discussed in the entire paper – from the spatial customization to the assembly strategies.

3. THE REGENERATION OF THE VACANT OFFICE BLOCK

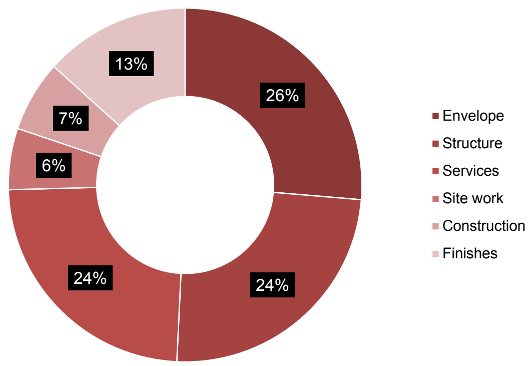


GRAPH 1 – VACANCY PER CONSTRUCTION YEAR (ADAPTED FROM REMOY, 2007)

The transformation of structural vacant office buildings to housing can give a solution to the inadequate housing market present in the Netherlands - mainly for young starters and students – and at the same time solve the vacancy problem for office buildings that do not comply to contemporary office standards and thereby do not have any future relevance in their original function (Remøy, 2007a). The regeneration of the office block, in making it appropriate for its new use, is the preparatory top-down framework facilitating the bottom-up redevelopment process. Classical urban redevelopment delivers ready made plans and buildings. The approach adopted here (van Schilfgaarde, van Hooff, & Ossewaarde, 1997) aims for a gradual development influenced by its future and current users thereby increasing in value during time. It facilitates the option of change in the development as well, thereby increasing the durability of the project. Before physically transforming the building however, the object should first be subject to research in order to develop a vision on the desired changes and redevelopment (Zijlstra, 2007). Next to historical, societal and urban aspects knowledge of the technological and structural condition of a building is of the upmost importance before transformation. This chapter first handles the scope within the office vacancy where after the technological and spatial conditions of a building are to be discussed, including embodied energy cycles, thereby defining an appropriate target group within the vacant office landscape. After that, attention will be paid to the historical, societal and urban aspects.

3.1 SCOPE

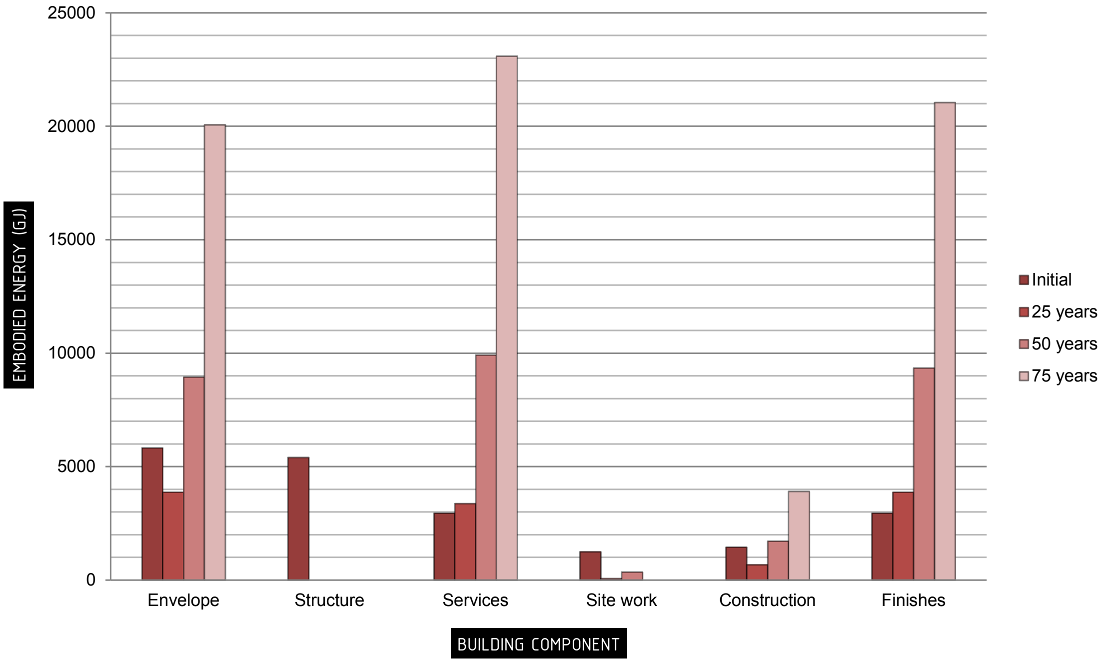
Examining the vacancy in the office market by construction year during the length of a few years, the trend of a replacement market can be deducted. Organisations and companies search for qualitative better, cheaper and newer options (Remøy, 2007b). Following graph 1, the vacancy rates in the construction period 1970-1999 increases, while the vacancy in the



GRAPH 2 – INITIAL EMBODIED ENERGY PER BUILDING COMPONENT (ADAPTED FROM COLE AND KERNAN, 1996)

most recent period decreases. The actual vacancy increases as well as is commonly known and accepted (Remøy & van der Voordt, 2014), thereby the share of the older buildings gets more significance and becomes an objective to focus on, as the newer built spaces are still applicable for office functions. When the capacity of a property to perform the function for which it was intended declines, it becomes functionally obsolete. This functional obsolescence may originate from sources as changes in the market or because of poor initial design (Allehaux & Tessier, 2002). The replacement market finds its origin in the functional obsolescence of the older generic office types, as there are more viable alternatives present.

Another assessment parameter where the feasibility of the conversion and redevelopment of office space constructed in the period of 1970-1999 can be determined is the embodied energy of the building, being the energy needed to initially produce the building taking transport, production and assembly into account (Cole & Kernan, 1996). The embodied energy reviewed over the life cycle of a building can be divided in the initial embodied energy and the recurring embodied energy, needed for replacement and refurbishment during its lifespan. Cole and Kernan (1996) defined



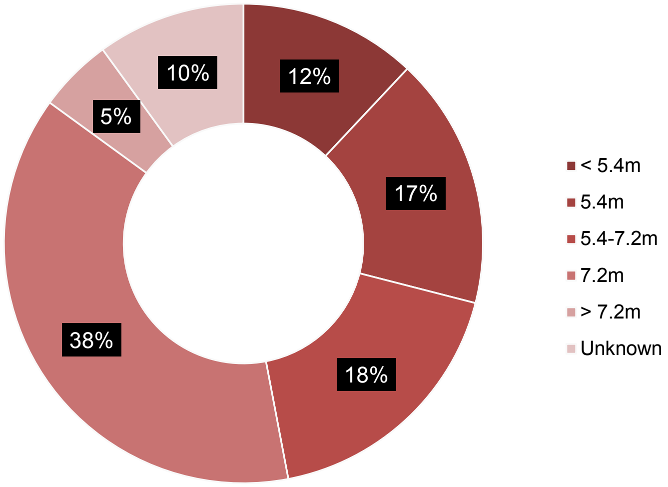
GRAPH 3 – INITIAL AND RECURRING EMBODIED ENERGY PER BUILDING COMPONENT (ADAPTED FROM COLE AND KERNAN, 1996)

the relative embodied energy for several building components for a generic European office building consisting of three storeys, as can be seen in graph 2. The envelope, structure and services all three have equal influence on the total size of the initial embodied energy needed.

A review of international research generally indicates that with exception to structural elements, all of the other components require varying levels of maintenance, repair and replacement during the life cycle of the building. The extent and intensity of these recurring embodied energy demands vary significantly, depending on how appropriately the durability of materials, assemblies and systems are harmonized, and how accessible they are for periodic maintenance, repair and replacement. Smaller renovations or refurbishments in an office building are required on average every 5 years (Douglas, 2006; Vijverberg, 2001). To extend the life span however, major renovations are required every few decades to keep the building up to date (Wilkinson & Remoy, 2011). When this recurring embodied energy required for these major renovations is taken into the equation, results differ greatly. Graph 3 shows the recurring embodied energy required after 25, 50 and 75 years of the initial construction, following the results from (Cole & Kernan, 1996) on the same generic office building. Where the structure requires no recurring embodied energy, the envelope and services require a lot of extra energy during the life span of the building. This problem arises due to the differential durability of the different building components. Where the structure has a durability of several centuries, the envelope and services requires (heavy) maintenance during the functional service life of the building. To reduce this recurring embodied energy in a redevelopment project, special attention can be paid to the reuse and recycling of building materials. The best way to achieve this is to make it easier to do so, by making use of design for (dis)assembly strategies to recover initial and prevent recurring embodied energy in a buildings life cycle (Crowther, 1999a). The design for (dis)assembly strategies are to be discussed later on in this paper. The combination of the growing vacancy due to the replacement market phenomenon discussed before in the period of 1970-1999 and the heavy maintenance offices constructed in the 70's and 80's are facing, makes the buildings out of this given timeframe appropriate for redevelopment where the starting point can be the base structure. As a rule of thumb, office buildings older than 25 years are most suitable in regards of embodied energy and vacancy rates to redevelop.

To further specify the target group of the vacant spaces, Keeris (2007) developed a layered overview of different forms of vacancy. The forms that apply to the transformation perspective as proposed in this paper are the structural vacancy where after 2 years every perspective on further rental possibilities disappeared and where the object doesn't comply with the required demand in relation to function and performance, and the locational vacant buildings where the location quality assessment does not comply to contemporary standards.

Buildings built in the '70's and '80's often have grid sizes varying in multiple length of 1.8m, like 5.4 or 7.2m, making buildings from this timeframe suitable for redevelopment. A typological analysis of 200 vacant office buildings in Amsterdam, performed by Koornneef (2012) shows us the most common grid sizes in office buildings, parallel to the façade, with the notion that the grid size perpendicular to the façade is in most cases the same for structural optimization. Columns form obstructions, thermal bridges and moisture leakages, unless being wrapped therefore the presence of a column inside the dwelling is preferably avoided. 12% of the construction grid sizes analysed are less than 5.4m and 10% of the analysed stock has no data on grid size. The most common construction grid size of typical



GRAPH 4 - RESULTS OF A TYPOLOGICAL ANALYSIS ON CONSTRUCTIONAL GRID SIZES OF 200 OFFICE BUILDINGS (ADAPTED FROM KOORNNEEF, 2012)

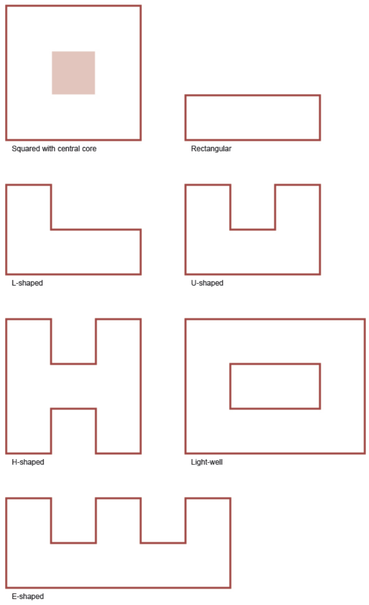


FIGURE 4 - GENERIC OFFICE TYPES (ADAPTED FROM HELLINGHAUSER, 1984)

housing projects in the Netherlands is 5.4m (Remøy, 2007b). By taking this as a normative, around 80% of the offices constructed with a grid are thereby appropriate for housing redevelopment, as they have a grid size of 5.4m or more.

3.2 CONDITIONS

Grid type office buildings from the 70's and 80's can in general be classified in 2 basic types (Remøy, 2007b). First the office tower, consisting of a column grid with free floor fields and stabilisation by means of a central core with central stairs and elevators integrated, where needed with extra stabilisation in the façade. Second, the low-rise, long stretched office building constructed with columns as well with free floor fields and stabilisation walls in 1 or 2 directions, depending on the used floor type. The core is mostly situated in the middle of the building, with two fire safety stairs at the front façades.

Several research has been done on analysing the beneficial and obstructive elements of these generic office types when being converted to housing (de Vrij, 2004; Gann & Barlow, 1996; Remøy, 2007b). Table 1 gives an overview of these factors as summarized by Remøy (see next page). Key issues in the top-down framework design facilitating the bottom-up redevelopment process according to (Schutten, 2007) are the internal zoning plan, the accessibility and spatial logistics, utility features and fire safety.

As previously mentioned in the scope, around 80% of the offices are appropriate for redevelopment into housing according to their constructional grid dimensions. In most cases, the height of the building opposes no problems (Gann & Barlow, 1996; Remøy, 2007b), as the height of an office is in general bigger than needed for Dutch housing, which is being set at 2.6m following the Bouwbesluit (the Dutch Building Regulations Act). Reviewing an analysis performed by Koornneef (2012) on 55 office buildings, the lowest net heights measured are 2.8m. The oversized depth of office buildings is often appointed as a problem in housing conversion, though if these are compared to usual depths of Dutch housing the differences are neglicible (Remøy, 2007b). Another problem in renovation is the deflection of floors during time (Koornneef, 2012), which are important to take into account when constructing with accurate digital fabrication techniques. To get a good overview of the spatial conditions of the complete building, including deformation and minor deflections in dimensions, a digital 3D model can be made using terrestrial laser scanning methods (Arayici, 2007; Hauschild & Karzel, 2011), as it often occurs that the original architectural plans are inaccurate, if they exist at all. (Kolarevic, 2003) entitles it as reverse engineering, capturing existing or as-built conditions, or even entire landscapes. Their accuracy provides a quick and precise alternative to common measuring methods. It thereby provides a good and detailed starting point for the redesign of the building in combination with the proposed digital fabrication techniques, where all can be monitored and facilitated by digital production and analysis. Gandhi, Magar, and Roberts (2014) also point out that with the use of 3D scanning methods, individualized products can be made available that are tailored to fit. This way, a new construction system can fit exactly within the physical and spatial imperfections of the base building.

The main problems, as stated by Remøy (2007b), Gann and Barlow (1996) and (Schutten, 2007), in the redevelopment are the building envelope, vertical transportation and accessibility, utility services, acoustical separation, and the lack and possibility of the provision of an outside space, giving a positive influence on marketability and rentability, next to the dwelling. All of these problems form an argument to redevelop with a box-in-box concept (Remøy, 2007b). Following this reasoning, the open building method with fit-out construction in offices as proposed by Kendall (2005) and the support and infill proposition of Habraken

	BENEFICIAL	OBSTRUCTIVE	SOLUTIONS
CONSTRUCTION	• Modular grid sizing of 5.4 or 7.2m, applicable to housing • High ceilings, lowest net heights 2.8m • Columns, free floor fields • Appropriate depth	• Locally lowered ceilings due to beams • Grid structure • Fire safety issues • Columns oppose obstructions (acoustic, thermal and moisture)	• Separate placement of units ensures acoustical quality and fire safety standards
FLOORS	• Designed for high floor loads, 300 kg/m². Normative for housing is 175 kg/m².	• Post tension bars; often low flexibility for vertical shaftwork • Low mass. Raised floor and lowered ceiling needed to comply to building regulations. • Deflection of floors	• Use existing elevators as utility shafts • New box-in-box construction • 3D scanning to map the deflections and deviations for digital fabrication input
ENVELOPE	• Modular grid sizing of 1.8m and loadbearing walls. Good connections possible.	• Curtain walls; bad technical conditions. No connections possible for function separating walls. • Cantilevered floors; applicability of balconies is difficult. • New façade is expensive.	• A new façade is needed in order to properly redevelop into housing solutions
VERTICAL ACCESSIBILITY	• Elevators are oversized for housing purposes.	• Often not enough escape routes. • Stairs and elevators account for relatively much space.	• Possibility of adding extra stairs inside or outside the building

TABLE 1 – BENEFICIAL AND OBSTRUCTIVE ELEMENTS IN OFFICE REDEVELOPMENT (ADAPTED FROM SEVERAL SOURCES)

(1972) come into the picture. The office building can function as the support or base building, where the dwellings are the customized fit-out construction according to building type, location and moreover user influence. By separating the dwellings, fire safety and acoustical separation is guaranteed. An outside space becomes possible within the original office fabric and the building envelope gets integrated in the fit-out of the dwelling. Internal zoning is then required to prescribe circulation, utility and free zones partly following the 'Support'-methodology as given by Habraken, Boekholt, Thyssen, and Dinjens (1976) in their book Variations. One of the best options for the utility services problem is the introduction of a raised floor where the desired slope can be achieved, mainly for the sewerage of the dwelling (Kendall, 2005; Zeiler, 2007). The overall capacity of the installations needed is a lot bigger for housing purposes than for an office purpose. A viable solution to this problem is to use present superfluous vertical elevator shafts as a new vertical ductshaft (Gann & Barlow, 1996; Remøy, 2007b). Sanitary rooms can be used as installation rooms where boilers and central heating systems are present. Other superfluous elevators may even be used for waste disposal, eliminating carefully planned building management regarding waste treatment (Gann & Barlow, 1996). In order to minimise the distance of the utility services to the vertical shaft, a service zone should be prescribed. If necessary when the distance becomes too large, the possibility of adding extra service shafts needs to be investigated, depending on the specific case.

Overall the technical, structural and spatial conditions need to be thoroughly analysed per case, as each building will oppose different problems and may accommodate different solutions to the problems presented above. The general building methodology will be the guideline in handling the difficulties and problems each unique redevelopment process faces in its top-down design stage, assigning different zones and functions within the support building, as an internal zoning plan to facilitate the bottom-up redevelopment.

3.3 URBAN EMBEDMENT

Architecture becomes successful the minute people can identify themselves with the architecture itself. Post-war urbanism and architecture has been built quite anonymously in relation to its direct environment and surroundings, thereby eliminating the uniqueness of a location and the identification people can gain from those specific locational characteristics (Colijn, 2007). This type of urban development is the exact opposite of what the people want, need and require. Social involvement only originates when people feel connected with the place. Amenity value is about emotion in the qualities of a building or neighbourhood: cultural, historical and societal in appearance and function (Benraad & Remøy, 2007). Overall, the appearance of an office building is to be accounted as negative. People would like to live in a building where they can identify themselves with, which means that the uniqueness of a building is an important aspect in redevelopment which should be respected in a social and historical context. This uniqueness will probably most of the time not be found in the building itself, but can be found in its direct context.

To be able to make an assessment of the vital urban conditions an office building needs to have in order to be successfully redeveloped, the "Transformatiepotentiemeter" – transformation potential measurement tool – developed by Geraedts and van der Voordt (2002) at the department of Real Estate & Housing at the Faculty of Architecture, TU Delft can be used. The tool combines location and building characteristics in an evaluation form. The more checkmarks are given, the lower the transformation potential. The tool is added as an appendix and can thus be reviewed.

FIGURE 5 – THE BARELY THERE GENERATION IN THE HOUSING MARKET, A GAP BETWEEN SOCIAL AND FREE RENTAL (DALHUISEN, 2013b)

To further embed the building into its context, an analysis of potential target groups and the urban setting is required (Reiner, 1979). In the connection of the building to its direct context, the street level space can be utilized for retail and commercial use and occupancy, as it generally has a higher floor height and street level space generally isn't suited for residential use (Hellinghausen, 1984). The street level space can also facilitate storage facilities of the residential units, depending on demand and design of the upper floors. It is therefore up to the designer to, according to the location analysis performed, assign public functions to the street level space that can work as an incubator. The densification in Rotterdam can be reviewed as a wrong example thereby emphasizing the importance of a good street level. Due to the many high-rise buildings present in the city nowadays they should give something back to the city in the plinth. This is however seldom the case. Blind street level façades, large parking entrances, facilities and container areas dominate the urban street views and experiences (Arends, 2012). On higher floor levels, communal or public spaces are possible as well at locations where interesting sight lines or connections to adjacent functions can be made, adding to the liveliness and experience of the building as a whole. Each specific case requires a different approach.

Next to the determination of neighbourhood viability, an analysis of the local housing market can be of use in determining the target group for the residential units. In the Dutch housing market there currently exists a gap for the 'barely-there' generation: successfully graduated, first job, single; the young and high potential (Dalhuisen, 2013b). They earn too much to rent in social housing, but too little too afford a living space in the free rental market, let alone to buy a house. Next to these high potentials, other common target groups that are appropriate for the housing solution offered here are elderly, students and newly formed families (Remøy, 2007a). Target groups are however hard to categorise, as own wishes and obstructions in their living situations prioritise their wished living conditions. The Dutch housing market isn't controlled by supply anymore, but by demand (Dalhuisen, 2013b). If the demand is so divergent, how can all these different desires be facilitated? A solution to this problem will be discussed in the next chapter.

3.4 DISCUSSION

The literature study performed outlined the structural, spatial and environmental conditions that should be taken into account during the redevelopment of a vacant office building. All of this gathered data can be formulated in a methodology or several design aspects when deciding to transform a building, dividing the aspects in an initiative phase and a support design phase.

First of all there's the initiative to transform, research needs to be done on the potential for transformation by the project developer or architect. The building is identified and thoroughly documented, along with a neighbourhood analysis to assess the viability of the transformation potential and to map the potential target groups. A helpful tool in doing so is the transformation potential meter, which can function as the start of an analysis. Along with this analysis, a survey on the structural conditions and adaptability potential of the building itself needs to be assessed. From here, the feasibility of transformation can be determined.

If the potential is there, the design process for the support building can begin. In the following, different steps are outlined as a part of this design process deducted from the literature study performed on the obstructive and beneficial elements in redeveloping:

- The architect performs a spatial and structural documentation of the present state of the building. From here, the strong and weak points can be determined following the presented matrix of beneficial and obstructive elements in an office building. After this step, the design process to prepare the support building can start.
- First, the overall circulation is assessed on soundness, condition and efficiency determining the circulation per floor and of the whole building. An important aspect to take in mind is the escape routing. Building regulations are often quite different due to the time and the housing function. Fire safety regulations, efficiency and volume of the routing are other factors to take in mind. What can remain, be removed and what needs to be added?
- Next to this the utilities can be mapped, where potential new vertical shafts can be investigated on their range in combination with the horizontal ductwork in a raised floor. Other criteria affecting the service cores are the individual fixtures that need to be served, capacity of existing cores and dimensioning in relation to capacity. The presence of optionally boilers or water tanks per floor influences the design of utilities as well.
- When the utility capacity and range is mapped, a zoning analysis can be performed on assigning an internal and external zone. The external zone, generally being placed on the parallel to the perimeter of the building is used for general and special purpose places (living room, bedroom, dining, hobby spaces). The internal zone will be used for service spaces like a bathroom, kitchen, toilet and laundry; to ensure a good connection to the primary utility shaftwork.
- Out of this zoning analysis, a possible plot division can be designed. This plot division can be based on the grid size, or can have no restrictions parallel to the perimeter at all. When dividing the plots in cooperation with the users, it must be ensured that there is no leftover space that is not being rented.
- An important aspect in the viability of the building is the urban embedment. Functions for ground level must be thoroughly investigated and the connection of this ground level to its surroundings must be carefully designed in terms of circulation, appearance and functionality. On higher floors, public or communal zones can exist as well, adding to the liveliness and embedment of the building.
- As a conclusive step, all of the steps taken before can be formulated in an internal zoning plan, prescribing a set of building rules ensuring the overall quality of the design, as the user will have a lot of influence on the end result.

By setting up game-rules for the use and subdivision of support structures, the architect makes a powerful gesture towards new social relations, new dwelling forms and typologies and thereby new cities.

The steps formulated above do not have to be designed in a chronological order. As it is designing, an iterative process is logical. When gaining new insights on a specific aspect it has consequences for another. The end result is a physical support design, ready for customized fit-out. This physical support design can be transformed in a 3D model using the scanning techniques mentioned, implementing deflections and deviations from the normative. This 3D model is, together with the formulated internal zoning plan, the starting point for the individual to design his own house.

3.5 CONCLUSION

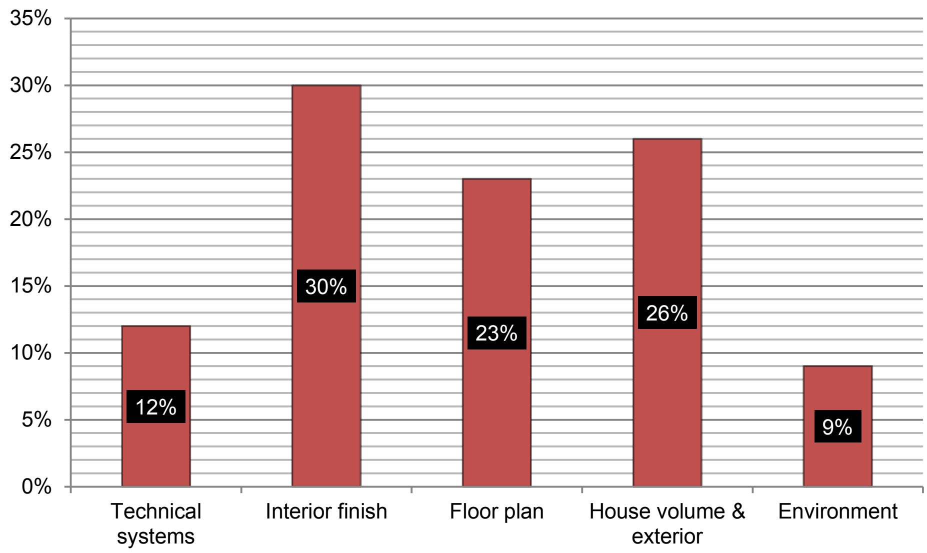
In order to determine the most appropriate office buildings for redevelopment, a market analysis from a literature study has been performed to set the scope. Results from this literature study has set the focus on buildings that are in need of a first major refurbishment and therefore require a certain relatively high amount of recurring embodied energy to be invested. These offices, dating out of the 70´s and 80´s, are in most cases rational and functional in design, where their grid sizes are in approximately 80% of the case appropriate for housing solutions. The challenge is to redevelop these offices with a building methodology that ensures a lower recurring embodied energy during time, thus reducing the life-cycle embodied energy. In the end, market conditions, location and building factors together determine the possibilities for redevelopment potential.

Furthermore, the steps formulated in the discussion as a result of the literature study serve as a generic methodology to use in the initiative to redevelop and design for a support structure. The aspects formulated do not necessarily have to follow in chronological order, as any design process shows some iteration. The physical end results functions as a support and base structure for the individual, mass customized fit-out dwelling. In general, the input for this fit-out dwelling is a detailed 3D model, including deviations and deflections in order to facilitate the high precision digital manufacturing processes and the internal zoning plan, setting out the game rules for the fit-out constructions.

4. AN ALTERNATIVE TO ANONYMOUS MASS-PRODUCED HOUSING SOLUTIONS

For residents or people in general, the quality of living, the well-being and welfare emerges when there is space for their own housing requirements (Colijn, 2007). More specifically, they would like to have an influence on the design of their own home, as the 'one size fits all' principle has proven to be inadequate in almost any case (Krug, 2014). This feature would lead to unique houses, but how can such a need be facilitated?

With the recent emergence of digital fabrication techniques, the production of 1000 unique products will cost the same amount of effort as the production of 1000 standardized identical ones (Kolarevic, 2003). Extrapolated to the housing market, a mass customized market emerges instead of the mass produced identical and anonymous housing solutions we are all familiar with. This mass production of unique and individualised products is called mass customization. Mass customization was first defined by Pine (1999) as *'developing, producing, marketing, and delivering affordable goods and services with enough variety and customization that nearly everyone finds exactly what they want'*. More recently, McKinsey addressed mass customization as a high potential business model, where digital technologies can drive the next wave of customization (Gandhi et al., 2014). The theories in potential, opportunities, threats, consequences and other implications for the different actors involved in a mass customized architecture world has been thoroughly discussed by Stoutjesdijk (2013), Kieran and Timberlake (2004), Piroozfar and Piller (2013)



GRAPH 5 – CUSTOMER PRIORITIES IN LEVELS OF HOUSING DECOMPOSITION (ADAPTED FROM HOFMAN & HALMAN, 2006)

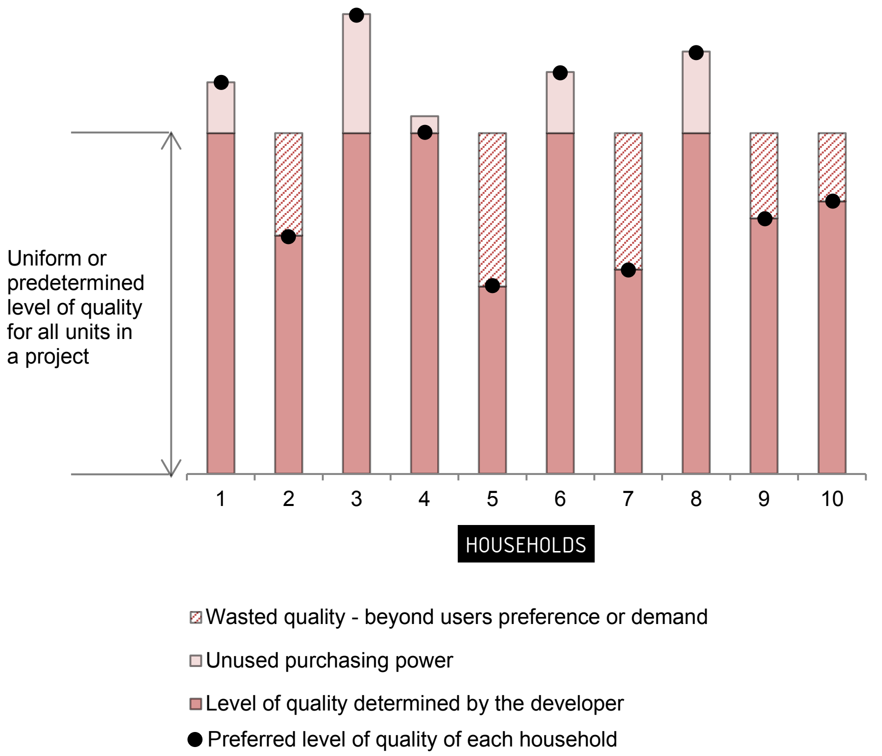
and Kolarevic (2003), among others. This paper will now focus on the potentials of mass customization for the housing market and the shift the contemporary market needs to make. After that, historical and contemporary case studies are presented and further analysed on their potential.

4.1 CUSTOMIZATION IN THE HOUSING MARKET

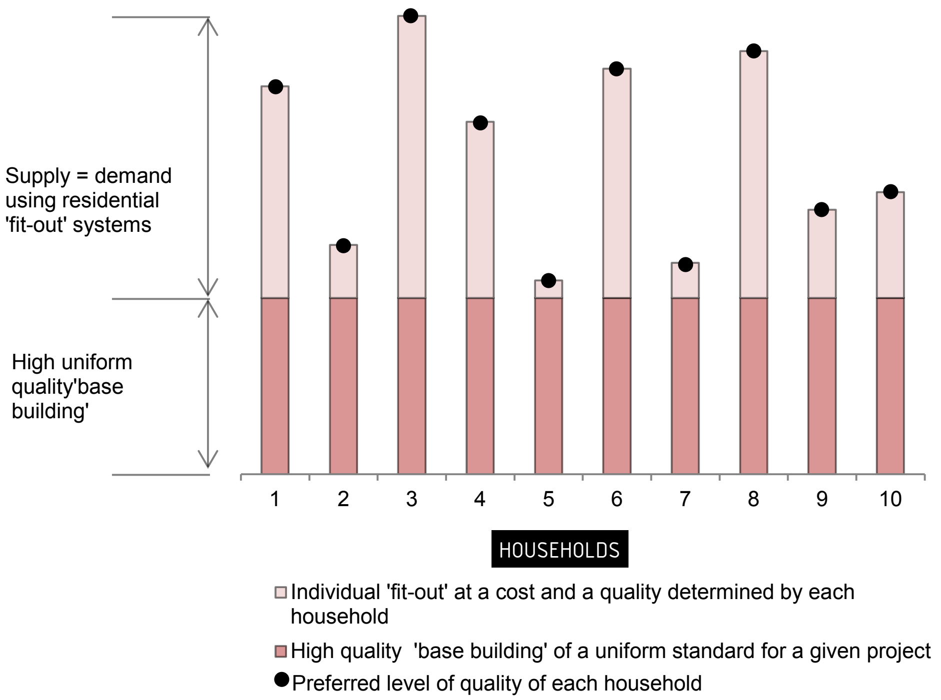
Mass customization applied to a dwelling can occur on several different scale levels (Krug, 2014). From a 3D printed door knob or name plate (S), to the door of a kitchen cabinet (M), to a façade or floor element (L) to the complete configuration of the house (XL). In the future, residents can easily adjust their house on all scale levels and order a unique or individualised product tailored to fit in their specific setting, from the ornament or the door knob to the actual volume. The scale level of the customization this research focusses on is the scale of the dwelling. More specifically, the spatial organisation and volume of a dwelling, within boundaries of the support or base building the vacant office block provides and the restrictions the eventual construction method prescribes. One of the main reasons for this focus is that a survey research found out that, next to the generally accepted interior customization of the finishes and furniture, the most desirable thing people would like to have influence on is the spatial organisation and the volume of their house (Hofman & Halman, 2006). Every family has its own preferences of living, hobbies and household that requires a different use and size of a space. On top of that, changes in a household or work cycle often require a desired change in the dwelling as well, aiming for a certain flexibility incorporated in the building method. The research was done with a vignette type of inquiry, asking whether people wanted to have influence on specific aspects at all, instead of giving a score to the different components.

Lichtenberg (2005) marks the current building industry as inefficient, contributing to irresponsible social problems and non-consumer oriented housing. A crash between the supply and social demand is almost inevitable, as is being confirmed by the customer preference research performed by Hofman and Halman (2006). (Dalhuisen, 2013b) reports that the current housing market is shifting towards a demand market instead of the supply market it used to be, suggesting that this crash can be averted. To facilitate a housing market that is being dominated by demand and thereby a big user influence, a shift in process thinking needs to be made.

The difference in mass customized and mass produced housing projects, being the shift the market needs to make according to Lichtenberg & Dalhuisen, has been explained and visualised in detail by (Kendall, 1999). In the traditional supply of housing households with differing preferences and economic possibilities are offered largely uniform dwellings to a standardized quality. As graph 6 illustrates, in this case some people will pay more than they can actually afford or more for what they want as opposed to others who would have to accept less than they actually want or afford. Following an open-building approach illustrated in graph 7, households share a high quality base or support building. Each can then design a fit-out according to their preferences and budget, matching supply and demand. Accounting durability, mass housing has proved inflexible and incapable of adjusting to social, economic and technical changes (Kendall & Teicher, 2000) where the open building method can easily undergo changes over time, evolving with the contemporary 'Zeitgeist'. Next to the conventional changes in cabinets, finishes and furniture an open building method can adjust to changing household conditions at a cycle of 10-20 years (Kendall, 1999).



GRAPH 6 – THE MISMATCH BETWEEN SUPPLY AND DEMAND IN A CONVENTIONAL RESIDENTIAL PROJECT (ADAPTED FROM KENDALL, 1999)



GRAPH 7 – THE MATCH OF SUPPLY AND DEMAND IN AN OPEN BUILDING RESIDENTIAL PROJECT (ADAPTED FROM KENDALL, 1999)

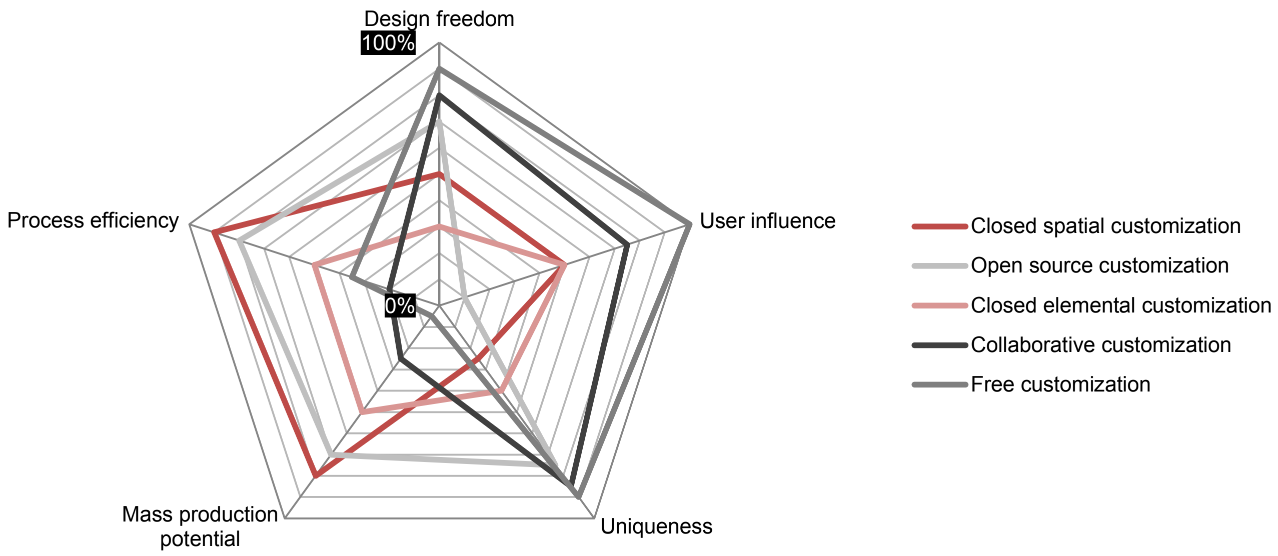
4.2 CASE STUDY ANALYSIS

In history, several attempts have been made to theorize on the mass customization of housing projects and research has been performed on the methodologies required, in general all following the support/base building and infill/fit-out principle. Examples can be found in the work of (Friedman, 1971), Habraken (Bosma, 2000; Habraken, 1972; Lüthi & Schwarz, 2013), Le Corbusier's plan Obus (Ackley, 2005; Pouliot, 2011), the principal post-war building method polykatoikia in the city of Athens (Emmanuel, 1981; Vittorio Aureli, Giudici, & Issaias, 2012) and the Kowloon Walled City (Girard, Lambot, & Goddard, 1993). More elaboration in the form of project descriptions of the precedents mentioned are included in appendix II, as they are part of an analysis on the mass customization potential in combination with the more contemporary precedents following in the next paragraph.

More recent initiatives can be found in the Tetterode-complex (Bijdendijk, 2006; Sep, 1992), het Wilde Wonen (Weeber & Vanstiphout, 1998), Torre David (Lambert, 2014; Urban Think-Tank, 2013), Solids (Bijdendijk, 2006; Wallagh, van de Riet, & Crooy, 2013), Almere Oosterwold (Oey, 2013), collaborative efforts between architect and user (Fenixlofts, De Hoofden), online housing configurators (Hermit house, Palet van Delft, Woonconnect, Woonmodule, Wenswonen), Wikihouse and the Grundbau + Siedler building by BeL Associates (Bernhardt & Leeser, 2010). Project descriptions of these are to be found in appendix III.

These more recent initiatives and the historical precedents have been categorized and further analysed on their mass customization potential, mainly focussed on the design freedom, user influence, potential for mass production, architectural quality (uniformity or uniqueness) and the estimated timeframe from initiative to completion. In this categorization the emphasis was on a division focussed on actual realised or on-going projects. The different customization categories the projects are grouped under are as follows:

- **Closed element customization**; this category contains most of the housing configurators present today. People can choose from different elements; different predetermined floor plans, façade lay-outs, several additions and exterior finishes. By limiting the choice to a predetermined set of elements, the actual process can be quite efficient (examples are Wenswonen, Woonconnect, Woonmodule, Palet van Delft)
- **Closed spatial customization**; instead of focussing on elements to be added or not as in the previous category, this type of configurator lets the user configure the actual spatial lay-out of the unit by varying several parameters. The expression is however strongly limited, as the prescribed construction type is dominant (an example of this style of configurator can be found in the Hermit House).
- **Collaborative customization**; this type of customization is a collaborative effort between architect and end-user. Together, they determine the spatial lay-out of the house including finishes and optional additions. This type of collaboration requires time, resulting in a longer process duration. The quality of delivered work is however high, as there is generally an architect involved (examples are Fenixlofts and De Hoofden – if the end user decides to use an architect in the realisation of their loft).
- **Open source customization**; the open source customization focusses on a constructional framework given, where each individual is allowed to build their own configuration within the given constructional framework. There is however quite some knowledge required of construction and connections to be able to design your own house, which makes the



GRAPH 8 – ANALYSIS OF MASS CUSTOMIZATION POTENTIAL OF CATEGORIZED CONTEMPORARY AND HISTORICAL PROJECTS WITH A CUSTOMIZATION ASPECT IN THEIR PROCESS (OWN ANALYSIS)

tool limited for mass-use. If the constructional framework can be implemented automatically, the tool would work as a completely open source customization service, but the category to be analysed here focusses on the actual example of the WikiHouse, where such an implementation of construction is not (yet) made.

- **Free customization**; the last customization category is the free building category. This category consists of several self-build projects, where the end-users are complete free in building, designing and engineering what they want. One of the early examples of this concept is the Tetterode complex, invaded by squatters and the Polykatoikia construction in Athens. More contemporary examples are the Solids in Amsterdam and the Grundbau + Siedler proposal of BeL Associates.

The different projects and thereby the categories have been thoroughly investigated and based on the insights of this research the following qualification has been made in graph 8. A separate analysis and brief description and argumentation of the values per category is implemented in appendix IV. Apart from the closed element customization, which scores quite moderate on all evaluation criteria a quite clear distinction between the other categories can be seen. The closed spatial customization and open source customization has high scores on process efficiency and mass production potential and lower on design freedom, user influence and uniqueness. The collaborative and free customization categories scores opposite, giving good results in the customization and freedom aspects but scoring worse on process efficiency and mass production potential.

Ideally, the optimal and best mass customization is being reached in a combination of the strong points of the two. There somehow needs to be a modular language in the construction system to facilitate a high process efficiency and mass production potential, without losing too much design freedom and user influence on the system. This language would then function as an intermediary between the freedom of choice and the ease and modularity of construction. Such a constructional language is present in the WikiHouse concept, although designing custom solutions is only reserved for those with knowledge of modelling according to the prescribed construction standards as there is no automatic translation from a simple drawing to a construction drawing.

4.3 DISCUSSION

Somehow, an easy translation from simple drawings to a construction drawing should be made. Therefore, an easy construction system with a modular aspect facilitates an easy translation and easy assembly. Elaboration on the contents and reference points of such a constructional logic is given in the next chapter. Westerholm (2013) sees the future of configurators in the form of a smooth interface that delivers a precise visual impact of the personalized choices. On top of that, enabling a mass customization service for the buyers without using the traditional labour effort makes sense businesswise. The 3D scanned model of the specific building can be the starting point for such a user oriented interface. From here, the translation to a construction grammar can be made after completion of the design, without having the customer ever to see this constructional logic. There have been some initiatives to facilitate the translation from a simple drawing – provided by the user – to production drawings adapting to the construction system, for example in the form of a Google SketchUP plug-in by Tubby, Burnham, and Green (2012). Several shape grammar studies (Bell & Simpkin, 2013; Sass & Botha, 2006; Sass, Michaud, & Cardoso, 2007) argue that the next generation of computational tools that place the individual (the customer) in the centre of the design process, if matched with a more rational approach to construction and fabrication, can enable a democratisation of excellent design and technology in housing. If software tools can be developed to produce extremely complicated parametric architecture like the works of Gehry, software applicable to the more common generic housing market should be easy to develop. The software part they are talking about is the rationalization of the plan drawings to a set of construction drawings. Bell and Simpkin (2013) also take note of the proponents of the domestication of parametric design that largely escaped the attention of the housing market. The market for developing configurators is growing, setting the standard from the general assembly line to a personal assembly line. Successful configurators proved that it isn't wishful to have a fixed roadmap within the configurator, but to set the experience of designing as a main feature (DPI, 2012).

The 3D scanned model with all the information regarding deflections and deviations and the lay-out of the support design, together with the proposed internal zoning plan from the architect form the boundaries and limits in the configurator in which the user is placed in the centre of the process. Other input in the configurator can be the local climatic data, from where the user for example can review the actual insolation in his design. Within this framework, the user is able to design his living environment. Rhythm, depth and dimensions – to name a few – form the barcode of an individualistic expression: the personalized dwelling. Each house has its own characteristics and becomes unique, adapting to the needs and wishes of its user. Following the processes analysed before, the following can be done and taken into account by the user itself in a user centered design process (van der Werf, 1993):

1. **Activity listing.** What does the user want to do in the dwelling? What are the hobbies of each individual and what are the things you like to do inside your house. Make a list of activities.
2. **Activity descriptions.** Following this list, a description of the actions performed can help in determining the amount of space required for such functions. A tool that can help in this aspect is a furniture map.
3. **Relational diagrams.** Which of these activities are to be performed within one space? From these answers, a spatial logic is coming forward, insight in what kind of rooms you actually want to have in your dwelling.
4. **Initial floor plan.** The actual placement of the rooms. There are different considerations:
    - the utility zone, prescribed by the internal zoning plan;
    - the need and place of an outside space;
    - placement of the entrance;
    - insolation, the amount of direct sunlight can be reviewed in the building model. Climate data can be imported and be a part of the design process as a form of performative architecture design (Kolarevic, 2003);
    - placement of space in relation to each other.
5. **Final design.** The actual drawing of the dwelling, ready to review and be changed and eventually to be send off to fabrication.

During this design process, the user should have the option to consult a professional about their plans to gain feedback, but this is up to the individual. This way, a user-centered design loop can be formulated in which the user can design its own house. The loop consists of the digital housing configurator, working like an IKEA kitchen builder, the option of consultation with a professional and several guidelines for the user to gain insight into his own living requirements. In the end, the final design as delivered by the client should be approved for building by the architect or principal client.

After completion and approval by the principal client or architect of the base building according to the prescribed set of rules and the internal zoning plan of the support building, a constructional logic parametrically defines the construction scheme and plans from the drawings provided by the configurator and thereby the user to make the design ready for fabrication and assembly. By making use of these digital solutions, the user can have an influence on its own house without the need to have any knowledge on construction or fabrication. An elaboration on the requirements and reference points for such a constructional logic is performed in the next chapter.

4.4 CONCLUSION

Following the analysis of the categorized precedents on their mass customization potential, the role of the user and architect can be redefined in order to accomplish an efficient design process. To facilitate this, the basis for the design process can be found in the digital 3D model of the support structure. From here, an initial plot can be chosen on where to design a custom dwelling.

With further input from the internal zoning plan and local climatic data, the user can follow a prescribed plan in order to gain insight in their own living requirements and to be able to design their own house in this digital environment. This user centered design process also offers the possibility to consult an architect. This is left up to the individual. Essentially each and every one can give form to its own process as well as their design result within a given set of circumstances and limits, specifically prescribed by each building.

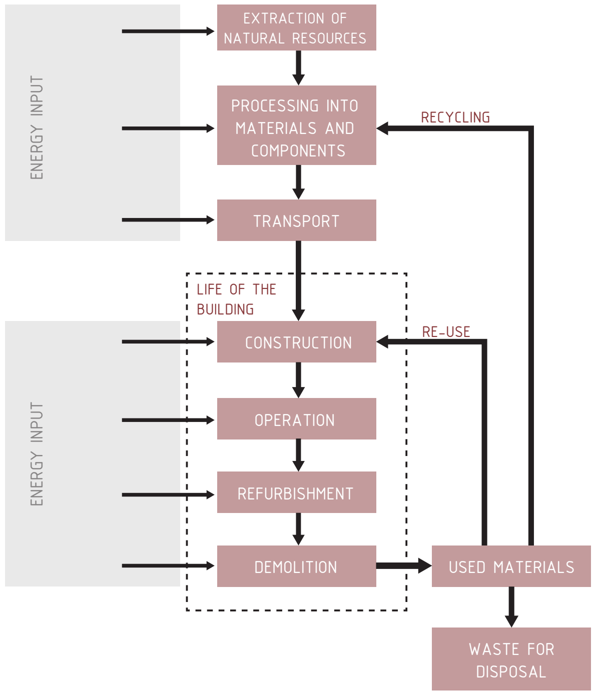
In order to comply to the building regulations, internal zoning plan and the constructional logic, the design has to be approved by the principal architect in order to be build. Once this is done, construction drawings can automatically ben generated and the digital production process can start.

5. THE DIGITAL REVOLUTION IN CONSTRUCTION AND THE SELF-BUILDING MOVEMENT

This chapter will focus on the requirements the proposed constructional logic needs to focus on. Fit-out constructions in support buildings have generally different requirements than regular constructional systems. First, some theory about design for manufacturing and (dis)assembly is discussed in order to get familiar with the design methodology, second several construction precedents are analysed on this methodology. From here, a discussion about the outcome of such a construction system gives the reference points for an actual design.

5.1 THEORY

Several arguments have been given on using a simplified constructional logic facilitating the mass customization aspect in a user centered design process. On top of that, a lot of people like to build their own house, emphasized in an enlargement of the so called self-building movement (Oey, 2013). More and more people like to have initiative in designing their own house, as well as actually building it. This chapter offers the foundation and reference points in order to design an appropriate construction system for the given case. Adaptation, flexibility and ease of construction are important requirements for the constructional system used. Following this reasoning, a construction system can be developed taking into account the parameters defined by the Design for Manufacturing and (Dis)Assembly strategy by Boothroyd and Alting (1992):



GRAPH 9 - STAGES OF ENERGY INPUT DURING THE BUILDING AND THE POTENTIAL RE-USE AND RECYCLING VALUES WHEN DESIGNING WITH DISASSEMBLY IN MIND (ADAPTED FROM CROWTHER, 1999)

- Minimize part count
- Standardized parts & materials
- Modular assemblies
- Efficient joining
- Minimize reorientation of parts during assembly and/or machining
- Simplify & reduce number of machining operations

Other general guidelines mainly focussed on the disassembly process that can be followed are given by the Active Disassembly Research (2005) group, the same emphasis on these aspects has been given in a historical research on disassembly projects by Crowther (1999b):

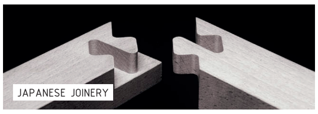
- Choose recycling compatible materials (as far as possible)
- Avoid using materials that require separating before recycling (re-use of a whole part is allowed)
- Use as few components and component types as possible, without compromising on structural integrity
- Making components to a size suitable for handling during (dis)assembly
- Integrate components relating to the same function where possible
- Standardise the use of fasteners – use commonly available material and maintain consistency
- Make components easily separable
- Using common building practice and user participation
- Use non-contaminating markings on materials for ease of sorting in the assembly process
- Maintain good access to components and fasteners

An additional argument in designing a constructional system with Design for Manufacturing and (Dis)Assembly parameters is the embodied energy discussed before. In designing a system where parts can be reused or recycled, the recurring embodied energy during the lifetime of a support building can be minimised and can therefore have several environmental benefits (Crowther, 1999a). Cycles can in potential be closed therefore introducing a more durable way of construction and fit-out, see graph 9.

5.2 CASE STUDY ANALYSIS

Focussed on (dis)assembly, several realised projects or construction methods have been analysed on their potential, pros and cons. The Packaged House System by Walter Gropius and Konrad Wachsmann (Herbert, 1984; Imperiale, 2012) dates back to the 1940's, more recent examples are to be found in the Instant Cabin constructed by Sass and Botha (2006), the Liina Transitional Shelter constructed by a team from the Aalto University and a a redevelopment method developed by AFFECT-T. On top of that, the Japanese joinery methods are also implemented in the analysis (Sumiyoshi & Matsui, 1989). Elaboration on the projects can be found in appendix V. The precedents are analysed on the aspects as given by Boothroyd and Alting (1992), results are given in the following table on the next page (a bigger version of the table is added in appendix VI).

The use of a universal connector as done in the Packaged House System opposes several big advantages in (dis)assembly, as there is one type of connection for every perpendicular or parallel joining. The connector has therefore the potential to be mass-produced, while the framework it builds can be mass-customized with digital fabrication, giving the wanted spatial freedom to the user. Van den Thillart (2004) also takes note of the need for universal assembly in building construction in order to facilitate customization. Universal assembly happens in the automotive industry and, when reviewing the automotive and the building industry, should be even easier to implement in the building industry, as most of

PRECEDENTS	Minimize part count	Standardized parts & materials	Modular assemblies	Efficient joining	Minimize reorientation of parts during assembly and/or machining	Simplify & reduce number of machining operations	DFMA score
 PACKAGED HOUSE SYSTEM	★★★☆☆ There are still a lot of parts present in the system, efficiency is achieved through the joining method.	★★★☆☆ Everything is factory made. Though, there are still a lot of different components present.	★★★★★ Every assembly is the same due to the fact that there is 1 joint.	★★★★★ Gropius and Wachsmann designed 1 universal connector for every joint.	★★★☆☆ Due to the fact that there are many different components, machinery and assembly is still quite labor intensive.	★★☆☆☆ The prefabrication of the parts was labour intensive.	★★★½☆
 INSTANT CABIN	★☆☆☆☆ With approximately 970 parts (including connections), there are a lot.	★★★☆☆ Parts are not standardized. The construction consists of one material, including connections.	★★★★☆ Each part has a specific structural function and is modular in use.	★★★★☆ Not the amount of connectors, but the friction-fit joining makes it efficient.	★★★☆☆ During machining no reorientation. Assembly is like a small puzzle.	★★★★★ The only machining operation is milling in 2D, so limited to 1.	★★★½☆
 LIINA TRANSITIONAL SHELTER	★★★★★ By using SIPs as a truss structure, the amount of parts is drastically minimized.	★★★★☆ The truss is modular and thereby standardized.	★★★★★ Connections are the same and occur in logical order.	★★★★☆ Just dowels, dovetails and ratchet straps act as connectors giving an airtight building.	★★★☆☆ During machining quite a lot. During assembly practically none.	★★☆☆☆ Making SIPs in the factory requires more labor.	★★★½☆
 BAMBOO MICRO HOUSING	★★☆☆☆ The bamboo and supporting structure account for a lot ofparts.	★★★☆☆ Materials are all standardized from production.	★★☆☆☆ The structures assembly can only be done as a whole.	★★★☆☆ Joining methods used are efficient but time intensive.	★☆☆☆☆ During machining, parts undergo heavy adjustments.	★★★☆☆ The bending of the bamboo straps makes the fabrication process unnecessarily complicated.	★★☆☆☆
 JAPANESE JOINERY	★★★★☆ Integrating the structural frame and joinery minimizes part count.	★★★☆☆ Standardized in production, although it needs quite some processing.	★★★★☆ The structures assembly is modular in its framework of joints.	★★★★★ The integration of structure and joinery makes for an efficient joining method, also erasing screws etc.	★★☆☆☆ The nature of the joinery requires a lot of reorientation during machinery.	★★☆☆☆ A lot of reorientation also ensures that the machining is quite time and labour intensive.	★★★☆☆

KEY DFMA PRINCIPLES

TABLE 2 – QUALIFICATION OF SEVERAL BUILDING METHODS ACCORDING TO DESIGN FOR MANUFACTURING AND (DIS)ASSEMBLY PARAMETERS

the buildings have much more simple geometries and spatial logics than the automotive industry handles. The addition of panels in the structural framework is however neglected in the analysis and should need more attention on the integration in the framework. Gropius and Wachsmann designed a sandwich panelled construction with the same principle, but then in fact the construction becomes much alike the Liina Shelter. The friction-fit connections of the Instant Cabin have as a quality that there is only one type of material (plywood sheets) from where the whole building can be constructed. The amount of parts and connection types makes the assembly process quite labour and time intensive in comparison to the building method the Packaged House System provides. The modularity in the Liina Transitional Shelter is the power of the construction method, yet as well its weakest aspect in its potential for mass-customization, as the structural strength of the whole is determined by the truss construction and the shape is thereby predetermined. The Bamboo Micro Housing projects is in its overall construction and assembly quite labour intensive, as there are many different parts and methods of connections. The elegant Japanese joinery methods unite structure and connection as one, although the production process of digitally milling the joints requires quite some reorientation and machine operations.

5.3 DISCUSSION

From the analysis performed several potentials can be deducted in developing a constructional logic facilitating the mass customized dwelling. There are however other limitations present to take into account when designing the constructional system. The character of the bottom-up redevelopment means that the actual appearance of the building as a whole is dynamic, meaning that a change in amount of dwellings or to the size of a dwelling can occur every day.
Therefore the construction system should be easy to handle by a person, meaning that the maximum weight of the elements should be limited to 23kg according to the NIOSH method[1], the maximum workload a person may handle according to Dutch legislation. Furthermore, the construction parts are bound to be transported by elevator, as a permanent building crane can be considered undesirable. The spatial dimensions of the elevator are therefore to be regarded as spatial normative for the constructional parts.

Following the developments of the self-build movement, the assembly and disassembly should be kept as simple as possible while following the DFMA requirements. The integration of the utilities is an important factor to be reckoned with as well, examples can be found in prefabricated sandwich panel systems, where electrical shaftwork is integrated in the bottom of the walls with removable sheeting. The sewerage and water logistics can be integrated in a raised floor system, references to such a kind of integration can be found in several developed infill systems as Matura, developed by the SAR under influence of Habraken (Kendall, 2010), the Cablestud system or the prefabricated system of Faay, serving the interiors of IKEA where flexibility is of the upmost importance in exhibiting their ever changing configuration of rooms.

The construction system will need to find a balance between modularity and freedom. A helpful tool in determining this balance is the modular coordination as (van der Werf, 1993) introduces. On the other hand, digital fabrication doesn't need such a form of modularity in order to successfully mass produce individualized dwellings. As can be seen in the Packaged House System, the modular element can also be the connection, unifying the connections while maintaining design freedom. The challenge of finding this balance is one of the most important design aspects in developing a successful constructional system as the transition point between the digital and the physical world.

1 Maximum workloads can be found on http://www.arbobondgenoten.nl/arbothem/lichblst/lift.htm

5.4 CONCLUSION

Where in the past custom architecture applied to the wealthy ones of our society, using an architect to create their 'dream-villas', digital fabrication techniques make it possible to, within a set of predetermined boundaries, give freedom to every individual that wants to build their dream house.

Following a constructional logic out of the digital design, their dream houses can be digitally fabricated either on- or off-site, depending on the fabrication method used. The design of such a construction system is bound to a lot of restrictions given in the discussion. Next to that, several analysed precedents pose opportunities in ease of construction. A balance needs to be found between modularity and freedom, determining an optimized translation between the digital and the physical.

6. CONCLUSION

In order to address the best applicable office buildings, a market analysis from literature has been performed to determine the scope within the vacant office stock. This study has learned that the office buildings, generally older than 25 years and in need of the first big renovation, have the highest potential for redevelopment. The vacancy rate of this group increases in relative and absolute terms; therefore it is a growing group of vacant stock that requires appropriate attention. The rational and functional way of building in the 70's and 80's, make that a high amount of this vacant stock (around 80%) is applicable in terms of spatiality for redevelopment. Further analysis in spatial and structural conditions has learned that the best way of redeveloping is to start from the structural frame, and work with a box-in-box concept. From here, the support or base building and fit-out, chassis + infill, or simply the open building method comes into scope. Open building is sustainable in such a way that it provides adaptation and flexibility for future changes in use, varying from a change in household or lifestyle to a change of function. A new fit-out construction with lower recurring embodied energy is required to make the whole construction more durable, reducing waste, increase efficiency and make the total concept flexible and adaptable. Specific constructional logics and techniques are required for such a fit-out method,

Starting from the initiative, several tools and options are given in determining the feasibility of such a redevelopment strategy. If the feasibility assessment returns back positive, the start for a support design can be made. In no particular order a documentation, circulation analysis, utility analysis, zoning analysis, plot divisions, identification of public and communal space and in the end an internal zoning plan can be developed, resulting in a physical support design.

This physical support design is then scanned for a detailed 3D model to function, together with the internal zoning plan and local climatic data, as input for the digital housing configurator as part of a user centered design process. In this process, the user has the possibility to develop his/her own design and has the possibility of consultation; ultimately giving freedom to the process. When finished, this design is approved by the principal architect and translated with the help of a constructional logic from the digital to the physical world to be realized and build.

The here proposed design methodology in open building is visualized on the next page in a scheme. This scheme is the general outcome of this research, next to the reference points for the constructional logic. The research was restricted to the analysis of possibilities, as well as an analysis of the boundaries and limits for such a system to work. It thereby gives a reference framework for an actual design of a constructional logic, facilitating the translation from the digital to the physical world.

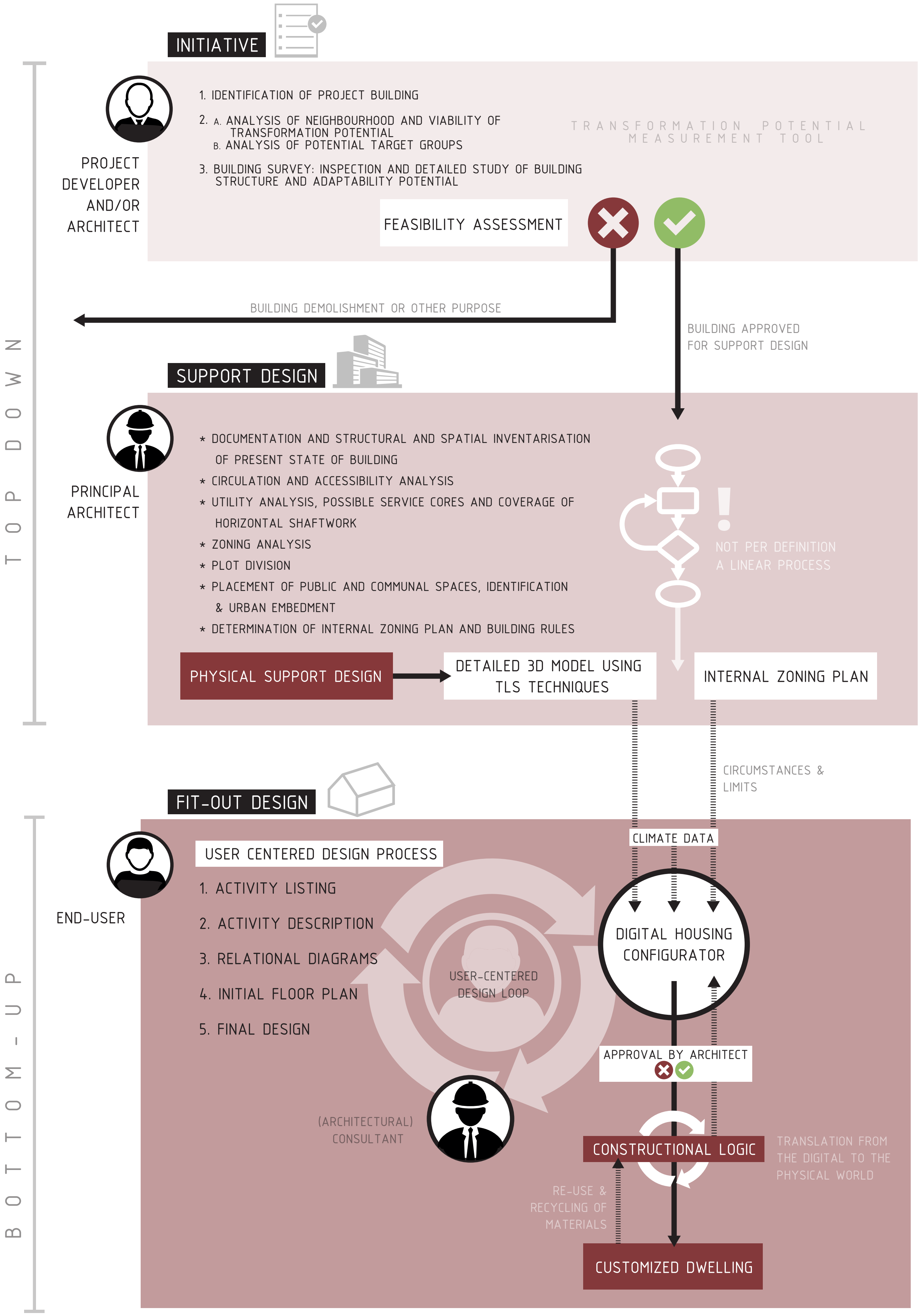
The redevelopment of a structurally vacant office building in the methodology as proposed here, can serve as an antidote to the sprawl of anonymous housing and contribute to the densification of a city by making optimum use of the vacant space, thereby creating a new typology in urban living enhancing the freedom of choice of the individual utilizing contemporary digital design and fabrication techniques.

Of course, the case of a vacant office building is just one of the possibilities offered by the proposed customized housing solution. One could imagine that each vacant building offers possibilities for such a solution, or there can even be support buildings build to precisely facilitate the process. With the vast amount of vacant space available, that last possibility seems a bit superfluous. The main innovation that this project has to offer is the streamlined process in combination with the presented construction logic, making the idea viable for every individual of our society, offering an alternative to the mass produced housing stock by slowly replacing it in a mass customized housing stock.

7. SUGGESTIONS FOR FURTHER RESEARCH

First of all, the proposed methodology can be tested in several case studies. Results from these case studies can function as feedback in further specifying the method. In the last chapter, reference points are given by means as a foundation to design a constructional logic meeting several requirements in the open building methodology. The research by design process of developing such a constructional logic is a topic to further research as well.

This paper has focussed on the design process in its methodology proposal. Next to the design aspect legal, financial and organisational aspects have an influence as well. These aspects can be subject to a literature study to further complete the proposal.


INITIATIVE
PROJECT DEVELOPER AND/OR ARCHITECT
1. IDENTIFICATION OF PROJECT BUILDING
2. A. ANALYSIS OF NEIGHBOURHOOD AND VIABILITY OF TRANSFORMATION POTENTIAL
B. ANALYSIS OF POTENTIAL TARGET GROUPS
3. BUILDING SURVEY: INSPECTION AND DETAILED STUDY OF BUILDING STRUCTURE AND ADAPTABILITY POTENTIAL
TRANSFORMATION POTENTIAL MEASUREMENT TOOL
FEASIBILITY ASSESSMENT
BUILDING DEMOLISHMENT OR OTHER PURPOSE
BUILDING APPROVED FOR SUPPORT DESIGN
SUPPORT DESIGN
PRINCIPAL ARCHITECT
* DOCUMENTATION AND STRUCTURAL AND SPATIAL INVENTARISATION OF PRESENT STATE OF BUILDING
* CIRCULATION AND ACCESSIBILITY ANALYSIS
* UTILITY ANALYSIS, POSSIBLE SERVICE CORES AND COVERAGE OF HORIZONTAL SHAFTWORK
* ZONING ANALYSIS
* PLOT DIVISION
* PLACEMENT OF PUBLIC AND COMMUNAL SPACES, IDENTIFICATION & URBAN EMBEDMENT
* DETERMINATION OF INTERNAL ZONING PLAN AND BUILDING RULES
NOT PER DEFINITION A LINEAR PROCESS
PHYSICAL SUPPORT DESIGN
DETAILED 3D MODEL USING TLS TECHNIQUES
INTERNAL ZONING PLAN
TOP DOWN
CIRCUMSTANCES & LIMITS
FIT-OUT DESIGN
CLIMATE DATA
END-USER
USER CENTERED DESIGN PROCESS
1. ACTIVITY LISTING
2. ACTIVITY DESCRIPTION
3. RELATIONAL DIAGRAMS
4. INITIAL FLOOR PLAN
5. FINAL DESIGN
USER-CENTERED DESIGN LOOP
DIGITAL HOUSING CONFIGURATOR
APPROVAL BY ARCHITECT
(ARCHITECTURAL) CONSULTANT
CONSTRUCTIONAL LOGIC
TRANSLATION FROM THE DIGITAL TO THE PHYSICAL WORLD
RE-USE & RECYCLING OF MATERIALS
CUSTOMIZED DWELLING
BOTTOM-UP

8. LITERATURE

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APPENDIX I

TRANSFORMATIEPOTENTIEMETER (THE POTENTIAL FOR TRANSFORMATION TOOL)
ADAPTED FROM: GERAEDTS & VAN DER VOORDT (2003)

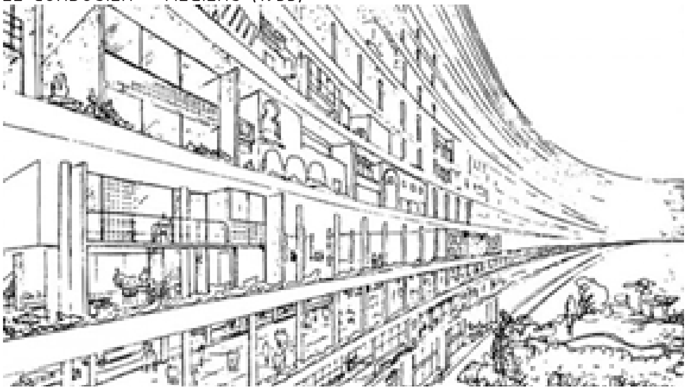
ASPECT	CRITERION	✓
LOCATION		
Urban situation	Office on remote industrial zone	
	Office in the middle of an office park	
	Office in area defined as priority area for offices	
Land property	Land rent	
Vacancy	Vacant for more than a year	
	Vacancy of surrounding buildings	
Character of urban situation	Location on or near city edge, ring roads	
	Desolated area	
	No greenery in the neighbourhood	
	Social depreciation, vandalism	
	Pollution; smell, noise, view	
Distance and quality of facilities	Shop for daily errands > 1km	
	Meeting place (café, snackbar, etc.) > 500m	
	Bank/post office > 2km	
	Basic medical facilities (doctor, pharmacy) > 5km	
	Sport facilities (fitness, swimming pool, sports park) > 2km	
	Educational facilities (nursery, school, university) > 2km	
Accessibility by public transport	Distance to station > 2km	
	Distance to bus, metro or tram stop > 1km	
Accessibility by car; parking	Many obstacles, limitations, poor flow	
	Distance to parking place > 250m	
	< 1 parking place / 100m^2 dwellings reasonable	
BUILDING		
Year of construction	Building was built or renovated recently (three years)	
Character of the building	Unrecognisable, non-eloquent*	
	Poor maintenance	
Extensibility	Not extensible horizontally	
	Not extensible vertically	
Structure	Structure in technically bad condition	
	Dense structural grid, < 3.6m	
Dimensions	Net story height < 2.6m	
Façade*	Façade openings not adaptable	
	Impossible to create windows which can be opened manually	
	Daylight entry < 10 percent of the living area	
Entrance (building, dwelling)	Impossible to create a socially secure entrance	
	Impossible to realise elevator in the building (if more than four floors)	
	Distance from dwelling to stairs/elevator > 50m	
	Impossible to realise escape stairs according to escape demands	
Installations*	No or insufficient conduits realisable	
Environment	Noise level at the façade > 50dB	
	Sufficient insulation between dwellings impossible	
	Sufficient insulation of façade impossible	
	Presence of dangerous materials in construction	
	No or little sunlight	

***** The fields marked do not generally apply to the proposed 'open building' transformation and therefore are not decisive factors in determining the transformation potential.

APPENDIX II

In this appendix, a short description of the historical precedents aiming for customization in housing solutions is given. It aims to give a short, general and to the point description of the literature present on the projects, aiming for a good understanding regarding the mass customization potential analysis performed in a categorization of these projects.

LE CORBUSIER – ALGIERS (1933)

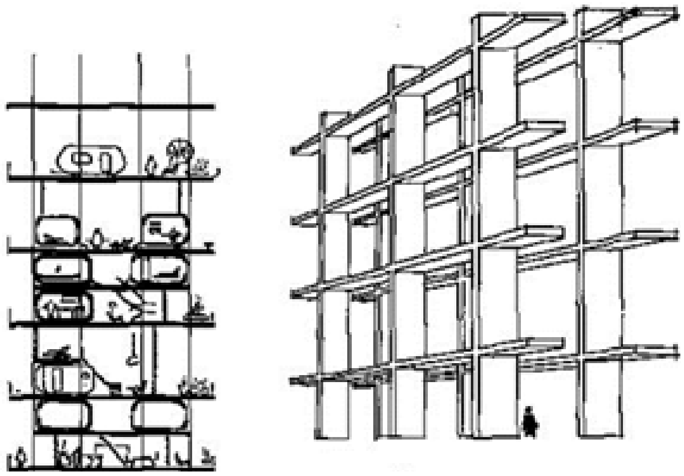


One of the most striking parts of plan Obus was the curvilinear complex of housing in the heights that was accesses the waterfront by an elevated highway, bypassing the Casbah of the city of Algiers. This residential part of the plan resembles a big open walled structure, where Le Corbusier drew different infills of housing. Although not taking the people of Algiers themselves in mind and just designing for the new business district he envisioned Algiers to be, the design and vision of plan Obus stays audacious and quite radical as a modernistic and iconic vision of the future. On the image the huge curvilinear wall is visible, with different housing units visualised in the compartments. *[Pouliot, 2011; Ackley, 2005]*

THE CITY OF ATHENS – POLYKATOIKIA (1930 -)

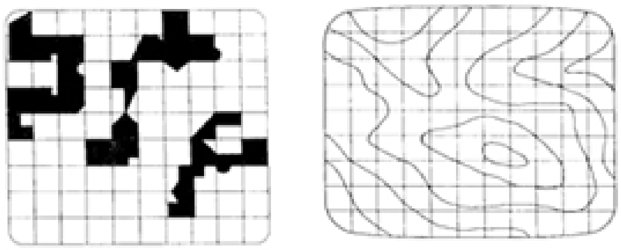
The polykatoikia's in Athens are an example, next to the Torre David and Kowloon Walled City of the "informal city". In contrast to the two, the polykatoikia is a more general accepted way of building in the city of Athens in the post-war period. The polykatoikia was originally conceived in the 1930's as a multi-storey apartment building for the Athenian bourgeouise. Specific laws allowed for a deregulation of the construction industry. Through the apparatus of the polykatoikia, the project of the city was advanced no longer through top-down master planning, but through the production of abstract legislative frameworks, which materialised in the bottom-up practice of self-building in structural frameworks. This building logic was extensively mobilised with the post-war reconstruction of Athens. Opposed the Dutch mass production of housing, the mass production in Athens limited itself to the facilitation of customized infills. *[Emmanuel, 1981; Aureli, Giudici & Issaias, 2012]*

HABRAKEN – SUPPORTS (1962)



In his first publication named Dragers dating from 1963 (English version 1972), Habraken proposes the separation of 'support' or base building from 'infill' or interior f it-out in residential construction and thereby aims to give inhabitants a meaningful and participatory role in the design process. The proposal is Habrakens view of an open, democratic society as a new conception of its physical counterform: the mass-produced public housing. Supports, his term for an interactive architecture of phenomena, thus became the descriptive and methodological basis for a rich body of architectural innovations, from participatory systems to open building, as Habraken focussed mainly on the societal and psychological impacts of his proposal, thereby facilitating the innovations later performed by his research group: the SAR. *[Habraken, 1972; Habraken, Boekholt, Thyssen & Dinjens (1976); Bosma, 2000; Lüthi & Schwarz, 2013]*

YONA FRIEDMAN – THE FLATWRITER (1971)



Friedman proposes to have user participation in the design process, as he sees that the conventional architectural design process does not fit contemporary standards. The majority of architects designing housing today do not work for millionaires, but for millions of individuals who will work or live in the architects' projects. The architect cannot study the behaviour of each user; instead, he constructs an ideal user – usually a mirror images of himself. Since he then designs for to a common standard of perfection, none of the individually imperfect users is satisfied. The Flatwriter is computer program facilitating the individual to print out his future housing preferences. He can locate his dwelling within a given infrastructure and is warned about the possible consequences of his decisions. His choices are predicated by a framework of existing stocks of prefabricated elements, service units, bathrooms and kitchen units. The user can in fact design his own house with the digital methodology Friedman proposes. *[Friedman, 1971]*

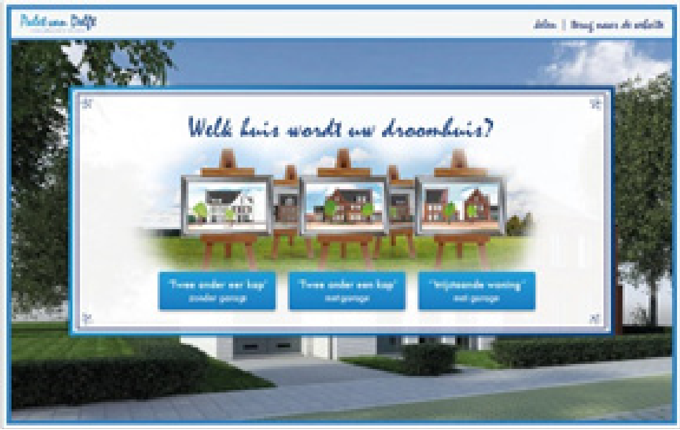
KOWLOON WALLED CITY (– 1990)

Kowloon Walled City was a densely populated, largely ungoverned settlement in Hong Kong. After the invasion of Japan in the 2^{nd} World War, China reclaimed rights to the former military fort of Kowloon. As refugees fled to the area, the city became a diplomatic no-man's land where neither the Chinese government nor the British colonial administration wanted to intervene. Between 1945 and 1990 – the date of tis demolishment, the population raised from 2,000 to 50,000 reaching a population density of 1,92 million people per km^2. The Kowloon Walled City was a closely-knit, self-sustaining community of people that actually loved their home, despite the poor living conditions. The Kowloon Walled City was an example of the result of an anarchistic architecture, where people had been given – unwillingly – complete freedom. [Girard, Lambot & Goddard, 1993]

APPENDIX III

In this appendix, a short description of the more contemporary precedents aiming for customization in housing solutions is given. It aims to give a short, general and to the point description of the literature present on the projects, aiming for a good understanding regarding the mass customization potential analysis performed in a categorization of these projects.

HOUSING CONFIGURATORS (PALET VAN DELFT, WENSWONEN (HEIJMANS), WOONMODULE (BBVH ARCHITECTS), WOONCONNECT)



A housing configurator is a customized website made for a specific residential project. Not only individual houses are possible to configure, whole neighbourhoods belong to the possibilities as well, for new built and renovation projects. Such a website contains a specific configurator where the principal clients customized information and functionality is displayed. He has control over what can be adjusted and changed.

Different housing concepts can be part of the supply, where end users can configure their house with a user-friendly interface. They can choose for instance if they would like to have an addition, dormer, conservatory and have an influence on the façade. The configurators limits itselves to these rigid choices however, where the users have no real influence on relationships between functions and actual sizes of rooms. The floor plan and volume, according to Hofman & Halman an important aspect to have influence on, are only offered in a few variations and no actual alteration on these variants offered is possible, therefore the customization is limited. *[woonconnect.nl; wenswonen.nl; woonmodule.nl]*

FENIXLOFTS

The Fenix warehouses, located opposite Hotel New York and the Rijnhaven Bridge, were built in 1922 in Katendrecht, Rotterdam. In the summer of 2013 Mei won the architect selection procedure for the design of the new volume and the redevelopment of the warehouse. A mixed programme of housing, workspaces, car park and leisure is planned for the older lower levels. On top of this Mei will design about 200 loft apartments whose occupants can arrange the interiors as they wish. The apartments can be divided both horizontally and vertically, a unique concept in the Netherlands. This individual arrangement occurs in cooperation with the architect, thereby facilitating a high quality outcome of the desired loft apartment.*[www.mei-arch.eu]*

DE HOOFDEN

It is everyone's dream to design their own dream house. De Hoofden tries to approach this dream by offering base-lofts only consisting out of an oversized space with a complete glass façade for an ultimate daylight experience, leaving room to complete design freedom. People are offered the possibility to collaborate with an architect on their dream project, or actually complete design and build their own house. People can live in ultimate freedom, within the boundaries of the oversized space given. *[dehoofden.nl]*

HERMIT HOUSE

The Hermit House collection consists out of a growing collection of 'design' units with a unique character. These units can be adjusted with several parameters within an app, keeping the main design features intact but varying in proportion. After adjusting these parameters, your own unique and individual design can be downloaded and built. Several ways are offered to realise the designs in an affordable way. From ready-to-build packages to do-it-yourself manuals, the Hermit House can be a complete DIY project or can be built for you. Adjusting these parameters is a form of a modular construction language, offering freedom of space within the design language the house contains. *[hermithouses.nl; archdaily.com]*

WIKIHOUSE

The WikiHouse is an open-source construction set with the aim to allow anyone to design, download and 'print' CNC-milled houses and components which can then be assembled with minimal formal skill and traning. The WikiHouse uses a construction language of integral wooden connections which play an important role in the structural integrity of the whole. The open-source aspect of the project has an enormous potential in letting every customer design their own house or pavilion. However, thorough constructional knowledge of the connections and limitations the system has is needed in order to be able to design your own. Thereby the system is limited to people with knowledge and know-how about the construction and the open-source aspect limits itself to quite a specific group of people. An intermediary is needed when people desire to build their house with this design grammar. *[wikihouse.cc]*

OOSTERWOLD

Within the area of Oosterwold, MVRDV proposes Freeland. Freeland is proposed as a radically liberated place where you have the right to define your own living space. Freeland celebrates individual desire: you can build whatever you want; in whatever shape you like; you decide how to use your space and how to behave. You can build a home of your dreams – a dome, a castle, or a simple prefab house. If you are happy living in a tent, that's okay too. One can call it I-Land. If you like, a software tool can help you to make your architecture and helps to realize ideas, the HouseMaker© will assist you in the design, arrangement and construction of the supplies and cost management. Freedom goes hand in hand with responsibilities as well. Of course Freeland does not exist outside law – it is not a complete anarchy. It is based on common sense: you can do whatever you want, but do not harm others. By not only developing your own plot, but also all the necessary components around it, including infrastructure, energy supply, waste disposal, water storage, and public parks, you do not only build your own home, but you also contribute to the development of your neighbourhood and your part of town.. The principle is simple: "You can do (almost) everything you want, but you have to organize everything by yourself." This gives room for (almost) all possible initiatives. *[Oey, 2012; mvrdv.nl]*

SOLIDS

A "solid" is a new highly durable and sustainable typology devised by Stadgenoot which is presented to the market as a newly built constructed shell, offering flexibility to the building's tenants to decide on the size, configuration and use of space. Tenants can rent their own plot in the base building, from where they are free to build whatever they like; varying from the scale of the utilities to the actual configuration and spatial lay-out of the building. Where the freedom is highly appreciated, people do felt 'lost' in the process of giving form to their own house as there were no basic utilities at all in the given base format. *[Wallagh, van de Riet & Crooy, 2013; Bijdendijk, 1996; architonic.com]*

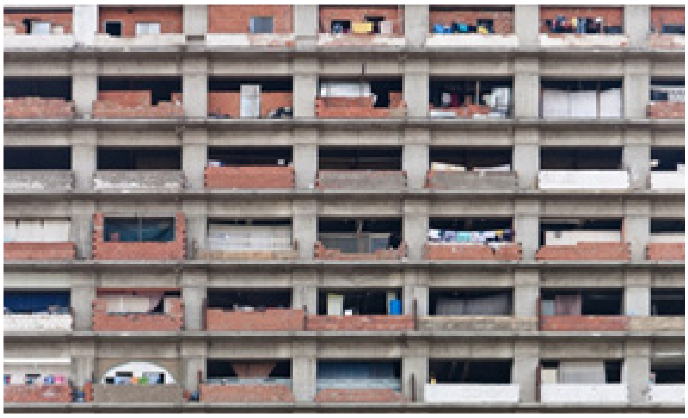
TETTERODE

Tetterode is a building that isn't finished and never will be. The building was invaded by squatters in 1981. After a long legal fight with the municipality of Amsterdam, housing association 't Oosten came up with a viable solution for both parties. Squatters were required to pay for a base rent for the building and were allowed complete freedom in what to do with the interior. The Tetterode complex is therefore a precursos to the Solids concept initiatied by Stadsgenoot (formerly known as 't Oosten). The freedom squatters like to have in designing their own living environment was projected on to the actual housing market and proved to be a success. *[Sep, 1992; Bijdendijk, 1996]*

GRUNDBAU + SIEDLER

The Grundbau + Siedler initiative by BeLassociates is a more contemporary way of giving form to the principles of the Tetterode complex and the Solids initiative. Here, the concept of base building is more dominant, as the structural shell is clearly made visible instead of the architectural exterior qualities the Solids buildings have been given. Delivered as a base building+, with basic utility features implemented, people are given a construction kit to design and build their own house. The intention here is that people can express their own living conditions to the outside, giving varying exterior appearances within the same building and thereby giving expression to the individual. The ground floor level is designed as a parking place with storage facilities for the houses. *[Bernhardt & Leeser, 2010]*

TORRE DAVID



Torre David, a 45-story office tower in Caracas designed by the distinguished Venezuelan architect Enrique Gómez, was almost complete when it was abandoned following the death of its developer, David Brillembourg, in 1993 and the collapse of the Venezuelan economy in 1994. Today, it is the improvised home of a community of more than 750 families, living in an extra-legal and tenuous occupation that some have called a vertical slum. Residents invaded the building and built their own house according to their own preferences with improvised materials and *[Lambert 2014; Caldieron, 2013; Urban Think-Tank, 2013]*

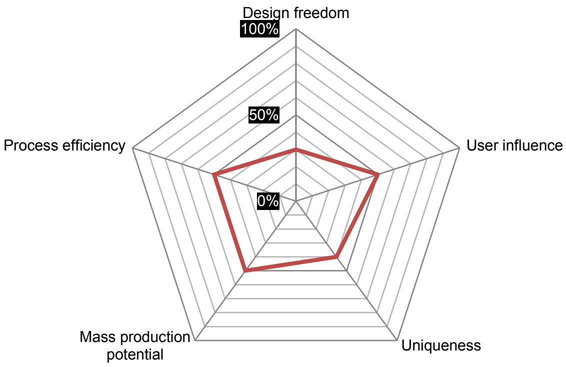
APPENDIX IV

The different aspects the projects have been analysed on are the following:

1. **Design freedom**; what are the limitations and boundaries the customization is faced with and how does this affect the design freedom of the architect or the end-user.
2. **User influence**; what is the actual influence the user has on the end result.
3. **Uniqueness**; how divergent are the different results given by the framework.
4. **Mass production potential**; in what manner is the proposed customization able to be produced in a mass production environment
5. **Process efficiency**; what are the consequences for the timeframe the project is being developed.

The values given to the different aspects are an interpretation on the knowledge gained in analysing the different projects in their process and end result. This interpretation will give an insight in the pros and cons of the several processes and the results can thereby help in determining the right process and system to be eventually used in the design proposal.

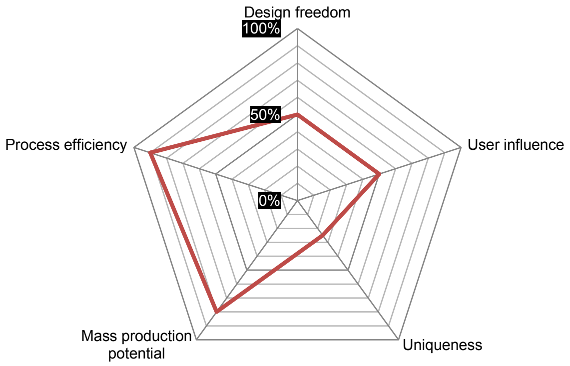
1. CLOSED ELEMENT CUSTOMIZATION



This category contains most of the housing configurators present today. People can choose from different elements; different predetermined floor plans, façade lay-outs, several additions and exterior finishes. By limiting the choice to a predetermined set of elements, the actual process can be quite efficient (examples are Wenswonen, Woonconnect, Woonmodule, Palet van Delft).

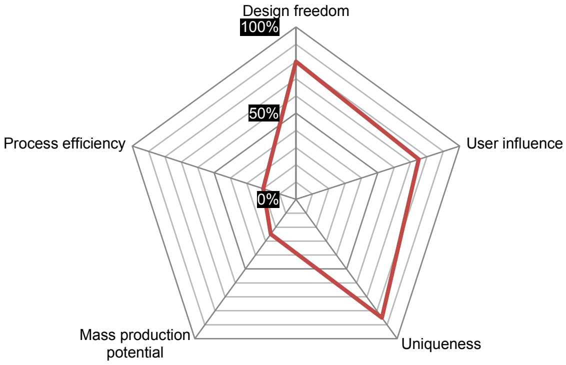
1. The design freedom is quite limited, as there are only specific elements to choose from in the configurator. The desire and wish to make certain (minor) changes to the elements as they are implemented in the configurator are not possible.
2. The user has an influence on several additions to the house and exterior appearance, although they are limited in their choice and thereby do not have an influence on the actual end result, as this is a combination of predescribed elements and thus a variation of all the possible outcomes.
3. Although there are quite a few combinations possible, the uniqueness stays limited to the choice of addition and lay-out. As a specific house is part of a larger configuration of houses, all in the same configurator, repetition will be inevitable in appearance and form.
4. In contrary to the uniqueness discussed, the limited choice offered to the client offers options for mass production. The construction being used in most of the closed element configurators is quite traditional and poses fewer opportunities for mass production of the different combined individual customizations.
5. The initial efficiency of the process is high, as clients can choose from a predetermined set of elements how their house needs to look like and therefore the design phase can be kept short. Most of the time conventional construction methods are being used and the users often need to wait until the complete project is being sold before construction begins. On top of that, the conventional construction methods pose longer building times as well.

2. CLOSED SPATIAL CUSTOMIZATION



1. The design freedom can mostly be found in the spatiality of the project, however, this spatial organization is again limited to extensive boundaries as there is quite a specific construction system present.
2. The user influence is essentially the same as in the element configurators, although the different parameters can parametrically be adjusted, giving some more flexibility in the end result.
3. Appearance and form is quite repetitive, as a certain construction system is being used.
4. As the constructional logic used is quite generic, the potential for mass production is high. The CNC method of producing poses more options to generate custom options than is being used here.
5. The process can be quite efficient, as from the moment the parameters are set by the client, a complete manual and construction drawings can be downloaded for production. The design phase can be kept short and the construction kit can either be delivered on site or milled or sawed by the user himself. Construction is done by means of self-building but the ease of construction limits the construction time drastically.

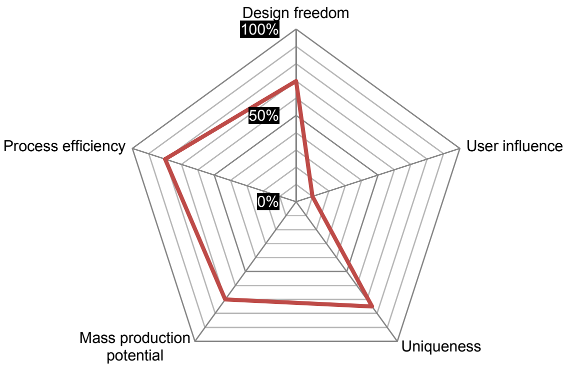
3. COLLABORATIVE CUSTOMIZATION



This type of customization is a collaborative effort between architect and end-user. Together, they determine the spatial lay-out of the house including finishes and optional additions. This type of collaboration requires time, resulting in a longer process duration. The quality of delivered work is however high, as there is generally an architect involved (examples are Fenixlofts and De Hoofden – if the end user decides to use an architect in the realisation of their loft).

1. The design freedom is high, as the architect and client together are responsible for designing the end result.
2. As the process is collaborative, the user influence is high as the user is a part of the complete design process and is only limited to the spatial framework of the plot they have bought or rented.
3. End results are unique, as they are specifically designed to the requirements of the user in collaboration with the architect.
4. As all the solutions are quite unique, the mass production potential is limited.
5. A process of collaboration from beginning to end is quite a time intensive process. The low potential for mass production means that the actual construction takes quite a time as well, thereby the process efficiency of such a customization process is generally low.

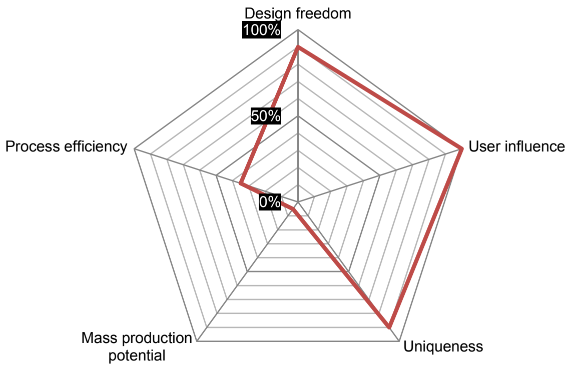
4. OPEN SOURCE CUSTOMIZATION



The open source customization focusses on a constructional framework given, where each individual is allowed to build their own configuration within the given constructional framework. There is however quite some knowledge required of construction and connections to be able to design your own house, which makes the tool limited for mass-use. If the constructional framework can be implemented automatically, the tool would work as a completely open source customization service, but the category to be analysed here focusses on the actual example of the WikiHouse, where such an implementation of construction is not (yet) made.

1. The design freedom has a high potential. As the opposed construction system proves to be highly flexible in terms of spatial organization, possibilities are nearly endless, if requirements of the constructional system are met.
2. The user influence is low, as the common end-user has no knowledge on the construction and connections required in open source construction projects as the WikiHouse. This knowledge is needed in order to be able to design a custom solution.
3. As the possibilities are nearly endless, each product could be unique. The constructional language is however commonly present in all the end products.
4. The mass production potential is generally high, as there is quite some modularity in the constructional language and the digital production methods are giving a high potential for mass production.
5. Designing can cost a lot of time, as all the connections and subdivisions need to be specifically designed per project. Once designed, the file 2 factory process is fast and efficient. The assembly can be done quite fast in relation to other processes analysed. The design phase mainly is the bottleneck, as all the connections and subdivision need to be carefully designed.

5. FREE CUSTOMIZATION



The last customization category is the free building category. This category consists of several self-build projects, where the end-users are complete free in building, designing and engineering what they want. One of the early examples of this concept is the Tetterode complex, invaded by squatters and the Polykatoikia construction in Athens. More contemporary examples are the Solids in Amsterdam and the Grundbau + Siedler proposal of BeL Associates.

1. People can do what they want, within the framework and plot size of the building they have. This self-build movement results in an almost ultimate design freedom.
2. The design freedom is given by the user influence, as they have full responsibility on the outcome.
3. Each project is made by a specific user and thereby each project results in a unique product.
4. As each project is being handled by the end users themselves, there isn't any potential in mass production.
5. Due to the fact that the users are given entire freedom, they generally also take a lot of time in designing and building their own house. They are commonly faced with unforeseen restrictions or requirements and the process from initiative to completion is, most of the time, more time and labour intensive.

APPENDIX V

PACKAGED HOUSE SYSTEM (WALTER GROPIUS & KONRAD WACHSMANN)

The “Packaged House” is an extraordinary example of a prefabricated modular construction system designed by Konrad Wachsmann and Walter Gropius. The “Packaged House” project is best known for its conceptual richness, but was never fully executed nor a commercial success. The project consisted of several designed panels, but the ingenuity of the plan was found in the X-shaped wedge connectors that linked each panel vis-à-vis a set of metal plates housed in the panel edge that proved to be the inventive, and consequently commercially noteworthy, element of the system. The wedge, which was essentially flat, replaced the standard Y-shaped connector that, because of its three dimensionality, proved harder to manufacture and easier to damage. A complete house could be assembled by means of 1 modular connector, making the assembly process fairly easy for any individual. *[Imperiale, 2012; Herbert, 1984]*

INSTANT CABIN (LARRY SASS - MIT)

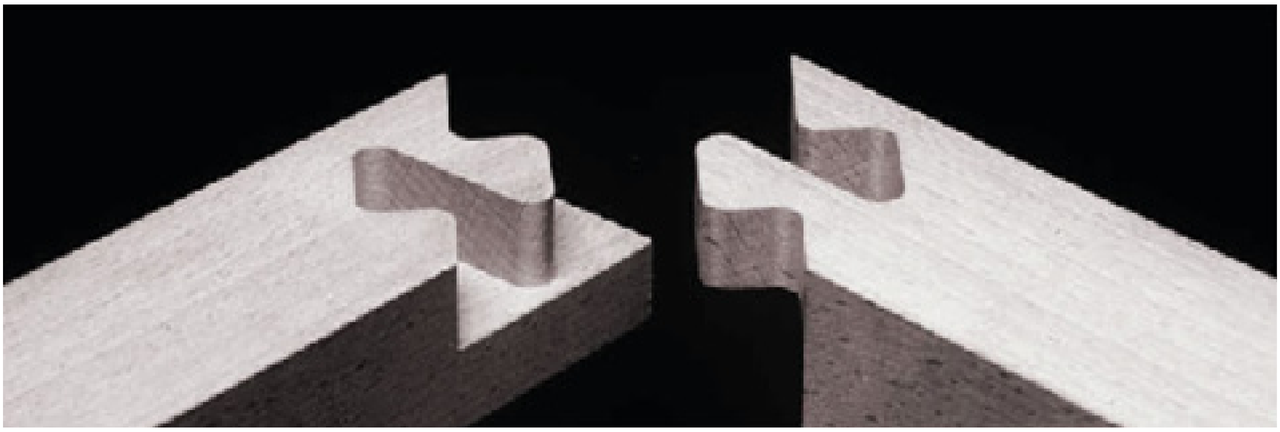
The Instant Cabin is an IKEA like house construction, mainly aimed at developing countries. The Instant Cabin is a structure prefabricated of one material (plywood) assembled with muscle and a rubber mallet. Nails, screws or glue are not needed for assembly and support. The project combines CAD technology with CNC machinery to build a complete house from computer model and raw plywood sheets with no drawings or paper documents adopted in the process. The computer is being used to convert a simple house shape into an assortment of special shapes and components complete with a number. The designer builds a computer model in 3D, flattens the objects to a horizontal position in CAD and then sends each component to a CNC router for cutting. Joinery between components is so precise that all parts can stay together by the power of friction alone. *[Sass, 2006; designinthemaking.org]*

LIINA TRANSITIONAL SHELTER (AALTO UNIVERSITY)

The Liina transitional shelter is a temporary building to be used in cold climates during crisis situations anywhere around the world. The shelter can be assembled by two adults in six hours with only common tools and a cartoon diagram. The Liina concept is based on a series of prefabricated sandwich panels that can be easily transported and assembled, and can be flatpacked into a small space. Each panel is 600 mm wide (half the dimension of a piece of plywood) to cut down on waste and to be easily carried by one adult. Six panels are joined together with simple, repeated wooden-dowelled joints to form a frame and tightened using nylon straps ('liina' in Finnish), like those used for the transportation of cargo. The strap creates air-tight joints without any metal fasteners or the use of electric-powered tools on-site. The frame is then tilted up and stacked one-by-one with the other frames and tied together with 3 straps. Finally, the building is protected from water and UV damage with a tent-like canopy. The modularity of the design makes it possible to add or subtract frames in order to increase or decrease the size of the shelter to accommodate the needs of the inhabitants. *[archdaily.com; blogs.aalto.fi]*

BAMBOO MICRO HOUSING (AFFECT-T)

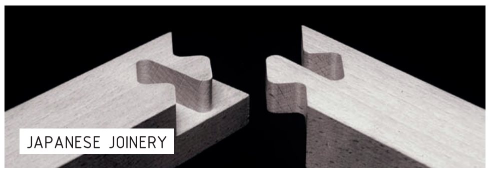
The designed micro-dwelling unit is approximately 3 meters wide by 2.5 meters long and 3.7 meters tall. The various sized units fit together to form a larger assemblage with some functioning as services for the larger communities and others as areas for communal dining, games, education, etc. The flexibility of the single unit aids in the overall adaptability of the larger community as units can be joined and easily separated and altered as the population changes. Allowing a simple in inexpensive structural system to service many different demographics of people. Built out of bamboo the house is meant to house an individual or couple and features a living area, kitchenette, bathroom, fold-out dining table, work area, and sleeping quarters. Using local materials a modular system was developed which can meet the needs of the many without housing while costing little to construct in time and money. *[affect-t.com, archdaily.com]*



There are many ways to join members together. Beams are tied with ropes, carved and assembled or connected with nails, screws and glue. In Japan, structures were erected using a unique joining method. Master jointers were dedicated craftsmen responsible for splicing and connecting elements of a building. Many factors had to be considered. The connections had to be strong enough to transfer forces such as bending, torsion and shear, yet appearance was an important factor. A variety of techniques sometimes simple, sometimes elaborate were developed. Solutions adopted took into account time dependent processes as shrinkage or slippage caused by dynamic loading. The intricacy of the internal structure of the joint is hidden by the apparent simplicity of its appearance. Various shapes connect into each other with ease. *[Kamiyama, 1989]*

APPENDIX VI

KEY DFMA PRINCIPLES

PRECEDENTS	Minimize part count	Standardized parts & materials	Modular assemblies	Efficient joining	Minimize reorientation of parts during assembly and/or machining	Simplify & reduce number of machining operations	DFMA score
 PACKAGED HOUSE SYSTEM	★★★☆☆ There are still a lot of parts present in the system, efficiency is achieved through the joining method.	★★★☆☆ Everything is factory made. Though, there are still a lot of different components present.	★★★★★ Every assembly is the same due to the fact that there is 1 joint.	★★★★★ Gropius and Wachsmann designed 1 universal connector for every joint.	★★★☆☆ Due to the fact that there are many different components, machinery and assembly is still quite labor intensive.	★★☆☆☆ The prefabrication of the parts was labour intensive.	★★★½☆
 INSTANT CABIN	★☆☆☆☆ With approximately 970 parts (including connections), there are a lot.	★★★☆☆ Parts are not standardized. The construction consists of one material, including connections.	★★★★☆ Each part has a specific structural function and is modular in use.	★★★★☆ Not the amount of connectors, but the friction-fit joining makes it efficient.	★★★☆☆ During machining no reorientation. Assembly is like a small puzzle.	★★★★★ The only machining operation is milling in 2D, so limited to 1.	★★★½☆
 LIINA TRANSITIONAL SHELTER	★★★★★ By using SIPs as a truss structure, the amount of parts is drastically minimized.	★★★★☆ The truss is modular and thereby standardized.	★★★★★ Connections are the same and occur in logical order.	★★★★☆ Just dowels, dovetails and ratchet straps act as connectors giving an airtight building.	★★★☆☆ During machining quite a lot. During assembly practically none.	★★☆☆☆ Making SIPs in the factory requires more labor.	★★★½☆
 BAMBOO MICRO HOUSING	★★☆☆☆ The bamboo and supporting structure account for a lot ofparts.	★★★☆☆ Materials are all standardized from production.	★★☆☆☆ The structures assembly can only be done as a whole.	★★★☆☆ Joining methods used are efficient but time intensive.	★☆☆☆☆ During machining, parts undergo heavy adjustments.	★★★☆☆ The bending of the bamboo straps makes the fabrication process unnecessarily complicated.	★★☆☆☆
 JAPANESE JOINERY	★★★★☆ Integrating the structural frame and joinery minimizes part count.	★★★☆☆ Standardized in production, although it needs quite some processing.	★★★★☆ The structures assembly is modular in its framework of joints.	★★★★★ The integration of structure and joinery makes for an efficient joining method, also erasing screws etc.	★★☆☆☆ The nature of the joinery requires a lot of reorientation during machinery.	★★☆☆☆ A lot of reorientation also ensures that the machining is quite time and labour intensive.	★★★☆☆