MASTER

3D concrete printing in architecture
a research on the potential benefits of 3D concrete printing in the construction of residential buildings in the Netherlands

Marijnissen, M.P.A.M.

Award date:
2016

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3D CONCRETE PRINTING IN ARCHITECTURE.
A research on the potential benefits of 3D Concrete Printing in the construction of residential buildings in the Netherlands

STUDENT
M.P.A.M. (Marjolein) Marijnissen, BSc
0740734
E-mail: marjolein.mar@gmail.com

GRADUATION COMMITTEE
Prof. Dr. Ir. B. de Vries (Design Systems)
Ir. Ing. A. van der Zee (Design Systems)
Ir. M. Willems (Architectural Engineering)

PROJECT
Digital Architecture
Architecture, Building and Planning

INSTITUTE
Eindhoven University of Technology
Department of Architecture, Building and Planning
Mailbox 513, 5600 MB Eindhoven
Tel: 31(0)40-247 3960
E-mail: secretariaat.b@bwk.tue.nl

DATE
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ABSTRACT
1. - ABSTRACT
In the 21st century a wide range of new construction methods and materials are introduced, however, with these new techniques, the boundaries in architecture and construction did not change significantly due to a deficiency in knowledge. The introduction of a new construction method or a new material should result in a new way of (thinking about) building, similar to the difference in designing with concrete or steel, the technique should have its own design language based on the knowledge about the technique. One of the new developments in architecture and construction is 3D Printing with a concrete like material. This technique can create the opportunity for personalization of large-scale residential housing for the lower and middle class of the Dutch population since it removes the restrictions on shape, that are present in the traditional way of building. By optimizing the printing process the material and labour costs can be decreased, leaving space for the personalization of the building. This process will change the design of the current house making it more structurally efficient, material optimized and customized considering user requirements.

Keywords: Additive manufacturing, 3D Concrete Printing, structural optimization, personalization
2

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2. - ACKNOWLEDGEMENTS
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INTRODUCTION

THE IMPORTANCE AND THE RESEARCH QUESTION OF THIS THESIS.
4.1. - INTRODUCTION - PROJECT MOTIVATION

Human history is often influenced by the introduction and use of new materials and technologies. […] Human civilizations are often divided into ages according to the materials that dominate in the society. For example, the Stone Age, the Bronze Age and the Iron Age. […] But with the economic growth and the progress of material science in the 21st century the evolution and application of new materials has been accelerated, resulting in a great amount of new materials but only a few people who know how the work with them.

Arroyo et. al., 2007, p.28-35

Architecture has changed radically in 20th and 21st century due to the development of materials and technologies. As stated by Kolarevic (2003) “freely form-able materials, such as concrete and plastics, have led, for example, to renewed interest into ‘blobby’ forms in the 1950s and 1960s “ (p. 48). But the biggest innovations related to new materials and production methods occurred in the 21st century supported by the computer in the form of digital fabrication. However, these new and significant developments are currently not reflected in the architecture even though they could provide a lot of benefits.

Image 4.1 shows an example of this. The house in the image is created with a concrete printer by the Chinese company WinSun in April 2014. However the house is constructed by a new and innovative technique, the house shows nothing related to this, it is just a traditional house but with a new material. The makers of this house forced a new technique and a new material into the shape of an already existing design, causing the benefits of the new technique not to be fully utilized or even not there at all.
Changes in the traditional way of building are only permitted if they are an improvement. Otherwise stay with what is traditional, for truth, even if it be hundreds of years old has a stronger inner bond with us than the lie that walks by our side.

Loos, A., 2013, p.11.

I think that techniques in architecture and structural design ask for a new way of building, with a change in traditional design, adjusted to the new technique. The main question in my graduation project will be:

How can the potential of new developments in construction methods and materials be expressed in architecture and construction in the Netherlands?

In order to answer this question I will first analyse the state of the art in new construction techniques and the current state of the Dutch built environment in order to find the proper scope of my research. This analysis will be done in the introduction of this book. Thereafter I will try to create a design language, suitable for the use of 3D Concrete Printing in architecture and construction in the Dutch built environment, considering the possibilities and impossibilities of the technique and the material. Finally this design language will be used to transform the design of the current terraced house into a new form of housing, suitable for the lower- and middle class of the Dutch population.
Architects have been drawing digitally for nearly thirty years. CAD programs have made two-dimensional drawing efficient, easy to edit and, with a little practice, simple to do. Yet for many years, as the process of making drawings steadily shifted from being analogue to digital, the design of buildings did not really reflect the change. CAD replaced drawing with parallel rule and lead pointer, but buildings looked pretty much the same. [...] It took three-dimensional-computer modelling and digital fabrication to energize design thinking and expand the boundaries of architectural form and construction.

Iwamoto, 2009, p.5

In “Translations from Drawing to Building,” Robin Evans (1997) expands on the inevitable separation architects encounter between drawing, the traditional medium of design, and building, the final outcome of their work. Digital fabrication is a process that creates a direct connection between design and construction. The disparity between drawing and building, as described by Evans, no longer exists. Drawings, created using 3D modelling software, are directly converted to an object by the use of new manufacturing processes such as laser cutting, water-jet cutting, CNC routing and 3D printing.

A clear explanation of digital fabrication and the possibilities this technique create is given by the National Centre of Competence in Research (NCCR) Digital Fabrication (2015) from the ETH Zürich:

The term “digital fabrication” means a seamless combination of digital planning with the physical fabrication process. The project data is sent to a machine, for instance a robot, and directly
implemented in reality. However, this exchange of information also works in the other direction, meaning that the physical conditions immediately influence the computer-aided designs. For architecture, this opens up possibilities that were previously undreamed of and go far beyond purely design-related aspects: new construction systems, material systems, resource-saving production, efficient yet flexible engineering and construction processes, and a transition from mass production to customised industrial production promise a decisive developmental step towards a sustainable building culture for the future.


Architects using digital fabrication no longer remain just draughtsmen, they become innovators, looking for and experimenting with new materials, new shapes and new manufacturing processes. Michael Speaks (2012) pleads for the importance of this research and calls it ‘design intelligence’. One of the unexpected consequences of the 2008 economic downturn has been that the debate over the value of architecture and design is now focused less on style and the exquisite, designed object, and more on the economic and societal value added by design. And that is because almost everyone now acknowledges that we need new design values as much as—perhaps more than—we need new designs. The most promising development, in this regard, and one that affects architecture and design practice as well as design education, is the growing recognition that design is not only a product—a table, building, plan or landscape—but is also a creative process and a powerful engine of innovation.
In contrast to the building industry the digital design and production techniques based on CAD/CAM technologies were widely adopted over the past two decades in many fields. The production of products in the automotive, aerospace, product design and shipbuilding industries was completely reinvented. As stated by Kolarevic (2001), we should look at these industries and try to learn from them how to improve the building industry. (p. 274)

3D printing is a common used application of digital fabrication. Where other digital fabrication techniques ask for post processing and knowledge of the technique, 3D printing is easy to understand and accessible. Besides that 3D printing is used for example for art, medical devices and fashion, the technique is becoming more accessible to the general public, 3D printing ‘stores’ show up in cities increasingly and designers start selling their 3D models instead of their products.

In architecture 3D printing is mostly used as a way to easily create scale models of buildings. Recently there have been some developments in 3D printing real scale buildings; the Canal House from DUS Architects as shown is one example. The printer used for this project is a FDM printer, which can print plastic elements of 2m (L) x 2m (W) x 3.5m (H). This means the printer does not print the whole house at once; it prints smaller elements that have to be assembled by hand which detracts from the concept of 3D printing.
3D Concrete printing.

An upcoming method of the 3D printing of large-scale buildings is printing with a concrete-like material. The printers used for this kind of 3D printing are not an enlargement of commonly used smaller printers but new kinds of printers, designed to print large objects. Today there multiple techniques which can create large objects, all the techniques are listed in Appendix A, in this chapter the most important techniques are described. These techniques are Contour Crafting, Concrete Printing and D-Shape.

Contour Crafting (CC), as shown in figure 4.4, is one of the oldest 3D printing techniques (Khoshnevis, 1998) The technique is based on extruding a cement-based paste against a trowel that allows a smooth surface finish created through the build up of subsequent layers. (Austin et. al., June 2011, p.263).

Concrete Printing developed by University of Loughborough is also based on the extrusion of cement mortar, however the extrusion process is more focused to retain 3-dimensional freedom with high resolution of material deposition, which allows for greater control of internal and external geometries (Austin et al., June 2011, P. 263) an example of the technique is shown in Figure 4.3.

The D-Shape process, as shown in figure 4.2, uses a powder deposition process, which is selectively hardened using a binder. Each layer of build material is laid to the desired thickness, compacted and then the nozzles mounted on a gantry frame deposit the binder where the part is to be solid. Once a part is complete it is then dug out of the loose powder bed. (Austin et. al., June 2011, p. 263)
## 4.2. - Introduction - Digital Fabrication

### Table 4.1: Properties of Large Scale 3D Printing Methods.

(Austin et. Al., June 2011)

<table>
<thead>
<tr>
<th></th>
<th>Concrete Printing</th>
<th>Contour Crafting</th>
<th>D-Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Process</strong></td>
<td>Extrusion</td>
<td>Extrusion</td>
<td>3D Printing</td>
</tr>
<tr>
<td><strong>Use of mold</strong></td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>Build material</strong></td>
<td>In-house Printable Concrete</td>
<td>Mortar mixture for mold and Cementious material for build</td>
<td>Granular material, sand/stone powder</td>
</tr>
<tr>
<td><strong>Binder</strong></td>
<td>None (Wet material extrusion)</td>
<td>None (Wet material extrusion and backfilling)</td>
<td>Chlorine-based liquid</td>
</tr>
<tr>
<td><strong>Nozzle diameter</strong></td>
<td>9-20 mm</td>
<td>15 mm</td>
<td>0.15mm</td>
</tr>
<tr>
<td><strong>Nozzle number</strong></td>
<td>1</td>
<td>1</td>
<td>6300</td>
</tr>
<tr>
<td><strong>Layer thickness</strong></td>
<td>6-25 mm</td>
<td>13 mm</td>
<td>4-6 mm</td>
</tr>
<tr>
<td><strong>Reinforcement</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>Mechanical Properties</strong></td>
<td>Tested with zero degree of layer orientation, the force was given from the top of the printed surface.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Compressive strength</strong></td>
<td>100-110MPa</td>
<td>unknown</td>
<td>235-242MPa</td>
</tr>
<tr>
<td><strong>Flexural strength</strong></td>
<td>12-13MPa</td>
<td>unknown</td>
<td>14-19MPa</td>
</tr>
<tr>
<td><strong>Print size</strong></td>
<td>&gt;1m</td>
<td>&gt;1m</td>
<td>&gt;1m</td>
</tr>
<tr>
<td><strong>Pre/Post Processing</strong></td>
<td>- Reinforcement after printing</td>
<td>- Reinforcement per 125 mm vertically</td>
<td>- Compression of the powder for next layer by a roller with light pressure prior to the deposition</td>
</tr>
<tr>
<td><strong>Pros</strong></td>
<td>-High strengths</td>
<td>Smooth surface by trowel</td>
<td>High strengths</td>
</tr>
<tr>
<td><strong>Cons</strong></td>
<td>Limited printing dimension by the printing frame, 5.4 m (L) × 4.4 m (W) × 5.4 m (H)</td>
<td>-Extra process (molding)</td>
<td>-Slow process</td>
</tr>
<tr>
<td></td>
<td>-Minimum printing process; deposition &amp; reinforcement</td>
<td>-Weak bonding between batches due to segmented backfilling batches by one hour interval</td>
<td>-Rough surface</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Limited printing dimension by the printing frame</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Massive material placement</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Removal of unused material</td>
</tr>
</tbody>
</table>
The main advantages of D-Shape are the high strengths and the fact that the unhardened sand acts as a temporary support for the layers above, because of which shapes that cannot be made by a single-material layer extrusion can be created using this technique. But the need for unhardened sand is also a huge disadvantage in my opinion. I do not see this technique being used on site, while the use of powder ask for a well regulated climate, rain and wind for example, can make the printing process impossible. Secondly, according to table 4.1. the technique asks for massive material placement, continuous compression of the sand and the removal of unused material which are both laborious and troublesome.

Both Contour Crafting and Concrete Printing do not require a powder bed; both the processes are based on extrusion, which makes them very similar at first glance. An advantage of Contour Crafting compared to Concrete Printing according to table 4.1. is the smoothness of the created surface. In contrast to the roughly layered surface, which is created using Concrete Printing, the constrain of the material extrusion within the trowel surfaces both in vertical and horizontal direction make it possible to create a smooth surface. But where the finished product of Concrete Printing is the actual object, Contour Crafting, according to table 4.1. only creates a mould which has to be filled per every 125 mm in height with a cement like material, which causes weak bonding strength and a longer production time. The only disadvantage of Concrete Printing as stated in table 4.1. are the limited printing dimensions.

At the Eindhoven University of Technology a new 3D printing technique has been developed. A
3D Concrete Printer (3D CP) with dimensions of 11m (L) x 6m (W) x 3m (H). The 3D CP has the characteristics of both Concrete Printing and Contour Crafting as the resolution of the printer can be adjusted to both techniques. In my opinion this 3D printer must be able to combine the best of both techniques and can be the most promising 3D printing technique for large scale buildings, I think this technique has the most design freedom, with the least amount of post processing and the most potential to be used on site.

**Advantages of 3D Concrete printing.**

The sustainability of traditional concrete is questionable, a lot of CO2 is emitted with the production of concrete but the raw materials of concrete are well stocked, concrete is 90% recyclable and the CO2 emissions of a concrete building in use is lower than that of other materials. (CRH Structural, 2015)

CyBe Additive Industries, a Dutch company who built their own Contour Crafting robot, created a mortar for their robot, “which produces 32% less CO2 compared to regular concrete, which makes it more environmentally friendly. In addition the mortar is completely reusable and thus greatly cuts down on waste and pollution”. (Alec, 2015) CyBe is not the only company creating a more sustainable concrete-like material for their 3D printer, WinSun, a Chinese company with a Contour Crafting printer, “uses a printing material created from recycled construction waste, industrial waste and tailings “(Starr, 2015). Another advantage, linked to the sustainability of the 3D printed concrete is the reduction of construction waste by 30 to 60 per cent.

![Figure 4.5.: Production costs. (Buswell et. al. 2006)](image)

![Figure 4.6.: Production time. (Buswell et. al. 2006)](image)
Besides the increase in sustainability, Michelle Starr (2015) also argues “a decrease in production time by between 50 and 70 per cent, and labour costs by 50 to 80 per cent.” The reduction in cost and time is also supported by Busswell et. al. (2006) as shown in figure 4.5. and figure 4.6. The reduction in costs is advantageous for both contractors and owners.

The reduction of the production time provides fewer and shorter disturbances in the direct vicinity of the location the 3D printed building or object is being built. 3D printing will also reduce nuisance by a non-traditional layout of the building site, with 3D printing, only the machine is required - maybe in combination with one or two supervisors- all traditionally used equipment which often cause inconvenience is redundant.

A more creative advantage of 3D printing is the ease with which special shapes can be made. This removes the boundaries -for example standard sizes - architects normally must abide.

Secondly 3D printing no longer means the mass production of a standard product to fit purposes, in other words one size fits all. According to Kolarevic (2003) “the technologies and methods of mass-customization allow for the creation and production of unique or similar buildings and building components, differentiated through digitally controlled variation” (p.53). Future owners of a 3D printed building can customize their building according to their own wishes without a lot of extra costs.
Figure 4.7.: Land Use in the Netherlands.
(CBS et. al., 2013, SILC 2015)
The previous chapters I have stated many advantages of 3D (concrete) printing as a construction method compared to the traditional way of building, but until now these advantages remain theories that have not yet been confirmed in reality. I think 3D Concrete Printing has a lot of potential; I think this construction method can, when used correctly, play a major part in future construction of our whole built environment.

Figure 4.7 shows the layout of the Netherlands, the centre of the chart shows the division of Dutch land in 2013 according to the CBS (in Dutch: “Centraal Bureau voor Statistiek”). The second ring shows that the built environment of the Netherlands – which covers one-seventh of the total area as visible in the first ring – consist mostly of residential buildings with 58% of the total built environment. In contrast to the rest of the world, the number one housing type in the Netherlands, according to the SILC (the EU statistics on income and living conditions) is the terraced house, as shown in the third ring of figure 5.11 According to Hulsman & Kramer (2014) all the Dutch terraced houses together have a length of ca. 16,000 kilometres. This is enough to uninterruptedly provide a road - in a straight line from Amsterdam to Beijing - on two sides with terraced houses (p.11, own translation).

In my opinion, 3D CP should be able to construct terraced housing, as the dimensions of a terraced house are not too large to be printed at once by a concrete printer. In addition the layout of a terraced house is relatively easy – compared to for example commercial buildings or apartment buildings – and because 3D CP is a new method of construction, which in itself entails
many problems, the simplicity of a terraced house provides an opportunity to focus on the translation of traditional building to building with a 3D concrete printer without further complexity. Finally, if 3D Printing will become useful in the world of architecture and construction it should be applicable on terraced housing as this type of housing forms the biggest part of the Dutch built environment.

Terraced housing in the Netherlands.

As shown in figure 4.8, the origin of the Dutch terraced house can be found in the ‘hofjes’ (best English translation: alms-houses) which were build from the fifteenth until the twentieth century in almost every Dutch city of some significance. Many ‘hofjes’ - mostly built by well-meaning rich people or churches, for poor widows and other needy who could not provide for their own housing - consist of a concatenation of identical houses around a garden.

It was until the second half of the nineteenth century, when manufacturers started building residential areas for their workers, that the terraced house became the norm for Dutch housing. In factory districts the terraced house became an important element. Terraced houses where constructed by housing corporations which were founded in the second half of the nineteenth century to build good houses for the lower incomes. In the large cities the terraced houses where build mostly outside the city limits; in the city itself the single story apartment became the predominant type. In small towns the terraced house became the dwelling type for the housing of workers. After the Second World War, terraced housing became the dwelling type for the lower- and middle-class in the entire

Figure 4.8.: Terraced housing in the Netherlands, a time line. (Pictures from Hulsman & Kramer, 2014)
In order to create a terraced house using 3D CP as the construction method, the characteristics of terraced housing have to be researched. Therefore the idea behind the design of current terraced houses should be considered rather than the actual layout of the houses. The deeper meaning of the term ‘terraced house’ should be examined and translated into the design language of the 3D CP. For example, the history of terraced housing shows this housing type often concerns saving costs - according to Gemeente Leudal (2011) the terraced house is the most inexpensive way of building - and therefore they are made in the most simple way a building could be made. This inexpensiveness is one of the adjacent characteristics of terraced housing and corresponds well with the advantages of 3D CP as this technique saves a lot of costs compared to traditional building. This is the type of characteristic that should be of concerned when creating a 3D concrete printed terraced house.
3D printing is slowly conquering the world; 3D printers are getting more accessible to the general public and industries increasingly start using the technique to improve their work. 3D printing has also shown potential in the building industry but here the innovation remains mostly a theory because of a deficiency in knowledge. The introduction of large scale 3D concrete printers in the last couple of years is a big step towards 3D printing in the building industry but because this technique is relatively young it has not proven itself yet. In my thesis I would like to investigate what the full potential of this technique is and show this by means of a design. The main question during this research will be:

*How can 3D Concrete Printing be beneficial to the construction of inexpensive, large-scale residential buildings in the Netherlands?*

In order to answer this question there are three important subjects. The first is the 3D Concrete Printer, as discussed before this construction technique has different requirements for a design than the traditional way of building; these differences have to be searched in order to create a language for designing with a 3D concrete printer in particular. This research brings me to the first sub-question for my thesis:

*Which guidelines must a design follow to fulfil the requirements of a 3D concrete printer?*

The second subject will define the characteristics of large-scale residential buildings in the Netherlands. Previously we discussed the terraced house being the number one housing type in the Netherlands. In my graduation project I would like to research this type of housing in order to find out why it is design as it is, and how this housing type will look when
3D concrete printed. The second sub-question will be:

*What are the characteristics of the meaning of the design of terraced housing in the Netherlands?*

The answer to the previous sub-question will result in a design language suitable for 3D concrete printed residential buildings. This design language will probably differ a lot from the traditional terraced house and will change the layout of the current house. The last sub-question will focus on the translation of traditional building into building with a 3D Concrete Printer.

*How does the use of 3D Concrete Printing have an influence on the design of large-scale residential buildings in the Netherlands?*

The ultimate goal of my graduation project would not just be a residential building, affordable for the lower- and middle class and completely constructed with a 3D Concrete Printer. The building also must have some architectural quality, it has to express the material it is made of; it has to be adjusted to its user(s) and it has to be produced according to all the advantages of 3D Concrete Printing. The building has to show the transformation of traditional into digital.
Figure 4.9.: Standardization of the built environment.
(Image from Orgut, 2014)
The most important thing in my graduation project is to find out what the combination of 3D Concrete Printing and terraced housing is. There are multiple concepts applicable to this combination but I think the most important concepts are low cost building and personalization.

Terraced housing in the Netherlands is designed as a cheap solution to provide relatively big and luxury housing for people with a low income. A result of this is standardisation, whole streets, or sometimes even residential areas, as visible in figure 4.9., consist of the same house. While there is a big difference in users, two young working people live in the same house as a family with 4 children. In the current built environment of the Netherlands the individual is not visible. Political, economic and architectural rules and restrictions define our built environment, which results in an anonymous and monotone landscape. The way we describe our house is something like “I live at number fifteen, the ninth house on the right.” Our house is often just defined by a number, there is not a personal characteristic by which the house can be marked as your house even though the house is considered the most valuable investment. In the house the most important moments of our lives takes place. This is why there is a need for personalization, the house should be adjusted to needs and satisfaction of the user.

We have seen that the most important reason for the anonymity of the built environment in the Netherlands is price. Building costs are a combination of material costs and labour costs (CBS, 2013). In the traditional way of building standardization was necessary to reduce the material costs of a house. Not only in design but

<table>
<thead>
<tr>
<th></th>
<th>Labour</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>House</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rent</td>
<td>35.9%</td>
<td>64.1%</td>
</tr>
<tr>
<td>Buy</td>
<td>36.1%</td>
<td>63.9%</td>
</tr>
<tr>
<td><strong>Apartment</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rent</td>
<td>34.3%</td>
<td>65.7%</td>
</tr>
<tr>
<td>Buy</td>
<td>37.5%</td>
<td>62.6%</td>
</tr>
</tbody>
</table>

Table 4.2.: Division of building costs.
(CBS, 2013)
Figure 4.10.: Concept of personalization.
also in building elements. The shape and size of the used building elements of the house are depending on standard sizes, everything that does not match these standard sizes significantly increases the price of the house. Besides the repetition of these building elements in multiple houses further decreases the costs of the house, resulting in entire streets with the same houses.

With 3D printing standardization is not necessary anymore. For a 3D printer, the material costs are only defined by the amount of used material, shape does not matter. So personalization, which often results in different shapes and sizes which can not be standardized, will not increase the material costs, and thus will not influence the construction costs of a house.

The fact that building costs are no longer depending on shape opens up the possibility for personalization of houses for the lower and middle class of the Dutch population. According to Adolf Loos (2013) this is a very important aspect in architecture.

*When it comes to your home, you are always right. No one else is right. […] Only you can furnish your home - by yourself. Only through this act does it actually become your home.***

*Loos, A. 2013, p.41*

Adolf Loos is in this quote only referring to personalization in the interior of the house, however he wrote this quote in the early 1900’s, when standardization in architecture just began to emerge. Today the need for personalization is much bigger than in that time, that’s why today personalization should not only refer to the interior of the building but to the whole building.
HOW TO PRINT WITH A 3D CONCRETE PRINTER?
5.1. - PRINTING LOGIC - MATERIALITY

The importance of material.

The character of the architectural space depends on how things are done and for that reason it is determined by the technical realization and by the structural composition of the substances and building materials used [...] under a surface lies a hidden secret, which means the surface depends on a concealed structure which existed before the surface, which created the surface and in a certain way the surface is a plane imprint of this structure.

Deplazes, 2008, p.19

It is impossible to remake the texture of a brick wall with wood, or copy a steel bridge (figure 5.1.) using only concrete (figure 5.2.). The characteristics of a material, both structural and aesthetic, are unique for every material and determine how a material can and should be used. Gottfried Semper (2004) supports this importance of material with his ‘Stoffwechsel’ (in English: change of material) theories.

When an artistic motive undergoes any kind of material treatment, its original type will be modified; it will receive, so to speak, a specific colouring. The type is no longer in its primary stage of development but has undergone a more or less pronounced metamorphosis.

Semper, 2004, p.250

3D Printed concrete.

3D printed concrete, as shown in figure 5.3., can be seen as a new material while the structural and aesthetic characteristics of this material do not match with those of other, already existing...
materials. This means, the possibilities and limitations of the 3D concrete printer and its material have to be taken into account in order to create a suitable design. But because 3D Concrete Printing is a relatively young method of building, research on the possibilities and limitations is still on-going and the full potential of the construction method is still unexplored.

Corners, for example, are a very interesting part of a 3D printed object. In contrast to the traditional way of building, in which 90-degree angled corners are commonly used, with 3D CP they are not as easy. As shown in figure 5.3, a normal 90-degree angle results in a strange ‘flip’ at the corners. The difficulty originates from the fact that ideally the printer follows a continuous motion, but at a corner the printer has to stop moving in one direction, rotate 90 degrees around its z-axis and accelerate in the other direction. Besides the nozzle of the printer should rotate 90 degrees in the corner to provide an extrusion of concrete in an equal direction before and after the corner. If one of these thing is not done, printing will result in a strange flip in the concrete or a thick corner with too much concrete.

As shown in figure 5.4, a solution to this can be a rounded corner, in which the printer has enough space to perform all the steps as described above. The interesting thing is that this type of corner would be difficult to make with the traditional way of building and thus shows a big difference between traditional building and building with a 3D concrete Printer.
Figure 5.5.: Forces inside the structure of a Gothic church.
For the printing process, a custom concrete mix was developed by SG Weber Beamix. The mortar is comprised of Portland cement (CEM I 52,5 R), siliceous aggregate, limestone filler and specific additives for ease of pumping, the rheology. The first printing and material tests with the 3D Concrete Printer showed that despite the difference between the concrete used for the printing process and traditional concrete, the basic characteristics are similar for both materials. One of these characteristics is the materials strength. As shown in figure 5.6., traditional concrete has a relatively high compression strength and a low tensile strength, these characteristics are similar for 3D printed concrete.

Since the design should be based on the characteristics of the used material, the strength of the concrete will form the first design guideline. The characteristics of the materials strength refer to a kind of Gothic architecture, like churches (figure 5.5.) and aqueducts which were built with stone or concrete and have a shape that is adjusted to handling compression forces. The way the forces are dealt with in this type of architecture will form the first design guideline for building with a 3D Concrete Printer as the concrete used for printing is unreinforced concrete, and thus without any tensile strength.

<table>
<thead>
<tr>
<th></th>
<th>Concrete compression strength</th>
<th>Concrete tensile strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>B45</td>
<td>27</td>
<td>1.6</td>
</tr>
<tr>
<td>B85</td>
<td>50</td>
<td>2.4</td>
</tr>
<tr>
<td>B115</td>
<td>64</td>
<td>2.7</td>
</tr>
<tr>
<td>B200</td>
<td>120</td>
<td>4.5</td>
</tr>
<tr>
<td>2.5% steel fibers</td>
<td>120</td>
<td>8</td>
</tr>
<tr>
<td>B200 1% steel/2% PVA fibers</td>
<td>120</td>
<td>10</td>
</tr>
</tbody>
</table>

**Figure 5.6.: Concrete strength properties.**

(Ultra Hoge Sterkte Beton, 2016)
5.2. - PRINTING LOGIC - THE PRINTER

**Figure 5.7.** Kuka robot used for 3D printing plastic and carbon fibres. (Cigaineiro, 2015)

**Figure 5.8.** Concrete column. (Amalgamma, 2015)

**Figure 5.9.** Plastic and carbon fibre printed structure. (Cigaineiro, 2015)
Importance of the printer.

Designing based on the structural characteristics of the concrete resulted in a copy of Gothic architecture in which the capabilities of the 3D Concrete Printer are not considered. Looking at other 3D printing projects it became clear that the combination of material and printer should determine what a printer can and cannot print.

For example, the robot in figure 5.7. is well suited to print the structure in both figure 5.8 and figure 5.9, because the robot can prints both plastic and concrete in x, y and z axis, however due to material properties of the plastic the robot can print in z axis without any support to print free form lattice structure. However with concrete, even though the robot kinematics allow for the tool-path to form lattice structure, the material properties do not allow printing of lattice structures without scaffolds or supporting material. Thus in case of concrete the robot deposits layers in x and y axis and gradually deposits layers over one another to form 3-dimentional stuctures in the z-axis.

This is also visible in the two projects with the difference in print path. The concrete column is printed with a solid 2 dimensional print path, while the plastic and carbon fibre structure is printed according to a more open and 3 dimensional print path.

This print path is what makes a 3D printed object unique and in this print path the possibilities of the material and the printer are incorporated.
5.2. - PRINTING LOGIC - THE PRINTER

Printer kinematics.

In order to find out how to print with the 3D Concrete Printer at the Technical University in Eindhoven it is important to understand how the printer works. A short explanation about the printer and the printing process is given by Bos et. al. accompanied by figure 5.11.

Concrete is mixed with water and pumped into a hose by a mixer-pump located on the side of the set-up. The hose is connected to the printer head situated at the end of the vertical arm of a motion-controlled 4 degree-of-freedom gantry robot. [...] Under the pressure of the pump, the concrete is forced towards the printer head an element consisting of several parts allowing the concrete to be printed at the desired location, at the desired speed, and under the desired angle. The end part of the printer head is the nozzle, a hollow steel element with a designated section from which the concrete filament leaves the printer and is deposited on the print surface.

Bos et. al. 2016, p. 4

The most important aspect about this explanation is the fact that the printer has 4 degrees of freedom, i.e. it can move in the x-axis, y-axis, z-axis and can additionally rotate around the c-axis at the tip of z-axis. This fact determines how the printer can move, and determines the range of motion within the printing bed, which influences to possibilities of the printer.
G-Code.

The 3D Concrete Printer is controlled by a G-code. G-code is the common name for the most widely used numerical control (NC) programming language. G-code is a language in which machine kinematics are defined. The “how” is defined by instructions on where to move, how fast to move, and which path to move on. The most common situation is that, within a machine tool, a cutting tool is moved according to these instructions through a tool-path and cuts away material to leave only the finished work piece. The same concept also extends to non-cutting tools such as forming or burnishing tools, photoplotting, additive methods such as 3D printing, and measuring instruments. (Saikrishna, M. et. al. 2016, p.348)

A G-code consists of G-codes and M-codes. The most important functions of G-codes, or preparatory functions, as explained by G.E. Thyer (1991, p.298) are G1 which causes the control system to operate in a linear interpolation mode. G2 will result in a movement in a clockwise direction around a circular arc and G3, this code is similar to G2 except that the movement is in a counter-clockwise direction.

Two other important g-codes are G90 and G91. G90 means the program uses absolute coordinates, while G91 uses relative coordinates. With the 3D Concrete Printer mostly G91 is used.

Besides G-codes there are also M-codes or miscellaneous functions. M-codes are usually specific for the machine. The most important M-codes of the 3D Concrete Printer are M50, this code stops the pumping of concrete and M51 which starts the pumping of concrete. Besides
5.2. - PRINTING LOGIC - THE PRINTER

G90 ; set to absolute coordinates

X Y Z ; move to absolute point with coordinate (x,y,z)

M50 ; start the concrete pump

G91 ; switch to relative coordinates

G1 X Y Z ; move with distance x, y, z, from the current point

G2 X Y Z I J C ; Move with a clockwise circular arc to a point with distance x,y,z from the current point around the point with a distance I, J, from the current point and rotate the nozzle c degrees

G3 X Y Z I J C ; Move with a counter - clockwise circular arc to a point with distance x,y,z around the point with a distance I, J, from the current point and rotate the nozzle c degrees

B-SPLINE ; Create a spline through the list of x,y, z, distances.
X Y Z
X Y Z
X Y Z
X Y Z
X Y Z

G90 ; switch to absolute coordinates

G1 X Y Z ; move the absolute coordinate (x,y,z)

M51 ; stop pumping

M30 ; stop the script.
; one empty line behind is necessary

Figure 5.15.: Example of a g-code.
M30 is an important M-code, this will end the script and needs to be on the end of every script in order for it to run.

An other important function in the G-code of the 3D concrete Printer is the command A, B or C-SPLINE. This command will create a spline through a given list of points, which makes it possible to print every shape by just dividing it intro smaller parts and exporting the coordinates of the points to the G-code.

A basic example of a G-code suitable for the 3D Concrete Printer is visible in figure 5.15.
Figure 5.16.: Different possible infills for 3D printing.
Stability of the printed object.

In other 3D printing processes the printed object consists of a boundary shape and an infill which makes the object strong and stable. A print path is a combination of the boundary of the object and an infill for this boundary. The infill is supposed to give strength and stability to the boundary and is necessary for a good print. Until now the tests with the 3D Concrete Printer are confined to just the printing of boundaries which results in a structurally unstable print and a reduction in the possibilities of the printer.

The addition of an infill for the 3D printed boundaries should increase the possibilities of the printer. There are different patterns suitable to create an infill for 3D printing, all with different advantages and disadvantages. The most common used pattern for 3D printing infills is the honeycomb pattern, this is because it was proven in 1998 by Thomas Callister Hales (2000) that the honeycomb pattern uses the least possible amount of material. Besides, the honeycomb pattern only consist of angles of 120 degrees, which are easy to print with the 3D Concrete Printer, as obtuse angles are easier to print compared to acute angles. The honeycomb pattern thus forms the first pattern to be used as an infill for 3D Concrete Printing.

In the next few pages different infills will be discussed, not all of these patterns are actual printed. The goal here was to create a script using Grasshopper and Python which can create an infill for every possible shape and the actual usability of the each pattern can be investigated.
5.3. - PRINTING LOGIC - PRINT PATH

The honeycomb infill.

The goal is to create one continuous path, with a honeycomb infill, suitable for all kinds of shapes and adjustable to different structural needs.

However, even though this goal can be achieved with the honeycomb pattern, the pattern is not suitable for the 3D Concrete Printer. The pattern does not allow enough freedom in scale and it is hard to create a solid construction with this pattern. Besides the pattern either does not fit in complex shapes or becomes really messy as visible in figure 5.18.
Figure 5.18.: Honeycomb pattern as infill for different boundaries.
5.3. - PRINTING LOGIC - PRINT PATH

The maze pattern.

The second pattern is a completely solid infill. In this pattern variations in size are possible without the print path becoming messy, since one direction of the print path is always on the same grid.

A disadvantage of this pattern is the fact that it has a lot of right (90 degrees) angled corners, which remain a problem with the 3D Concrete Printer. Besides, the pattern is based on multiple directions, which makes the printed object structurally heterogeneous.

As mentioned earlier, with this pattern the elements have to be completely filled, this restricts the possibility for material optimization which also acts as a big disadvantage. The biggest advantage of 3D printing is material optimization, and since the restrictions in pattern does not allow for this, the advantages of 3D printing will not be properly used with this pattern.
Figure 5.20.: Maze pattern as infill for a boundary and different scales.
Figure 5.21.: Different directions for use of 3D print structure.
During the ongoing printing tests with the 3D Concrete Printer a new 3D print structure was created which can lead to an increase in structural capabilities of the printed object and can also contribute to material optimization.

The 3D print structure, as visible in figure 5.22., is created when the printer moves at a slow speed, high above the printing object. This causes the extruded concrete to curl up before it touches the printing base or the previous layer. These curls have the potential to increase the strength of the printed concrete. However the direction in which the 3D printing structure is used has a big influence on the strength of the concrete.

The printed structure can be used in three directions, the first is the print direction in which the 3D print structure does not have a lot of influence on the structural capabilities of the concrete. In the second direction the 3D printing structure is rotated 90 degrees along the axis parallel to the 3D print structure which will significantly increase the capabilities of the concrete. For the third direction the structure is rotated 90 degrees along the axis perpendicular to the 3D printing structure which will decrease the structural capabilities of the concrete.

Because the second direction creates the best structural capabilities this direction was used in further research on the print path. This causes the fact that direction and orientation become really important in the project in order to create an structurally homogeneous object with the best possible structural characteristics.
5.3. - PRINTING LOGIC - PRINT PATH

Figure 5.23.: Elevation of 3D print structure, why flat layer is needed.
Although the found 3D print structure opens up a lot of possibilities for the structural characteristics of the 3D printed concrete, the structure also contains some disadvantages.

The main problem with the structure is that it is unstable while printed, due to the dormant state of the concrete. This makes the deposited material unpredictable, the printing variables determine certain aspects of the structure, like size and height of the printed filament layer, but the actual geometry and location of material deposition of the 3D print structure is not predictable. As a result of this it is not possible to create a print path in which the 3D printed structure of one layer is placed exactly on top of the previous layer, which can lead to a messy and heterogeneous structure for which the structural characteristics are unpredictable.

In order to solve this instability in the material geometry of the 3D print structure, an extra flat layer is printed after each layer that contains the 3D print structure. In this way the 3D printed structure always connects with this layer, and is always placed on top of the previous flat layer, making the structure predictable and more homogeneous in structural characteristics.
5.3. - PRINTING LOGIC - PRINT PATH

The linear pattern.

The final print path is based on one direction to create a 3D printed object which has uniform structural performances and is based on the capabilities of the 3D printer and its material properties. Besides, the amount of corners is reduced with this print path to decrease the amount of changes in direction which decrease the precision of the printer.

A disadvantage of this print path is that it does not allow variation. However, the 3D print structure as described before is adjustable with change in speed and nozzle height of the printer and will result in a variation as shown in the right of figure 5.26. An advantage to the fact that variation is not achieved by variation in print path but by the 3D print structure is that the variation does not increasing complexity of the print path.

Figure 5.26.: Linear pattern.
Figure 5.27.: Linear pattern as infill for different boundaries.
5.3. PRINTING LOGIC - PRINT PATH

Figure 5.28.: Printing process according to print path.
The print path.

The created print path results in a printing process which is visible in figure 5.28. The first step is the rotation of the object that has to be printed, with 90 degrees, this is to ensure that the 3D structure, which will be printed, will match the direction of the best structural performance.

This rotated object is divided into alternate layers of 10mm and 30 mm layer height. On these layers the print path is created. This information will be exported into a G-code for the 3D Concrete Printer.

The 3D Concrete Printer follows this G-code and alternatively prints a 3D curled-up layer along with a flat layer. As printing the 3D print structure along the height of the layer will decrease the structural capabilities of the concrete, a normal, flat, layer will be printed in this direction, because the 3D curled layer is three times the height of the normal flat layer i.e. 30mm, the normal flat layer needs to be printed 3 times, i.e. 3X10mm, to match the height.

After the complete object is printed according to this logic and the concrete is hardened, the object can be rotated 90 degrees and used structurally in the rotated side. The final object is visible in figure 5.29.
5.3. - PRINTING LOGIC - PRINT PATH

Figure 5.30.: Chair according to print path.
Use of the print path.

This logic of 3D printing with alternative layers is applied on a chair design, to investigate the printing capabilities with this print path as well as structural performance of the element with this logic. A chair being a smaller object and yet requires enough structural capabilities according to its size to perform its function, it is easier to test various logics with a chair design. If a design logic works with significant printing and structural capabilities, it can be scaled up to be applied in a building scale.

The images on the left shows the designed chair according to the applied print path logic. First the chair is printed on the side, and then flipped 90 degrees so that the layers are in direction of seating area, on which the seating load will be applied on the chair when a person sits on the chair.

This logics also helps to avoid any scaffolds required to print the legs of the chair. As, if the chair would be printed in the direction of seating, to print the seating area a scaffold needs to be printed first to act as the printing bed or there cannot be any material scooped out from underneath the seating area. Which would be a wastage of material, as structurally it would not be required and would increase the weight of the chair.
5.4. - PRINTING LOGIC - MATERIAL REDUCTION

Building method:

Traditional building  
Contour Crafting  
3D Concrete Printing

Elevation - front view:

Section - top view:

MATERIAL USE:

100% Elevation  
100% Section  
100% Total

100% Elevation  
50% Section  
75% Total

50% Elevation  
50% Section  
50% Total

Figure 5.34.: Advantages of 3D concrete printing related to material use.
Need for optimization.

An important aspect of the concept of this project is the fact that the created house should be affordable and thus the building costs should be low. Building costs are a combination of labour costs and material costs. We have seen that the most expensive part of the building costs is the material and more specifically, in this type of project, the amount of used material.

Material costs can be reduced by structural optimization. Figure 5.34. shows that this optimization can lead to a reduction of the used material of up to 50% compared to traditional building. A part of this percentage is based on the 3D printing structure, an other part is based on the reduction in used material in the horizontal section of the building, the inside of the walls, which does not have to be solid anymore but can be adjusted to the structural needs. The final part of the material reduction is caused by the possibility to optimize the elevation of the wall, to remove the unnecessary material.

This combination of optimization of the used material should play an important role in the further design of the chair and finally the house as well. This chapter will mostly focus on the structural optimization of the elements, which may be a chair or an element of the house like for example wall, column, etc.
Figure 5.35.: Different types of structural optimization.
(Based on illustration of Christensen & Klarbring, 2009, p.p.5-6)
Structural optimization.

A structure in mechanics is defined by J.E. Gordon (1978, p.17) as “any assemblage of materials which is intended to sustain loads.” Structural optimization is the subject of making an assemblage of materials to sustain loads in the best way. (P.W. Christensen and A. Klarbring, 2009, p.1). The term “the best way” is a broad concept, in this case however it refers to the optimization of the material distribution in a structural element.

There are three types of structural optimization, sizing optimization, shape optimization and topology optimization. P.W. Christensen and A. Klarbring (2009, pp. 5-6.) explain these types of optimization as follows. Sizing optimization is based on optimizing the cross-sectional areas of truss members. Shape optimization is based on describing the shape of a beam-like structure. Topology optimization is based on material removing by letting cross sectional areas take the value zero.

Because the resolution of the 3D Concrete Printer is well suitable for topology optimization, this will be the technique used for the further reduction of the material costs by the printing logic.

The purpose of topology optimization is to find the optimal lay-out of a structure within a specified region. The only known quantities in the problem are the applied loads, the possible support conditions, the volume of the structure to be constructed and the possible some additional design restrictions such as the location and size of prescribed holes or solid areas.

5.4. - PRINTING LOGIC - MATERIAL REDUCTION

Figure 5.36.: General layout of a grasshopper script with Millipede for topology optimization.
With traditional subtractive manufacturing of casting in mould and scooping out materials with CNC. The principles of topology optimization was difficult to apply for manufacturing. However with additive manufacturing with 3D printing, material deposition according to topology optimization is relatively easier to apply. As the areas of the elements which do not require materials can be left out without depositing any materials and printing the remaining structure according to structural performance.

In order to structurally optimize a geometry, a structural optimization plug-in called millipede is used. Millipede is a structural analysis and optimization component for Grasshopper. As explained by Michalatos (2016) Millipede allows for very fast linear elastic analysis of frame and shell elements in 3D, 2D plate elements for in plane forces, and 3D volumetric elements. All systems can be optimized using built in topology optimization methods and have their results extracted and visualized in a variety of ways.

The scripts starts with the input of the structural data. In this case the structural data consists of a bounding box of the geometry, load conditions and support conditions. After the software receives this input the software combines this into one structural model, which is called a Topostruct 3D model, or FE in figure 5.36.

This structural diagram is discredited. The bounding box and the load and support conditions are divided according to a grid, defined by the amount of divisions in x direction,
5.4. - PRINTING LOGIC - MATERIAL REDUCTION

Figure 5.37.: The topostruct 3D solver of Millipede.
which is the input for this step.

In the next step this structural model is the topostruct 3D solver, as visible in figure 5.37. This function is used for structural calculations. Important parameters in this step are the amount of steps, the amount of smoothing and the density goal. The amount of steps determines the amount of calculations done while running the script once. The density goal determines how dense the structure should be, giving this a low value will result in a slim structure while a high value will result in a heavy structure. And the amount of smoothing determines the smoothness of the final outcome.

After this calculations the outcome of the optimization becomes visible. The last input parameter is the density of the outcome, a slider that determines what percentage of the material of the bounding box will be visible in the final geometry.

The second last step, the calculation step is the most important one and determines the actual outcome of the optimization. This step needs to be repeated several times, determine on the amount of steps, to create the best end result.
Optimization iterations.

An interesting question relating to structural optimization is when to stop optimizing. As visible in figure 5.39, there are two variables related to this question, the amount of iterations and the percentages of removed material.

In order to create a well optimized structure the amount of iterations should be increased until there is no change in the (structural) geometry with a further increase in steps. After this amount of steps is reached the amount of material should be set to about 50 percent of the total material, since this is the basic goal of topology optimization.

However, beside the structural logic of optimization, the aesthetics should also be taken into account. If 45 or 55 percent material use creates a more interesting geometry this percentage should be chosen instead of the structurally desired 50 percent. The chosen percentage can not derogate too much of the 50 percent as this will result in a structural incorrect geometry or the use of too much material.

Figure 5.38.: Chair optimization, difference in step count and percentage of material.
12 steps 70%
20 steps 70%
28 steps 70%
28 steps 70%
28 steps 50%
28 steps 30%
5.4. - PRINTER LOGIC - MATERIAL REDUCTION

Figure 5.39.: Differences in 3D print structure.
Optimization of the print path.

We have seen previously that variation in print path is controlled by the variation in 3D printing structure. This variation can increase the material reduction in the printed object. Different options of print geometries are possible by a change in printing speed, printing height and rotational angle of the nozzle, without having complex print paths. This gives the flexibility to vary the geometry of the deposited material within the same element based on material requirements without altering the print path mid way through the prints.

By playing with print speed, print height and angle of nozzle various intricate designs can be printed which are aesthetically appealing and have high structural performance with material optimization. In the figures 5.40. and 5.41. multiple examples of the printed 3D structure are visible. However, these are just a small percentage of the total possibilities. Every small change in printer settings will change the way in which the material is deposited slightly.

The enormous amount of possible variations in 3D printing structure allow the adjustment of material use per location in the print path and thus contributes to the reduction of material use in the printed object. The 3D printing structure itself can reduce the used material up to 25% compared to a print using only flat layers. This percentage can be increased even more when the 3D printing structure is adjusted to the structural needs of the object.
Figure 5.41.: Adjusting the 3D print structure to the structural situation of the object.
In order to increase the percentage of material reduction by adjusting the 3D print structure, the structural data, found during the optimization process, will be linked to the print path in the form of the print speed.

Structural optimization calculates the forces inside the whole structure and removes the material without any significant forces. Due to structural optimization the forces inside the resulting geometry are calculated as well. These forces will be linked to the script of the print path. On every point on the print path the script can find the forces on that point and compare it with the data in the other points and adjust the 3D print structure to the needed amount of material by changing the speed of the printer.

This way the material used in the print path will be minimized, on places where the structure has a lot of forces, the 3D printed structure will be dense while the density will decrease if the forces of the structure will decrease.
The printing logic.

The complete printing process of the 3D Concrete Printer is now determined and visible in figure 5.43. The first step in the process is the structural diagram which includes the bounding box of the chair with load and support conditions. This for the input for the optimization with Millipede which will create an optimized shape of the chair. The optimized shape will be rotated 90 degrees to create the print path. The print path is created as described before in the print path subject with alternating layer of 10 and 30 mm. Additionally the print path takes the forces in the structure into account, so the speed of the printer is continuously adjusted to needed material. Finally the print path is converted into a G-code and printed. Once the concrete is hardened the chair can be rotated 90 degrees and used.

Figure 5.42.: 3D Concrete Printing process.
Figure 5.43.: The design optimized chair.
Final design of the chair.

The structural optimization of a printed geometry will have a huge impact on design. According to the design of the chair this impact becomes visible.

The differences between the chair on page 64 and the chair on the left in figure 5.43. is purely due to structural optimization. The bounding box, i.e. the starting geometry of the chair on the left is exactly the same as the chair on page 64. However due to structural optimization, the material used on the chair on the left is only about 50% of the chair on page 64 while this reduction of material does not have a negative influence on the structural capabilities of the chair.
6 3D CONCRETE PRINTING

WHICH GUIDELINES MUST A DESIGN MEET TO FULFIL THE REQUIREMENTS OF A 3D CONCRETE PRINTER?
Figure 6.1.: Different structural conditions and their optimized geometry.
Topology optimization in a building.

We have seen how structural optimization can influence the design of a chair by decreasing the amount of used material and thus reducing the material costs of the object.

The same process can be applied in a building scale to reduce material cost in the same way as done with the design of the chair. But additionally with the design of a building, other building elements like windows, doors and stairs, should also be taken into account.

On the left, in figure 6.1. the influence of the structural diagram on the optimized design of a wall is visible. The figure shows that the structural diagram used for topology optimization determines the shape of the wall, a difference in structural diagram results in an appreciable change in design.
On the right, in figure 6.2, the influence of the structural diagram of a building element, a wall in this case, on the design of the optimized structure is visible. This influence should be taken into account while designing the building. The structural diagram should provide an optimized structure that is adjusted to the required design of the building element.

In other words, the structural optimized element should be related to other building elements like windows and doors. The location of these building elements can never be overlapping with the optimized structure and the optimized structure can never be on the location of another building element. In order to do this the structural diagram should be adjusted to the desired design.
Figure 6.3.: Different possible divisions in building elements.
Labour reduction.

Besides material costs, the costs for labour also need to be reduced, this can be done by a smart division in building elements.

Where one room in traditional building is mostly made out of 6 elements, the walls, the ceiling and the floor as visible in the top of figure 6.3. It should be possible to reduce this number to 2 with 3D Concrete Printing.

This can be done by dividing and printing the room into two halves and flipping them in position. Each part is printed flat, with the front wall and the back wall printed first. Then the roof, floor and two adjacent side walls are printed on top of the flat façades. With this strategy of printing no supporting scaffold is required to print the roof. And the opening in the building as well can be printed along in the X-Y axis rather using printing it in the Z-axis with support scaffold. Different steps involved in printing with this strategy is illustrated in the bottom of figure 6.3.

A interesting design guideline that comes with this printing concept is the fact that every wall in one direction of the building results in an extra printing part.
Rotation 1.

With the current setup for 3D Concrete Printing in TU/e, a gantry robot which has 4 degrees of freedom (x,y,z and an additional rotational axis c) is used. When the printer is moving in x-axis the motors of the other two axes are not being used so they are in rest mode, and when the printer moves to another axis y-axis or z-axis, the motor needs to start from zero. This causes a slight delay of micro seconds in synchronization of robot kinematics with extrusion speed of the concrete out of the nozzle. To avoid this everything should be printed with a small angle of rotation. This makes sure that the printer will never be moving only x, y, or z direction but will always move in at least two directions, which will increase the precision of the printer.

Rotation 2.

In order to maximize the structural capabilities of the printed concrete, the 3D printed structure should be rotated 90 degrees around the axis parallel to the curls of the 3D print structure. This results in a new way of designing the building, even though the building should be designed for the use direction, during the design process the building should also be considered in the printing direction, as this direction determines the print-ability of the building.
Motor X on, Y off

Stop motor X, start motor Y

Motor X off, Y on

Motor X on, Y on

Motor X on, Y on

Figure 6.4.: Advantages of rotation of the object.

Figure 6.5.: The concept of rotating the printed geometry.
Linear pattern.

The structural print path should be linear and based on only on the direction in the middle of figure 6.6. To guarantee a homogeneous structure with the highest possible structural capabilities. An additional advantage of this logic is the fact that the amount of corners can be reduced which increases the precession of the printer.

Material in the other direction should not contain the 3D structure but should consist of a flat layer of concrete, because the use of the 3D structure in this direction will result in a decrease in structural capabilities of the concrete.

Base of the print part.

For the object in figure 6.7. to be used in the direction placed it is important to note that, since the object needs to be printed in while rotated 90 degrees for structural stability, this logic cannot be applied in this case as there is no flat plane for the object to be printed on. In absence of the flat plane, while printing the object as shown in figure 6.7. it would be unstable and would result in a failed print.

However the object can be divided diagonally in two halves and printed along its diagonal, so that it has a flat base to be printed as shown in figure 6.8. and once printed can be attached and flipped 90 degrees to be used along the direction of structural stability.
Figure 6.6.: Different possible directions to use the printed object.

Figure 6.7.: Not printable geometry.

Figure 6.8.: Printable geometry.
Cantilevers.

While printing elements which have a degree of cantilevering, it should be considered that while printing, the concrete filaments being in its dormant state cannot be cantilevered to huge angles as it may not be able to support its weight and may collapse. Thus considering this limitation of this property of concrete, with experiments on printing cantilevering layers with the 3D Concrete Printer it has been noted that the maximum allowable angle for cantilevering should not be more then 30 degrees as shown in figure 6.9. and 6.10.

Another point to be considered is, the cantilevering is more suitable along the printing direction as there would be a supporting layer underneath the extruded concrete to support the cantilevered geometry as shown in figure 6.10. However while cantilevering perpendicular to the printing direction, there would not be enough surface of the layer to support itself, cantilevering as shown in figure the middle image of figure 6.10. would result in a collapse of the printed layer.
Figure 6.10.: Overview of Cantilevers.
Print parts.

If the direction of the rotation for printing is along the x-axis, then every wall in the x direction would double the number of printed parts. As shown in figure 6.11, for a simple cuboid house which is placed along the y-axis, every wall in the x direction would divide the cuboid in two halves to be printed and attached together. However, any number of walls in the y direction would not influence the number of segments to be divided for printing as shown in figure 6.12.

With the above mentioned logic, while designing the house it should be considered to keep the number of walls perpendicular to the printing direction to be kept minimum, or the printing orientation should be kept along the direction of maximum number of internal walls.

*Figure 6.11.: Logic of division of printing parts.*
Figure 6.12.: Influence of the addition of walls in multiple directions.
Optimization.

An important aspect of the project is taking advantage of the capabilities of 3D printing for material reduction due to structural optimization and optimization of the print path. So every element of the building should be designed considering the printing capabilities and minimizing the material use with structural optimization to deposit materials where required and the remaining areas can be filled with non-structural materials to enclose the surface.

Openings 1.

However while designing with structural optimization the functionality of the building should be also considered. For example as shown in figure 6.14., the opening in the building should be considered in the boundary constrains according to suitability and requirements of the user, rather then having unsuitable opening provided by the structural optimization process. Besides, the exact location of the openings should also be adjusted to the shape of the optimized structure. The size and location of openings in the house can never interfere with the optimized structures of the house.
Figure 6.13: Optimization of the elevation of the wall.

Figure 6.14: Connection between the optimized structure and the desired openings.
6.3. - 3D CONCRETE PRINTING - GUIDELINES

Openings 2.

Openings can only occur on specific positions in each print part, depending on the printing direction of the print part.

Openings in the flat base of each print part can be everywhere since all geometry in this side is printed flat on the floor. However in the standing walls, floor and ceiling of the print part, openings can only be placed at the end of the print part, the highest point. This because otherwise the openings will form a large cantilever that can not be printed.
Figure 6.15.: Restrictions on the location of openings.
07 TERRACED HOUSING

WHAT ARE THE CHARACTERISTICS OF THE MEANING OF THE DESIGN OF TERRACED HOUSING IN THE NETHERLANDS?
7.1. - TERRACED HOUSING - CHARACTERISTICS OF TERRACED HOUSING

Figure 7.1.: The analysed houses.
(Funda, 2015)
In order to design a house similar to the current Dutch terraced house, it is important to find the underlying characteristics of terraced housing. In order to do this twelve terraced houses build from 1900 until 2010, one every 10 years area analysed.

The reason these 12 houses are researched instead of 12 houses build in the same period, is because almost every 10 years a new type of terraced housing was build in the Netherlands. All the different typologies of housing with different periods have certain advantages and disadvantages attached to the design. The research compared all the different typologies of terraced housing from different period, instead of different typologies from the same period.

The houses for the research are selected according to design of the typology which symbolizes the housing design in a particular period of time. Even though all houses do not have the same size or the same price, the fact that they represent the standard house for each time frame results in an interesting analysis. As a result from this research, different typologies can be categorized in accordance to its design efficiency and an average quality of all terraced houses can be mapped to act as guidelines for the design of 3D concrete printed house.

The complete research analysis on terraced housing is included in Appendix B. This chapter will focus on the conclusions of the research and the creation of a design brief for the 3D concrete printed house.
7.1. - TERRACED HOUSING - CHARACTERISTICS OF TERRACED HOUSING

Figure 7.2.: Example analyses, house build in 1960
The easiest conclusion of the research on terraced housing in the Netherlands is the average functions, dimensions and the quantitative data. But more interesting is the qualitative data of the research. Some additional examples of the qualitative rules found during the research will be provided.

The first example is the fact that every terraced house should have a back garden, as it is one the prominent advantage of a terraced house compared to an apartment.

The house should provide the opportunity for some sort of personalization; it is necessary to be able to identify the house as your house. The personalization improves with a front garden.

The façade of the house should have the maximum possible amount of openings. Examples, of the houses studied on this research, provides us with the conclusion that the houses with the most openings have the least amount of additions, and additions often increase the amount of openings.

The house should have enough space for a family of at least 4 people to comfortably live in.

Besides, the thresholds should be clustered to provide a maximum usable space and create a clear routing in the house, which is the next requirement. The clear routing also contributes to a clear gradient in accessibility of the house.
7.1. - TERRACED HOUSING - CHARACTERISTICS OF TERRACED HOUSING
Besides the quantitative and qualitative conclusions about the average of all houses, it is also possible to define the best type of terraced housing. Related to the amount of adjustments to the house, the amount of comfort the house provides and the size of the house, it is possible to define the qualities of a good house.

In order to create a real comparison, the terraced house from 2010 is left out of the conclusion, since this house is not old enough to show the user marks and possible adjustments. The rest of the houses have existed long enough to show traces of modifications done according to users needs.

The first conclusion is that the houses build from 1900 until 1920 are quite small for a modern family to live in. The houses build from 1930 are comparatively much bigger in size and thus are more suited for a modern family.

The houses build after 1980 also are not very convenient. This is visible through the amount of adjustments and additions made. Even though these houses are relatively new, the amount of adjustments and additions is much more than the examples of houses built during 1940's and 1960's. This also counts in some way for the houses build in 1930 and 1950.

The conclusion drawn from this study is that, the houses built around 1940, 1960 and 1970 are the most convenient for users according to its size and functionality.
The conclusions, resulting from the analysis on terraced housing, should provide the guidelines of the 3D Concrete Printed house. Important to not is the fact that these guidelines should be seen as the minimum requirements of the printed house, since the use of 3D Concrete Printing provide the possibility to improve this type of housing.

The house that will be designed with the 3D Concrete Printer should consider the design of the terraced houses built in 1940, 1960 and 1970 since these houses prove to be the most efficient typology of terraced housing. This is however, a very basic guideline that needs to be more specified.

As seen before, the quantitative data of the research, the minimum size of the house and number of rooms, the functions of these rooms and the percentage of openings in the facade, can be used as the first requirements for the printed house.

Also qualitative requirements related to the comfort of living in the house should be considered. A first example of this are commonly used relationships between functions and the routing in the house. In current terraced housing, there are a certain amount of commonly used relationships that provide a comfortable house. These relationships should be present in the printed house. This also counts for the amount of storage space in the house.

As an addition to quantitative requirements regarding the size of the openings in the house, the location of the openings in relation to the rooms inside the house should also be considered.
As a final example of the guidelines for the printed house the personalization is considered. As stated before, the 3D Concrete Printed house should increase the amount of possible personalization of the house. The research on terraced housing in the Netherlands shows however that there is a difference in the need for personalization throughout the house. For example, the front facade of terraced housing is often anonymous while the back facade shows the user marks. This difference should be considered in the design of the printed house.
08 NEW WAY OF BUILDING

HOW DOES THE USE OF 3D CONCRETE PRINTING CHANGE THE DESIGN OF TERRACED HOUSING?
Figure 8.1.: Analysis on the needed printing parts of a existing terraced house.
The results of the previous research, provided a design language which can change the current design of low cost housing in the Netherlands. When 3D concrete printing was considered to print an excising terraced house, a lot of problems were identified.

The first problem is linked to the amount of printed parts. It becomes clear that the existing terraced house needs to be printed in a lot of parts because of the corridor in the middle of the house, which causes a lot of divisions in both sides of the house.

This corridor will form the key element in the shape of the house. The first goal is to reshape and replace the corridor in order to reduce the amount of parts to be printed for the house.
Figure 8.2.: Analysis on the division in printing parts of the walls.
Division of walls in print parts.

The top of figure 8.2. shows five possibilities for the division of the floor plan, created as a solution to the problem with the corridor in current terraced housing as described before. In order to choose one way of dividing this floor plan into print parts, the five options are analysed on the amount of connections, the way of assembling the print part and the functions of the building. This analysis is visible in the bottom of figure 8.2.

The first guideline for determining the proper way of dividing the parts is the amount of connections that have to be made while assembling the parts; there are two type of connections. For first type of connection, marked with a red circle, two ends of the print art need to be connected, which is a labour intensive connection. The second connection however, marked with a pink circle, connects the end of one building part with the side of the other part, this connection is easier to realize.

After leaving out the options with a big amount of connections, the options are analysed on the way of assembling. Sliding one part in between the other parts, the single arrows in the image, can cause difficulties in the building process, because of this these alternatives are not suitable.

The main difference between the two remaining parts is the difference in the functions that belong to the different parts, because the logic of the building seems more clear if the separated part contains only one function and the other part the rest of the functions, this option will be used in further research.

Figure 8.3.: Final division in printing parts of the walls.
Figure 8.4.: Analysis on the division in printing parts of the floor and ceiling.
The division of printing parts, as shown in figure 8.3, divides the building in one central function, the remaining functions and the facade. A big advantage of this division method is the fact that the facade is not structural, which means it can provide a great opportunity for personalization.

**Division of floor and ceiling.**

Besides the division of the walls in different print parts, the floor and ceiling of the building also need to be divided in print parts, related to the division of the walls. Again there are five possible options for this division, as shown in the top of figure 8.4.

It is important to determine if the proposed divisions do not interfere with the structural aspect of the building. Alternatives with too much of deviation from the actual structural model, red in the analysis in figure 8.4., are not suitable.

The way of assembling the print parts again determines the suitability of the option. The options which do not need to be assembled by sliding parts in between each other are considered for the final division. This leaves two possible options, the amount of connections, marked in red in figure 8.4., determines which method will be chosen.

The final division of printing parts is visible in figure 8.5.
Figure 8.6.: Basic layout of the floor plan.
The basic floor plan.

The floor plan of the house should consist of 3 printing parts, a core with a common function, a big part containing more private functions of which at least two are from one facade to the other. The final print part is the facade which is free for personalization. Also the size and functions of the floor plan can be adjusted according to the users wishes.
8.2 - NEW WAY OF BUILDING - BUILDING ELEMENTS

Gothic structural principle

New structural principle

Figure 8.7.: Logic behind the structural diagram.
When starting topology optimization for a rectangular building the results refer to a type of Gothic architecture. The structure appears like the structural elements of cathedrals, such as vaults, arches etc.

This structure however, does not suit 3D Concrete Printing as each arch requires two print parts. This is because the arch is printed on its side, and the printer can only print half of the arch. Where the cantilever of the arch switches from one side to the other, it is no longer possible for the printer to print the arch. Which results in double the amount of printing parts.

In order to solve this problem a variation on the Gothic structure is created. This variation is visible in the bottom of figure 8.7. In this variation, rooms no longer have a complete arch but only half an arch. The forces which are usually in the other side of the arch will now be transferred to the opposite room, which supports the arch structure. Finally, in the last room, the arch is supported by a thick column which carries the loads from the remaining part of the arch.

This variation in structure corresponds to the designed print parts of the house. Each print part supports the other part and together the parts form a stable structure. The reason this is possible is because the parts are rotated 90 degrees when printed, and thus do not need each others support when printed. This process does however ask for a particular printing sequence. The parts have to be placed opposite to the sequence in which they support each other. So first the final thick column will be placed, then the room which needs this column
Figure 8.8.: Structural diagram.
for support and so on.

The structural system as described before is not directly related to the printing parts of the house. As visible in figure 8.8 the biggest printing part of the building is structurally divided into three pieces. Of which two are supported by the facade and one is supported by the core. The rest of the print parts are also the structural parts, where the core is supported by the facade and the facade supports the core and the two parts of the main building.

In the bottom of figure 8.8 on the left, the load conditions of the structural diagram are visible. The right of this image shows the support conditions, and here it is visible where the parts support on each other.

The structural diagram of the building forms the input for topology optimization in Millipede and Grasshopper. In the left of figure 8.9, the input for the topology optimization is visible, the load conditions in blue, the support conditions in pink and the boundary conditions in grey. After providing Millipede with this input the optimized structure is calculated.
Figure 8.10.: Different possibilities for the location of walls.
Walls.

The previously discussed optimized structure is only based on the overall geometry of the house and does not take the walls into account, it is necessary to add walls to the optimized structure to provide the needed privacy in the rooms of the house. Besides, the non-structural walls can contribute to make the house more printable, since they make the structure more continuous.

The biggest challenge here is where to place the walls. Even tough they are designed in the initial design, due to optimization the location and size of the walls may have to be adjusted or the wall needs to be removed. Besides, it is important to decide where to place the walls related to the optimized structure. Since these walls have to increase the print-ability of the structure and influence the aesthetics of the building.

There are four options for the location of both the interior and the exterior walls related to the optimized structure. Each of these options influences aesthetics and the print-ability of the building. In order to choose between the four options these concepts should be taken into account.
8.2 - NEW WAY OF BUILDING - BUILDING ELEMENTS

Figure 8.12.: Integration of the structure in floor and ceiling.
Floor and ceiling.

The structural optimized elements are not only incorporated in the walls of the house but also in the floors and ceilings. Because the optimized structure has a relatively large height this will reduce the height of the floors. Besides, it also saves material.

The incorporation of the optimized structure in the floor and ceiling influences the print path and the 3D structure of the printed concrete. Where the floor and ceiling are not part of the optimized structure, the print speed is higher, creating a more open 3D printing structure. But on the locations where the floor and ceiling are part of the optimized structure the speed of the print path is adjusted to the structural data on that location.

This way the total amount of material is reduced by incorporating two elements into one and adjusting the used material to the structural needs of the element.
Figure 8.13.: Advantage of optimization compared to a not optimized geometry.

Not optimized structure

Volume: 58,47 m³
100%

Optimized structure

Volume: 26,95 m³
46,09 %
Proof of concept.

In order to show that material optimization helps in reducing the building cost. A comparative analysis is made between a structural element of the house with optimization and one without, as shown in figure 5.13. As mentioned earlier, the amount of used material, directly influences the overall cost of the building.

If the design would not have been optimized the section of the building elements would have to be thick and bulky, since the maximum amount of forces can be anywhere in the structure and the element should be able to deal with these forces everywhere. Due to structural optimization, the place for maximum stress in the structure can be identified and, the maximum amount of material needed to support the element can be placed at the required location, and thereby reducing the amount of unnecessary materials in the element and eventually bring down the building cost.

The same goes for the deposition of the material, the 3D print structure.
8.2. - NEW WAY OF BUILDING - BUILDING ELEMENTS

Different approaches

Standard openings

Optimization openings

Figure 8.14.: Different concepts regarding openings.
Openings.

It was stated earlier that the place and size of the openings should be related to the optimized structure. This because openings should not be placed on the part of the wall where material is needed for the structure. However, an interesting question is how to create openings in the design. Structural optimization creates openings in the structure that are based on the structural aspect of the building and therefore are freely shaped, it does not matches the standardized dimensions. It is important to define how to use these created openings. Does the optimized structure determine only the place of the openings (figure 8.14. right) or does it also determine the size and shape of the openings (figure 8.14. left)?

The most important aspect related to this question is building costs. It might be aesthetically preferred to use the opening in the optimized structure as the actual opening, however this will escalate the expense of glass due to its irregular shape. So since the goal of this project is to create an inexpensive house, the optimized structure should only determine the place of the openings. The actual opening should be cheap, resulting in standard rectangular glass windows, as visible in the middle image of figure 5.14., or in walls with standard doors, as visible in the bottom image of figure 8.15.

Even tough this solution is best for the design of housing for the lower and middle class of the Dutch population, it is unfortunate that the structure is not used as the actual shape of the openings as this shows the concept of topology optimization and decreases the amount of concrete used in the building. However, the price of an irregular shape glass sheet will be much
Figure 8.15: Possibility of the structure as a threshold.
higher than the price of the extra used concrete, making it the best solution in this research. Besides, in some parts of the building structure there is an opportunity to use the structure as the actual shape of the opening. This opportunity arises when the opening does not need to be filled with a door or a window, the structure can be used as a smooth threshold inside the house. As visible in the top image of figure 8.15, this can results in an interesting division between spaces.
FINAL DESIGN

VISUALIZATION OF A 3D CONCRETE PRINTED HOUSE
Figure 9.1: Concept design 1.

9.1. - FINAL DESIGN - DESIGN 1

<table>
<thead>
<tr>
<th>Household</th>
<th>Function</th>
<th>Design</th>
<th>Functionality</th>
<th>Wall type front facade</th>
<th>Wall type back facade</th>
<th>Wall type interior</th>
<th>Total area</th>
<th>Area inside</th>
<th>Area outside</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>241 m²</td>
<td>207 m²</td>
<td>34 m²</td>
</tr>
</tbody>
</table>
The first design is created for a family with one or two older children. It also includes an office at home, which increases the importance of thresholds inside the house. The design contains multiple common areas, so that the places for family leisure and work can be separated. While designing the house, the gallant and the monumental characters are given importance for the clients visiting the office. The interior needs to be lavish, luxurious, unique and surprising to impress these clients. The aesthetics of the house are given more importance than the functionality of the house.

As shown in figure 9.1, the house contains three different types of walls based on the location of the structural skeleton. For the exterior there are two options, one for the structural wall of the back facade, and the other for the structural walls of front facade and the exterior walls on either sides. While the third type is used for the interior walls.

The house has a total area of 241 m² and provides a balcony area on every floor. The total inside area of the house is 207 m². Which makes the house comfortable to live in.
9.1. - FINAL DESIGN - DESIGN 1

Figure 9.2.: Functions - design 1.
In order to fulfil the need for thresholds the private part of the house has a different entrance from the office. Besides each of the upper floors provide a common area, this way there are multiple common rooms in the house. For example, the children spend time with their friends on the third floor in a seating area while the parents are in the living room. These additional common areas increase the privacy and possibilities inside the house.

The house has 4 bedrooms which all open up to common rooms connected to an outside area. Apart from the office, the first floor of the house is similar in functions and size to the first floor of current terraced housing.
9.1. - FINAL DESIGN - DESIGN 1

Figure 9.3.: Building elements and structural elements - Design 1.

Figure 9.4.: Structural diagram - Design 1.
The structural diagram of the first design contains 5 structural parts which are similar to the printing parts on the facade and the core of the building. The main part of the building is divided into three structural parts, one supported by the core of the building and two supported by the facade.

The structural diagram of the building is visible in figure 9.4., the load conditions (blue), the support conditions (pink) and the boundary conditions (grey) form the input for topology optimization. The results of the structure from topology optimization is visible in figure 9.4.
9.1. - FINAL DESIGN - DESIGN 1

Figure 9.5.: Floor plan - first floor - design 1.
Figure 9.6.: Floor plan - second floor - design 1.
Figure 9.7: Floor plan - third floor - design 1.
Figure 9.8.: Floor plan - overview of sections and elevations - Design 1.
Figure 9.9.: Front facade - Design 1.
Figure 9.10.: Back facade
- Design 1.
9.1. - FINAL DESIGN - DESIGN 1

Figure 9.11.: Section A-A - design 1.
Figure 9.12.: Section B-B
- design 1.
9.1. - FINAL DESIGN - DESIGN 1
Figure 9.14.: Section D-D - design 1.
9.1. - FINAL DESIGN - DESIGN 1
Figure 9.16.: Section F-F
- Design 1.
Figure 9.17.: Render 1 - living room - design 1.
Figure 9.18.: Render 2 - office - design 1.
9.1. - FINAL DESIGN - DESIGN 1

Figure 9.19.: Render 3 - Bedroom -
- design 1.
Figure 9.20.: Render 4 - Bedroom - design 1.
9.2. - FINAL DESIGN - DESIGN 2

Household

Function

Design

Functionality

Wall type front facade

Wall type back facade

Wall type interior

Total area  

Area inside  

Area outside
The second house is designed for a big family with young children and will only be used to live in. For this house, functionality of the spaces is given more importance than the aesthetics of the house. The main idea behind the house is to provide comfort to the family that lives in it. In this house thresholds are also important but in a different way. For example on the first floor there should be as less thresholds as possible to provide the opportunity for the parents to always look after the kids.

The house has three different wall types. Two for the exterior walls. For the first exterior wall type, the structure is visible on the outside and is used for the back facade. The second exterior wall type, shows the structure on the inside and is used for the front facade. For the interior, the wall is always placed on one side of the structure. This is linked to the functionality of the building. This way it is possible to only show the structure in the common areas of the house and leave out the structure from areas such as the children’s bedrooms, considering safety of the children.

The total area of the house is 267 m². This is enough space for the whole family to comfortably live in. The reason this design does not have any outside space is again because of safety for the children, for whom balconies are not safe.
Figure 9.22.: Functions - design 2.
The functional relationship in the second design do refer to those in the traditional terraced house more than those in first design do. All the rooms in the house are connected by a central corridor which is the core of the building.

The first floor of the house is an open plan with only an entrance and a toilet in the middle. The rest of the floors are divided according to a more traditional layout.

As an addition all bedrooms, the bathroom, the living room and the kitchen are connected to a storage. This way children’s toys and other stuff not required on a daily basis can be easily stored in the house. This storage also contributes to the print-ability of the house, as the storage area is placed along the side facade of the house on each floor. It becomes possible to print a space dividing wall over the whole width of the house without any difficulty in sliding the print parts into each other while assembling. As the width of the storage area does not need this wall a gap is created for easy assembling.
9.2. - FINAL DESIGN - DESIGN 2

Figure 9.23.: Building elements and structural elements - design 2.

Figure 9.24.: Structural diagram - design 2.
The structural diagram of the second design also contains 5 structural parts which are similar to the printing parts on the facade and the core of the building. The main part of the building is divided into three structural parts, one supported by the core of the building and two supported by the facade.

The structural diagram of the building is visible in figure 9.24., the load conditions (blue), the support conditions (pink) and the boundary conditions (grey) form the input for topology optimization. The results of the structure from topology optimization is visible in figure 9.24.
9.2. - FINAL DESIGN - DESIGN 2

Figure 9.25.: Floor plan - first floor - design 2.
Figure 9.26.: Floor plan - second floor - design 2.
9.2. - FINAL DESIGN - DESIGN 2

Figure 9.27.: Floor plan - third floor - design 2.
Figure 9.28.: Floor plan - overview of sections and elevations - design 2.
Figure 9.29.: Front facade - Design 2.
Figure 9.30.: Back facade - design 2.
9.2. - FINAL DESIGN - DESIGN 2

Figure 9.31.: Section A-A - design 2.
Figure 9.32.: Section B-B - design 2.
9.2. - FINAL DESIGN - DESIGN 2

Figure 9.33.: Section C-C - design 2.
Figure 9.34.: Section D-D - design 2.
9.2. - FINAL DESIGN - DESIGN 2

Figure 9.35.: Section E-E - design 2.
Figure 9.36.: Section F-F - design 2.
9.2. - FINAL DESIGN - DESIGN 2

Figure 9.37.: Render 1 - living room - design 2.
Figure 9.38.: Render 2 - kitchen - design 2.
Figure 9.39.: Render 3 - Bedroom - design 2.
Figure 9.40.: Render 4 - Bedroom - design 2.
9.3. - FINAL DESIGN - DESIGN MOTIVATION

Figure 9.41.: Floor plans - design 1.

Figure 9.42.: Floor plans - design 2.
Personalization.

The two designed houses differ a lot from the traditional terraced house. In order for the designs to function, they should not decrease the comfort of the traditional terraced house but should improve it. The biggest improvement of the designed houses compared to the traditional terraced house is the opportunity to personalize the house. Like Mies van der Rohe stated in 1927 on the importance of personalization:

*Today the factor of economy makes rationalization and standardization imperative in rental housing. On the other hand, the increased complexity of our requirements demands flexibility. The future will have to reckon with both.*

*Frampton, K., 1985, p.167.*

The solution of Mies van der Rohe to this problem was a skeleton construction, which created the opportunity for rationalized building methods while providing the possibility to freely divide the interior, which is some kind of personalization.

Back in the early 1900's this was the best solution to the combination of the economic problems and personalization. With 3D concrete printing however, the economic aspect of building does no longer need rationalization and standardisation. Printing different shapes of concrete will be the same price as printing the same shapes, as long as the amount of material is the same. Personalization of the whole house is possible without an increase in costs and that is the reason why this way of building forms a great improvement to the traditional way of building, it responds to the growing need for personalization.
9.3. - FINAL DESIGN - DESIGN MOTIVATION

**Figure 9.43.:** Living room and kitchen with concrete structure - Design 2 - First floor.

**Figure 9.44.** Bedroom without concrete structure - Design 2 - First floor.
Concrete Structure.

However the house does not only provide just personalization, in order to do this a lot of things we know that are common or even obvious in traditional (terraced) housing, change in the 3D concrete printed house.

The most obvious difference is the presence of the concrete structure inside the house. This will not only give the house a different look but will also interfere with the way the house is used. For example people like to have straight walls against which they can put their closets, paintings and other furniture. The structure will decrease the area of straight walls. In order for this to not interfere with the use of the building in both the design the maximum possible area of straight walls is realized. Besides in some places in the design the structure also contributes to the furniture. For example the structure can be used as the boundary of a closet. This way the structure becomes useful and the area of straight wall that is taken over by the structure now has a function, making the straight wall not necessary at this point. Also the structure can be used as a space dividing element, i.e. a smooth threshold.

The opinions about the aesthetics of the structure will be divided. Some will think it’s a nice shape, others will think it is stupid to have a tree of concrete inside the living room. But as said by Adolf Loos (2013) the beauty of a practical object can only be determined in relation to it’s function. (p.32.) Relating this to the concrete structure will make the structure beautiful. It does what it is supposed to do and since it is structurally optimized it also does it in the best possible way.

However if the user of the house really does...
9.3. - FINAL DESIGN - DESIGN MOTIVATION

Figure 9.47.: Living room and kitchen with concrete structure - design 2 - first floor.

Figure 9.48.: Bedroom without concrete structure - design 2 - first floor.
not want to see the concrete structure in every room he can choose to place the walls on one side of the structure. As visible in figure 9.50, it is possible to place the walls in such a way that only the common functions in the house show the concrete structure, and the private functions, i.e., the bedrooms and the study, are free from the structure.
9.3. - FINAL DESIGN - DESIGN MOTIVATION

Figure 9.51.: Front facade without concrete structure - design 1 - second floor.

Figure 9.52.: Back facade with visible concrete structure - design 1 - second floor.
Facade.

An other big question related to the two proposed designs can be the difference in front and back facade. There are three reasons for this contradiction between the façades of the houses. The first is related to the traditional terraced house. In this house the front facade is mostly similar to the one of the neighbour, the neighbours neighbour and so on. This facade shows almost no personalization and is bound to rules. The back facade however is mostly adjusted to the user. This is the place where additions, new windows and different materials can be found. Design 1 refers to this difference in facade of the terraced house.

The second reason is linked to a famous quote by Adolf Loos (2013).

"The room has to be comfortable, the house has to look habitable."

In this quote the difference between the room and the house is in the words 'be' and 'look'. The house is about the looks, it is about showing something to the world, it needs to have some kind of status. The room however is for you, it does not have to show anything, it should be adjusted to your wishes. Because of this the front facade in design 1 is strict and gallant. It shows the passer-by the status of the user of the house, forming a mask of the house. The back facade does not have to show a mask, it is a personal object, it can be adjusted to the users wishes and needs to be comfortable for the user.
9.3. - FINAL DESIGN - DESIGN MOTIVATION

Figure 9.53.: Front facade without concrete structure - design 2 - first floor.

Figure 9.54.: Back facade with visible concrete structure - design 2 - first floor.
The final reason is a practical one. The house needs to be printed in a maximum of three printing parts. In order to do this, the printing base of the parts needs to be flat. Because the front facade of the house is the printing base this facade needs to be flat, which means that the dividing wall needs to be on the outside of the structure, as this printing direction is the same for the back facade. The walls on the back facade needs to be placed on the interior side of the concrete structure.

This difference is clearly visible in the second design. Even though this design did not take the concepts as described before into account. It still matches these concepts in some way, just because of the way of construction.
10

FABRICATION

HOW WILL THE HOUSE BE BUILD?
Figure 10.1.: The 3D Concrete Printer.
Current 3D Concrete Printer.

Figure 10.1. shows the existing 3D Concrete Printer at the Eindhoven University of Technology. As mentioned earlier the dimensions of this printer are limited to 11m (L) x 6m (W) x 3m (H), as the printing strategy applied for this printer is to print parts of the building in smaller scale off site and assemble them at site. However for this research this printer does not satisfy the needs of the design requirements, as the printer limits the scale of printed parts. It also does not allow of on-site printing which is an essential part of this research proposal. However the strategy applied by this printer to use a 4 degree of freedom gantry system can be applied for the proposed research.
Figure 10.2.: the modified printing combination
The modified printer.

As mentioned earlier due to the design constraints of the 3D Concrete Printer used at the Eindhoven University of Technology, modifications in the printer design needs to be done to suit the requirements of the project. The various modifications in the printer design are:

- The scale of the printer needs to be increased to increase the printing bed.

- An additional printing bed along the Z-axis is introduced.

- The length of the printing direction along the X-axis can be incrementally increased.

- An additional hydraulic system is introduced along Y-axis, for the ease in filling the printed part to 90 degrees.

The modifications result in a printing combination, existing of two parts, the printing bed and the concrete printer.
The introduced printing bed has three functions. First it can move in Z-axis, which helps to print different parts along each floor. Secondly movement in the Y-axis allows the printing bed to make space for new prints after placing the parts to the desired location along the Y-axis. Third is the additional hydraulic lifting system which helps in flipping the printed parts in 90 degrees and placing them along the Y-axis before making space for the next print.
As explained earlier the direction of movement of the printer along the X-axis can be increased incrementally. This gives an additional advantage to the printer as multiple houses can be printed at the same time without completely shifting the printer from one location to another. It also increases the construction speed of the houses, as after each print, the printed parts cannot be removed until to have achieved structural strength after drying of the concrete. So while one printed part is left of drying another part of the second house can be printed at ease, without wasting time.
Figure 10.5.: Printing process.
**Fabrication sequence.**

The first step in the fabrication process of the house is printing the concrete structure. Each floor of the house is printed separately and each floor is divided into 3 printing parts, related to the facade, core and the functional part of the basic floor plan. The different printing parts are printed when they are rotated 90 degrees. After each of the parts is printed it will be assembled, connected to the parts already printed. The sequence of printing is really important since each part support or is supported by another part. The final step is the finishing, after all parts are printed and assembled the windows and doors can be placed in the printed structure.

In the following pages the printing process for an element is illustrated step by step.
Step 1.

The printing starts with printing the front facade of the ground floor on the printing bed as shown in figure 10.6. The facade of the building is printed flat with additional adjoining walls perpendicular to the facade wall printed over it in the z-axis. After completion of printing of the facade element for the first house, it is left undisturbed on the printing bed for drying of the concrete.
Step 2.

While the print part is kept for drying, as illustrated in figure 10.7, first the yellow gantry system moves up in the z-axis and supports itself in the red part of the machine.
10.2. - FABRICATION - PRINTING PROCESS

Step 3..

Then the red supporting rails moves incrementally along the x-axis to print the next house in the adjoining printing bed as illustrated in figure 10.8.
Step 4.

The gantry system lowers itself to the printing position to start printing the second house. The printing strategy applied for the second house is the same as that of the first house. This process is clearly illustrated in figure 10.9.
Step 5.

Following the previous steps, the printing process is repeated after each print according to the number the houses required to be printed along the same length.
Step 6.

As the print dries up in the printing bed, the printing bed moves flips the bed 90 degrees with the hydraulic system to place the printed element in its position.
Step 7.

The printing bed is kept in this position until the printed element is properly connected and placed in its location. This step can be simultaneously repeated for all houses. The advantage of the separate construction for the printing bed is the fact that the flipping of the hardened concrete elements is independent from the concrete printer, which saves time and labour during the printing process.
Step 8.

Once the printed part is placed in its position the printing bed rotates itself flat to its original orientation.
Step 9.

Similar to the movement of the printer, the print bed can be moved to the desired printing location. The first step in the movement of the printing bed is a movement in Z-direction to create a free height.
Step 10.

Next, the print bed can move along the y-axis to reach the desired location of the next print.
10.2. - FABRICATION - PRINTING PROCESS

Step 11.

Once the desired location in Y-axis is reached, the print bed can be lowered in place for the next print part of the building.

After all the elements of the ground floor for all the houses are printed, the printing bed in the corresponding houses, moves up in the z-axis and positions itself above the first floor, to create printing space for the elements of the next floor.
Figure 10.17.: Lightweight concrete floating in water.
In order to further decrease the labour needed to fabricate the house a new way of insulation is needed. Since with the old method, the 3D Concrete Printer should be interrupted halfway through the print for the insulation to be applied.

As supported by R.M.E. Diamant (1986), thermal insulation is largely dependent upon the percentage of void spaces in the structure. The 3D printed structure can increase the insulation of the building, however this is not enough. In order to meet the requirements regarding insulation of a building, lightweight concrete can be used as insulation material. The thermal properties of lightweight concrete have proven to be good enough as an insulation material by Ünal et. al. 2007.

The advantage of using lightweight concrete as the material for insulation in the building is the possibility to print this material with the 3D Concrete Printer. This will decrease the labour costs of the building since the insulation can be incorporated in the print path. The next pages will show the print path of different building elements related to the use of lightweight concrete.
Figure 10.18.: Overview of the interesting locations regarding insulation.
Figure 10.19.: Lightweight concrete - corner detail.
10.3. - FABRICATION - INSULATION

Figure 10.20.: Lightweight concrete - floor detail.
Figure 10.21.: Lightweight concrete - structure detail.
Figure 10.22.: Fabrication process of a window detail.
Even tough most details of the building are related to the print path for the 3D Concrete Printer, there are some points in the structure in which the printed concrete is connected to an other material. This chapter will show three different details for the connection between the printed concrete and material for the openings in the building.
10.4. - FABRICATION - DETAILS

Figure 10.24.: Fabrication process of a detail regarding a structure, a floor and a window.
Figure 10.25.: Detail regarding a structure, a floor and a window.
10.4. - FABRICATION - DETAILS

Figure 10.26.: Fabrication process of a corner with concrete and glass.
Figure 10.27.: Detail of a corner with concrete and glass.
CONCLUSION

HOW CAN 3D CONCRETE PRINTING BE BENEFICIAL TO THE CONSTRUCTION OF INEXPENSIVE, LARGE-SCALE RESIDENTIAL BUILDINGS IN THE NETHERLANDS?
This thesis was impelled by my personal dissatisfaction with the use of new construction methods and materials in architecture and structural design. In my opinion new techniques are not used in a way in which they can show their full potential, nor do they create new insights in architecture and structural design, most of the new techniques just copy the existing way of building in a new material or with a new technique. With this thesis I wanted to radically expand and change the boundaries in architecture and construction by considering the possibilities of the 3D Concrete Printer, built at the Technical University in Eindhoven.

In my opinion the potential benefit of 3D Concrete Printing, when applied on large-scale residential housing, is the opportunity for personalization. In the current built environment of the Netherlands the individual is not visible. Political, economic and architectural rules and restrictions define our built environment, which results in an anonymous and monotone landscape. The way we describe our house is something like “I live at number fifteen, the ninth house on the right.” Our house is often just defined by this number, a personal characteristic by which the house can be marked as a personal possession is absent even though the house is considered the most valuable investment. In the house the most important moments of our lives take place. This is why there is a need for personalization, the house should be adjusted to needs and satisfaction of the user.

The reason that personalization becomes an option with 3D Concrete Printing is the independency of shape on building costs. Imagine a concrete cuboid from 1m$^3$ in size from which the dimensions are variable. In the traditional
way of building a slight change in dimensions of the cuboid results in the need for a new mould to cast the concrete in, so even though the amount of used material is similar in every cuboid, if the dimensions do not fit the standardized mould, the costs of the construction will increase significantly. With 3D printing however, the influence of shape on the price of the cuboid is eliminated, even printing a sphere instead of a cuboid will not affect the price of the concrete as long as the quantity of used material remains the same. As a result of this, standardization of buildings or building elements is no longer needed with 3D Concrete Printing.

In order to provide the maximum possible amount of personalization, the construction costs of the building need to be reduced. Construction costs are a combination of material costs and labour costs. In order to decrease these construction costs it is necessary to consider the design requirements of the 3D Concrete Printing. If the printing process is used efficiently, the cost of manufacturing would be minimal.

The demands of the 3D Concrete Printer are determined by the possibilities in movement of the printer, combined with the properties of the material used to print. This combination is incorporated in a print path. The logic here is to optimize the printing process in the smallest possible scale, the print path, to create the most efficient result on the big scale, i.e. the complete building. For the 3D Concrete Printer the most efficient print path is based on one direction, with a minimal amount of corners and the possibility to adjust the deposited material to the structural needs of the object by a change in 3D printed structure. Which is done by a change in printing height and printing speed. This way the
material is used in a way it has the best structural capabilities and the material is only used where it is needed. Besides, the variation in printing structure by a change in printing height and speed decreases the complexity of the print path for the 3D Concrete Printer.

However the optimization of the print path for the 3D Concrete Printer results in a reduction of material use and thus a reduction of the building costs, the optimization of the printed material on a large scale can further increase the efficiency of the printer and does still consider capabilities of the 3D Concrete Printer. For further reduction of material use topology optimization is applied. This optimization method removes the material from the places in the structure where there are no forces and leaves only material where it is structurally needed. Combining this with the created print path and the possible variations in this path, the 3D Concrete Printer will be able to reduce the material use in the building up to 50%.

The only thing left, possible to decrease the building costs of the 3D Concrete Printed house, is a reduction in labour costs. For this reduction again the possibilities of the printer need to be taken into account. With the 3D Concrete Printer it is possible to create any kind of shape, starting from a flat printing base, until there is a second horizontal part. This horizontal part needs to be cantilevered which is not possible to print with the 3D Concrete Printer. The reduction of the amount of horizontal parts, starting from the chosen print base, provides the least possible amount of print parts, which will decrease the amount of needed labour for assembling the parts. This will decrease the labour costs of the building and thus the total construction costs.
The combination of material and labour reduction in the printing logic of the 3D Concrete Printer results in a set of rules for designing with a 3D Concrete Printer, which differentiate a lot from the traditional way of building. However, the goal of the thesis was to create a house that is similar to the current terraced house in the Netherlands, a house suitable for the lower- and middle class of the Dutch population. The house needs to be designed considering the characteristics of current terraced housing, which means that the average characteristics of current terraced housing form the minimal needs for the designed house. These characteristics do not only imply the minimal square meters of the house or the size and the amount of openings in the facade but also for example the possibility to personalize the house or the way in which the house is used in a practical sense.

As stated before the characteristics of current terraced housing in the Netherlands form the minimum needs for the 3D Concrete Printed house, combining them with the found guidelines for printing with the 3D Concrete Printer however, ask for a significant change in the design of the house. In this combination, the actual change in boundaries in architecture and construction becomes visible. Take for example the size of the printer. The average terraced house has a width of 5.638 mm and a depth of 10.346 mm if I want to print a house of these dimensions with the 3D Concrete Printer on site, it means that the longest side of the house will be printed on the side of the 3D Concrete Printer that has a restriction in size, while the shortest side will be printed on the side of the printer that has not got any boundaries. Besides, the rules regarding the reduction of labour costs also do not add
11. Conclusion

up with commonly used floor plans in current terraced housing. The current terraced house has too many horizontal parts which results in a great amount of printing parts and thus needs large amount of manual labour, which increases the labour costs.

The previously described differences between traditional building and the printing logic of building with a 3D Concrete Printer mostly have an impact on the general shape of the house, which is visible in the layout of the floor plan. The material reduction however, significantly changes the design of the house. Walls for example, will no longer remain flat building elements but due to structural optimization will become interesting structures inside the building that can create new spaces or exciting new thresholds. And within these structures the house can be transformed according to the user’s requirements.
WHAT IS THE IMPACT OF 3D CONCRETE PRINTING AND WHAT ARE TOPICS FOR FURTHER RESEARCH?
Figure 12.1: Impact on 3D Concrete Printing on the urban tissue.
Impact on urban planning.

Due to the impact of 3D Concrete Printing on the design of large-scale residential buildings, the urban landscape of the Netherlands will change. The contentious, anonymous lines of housing will be transformed in a combination of houses with different sizes and shapes. This is the complete opposite of what urban planners have been trying to achieve in the Netherlands.

Where housing in the Netherlands is often restricted by rules about height, material and place of the building, the introduction of 3D Concrete Printing in the built environment will ask for a reconsideration of these rules or a decrease in the possible amount of personalization of the houses.

Besides the variety in the design of the different houses the dimensions of the new designed houses also have an impact on the urban landscape. No longer are the houses bigger in depth than they are in width, they are rotated 90 degrees relative to the street. This can have an impact on the length and width ratio of the building blocks in the urban tissue.

It is up to the urban planners of the Dutch built environment to develop a solution to the changes that come with the introduction of the 3D Concrete Printer. Further research in the urban field is necessary to create a statement on this topic.
Figure 12.2: Renzo Piano’s prototype for a flexible mould, used for shaping of plastic.
(Piano, 1969)
Flexible mould.

During this research the possibilities of the 3D Concrete Printer, without any additional resources, are investigated. There is however ongoing research on additional resources that can increase the possibilities of the 3D Concrete Printer. An example of one of the possible additional resources is a flexible mould.

In order to extend the amount of printable shapes a flexible mould could be interesting. The use of a flexible mould in architecture was first developed by Renzo Piano in 1969, who designed a flexible mould for the production of double-curved fibre-reinforced plastic elements. But recently the connection between a flexible mould and concrete is made by H.R. Schippers (2015), who proved that it is possible to use a flexible mould to create double-curved concrete elements.

During my research some test with the 3D Concrete Printer and a flexible mould have been conducted, however the use of the flexible mould asks for a new logic behind printing the concrete. It is proven that the use of a flexible mould can increase the possibilities of the 3D Concrete Printer but more research is needed to determine the most efficient way of using the flexible mould as an additional resource for the 3D Concrete Printer.
Printing multiple materials.

An second addition to the 3D Concrete Printer can be the possibility to print multiple materials with the printer. During my research I assumed that printing both structural and lightweight concrete with the printer is possible since the printing of these two materials follow a similar process. But when it comes to printing with a non concrete-like material further research is needed.

The reason this research can be interesting is for example the possibility to print the non structural elements with other, lighter materials. This can decrease the total weight of the structure which can reduce the amount of structural concrete needed and thus reduces the amount of material needed in the building which decreases the costs of the building.

Another benefit can be the opportunity to print cantilevers. If the printer is capable of printing a temporary support structure on which the concrete structure can be printed, the horizontal parts in the printing part no longer increase the labour costs.

The final advantage can be related to the openings of the building. Research on 3D printing glass is conducted by Neri Oxman (2015). If the 3D Concrete Printer is able to incorporate printing transparent glass the freedom of design in openings in the building significantly increases.
Reinforcement.

A commonly asked question on 3D Concrete Printing is the need for reinforcement? However the design of the house being completely based on compression as in the case with historical structures like Gothic cathedrals, aqueducts, etc., the requirements related to reinforcement can be ignored, which has been the concept in this thesis.

The addition of reinforcement to the printed concrete can however increase the possibilities of the 3D Concrete Printer and the associated design. The reason I choose not to use reinforcement in this thesis is the fact that the way in which reinforcement is added to the concrete is a research in itself.

The traditional way of reinforcing concrete, with steel bars, is a labour intensive job and would decrease the advantages of 3D printing. This is why the reinforcement of 3D Printed Concrete will probably be executed by the addition of fibres in the concrete mixture. This is however, a new technique and the proper way of adding the fibres to the concrete in the right way still needs to be investigated.
REFERENCES
13.1. REFERENCES - LITERATURE


Contour Crafting.

Contour crafting (CC) is a method of layered manufacturing (LM) process that uses polymer, ceramic slurry, cement, and a variety of other materials and mixes to build large scale objects with smooth surface finish (Khoshnevis, 1998). The extrusion process forms the smooth surface of the object by constraining the extruded flow in the vertical and horizontal direction to trowel surfaces. The orientation of the side trowel is dynamically controlled to conform to the slope of surface features. The side trowel allows for thicker material deposition while maintaining smooth surface finish (Khoshnevis et. al., 2006).

D-Shape.

The D-Shape process uses a powder deposition process, which is selectively hardened using a binder. Each layer of build material is laid to the desired thickness, compacted and then the nozzles mounted on a gantry frame deposit the binder where the part is to be solid. Once a part is complete it is then dug out of the loose powder bed. (Lim et al., 2012).
Concrete printing.

Concrete Printing is based on the extrusion of cement mortar. Development has been to retain 3-dimensional freedom and has a smaller resolution of deposition, which allows for greater control of internal and external geometries. (Lim et al., 2012).

Yingchuang.

The Chinese company Yingchuang uses a 150(L) x 10(W) x 6.6(H) m printer to print large scale building components at high speed in their factories. The method is similar to Contour Crafting: an inner and outer leaf is printed, followed by a zigzag shaped inner structure. Pictures show reinforcement being placed in between layers during printing. With this technique, the company has realised multiple houses, a five-story apartment block and a 1,100 square meter mansion. The mixture used contains glass fibre, steel, cement, hardening agents and recycled construction waste materials (Yingchuang, 2015).
TotalKustom.

Contractor Andrey Rudenko has developed a printing technique, similar to Contour Crafting, but with a much smaller layer height (5mm). He believes that, in contradiction to Yingchuang, a cheap house built in a small time span is not the right target. Homes of good quality, which will take longer to build than cheaper buildings, will be more beneficial when including aspects like plumbing, insulation and electrical aspects in the construction process (www.3dprint.com, 2014).

CyBe Additive Industries.

A third party that has adopted the CC technique is CyBe Additive Industries, founded in the Netherlands. This company uses a type of mortar that reaches a bearable strength within minutes. CyBe experiments by attaching a print head to a regular robot-arm, allowing for high diversity in print speed and strategy (Anderson, 2015).
BetAbram.

Slovenian company BetAbram is developing 3D concrete printers for commercial use. Varying sizes of printers will be up for sale and the company has showed their use by 3D printing a concrete staircase. Additionally they are researching a printable concrete, which may be purchased along with all required printer equipment (Alec, 2014).

Emerging Objects.

A similar technique to D-Shape is applied by Emerging Objects (EO), a subsidiary of Rael San Fratello Architects. EO uses a fibre reinforced cement mixture with small-sized aggregates, applying adhesives to improve workability of the mix. This printing method uses two types of binder: an alcohol-based binder, which is a water-soluble synthetic polymer that has high adhesive and mixing properties and high tensile strength. It will help the mix cure more rapidly and cause it to be denser and have greater flexural strength. A secondary binder is added to further strengthen the material, by both hydrating the material and joining the fibres to the concrete mixture. The result is a hybrid concrete polymer (Rael & San Fratello, 2011).


APPENDIX 2

TERRACED HOUSING IN THE NETHERLANDS, 1900 - 2010.
B.1. - APPENDIX 2 - THE HOUSES

Build year: 1900
Location: Weerdstraat 64
City: Meppel
Plot size: 95 m²
House size: 90 m²

Build year: 1910
Location: Lindestraat 27
City: Zwolle
Plot size: 114 m²
House size: 94 m²

Build year: 1921
Location: Grote Beerstraat 40
City: Amsterdam
Plot size: 92 m²
House size: 63 m²

Build year: 1939
Location: Hatertseweg 70
City: Nijmegen
Plot size: 201 m²
House size: 125 m²

Build year: 1948
Location: Colijnstraat 31
City: Breda
Plot size: 144 m²
House size: 76 m²

Build year: 1959
Location: v.d. Werffstraat 23
City: Eindhoven
Plot size: 173 m²
House size: 105 m²

Build year: 1978
Location: de Hoefkamp 1010
City: Nijmegen
Plot size: 157 m²
House size: 140 m²

Build year: 1990
Location: Grote Dijk 6
City: Breda
Plot size: 151 m²
House size: 130 m²

Build year: 2011
Location: Zeilvaart 18
City: Arnhem
Plot size: 141 m²
House size: 109 m²
Build year: 1930
Location: Eckartseweg Zuid 380
City: Eindhoven
Plot size: 132 m²
House size: 120 m²

Build year: 1969
Location: de Koppele 152
City: Eindhoven
Plot size: 300 m²
House size: 130 m²

Build year: 1998
Location: Opera 173
City: Eindhoven
Plot size: 176 m²
House size: 160 m²
Building block: Closed
House dimensions:
Width: 5300 mm
Length: 10540 mm
Ratio: 1 : 1,99

Building block: Semi-closed
House dimensions:
Width: 6060 mm
Length: 6790 mm
Ratio: 1 : 1,12

Building block: Semi-closed
House dimensions:
Width: 5400 mm
Length: 9200 mm
Ratio: 1 : 1,70

The house
B.2. - APPENDIX 2 - SITUATION
Garden Size: 74 m²
Front garden: 0 m²
Back garden: 74 m²

Garden Size: 238 m²
Front garden: 45 m²
Back garden: 193 m²

Garden Size: 85 m²
Front garden: 0 m²
Back garden: 85 m²
Front garden: /  
Back garden: 2  
Orientation: east / west

Front garden: 2  
Back garden: 1  
Orientation: north east / south west

Front garden: /  
Back garden: 2  
Orientation: north west / south east
B.3. - APPENDIX 2 - FLOOR PLANS
1. Entrance
2. Toilet
3. Living Room
4. Dining Room
5. Kitchen
6. Storage
7. Scullery
8. Bathroom
9. Bedroom
10. Corridor
11. Staircase
12. Closet
13. Attic
B.3. - APPENDIX 2 - FLOOR PLANS
B.3. - APPENDIX 2 - FLOOR PLANS
Smoothest threshold

Hardest threshold
B.3. - APPENDIX 2 - FLOOR PLANS
B.4. - APPENDIX 2 - FAÇADES