3D PRINTING CONCRETE ONTO FLEXIBLE SURFACES

Chris Borg Costanzi

Master (msc) Thesis

' 3d Printing Concrete onto Flexible Surfaces'

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Author

Chris Borg Costanzi [BE&A Hons]

SSID: 4411439

Mentors

Prof. Dr.-Ing. Ulrich Knaack	AE+T - Design of Construction
Dr.-Ing. Marcel Bilow	AE+T - Product Development
Prof. Dr-Ing. Rob Nijsse	AE+T - Structural Design

External Committee Member

Frank Koopman	Heritage and Architecture

Delft University of Technology

Faculty of Architecture and the Build Environment

Department of Building Technology

01.West.110

Julianalaan 134

2628BL Delft

The Netherlands

ABSTRACT

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The cost associated with producing concrete elements has a direct link to its geometry. Further cost is incurred if panels have variable thicknesses throughout their cross-section. These variations can take the form of edge-returns in cladding elements (required for detailing), stiffening ribs (required for structure) or simply surface textures (required for architectural expression). In the context of free-form concrete geometries, fabrication of such features becomes even more difficult. Current moulding systems for such elements are in no means cost-effective as individual moulds are still required for every unique panel. What is required is a more flexible approach to the fabrication of complex free-form geometries: a hybrid system of already-existing techniques.

The proposed setup will be a combination of existing systems which includes flexible moulding to cast double-curved panels of uniform cross-section and concrete additive manufacturing for the addition of surface details. The study will explore the possibility of efficiently fabricating complex free-form concrete panels with integrated edge details, ribs and/or surface textures in a more effieient manner than current moulding techniques

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To M.K

join the darkside - we have pencils, computers and 3D printers

1 INTRODUCTION

[1.0] REALIZATION OF FREE-FORM ARCHITECTURE

Throughout the last decades, the realisation free-form architecture has become more commonplace in guiding the direction of contemporary architecture. The radical liberation of the straight and planar to the curved and free is evident in the early works of architects such as Frank Gehry and has now become the paradigm for what Patrik Schumacher refers to as Parametricism (Schumacher, 2008)]. The digital age we are currently living in has given architects and engineers the necessary tools to express themselves with unprecedented liberation [figure 1]. We are seeing a new universe to slowly unfold in front of our very eyes; a strange (and exciting) universe filled with distorted blobs and alien forms [figure 2] ; representing a society of movement, communication and liberation of form.

Figure 1 : Liberation of the line. Zaha Hadid Dongdaem Plaza (2013).
Source: www.zaha-hadid.com

Figure2 : an age of distorted blobs.
Peter Cook | Kunsthaus, Graz (2003)
Source: google images

This has been enabled through the availability of advanced modelling and parametric software packages such as Rhinoceros, Maya and Grasshopper, allowing the new generation of architects and students to deal with complex forms from an early stage of design. Using parametric algorithms and optimizations strategies, the entire process of designing complex forms can easily be integrated to include structural and environmental optimization parameters.

So, why is it that, in an age with so much freedom of information and software; an age where the architect has evolved new skill-sets to become more akin to digital sculptors; an age which should be ripe for the physical manifestation of such free-form shapes, are such geometries still confined to only a handful of iconic buildings? To the domination of architectural competition entries? To the computer screen?

This imposed limitation is largely due to relationship between cost and the extra efforts required for manufacturing and handling complex curved geometries. Further costs are added when façades are non-repetative in nature (which is the situation in most cases) and have additional geometric complexities. However, there still exist drastic limitations due to the cost of producing free-form geometries using non-conventional methods. This is due to different techniques either not providing a satisfactory level of detail, being too energy/labour/material wasteful in their process or simply not yet developed enough to be brought to the mass-production scale. (figures [3, 4, 5])

Figure 3 : Milling techniques can be used to generate complex free-form geometries. How viable is this for large-scale structures?
source: accentform.com

Figure 4 : Use of milled formworks on free-form concrete element - effectively building the structure twice.
source: tailorcrete.com

Figure 5 : Intricate surface detail achieved using expensive milling techniques
source: tailorcrete.com

[1.1] ADVANCED MOULDING TECHNIQUES

There are currently numerous methods in which free-form concrete elements can be produced. Although it is possible to rely on traditional formwork systems for the production of such buildings, more advanced, accurate and efficient techniques are becoming more available. Robotic milling, for example, can be used to produce accurate moulds from foam, wood and polystyrene blocks in which concrete can be cast. If a building skin is made up of highly repetitive elements, this moulding technique could prove to be a viable method for producing double-curved elements, as has already been demonstrated in numerous projects such as the Spencer Dock Bridge in Ireland, which made use of over 1500 EPS blocks (D. Lee, 2015)

However, since by definition, free-form geometries differ from mathematically described primitives such as spheres, cylinders and cones, generating highly repetitive geometries can be daunting and even impossible task (Schipper, 2015). This is an issue which has been studied and tackled over the years; Evolute (M Eigensatz M. K., 2012) created an algorithm that reduces the number of unique elements in a given building envelope. The case study shown in figure 6 below shows how the number of unique moulds required for the production of a facade was drastically reduced from 50,000 to just over 7,000.

Nonetheless, considering the fact that they would most likely be discarded after use, having such a large number of individually-manufactured moulds is far from the ideal situation. In response to this, researchers at TU Delft recently developed an adaptable moulding system for the production of double-curved concrete elements [figure 7]. As the name implies, the method consists of a flexible mould which can be adjusted and re-shaped for the mass-production of different concrete elements; effectively eliminating the issues related to non-repetative penalization.

However, since by definition, free-form geometries differ from mathematically described primitives such as spheres, cylinders and cones, generating highly repetitive geometries can be daunting and even impossible task (Schipper, 2015). This is an issue which has been studied and tackled over the years; Evolute (M Eigensatz M. K., 2012) created an algorithm that reduces the number of unique elements in a given building envelope. The case study shown in figure 6 below shows how the number of unique moulds required for the production of a facade was drastically reduced from 50,000 to just over 7,000. Nonetheless, considering the fact that they would most likely be discarded after use, having such a large number of individually-manufactured moulds is far from the ideal situation.

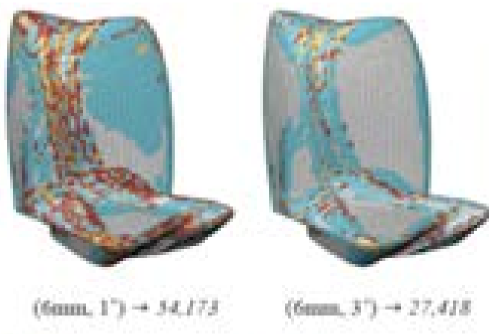


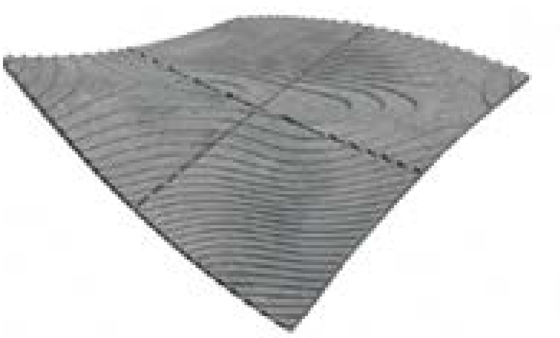
Figure 6 : Rationalisation of number of unique moulds for free-form façades.

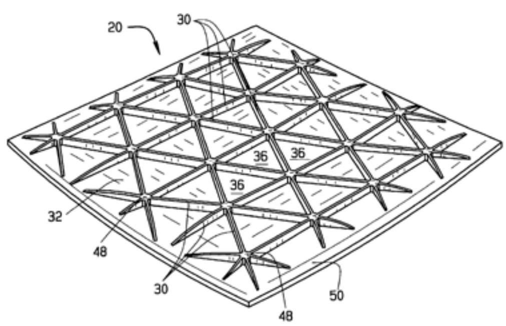
Figure 7: Early principle of Flexible-mould system. Concrete is deformed on an adjusteable pinbed, eliminating the need for moulds for each unique panel.
source: Shipper,H. 2015

[1.2] GEOMETRICAL COMPLEXITY

The production cost of an element has a direct link to the geometric complexity; Further costs are added when façades are non-repetative in nature (which is the situation in most cases) and have additional details such as edge returns (providing monolithic appearances to buildings), structural ribs (providing stiffness to panels) and surface textures (providing architectural features). Edge-returns may be defined as up-stands from the perimeter of panels, as displayed in the figure below and are used to hide the sub-structure which may become visible when viewing joints from obscure angles. (T Henicksen, 2015). It is these small additional details which can really enhance the overall quality of a building envelope. Moreover, in his master thesis Matten (Maten, 2011) showed that the integration of stiffening ribs in a regular dome structure reduced the overall weight by almost 30% when compared to an equivalent-strength shell with regular cross-section.

While there is a demand for the integration of these details, the currently available means of production are costly, time-consuming and/or inefficient in the material use; requiring substantial effort for the integration of relatively small details. As such, in the current state of things there seems to be no cost-effective method for the production of free-form concrete elements having additional geometrical complexities. The scope of this research will focus on proposing an outline for a more cost-effective fabrication technique for the manufacturing of free-form concrete elements having additional geometric complexities.





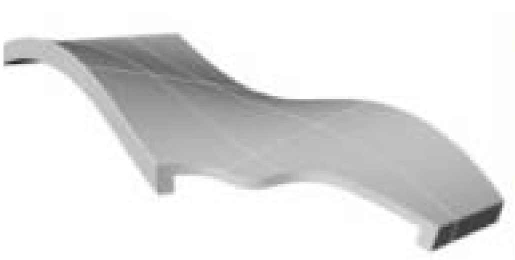


Figure 8 [top left]: Double curved concrete panels with additional geometric complexity: surface texture.
source: author

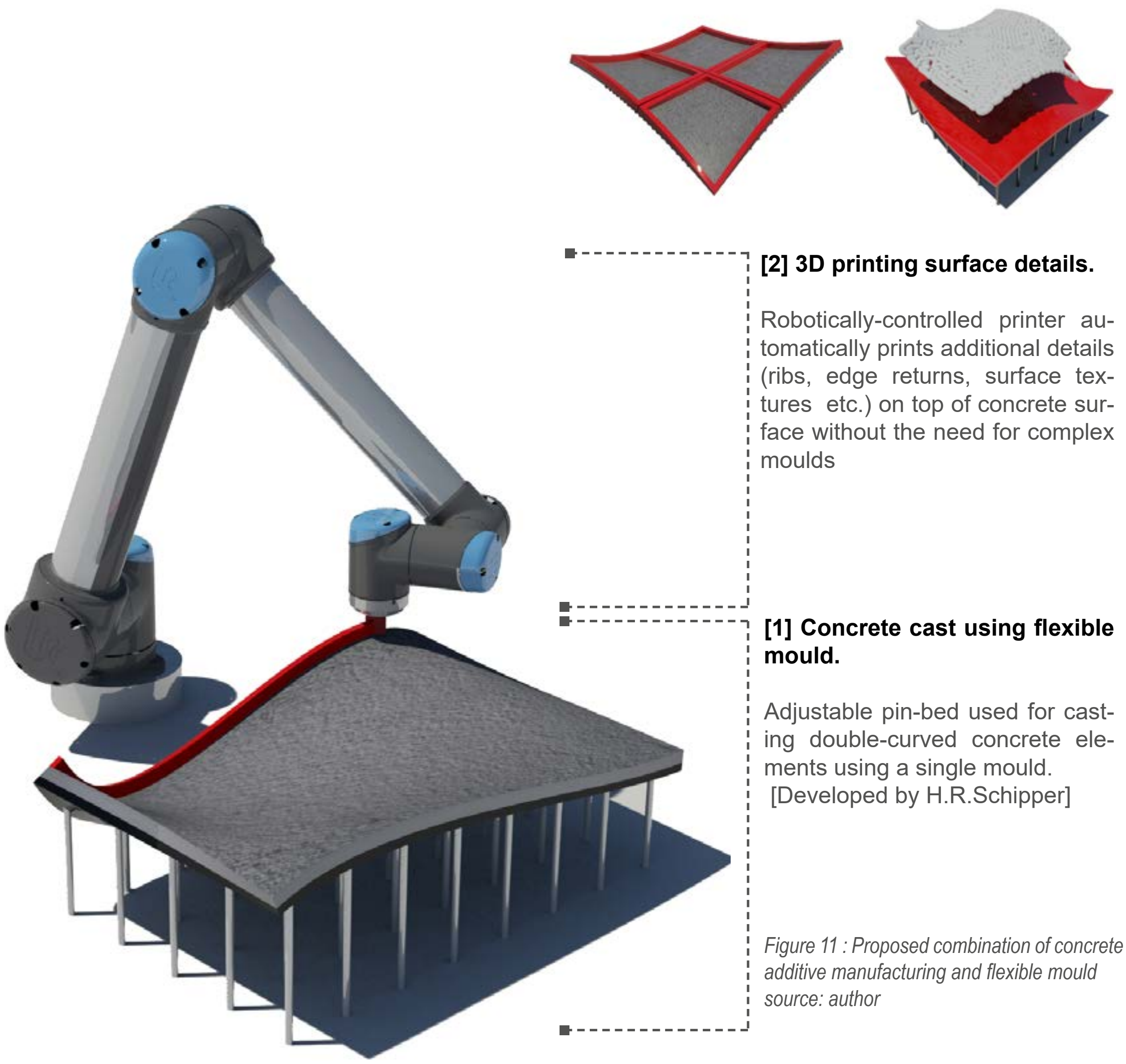
Figure 9 [top right] : Double curved panels with additional geometric complexity: stiffening ribs.
source: add source

Figure 10 [bottom left] : edge return
source: Henriksen [Henriksen, 2015]

[1.3] PROPOSAL FOR HYBRID FABRICATION TECHNIQUE

The flexible mould which was developed at TU delft offers an efficient solution for producing double-curved concrete elements. However, while it does off a very material-efficient technique to manufacturing free-form and double-curved elements, it is currently only limited to producing concrete elements with constant cross-sections; i.e those without edge returns, ribs or surface textures.

What this study proposes is an additional step to this production technique; a hybrid system which combines the flexible mould with another efficient manufacturing process, Concrete Additive Manufacturing. The principle described in figure 10 below shows the proposed setup: casting concrete on the flexible mould and, whilst still in its plastic state, printing on additional details (such as edge returns, stiffening ribs or surface patterns) using robotically-controlled additive manufacturing. This, in theory, could result in a far more efficient method for producing



[2] 3D printing surface details.

Robotically-controlled printer automatically prints additional details (ribs, edge returns, surface textures etc.) on top of concrete surface without the need for complex moulds

[1] Concrete cast using flexible mould.

Adjustable pin-bed used for casting double-curved concrete elements using a single mould. [Developed by H.R.Schipper]

Figure 11 : Proposed combination of concrete additive manufacturing and flexible mould source: author

[1.4] PROBLEM STATEMENT

Existing manufacturing techniques for the production of complex free-form structures are not sufficient for a truly cost-effective approach to the realization of free-form concrete elements with complex surface and sectional details. Traditional moulding methods remain wasteful and limit the possibilities of design. New flexible molding techniques provide a cost-effective solution for the manufacturing of free form façades. Even though flexible moulds allow for non-rationalized panelling, they limit the possibilities for complex surface detailing. New upcoming techniques, such as 3D printing of concrete, allow for detailing but lack in surface finishing.

The currently available manufacturing techniques do not yet offer a truly cost-effective, waste-less approach to the realization of free-form concrete elements with additional surface complexities. The combination of 3D Concrete printing in combination with adjustable mould system is one potential fabrication technique which can satisfy this issue.

[1.5] RESEARCH QUESTION

[1.5.1] MAIN QUESTION

In the context of manufacturing complex free-form concrete geometries, the concept of the combination of 3d Concrete printing and concrete cast using a flexible mould system was established as a potential cost-effective solution to mould-based techniques. The combination of these two techniques, to the author's knowledge at the time of writing, has not yet been researched. Thus, the following research question to the topic formulated states:

What is an effective methodology of combining 3D Concrete printing and concrete cast using an adaptable system for the production of free-form complex concrete geometries?

[1.5.2] SUB-QUESTIONS

In order to propose a new manufacturing system, it is first imperative to study what systems already exist to understand the feasibility.

What are the manufacturing techniques currently used for fabricating free-form concrete elements with additional surface details?

- *How material and energy efficient are these production techniques?*
- *What are the geometrical limitations of these techniques?*

While such a combination could open up new possibilities in effective manufacturing techniques, it could also be limited to purely novel applications. Thus, a sub question to the research methodology is to determine:

While such a combination could open up new possibilities in effective manufacturing techniques, it could also be limited to purely novel applications. Thus, a sub question to the research methodology is to determine:

What are the practical applications for 3DCP on double-curved concrete surfaces?
- *Geometries and details possible*
- *Applications possible – Architectural, structural.*

As the combination of 3D-Printed concrete and cast-concrete as a free-form surface has not yet been explored, to the author's knowledge at the time of writing, the following sub questions arise

What are the limitations and benefits of combining 3DCP and adjustable moulding systems?
- *What level of detail is possible to be achieved?*
- *What effect does the shape/size of end effector have on the extruded material?*

[1.6] AIMS

The aims of this study are to:

1. To establish a cost-effective manufacturing framework using the combination of 3D Concrete Printing and an Adjustable Mould system for the production of Free-form complex concrete geometries.

2. To identify the potentials and limitations of combining two previously distinct Manufacturing techniques

3. To identify the foreseeable applications of the combinations of such techniques

[1.7] OBJECTIVES

1. To establish a cost-effective manufacturing framework using the combination of 3D Concrete Printing and an Adjustable Mould system for the production of Free-form complex concrete geometries.

2. To identify the potentials and limitations of combining two previously distinct Manufacturing techniques

3. To identify the foreseeable applications of the combinations of such techniques

[1.8] FOCUS AND RESTRICTIONS

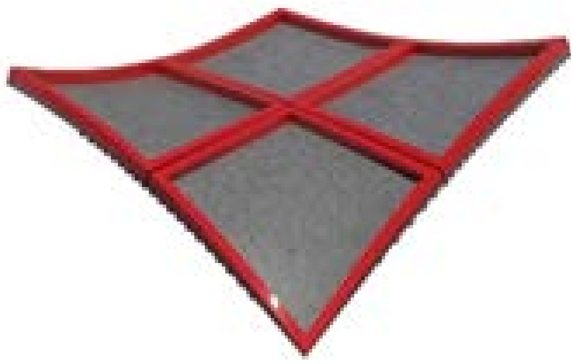
At the time of writing, the foreseeable applications for such a technique can be divided into three categories:

a. *Architectural: Referring to the application of printing intricate surface patterns and textures generated using digital modelling techniques.*

b. *Façade Detailing: Referring to the application of printing in edge-returns around the perimeter of free-form concrete panels*

c. *Structural: Referring to the application of printing ribs with the aim of stiffening the Element as a whole.*

Due to time and resource restrictions, the focus will be on printing edge details on the perimeter of a panel. This restriction will allow for a proof-of-concept for the manufacturing technique without getting lost on the subjectivity of generating patterns for case [a] or the analysis and form generation of case [c]



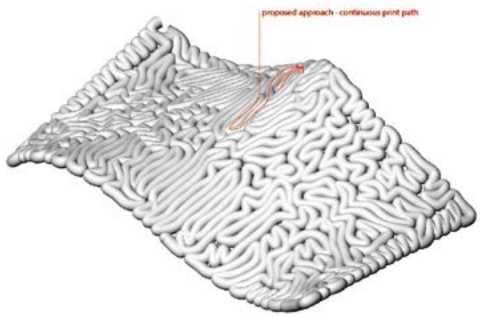


Figure 12 : Printing strategies: [left] Printing edges and casting. [right] fully-pinted panels
source: author

2 LITERATURE REVIEW

[2.1] CLASSIFICATION OF GEOMETRY

Prior to evaluating the current manufacturing techniques, it is necessary to have some form of shape classification as well as their degree of complexity. This will allow for a proper comparison between existing manufacturing techniques and allow for proper mapping of their respective advantages and limitations.

[2.1.1] CLASSIFICATION OF GEOMETRY : CURVATURE

The following section will give classifications for different geometries, as well as a description of certain terms which will be used throughout the thesis. From a geometric point of view, the complexity of a given shape can be classified in terms of curvature (S. Floery, 2010) and may be distinguished as the following:

a. Flat/Planar Surfaces
b. Single Curvature Surfaces
c. Double Curvature Surfaces

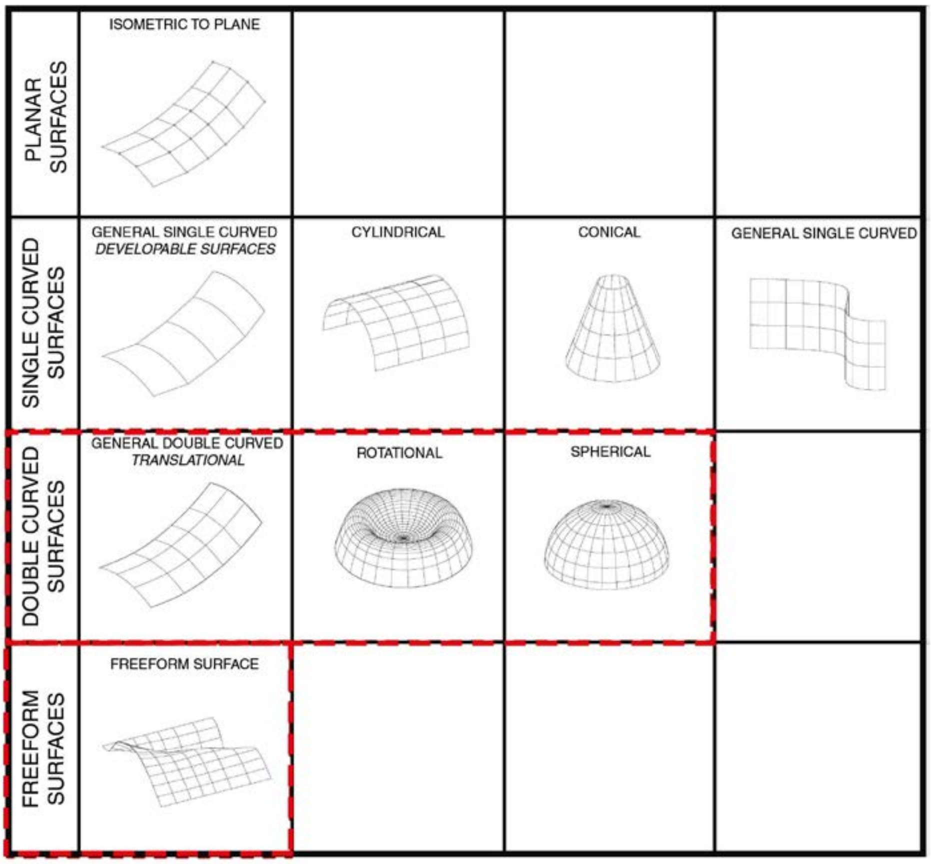


Table 1: Classification of Geometry. Red box indicates area of interest for this thesis
Source: Author's interpretation of Henriksen, 2015]

Whilst planar surfaces are the easiest geometries to produce, when used in the context of curved buildings the results are usually faceted due to approximation; a characteristic which may not portray the desired aesthetic of the building [Table 1] (M Eigensatz M. D., 2010). Figure 11 shows the use of panellized planar surfaces to represent double-curved and free-form elements - while the result does give the representation of a free-form building, it may not necessarily adhere to all architect's standards for aesthetic requirements.

Figure 13: Using planar surfaces to approximate free-form shapes.
Source: http://www.discretization.de

Smoother results can be achieved with the introduction of degrees of curvature; single-curved panels may give more fluid results, however this is highly dependent on geometrical restrictions as shown in Table 1. As demands for more fluid free-form buildings increase, the shift towards doubly-curved and free-form penalisation becomes more apparent.

The issue, however, is that while there have been good advances in digital modelling techniques that allow for fluid, free-form architecture, the digital machining and production technologies are still lagging behind (T. Henriksen, 2015). These unparalleled developments between manufacturing and digital design impose several limitations and become more apparent when geometries have additional complexities such as edge-returns, stiffening ribs, offsets etc.

The context in which this thesis will be concern relates to double-curved and free-form surfaces, in other words, those which are currently the most complex to realise.

[2.1.2] CLASSIFICATION OF GEOMETRY : ADDITIONAL COMPLEXITY

Whilst In the previous section geometries were classified in terms of their curvature, this section will classify geometries in terms of variations in their cross-sections. These variations include stiffening ribs, edge returns, offsets and architectural patterns and are shown in Table 2.

Each of these surface variations are used in different contexts and, thus, have different requirements. Edge returns and offsets are architectural up-stands around the perimeter of panels and thus require smooth and monolithic appearance (T. Henriksen, 2015) with the underlying difference between the two beings that offsets usually have significant depth. Stiffening ribs, on the other hand, can be used to increase the structural efficiency of a panel as shown by Maten (Maten, 2011) and thus has different requirements. Nonetheless, each of these features have similar production processes for planar surfaces, however as curvature of panels increases, the

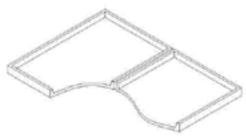
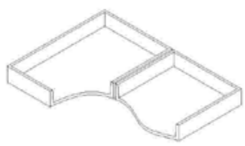
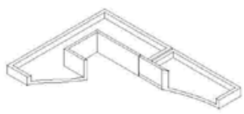
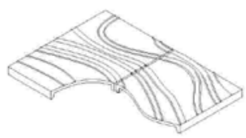
EDGE RETURNS		- upstand around perimeter of panel used to hide sub-structure - surface finishing - not so significant depth
STIFFENING RIBS		- upstand around perimeter panel \ inside panel used to increase structural and material efficiency - significant depth
OFFSETS		- upstand around perimeter of panel near openings / overhangs - surface finishing
SURFACE PATTERNS		- architectural ?

Table 2: Classification of Surface complexity
Source: author, edited Henriksen 2015

In his recent PhD Publication of thin-Walled GFRC panels with complexities, Henriksen shows how the difficulties of manufacturing increase as panels move from flat geometries to free-form surfaces. Table 3 shows how as curvature increases, difficulty of production increases. The same can be said for increasing surface details with the most difficult panels being free-form panels with additional details.

Curvature	Homogeneous Surface	Returns, Offsets, Stiffening Ribs	Constant Curvature	Changing Curvature	Changing curvature with additional features
Flat	*	**	X	X	X
Single Curved	**	***	****	*****	******
Double Curved	***	****	*****	******	******
Freeform	****	*****	X	******	******

*Table 3: Classification of manufacturing difficulty. [Difficulty increase represented by number of * with * being easiest and ****** being the most troublesome]*
Source: Henriksen, 2015

[2.1.3] DISCUSSION

As was shown in this section of literature, as geometries become more free-form and complex, so do their underlying manufacturing techniques. Flat / Planar surfaces are by far the easiest elements to produce and as a result, are often used to represent curved buildings, as shown in figure 11. Although this approach can indeed give the impression that the building is comprised of double-curved elements if used in the correct size and tessellation and if seen from the required distance. However, for buildings with greater degree of curvature or with stricter aesthetic requirements (and higher budgets), double curved and free-form elements will most likely be used.

Although it is currently possible to produce all the geometries described in Table 3 in one way or another, production methods can become complex and material-wasteful as will be shown in the following chapter. As Henriksen (T. Henriksen, 2015) notes in his research, new approaches to the advances in the design and production of elements having complex geometries should be capable of efficiently producing all four surface categories.

[2.2] EXISTING FABRICATION TECHNIQUES FOR THE PRODUCTION OF FREE-FORM CONCRETE GEOMETRIES

The overall aim of this thesis is to provide a fabrication solution to the production of free-from concrete panels having geometrical complexity. In order to be able to improve on existing concrete fabrication systems it is imperative to have an evaluation on the existing fabrication Techniques. This, in this chapter I shall describe the most commonly used and relevant formwork systems for the production of free-form concrete panels.

Whilst In the previous section geometries were classified in terms of their curvature, this section will classify geometries in terms of variations in their cross-sections. These variations include stiffening ribs, edge returns, offsets and architectural patterns and are shown in Table 2.

Each of these surface variations are used in different contexts and, thus, have different requirements. Edge returns and offsets are architectural up-stands around the perimeter of panels and thus require smooth and monolithic appearance (T. Henriksen, 2015) with the underlying difference between the two beings that offsets usually have significant depth. Stiffening ribs, on the other hand, can be used to increase the structural efficiency of a panel as shown by Maten (Maten, 2011) and thus has different requirements. Nonetheless, each of these features have similar production processes for planar surfaces, however as curvature of panels increases, the

[2.2.1] COMPUTERISED NUMERIC CONTROL [CNC] MILLING

Computerised Numeric Control (CNC) milling is an advanced solution to producing complex forms in concrete. In this fabrication technique, a spinning chisel is used to essentially carve out complex moulds in wood, synthetic materials, foams and metals, generated using 3D-CAD models. (Schipper, 2015). The most common material used in this system is EPS; timber is generally used when low-curvature is required due to the complexity of manufacturing. The chisel is usually mounted onto a Robotic arm to increase the reach and degrees of freedom or on gantry system.

Materials cast using this method of fabrication offer several advantages to traditional systems of forming. The greatest advantage is perhaps the freedom of forms that can be realised – practically any form can be realised, so long as no internal cavities exist (Vergaeg, 2010). Moreover, geometries of the milled element are directly generated from a 3D-CaAD model, drastically reducing problems of misinterpretation of geometries and human errors.

The accuracy of such moulds is greatly dependant on the diameter of the chisel: narrower chisels provide greater resolution, however this also resulting a longer tool path needed to be milled, resulting in an increase in fabrication time (Vergaeg, 2010)]. Moreover, milled blocks are also never completely smooth and generally either require additional coatings of Polyurea or Polyurethane (Schipper, 2015) to provide a smooth surface or further processing after casting. The geometrical complexity that can be realised is also highly dependent on the mounting system the tool bit is attached to: while 6 degrees of freedom gives the most freedom of fabrication, it is also the most costly; reducing the degrees of freedom also reduces the degree of complexity possible.

Numerous buildings and installations have been realised using this technique. The EPFL learning center in Lausanne made use of a combination of 1500 wooden moulds coupled with standard scaffolding, whilst the Spencer Dock Bridge was constructed using EPS formwork. More recently, Tailorcretete constructed a free-form concrete structure using robotically-milled EPS moulding systems (Tailorcrete, 2014). The architects used the advantage of milling precision to even include fine surface details in the form of controlled 'dots' allowing for a great degree of design freedom. The drawback, of course, being that this constituted large periods of milling time as well as wasted formwork. Moreover, complex reinforcement had to be fabricated to match the shape. [figure 12]

Figure 14: Production process of free-form concrete sculpture using CNC-Milled EPS blocks. source: Tailorcrete

[2.2.2] CONCRETE ADDITIVE MANUACTURING

The use of Additive Manufacturing concrete in the construction for the production of free-form members is becoming more commonplace. Additive manufacturing processes are capable of translating 3D Digital models into physical representations by subsequently bonding layers of material (R.A Buswell, 2013 (chec)). Concrete additive manufacturing works in the exact same principle, as shown in figure 15 below. This layer-by-layer approach allows for fairly-freeform elements to be realised, though in most cases, the geometries are restricted to being self-supporting during printing to avoid collapse. (D.Lee, 2015)

The printing techniques offer a very rapid means to produce certain geometries and, contrary to other techniques such as milling, generally do not have any wasted materials except for support material in some cases. The greatest advantage with concrete additive manufacturing is that, generally speaking, no additional cost is associated with product complexity and customization. Still in its relative infancy, it has applications ranging from mass-production of small and medium-scale buildings (Winsun) to printing entire coastal reefs for ecological regeneration (3ders.org, 2012) However, the layer-wise approach to manufacturing may lead to very rough surface textures [figure 16] resulting in some techniques, such as D-shape, requiring extensive post-processing.

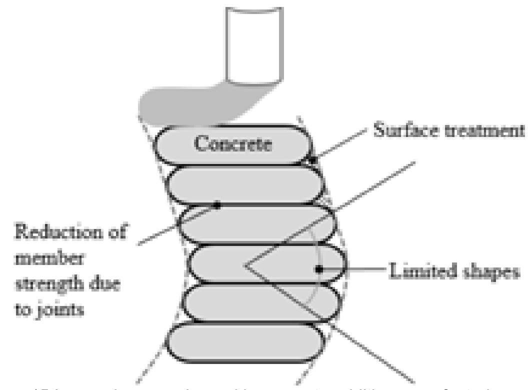


Figure 15 Layered approach used in concrete additive manufacturing source: D.Lee et Al, 2015

Figure 16: Manufacturing of free-form panels using concrete additive manufacturing. Note: surface finish exhibits layered texture source: Buswell et al. Lonborough university

[2.2.3] FABRIC FORMWORK

Textile, or fabric, forming is a fabrication system which involves the use of membranes, fabrics and/or plastics as the main material for concrete moulds. Unlike most other formworks such as CNC milling and traditional formworks, the method makes use of flexible materials which deform under the pressure of wet concrete. Controlling the deformation of the fabrics can result in forms exhibiting curvature and, when used in combination with certain plastics, can also show excellent surface finishing that is not usually associated with concrete. (Schipper, 2015)

The technique has been heavily researched, particularly at the University of Bath (J.J Orr, 2012 (check)) and is most active in the CAST Group, headed by Mark West at the university of MIT on both structural and architectural applications. Research into the production of double-curved panels for façade elements conducted by (Vergaeg, 2010) produced double curved elements having superior surface finish by integrating ETFE Foils. However, it was also shown that the freedom of form as well as control over geometry is quite limited when compared to other techniques. This is because textiles have to be stressed between an external moulds which defines the desired shape.

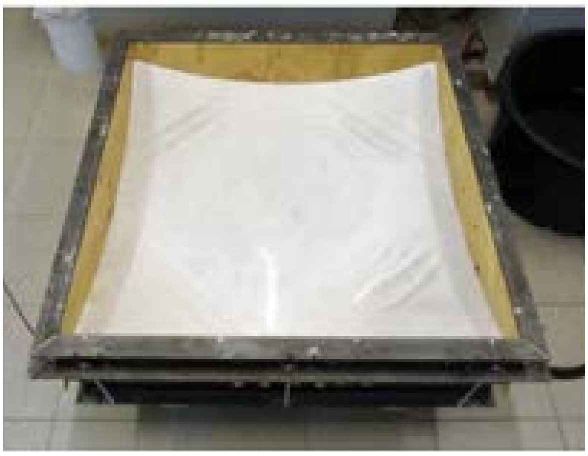


Figure 18 [top left] Fabric casting principles: Membrane is stretched across a pre-defined border into which concrete is case
source: Vergaeg, 2010

figure 19 [top right] Smooth finish of concrete cast using textile
source: Vergaeg, 2010

Figure 20 [bottom} More complext patterns being cast using more complex moulding systems
source: C.A.S.T

[2.2.4] FLEXIBLE MOULD SYSTEM

The principles of flexible moulding systems are relatively straight forward. An adjustable formwork, consisting of materials such as rubber (Schipper, 2015) or even steel meshes (A.Pronk, 2014), is deformed into a curved surface by means of pistons, actuators or pin beds .This deformed surface serves as a base surface on which materials can be formed or cast. Although concepts for adaptable moulding systems have been in development since as far back as 1969, with research on adaptable moulding systems for the use of FRP being carried out by Renzo piano, it is only recently that extensive progress has been made on the system being used as an efficient fabrication technique for concrete elements.

The adaptable system developed by Schipper has a very smooth production line;

a. A pin-bed is adjusted such that it represents the overall shape of the desired geometry to be cast. The data for pin heights can be extracted from digital models used to generate the geometry. At this point, the flexible mould is still kept horizontal

b. A laser is used to project the boundaries of the curved element onto the horizontal . Edges are cut out of flexible material and positioned on the mould.

c. Concrete is cast inside the mould and left to set for a short period of time to allow for concrete to gain initial strength. This is an important step, as if concrete is left too fluid it will fall out of the mould; too stiff and cracks will appear.

d. The mould is left to deform to a shape defined by an underlying pin-bed. At this stage, the concrete is still wet and as such must be left to harden for a period of time

e. Once the concrete has set, it is de-moulded and the entire process is repeated again

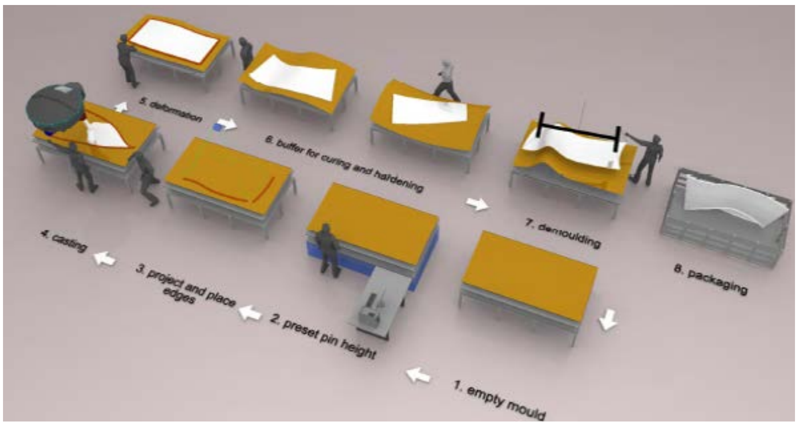


Figure 21 Flexible Mould Production Process
source: H.R Schipper, 2015

The advantage with such a system over other techniques is that there is considerably far less wasted material; it is only the edge boundaries that are have to be produced with every unique panel. In combination with multiple flexible mould, this production technique can serve as an efficient method for the mass-production of double-curved concrete elements.

The limitations with this method, however, is that it currently can only produce concrete elements of constant thickness; there is currently no possibility of adding extra complexities such as stiffening ribs or edge return details. For this to be possible, it a negative mould would most likely have to be used as shown in figure. In this aspect, integration would add considerable complexity to the manufacturing process [Schipper]

Figure 22 : Curved element with additional geometric complexity
source: H.R Schipper, 2015

Figure 23 : Manufacturing principle Ribbed Elements
source: Author [interpretation of Matten(?) check source]

[2.2.6] PNEUMATIC FORMWORK

Though generally used on larger scales than individual panels, vacuumatic systems make use of air pressure to inflate formwork onto which concrete is sprayed. An alternative method which uses the same underlying principle is to first cast concrete ontop of an uninflated sheet which is gradually inflated while the mix is still wet. These are commonly referred to Bini Shells, first used as far back as 1964.

More recent developments in the class of pneumatic concrete forming were achieved by Frank Hubeijen. The research which was focused on the use of Vacuumatics, showed that plastic enclosures willed with particles could be filled with concrete, inflated and shaped for forming. Although this system was shown to have great potential in the fact that very little formwork is needed, issues regarding accurate shaping still need to be figured out. Moreover, since the deformed shapes start out from flat pieces of material, geometries used should, by definition, all be developable surfaces.

Figure 24 Developable concrete strip - Horizontal element transformed into arch
source: F.Hubijen, 2015

[2.2.7] ADDITIVE/SUBTRACTIVE MANUFACTURING

Current research on-going at the Danish Technical University is exploring the potential of a hybrid approach to manufacturing double-curved and free-form laminated concrete panels. Using a combination of robotically-controlled subtractive manufacturing, additive manufacturing and assembly, the novel approach to fabrication is capable of embedding carbon-fibre meshes directly into free-form panels: providing a solution to complex bespoke reinforcement strategies.

This approach prints concrete directly onto a milled surface instead of casting - while it allows for the integration other features, such as reinforcement, the overall surface finish is that having a distinct layered texture, which may require post-processing to achieve a smooth surface.

The speed of producing a panel is unknown to the author at the time of writing (information obtained is through correspondence), and as such it is unknown whether printing an entire surface will be a faster technique as opposed to more established techniques such as sprying or casting. However, print speeds and resolution of concrete additive manufacturing are expected to keep on improving (Buswell). The greatest advantage of this approach therefore lies in the ability to make use of multi-material additive manufacturing; combining different materials (such as carbon fiber reinforcement) into a single element.

While this is a very innovative fabrication technique, there seem to be some drawbacks. Firstly, the use of CNC Milled-moulds present the same material waste as in all cnc-milling fabrication approaches. Secondly, as shown in figuress 22 and 23, the use of 3D Printing results in a certain surface characteristic which may not meet aesthetic requirements.

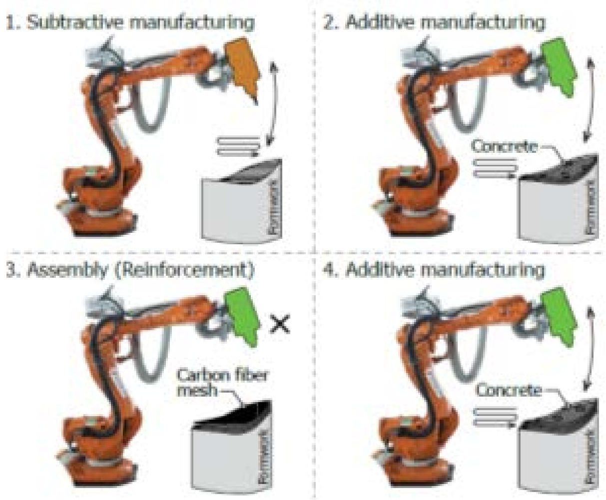


Figure 25: Hybrid manufacturing technique usingCNC-Milling and Additive Manufacturing.
Source: Silva,2015

Figure 26: Hybrid manufacturing technique usingCNC-Milling and Additive Manufacturing - Prototype
Source: Silva,2015

[2.2.8] HYBRID: FLEXIBLE MOULD D AND WAX

In an attempt to mitigate the issues of waste exhibited by CNC milling, researchers at ETH Zurich developed a hybrid manufacturing system consisting of an adaptable surface and wax. In the system proposed by ETH Zurich (S Oesterle, 2012) , a flexible mould is used in a similar manner to that developed by Schipper. The difference in techniques is that hot wax is cast onto the flexible bed which then solidifies to serve as temporary concrete formwork. The wax is later melted down and re-used in the same process.

This technique is particularly useful for producing concrete elements having variations in cross-section (as shown in figure 27). It also reduces the turn-over time since once the wax is demoulded, the adjustable mould can be used to cast new elements. The downfall with this technique is that far more formwork is produced for the production of a single element (one panel would require two wax moulds) as well as energy required to re-melt wax back into its liquid form once the concrete has been set.

Similar to the other hybrid system described above, one of the major issues here is generating the edge definition for a panel which is generally normal to the edge of a surface. In the case of flat and single-curved panels, this does not pose much of a problem, however, moving towards double-curved and free-form surfaces these edges become twisted as shown in figure 26 below. This adds a certain degree of complexity in the manufacturing process.

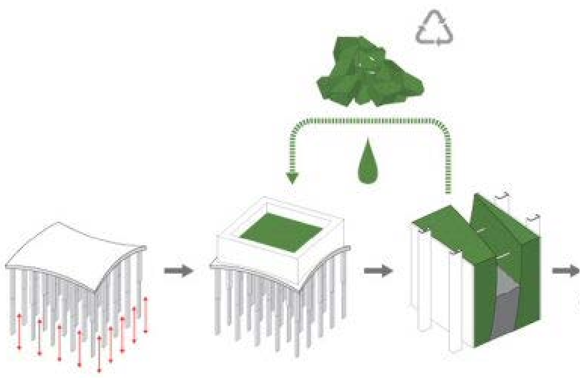


Figure 27: Zero-Waste Mould Concept with flexible mould
source: Tailorcrete.com

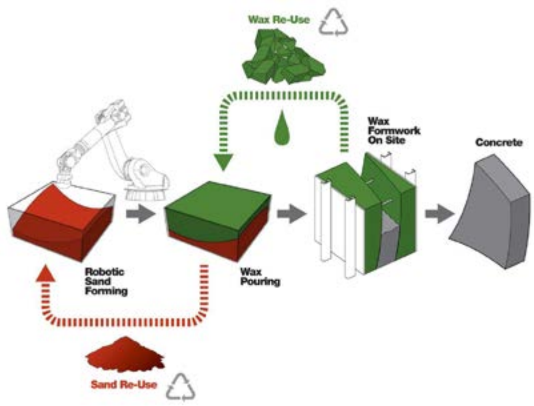


Figure 28: Zero-Waste Mould Concept II
source: Tailorcrete.com

[2.2.9] HYBRID: MILLED MOULD D AND WAX

In keeping in the same theme of Wasteless-processes, the same research group at DTI developed a hybrid manufacturing technique using CNC-milled sand and wax casting. The principle is based on using wax as a primary mould on which wax is cast. Wax cast is later used as a moulding formwork, similar to the concept explained above. The advantage of such a system is that more intricate detailing, edge returns etc. are most-likely possible to be achieved using the same principles of robotic CNC moulding.

The drawback of this system, however, is that a single concrete element depends on three independent fabrication processes (the milling of primary sand mould; the casting of two wax moulds and casting of the final formwork) as well as the issue of requiring energy to melt down the wax to be re-used.

[2.2.10] HYBRID: MILLED MOULD D AND WAX

A method currently being researched in response to the issues of reliance on milled moulds is that of Thomas Henriksen (T. Henriksen, 2015) Henriksen acknowledges the fact that for complex geometries, expensive and time-consuming CNC-machined moulds are needed, which can only be re-used a number of times.

In a similar concept to 'Zero Waste Mould' (S Oesterle, 2012) described in sections 2.2.6/7, the proposed system makes use of a flexible table to cast negative moulds, eliminating the issue of complex 3d Milling. By first projecting the intended geometry onto the flexible surface, the correct shape of the new mould is formed. Fast-curing expandable foam is then cast in between borders defining geometry – allowing for a far quicker turn-over time (30minutes) (T. Henriksen, 2015). The result is a far quicker manufacturing process since concrete casting is done on the foam moulds and not the flexible table; allowing for the full potential of the flexible table to be used. The manufacturing is still in development: while it does offer a far less material-wasteful alternative to CNC milling moulds, foreseeable issues regarding generating the proper edges to define the shape arise. Moreover, the use of expandable foam as well as creating of edges results in more material waste than that generated using the flexible mould method – as such a balance is what is needed. The limitations of geometries for this production method are the same as those of the flexible mould system.

Table 4 shows a summary of the techniques discussed in this section, pointing out important advantages as well as limitations. Milled formwork gives the greatest freedom in generating geometries with all degrees curvature. However they are also the most material wasteful, even when there is repetition, and also take a considerable amount of time to be produced

Other systems, such as pneumatic and fabric forming systems perform better in terms of material use, however there is a lesser degree of accuracy and have greater geometrical limitations.

The adaptable mould system presents a very promising solution to the issue of wasted material (milling) and accuracy (fabric forming). Using a flexible formwork allows for double-curved and free-form geometries to be produced without the expense of wasting material. While there is a certain degree of restriction on the curvatures that can be produced, the majority of panels used in façades are not composed of extreme amounts of curvature anyway.

Hybrid systems, such as those proposed by Henriksen (T. Henriksen, 2015) and Oester (S Oesterle, 2012) , speed up the manufacturing process by using the flexible table to cast moulds instead of concrete. The use of fast-curing moulding material speeds up the turn-over time and frees up the flexible table to be used at a higher rate of production. This, however, presents new challenges: The wax formwork presented in the Zero-Waste concept requires two moulds to be cast for every concrete panel (S Oesterle, 2012) which later have to be melted down to be recycled, presenting a new issue of high energy input. While the use of expanding foam presents a rapid method to produce negative moulds, the result of this method is a new form of waste-stream generated – though this can be improved through the use of biodegradable materials. In both cases, generating 'boundary edges' perpendicular to the surface can become problematic especially when dealing with double-curved and free-form panels.

While it cannot generate the same curvatures as those possible with CNC milling, it has a very low level of material waste. Hybrid systems, such as those proposed by Henriksen (T. Henriksen, 2015) and Oesterle (S Oesterle, 2012) speed up the manufacturing process by using the flexible table to cast negative moulds on which concrete is cast; allowing for a faster turn-over time. This, of course, comes at the expense of having to introduce additional materials and steps in the manufacturing process.

The use of Additive manufacturing on a temporary support mould seems to offer great potential as a fabrication strategy. Although the proposal put forward by Silva (Silva, 2015) seems to have some limitations such as wasted material using milled formwork and surface finishing not being to a high degree, there is potential for some improvement. Rather than using milled moulds, for example, perhaps an adjustable formwork could be used to generate the temporary mould, eliminating the issue of waste material. Regarding surface texture, one solution could be to spray on an initial layer of concrete that would provide a smooth surface finish onto which successive lamination layers of reinforcement and concrete can be printed.

[2.2.11] CONCLUSION

While there is no one ‘perfect’ manufacturing technique for the production of double-curved/free-form panels, it is an adaptable moulding systems which seems to show the greatest potential to provide an efficient means of fabrication for these geometries. Hybrid systems which combine the use of the adaptable mould and other systems also show great potential, however the issues of additional material use for generating negative moulds, as well as the issue of complex edges (section 2.2.8) need to be solved.

Using Additive manufacturing in combination with the adaptable mould system also shows great potential in producing far more complex geometries, however the issues of surface finish also needs to be solved.

[2.3] EXISTING FABRICATION TECHNIQUES : FREE-FORM CONCRETE ELEMENTS WITH ADDITIONAL SURFACE DETAIL

While the previous chapter focused on manufacturing techniques used for the production of double-curved concrete panels, the following chapter presents an overview of techniques used specifically for the addition of surface details as defined in section 2.1. These techniques will be represented by a series of case-studies of real-life projects, patents and on-going research.

[2.3.1] MILINKOVICH: PATENT FOR RIBBED ELEMENTS

Milinkovic (Milinkovic, 2010) have patented a manufacturing technique for the production of ribbed concrete panels. The principle makes use of a double-mould system: a 'negative' steel box which is enclosed by series of removable steel plates [figure 27]. The results are flat panels with reinforcing ribs around the perimeter as shown in figure which can be used for the construction of simplified buildings with high amounts of repetition. The same principle can also be used for the production of edge returns and offsets of simple flat-surfaces.

Although Milinkovic's technique can be used for the production of ribbed panels (and potentially, edge returns/offsets), it is severely limited to simple flat geometries with high amounts of repetition, such as the hangar-type of structures displayed in figures 28. For the production of elements with curvature, far more complex moulds are required. The greatest issue, however, is that this casting technique is heavily reliant on repetition of simple geometry and has no real place in bespoke construction.

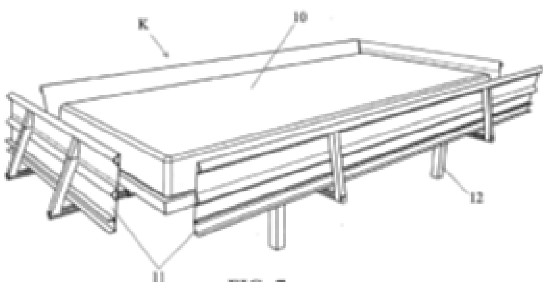


Figure 29: Heavy steel plates used to define edges and ribs in the Milinvoich Method
Source: Milinkovich&Milinkovich, 2010

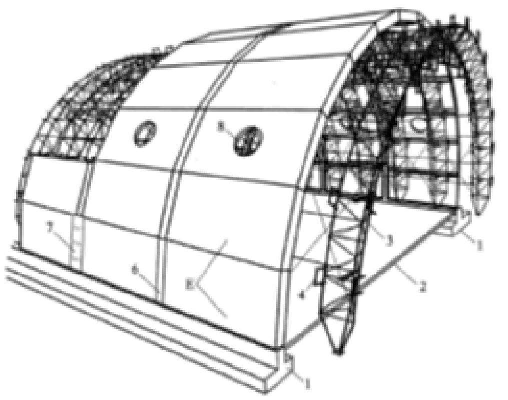


Figure 30: Production technique best suited for heavy-repetition and simple geometry, such as hangars.
Source: Milinkovich&Milinkovich, 2010

[2.3.2] CNC MILLED MOULDS

Advanced moulding systems provide an automated and precise method for casting concrete elements. These fabrication techniques are commonly used for constructing complex ribbed structures in concrete, edge returns and offsets. Similar to the principles described in Milinkovic's Patent, double-sided moulds are required to create the desired geometry

The pre-fabricated concrete canopy in Hilversum, for example, was cast using milled timber formwork and Fibre-reinforced Ultra High Performance Concrete (F. Van Herwijnen, 2005). Wooden blocks were used to provide a counter mould in which the UHPC was poured.

Figure 31: Wooden counter mould used into fabricate ribbed elements in Hilversum
source: Herwijnen, 2005

Figure 32: Complete canopy in Hilversum
source: Herwijnen, 2005

Although a very complex rib-pattern was cast using this system resulting in a high degree of structural and material efficiency (P.Block, 2014), there was also a high amount of energy-input required to produce the mould. This also means that new complex moulds would be required for each unique flooring system.

Both these examples show the potential of using milled moulds for producing ribbed elements as well as those with additional details such as edge returns, offsets and surface textures. However, while there is far more design freedom than the method patented by Milinkovich, the underlying problem of non-adaptability still remains. Moreover, this method is low and costly, given the milling time required to make each mould (T. Henriksen, 2015)

In the concluding remarks, Block (P.Block, 2014) acknowledges that while using milled formworks provide an effective means for casting these complex geometries, a more flexible approach is needed for bespoke-fabrication strategies for the system.

Figure 33: Use of multiple EPS Moulds to create rib-stiffened funicular floor system. The result is a neat and accurate geometry, however, is the manufacturing process efficient?
source: ETH Block Research Group

[2.3.3] CONCRETE ADDITIVE MANUFACTURING

Concrete Additive manufacturing is making its way into the construction industry. Although there have not yet been any applications specific to the printing of additional details as described, it's use to print walls shows potential hypothetical application to the area of concern.

3DCP, for example, uses UHPC to produce free-from massive wall systems, whilst contour-crafting uses lower-strength mortars to create outer skins of walls. The underlying difference between these two techniques is that although 3DCP uses a higher-strength mix, the results are usually messier. Contour-crafting, on the other hand, uses side-trowels to create neat, well-defined extrusions in mortar. It can be foreseeable that these could easily be applied to other applications such as stiffening ribs, edge returns and textured faces on free-form concrete panels.

Figure 34: Use of multiple EPS Moulds to create rib-stiffened funicular floor system. The result is a neat and accurate geometry, however, is the manufacturing process efficient?

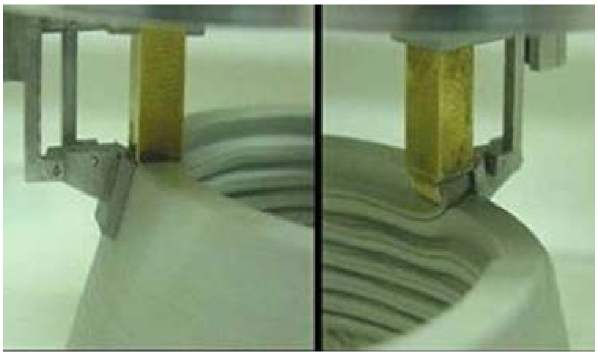


Figure 35: Use of multiple EPS Moulds to create rib-stiffened funicular floor system. The result is a neat and accurate geometry, however, is the manu-

[2.3.4] HATSCHEK METHOD / HYBRID FOAM AND FLEXIBLE MOULD

The automated pre-mixed method is generally used to produce flat thin sheets of glass-fibre reinforced concrete. It is also possible to fold the concrete sheets whil¬e they still exhibit plasticity (i.e in their 'greenstate') (T. Henriksen, 2015), however, additional supports are required to prevent these folds from breaking off.

When it comes to producing single, double and free-form elements it is not possible to use this folding technique since it would result in 'creasing' and formation of ripples along the upper surface (T. Henriksen, 2015). Thus, while this method does give a relatively simple solution to producing flat panels with some degree of complexity (namely edge returns and offsets; ribs are not possible), it is not a preferable technique for producing single, double and free-form elements with the added complexities.

A method currently being researched in response to the issues of reliance on milled moulds is that of Thomas Henriksen (T. Henriksen, 2015) Henriksen acknowledges the fact that for complex geometries, expensive and time-consuming CNC-machined moulds are needed, which can only be re-used a number of times. In a similar concept to 'Zero Waste Mould' (S Oesterle, 2012) described in sections 2.2.6/7, the proposed system makes use of a flexible table to cast negative moulds, eliminating the issue of complex 3d Milling. By first projecting the intended geometry onto the flexible surface, the correct shape of the new mould is formed. Fast-curing expandable foam is then cast in between borders defining geometry – allowing for a far quicker turn-over time (30minutes) (T. Henriksen, 2015). The result is a far quicker manufacturing process since concrete casting is done on the foam moulds and not the flexible table; allowing for the full potential of the flexible table to be used. The manufacturing is still in development: while it does offer a far less material-wasteful alternative to CNC milling moulds, foreseeable issues regarding generating the proper edges to define the shape arise. Moreover, the use of expandable foam as well as creating of edges results in more material waste than that generated using the flexible mould method – as such a balance is what is needed. The limitations of geometries for this production method are the same as those of the flexible mould system.

Figure 36: Double Mould system for casting double-curved geometry with additional detail
Source: Henriksen, 2015

[2.3.5] COMPARISON AND DISCUSSION

The presented case studies show that there are multiple techniques available for producing flat panels with some additional details, however, as geometries become more complex, options begin to reduce. The Milinkovich approach can be used produce flat panels with edge returns and stiffening ribs if the geometries are simple and have a high degree of repetition (ideally buildings based entirely on repetition due to the complexity of the mould). Producing elements with additional curvature becomes very problematic and unfeasible. Using milling techniques, it is technically always possible to produce complex geometries of all curvatures; of course more complex geometries result in much more complex milling strategies. Other methods, such as the sprayed techniques can also be used but also rely on milling strategies for more complex geometries. As was also described in the previous section, there seems to be a need for a more flexible approach to manufacturing these geometries. The method proposed by Henriksen seems provides a hybrid system that eliminates the issue of milling whilst also reducing the turn-over times. By creating offsets, it is technically possible to cast in edge details and returns, resulting in panels of monolithic appearance. The issue, however is that a dual-moulding system is still required – although this still presents a far better solution than complex milled moulds. Moreover, edges that are used for casting in material can become complex [table 5]

PANEL GEOMETRY	ADDITIONAL DETAILING	Milinkovic	Milling	Flexible Mould + Negative	Sprayed	Premixed	Automated Premix
Flat	Plain	✓	✓	✓	✓	✓	✓
	Edge Return	✓	✓	*	✓	✓	*
	Offset	✓	✓	*	✓	✓	x
	Ribs	✓	✓	*	✓	✓	x
	Architectural	x	✓	x	x	x	x
Single Curved	Plain	-	✓	✓	✓	✓ [for small	✓
	Edge Return	**	✓	*	✓	✓ [uniform thickness]	*
	Offset	-	✓	*	✓	x	x
	Ribs	**	✓	*	x	x	x
	Architectural	x	✓	x	x	x	x
Double Curved	Plain	-	✓	✓	✓	✓ [for small	x
	Edge Return	**	✓	*	✓	✓ [for small	x
	Offset	-	✓	*	✓	x	x
	Ribs	**	✓	*	x	x	x
	Architectural	x	✓	x	x	x	x
Freeform	Plain	-	✓	✓	✓	x	x
	Edge Return	**	✓	*	✓	x	x
	Offset	-	✓	*	✓	x	x
	Ribs	**	✓	*	x	x	x
	Architectural	x	✓	x	x	x	x
Notes		Individual moulds for unique panels	Individual moulds for unique panels	Semi-flexible. Requires individual mould for ribs etc for unique panels			

Table 5: Comparison of techniques and geometry.
Source: Author

As was the case with producing free-form geometries of constant thickness, a more adaptable and flexible approach to manufacturing is required for the production of free-form geometries with additional complexity. The use of milling as moulding systems is material-wasteful to be efficient for bespoke, non-repetative complex geometry façades.

What is needed is an adaptive forming system that can be used to produce double-curved and free-form geometries as well as the added complexities without relying on complex moulding systems. The flexible mould system developed by Schipper has already been proven to be an effective means to produce free-form panels, however lacks when it comes to the integration of surface detail. Concrete additive manufacturing, on the other hand, offers a solution to producing geometries without the need of additional moulding; however it can be regarded as a time-consuming for the fabrication of entire surfaces and does not achieve the same degree of surface finish as cast concrete. The combination of these two systems could provide a solution to integrating additional details such as returns and stiffening ribs; first casting smooth concrete using the flexible mould and later printing on additional surface details without the need of additional moulds.

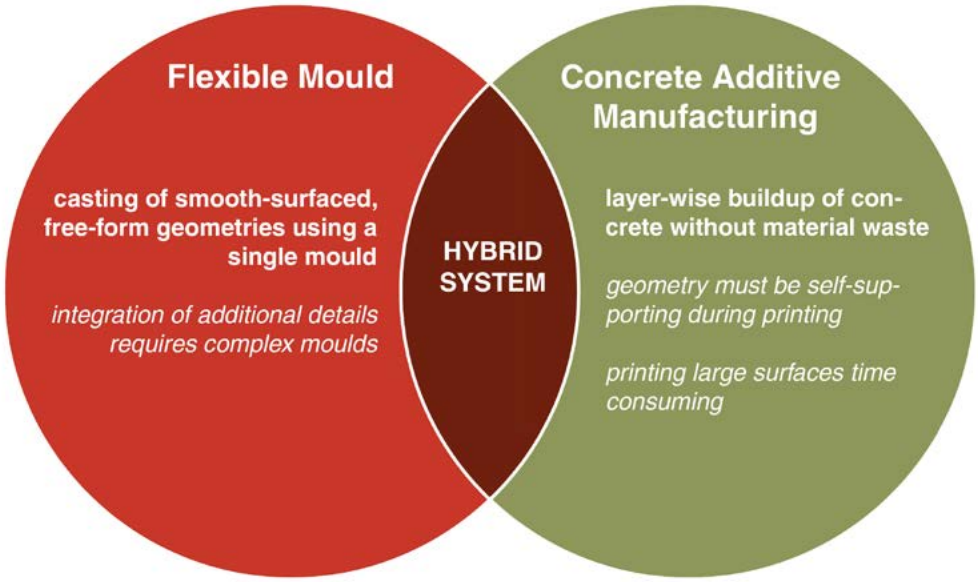


Figure 37: Hybrid manufacturing system that combines flexible moulding for generating temporary surface and additive manufacturing for the addition of detail
Source: author

a rapidly-developing field of study, with initiatives being taken by private stakeholders, universities and hobbyists. This has resulted in numerous individual and private studies, which can globally be classified into three main techniques:

The similarities in the techniques lie in the fact that they all adopt a layer-by-layer approach; however they are all distinct in terms of material us and machine setup. This has resulted in different processes which all have their own set of unique advantages and disadvantages. These factors will be studied and analysed in later parts of this chapter.

The deposition head mounting is, frame, robot or crane mounted. Contour Crafting has been developed to be a crane-mounted device for on-site, in-situ applications. Both D-Shape and Concrete Printing are gantry based off-site manufacturing processes, although there is no specific reason why either process cannot be used on-site. The three processes are all similar in that they build additively, however the processes have been developed for different applications and materials, which results in each having distinct advantages. The D-Shape process uses a powder deposition process, which is selectively hardened using a binder in much the same way as the Z-Corp 3D printing process [18]. 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 (Witte, 2015).

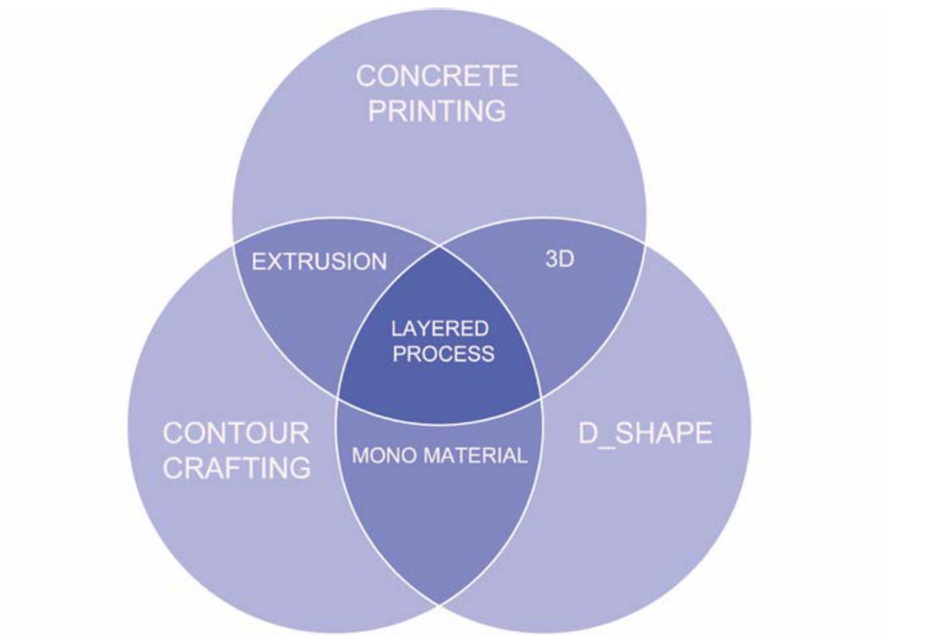


Figure 38 - Overview of Concrete AM Techniques. source - Development in the construction scale AM source: Buswell. edited by author

D-SHAPE

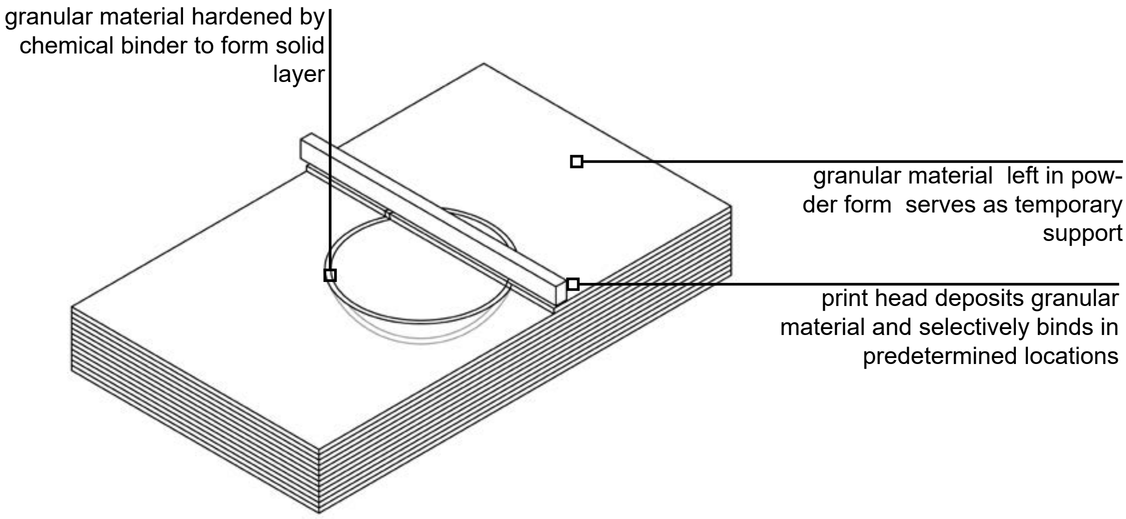


Figure 39 - D-Shape Printing Process
source: author

The D-Shape AM process is achieved by selectively hardening successive layers of granular powder deposits by the addition of binding agents in specific locations [figure 35]. Successive layers of hardened material eventually defines the print geometry whereas powder material has been left in loose form is used as a temporary support during the printing process (D-Shape, D-Shape, 2012). The drawback with this manufacturing technique is that it is a very slow printing process when compared to other concrete additive manufacturing techniques. It also requires extensive post-processing after printing to clean away powder and to grind down the surfaces if smooth finishing is required. Figure A shows one of the earliest printed prototypes using the D-Shape method (3ders.org, 2012). Although it was possible to print a completely free-form prototype, the print took two weeks to complete and required a further week for finishing. Moreover, the powder-process meant that a considerable amount of material was not actually used in the print

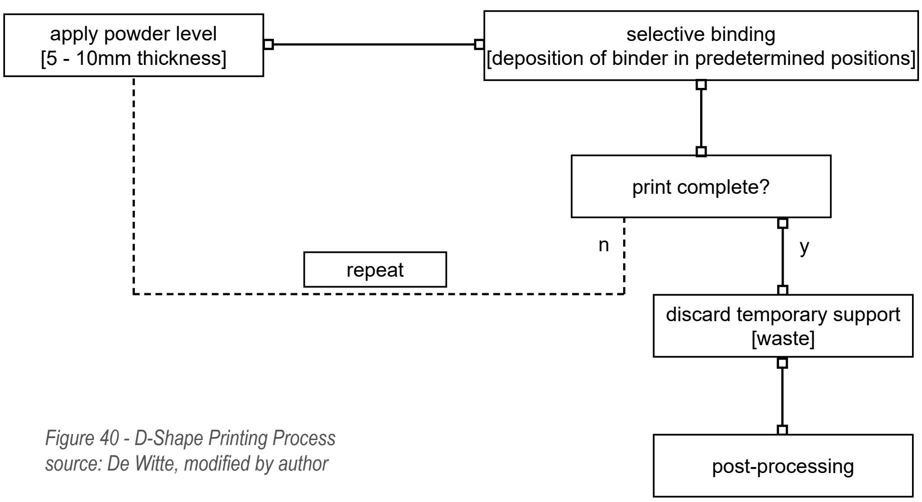


Figure 40 - D-Shape Printing Process
source: De Witte, modified by author

[2.4.1.1] PRINT SPEED AND RESOLUTION

The print resolution (in other words, the range of layer thicknesses that can be realised) ranges from around 4 - 6mm (LIM, 2012), meaning that high although high resolution prints are possible. However, this comes as a trade-off to build speed (the amount of layers to achieve a desired height). The D-shape process is achieved by using a gantry-system having multiple nozzles to spray binding material onto the build material (which has to be pushed over the build area with every pass) (Witte, 2015). The result is that large surface areas can be printed with a single pass of the gantry head. The consequence, however, is that a far more complicated system is

[2.4.1.2] MATERIALS

The materials used for D-shape construction is more akin to sandstone than it is to concrete. Granular materials, such as sand, dust and gravel, are bound together by controlled-deposition of binding materials. The results are marble-like materials. The process generally uses granular materials (sand, dust, gravel etc.) and, through the binding process, returns a marble-like material (D-Shape, D-Shape, 2012)

[2.4.1.3] APPLICATIONS

D-shape has potential in many sectors of the industry. The European Space Agency (ESA), for example, is studying the possibilities of using the D-shape technique for printing lunar structures (LIM, 2012). The More down-to-earth realised applications of this technique include the printing of artificial reefs, building elements as well as scenery for the movie industry. (D-Shape,

Figure 41 - D-Shape Printing Process used to construct artificial reef
source: D-Shape.com

Figure 42 - D-Shape Printing Process in hypothetical building
source: D-Shape.com

[2.3.2] 3D CONCRETE PRINTING

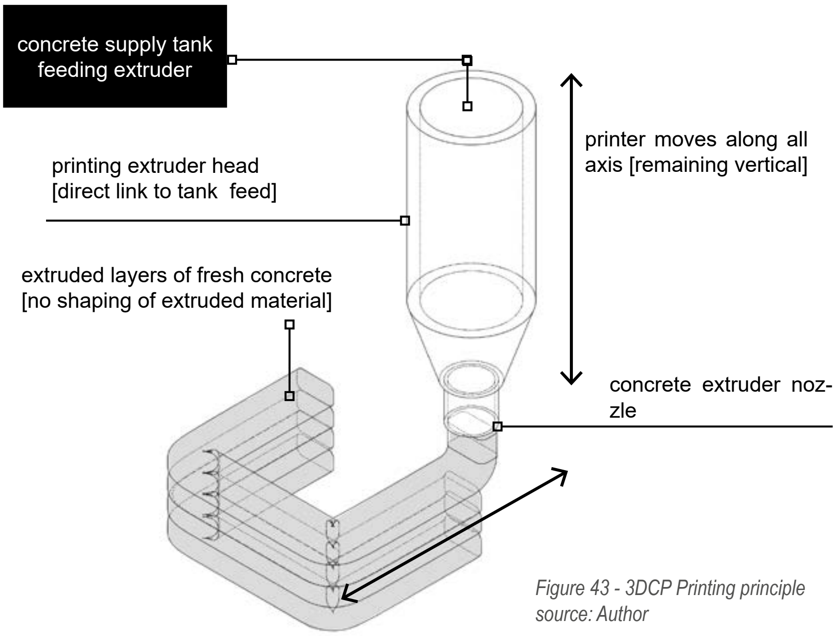


Figure 43 - 3DCP Printing principle
source: Author

3D Printing Concrete (3DCP) is a process based on the extrusion of cement mortars. Mixes are stored in a tank and transported through a feed, finally extruded through a nozzle to form printed layers of concrete. Unlike the D-shape process, 3DCP is a wet manufacturing process where successive layers of wet extruded material are bound in a layer-wise approach. (LIM, 2012). Similar to the D-shape process, 3DCP also requires additional support when it comes to creating overhands and other shapes which are not self-supporting during fabrication, allowing for a vast amount of free-form geometries that can be printed (however this comes at the expense of additional maintenance, cleaning and control, as well as the secondary structure that has to be cleaned after printing). Because material is simply extruded and deposited, elements creating using this method usually have a distinct surface finish that depicts the individual layers of printed concrete.

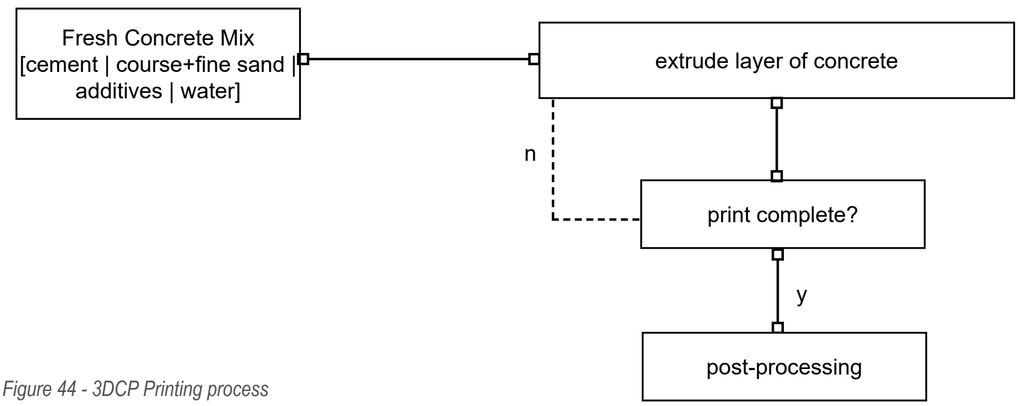


Figure 44 - 3DCP Printing process
source: De Witte, modified by author

[2.4.2.1] PRINT SPEED AND RESOLUTION

The print resolution in 3D printing concrete has a layer range from around 6 - 25mm, meaning that layers are possible to be built up in a greater thickness to those produced by D-shape. This means that geometries can be built up using far fewer layers, thus having a faster build-up speed. Moreover, the use of a single nozzle means that, contrary to the D-shape process, only the material required is deposited during the print (and not additional powder support material). However, the use of a single nozzle also means that it must traverse the entire printing path, which could result in longer printing times compared to other fabrication techniques (LIM, 2012)

As the material is simply deposited in a layer-wise approach without shaping, elements printed using this method generally have a rough surface finish which is characterised by the depiction of printed layers. Thus, for smooth surfaces, a certain degree of post-production is required to sand-down and smoothen printed surfaces if needed.

[2.4.2.2] MATERIALS

The requirements of concrete mixes used in additive manufacturing are somewhat different than those required for regular cast concrete mixes, as will be discussed in section 2.6. High-performance cement-based mortars have been developed for Concrete printing (LIM, 2012) comprising of 54% sand, 36% reactive cementitous compounds and 10% water(by mass). The compressive strength of the material used generally is to the order of around 70-100Mpa, making it a far stronger material when compared to that used in other processes such as contour-crafting. Studies also show that there are less voids in printed concrete when compared to that which is cast, this is due to the higher density (usually around 2350Kg/m3) when compared to regular concrete (2250kg/m3). (Witte, 2015)

[2.4.2.3] APPLICATIONS

Although the applications of 3D concrete printing are very open to interpretations, it is currently being marketed towards the construction industry. Skanka, are also currently working on the commercialisation of 3DCP for the use in construction and high-rise buildings. [Source: Buswell]

Figure 45 - Free-form 3DCP elements developed at Longhborough University
source: Buswell

[2.4.3] CONTOUR CRAFTING

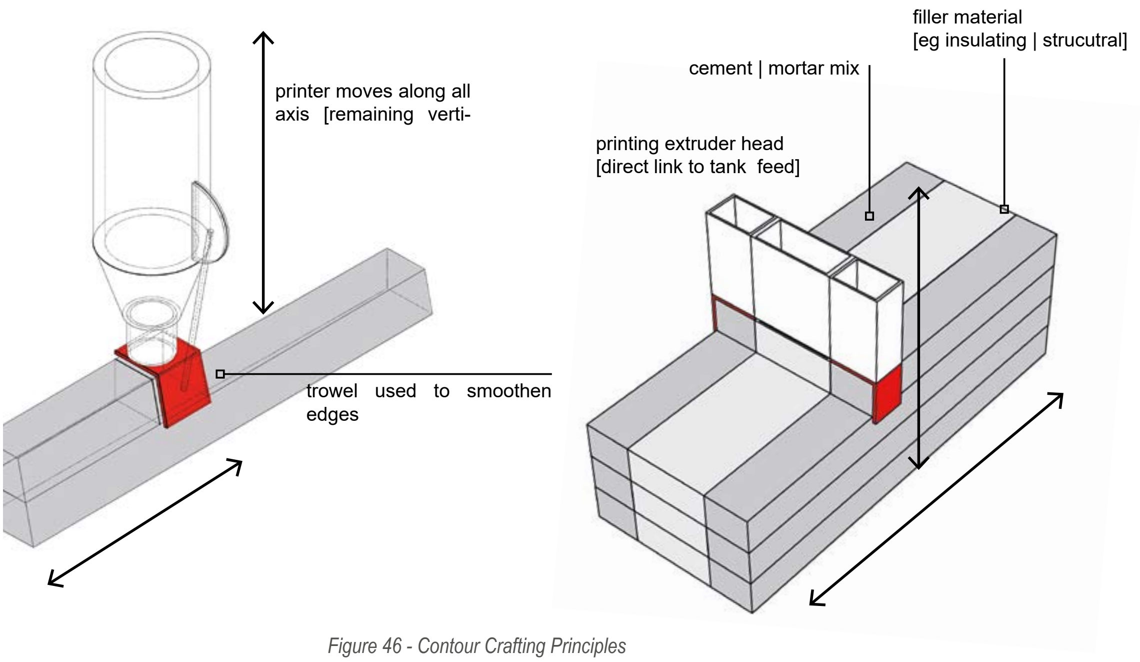


Figure 46 - Contour Crafting Principles
source: author

Contour Crafting (CC) is an additive manufacturing technique making use of computer-control of a nozzle and trowel to create smooth, free-form surfaces. (Khoshnevis et al. & Khoshnevis et al, 2001). The use of trowels is the main feature distinguishing this technique from other concrete AM techniques. The trowels act as solid planar surfaces which instantaneous smoothen and shape extruded material to an exceptional degree of accuracy, in a manner very similar to ancient sculpting techniques (Khoshnevis, 2004)

During this process, automated control is used to exploit the superior surface forming capabilities of trowelling to create accurate, smooth surfaces; combined with a layering technique, this allows for far more complex and free-form geometries than traditional hand-work and sculpting. Generally, it is also used as a hybrid system; combining extrusion (which forms the object surface) and filling to build the core (Khoshnevis et al. & Khoshnevis et al, 2001) The extrusion nozzles may have top and side trowels; the number depending on the degree of accuracy needed. The trowels smoothen the material as it is extruded; resulting in neat, smooth surfaces. Generally speaking, the process is used to build the outside of the object and after its completion filler materials (such as concrete or insulation) is filled into the void. (Witte, 2015)

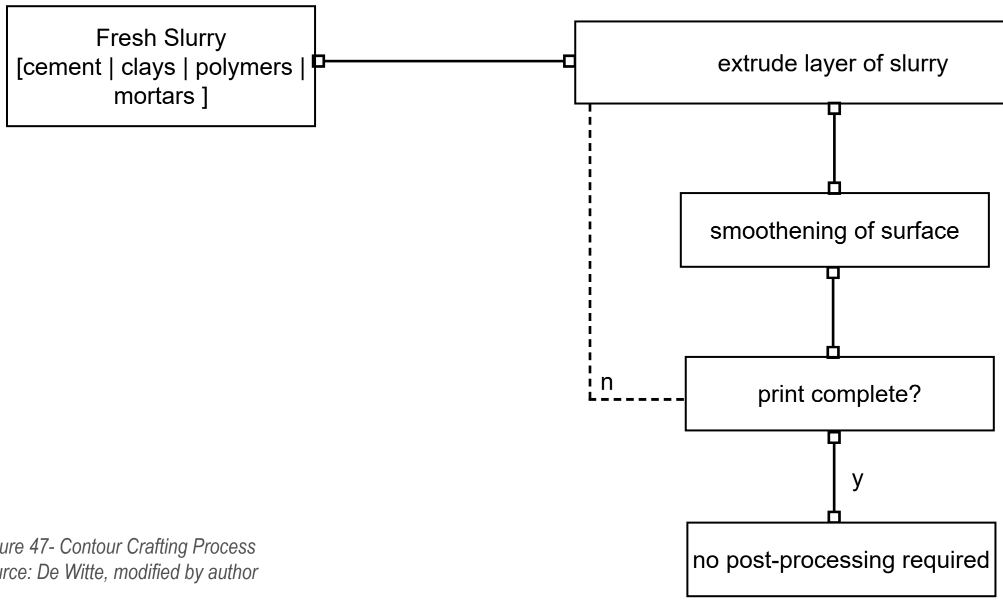


Figure 47- Contour Crafting Process
source: De Witte, modified by author

[2.4.3.1] PRINT SPEED AND RESOLUTION

In most cases, contour crafting has the quickest printing times between successive layers. This is achieved by printing an entire layer with the possibility of multiple heads mounted on a single gantry as shown in figure 42, 44. Contour crafting also makes use of larger diameter heads which has a direct impact on the possible layer-heights possible to achieve. This, in turn, reduced the time taken to build up successive layers. As described earlier, smooth surfaces can be achieved, however this depends on the number of trowels used: surfaces will only be smooth if they are extruded along a trowel.

[2.3.3.2] MATERIALS

The mixes used in contour-crafting are usually contain very high cement content; so much so that it is more akin to mortar than it is to concrete (Witte, 2015). As with concrete used for 3DCP, plasticisers are used to increase workability of the concrete mix to allow for better extrudability. Table 6 shows typical mix proportions, consisting of cement, sand and plasticizers. Compared to regular concrete which uses a sand: binder ratio of around 17:83, mortars used in contour-crafting have a relatively higher ratio of around 52:48. The high amounts of Portland cement will cause a lot of internal shrinkage in the concrete due to the expansion and shrinkage caused by the head to this exothermic reaction.

The mixes used for contour crafting are also considerably weaker than those in 3D concrete printing (to the order of around 19N/mm2) [Hwang&Khoshnevis, 2004). However, elements that are printed using contour-crafting usually have filler materials (such as concrete) to add load-bearing strength.

[2.4.3.3] APPLICATIONS

There are numerous applications for Contour Crafting in the building industry. Below, for example, shows a gantry system onto which nozzles are mounted. These move in two parallel lanes, allowing for buildings, such as houses, to be automatically constructed in a single run. More conventional structures, such as domes and vaults, may also be built without the need for support materials. It is the construction of horizontal elements, such as floors, which either require support structures or to be fabricated as a single element.

Because the manufacturing process makes use of robotically-controlled systems, contour crafting can also be used for other applications such as automated tiling, plumbing and reinforcement: Different applications simply call for the use of different heads and G-Code generation.

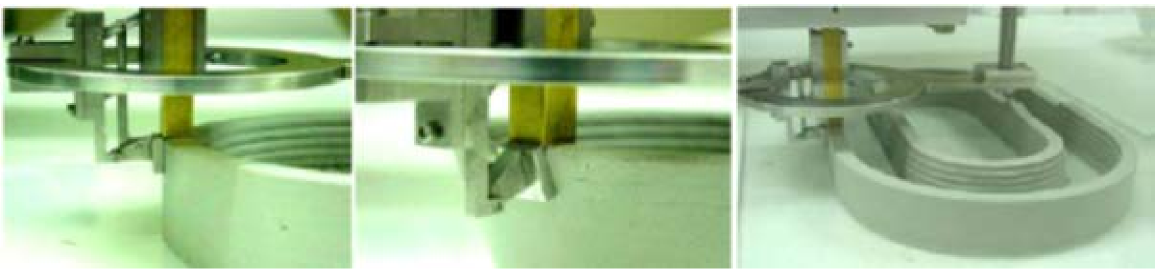


Figure 48 - Contour Crafting Principles - achieving smooth surfaces by means of trowels
source: 3Ders.org

[2.4.4] COMPARISON AND DISCUSSION

The overviews of printing techniques described in the previous sections are tabulated in the table below. [Table 6]. It has been shown that although the processes are all similar, in the sense that they are additively built, the processes are all distinct from one another due to the different purposes they were created for. This has resulted in numerous advantages (and disadvantages) for each manufacturing technique.

While D-Shape allows for the most freedom of form when it comes to generating elements, it does come with substantial material waste, inferior finish and long print speed. In the context of the proposed hybrid system of flexible mould and concrete additive manufacturing, there seems to be little room (or need) for integration do to the very specific manufacturing process involved [reword]

Concrete additive manufacturing also seems to allow for good freedom of shape control, however it does not have smooth or neat surface finishing. Thus, if this method of manufacturing was to be used in combination with a flexible moulding system, one would imagine that substantial post-processing would be required to get smooth results.

Contour-crafting, on the other hand, gives very smooth extrusion results when using the proper trowels. The use of weaker mortar materials is perhaps it's only disadvantage over 3D Concrete Printing.

In the context of combining additive manufacturing with a flexible mould system, it is contour crafting and 3d Concrete printing which seem to have most potential: There would be no need for this marriage of techniques using D-shape as the powder-based system provides its own temporary support.

	CONTOUR CRAFTING	CONCRETE PRINTING	D-SHAPE
PROCESS	Extrusion	Extrusion	3D-Printing
USE OF MOULDS	yes	no	no
BUILD MATERIAL	Mortar mixture for mould / cementitious	In-house Printable Concrete	Granular Material
BINDER	None	None	Chlorine-based liquid
NOZZLE DIAMETER	15mm	9-20mm	0.15mm
NOZZLE NUMBER	1	1	6 - 300
LAYERTHICKNESS	13mm	6-25mm	4-6mm
REINFORCEMENT	yes	yes	no
Compressive Strength	~18Mpa	~70-110MPa	~235-242MPa
Surface Quality	Smooth	Layered	Layered
Advantages	Smooth surface by trowels	High Strength	High Strength
Disadvantages	Extra Process (moulding)	Limited printing dimensions for a given printing	Slow Process
	Weak Bonding between new batch mixes		Rough Surface
			Limited Printing Dimensions
			A lot of Material placement
			A lot of Post-Processing required

table 6: comparison of concrete additive manufacturing techniques
source: author

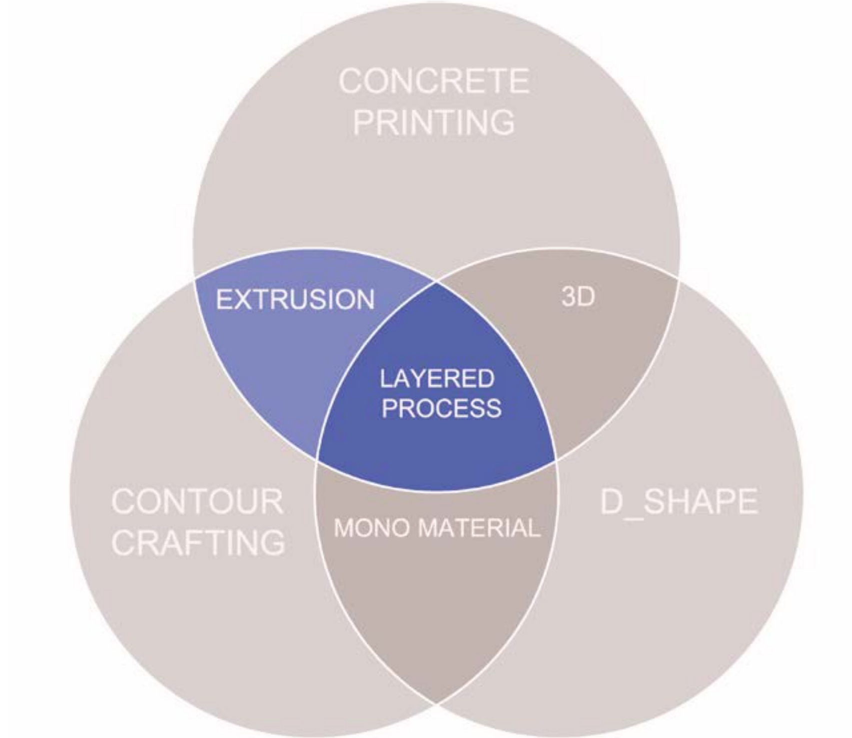


Figure 49 - Proposed system to have combination of 3DCP (material strength) and Contour-Crafting (smooth finish)

[2.5] CONCRETE AS A MATERIAL FOR PRINTING

Traditionally, concrete is usually poured into formworks and later vibrated in order to fabricate building elements. Alternative strategies, such as self-compacting and sprayed concrete, have been developed so as to mitigate the compaction process during casting. Although self-compacting concrete eliminates the need for vibration through the use of superplasticisers, smooth grading and considerable amounts of cement volume; it still requires formwork to define the shape. Sprayed concrete, on the other hand, is an approach that makes use of backing material to eliminate the need for temporary formwork. In this case, mix proportions are designed to have a high cement content in order to facilitate adhesion and buildup-thickness as well as to form a lubricating layer inside the extrusion pipe, ensuring that the mix is pumpable and sprayable.

Concrete used as Additive manufacturing benefits from the advantages of both self-compacting concrete (in other words, can self-compact without the need for additional vibration) and sprayed concrete (where concrete is extruded from a nozzle to fabricate forms). In the process of printing, the self-compacting properties are used to extrude consistent filaments, whilst the principles of sprayed concrete ensure that wet concrete can be extruded without blockages.

The following chapter of literature will give an overview of the main characteristics which have to be considered when designing a mix for concrete to be used in an additive manufacturing process.

[2.5.1] INTRODUCTION

The basic requirements for concrete used in the context of printing differ to those used for traditional casting in formwork. This is due to the unique process that concrete has to go through to be printed and thus requires a unique method of preparation. A basic process that concrete goes through is shown in figure 46 below; once it is prepared, it is usually temporarily stored in a hopper or tank from which it is pumped through to nozzles through which the material is extruded as continuous filaments which are built up in layers.

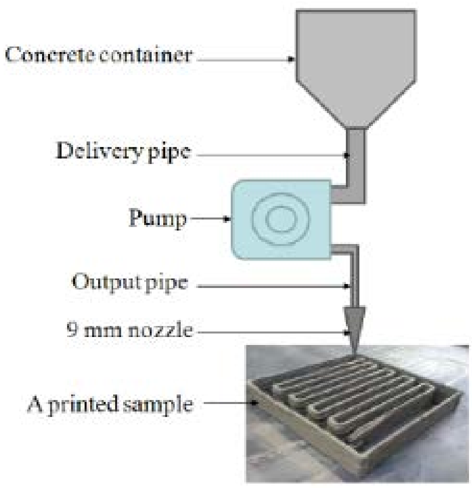


Figure 50 - Typical concrete printer setup
source: Buswell

Due to this very particular process, concrete must have an acceptable level of extrudability; in other words, it must flow continuously through the pipes to the print head and finally extruded in filaments. These filaments, in turn, must be able to be able to retain their shape and bond to one another to form strong, monolithic layers of concrete that define a geometry. Moreover, the material must also be positioned properly and maintain its position without collapse. These are all requirements which are not usually referred to in conventional casting techniques.

As shown by Maeleb, Le and Anell, achieving these basic properties is far easier said than done as they tend to be contradictory to each-other. Figure 47 below shows how, for example, a certain workability is needed to maintain a constant and consistent flow of material. Moreover, this workability has to be maintained for a certain amount of time (open time) in order to avoid blockages in the pipework. On the other hand, the requirements for maintaining a certain fluidity of concrete can help in avoiding blockages as well as bonding of wet concrete, it could also be detrimental to maintaining a constant extruded shape. [Reference Maeleb] for a mix with too much fluidity could result in weak filaments and hence collapse. Moreover, it is commonly appreciated that increasing water:cement ratios can increase this fluidity but also reduce the compressive strength of a mix.

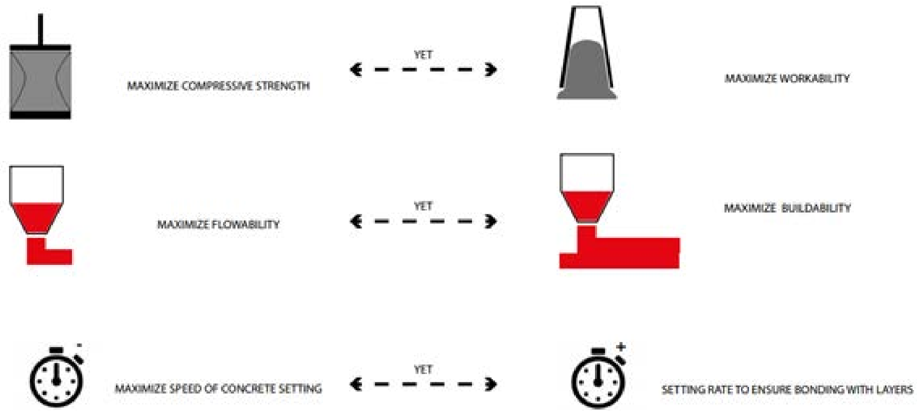


Figure 51 - contradictions in concrete additive manufacturing mixes.
Source: Malaeb, edited by author

Thus, when dealing with so many contradictions, researchers such as Maleb, Austin and Lee first defined important criteria to help with mix design. The most important fresh state properties have been defined as:

A. Extrudability

B. Workability

C. Open Time

D. Buildability

[2.5.2] EXTRUDABILITY

This is defined as the ability of concrete to pass through the small pipes and nozzles of the print head. When dealing with concrete mix design, it is the first criteria which must be met since concrete must, first and foremost, be capable of being extruded through a print head. As will be discussed in the next section, extrudability of concrete mixes is greatly affected by the Sand:Binder ratio, Water:Cement ratio and the presence of admixtures.

[2.5.3] WORKABILITY

This refers to the degree of each by which concrete can be mixed, places and finished to form homogeneous condition. In the context of 3DPC, this is the main underlying characteristic of a concrete mix that has a direct impact on extrudability capabilities.

[2.5.4] OPEN TIME

The open time of a concrete mix relates to the time in which the concrete mix remains fluid enough to be sufficiently pumped from the storage tank to the nozzle. Maled defines this as a representation of workability change over time. This is an important aspect as a concrete mix with a low open time will most likely quickly become stiff, having negative effects on extrudability and buildability and possibly clogging up print heads and feeds.

[2.5.5] BUILDABILITY

Traditionally, concrete is poured into a formwork as a fluid and as such has no requirements to be self-supporting. Buildability, however, is an important aspect unique to concrete additive manufacturing and refers to the ability of concrete to be laid down and remain in position. A concrete which has good buildability is one which is stiff enough to support layers without collapse and minimal deformation yet not be too stiff as to have an effect of extrudability and surface quality (which must be without cracks). The buildability of a mix has a direct relationship with the workability and extrudability as the fluidity of a mix determines how stiff it is. In the context of 3dCP it is usually addressed by the inclusion of chemical accelerators, as demonstrated by Maleb etc which are added prior to concrete being extruded from a print head.

[2.5.6] CASE STUDY: MIXES USED IN RESEARCH

The basic requirements for concrete used in the context of printing differ to those used for traditional casting in formwork. This is due to the unique process that concrete has to go through to be printed and thus requires a unique method of preparation. A basic process that concrete goes through is shown in figure 46 below; once it is prepared, it is usually temporarily stored in a hopper or tank from which it is pumped through to nozzles through which the material is extruded as continuous filaments which are built up in layers.

[2.5.6.1] EXTRUDABILITY

Testing for extrudability was always the first parameter to be tested in all case studies. This is because the concrete must, first and foremost, be able to be pumped through a print nozzle in a satisfactory manner without blockages. Lee and Maleb optimized the preliminary mix by varying the sand content in increments of 5% [55-75%] whilst varying the binder content between 45-25% respectively. In all cases, the binder was kept at a constant ratio of 70%CEM 1 52.5R, 20% fly ash and 10% silica fume and 0.28WC. Maleb et al adopted a similar approach though also varied the water: cement ratio as well as nozzle diameter.

In both cases, it as shown that increasing the cement content and decreasing the sand content gives better extrudability results. Le explains that this is because a high sand content causes sand segregation in the nozzle; and was present in both the 9mm diameter nozzle and 20mm diameter nozzle. Moreover, they also show the effects of suerplasticiser on concrete mix. For a good extrudability, paste must be fluid enough to be extruded through a nozzle, firm enough to hold its shape but not too stiff so as to cause cracks. Thus, superplasticisers are used to increase the fluidity of the mix without compromising strength.

In all cases, they show that too much superplasticers causes mixes to be too wet, causing severe degradation (lee). Too little superplasticisers, on the other hand, resulted in cement being too stiff and hence blocking the nozzles. In both cases, 1 superplasticers by mass provided good results. The criteria for assessing extrudability of printed concrete are assessed in a unique way. As Le describes, as concrete is cast, the extrudability was evaluated using visual inspection of the extruded filament which had to be continuous without the formation of any cracks. Lee did this by printing strips of 450mm long filaments for a total length of 3000mm. The extrude was assessed on a pass/fail basis and a similar approach was also adopted by Maleb and Lund. [figure 48]

[2.5.6.2 WORKABILITY

Once proper mix designs were found in terms for the dry mix constituents, testing for workability was determined in parallel to extrudability. The strategy for determining workability was different in different cases. Lee ET all adopted a shear-vane apparatus in order to define the workability in terms of the fluid shear resistance. Maleb and Lund on the other hand used flow-test apparatus.

[2.5.6.3] OPEN TIME

Once a proper mix was found having satisfactory extrudability which could be defined by its mix proportions and workability, criteria for open time were tested. Lee classified this as the change in shear resistance over time, whilst Maleb determined this by examining the change in flowability over time. As by this stage, certain parameters had already been established for extrudability, the open time of the concrete was studied by the addition and variation of chemical retarders, keeping the already-established mix proportions constant.

Although Maleb and lee show that the use of retarded had a positive effect on open time, allowing for larger batches of concrete to be mixed, excessive use of retarder had drastic effect on the one-day strength. Lee, for example, recorded that a 0.5% retarded had a 20MPa strength, whilst a 1% addition resulted in a 1MPa strength.

[2.5.6.4] BUILDABILITY

The buildability of the optimum mix in terms of extrudability, workability and open time (0.5% retarder with a 100 minute open time) was examined to find the optimum by varying the dosage of superplasticiser which resulted in different shear strength of the fresh concrete. The results confirmed that outside of 0.3 – 0.9 kPa shear strength the concrete could not build a test sample due to being either too wet or too stiff (Fig. 13). A mix with 0.3 kPa shear strength could only build 4 layers for a 1 filament group and 7 layers for a 5 filament group and the filaments were deformed considerably. A mix with 0.9 kPa shear strength could not build 2 layers correctly as some broken points occurred in the filaments. The optimum mix in terms of buildability was again one with a 0.55 kPa shear strength as it could build up to 15 layers for a one-filament group and up to 34 layers for a five filament groups.

Figure 52- [left] Test example of extrudability tests in concrete. [right] buildability tests in concrete
source: Buswell, 2010

2.5.3 Mix Design Results

OPTIMAL MIX DESIGN	
With Additives	
Cement	125g
Sand	80g
Fine Aggregate	160g
Water:Cement	0.36
Accelerator	1mL
retarder	0.625mL

Lonbourough	
OPTIMAL MIX DESIGN	
CEM Type 1 52.5	70%
Fly ash	20%
Silica Fume	10%
Micropolypropylene fibers	1.2Kg/m3
Superplasticiser	1%
Retarder	0.50%

MATERIAL		Percentage	Weight	Density	Volume
		%	Kg	Kg/m3	
Water			228	1000	0.228
Cement			659	3000	0.2197
Silica Fume			83	2600	0.0319
Fly Ash			87	2280	0.0382
Sika Crack Stop			1.2	900	0.013
Superplasticiser	Sikament EVO26	1.26	8.3	1080	0.0077
Retarder	Sika Tard 932	0.5	3.3	1160	0.0028
Fine Sand	Baskarp 15	80	915	2650	0.03443
Coarse Sand	Baskarp 95	20	228	2650	0.0861

3 DESIGN OF PRINTER EXTRUDER

[3.0] DESIGN OF CONCRETE END-EFFECTOR

[3.1] DESIGN OF MANUALLY-CONTROLLED END EFFECTOR

The first part of the study focuses on development of a non-automated end-effector for printing. This was done so as to focus on the effects of different opening shapes and sizes as well as the material used. From literature review an case studies, the main features which will be studied in the generation of the printer head will be:

- Underlying Mechanism of extrusion
- Shape of the orifice of the extruder

There are multiple mechanisms which can be used to drive the flow of concrete through a nozzle. Through literature it was found that the three main possibilities are Screw Mechanisms, Pump Mechanisms and Gear Mechanisms as illustrated below.

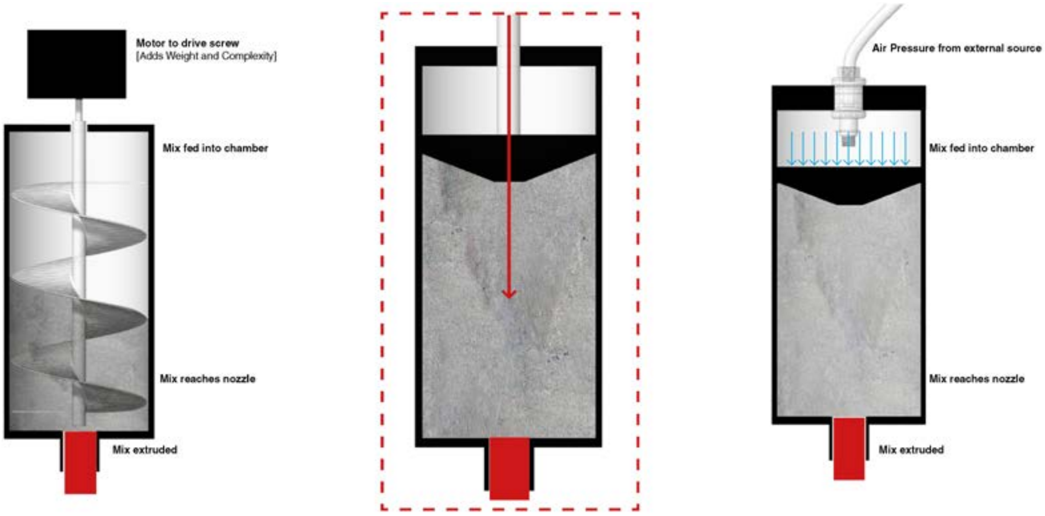


Figure 53- principle mechanisms used for driving concrete. source: author

In the auger setup, an Archimedes screw is use to convey fresh concrete mix through a nozzle after which it is extruded. The advantage with such a setup is that fresh concrete is kept continuously moving and has been commonly used in 3D Concrete print heads. The issues with this system is that there must be a direct relation between the rotation of the auger screw and the movement of the print head in the x,y,z axes. The pumped system makes use of air pressure or plungers to force fresh mix through an extrude head. This method has also been proven to be an effective means of printing – the extrude pressure has to be calibrated in accordance with the motion of the print head. The table below shows an evaluation on the three type of printer head systems in terms of their complexity, ease of manufacture and created pressure, based off research conducted by [Lund]. The Screw and gear systems were given a higher rating of ease of manufacturing and simplicity. This is because the pump system can easily be mimicked by means of a piston/syringe system should it have to be done manually.

CRITERIA	SCREW SYSTEM	PUMP SYSTEM	GEAR SYSTEM
PRESSURE CREATED	•	•	•
SIMPLICITY	••	•	••
EASE OF MANUFACTURE	••	•	••
TOTAL	•••••	•••	•••••

table 7: comparison of driving mechanisms

[3.1.1] INITIAL TESTS, OFF-THE-SHELF PRODUCT

The first tests were carried out using off-the-shelf products in order to eliminate the complicated process of making a concrete mix for printing. This step was done in order to understand how the principle of the print-head would work. Thus, SchonoxQ9 a Trixotropic material, was chosen as it was known to exhibit properties similar to those required for 3D printing and was thus deemed an appropriate approximation which can easily be made. The paste was created on a trial-and-error basis by gradually decreasing the water:cement ratio until desirable proportions were found for extrudability and buildability

[3.1.2] EFFECTS OF OPENING SHAPE AND SIZE

The shape of the nozzle extruder is an important factor that must be considered for printing. The geometries which were considered were the circle and square. Initial extrusions were carried out using a print head with a 20mmm Diameter circle nozzle and 20x20mm square nozzle [figure 54]. The results were similar to those exhibited by Buswell as well as Anell; where the filaments extruded with the square nozzle having a squared cross-section whereas those extruded through a circular nozzle were more oval in cross-section. Hongkyn Kwon confirms this [experimentation and analysis of contour crafting process using uncured ceramic materials] and also adds that the surface finish created with a square nozzle is better compared to an oval one. Moreover, a square nozzle will also facilitate better build-up of layers.

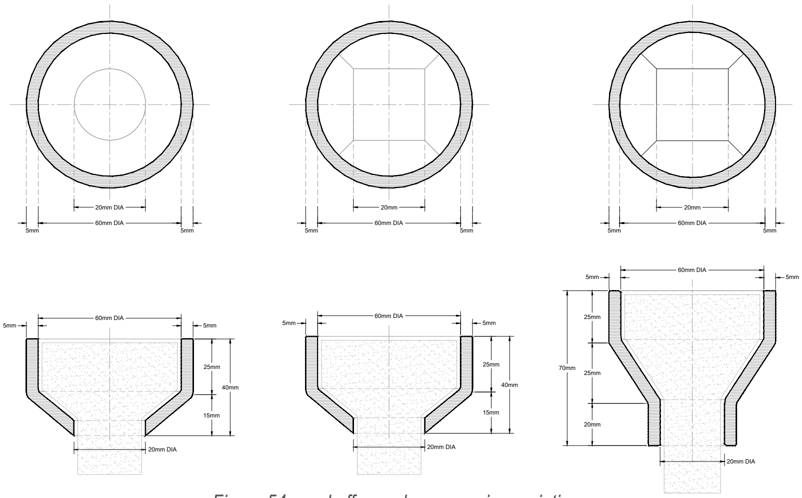


Figure 54 - end effecor shape opening variations.
source: author

[3.1.3] DRIVING MECHANISM

In order to carry out the initial tests, a caulking gun was modified to allow for interchanging different nozzle openings. The different openings were 3D printed in ABS and attached to the gun as shown in the figures below. This allowed for the studying between circular and square openings as well as the effects that different diameters had on the flowablity of the material. As was experienced by researchers in the literature review, a larger opening allowed for material to flow far easier. An opening of 15mm, for example, proved to be quite strenuous to extrude material out of and the final chosen opening size was that of 20mm at it allowed for easily-flowing material.

Figure 55 - end effecor comprised from caulking gun
source: author

[3.1.4] EXTRUDING ONTO CURVED SURFACE

Initial tests were carried out by extruding onto an existing curved surface, represented by a steel mesh suspended between four control points. For this setup, a concrete border was extruded to define a geometry and material was later cast in between to result in a solid panel. The intention of this initial test was to see whether cast and extruded material would bond together and whether the extruded material would maintain its shape even when extruded on a curved surface.

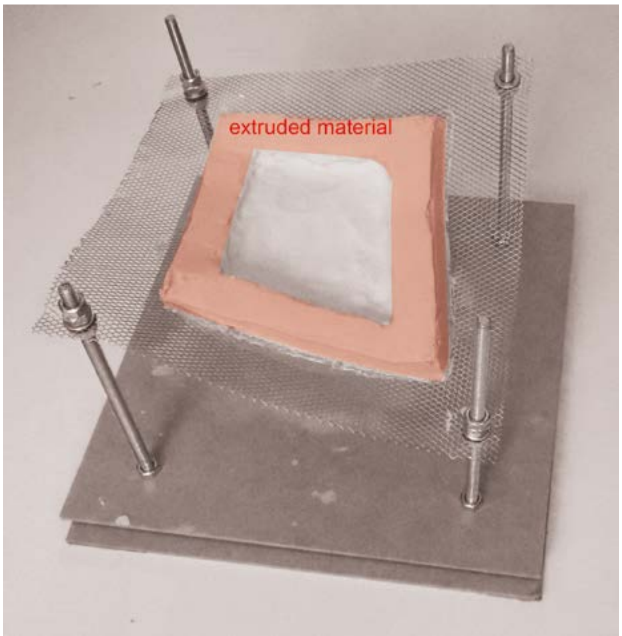


Figure 56 - initial prototype: extruded edges with cast cement
source: author

[3.2] DESIGN OF ROBOTICALLY-MOUNTED END EFFECTOR

The results of the initial tests using a manually-controlled setup indicate that an opening of 20mm is sufficient for extruding material. Openings of smaller dimensions were problematic for extruding material. This is further discussed in section 5.1.2

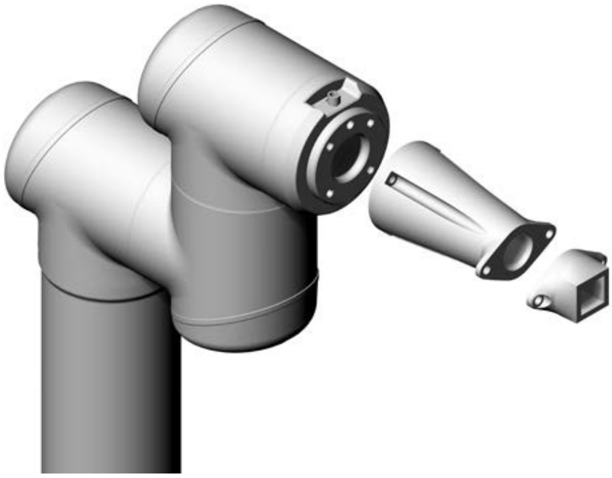


Figure 57 - [left] UR10 Robot
[right] End Effector Attachment
source: author

4 DIGITAL DESIGN

[4.1] DIGITAL DESIGN : GENERAL WORKFLOW

Although there are multiple methods in which the proposed combination of robotically-controlled concrete additive manufacturing and an adjustable mould can be used, the underlying principle for digital design work-flow remains the same for all foreseen cases.

For a completely automated and, hence, efficient workflow, it is envisaged that 3d file may be used to setup an adjustable surface in the most optimal positioning and directly communicate with the robotically-controlled 3d printer. This workflow will begin with analysing and referencing a given façade panel, orienting it onto an adjustable surface such that its positioning causes the least amount of global displacement, h Figure 1. Once an optimal positioning of the adjustable surface is determined, data for pin heights that define the surface are either extracted for manual setup, or communicated to servo-motors for automatic adjustment. The physical surface which has now been defined is scanned for the robotic arm to orient itself as well as to check for differences between the physical and digital surfaces.

Simultaneous to the adjustment of the surface, a G-Code for controlling the movement of the robotic arm is created from the positioned geometry. This is a set of movement instructions sent to the machine in the form of XYZ co-ordinates, movement speed and direction.

The final step in the process is the actual movement of robotic arm along the set-up surface. As the arm moves along the surface, material is extruded at a rate which depends on movement speed and acceleration, layer height as well as mix consistency.

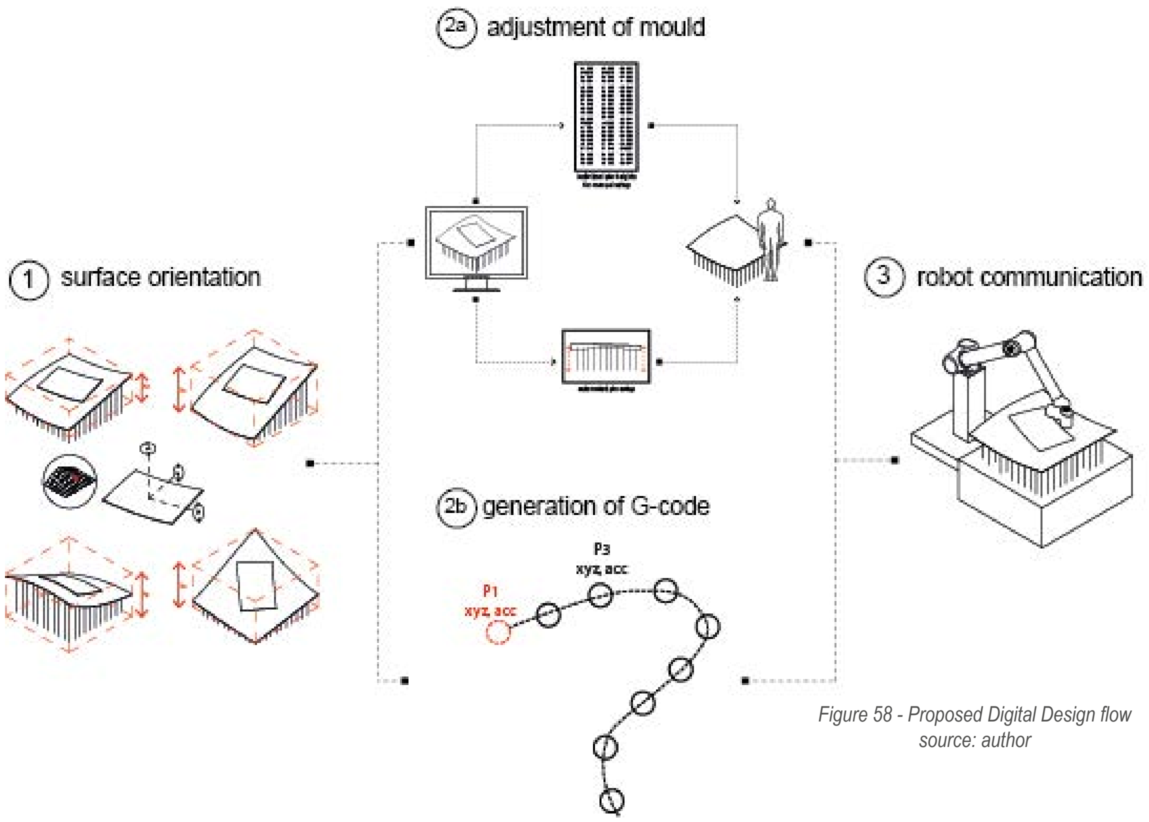


Figure 58 - Proposed Digital Design flow
source: author

[4.1.1] OPTIMIZING POSITIONING OF FLEXIBLE MOULD

Individual façade panels are digitally oriented onto an adjustable mould. This is achieved by systematically rotating the surface in 3D space until a bounding box with minimal height (h) is created. For this study, the evolutionary solve, Galapagos, was used to simultaneously rotate a surface between 0-360 degrees for xy, xz and yz planes about it's centroid. The output having the smallest height, h, is taken for having the shallowest angle on the adaptable mould and, hence, of most desirable orientation. This is because it causes the least amount of variation within the surface

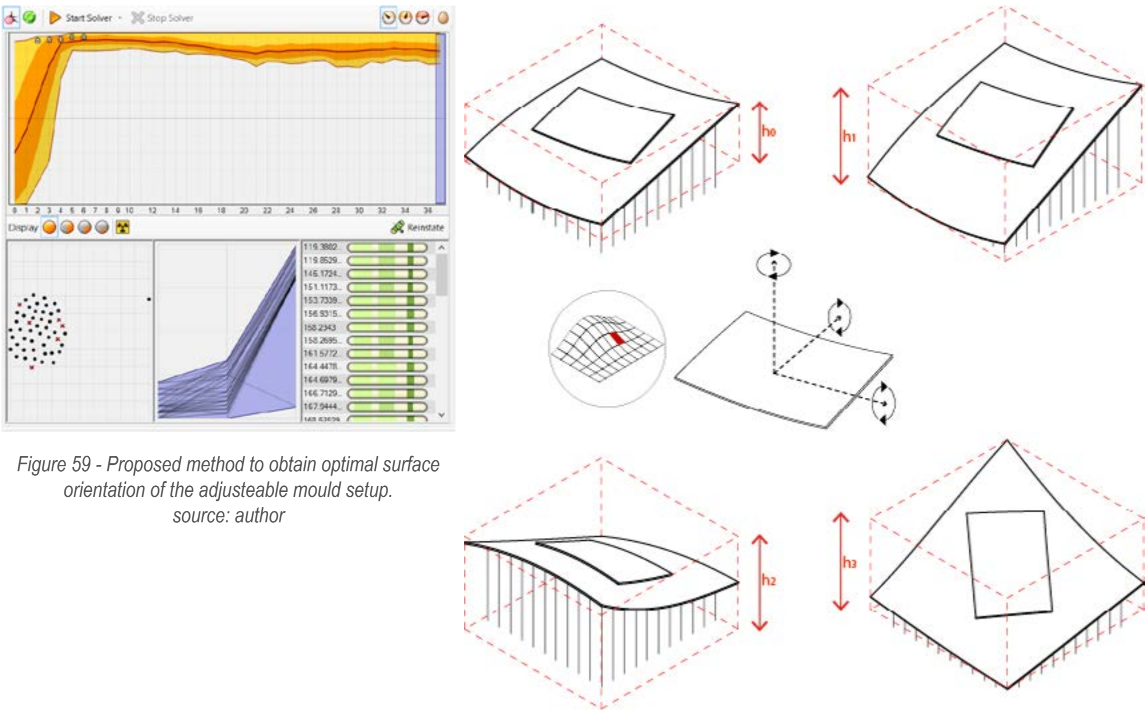


Figure 59 - Proposed method to obtain optimal surface orientation of the adjusteable mould setup. source: author

[4.1.2] DIGITAL COMMUNICATION WITH ADJUSTEABLE MOULD

Once a surface is digitally oriented onto the adaptable mould, individual pin heights that define the surface are exported from the digital model. The physical pins are may be manually adjusted according to the exported data to define the temporary surface. Alternatively, pins are automatically adjusted by communicating with servo motors that are used to drive the pin bed. With this method, an external communication device, such as Firefly for Grasshopper is needed to set up communication. This automated approach has already been demonstrated in the kine-mould to produce free-form glass panels [pronk et al].

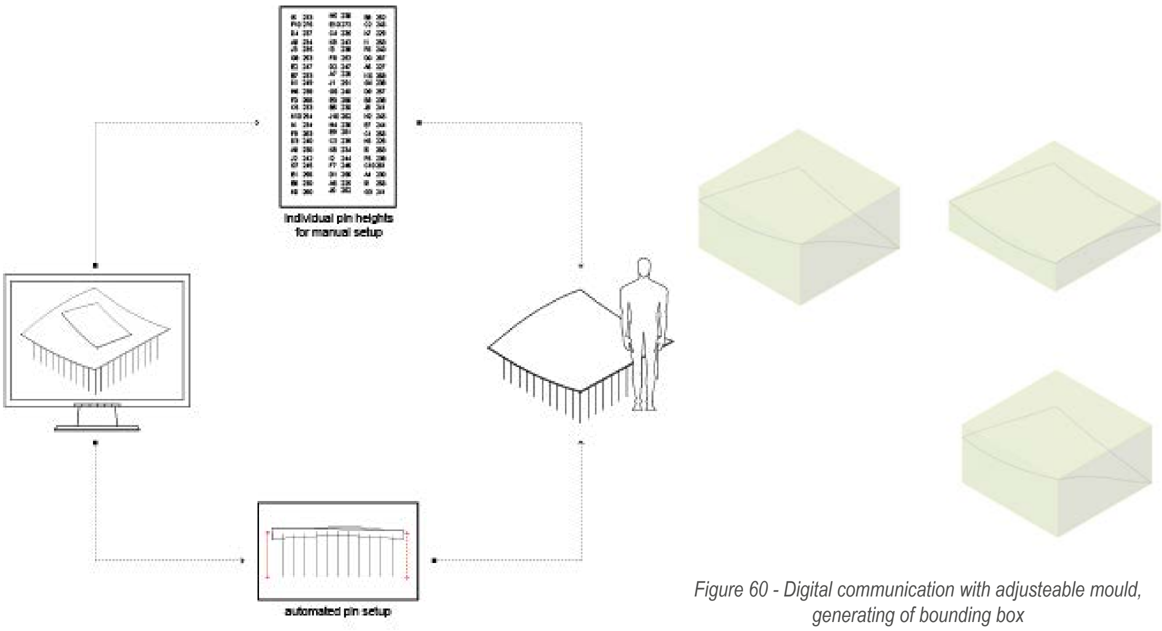


Figure 60 - Digital communication with adjusteable mould, generating of bounding box
source: author

[4.1.3] GENERATION OF G-CODE

G-code refers to the control language used for any computer numerical control machine (CNC), including the majority of 3d printers and robotic arm. It is a method of communicating to the machine the desired movements and actions that are to be taken. These commands also include speed, orientation, actuator control etc. In most cases for standard 3D printing, G-code is generated by slicing a 3D Model into a number of layers, with G-code generated for each layer. This is by far the easiest way to generate the required set of controls, however it comes at the expense of flexibility.

For the proposed setup, a lower-level Me-code approach is used. This is because a large degree of flexibility is required due to the use of a 6-axis machine over the 3-axis gantry system found in most 3d printing systems as well as the need for calibration of movement with a free-form surface. This approach allows for a print path to be defined from a single curve rather than slicing a three-dimensional object. This is of particular importance as the sequence in which the object is printed is critical.

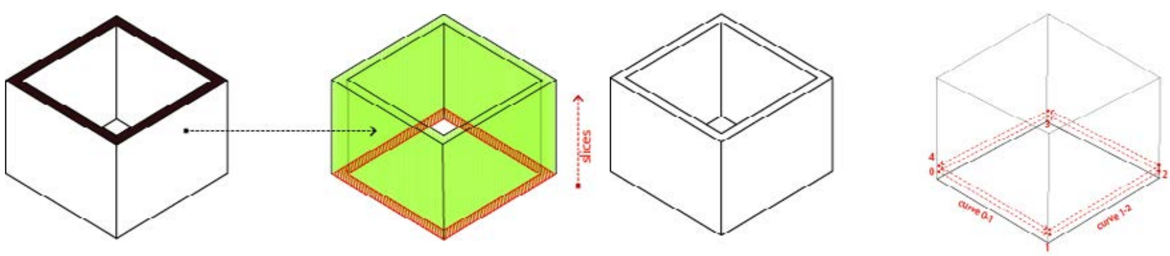


Figure 61 - proposed strategy for generating G-code
source: author

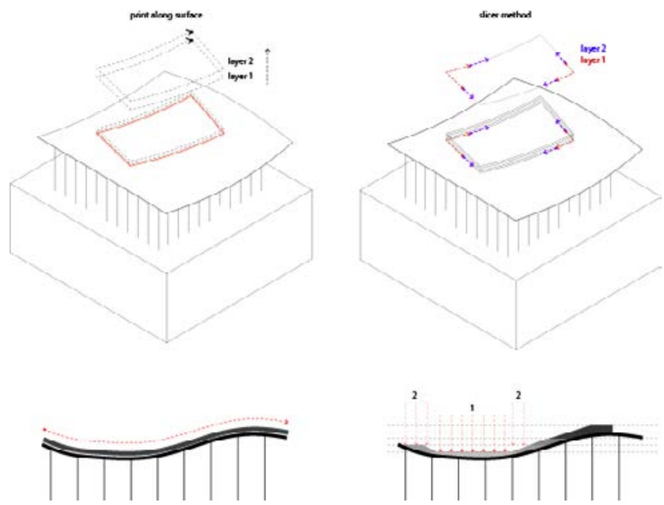


Figure 62 - proposed strategy for generating G-code
source: author

A line-based approach will allow for a print path that directly follows the contours of a surface in a pre-determined fashion – a Slicing approach will always print in the order in which the geometry is sliced. Figure x shows the implication in the differences between the two approaches.

In all cases, a curve is used as an input for defining the geometry to be printed – both for fully-printed panels as well as for printing boundaries. The simplest way to control robotic movement is to utilize a Point to Point strategy. Using this method, the start and end points of a desired path are defined, however the robot will take the fastest route to move from one point to another. In most cases, this is not usually problematic, however, since a very accurate print path that follows a surface is needed, a different approach has to be undertaken.

One way to solve this issue is to divide a curve into a large number of points such that the interpolation between each successive point becomes negligible and hence, more accurate. This approach is particularly useful for printing complex shapes which have frequent changes in direction

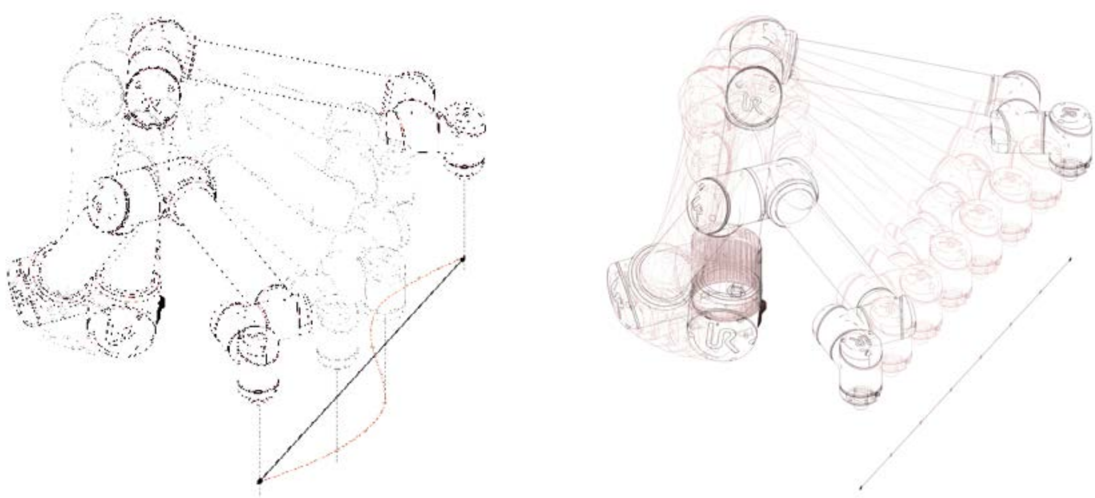


Figure 63 - proposed strategy for generating G-code
source: author

The setback with this approach, however is that having a large amount of points to process has a drastic effect on the speed of communication between robotic arm and computer setup. Furthermore, as will be shown in section 4.2, having a large amount of points which are closely spaced together causes articulated arms to have a jittery movement, due to rapid accelerations and decelerations of servo motors over a short period of time. In order to achieve a smooth print path, a balance between acceleration, velocity and the number of points used is needed and can only be achieved via trial and error.

The approach used for this study is to divide a given curve into a number of points such that the distance between successive points is never less than one quarter the diameter of the end effector and more than its diameter. Once the smoothest paths are found, further refinement is done by adjusting the rounding. This is a refinement step where points falling within a given proximity are simply interpolated rather than taken as start/stop points. The result is that there is less acceleration and deceleration between successive points and hence a more fluid movement.

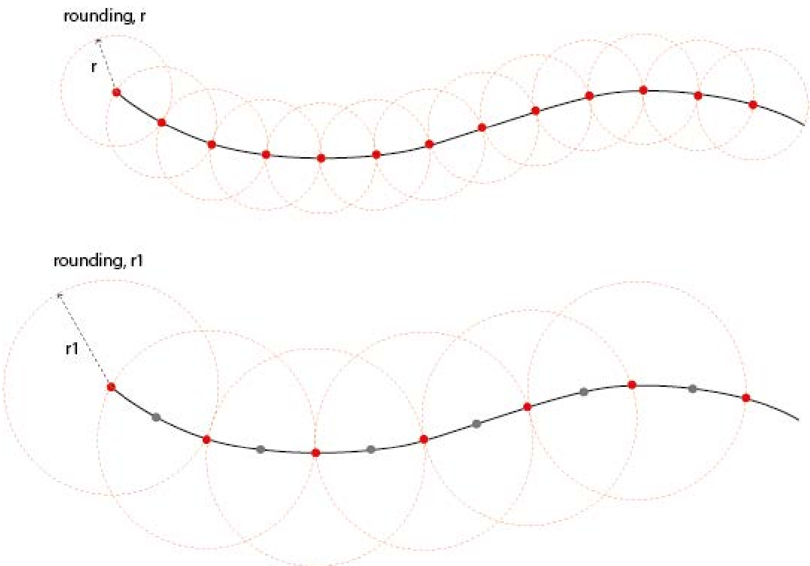


Figure 64 - proposed strategy for generating G-code
source: author

[4.1.4] COMMUNICATION WITH ROBOT AND CALIBRATION OF FLOW

Communication between computer and robot is initiated using Scorpion for Grasshopper; an open-source plugin for robotic control. G-code generated is streamed and directly converted into the physical movement of robotic arm.

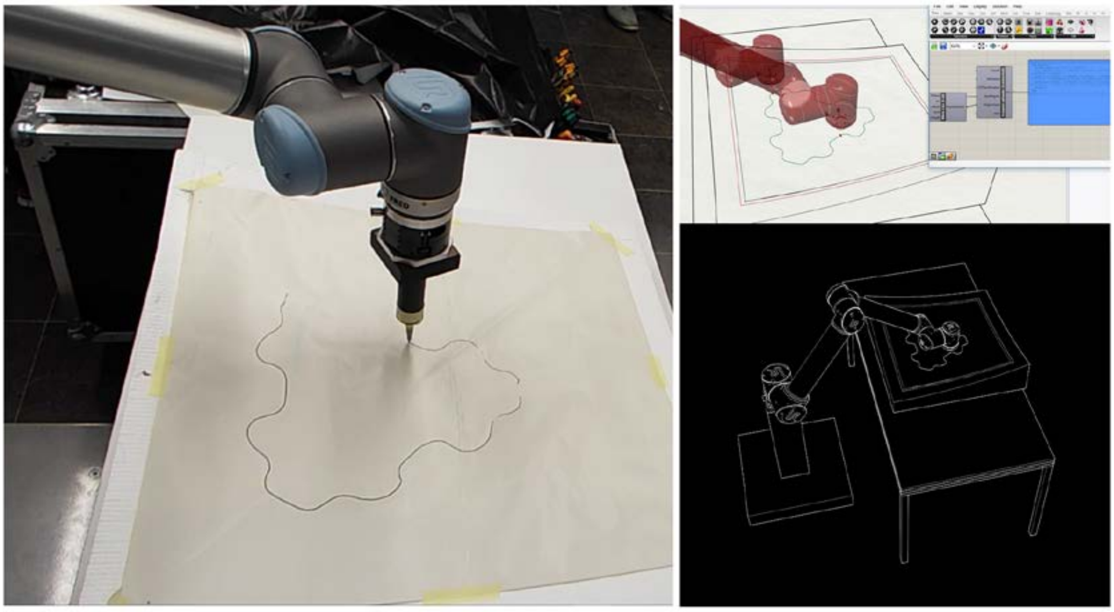


Figure 65 - calibration of robotic movement
source: author

The flowrate used for printing is highly dependant on the velocity with which the robot moves, the consistency of the material as well as the complexity of shape being printed. A more complex geometry, for example, will require a slower printing speed. This is due to a higherfrequency in changing direction, resulting in the requirement for a lower rounding value and hence, slower movement speed. Bournelli's eqution is used to determine a bencmark for initial printing pressure, for a given movement speed. This is the reference driving pressure that has been used for the initial setup of all prints. Adjustments were made during individual tests to account for slight variations in consistency between each mix. Assuming an incompressible material moving at laminar flow, and a mix of 2250Kgm3 and the setup shown on the next page.

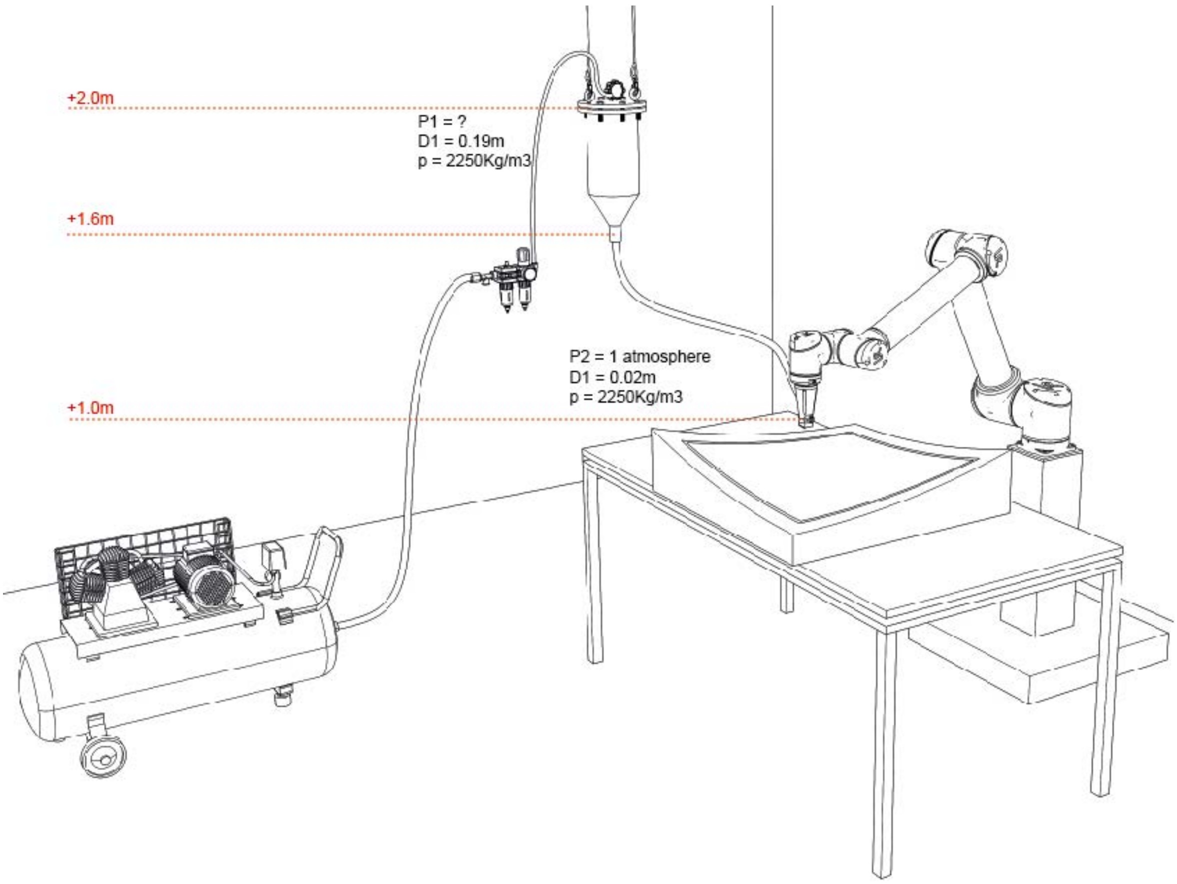


Figure 66 - schematic drawing of setup
source: author

Bernoulli's equation is expressed as:

$$P_1+0.5\rho V_1+ \rho gh^2 = P_2+0.5\rho V_2+ \rho gh_2$$

Where:
ρ is Density
P1 is driving pressure
P2 is presure at exit
h1 is height of pipe1 from reference
h2 is height of pipe2 from reference
V1 is velocity of fluid
V2 is velocity of fluid

Assuming the robotic arm moves with an average of 0.5cm/2, velocity at exit should equal this. Moreover, Pressure at the exit of the nozzle is equal to atmospheric pressure. A target density of 2250kg/m3 for material is assumed.

Then:
A2 = A1 [D1/D2]2 = A1[20/190]2 = 0.011A1
A1V1 = A2V2
V1 = [A2/A1]V2 = 0.011A1V2 = 0.00165V2
P1 = P2 + ρgh2 + 0.5ρv22 – ρgh1 – 0.5ρv12
P1 = 1 + 0.5ρ[V22 – V12] + 1 – 2

In an ideal setup is one which is fully automated, where a single digital file is used to automatically position a surface onto an adjustable mould in the most efficient orientation possible. The same model is then used to either communicate with a series of servo motors to automatically adjust a physical surface, or output relevant positioning for manual adjustment. Simultaneously, G-code is created, depending on the geometry used which is then communicated to the robotic arm for printing.

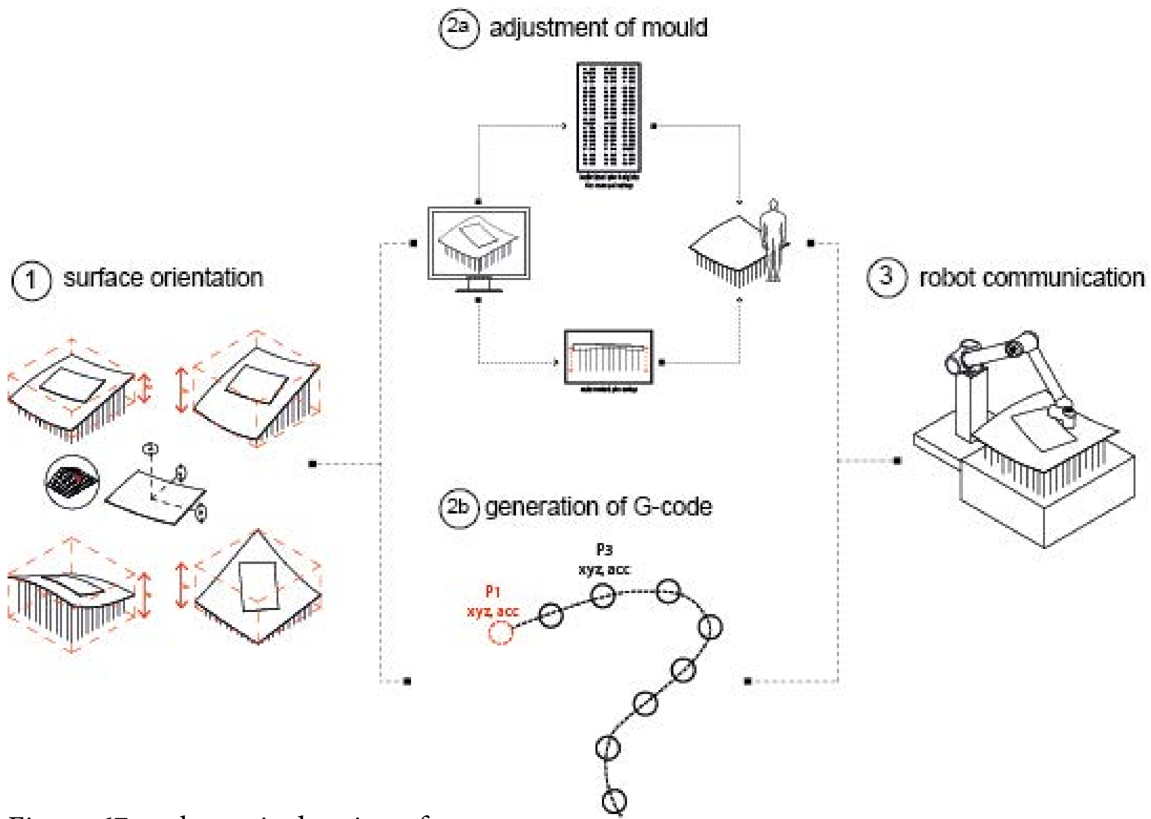


Figure 67 - schematic drawing of setup
source: author

[4.2] GEOMETRY STUDIES

[4.2.1] FULLY-PRINTED PANELS

The first type of geometry that was studied is a fully-printed concrete panel. The purpose of the test was to study the possibility of printing panels in a novel approach to layering. Conventionally, 3d printing is achieved by using a layer-wise approach. The principle of the new approach is to create a print single path using circle-packing principles and differential growth. This is done by populating a given surface with a number of points which are moved until they have a constant distance apart from one another, the distance being half the width of the extrusion nozzle. These points were then used to interpolate a single curve serving as the final print path.

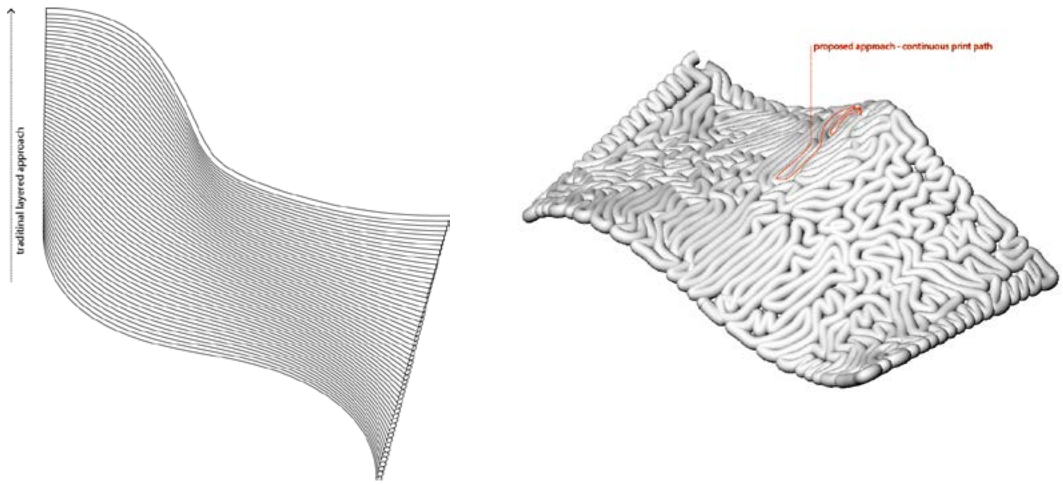


Figure 68 - [left] traditional layered approach to printing. [right] proposed method using differential growth
source: author

The differential method for generating surfaces is a phenomenon found in nature, where complex and free-form shapes have to be generated in the most optimal form possible. In the case of Corals, for example, differential growth is used to grow fibrous tissue in a method which is based on the contours of a surface. The same principle of growth structure is also found in bacterial cell generation in the human stomach as well as the structur of human fingertips. The translation of organic growth patterns to architectural applicatons could have benefits apart from generating print paths desined or a specific curvature. Neri Oxman uses the same principle for generating 3D-Printed Bio-Suits based off the contours of the human body. In this example, print paths are generated at variable dimensions to also allow for optimal dispelling and abroption of heat.

Figure 69 - 'Brain Coral' surface generated using differential growth patterns displayed in nature

Figure 70 - Differential growth patterns used to generate complex, surface-grown biostructures
source: Neri Oxman

Circle packing/sphere collisions refers to the arrangement of circles in a boundary, positioned such that no circles overlap yet remain mutually tangent to one another. In the simplest examples, such as hexagonal packing, circle fill a space such that each circle touches four sides (naked boundary) or 6 sides (clothed). Extracting the centroids of each circle produces a tangency network graph – a triangulated network of lines representing packed circles.

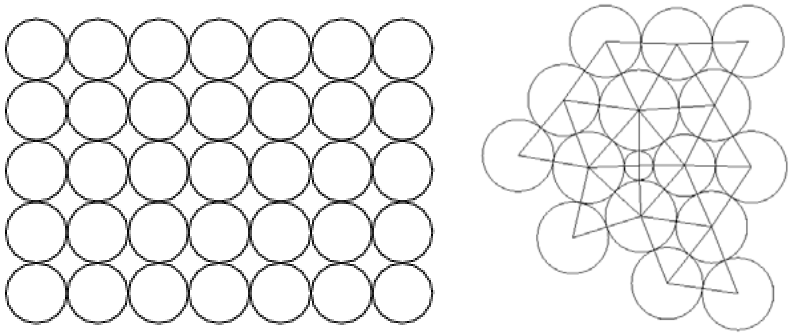


Figure 71 - Circle[spherical] packing principles used to generate print paths
source: Author

As a result of the great advancements in computational designs, far more complex circe-packing patterns can be realised. One such area of research is the use of differential growth patterns, where a curve is divided into a number of points, the points successively positioned such that they become centroids for circle packing. The length of each curve is then increased and points are re-arranged for a new circle-packing pattern. This process is repeated until an entire area is

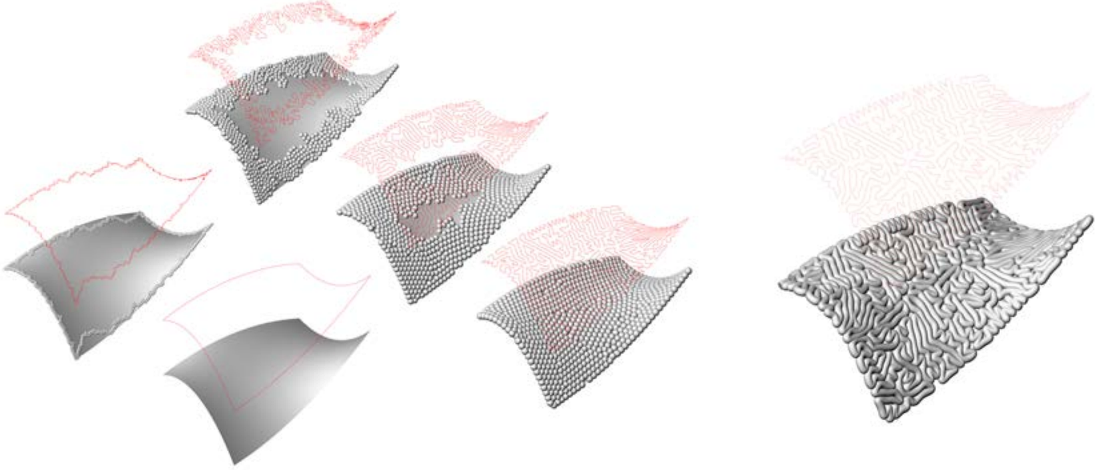


Figure 72 - Differential growth algorithm used to generate print paths for a given surface
source: Author

By using digital design tools, the extracted curve may be converted into G-Code and communicated to a robotic arm and printer. This is done by dividing the curve into a number of points at a regular interval and extracting the XYZ co-ordinates of each point. Additional information, such as normal to a surface at a given point may also be extracted and used to ensure more accurate positioning of the robotic arm with the surface.

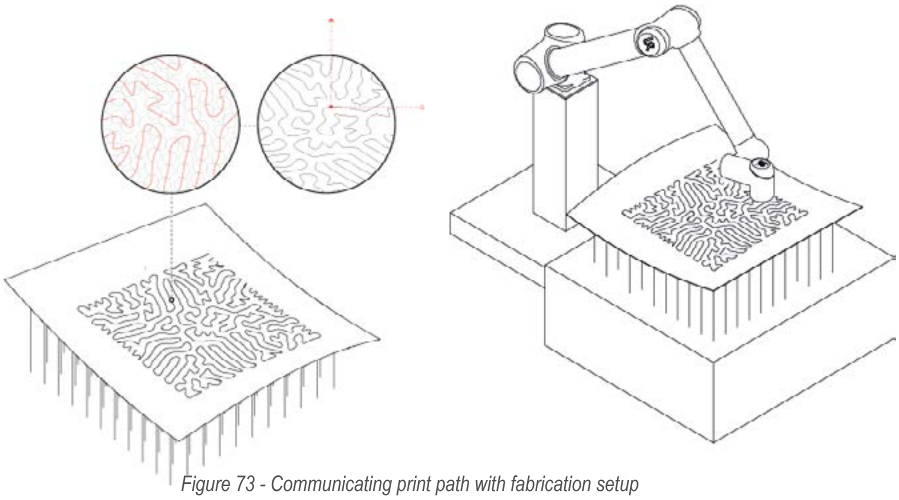


Figure 73 - Communicating print path with fabrication setup
source: Author

[4.2.1.1] GENERATING G-CODE: ROUNDING/ACCELERATION/VELOCITY

Paths generated using this method have an almost continuous change in speed and direction. In order to maintain an accurate and smooth movement of the robotic arm, a high number of divisions is needed with a low value for rounding. This will ensure that the actual path followed by the robotic arm is as accurate as possible. In order to avoid high degrees of jittering, a very low velocity and acceleration is needed. From initial tests, the most acceptable division length was found to be between 1mm and 5mm, which gave an average of 0.5mm deviation from curves generated using this method. These values were used for obtaining initial divisions of the curve and served as the basis for obtaining rounding values. Currently, the effects of rounding cannot be digitally simulated as they are a property of the physical mechanics of a robotic arm. Thus, calibration of rounding is described in section 4.1.3 alongside physical testing.

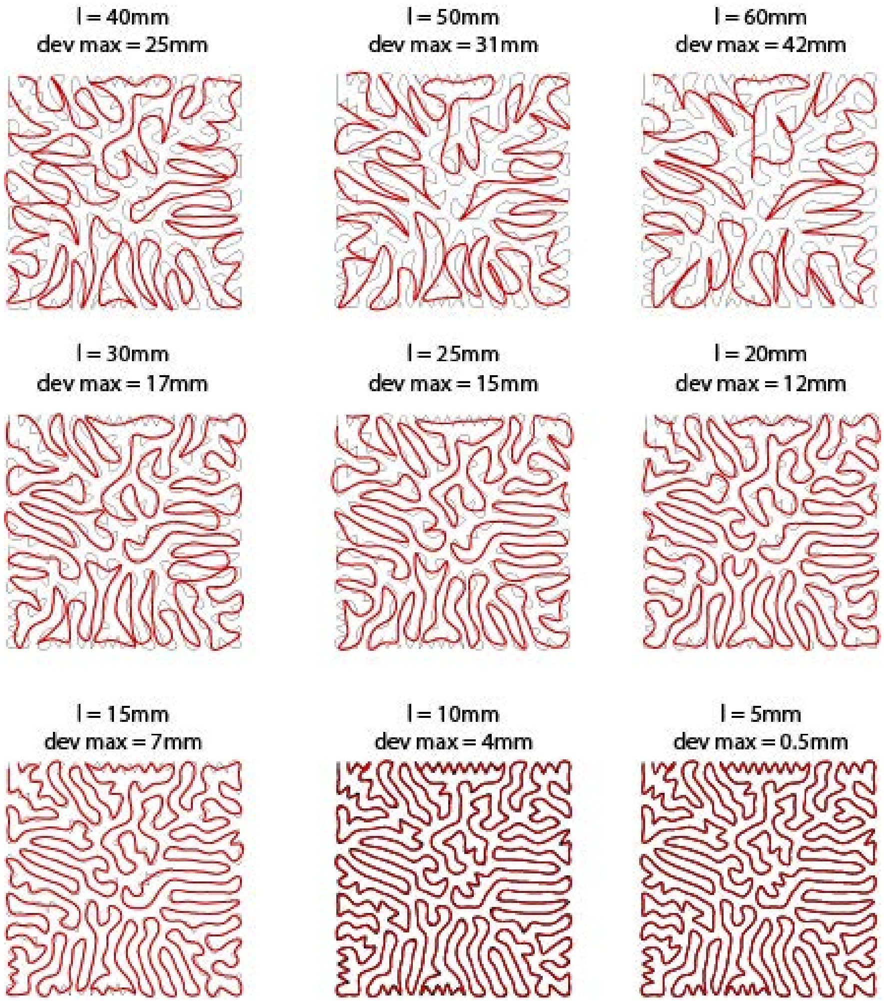


Figure 74 - effects of rounding and division on accuracy
source: Author

[4.2.2] PRINT AND CAST-PANELS

The second set of geometries which were tested were those which are a combination of concrete additive manufacturing and casting. The principle being that 3d printed concrete will serve as a formwork for casting in, later forming part of a free-form panel. While the creation of free-form panels is already possible using the standard flexible mould setup, the advantage of using printed concrete as a temporary formwork is that far more complex shapes can be realised with less waste as the formwork eventually forms part of the final panel. This is achieved by extracting a curve from the perimeter that defines a shape and converting it into G-code for the robotic arm to follow.

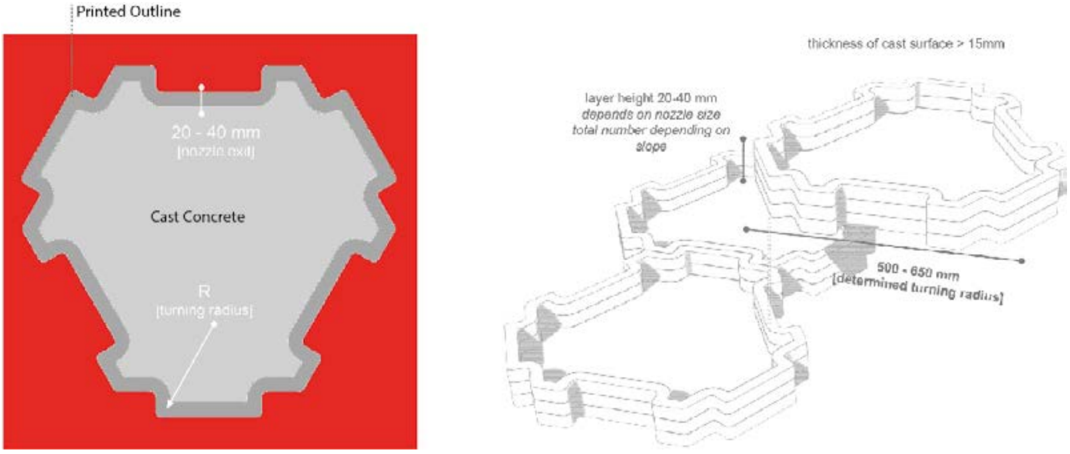


Figure 75 - proposed study of complex interlocking geometry
source: Author

Since it is already possible to efficiently produce rectangular and relatively simple geometries, a series of complex interlocking panels were taken as a case study. The base geometry studied is of a series of hexagonal panels, chosen due to already having a certain degree of complexity. Furthermore, studies carried out by Menges et al show that the force flow in hexagonal panels occurs by means of in-plane shear forces around the perimeter – the area where thickness can be varied and controlled as it is printed. Further complexity was added to the panels by the addition of notches to increase the shear area to create interlocking geometry.

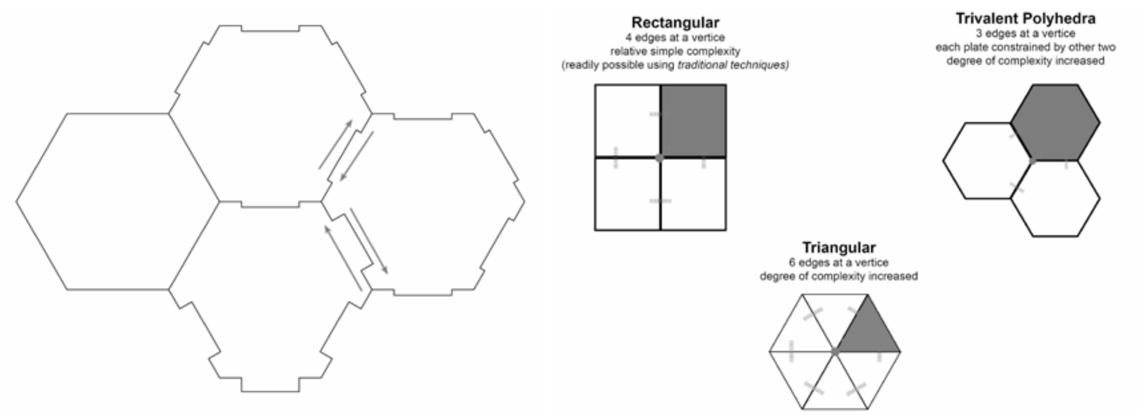


Figure 76 - proposed study of complex interlocking geometry
source: Author

One of the major drawbacks with concrete additive manufacturing is that creating sharp and right-angled corners involves very complex movements and control mechanisms to stop and start the flow of material each time there is a change in direction. Figure X shows how, currently, the best solution to this is to make use of side trowels which are used to cut material at sharp corners, rotate and continue printing. As was found during early tests, this tends to result in dis-continuity in material wherever there is a change in material. Thus, geometry printed requires a certain degree of filleting at the edges to allow for a continuous printing process. Following a series of printing tests concerning different turning radii, a minimum acceptable radius was found to be equal to the diameter of the opening of the nozzle used. This information was then relayed back to the parametric model that generates the geometry.

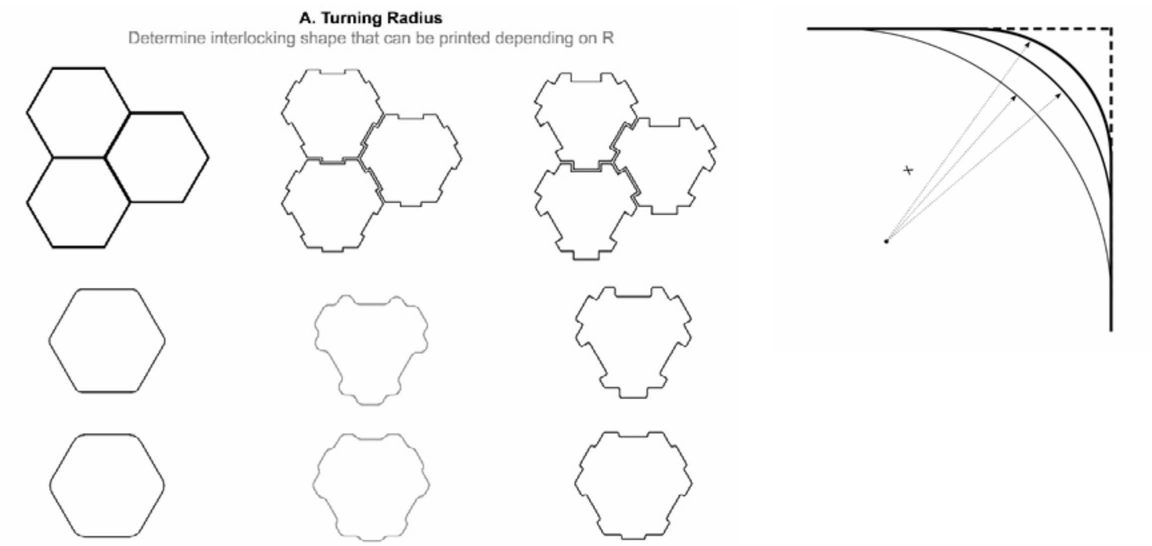


Figure 77 - proposed study of complex interlocking geometry
source: Author

[4.2.2.1] GENERATING G-CODE

The print path used for this geometry is generated by extracting the perimeter of a shape to be cast as a single curve. As opposed to the fully printed panels, the print path used are relatively less complex with far less changes in direction of printing. However, the main challenge for this type of geometry is printing multiple layers on top of each other in order to achieve a certain perimeter thickness. This is to ensure that concrete can be cast within the geometry without any overflow of material. As the geometry consists of sections which have a change in direction and those which are relatively straight, the input curve is analysed for its rate of change of curvature. Areas which exhibit a higher degree in the rate of change in curvature are divided into a higher number of points, this is to ensure that accuracy is maintained. Sections which have a lower change in curvature, such as straight line sections, are divided into less points since the robotic arm will naturally follow the straight line.

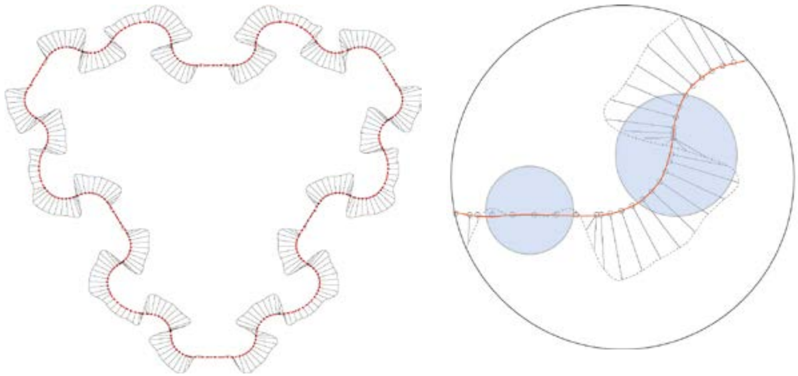


Figure 78 - Effects of rounding and subdivisions on geometry
source: Author

For generating multiple layer heights, traditional slicing techniques cannot be used as the order of printing is not ideal for printing with no stop/start function. Instead, a series of splines are copied and projected in a direction normal to the base surface. The orientation of the projection is important as it has a drastic effect on the way layers are stacked and hence on how different panel can be connected together. Figure 79 shows the implications of stacking layers vertically and in a direction perpendicular to the surface. Tests carried out in showed that layers which were printed normal to the surface were also more stable due to a larger contact area being used.

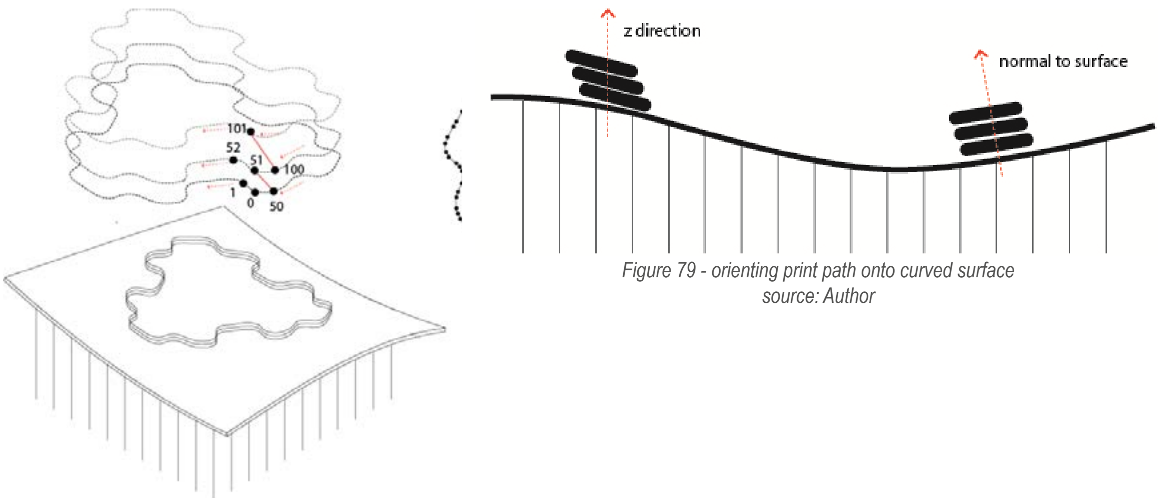


Figure 79 - orienting print path onto curved surface
source: Author

The layer height that is printed is greatly determined by the print speed and size of the nozzle. When printing at faster speeds, material has a tendency to stretch out and become thinner. However, since printing complex shapes requires a relatively slow printing speed to ensure a constant and smooth movement, the layer heights may be assumed to be extruded at a dimension equal to the size of the nozzle opening. Over calculating a layer-height would result in material being extruded from a considerable height, which makes the stacking of layers even more difficult. Moreover, under-calculating the layer height could result in collisions between the printing nozzle and extruded material, potentially resulting in smudging and collapse of printed material.

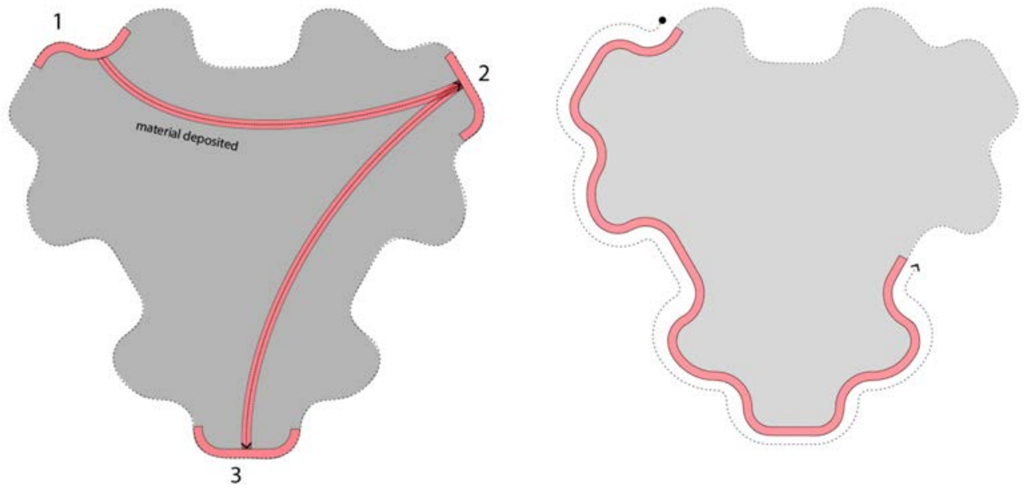


Figure 80 - [left] traditional method for printing in layer-wise approach. [right] proposed method for printing in line-based approach.
source: Author

The layer height that is printed is greatly determined by the print speed and size of the nozzle. When printing at faster speeds, material has a tendency to stretch out and become thinner. However, since printing complex shapes requires a relatively slow printing speed to ensure a constant and smooth movement, the layer heights may be assumed to be extruded at a dimension equal to the size of the nozzle opening. Over calculating a layer-height would result in material being extruded from a considerable height, which makes the stacking of layers even more difficult. Moreover, under-calculating the layer height could result in collisions between the printing nozzle and extruded material, potentially resulting in smudging and collapse of printed material.

In this respect, the best spacing between exit nozzle and the closest surface was found to be taken as the nozzle dimension perpendicular to direction of travel + [10 to 15mm]. When test prints were conducted at a height over the additional 15mm, it was more difficult to achieve stacking especially on an incline. This is further explained in section 5.0

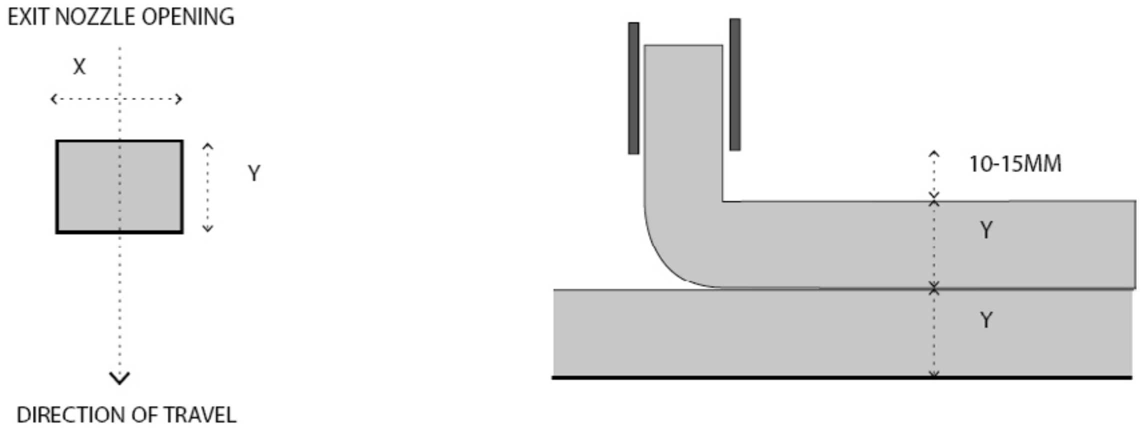


Figure 81 - effects of layer height and nozzle opening
source: Author

[4.2.2.2] CASTING

Once the perimeter of the desired shape if printed, material is then cast in the void to form a closed panel. In order to ensure proper bonding between printed and cast material, the same mix used for printing was used for casting. In one set of tests, superplasticer was added to the mix used for printing. In an alternative set of tests, the water:cement ratio was increased to allow for easier casting.

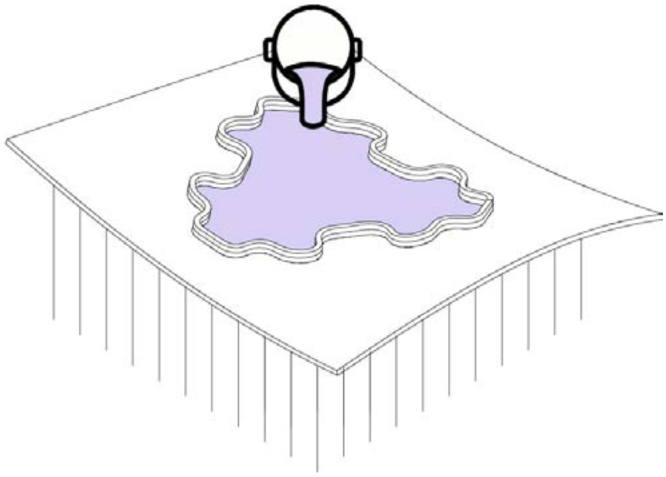


Figure 82 - Proposed principles for printing and casting
source: Author

5 EXPERIMENTAL SETUP

[5.1] EXPERIMENTAL SETUP

Once a digital design strategy was setup, physical printing tests were carried at TU Darmstadt using a custom-designed end effector and UR10 Robot. In order to properly focus on the actual printing process, a number of simplifications were assumed.

While the adaptable mould has already been proven to be fully functional, the aim of this thesis was to identify the potentials of combining robotically-controlled additive manufacturing with a free-form temporary surface. For this reason, the adjustable mould was approximated to a milled EPS mould with the same surface finish. This was used to represent a single static state of the adaptable mould, allowing for focus to be directed towards the actual printing process, orientation between the mould and robotic arm and printing of geometries.

The final setup used consisted of a UR10 Robotic arm, 3D-Printed end effector, Pressure drive system and milled formwork approximating a single-state of the adaptable mould. Figure X shows a schematic of how this setup was achieved in Darmstadt.

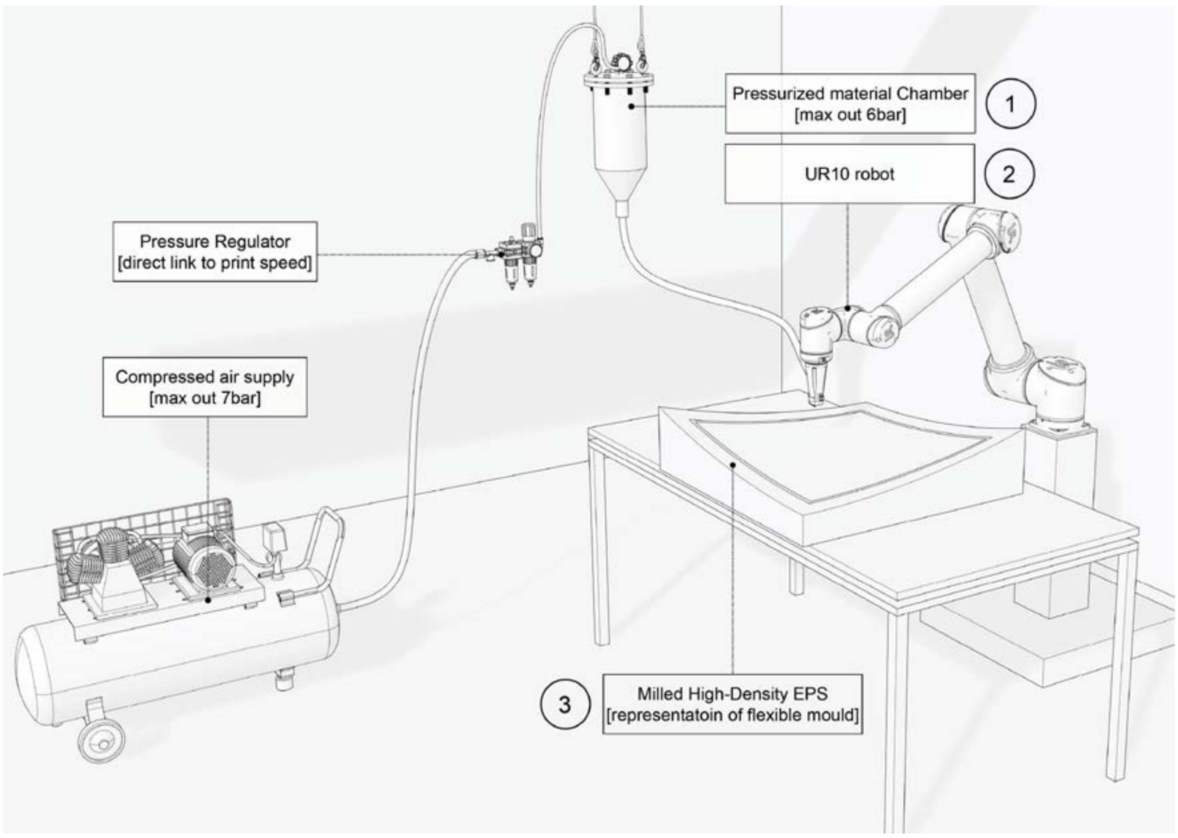
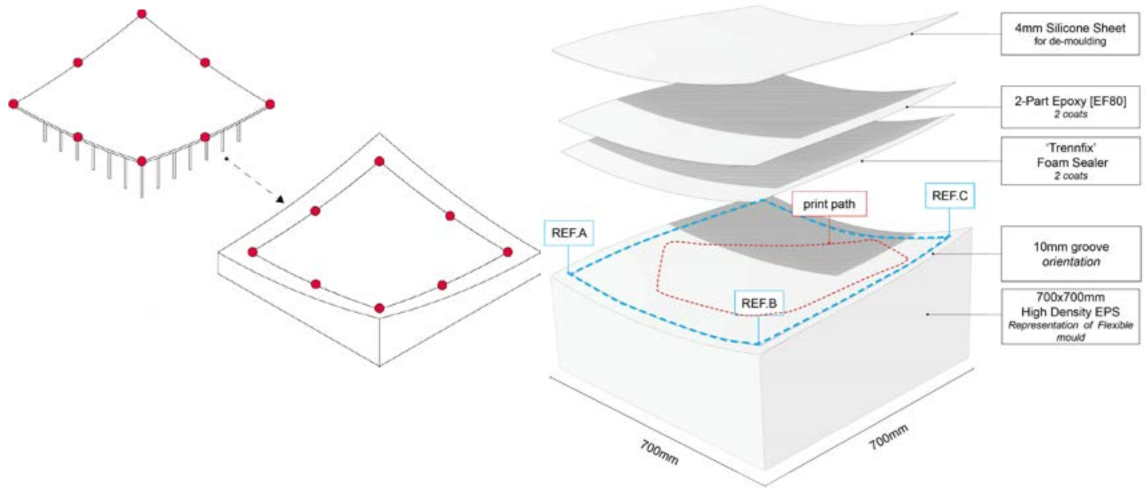


Figure 83 - Setup at DDU Lab, Darmstadt
source: Author

[5.1.1] APPROXIMATION OF ADJUSTEABLE MOULD

A milled high density EPS mould was used to approximate the adjustable mould. This had a dimension of 700x700mm with a printable area of 600x600mm which is close to that available using the adjustable mould. The slightly smaller dimension comes from the reach capabilities of the robotic arm available which would not be able to cover a 1000mm x 1000mm area. Reference points (indicated in red in figure 84) were included to allow for proper orientation of the UR10 robot with the physical mould. The would also need to be included in the adaptable mould setup. Initially, the mould was coated with two layers of Trennfix foam sealer and 2-Part epoxy resin [EF80]. However, in order to mimic the surface finish of the adaptable mould, a 4mm silicone rubber sheet was eventually used as the final surface of the milled mould. In order to allow for easy demoulding, the silicone surface was rubbed with a very thin layer of demoulding agent, rubbing off any excess so as to avoid concrete from slipping when being printed.



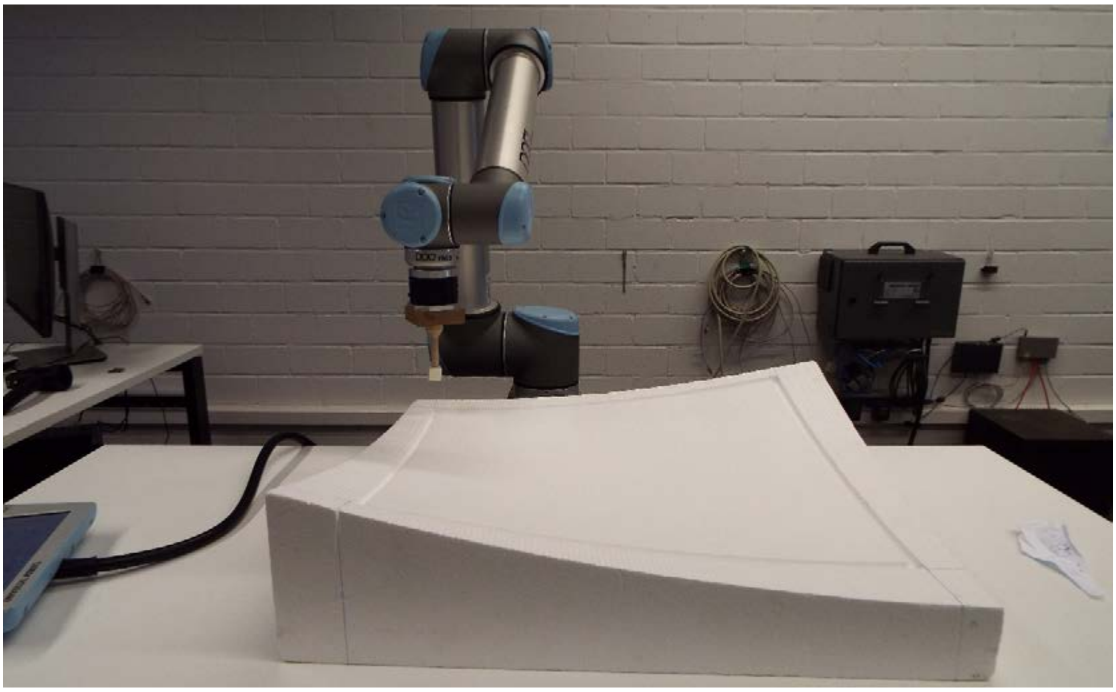


Figure 84 - Digital to physical: Approximation of flexible mould, Buildup of CNC Milled Mould
source: Author

[5.1.2] END EFFECTOR DESIGN

The final end effector used was a result of numerous iterations, evolving from attachments to a manually-controlled caulking gun to one which is mounted onto the robotic arm. The first design alterations included the use of brass side trowels which are used to maintain a constant filament shape very much the same way that contour crafting works. However, these were excluded from the final design as they were proved to be an un-necessary additional complexity added to the research. The use of trowels, for example, would also require the need for a proximity sensor to be included into the end effector to ensure that the nozzle is kept at a constant minimal distance from the surface as well as to avoid collisions (these could either damage the mould, brass plates or robotic arm)

Figure 85 - evolution of mechanically-driven to pressure driven material deposition
source: Author

The end effector design used consisted of a 190mm long 3D printed mount in PLA with a 5mm wall thickness. This is attached to the UR10 by means of 4 m6 bolts The nozzle was designed as a 20mm x 20mm square opening bolted onto the main end effector body. A void in the side of the nozzle body allowed for the insertion of a ½'' plastic feed pipe which was held together by friction. The mounting for this design was later upgraded as a clamping device to allow for quick attachment and release to and from the robot arm.

[5.1.3] DRIVING SYSTEM

The first design setup consisted of a mechanically-driven system to extrude material. This consisted of a threaded rod, driven by a servo motor to create the necessary pressure. A 1m, 100mm diameter PVC pipe housed the material which was connected via a flexible pipe to the extrusion nozzle.

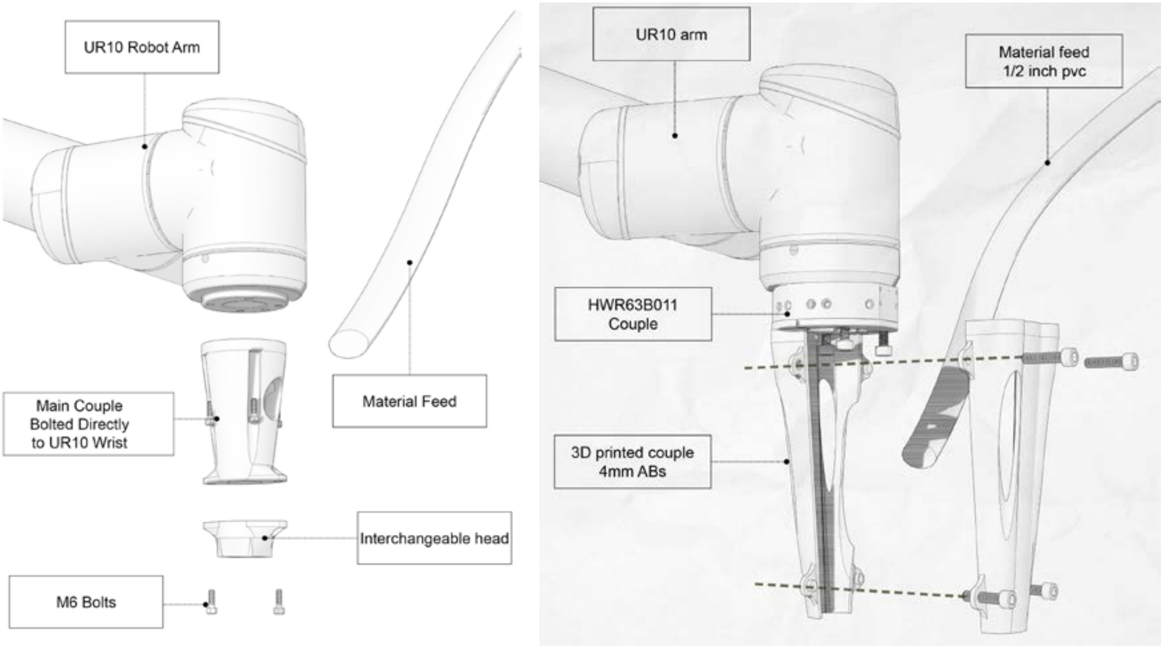


Figure 86 - schematic drawings of printed end-effectors
source: Author

[5.1.3.1] MECHANICAL DRIVE

The first design setup consisted of a mechanically-driven system to extrude material. This consisted of a threaded rod, driven by a servo motor to create the necessary pressure. A 1m, 100mm diameter PVC pipe housed the material which was connected via a flexible pipe to the extrusion nozzle. After initial testing in Darmstadt, however, it was found to be too problematic to drive the material, particularly for the relatively high pressures needed to drive the material and to maintain a constant rate of extrusion. This was despite oiling the internal surfaces of the components. Moreover, the system proved to be too bulky to set-up within the limited working space available. For this reason, a more compact, air-driven system was opted for.

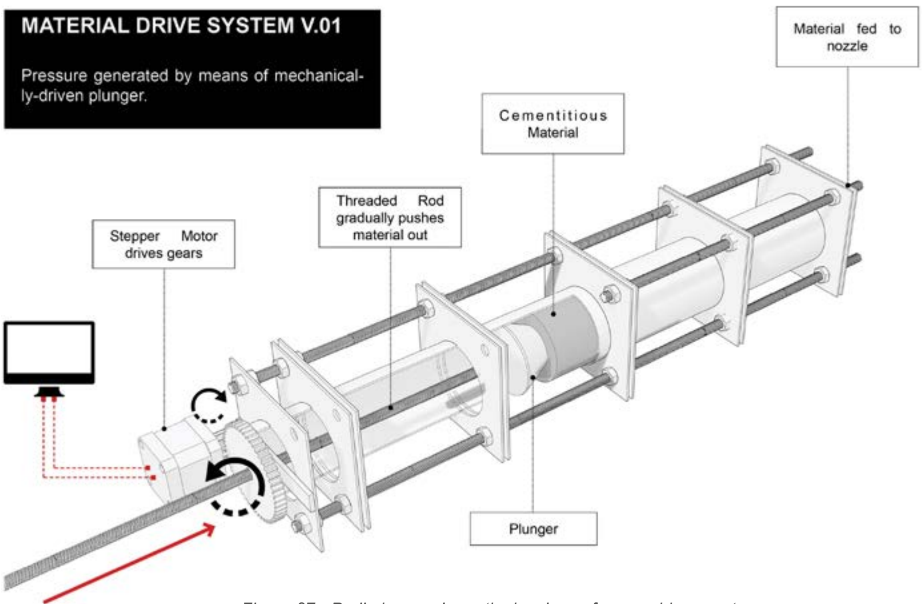


Figure 87 - Preliminary schematic drawings of screw-driven system
source: Author

[5.1.3.2] AIR-PRESSURE DRIVE

An air-pressure chamber, provided by TU Darmstadt was used as the final material-delivery system. Originally intended for being used for more viscous materials, such as clay, a ½'' acrylic plunger was fabricated to replace the 5mm flexible pvc that is usually used. This had a maximum volume capacity of 0.01cubic meters, allowing for a maximum 8 meters of continuous extrusion of a ½'' diameter filament. The maximum safe driving pressure capacity was recommended not to exceed 5bar. From initial calculations, assuming a mixture of 2200kg/m3 density, a driving pressure of around 2 – 3 bar would be needed, depending on the velocity with which the robotic arm was moving. Pressure was supplied at 7bars and regulated to the necessary pressure before entering the chamber. As the driving pressure was very sensitive to the consistency of each individual mix used, the pressure regulator was used to manually calibrate the necessary pressure needed for each new print.

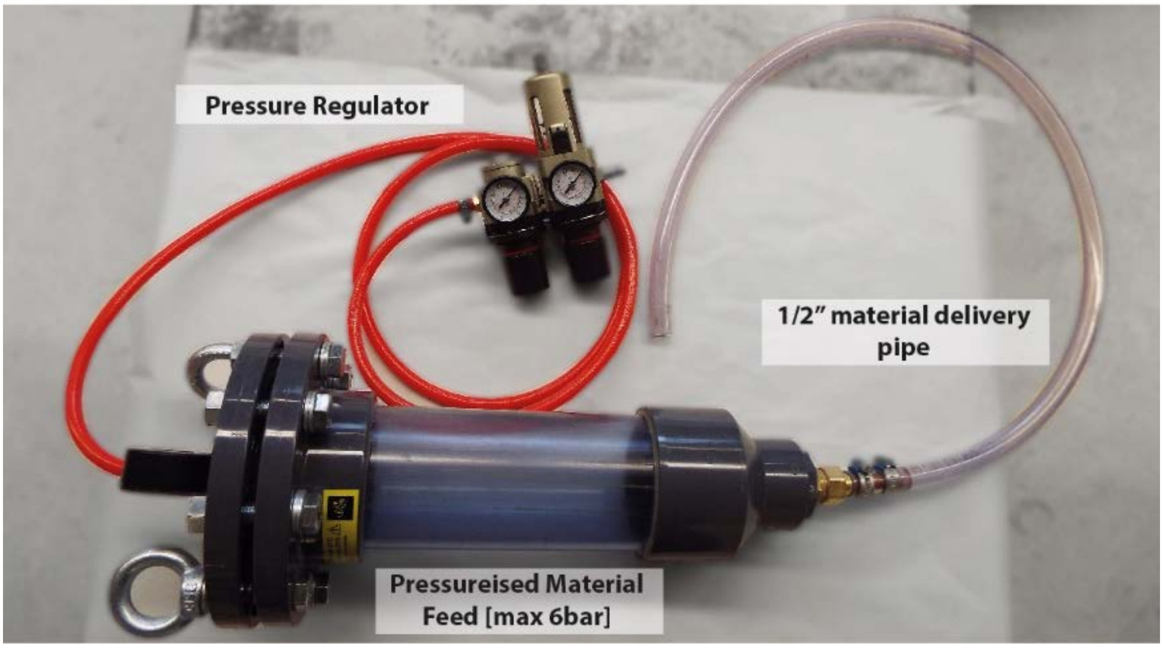


Figure 88 - Pressure-driven system setup
source: Author

[5.1.4] DIGITAL WORKSPACE

In order to set up communication between the robotic arm, end effector and milled mould an accurate model of the workspace, that is, the physical environment that the robot operates in, had to be digitally created. The accuracy of the model especially important for the study as there was no feed-back system (such as proximity sensors or scanners) which would allow the robotic arm to know it's actual position in physical space and also served as the principle basis for orienting and calibration of the robotic arm.

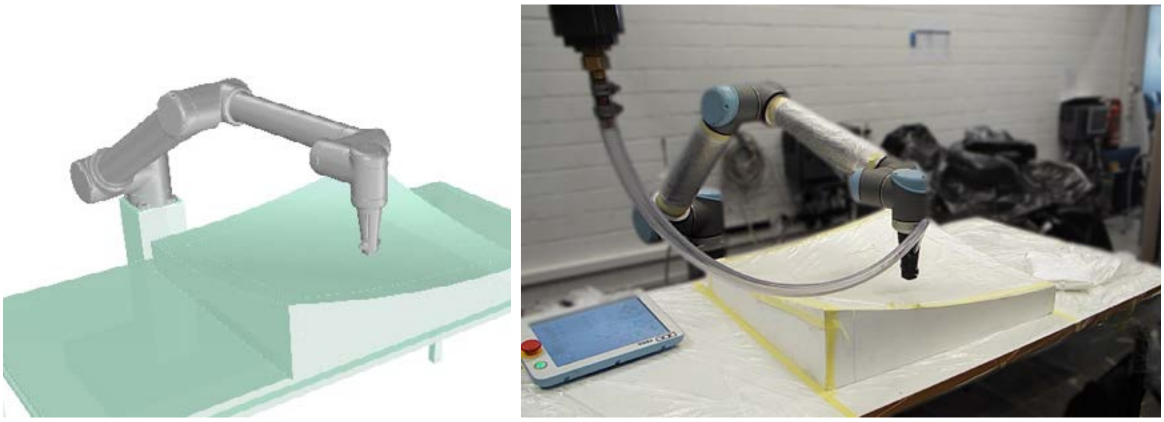


Figure 89 - Communicating digital to physical workspace
source: Author

[5.1.4.1] REFERENCING

The digital model is also used to determine where the physical mould can be set up. By extracting the work envelope (purple in figure x) in other words, the volume which the robotic arm can reach, the mould can be positioned and checked for any issues of reach.

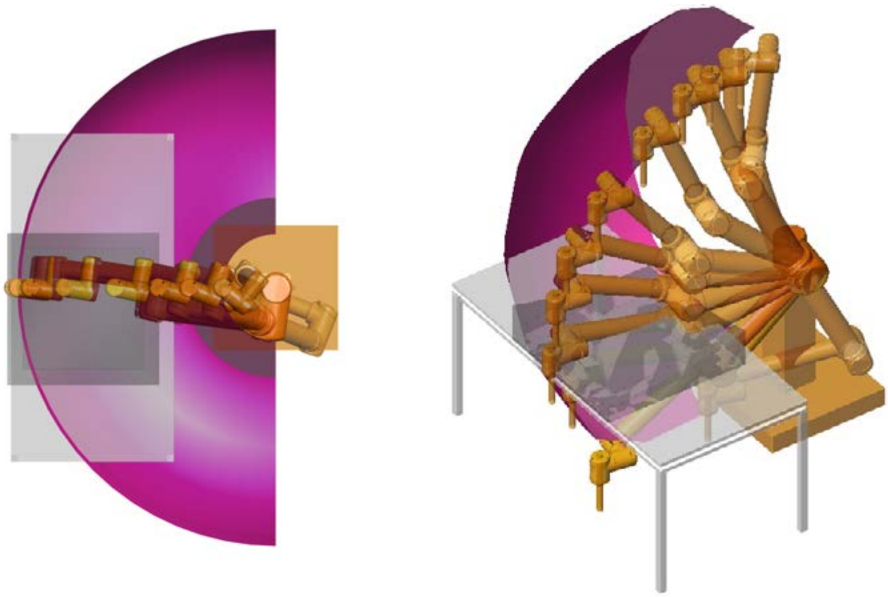


Figure 90 - Digital Work Envelope of used setup
source: Author

The positioning of the mould within the work envelope where the robot can reach may be considered as the first degree of calibration. What is now needed is to relay the actual positioning of the physical mould back into a digital model. This is done so that the path generated on the digital surface follows the exact same position along the physical mould and any incorrect calibration at this stage is likely to result in collisions between the robotic arm and physical mould. For this reason, a number of points are marked along the perimeter of the physical mould which are also known in digital space. At the beginning of each test print, the robotic arm moves to the reference points in physical space and the mould's position is adjusted as necessary. For this stage, an 8mm wooden dowel is used as an end effector so as to add more precision.

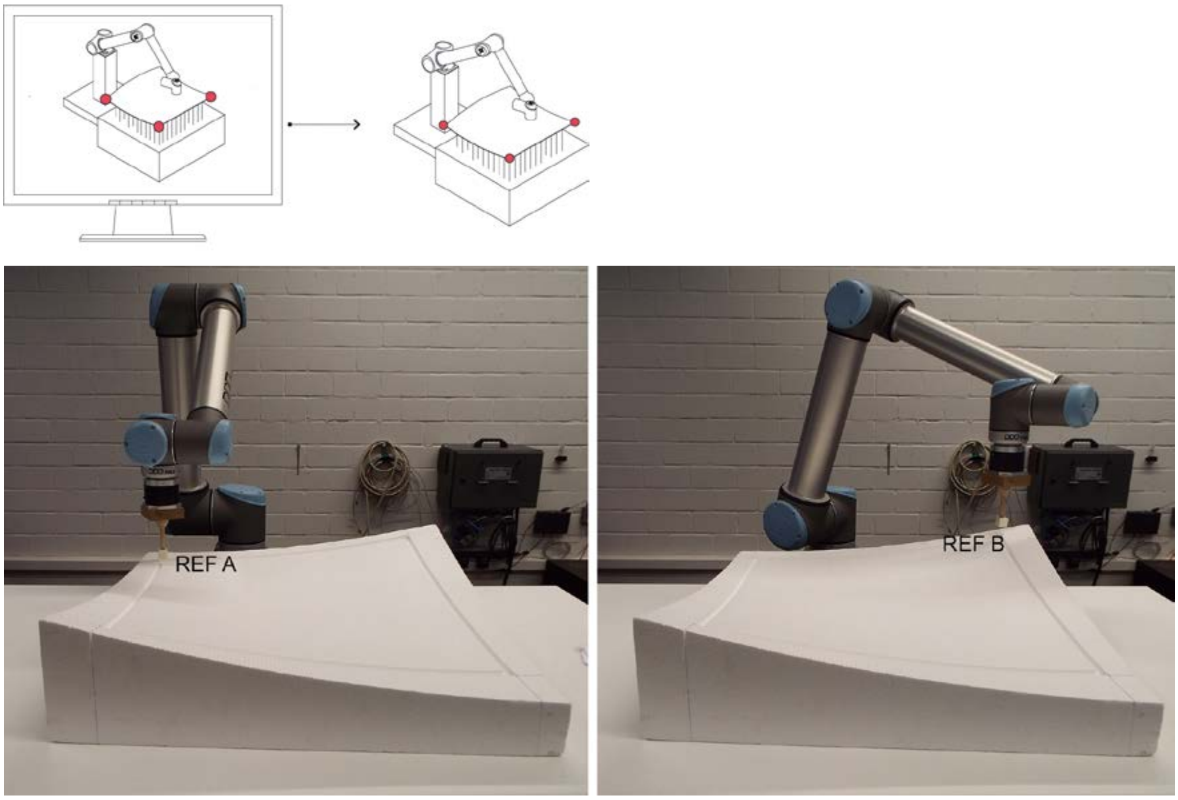


Figure 90 - Referencing physical model to digital model using reference points
source: Author

[5.1.4.2] ORIENTATION

Prior to conducting printing with material calibration for rounding, acceleration, velocity and number of divisions was conducted using the robotic arm. A pen was attached as an end effector in order to draw the path taken by the robotic arm. Figures x shows a case for an interlocking geometry which was divided into points with a spacing of 20mm and rounding varying from 50 to 1mm. In all cases, velocity was kept to 0.15cm/s. This was repeated for three cases:

a. Keeping the end effector parallel to the Z axis
b. Orienting the end effector to constantly be normal to the surface
c. Orienting the end effector to be normal to the surface and rotate with the direction of travel.

Initial tests were carried out keeping the end effector parallel to the Z axis to achieve a bench-mark on what values of rounding and velocity should be used. This is the simplest method of control of the 3 cases as it has the least amount of stress on motors which could cause un-smooth movement. Once the most optimal values were found for this case, they were used as a benchmark for calibrating the remaining two cases.

The path having 50mm rounding had the smoothest overall movement, however was also the most inaccurate. As seen in the first image of figure X, there was a tendency for skipping and discontinuity in the path traced. This is due to the robotic arm not following the surface when moving between points, but taking the path which caused least stress on its motors. This caused the pen to be lifted off from the surface in the areas shown below. As the rounding was reduced towards 1mm, the print path became more accurate with the true shape. Although jittering did occur, particularly for a rounding of 1mm, it was resolved by decreasing the velocity of the robotic arm to 0.1cm/s.

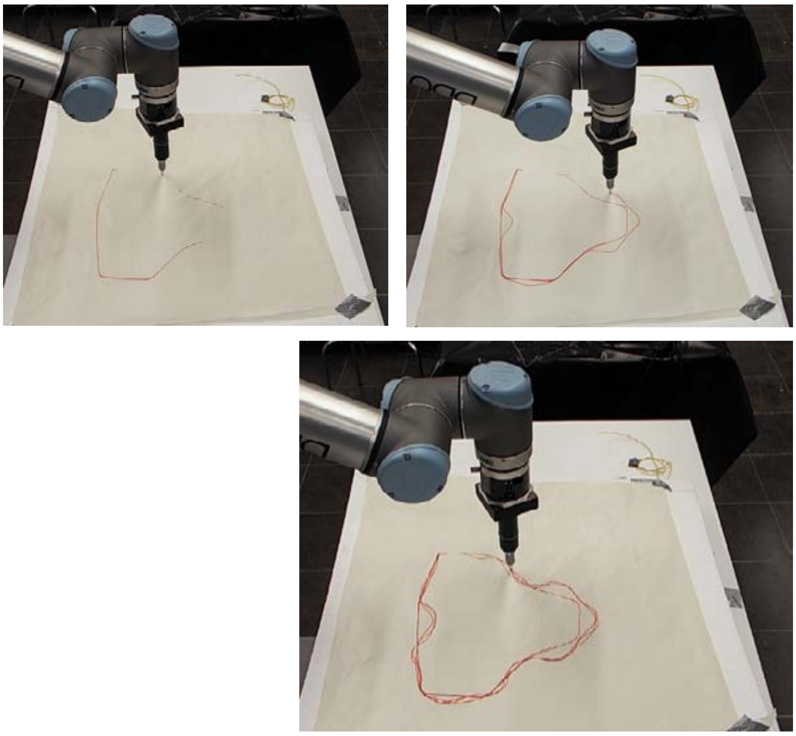


Figure 91 - Effects of rounding values in generating ideal shape
source: Author

[5.1.4.3] ORIENTING NORMAL TO SURFACE

The testing for calibration was repeated, now maintaining the printer head oriented perpendicular to the normal of the surface. The reason why this was done is that an additional servo motor is now in use to maintain the orientation. This had no major noticeable on the settings obtained for maintaining orientation with the Z axis and thus the same settings were maintained.

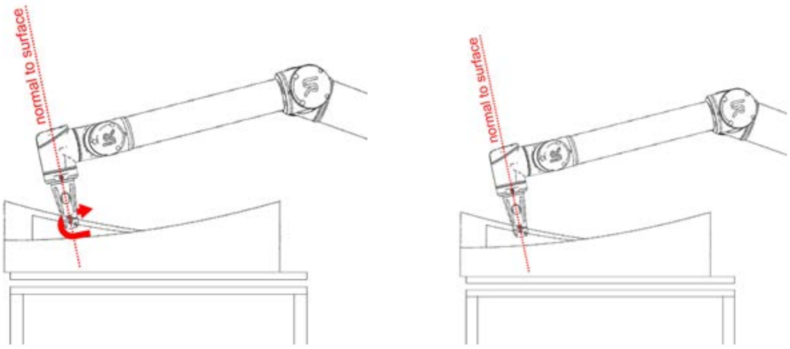


Figure 92 - Different orientation strategies. left, normal to surface and orinted to direction of travel. Right. Normal to surface with constant orientation
source: Author

[5.1.4.4] ORIENTING NORMAL TO SURFACE + ROTATION WITH TRAVEL DIRECTION

When the path included the need to orient the nozzle to per perpendicular to the direction of travel, the movement became less smooth. This is because an additional servo motor was being used to constantly rotate the end effector. Using the settings obtained in the first part of calibration caused the movement to become more jittery. Thus, the movement speed was further reduced to 0.9cm/s.

[5.1.5] CONCLUSIONS

The UR10 was not built to have smooth movement in mind as most applications robotic arms are used for are those which require movement between one point and another. Such as transporting a block between point A and B. The requirements for a constantly smooth path are thus not usually required. The calibration was thus done primarily to understand the factors leading to smooth movement. Moreover, this step was used to ensure that a smooth and constant movement was maintained during printing. Any jittering and rapid changes in velocity during printing would result in discontinuity in the material deposited.

6 PRELIMINARY TESTS

[6.1] PRELIMINARY TESTS

The printing setup was assembled at the Digital Design Unit (D.D.U) at the University of TU Darmstadt, Germany.

[6.2] MATERIALS

The material used was Schonox Q tile glue. This was chosen as a material choice as it was known to exhibit trixotropic properties and behaved very similarly to the material used for concrete additive manufacturing. The material was unreinforced and did not contain any fibres. Mixes for extrusion required a near 0 slump so as to maintain its shape after extrusion yet required to be fluid enough to be extruded without cracking. The trixotropic properties allowed the material to become fluid when agitated by air pressure and maintain its shape after extrusion.

Trial mixes were carried out for 0.2, 0.25, 0.3, 0.35, 0.4 and 0.45 water:binder ratios (by weight). As material was limited and expensive, the test batches were limited to 1000g each. After mixing the materials for 1 minute by means of a hand-held auger mixer, the material was transported to the material chamber. Once inside the chamber, a Perspex plunger was used to compress the material whilst shaking to avoid any air bubbles. The material was then extruded under pressure by slowly increasing the input air pressure. The mixes containing 0.2 and 0.25 water:binder ratio were not extrudeable. The driving pressure required was nearing the 4 - 5bar safety limit of the pressure chamber and still had too slow of an extrusion rate.

Figure 93 - Initial testing using pressure drive for material. [left] material too stiff an clogged in feed pipe. [right] material too fluid and prone to splatter source: Author

Mixes of 0.3 water:binder ratio were extrudeable using a pressure of around 3bar, however the extruded material had a tendency to crack after exiting the nozzle. Mixes of too high of a water content were too-quickly extruded and had a tendency to cause splattering. The mixes were also unable to maintain layer buildup as the material would slip off the underlying layer and deform.

Mix	Water (g)	Powder (g)	Water:Binder	Remarks
1	200	1000	0.2	Unextrudeable
2	250	1000	0.25	Unextrudeable
3	300	1000	0.3	Extrudeable, cracking
4	350	1000	0.35	Extrudeable
5	400	1000	0.4	Extrudeable
6	450	1000	0.45	Too Fluid, Splatter

table 7 - Results of water:cement ratio on ability to extrude material
source: Author

A mix having water:cement ratio was ultimately used. This mix was chosen because it the lesser amount of water would result in greater ability for material to maintain its shape after extrusion due to having a lower slump. Moreover, a very slow extrusion speed is needed in order to extrude in synchrony with the movement of the robotic arm. Utilizing a material which was less fluid would thus also allow for slower extrusion speeds.

[6.3] PRELIMINARY TESTS USING ROBOTIC ARM

Batches of 4KG were made for each testing print. These were mixed in a separate laboratory using the setup described in the previous section and transported to the robotic arm. The time between mixing and printing was thus around 3 – 4 minutes. The first extrusion test carried out was to calibrate the extrusion rate with the movement of the robotic arm. Figures x below show that an extrusion rate which is too fast relative to movement causes the filament to curl. This was controlled by manually adjusting the input pressure to match the velocity until continuous filaments were achieved.

Figure 94 - Calibration of movement with extrusion rate. Top left, speed too high; most pronounced deviations. Top right, lower speed with less pronounced eviations. Bottom right: good calibration with minimal deviations
source: Author

A slightly lower pressure than calculated was required. This is most likely due to the arbitrary value of density taken for the material as well as the head level changing as the robotic arm moved. Nonetheless, a driving pressure of 1.8 bar was found to be optimal for matching the velocity of the robot arm with the extrusion rate. This coupled with a movement speed of 1cm/s proved to give satisfactory results and consistency in the filament extruded.

After printing the outline of an arbitrary shape, in this case, a circle, material was cast into the void as a first attempt for combining printing and casting. 100ml of water was added to the mix that was used for printing in order to make it more castable and increase the slump. The material was added manually by means of a trowel and left to cure for 24 hours. Unfortunately, the mould had not yet been treated with a silicone layer and release agent, causing the prototype to break after de-moulding. Initial tests using a release agent showed a conflict between the need for easy demoulding and printing at an incline. While it is beneficial to have release agent to remove the sample without cracking, particularly as it is un-reinforced, the presence of release agent caused the filaments to slip while printing on an incline. As seen in figure 95 below, applying a generous layer of oil caused the filament to drag along the surface as the robotic arm moved, completely distorting the printed shape.

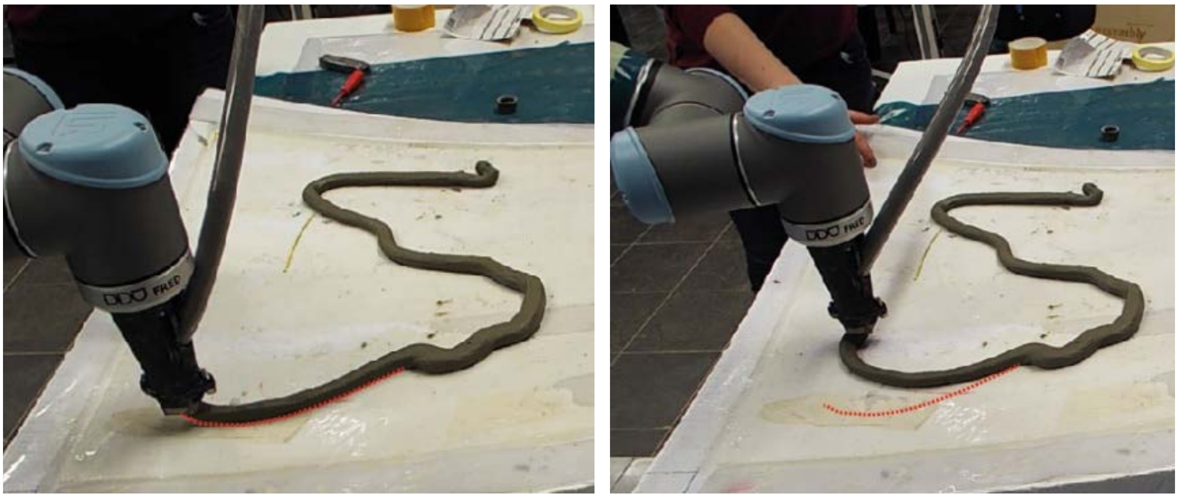


Figure 95 - Slippage of filament due to excess use of release material
source: Author

Thus, after the release agent was added, a clean cloth was used to wipe away all the excess oil to leave behind as little residue as possible. The print speed was also reduced by 2% whilst maintaining the same air pressure. This allowed for thicker filaments to be extruded and increased the contact area between material and the surface.

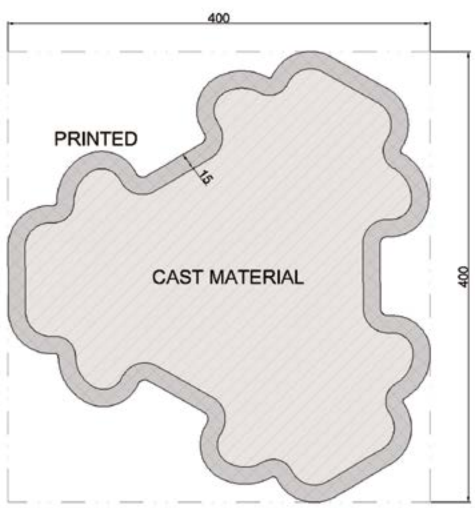
[6.4] PRINTING OF POTOTYPES

Due to limited time and availability of the robotic arm during the stay at TU Darmstadt, a limited number of prototypes were printed. The aim of these prototypes was to obtain a proof-of-concept for manufacturing fully-printed panels, panels which combined casting and printing and panels which had further details printed after casting (example, ribs) Material was prepared as described in section 6.2. To allow for easier demoulding, a 4mm silicone sheet was added to the final layer and lightly coated in vegetable oil to act as a release agent.

[6.4.1] PRINTING AND CASTING

Printing was carried out to test the concept of first printing a geometry outline and then filling in the void with cast material. The objective was to manufacture geometricaly-complex freeform panels. The print path used for these prints contained an additional path to allow for calibration of pressure and velocity before beginning to print the final shape. The geometry consisted of the interlocking panel described in section XX and was designed to have a total of 2 layres of 2cm height each. A total 3 panels were printed using this method

The first specimen consisted of three layers. However, due to a malfunction in the communication of the Gcode, one of the layers was printed in the wrong position, leaving half the geometry to have a buildup of 3 layers and the other half to have a build-up of 2 layers. Nonetheless, this served as a good first prototype as the filaments which did stack up held together in an acceptable manner without collapse or over turning. The perimeter printed served as a formwork for casting material in. 100ml of water was mixed in with the material used to extrusion and was then manually cast on the mould. A trowel was used to distribute the material evenly, ensuring that there was interaction with the printed edges.



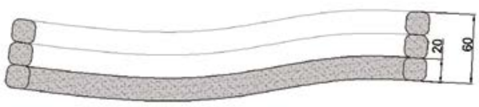


Figure 96 - Schematic of Typical interlocking panel source: Author

Figure 97 - Printing of stacked filaments
source: Author

The remaining prototypes were slightly reduced in size so as to reduce the file size and the chances of error during printing. The number of layers was also reduced to two. The print for these prototypes was more successful as there was no error during the process

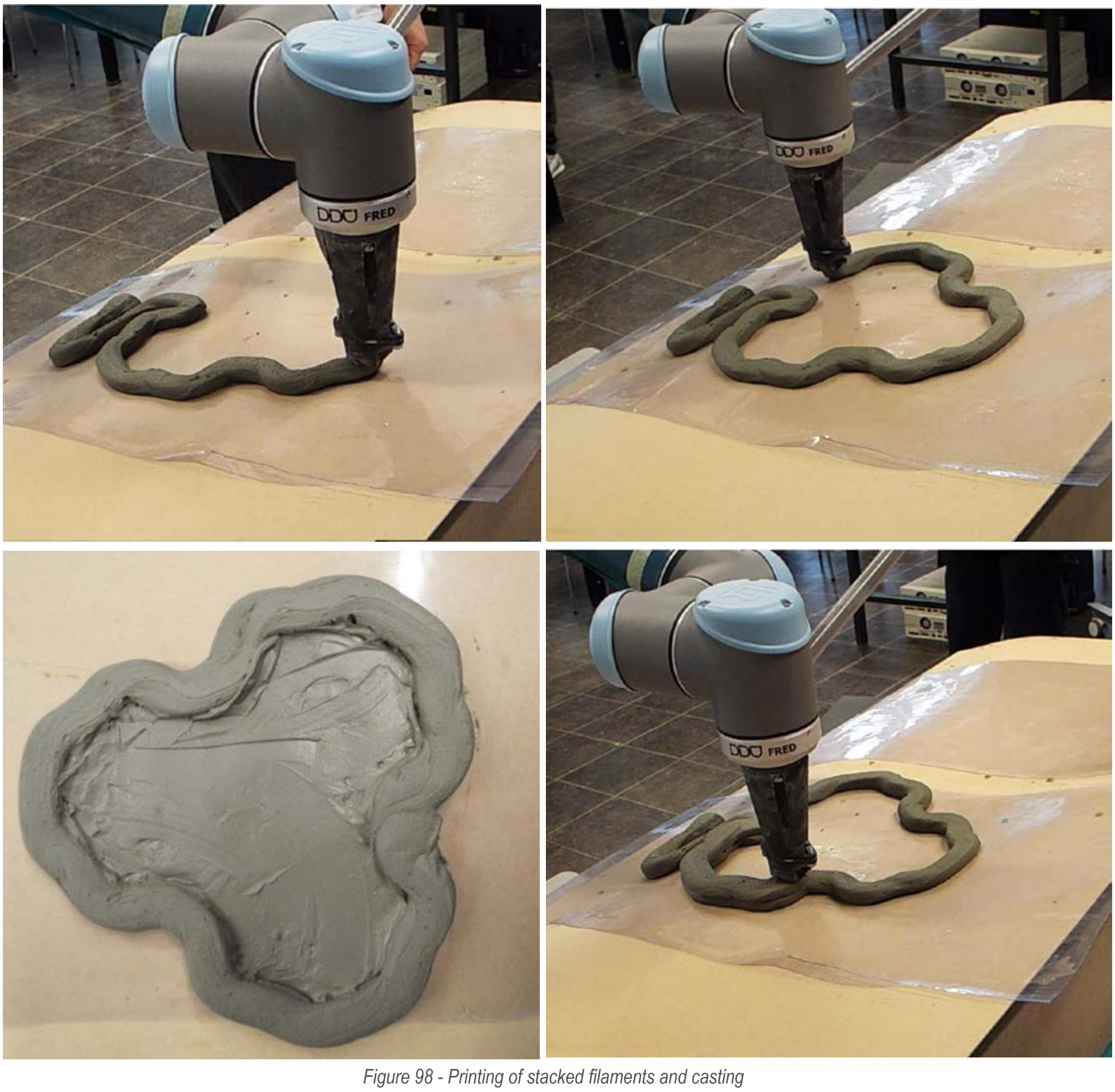


Figure 98 - Printing of stacked filaments and casting
source: Author

Demoulding took place after 24 hours to ensure the samples had gained sufficient strength. No shrinkage cracks were observed, however the interface between printed concrete and cast concrete produced a seam. This was most likely due to the casting mixture not being fluid enough reach and fill all the areas. This was exhibited in the interfaces of all the samples printed.

Figure 99 - Printed and cast panels. Note interface between printed and cast material
source: Author

[6.4.2] FULLY PRINTED PANELS

The second test was on the production of fully-printed panels as an alternative to the traditional layering techniques. The digital file created was far heavier than the one generated in the previous printing tests AS the path had an almost-constant change in direction, requiring a high degree of point divisions with a very low rounding value. In order to reduce the size of the file used, the nozzle was not oriented to the direction of travel, but kept parallel to the Z axis. By keeping the nozzle oriented to the Z axis allowed for a very smooth printing process with very little interruptions was achievable. As the offset of the printing path was set to half the diameter of the printing nozzle, filaments were deposited next to eachother and bonded from the sides. The print speed was set to 0.06cm/s to ensure a very slow and controlled movement. There were some overlaps and spaces in some areas however. This was due to the fact that even with a very small value of rounding, there will always be a degree of inaccuracy between the original print path and the one communicated with the robot.

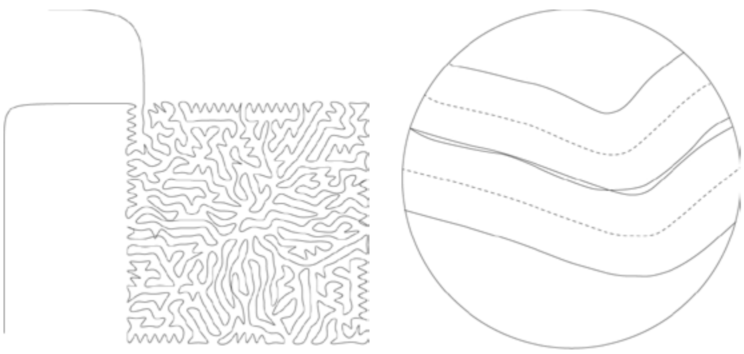


Figure 100 - Generatin of print path
source: Author

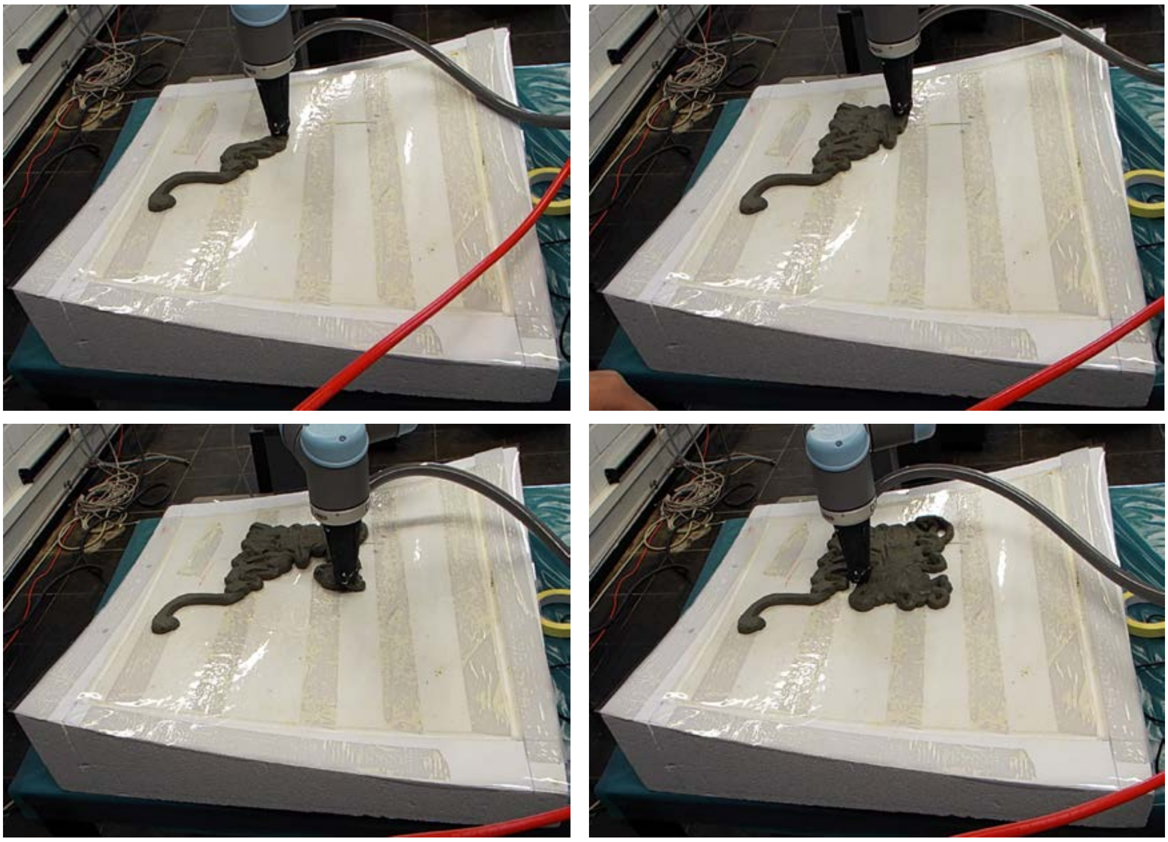


Figure 101 - Printing of fully-printed panel prototype
source: Author

[6.4.2.1] DISCUSSION AND CONLUSION

The final results displayed a number of issues. The first sample had malfunction during printing which left a void in the centre of the panel, resulting in an incomplete print. The filaments which were properly laid down did however bond well with one another. The second sample printed had a better consistency, however, due to a badly-set printing speed, there as too much overlap between filaments, resulting in filaments not being stuck side by side, but on top of one another.

Figure 102 - Printing of fully-printed panel prototype
source: Author

While there is potential using this method, time and material restrictions only allowed for a small amount of physical printing, meaning that the actual printing of a perfect panel could not be achieved in the time span. Although the panels printed were less than ideal due to voids and gaps between filaments, they still managed to reatain their shapes and support themselves once demoulded. As a second batch of studes, the same printing path was extruded ontop of already-cast material, such that an underlying layer of continuous materil is supported.

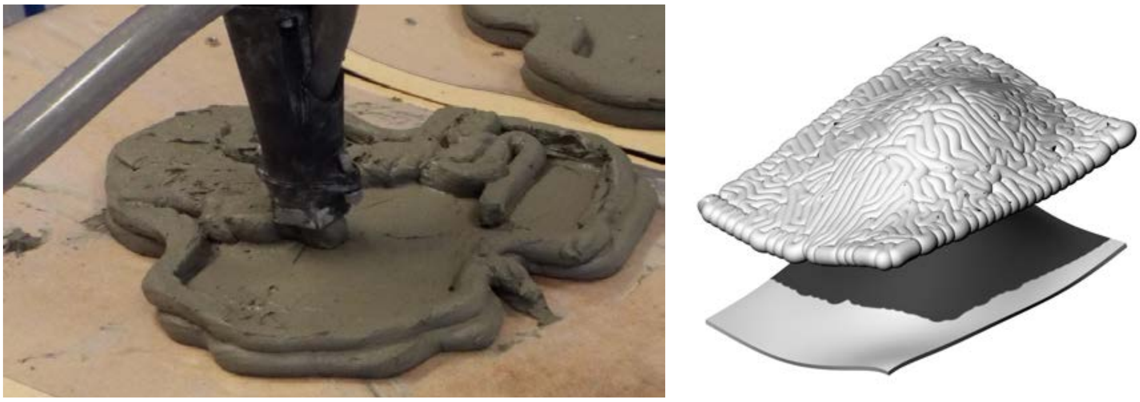


Figure 103 - Printing of fully-printed panel prototype
source: Author

Nonetheless, the final printing prototypes show the potential of a printing strategy whereby print paths are generate based off the curvature of a given surface uing differential approach. However, in order to achieve panels with a higher degree of accuracy, better control of the robotic arm is needed. Particularly, an interface has to be setup where the speed of the robotic arm movement and pressure used to drive material is automated. For these print tests, where there was a constant change in movement speed, material pressure was controlled manually. This may be on of the factors which led to filaments being discontinuous in certain areas.

[6.5] SCHEMES AND DETAILING

[6.5.1] FULLY PRINTED PANELS

The main benefit of having fully-printed panels which follow the use of differential growth is that the print paths are specifically generated to suit the curvature of the geometry being printed. As opposed to traditional printing techniques, where a given geometry is printed with the same orientation, using this approach allows for the printing of panels having consistent thicknesses.

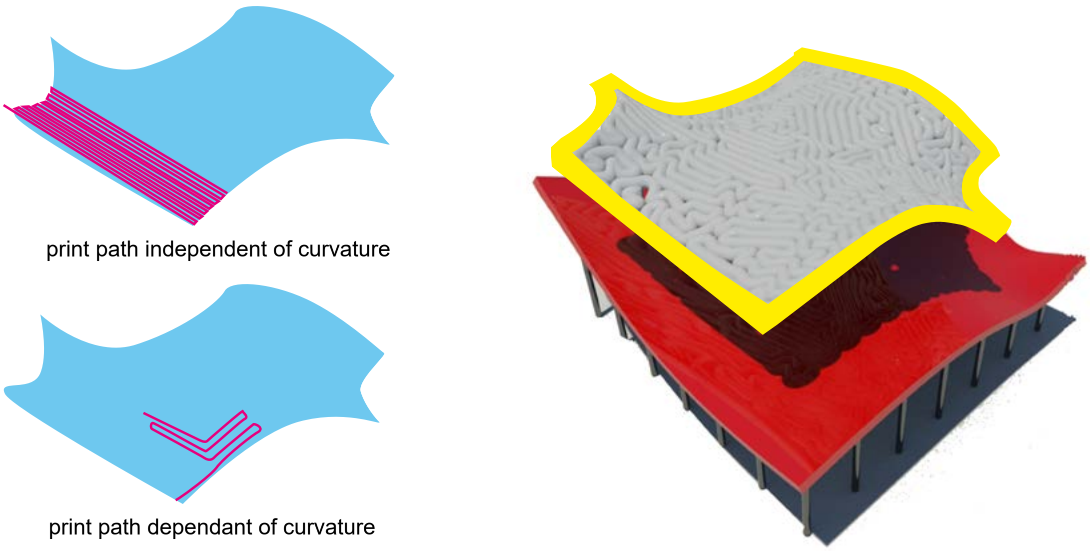


Figure 103 - Printing strategy for fully-printed panel
source: Author

In terms of detailing and connections, it is imagined that an additional perimeter is printed along the edge of the panel which would allow for the attachment of any external fixings. These can be used to serve as mountings such as clamps or bolting. Figure 105 below shows an example of how this may be achieved. For the bolting solution, bolts are connected via the edge perimeter and fixed into a facade substructure. For a clamping solution, the edge perimeter is printed in multpple layer heights to allow for additional grip area.

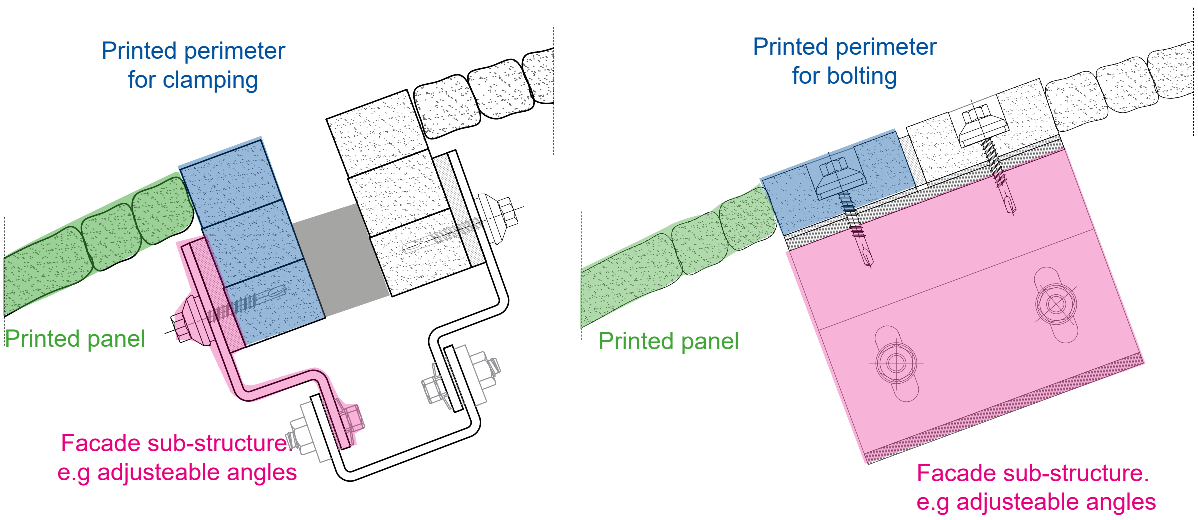


Figure 104 - Printing of fully-printed panel - Detailing. [Left: clamped. Right - bolted]
source: Author

Figure 105 - Potential schemes for Fully-printed panels. [Left: facade Panels. Right: Printed with Edge perimeter]
source: Author, 3TU Lighthouse 2016

The schemes above show two potential areas where the printing panels could be adopted. The left hand side illustrates a free-form facade panel designed with the same connection principles as illustrated in figure 104 on the previous page. The right hand-side image illustrates the result of the 3TU Lighthouse Project which ran in parallel to the thesis study. In this scenario, the edge perimeter is first printed and material then cast, however it indicates the edge perimeter which could be used for connection details. Figure 106 below illustrates a scenario where the same panels with edge perimeter are used for self-supporting elements.

Figure 106 - Potential schemes for Fully-printed panels.
source: Author

[6.5.2] PRINTED AND CAST PANELS

As already indicated, the main benefit of printing a perimeter onto curved surface and later casting material is that complex shapes can be realised. Although the prototypes printed in section 6.3 are far from being perfect, they still show the potential once issues such as accuracy of robotic movement and more exact interaction between cast and printed material is achieved. Figure 107 below illustrates the process of first printing the outline of a panel onto a readily-oriented surface into which concrete is then cast.

Figure 107 - Process for fabricating Printed-and-cast-Panels.
source: Author

The detailing schematic for panels manufactured in this way are also imagined to follow the same principles as described in section 6.5.1. As in the previous case, the edge perimeter is used to either bolt or clamp onto a sub-structure of a facade. Figure 108

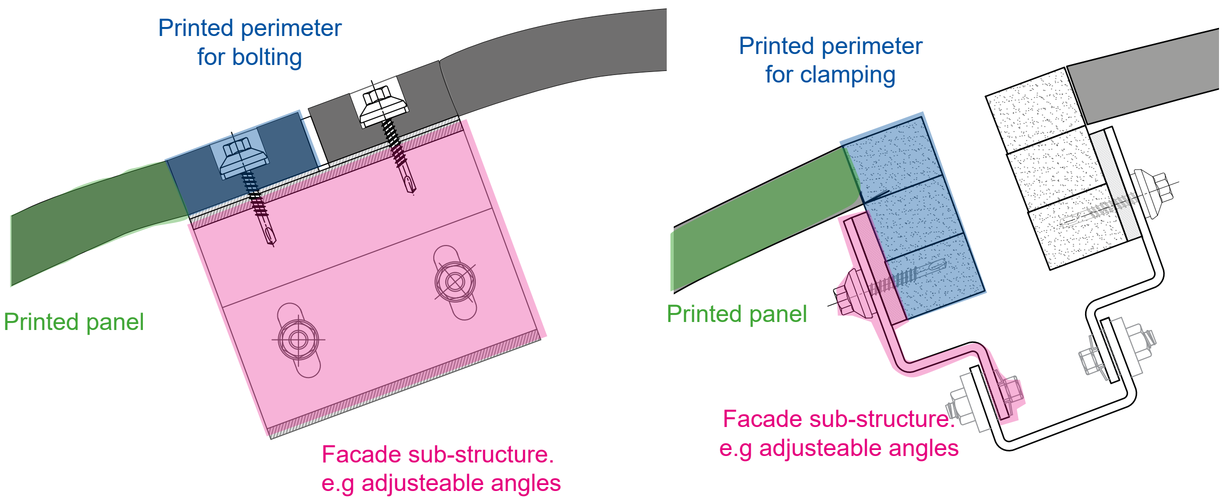


Figure 108 - Detailing for cast and printed panels
source: Author

Figure 109 - Potential use for cast and print panels
source: Author

7 CONCLUSIONS

Discussion and conclusion

The aim of this thesis project was to study the potential of combining two previously distinct manufacturing techniques; concrete additive manufacturing and an adaptable formwork.

Concrete additive manufacturing allows for the fabrication of relatively complex concrete structures by the controlled deposition of filaments. While the major benefit is that it requires no formwork and hence, is highly efficient in terms of the material used, its drawback is that any printed geometry has to be self-supporting during the printing process in order to avoid collapsing. The result is that the relatively simple geometries being produced can already be fabricated using existing techniques such as extrusion and pre-cast systems. The adaptable formwork system, developed at TU Delft, is a manufacturing technique used for producing free-form concrete panels. In its simplest form, an adjustable pinbed is used to deform a metallic mesh which serves as a temporary formwork for casting concrete. This makes it a far more efficient manufacturing techniques for producing freeform concrete panels when compared to other techniques such as casting in milled formworks. The limitation of this technique, however, is that a temporary formwork is still required to define the shape of each element cast. Moreover, the production of complex geometries and elements with varying cross-sections requires even more complicated formwork and can reach a point where it becomes counter-intuitive.

The use of an adaptable mould as a temporary support for concrete additive manufacturing had not yet been explored academically. This led for an exciting opportunity to explore the potential of a new manufacturing process, yet also left a considerable amount of room for failure of the concept. Due to limited time of the thesis as well as continuous development of potential uses, only a few ideas were tested. Printing an entire panel using a differential growth algorithm to generate a print path proved to be an exciting new application which emerged from the combination. This alternative to the traditional layered approach to printing could allow for more exciting freeform panels, however, at this stage it seems best reserved for architectural applications.

The second area explored was the combination of additive manufacturing with casting. The intent was to print complex formwork onto the adaptable mould into which material could be cast. This allows for the fabrication of far more complex geometries that are currently produced using the adaptable mould system, and also holds potential for integrating further details such as edge returns or structural ribs into the element. Currently, all the prototypes that were printed exhibited a seam at the interface between the cast and printed material and further research would be needed to attempt to remove this.

Overall, the thesis was somewhat successful in showing that there does in fact lie potential in the combination of these two fabrication techniques. However, although only two potential areas were explored, a bulk of the thesis was focused on setting up a methodology for robotic control for the use of additive manufacturing, the development of end-effectors and setting up an interface between robotic arm and temporary surface. These principles are not only applicable to the two studies explored, but can be used as a template for further research on the topic.

Moreover, throughout the development of the thesis, a number of new potential applications have emerged some of which also merit additional exploration. Particularly, the issue of reinforcement had been omitted from this thesis, although it is conceivable that fiber-reinforced concrete could be used as a printing material. Additionally, the printing of post and pre-tensioneable ribs onto existing panels seems to be another potential area of interest to be further explored.

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