MASTER

Flexible mold
an innovative production method to produce precast double curved concrete panels

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precast double curved concrete panels

Flexible Mold

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Abstract

3D-modelling programs enable architects to design the most complex geometries for buildings, see figure 1. However, no economical manufacturing techniques are available to build these freeform buildings. Freeform buildings are characterized by many single or double curved surfaces which are none repetitive (Pottmann, H. et al, 2007). This means that for every panel a separate mold is needed. Current mold techniques such as CNC foam milling are only economical if some repetition is present, but in the case of freeform architecture, the current mold techniques are not efficient enough. Because of this inefficiency it limits the architects in freedom of design, and makes it only possible to apply freeform façades in big budget project. Furthermore, property developers will likely discourage this design because of the high production cost.

To close this gap between freeform modeling and manufacturing, over the years several researches have been carried out to manufacture double curved panels with a reconfigurable mold. The idea of a reconfigurable mold is that the mold’s surface can be easily adjusted into different shapes. Thus with one mold many different curved elements can be produced. The research of reconfigurable mold for architectural use is still very new and requires much more development (Munro, 2007). A reconfigurable mold not only has the potential to offer a more economical alternative, but can also contribute to sustainable development because of the elimination of the waste flow.

Cast materials such as concrete have all the geometric freedoms, thus are very suitable for complex geometric buildings. The goal of this research is to develop a mold technique to produce double curved concrete elements in an economical and sustainable manner.

The geometry of freeform surfaces, flexible mold techniques and concrete technology have been analyzed to define boundary conditions for the development of a new flexible mold system.

Flexible molds can be divided into four classes (see figure 2):
- Pin-bed surface
- Supported membrane
- Tensioned membrane
- Pressurized membrane

In the same order as the classes are listed, they show a decrease in density of the actuators and a decrease of the investment costs. For architectural façade elements, only low curvature elements are desired. This means that the density of the actuators of the pin-bed is redundant. The cheapest mold system for these
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gEometries is the tensioned membrane mold, which has as a drawback that the membrane needs to be manipulated manually to form synclastic shapes. The more expensive supported membrane mold can be adjusted completely automatically for synclastic and anticlastic curvature. Investment costs of a flexible mold are high. This is especially disadvantageous for concrete panel production because of the 24 hour inactivity during hardening. The demold time of concrete can be reduced up to one hour. This requires specific admixtures and heat treatment which makes the casting process more expensive and the concrete properties inferior in comparison to ordinary concrete. Instead, a different approach has been chosen to increase the productivity: the production of a reusable intermediate mold on the flexible mold. In this way, the concrete casting process is separated from the flexible mold. Multiple intermediate molds can be produced on the flexible mold, while the concrete hardens on the intermediate molds. When the concrete panel is demolded, the intermediate mold can be reused for the next production cycle.

A suitable manufacturing technique for a rapid production cycle is thermoforming. Free forming, a thermoforming technique used to produce skylights, forms the sheet without the use of a mold by exerting air pressure only. The mold design developed in this thesis combines the free forming technique with the tensioned membrane mold. The polymer sheet will be pressed between two mold edges and tensioned by applying tensile stresses at the edges. Thermoplastic materials with a high strain hardening property such as PMMA or PETG, show a uniform strain behavior which is a prerequisite for this technique.

A prototype has been developed and tested in a convection oven, see figure 3. This technique focuses mainly on the edge connection of the panels to obtain a fluid transition. To control this, the mold edges can be adjusted in height and angle. Furthermore, a flexible silicone rubber guides the membrane to the edge to avoid ‘kinks’ between two panels.

Test results show that smooth curvatures can be obtained by prestressing the polymer sheet. The prestress needs to be applied in flat sheet position; otherwise the edges will be tensioned only instead of the complete surface.

Two concrete casting techniques have been tested on the intermediate molds. By placing two intermediate molds on top of each other with spacing, wet-casting can be used to pour the concrete in the closed mold. This results in a double curved panel with a constant thickness and two smooth surfaces.

This new innovative production technique has also future potential for uses other than the production of concrete panels. Because the polymer surface is free from any friction, a maximum transparency is obtained. PMMA, which is used as an alternative for glazing, can now be shaped into any desirable freeform without compromising for the optical quality and can be used as a direct end product as a facade element.

![Figure 3 Prototype flexible mold inside convection oven](image-url)
Preface

This thesis is written for the completion of the master track Building Technology of the faculty Built Environment at Eindhoven University of Technology, the Netherlands.

The theme of this thesis is the manufacturability of free form concrete façade panels for architectural use. A new innovative production method has been developed and tested which is reported in this thesis. A successful completion could not have been established without the contribution of others.

First of all I would like to thank my graduation committee prof.dr.ir. J.J.N. Lichtenberg, ir. A.D.C. Pronk Pronk, and ir. M.M.T. Dominicus who guided me throughout the process and shared their knowledge and provided me with helpful insights.

For the specific study on concrete technology and polymers I would like to thank respectively prof.dr.ir. H.J.H. Brouwers and prof.dr.ir. H.E.H. Meijer for sharing their knowledge.

Furthermore I would like to thank dr.ir. M. Kaufman and ir. B. Waeyenbergh of Sirris composite application lab (Leuven) for the use of their facilities and their assistance with the experiments in the convection oven.

I would like to thank ir. H.R. Schipper, PhD candidate doing research on reconfigurable mold techniques for precast double curved concrete panels, for sharing his knowledge on this topic and for letting me attend experiments of the reconfigurable mold.

Finally, many thanks go out to my partner, family and friends who supported me with patience throughout the whole process.

Fritz Gard
October, 2013
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1 Introduction
1.1 Reconstruction of Philips Pavilion

In 1958, Philips was represented with an own pavilion at the World’s fair in Brussels. The ingenious idea of demonstrating the sound and light possibilities of Philips’ technologies rather than showing them came from Louis Kalf, then the Artistic Director of Philips. Le Corbusier was asked for the design in 1956 and immediately agreed because of the unique possibility to combine sound, light and architecture in one design. Le Corbusier focused entirely on his ‘Poème électronique’ which was a synthesis of sound, light, colors and images, and delegated the actual architectural design to Iannis Xenakis (Xenakis, 2008).

In only a few months approximately 1,500,000 spectators visited the Philips Pavilion. In spite of this enormous success, the pavilion was destroyed in 1959. Over the years, the idea for a reconstruction of the Philips Pavilion was raised several times. The first concrete initiative was proposed by the foundation Alice in 2003 to rebuild the Philips Pavilion on the location Strijp S, a district in Eindhoven in the Netherlands. Strijp S is an important district for the ambition of Eindhoven to become the Cultural Capital of Europe in 2018, thus making the Philips Pavilion a part of it. After settling juristic matters with the ‘Fondation le Corbusier’, a feasibility study was initiated in 2010. This resulted in a foundation called ‘Reconstruction of the Philips Pavilion 1985’ in the beginning of the year 2012. This foundation was established to better coordinate, follow and promote the reconstruction (Riemersma, 2012).

In response the Technical University of Eindhoven, under supervision of assistant professor Arno Pronk, has started to research the possibilities of a more cost-efficient construction method for double-curved surfaces in concrete. Two methods for the wall structure have been developed, see appendix B.

One of the main aspects for the reconstruction is the structure of the pavilion. The original structure is exclusively based on self-supporting hyperbolic paraboloids which are constructed of panels that are tensioned by two grids of steel cables. During that time an innovative production process was used to manufacture the double curved concrete elements: the slabs were cast in sand molds on the ground. The production method is very labor intensive, thus making it too expensive for present day manufacturing (Riemersma, 2012).

Although the double curved concrete elements will not function as the main support structure for the reconstruction of the pavilion, they will still be used to resemble the original design. Up to date there exist no economical fabrication methods to produce those double curved concrete panels. Thus a feasible manufacturing method needs to be developed to produce the double curved concrete elements.

Fig 1-1 Philips Pavilion (Le Corbusier, 1958)
1.2 Problem description and relevance

For nearly 30 years, architects have been using computer aided design (CAD) software to draw digitally. Digital drawing made two-dimensional drawing more efficient, easier to edit and more simple to do. CAD programs were in the beginning merely a replacement for 2D-drawings. Thus the shift from analogue to digital drawing was not reflected on the building design itself. Only when 3D-modelling programs and digital fabrication methods were developed, the shift to digital drawing could be noticed in the complex geometries of the buildings (Iwamoto, 2009).

Cast materials such as concrete have all the geometric freedoms, thus are very suitable for complex geometric buildings. Heinz Isler, as an architectural/engineering pioneer, already showed the unlimited form properties of concrete in his shell structures (Veenendaal, 2010), see figure 1-2.

Fig 1-2 Concrete shells (Heinz Isler, 1968)

Traditional timber or steel molds are labor intensive and expensive techniques when many non-repetitive molds are needed to cast single or double curved concrete elements. Thus the development of digital fabrication, such as CNC foam milling, enabled this new architecture to be more cost-competitive.

The expressive buildings of Frank O. Gehry that show vivid complex geometry have used digital fabrication techniques to realize the buildings. The ‘MARTa Museum‘ in Herford or ‘der neue Zollhof‘ in Düsseldorf, see figure 1-3, are for example built with CNC foam and timber molds for pre-cast and in-situ concrete. Gehry Partners and its associative firm Gehry Technologies contributed a lot to the development of digital fabrication.

Although the CNC foam milling and CNC timber and steel cutting reduced the production time and costs for fabricating molds, it is only cost-competitive when some repetition of elements is present. Freeform buildings are characterised by many single or double curved surfaces which are none repetitive (Pottmann, H. et al, 2007).

This means that for every cast element a separate mold is needed. Current mold techniques are only economical if some repetition is present, but in the case of freeform architecture, the current mold
techniques are not efficient enough.
Because of this inefficiency it limits the architects in freedom of design, and makes it only possible to apply freeform façades in big budget project. Furthermore, property developers will likely discourage this design because of the high production cost. To close this gap between freeform modeling and manufacturing, over the years several researches have been carried out to manufacture double curved concrete elements with a reconfigurable mold. The idea of a reconfigurable mold is that the mold’s surface can be easily adjusted into different shapes. Thus with one mold many different curved elements can be produced. Reconfigurable mold applications are meant for manufacturing situations where part variety is high and production quantities are low such as the aerospace and building sector.
The research of reconfigurable mold for architectural use is still very new and requires much more development. This is indicated by the fact that only very few reconfigurable molds, including aerospace and marine sector, are sold commercially although the interest for reconfigurable molds has not decreased (Munro, 2007). A reconfigurable mold not only has the potential to offer a more economical alternative, but can also contribute to sustainable development. The best known definition of the concept sustainable development comes from Our Common Future, a report written by the World Commission on Environment and Development (WCED). It states that sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Sustainable development is regarded very important and thus implemented on international and national level through policies. The construction industry is an important sector for sustainable development which is responsible for high-energy consumption, solid waste generation, greenhouse gas emissions, pollution and resource depletion. Almost 40% of the world’s consumption of materials is used for the built environment (Ortiz 2009).
The manufacturing process is part of the building life cycle and thus plays an important role in sustainable building. Greenberg (2012) addresses six elements for sustainability manufacturing: waste, water, energy, management structure, supply chains, and ecosystem management. Because a reconfigurable mold may reduce waste and energy flows, this technique contributes to sustainable development. Below a theoretical framework summarizes the scientific and social relevance.

### 1.3 Research objective

![Theoretical Framework]

Fig 1-4 Theoretical Framework
The goal of this research is to develop a mold technique to produce double curved concrete elements in an economical and sustainable manner. Reconfigurable molds have the potential to be a competitive alternative to other existing molding techniques for low repetitive double curved concrete elements. The main research question is formulated as follows:

*How can pre-cast double curved concrete elements be manufactured with reconfigurable mold techniques?*

The sub-question can be divided in three different aspects: geometry, concrete technology and the mold technique.

Sub-questions:
- What are the geometric boundary conditions of concrete panels for freeform facades?
- What are the limitations of concrete casting techniques?
- What is the most suitable reconfigurable mold technique?
- Which materials are suitable for the production method?

### 1.4 Approach

The research model based on the systems approach by G. Pahl and W. Beitz will be used for this thesis, see figure 1-5. It includes fixed steps, each involving analysis and synthesis. The steps are indicated on the right side of the research model. Within this model, the cyclical iterative design process based on Stefan Thomke has been used to further specify the research model. The first step is the problem analysis, here the problem and research questions are defined. In the second step the criteria will be formulated for the mold technique, concrete technology and the geometry in freeform architecture mainly through literature study. When all the criteria are defined, they are the starting point for the design process. The cyclical iterative design process consists of designing, producing prototype, testing and evaluating. This cycle will be used for parts of the system, i.e. materials, and eventually for the complete mold technique. This cycle should result in a prototype. The double curved concrete panel which will be produced with the designed reconfigurable mold will be evaluated for geometry and quality. This report is divided in a similar order as the research model.

The chapters 2, 3 and 4 are mainly literature study of respectively the geometry, mold techniques and concrete technology. Chapter 5, concept, is the synthesis of the information analyzed in the previous chapters. Chapter 6 discusses the backgrounds of thermoforming techniques which will be used for the design. Subsequently, the concept will be elaborated into a design in chapter 7. In chapter 8, a generative model with grasshopper in rhinoceros is made for the mold. Chapter 9 shows test results of the mold. Finally, chapter 10 concludes this thesis and evaluates the developed reconfigurable mold.
Fig 1-5 Research model
2 Geometry

This chapter explores the geometry of freeform surfaces and analyzes two freeform buildings.
2.1 Freeform surfaces

Freeform surfaces are, as the name implies, forms without any restriction. These surfaces have complex geometry with smooth fluid curves. Those surfaces are built with freeform splines, i.e. NURBS in computer modeling (Pottmann, 2007). No mathematical backgrounds will be given because that is beyond the scope of this thesis. Also mathematical defined surface such as hyperbolic paraboloids (hypars) used in the Philips Pavilion, can fall under the definition of free form architecture. Any building that deviates from orthogonal or flat surfaces can be named freeform architecture.

2.1.1 Curvature classification

To classify surfaces, the Gaussian curvature can be used. The Gaussian curvature $K$ is the product of the two principle curves ($k_1$ and $k_2$) at any given point on a surface. A normal vector can be defined for any point on the surface. The plane containing the normal vector intersecting the surface defines the curvature of that point, see figure 2-1. A principle curve is either the minimum or maximum curvature of that given point, denoted by a negative or plus sign respectively. When multiplying both principle curvatures, three classes of surfaces can be distinguished: zero- or monoclastic, anticlastic and synclastic, see figure 2-2.

3d CAD programs, such as Rhinoceros, contain the Gaussian curvature analysis command. The analysis shows the three classes and the value indicated by colors. Figure 2-2 shows an example of the Gaussian curvature analysis in Rhinoceros. Red indicates synclastic, blue anticlastic and green monoclastic.

![Fig 2-1 Principle curvature of surface](image1)

$\begin{align*}
\text{synclastic} & : k_1 k_2 > 0 \\
\text{anticlastic} & : k_1 k_2 < 0 \\
\text{monoclastic} & : k_1 k_2 = 0
\end{align*}$

![Fig 2-2 Gaussian curvature K](image2)
2.1.2 Grid-generation

Many different grid-generation methods can be used to divide a surface. Specifically for irregular freeform surfaces, the projection and isocurves methods are suitable techniques for division. Those two techniques will be discussed briefly in the following paragraphs (Hartog, 2008).

Projection

The projection method projects a flat grid onto the surface. The grid can contain any irregular geometry but orthogonal rectangular and square grids are the most common for the projection method. The angle in plane of the panels remains the same as the projected grid. An advantage of this is that the grid can be generated with the same dimensions as the flexible mold, which makes the production of the panels easier. A drawback of the projection method is when the surface contains highly shaped regions that it causes a high deviation in panel size, see figure 2-3. This can be compensated by adjusting the grid size at these particular regions.

![Fig 2-3 Projection method](image)

Isocurves

All surfaces built with NURBS contain isocurves. Isocurves run along the surface in U and V direction, thus creating a grid. The grid can be influenced by ‘rebuilding’ the surface and assigning more isocurves in U and/or V direction. The surface geometry is affected when rebuilt, but it will only show minimal deviations. An advantage is that the isocurve method can generate a grid with small size variations on surfaces with highly shaped regions. See figure 2-4 for the isocurve method.

![Fig 2-4 Isocurve method](image)

2.1.3 Segmentation

The geometry of the panels’ edges is an important aspect concerning the assembly and transport (vulnerability) and connection of the panels. An angle of 90 degrees of the edges is most favorable concerning these aspects. The connection types is beyond the scope of this research and will not be further elaborated. Several methods are available to segment a free form surface: vertical, horizontal, combination vertical and horizontal, perpendicular, and radial (Hartog, 2008).

The vertical and horizontal method segment the curved surface either vertical or horizontal. This method will only approach 90 degrees angled edges if the surface is positioned in the respective orientation, otherwise variation can become huge. A combination of the horizontal and vertical segmenting improves the edges for both orientations, see figure 2-5. The radial method uses one or more center points for radial segmenting. The radial segmenting method is appropriate for spheres, but the results for free form surfaces are less satisfying. Only the perpendicular segmenting method creates a constant 90 degrees angled edge irrespective of the
orientation of the surface. This inevitably creates a torsioned edge, see figure 2-6. The perpendicular segmenting method is favored over the other methods because all the edges of the surface are shaped in a 90 degrees angle which makes the panels less vulnerable for transport and assembly.

2.2 Freeform architecture

‘Freeform’ is a relative concept. Although optimization has undoubtedly taken place for every single building, some high-budgeted projects indeed have fabricated exclusively unique non-repetitive panels. The Kunsthaus Graz in Austria designed by Peter Cook and Colin Fournier is an example of a true freeform building, where each panel is fabricated with a separate mold, see figure 2-7. The following paragraphs first elaborate the freeform optimization process and subsequently explore the geometry of two freeform buildings, with special focus on the Phillips Pavilion.

2.2.1 Freeform optimization

Although the term ‘freeform’ is used for many irregular smoothly curved building façades, in most cases the concept ‘free’ applies to the sketches of the architect only. The buildings’ geometry is subsequently optimized for several reasons. Gehry’s office is an excellent example for the use of rationalization of the design development. Rationalization is used for cost, complexity, material and structural considerations. The façade panels are for example categorized in the following hierarchy with increasing costs: straight, flat, curved, double curved, and highly shaped. Considering the costs, the design team uses a rule-of-thumb that keeps the highly shaped pieces to five percent. Gehry states: ‘flat pieces cost one dollar, single curvature pieces cost two dollar; double curvature pieces cost ten dollars. The good thing about the computer is that it allows you to keep a close control over the geometry and the budget’ (Lindsey, 2001).

Eigensatz, Kilian, Schiftner, Mitra, Pottmann & Pauly (2010) designed a system to rationalize freeform surfaces. The system can optimize the geometry of the panels
allowing a certain amount of deviation from the original geometry and a kink angle between the panels. Furthermore, the allowable kink angle is related to the visibility of the surface; if a certain part of the façade is less visible, the allowable kink angle is higher.

Figure 2-8 illustrates the panelization and optimization of the National Holding Headquarters in Abu Dhabi by Zaha Hadid. The figure shows the maximum allowable kink angle, the costs of the façade depending on the kink angle and the necessary mold types and reusability of the molds. Considering the reduction of costs that can be realized by optimization, it is evident to rationalize the geometry. This is only true when non-repetitive double curved surfaced molds are substantially more expensive than other mold types. If double curved surfaced molds can be produced at a much lower cost, the optimization process has less value.

2.2.2 Mercedes Benz Pavilion
Bernhard Franken designed the Mercedes Benz Pavilion for the EXPO 2000 Fair in Munich for the promotion of the new ‘Clean Energy’ concept-car by BMW. For every glass panel a separate CNC milled foam block has been produced. The isotope grid generation technique has been used, which divides the surface in plural directions with parallel curves. Quadrangular elements are formed by this method. The Gaussian analysis shows that the ‘bubble-shaped’ pavilion shows mainly synclastic curvature and less anticlastic. Figure 2-9 shows the Gaussian analysis, foam molds and structure of the Mercedes Benz Pavilion (Luca et al, 2002).
Fig 2-9 Mercedes Benz Pavilion (Bernhard Franken): Gaussian curvature, molds and structure.

Fig 2-10 Hypar with straight lines.

Fig 2-11 Gaussian analysis of hypar
2.2.3 Philips Pavilion

Most freeform buildings have a combination of synclastic and anticlastic curvature, but the Philips Pavilion is constructed of solely anticlastic shaped surfaces: hyperbolic paraboloids (hypar). Hypars are double ruled surfaces, which means that every point on the surface has a straight line that follows the surface, see figure 2-10. It is a mathematical based surface which makes structural load calculations easier. The Philips Pavilion is constructed of nine self-supporting hypar shells which are divided into 2000 panels of approximately 1m² (Xenakis, 2008). The Gaussian analysis in figure 2-11 shows that the segments are solely shaped anticlastic. The planarity, the height difference between the highest and lowest point, is also measured of the individual panels, see figure 2-12. Hypars can have an orthogonal grid if both boundary edges have equal lengths. This is not the case for the Philips Pavilion which creates skewed panels, see figure 2-13.

![Fig 2-12 Planarity of panels Philips Pavilion](image1)

![Fig 2-13 Skewed panels of Philips Pavilion](image2)

2.3 Conclusion

‘Freeform’ is a relative concept because the geometry of freeform buildings is optimized in almost all cases to reduce the amount of molds and therefor reduce the production costs.

Free form buildings show both synclastic and anticlastic curvature. The Philips Pavilion is constructed of solely anticlastic panels with a maximum panel planarity of 215mm.

Projection is the most suitable method for dividing a freeform surface when a fixed in-plane angle is required. This can be advantageous for the panel production on the flexible mold because a fixed orthogonal mold-layout can be used.

The perpendicular segmenting method should be used to achieve 90 degrees angled edges. This reduces the vulnerability during transport and assembly.
This chapter explores and analyzes existing mold techniques for freeform panels. In specific, the flexible mold will be elaborated in more detail.
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3.1 Existing mold techniques

Mold techniques for the use of freeform surfaces can be divided into three categories according to Helvoirt (2005):
- Static molds
- Reusable molds
- Flexible molds

3.1.1 Static molds
The static molds are, as the name implies, permanent. Once the mold has been produced, it can be re-used multiple times, but always with the same geometry. Below a list of common static molds is given for single or double curved concrete elements (Schipper, 2011):

Foam formwork
A foam block (XPS/EPS) is shaped using Computer Numerical Control (CNC). Two variants are used: milling or cutting. A hot wire is used for cutting; this creates smooth surfaces but is only suitable for single curved/ruled surfaces. Milling (figure 3-1) on the other hand, enables to fabricate almost any desired shape. Depending on the dimension of the milling head, the milling process can be time consuming or the surface quality is very low. In any event, a completely smooth surface cannot be achieved by milling, thus the foam is usually covered with a polymer resin. Although the foam block can be recycled in theory, it is often not economical because of the separation process of the resin cover.

Timber molds
Timber molds are ideal for single curved molds. Plywood or fiberboards can be easily bend in one direction, thus creating relative easy large curved surfaces, see figure 3-2. CNC milling and cutting can also be used for timber, although this makes the molds more expensive. For very low curvature, fiberboards can be bend in two directions. This requires a lot of expertise and is difficult to execute.
Steel molds
Steel molds have the same geometrical advances and constraints as timber molds. They are more expensive but can be reused more often than timber molds. If sufficient repetition is found in the project, steel molds are economical to use, see figure 3-3.

Inflatable molds
Inflatable molds are mostly used to make domes (synclastic curvature), see figure 3-4. A combination of pneu’s and membranes offer more geometrical possibilities. Pronk and Houtman (2004) have realized a blob with synclastic and anticlastic curvature using this method, see figure 3-5.

Fabric molds
Fabric formworks can be used to form columns, walls, beams, trusses, slabs, panels, and thin-shell structures in both precast and in-situ construction. Due to the efficient tensioning, fabric formworks are very light (West, Araya, 2009). The main constraint of this method is the inevitable synclastic curvature that appears due to the pressure of the cast material.

3.1.2 Reusable molds
Reusable molds, or re-shapeable molds, are for example clay or sand molds. A huge advantage is the elimination of waste, so it is an sustainable production method. On the other hand, producing these molds is very labor intensive and is therefore in most cases not competitive to other existing mold techniques. The production method of the panels for the Philips Pavilion is an example of this method, see figure 3-7.

3.1.3 Flexible molds
Flexible or reconfigurable molds can be adjusted into new shapes very easily. A flexible membrane is for example used which is supported by adjustable actuators. The main advantage is that no waste is created, thus one flexible mold can be used for many differently shaped surfaces. The main drawback is the high investment costs in comparison to other
earlier mentioned techniques. Although the investment is high, this technique has its advantages over others in freeform design. For all above mentioned mold techniques, except for the flexible mold, some repetition of elements is necessary to have an economical production. For the case of freeform buildings, for which every panel is unique in its kind, the flexible mold technique is the only system which may offer an economical alternative.

The table below summarizes some key aspects of the mold techniques.

<table>
<thead>
<tr>
<th>Molds</th>
<th>Curvature</th>
<th>Costs</th>
<th>Waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNC foam milling</td>
<td>Anti- and synclastic</td>
<td>0</td>
<td>++</td>
</tr>
<tr>
<td>CNC wire cutting</td>
<td>Monoclasic</td>
<td>-</td>
<td>++</td>
</tr>
<tr>
<td>Timber mold</td>
<td>Monoclasic</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Steel molds</td>
<td>Monoclasic</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Inflatable mold</td>
<td>Mainly synclastic</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Fabric mold</td>
<td>Mainly synclastic</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Inflatable + membrane</td>
<td>Anti- and synclastic</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Flexible mold</td>
<td>Anti- and synclastic</td>
<td>+</td>
<td>No waste</td>
</tr>
</tbody>
</table>

The following chapter takes a closer look at flexible molds.

### 3.2 Flexible molds

The first patent for a reconfigurable mold is by Cochrane which dates back to 1863. This mold consist of a close-packed matrix of threaded rods that are manually adjusted to create the desired forming surface and a matrix of hydraulic pistons in an oppositely arranged die that when pressurized, form the material placed in between them (Munro, 2007). Since 1863 till 2003, 38 patents have been found by Munro (2007) of which half of them are registered after 1990. The majority of the patents found by Munro describe applications for high deforming loads, such as metal sheet forming. That’s why closed-packed pin matrix molds are dominantly represented in his paper to uniformly spaced pin beds. Most research has been done for the aerospace or marine sector. Below more recent researches are described for architectural application.

#### 3.2.1 Classification

The flexible molds can be divided into four classes:
- Supported membrane
- Pin-bed surface
- Tensioned membrane
- Pressurized membrane

Each category will be exemplified in the following paragraphs, see also figure 3-16.

#### 3.2.1.1 Pin-bed surface

The pin-bed surface is a high density pin-bed on which the desired material can be formed directly.

Boers (2013) developed the OptiMal forming mold which consists of a high density pin-bed. The pins can be adjusted in height to generate a free form surface. 

Fig 3-8 OptiMal Forming by Boers
Subsequently, a plastic sheet is heated and shaped into the mold by air pressure. The high density of pins allows highly shaped surfaces, but also contributes to very high investment costs. The main focus of his technique is to produce polymer casings for unique objects.

3.2.1.2 Supported membrane

The supported membrane consists of a flexible membrane that is supported and adjusted by spaced actuators. The membrane should be flexible enough to be able to deform and stiff enough to avoid sagging in between the actuators. Several researches have been conducted which fall into this category.

Vollers and Rietbergen designed a flexible mold which has been further developed by Huyghe and Schoofs (2009) for concrete and plastic panels, see figure 3-9. It consists of CNC spaced actuators which support a wooden top-layer which creates a continuous surface. The mold can be adjusted very easily and fast with a computer model. Because the actuators are not fixed to the top-layer, enough downward pressure is needed to assure that the wooden layer touches the actuators and thus follows the intended curvature.

Raun (2012) designed a similar mold, except that the top-layer is an elastomer and is fixed to the actuators, see figure 3-10. To cast concrete, without a contra mold, the concrete first needs to cure a while in a flat state before it can be deformed. The viscosity plays an important role in the geometry of the concrete panel. Both mold techniques described above cast the concrete on a flat positioned mold surface and deform the surface after a certain time interval.

Roel Schipper (2011) uses a different method. Instead of configuring the surface of the mold with the concrete
on top, the concrete is cast on a separate flat surface and lowered after a while onto the fixed actuators, see figures 3-11 and 3-12. This reduces the necessary loadbearing capacity of moveable actuators. With this system, the membrane cannot be fixed to the actuators, this needs additional attention concerning the shape accuracy.

Oesterle, Vansteenkiste and Mirjan (2012) from the ETH in Zürich designed a reconfigurable mold with spaced actuators and a rubber top-layer. Re-usable wax is cast on the formwork to form a contra-mold with a flat-backing. Two oppositely placed wax-molds can be used to cast concrete on-site. In this case, a re-usable intermediate mold is produced on the flexible mold to use it for on-site application, see figure 3-13.

3.2.1.3 Tensioned membrane
The actuators of the tensioned membrane mold are positioned at the edges only, the surface in between is defined by a tensioned membrane which is clamped between a top and bottom frame with curved edges. The curvature of the surface is defined by the curvature of the edges, pretension and if necessary additional manipulation of the membrane by using for example inflatables.

Pronk, Rooy and Schinkel (2009) designed a flexible mold to produce polyester panels, see figure 3-14. The mold consists of a tensioned membrane which is shaped by curved edges and by pushing inflatables into the membrane. The production of polyester panels is done by vacuum injection. The driving idea of this technique is to use as few actuators as possible to keep the flexible mold low tech, thus affordable. Without inflatables, only anticlastic shapes can be generated. Using inflatables creates endless shaping possibilities, but also introduces a manual fabrication step to produce the inflatables. Furthermore, this technique emphasizes on the accuracy of the edges, which is important for the fluidity and connections of the panels, and less on the surface in between which has more tolerance.
3.2.1.4 Pressurized membrane

Vacumatics, designed by Huijben (2012), is a technique which uses vacuum to rigidize the mold, see figure 3-15. In fact, the mold consists of a bag filled with granules which can be formed freely with normal air pressure. Once the bag has been formed in the desired shape, vacuum will be drawn. A major advantage is the low investment of this technique. On the other hand, a major drawback is that the bag has to be shaped by hand. Arches can be formed quite easily, but other forms require intense labor.

Figure 3-16 illustrates the four categories of the flexible molds.

Fig 3-15 Vacumatics by Huijben

Fig 3-16 Classification flexible molds

3.2.2 Analysis

This chapter elaborates some important aspects that have been analyzed.

Intermediate mold

Munro (2007) stated that one of the reasons for the lack of commercial use of reconfigurable mold techniques is that the market is too limited by virtue of the high retail price. One way to make it more economical is to make the machine more low tech, thus cheaper. Another approach would be to increase the revenue by increasing the productivity. The fact that concrete needs to cure results in an in-activity of the reconfigurable mold for approximately one day, thus has a huge impact on the productivity.
An analysis has been carried out for the existing flexible mold techniques. The molds have been compared to each other for the cost price per panel. For this comparison, all molds are assumed to produce concrete elements which have to cure for one day. An alternative to increase the productivity is rapid accelerating concrete which will be discussed in the next chapter. The analysis shows that the system of Oesterle et al, in which they use the flexible mold to produce a temporary contra-mold, has much potential to raise the productivity of the flexible mold and thus reduces the cost price per panel.

In appendix C, a matrix is shown comparing several variables of the mold techniques.

**Density of actuators**

Another conclusion that can be drawn from the matrix is that the density of the actuators has a huge influence on the costs, as is illustrated in figure 3-17. The higher the density, the higher shaped pieces can be produced, the higher the costs. For architectural use, the curvature is very limited, thus a high density pin bed is redundant. The balance between costs and necessary curvature should determine the density of actuators.

**Top layer**

The two main challenges of the flexible mold are the material choice and connection type of the top-layer. This layer needs to be flexible enough to be shaped into many forms, and rigid enough to withstand deflection. Furthermore, if the actuators are connected to the top layer without hinges, this layer needs to stretch as well to compensate for the difference in length. Designing a connection that can freely move in the y and x and is fixed in the z direction is difficult to realize, none of the above mentioned mold technique have used such a method. Vollers and Rietbergen have fixed one corner point and choose to leave all the other points unfixed. This is a very simple and clever solution. The only drawback is that enough downward pressure is required to make sure that the top layer touches the actuators.

**Robot and step motor**

Some flexible mold systems make use of a robot and others of a step motor to adjust the actuators. Depending on the processing time of the intermediate mold, either two can be the cheaper alternative. The breakeven-point, as is shown in figure 3-18, is around 15 minutes. This means that if the production cycle of the intermediate mold takes longer than 15 minutes, the robot would be the best choice. If on the other hand the production cycle takes less than 15 minutes, a step motor would be a more economical choice.
3.2.3 Conclusion
Flexible mold techniques offer an economical alternative to conventional molding techniques for non-repetitive elements. The cheapest mold system is the tensioned membrane mold, which has as a drawback that the membrane needs to be manipulated manually to form synclastic shapes. The supported membrane mold can be adjusted completely automatically for synclastic and anticlastic curvature. For architectural façade elements, only low curvature elements are desired. This means that the density of the actuators of the pin bed is redundant. Depending on the processing time, either a robot or a step motor should be used to adjust the flexible mold. The step motor is more economical for production cycles below 15 minutes.
4 Concrete technology

This chapter explores the concrete casting techniques and looks into the accelerated hardening technology.
4.1 Introduction

Precast production has several advantages over in-situ casting. The protected and clean environment of workplace ensures better quality and higher performance. Vamberský (2010) summarizes the disadvantages of in-situ casting using the 3D Building Syndrome: dirty, dangerous and difficult. Furthermore, the higher demand on working conditions also causes the rising cost of labor. Thus precast concrete offers the possibility for better controlling conditions, more efficient and cheaper production and higher quality products.

To explore the limitations of precast concrete for Double Curved Concrete (DCC) elements, current production techniques and fundamentals of concrete chemistry need to be understood. This chapter aims at answering two main questions:
- How fast can DCC elements be demolded?
  This determines the production rate
- What is the maximum curvature for DCC elements?
  This determines the design freedom

To answer those questions, this chapter has been divided into 5 sub-chapters. The chapter ‘Ingredients’ describes the basic constituents of concrete. Subsequently, the current production techniques for precast concrete are discussed. Next, the rheology of fresh concrete is discussed which is important to find the limitation of the curvature. Finally, accelerated hardening is explored to determine the maximum production speed of DCC. This chapter also zooms into the hydration process.

4.2 Ingredients

Concrete, which is derived from the Latin word ‘concretum’, means ‘to grow together’. This is in fact what actually happens during hardening of concrete. Concrete is an artificial stone which primarily consists of a hydraulic binder, water and aggregates. A more elaborated list of the ingredients of concrete is given below (Levitt 2008). Different combinations of ingredients result in different concrete properties. High performance concrete, early strength concrete and self-compacting concrete are examples of concrete mixes.

4.2.1 Cements
Cements are the hydraulic binders of concrete. Those binders are responsible for the cohesion of concrete. The cement hardens when mixed with water because of the process of hydration. Many types of cements are available with each having different characteristics such as hardening time. The following four are the most used cement types: ordinary Portland cement, Blast-furnace-cement, Puzzolan, Aluminium cement.

4.2.2 Aggregates
Aggregates provide bulk to the material and withstand compressive stress. Also the addition of fibers belong to this group. There are three categories of aggregates:
- Normal weight aggregates (NWA) such as gravel and sand,
- Low density aggregate (LWA) such as pumice, a porous and permeable volcanic rock and
- High density aggregate (HWA) such as ironstone.

4.2.3 Water
Water is necessary for the process of hydration. The water/cement ratio determines...
the workability and final strength. The w/c ratio is a crucial factor for the quality of the concrete. The lower the w/c ratio, the stronger the concrete. But a too small w/c ratio, may affect the workability too much which will therefore decrease the quality of the concrete.

4.2.4 Admixtures
Admixtures are constituents which can be added to the concrete mix to aid in characteristics of the fresh concrete. Admixtures can be used for example to reduce the amount of water in the mix, increase workability, make a self-compacting concrete, accelerate or retard setting and hardening.

4.2.5 Additives
Additives are fine grained materials that have hydraulic properties. They are added to the concrete mix to improve the properties. Additives are processed by-products or co-products from other industries such as fly-ash.

4.2.6 Reinforcement
Bars or fibers are integrated to reinforce the concrete. The function of reinforcement is to increase the tensile strength in the tensile stress zone. Whereas concrete has a high compressive strength, steel bars and steel, synthetic, glass or carbon fibers contribute to the tensile strength. Common used steel bars are stiff and need to be bent in advance into the appropriate curvature of the mold. Because the steel bars are not flexible, they cannot be used for the delayed deforming production technique (Janssen, 2011). See the next chapter for more detail on the delayed deforming technique.

4.3 Production techniques
The precast production techniques can be divided in six categories: wet-cast, dry-cast, extrusion, autoclave, viscous-cast and delayed deforming. The following paragraphs elaborate those in more detail (based on Levi 2008). Spraying, or shotcreting, is not included because it is mainly used in-situ. Moreover, the inferior concrete property in comparison to other casting techniques makes it less suitable for the precast industry.

4.3.1 Wet-cast
Wet-cast refers to a concrete mix which is fluid. The liquid character of this mix ensures a high workability and can be easily poured into complex shaped closed molds. Wet-cast concrete needs to be compacted which is done by vibration in most cases. A pressing technique for the wet-cast is also possible. In this technique the excess water is pressed out of the mix which gives the concrete initial green strength (see earth-moist cast). This green strength enables immediate demolding. Wet-precast is used for complex geometry or customized products.

4.3.2 Dry-cast
Earth-moist concrete is used for dry-casting. If the mix is squeezed in one’s hand and a cohesive ‘sausage’ is obtained, it is earth-moist. The water content of earth-moist concrete (w/c 0.2 to 0.36) is much lower than wet-cast concrete (higher than 0.4), hence the name. Characteristic of earth-moist concrete is that they have zero slump and that the unit can be demolded instantly once compacted. Either vibration or pressing (stamping) is used to compact the fresh concrete. The direct stripping of
the form is due to green strength. Green strength is defined by Bornemann (2005) as strength of the unhardened product to keep its original shape until the cement starts to set and the hydration products provide sufficient strength. This means that the concrete has not gained any significant strength, only enough to retain its shape.

Earth-moist or dry-cast is used for mass-production such as concrete pipes, blocks and tiles.

The main differences between wet- and dry-cast concrete are that dry-cast concrete have smaller aggregates, wet cast has less cement and higher quality finishing (less porous).

4.3.3 Extrusion
Extrusion utilizes earth-moist concrete as well. Thus the properties of extrusion are similar to earth-moist cast. Concrete products that are produced by extrusion are for example roofing tiles and (hollow core) beams.

4.3.4 Autoclave
Autoclaving is a technique in which the concrete is exposed to a temperature of 200 °C and a pressure of 12 atmospheres. Those conditions result in a chemical reaction between any suitable lime and fine siliceous components to form calcium silicate. Autoclaving is mainly used to produce autoclaved aerated concrete blocks (AAC) which are light and thermal insulating.

4.3.5 Viscous-cast
A concrete paste with a viscosity in between dry- and wet-cast is utilized for this method. For this method, the concrete is manually applied on an open (curved) mold. The viscosity of the concrete paste should be high enough to prevent it from flowing down the slope, but also low enough to avoid high compacting energy. Furthermore, the concrete paste should be able to be sculpted by hand.

4.3.6 Delayed deforming
This technique is used in many flexible open mold techniques. The first step is to cast a fluid concrete paste in a horizontal position. After some time of hardening, the paste will gain enough stability to be deformed into the desired shape without dimensional deviations. The paste is still partly hardened, which enables to heal the occurring cracks. The rheology of the concrete paste is an important factor for this technique; this will be discussed in the next chapter.

4.4 Rheology
The material concrete is very suitable to make complex shapes because of its fluidity. DCC elements can be poured easily in a closed formwork. But when an open mold is preferred, the consistency of the paste is an important factor to prevent the concrete to flow away to the lowest points. Rheology is ‘The science of the deformation and flow of matter’ (Tattersall 1983).

When the delayed deforming production technique is used, the fresh concrete must have enough resistance to be stable at a certain slope and it must be plastic enough to follow the deformation and the curvature of the mold. To cast concrete on a double curved open mold, first the fresh concrete will be cast on a flat mold, which will be deformed in the desirable shape once the paste has the right workability. The Bingham equation describes the behavior of fresh concrete (Tattersall 1983):
The Diagram illustrates the rheology of A: normal concrete, B: unknown C: self-compacting concrete.

From this diagram it can be concluded that self-compacting concrete is very suitable for an open mold because it has very high viscosity with a low yield stress. Thus only a small force will make the concrete flow, but it will only flow very slowly with high resistance.

Janssen (2011) did some experiments on the rheology of concrete for casting on an open mold. Two aspects were important:

- **Slope stability**
  The concrete should be stable enough to retain shape. The longer the time before deformation, the more stable the fresh concrete will be and thus a bigger slope can be achieved.

- **Crack limit**
  When the time before deformation takes too long, and the paste starts setting, cracks will occur.
  Thus an optimum exists for the time before deformation and the maximum slope. B. Janssen (2011) experimented with different concrete mixes and different times for deformation.

The best result is achieved with a concrete mix shown in figure 4-2. The adjuvant is a plasticizer which makes the concrete mix self-compacting. Figure 4-3 shows the relation between the radius and time of deformation. The linear line indicates the slope stability over time, the curved line indicates limitation because of cracking, and the gray area is the deformable area. The minimum radius possible with this concrete mix is 1.5 meter, if deformed after 30 minutes.
4.5 Accelerated hardening

The previous paragraphs described production techniques for immediate demolding. The so-called green strength assures form-stability, but the product has not gained any significant strength yet. Flat concrete elements can be demolded and stored for curing in a separate place. DCC elements on the other hand have no flat back, thus when demolded, stresses will occur. To resist those stresses, the concrete element needs to gain some strength. This chapter will look into the amount of time which is necessary to gain enough strength to demold a DCC element.

M. Leivo (1995) summarized the value of accelerated hardening as follows:

- Shortening the turnaround time is an effective way of reducing costs: faster manufacturing leads to a decrease in non-processing activities.
- Accelerated customer-oriented production offers a competitive advantage in that the customer will likely be willing to pay more.

4.5.1 Methods for accelerating strengths:

The methods for accelerating hardening can be divided in four groups: concrete technology, chemical, physical and a combination of those three (Franjetic, 1969).

Concrete technology

This group of methods is mainly based on the compaction or porosity of the concrete and the surface area of cement. Methods include:

- High early strength cements
- More cement
- Sieve curve
- Reduction of W/C factor
- Compacting techniques for concrete

The high early strength cements are grinded smaller, thus resulting in a higher surface area for hydration, see fig 4-4. More cement obviously results in more hydration.

Fig 4-4 High early strength cement protland C
The sieve curve influences the structure of the concrete: a good distribution of aggregates ensures better compaction. The reduction of the W/C factor directly influences the porosity because of the evaporating water.

**Chemical**
Chemical accelerators influence the setting and hardening time of concrete. Which influence this has will be elaborated in the chapter ‘hydration process’. Chemicals which are used are water glass, calcium chloride and carbonization.

**Physical**
This group encompasses heat treatments with or without pressure. Hydration is a chemical reaction which reacts faster with higher temperatures, thus accelerating the process of hardening.

**Combination**
Often a combination of the above is used to accelerate the process of hardening.

### 4.5.2 Hydration process
To better understand what the possibilities and limits are for chemical and physical methods for accelerating hardening, the hydration process needs to be studied more closely.

In chemical terms hydration is a reaction of an anhydrous compound with water resulting in a hydrate. The hydration of cement is a complex process consisting of a series of chemical reactions that occur parallel and successively (Franjetic, 1969). The hydration of Portland cement will be discussed only in this section. Other cement types such as blast-furnace-cement and puzzolan are known for slower hardening which is not suitable for the use of accelerated hardening. Aluminiumcement is a rapid hardening cement but has a setting time similar to that of Portland cement. For this purpose it suffices to explore the hydration of Portland cement only.

Tricalcium silicate is the main and most important constituent of Portland cement which controls to a great extent the setting and hardening of cement. The two concepts, setting and hardening, have different properties and should be distinguished clearly. This will be elaborated in the next sub-chapter. The hydration of tricalcium silicate is very complex and is still not fully understood. The reaction written in cement chemist notation is:

$$2\text{C}_3\text{S} + 6\text{H} \rightarrow \text{C}_3\text{S}_2\text{H}_3 + 3\text{CH}$$

The paste hydration is characterized by four stages (Hewlett, 1998):

- **Pre-induction period**
  This is a short period of a few minutes, initiated immediately after mixing with water. Only a low fraction of C3S hydrates. During this reaction a thin cement gel will be formed on the tri silicates which bursts open because of the osmotic pressure. The cement gel layer will become thicker and act as a protective layer which blocks water and thus reduces the hydration reaction.

- **Induction (dormant) period**
  The reaction speed is reduced and stays low for some time.

- **Acceleration stage**
  The slow diffusion of water builds up a pressure which eventually burst the skin of cement gel again and causes an acceleration of hydration.
- **Post-acceleration stage**

  Hydration rate slows down gradually because the concentration of clinkers for hydration declines.

  The process of hydration is illustrated in the following figures.

---

**4.5.3 Setting versus hardening**

Setting means that the paste consistency changes from plastic to a solid material, with barely measurable strength. Hardening follows the setting of the paste and is the subsequent phase in which the hardness and strength is developed. Initial set indicates the stiffening of the paste, which is not allowed to be mixed again. The final set indicates the beginning of the hardening process (Franjetic, 1969).

The following figure illustrates the above distinction showing the setting of concrete over time without gaining significant strength.

---

The following paragraph describes the chemical background to understand the different properties of fast-setting and rapid hardening cements.

Within minutes following mixing, flocculation of the cement particles occurs which increases the viscosity of the paste. This process is reversible. The viscosity of the paste increases due to hydration of the cement. In the acceleratory stage of
hydration, the amount of hydrated material causes the setting of the cement. Those chemical bonds are not restored if broken down, which is the case with flocculation. Setting is the loss of deformability. After setting, the number of contacts between the particles is still low, thus the strength is low. To ensure acceptable setting characteristics, gypsum is added to acts as ‘set regulator’. With sufficient calcium sulfate (gypsum), the hydration of C₃ₐ and C₄(AF is reduced during the pre-induction period. If calcium sulfate would be absent, plate-like crystals of C₆(A,F) H (AFm) are formed which cause a quick set. The weak microstructure of the AFm platelets reduces the strength development (Hewlett, 1998).

This gives the chemical background to the two main subdivision of accelerating admixtures:
1. Rapid set accelerators which mainly affect tricalcium aluminate phase (C₃A)
2. Rapid hardening, which affect mainly the C₃S phase for high early strength.

Although the successive processes of setting and hardening can theoretically not be clearly distinguished from each other, fast setting does not mean fast hardening. Fast setting cements are mostly used for i.e. shotcreting. The compressive strengths of fast setting cement are usually significant lower than the normal setting cements. Furthermore, the rapid-hardening cements show a normal-setting time (Czernin, 1977).

Water glass is an accelerator used widely for shotcrete applications. It cuts the open time of the mix to a few minutes.

At early concrete age, the water glass (sodium silicate) accelerates the compressive strength, but at later age causes some strength loss (Leivo, 1995). Figure 4-8 shows the influence of the amount of water glass to the compressive strength development over time.

**4.5.4 Demold time for DCC**

The fastest hardening concrete that could be identified in the literature is from Leivo (1995). The best result is achieved with a combination of water glass and heat treatment. Heat treatment should start after setting or heat should build up gradually. This is because the captured air in the plastic paste will expand and destroys the structure of the cement, thus making the concrete less strong. This indicates that the setting time of concrete is the most influencing factor for the time of demolding. Figure 4-9 shows the compressive strength against the time. The heat treatment started 30min after mixing.

The minimum compressive strength required for DCC elements is illustrated in figure 4-10. The most favorable situation is used, which is a reinforced concrete element. This means that the concrete only needs to take up compressive strengths. A concrete element of 1.5 square meter has been used for the calculation.
So at least 0.77 N/mm² is required to resist the dead weight. The diagram of Leivo (1995) has been extrapolated to estimate the time needed to achieve the required compressive strength, see figure 4-11. This diagram indicates that it takes at least 1 hour to gain a strength of 1N/mm².
4.6 Conclusion

The production techniques showed that earth-moist castings enable immediate demolding because of green strength, but this is only the case for flatback products. So DCC elements require some strength to resist its dead weight if stored without mold. Rapid early strength can be achieved by accelerating hardening techniques. They show that the setting of concrete has a great share in the time for demolding: rapid hardening cements show a similar setting time as normal concrete.

The field of study of rheology is important for the casting of concrete on a curved open mold. High viscosity is required to ensure the stability of the concrete. Self-compacting concrete is very suitable for the delayed deforming technique.

The two question presented in the beginning of this chapter have been answered thoroughly in this chapter. Two short answers are presented here:

- How fast can DCC elements be demolded?
  Demolding of a DCC of 1.5 m$^2$ takes at least 1 hour.

- What is the maximum curvature for DCC elements?
  The minimum achievable radius is 1.5 meters on an open mold.
This chapter synthesizes the previous analyzed aspects and further elaborates the conclusions to develop a concept for a flexible mold.
5.1 Synthesis

Three aspects have been analyzed in the previous chapters: geometry, mold technique and concrete technology. These aspects define the boundary conditions and are the underlying variables for the concept forming of the new mold technique. Because the variables are interdependent, they cannot be optimized separately. Changing one variable influences the possibilities for the others. This means that one ultimate solution for all situations does not exist, the solution is case specific. This is illustrated in the following paragraph.

The cheapest mold system is the tensioned membrane. This system is particularly useful for the production of anticlastic shapes, thus for the Philips Pavilion. Other forms can be manufactured but include time consuming manual steps and the result is less accurate/predictable in comparison to the supported membrane mold. Although the tensioned membrane is the cheapest mold, for synclastic shapes it may not be preferable. Table 5-1 illustrates the relation between the geometry, mold technique and costs. The choice of technique will be elaborated later in this chapter.

Table 5-1 Relation between geometry, mold technique and costs

<table>
<thead>
<tr>
<th></th>
<th>anticlastic</th>
<th>synclastic</th>
</tr>
</thead>
<tbody>
<tr>
<td>tensioned membrane</td>
<td>cost</td>
<td>suitability</td>
</tr>
<tr>
<td>supported membrane</td>
<td>cost</td>
<td>suitability</td>
</tr>
</tbody>
</table>

As has been stated previously, the aim of making the production method more economical can be realized by increasing the productivity. This can be done in two ways, as has been illustrated in the previous chapters. The first option is to accelerate the hardening process of the concrete so that the concrete can be demolded within a reasonable time. As has been concluded in chapter 4, demolding of a double curved concrete element can take place after approximately one hour hardening. The second possibility to increase the productivity is to use an intermediate mold. In this case, with the expensive flexible mold, an intermediate mold will be produced which will be removed from the flexible mold and placed elsewhere on which the concrete can be cast. This enables the flexible mold to produce multiple intermediate molds while the concrete cures. Using an intermediate mold instead of the accelerating method, enables the use of ordinary concrete which is cheaper and of better quality.

For those reasons, the method of using an intermediate mold is chosen. The next sub-chapter explores which material and method is the most suitable to produce an intermediate mold.

5.2 Materialization intermediate mold

To determine the most suitable material and technique to produce an intermediate mold, the system requirements need to be defined. The main parameter is time; the production cycle should be as fast as possible to ensure a high productivity. The intermediate mold should be made of a re-usable material to reduce the waste flow. The surface quality is also an important parameter to enable direct concrete casting without additional surface treatment. Furthermore, the technique should be low-cost which is indicated by low-tech, light machinery and a low energy flow.
The search starts by identifying suitable materials and techniques. A common way of classifying materials is presented in table 5-2 (Kakani, 2004). The green colored materials can be re-shaped by adding or subtracting energy from the material. The formability of clay depends on the moisture content. Sand or any other filling material can be used for vacuumatics, which will be explained further below. Phase change materials and shape memory alloys are smart materials that could be used for its adaptive capability. Because of the high price, they have not been further considered as a suitable material for the intermediate mold.

The Taxonomy of Manufacturing Methods by Todd (1994), see figure 5-1, has been used to identify useful manufacturing techniques. The yellow colored blocks indicate this path. Only mass-conserving manufacturing techniques are suitable to form a re-shapeable material on the flexible mold. The green boxes show the techniques which will be further evaluated for their suitability.

Table 5-3 shows which re-shapeable material can be used for the selected manufacturing techniques. This process-material matrix is based on Ashby (2011).

---

**Table 5-2 Material classification, in green reshapesable materials**

<table>
<thead>
<tr>
<th>Group</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metals</td>
<td>Steel, iron, aluminum</td>
</tr>
<tr>
<td>Ceramics</td>
<td>Glass, clay, sand</td>
</tr>
<tr>
<td>Polymers</td>
<td>Thermoplastics, thermosets, elastomers</td>
</tr>
<tr>
<td>Composites</td>
<td>Reinforced polymers, concrete, wood</td>
</tr>
<tr>
<td>Advanced materials</td>
<td>Phase change materials, shape memory alloys</td>
</tr>
<tr>
<td>Other</td>
<td>Water</td>
</tr>
</tbody>
</table>

---

**Fig 5-1 Taxonomy of manufacturing methods**
Flexible Mold - an innovative production method to produce precast DCC panels

To determine which combination of material and manufacturing method is the best choice for the intermediate mold, the materials and techniques need to be compared. The factors determining material selection have been used according to Kakani (2004). Kakani distinguishes four main categories: manufacturing processes, functional requirements, cost considerations and operating parameter. Each category has been specified with variables. The operating parameter is left out because it is not applicable for this situation.

- **Manufacturing processes**
  
  *Low load process*: the manufacturing technique should be a low load process to avoid overload of the actuators.

- **Functional requirements**
  
  *Surface quality*: the surface quality should be high enough to be used directly for concrete casting.
  
  *Re-usability*: the material should be re-usable to eliminate a waste flow in the production cycle.

- **Cost considerations**
  
  *Raw material*: although the material will be re-usable, a cheap material keeps the investment costs low.
  
  *Processing*: the processing energy is probably the main cost factor and should be kept to a minimum because this will be a continuous expense.

The low load process and surface quality are variables for the manufacturing technique. The material and processing costs are related to the material. First the best choice of material is determined for the techniques separately. As an example the cast molding is shown in table 5-4. For cast molding, the material needs to be melted. The process energy required depends on the melting temperature, heat capacity and density of the material. As can be seen in table 5-4, both the thermoplastic and composite are the most suitable material for the cast molding technique. For the other material selection see appendix D. Next, the manufacturing techniques are compared to each other determining the most potential for the use.

**Table 5-3 Process-material matrix**

<table>
<thead>
<tr>
<th>Material</th>
<th>Vacuumatics</th>
<th>Pressing</th>
<th>Cast moulding</th>
<th>Injection moulding</th>
<th>Thermoforming</th>
<th>Spray-up</th>
<th>Stretch forming</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermoplastic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand (Granular)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 5-4 Material selection for cast molding**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermoplastic</td>
<td>160</td>
<td>1500</td>
<td>1000</td>
<td>240</td>
<td>2</td>
<td>2000</td>
</tr>
<tr>
<td>Metal</td>
<td>1200</td>
<td>440</td>
<td>7000</td>
<td>3.696</td>
<td>0.6</td>
<td>4200</td>
</tr>
<tr>
<td>Glass</td>
<td>1000</td>
<td>700</td>
<td>2000</td>
<td>1.400</td>
<td>1.5</td>
<td>3000</td>
</tr>
<tr>
<td>Composite</td>
<td>160</td>
<td>1500</td>
<td>1000</td>
<td>240</td>
<td>2</td>
<td>2000</td>
</tr>
</tbody>
</table>
of an intermediate mold, see figure 5-5.
Vacuumatics is not suitable because of the rough surface quality. Clay pressing metal stretch forming and injection molding are not selected because of the high load processing. Thermoforming utilizes a lower processing temperature than polymer casting and spray-up method, which makes it more lucrative from an energy flow point of view. Furthermore, polymer casting uses more material and therefore more processing energy because of the flatback geometry. Considering the specified variables, thermoforming is the most suitable technique to produce an intermediate mold on a flexible mold. It is an easy and above all fast shaping technique. The following sub-chapter elaborates the concept based on the thermoforming technique.

### 5.3 Concept

The following paragraphs will only discuss very briefly the thermoforming principles; just enough to understand the decision that has been made to develop the concept. The next chapter will go into more detail concerning thermoforming. Thermoforming is the process of forming a heated thermoplastic polymer under the melt temperature. In principle, two main forming techniques can be distinguished within the thermoforming: forming on a mold, or free forming. The ‘forming on mold’ technique forms a heated sheet by either over/under pressure or mechanical force against the mold surface. Free forming, in contrast to forming on a mold, means that the polymer which will be shaped does not contact any mold surface. This technique is used for making skylights or windshields. The pieces are formed by either over or under pressure which forms the sheet in a spherical shape. An advantage of this technique is that no friction of the sheet can take place which results in a maximum surface quality. Preliminary test that have been conducted (see next chapter), show that anticlastic shapes can be formed without using a mold by only applying tension.

Three different thermoforming concepts are possible:

1. **Thermoforming on a supported membrane mold**
   The polymer sheet will be shaped on the top layer of the flexible mold.

2. **Thermoforming on a tensioned membrane mold**
   The polymer sheet will be shaped on the tensioned membrane of the flexible mold.

3. **Free forming based on tensioned membrane mold**
   The polymer sheet will clamped at the edges and be shaped by tensile stresses only, no contact with mold surface.

<table>
<thead>
<tr>
<th>Manufacturing process</th>
<th>Functional requirement</th>
<th>Cost consideration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low load process</td>
<td>Surface quality</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Re-usability</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T_s$, or $T_f$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heat capacity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Density</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Processing time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Raw material</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S[$$/kg]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Raw material</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S[$$/m²]</td>
</tr>
<tr>
<td>Vacuumatics (sand/ granular)</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Pressing (clay)</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Cast molding</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Thermoforming (thermosetting)</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Stretch forming (metal)</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Spray-up (thermosetting)</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Injection- molding (thermosetting)</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>
Flexible Mold - an innovative production method to produce precast DCC panels

Considering geometry, technique, costs and future potentials, the free forming concept based on tensioned membrane has been chosen to be elaborated. As discussed in chapter 5.1, the tensioned membrane is the cheapest alternative and can produce the anticlastic shapes necessary for the Philips Pavilion. Furthermore, the combination of free forming with the tensioned membrane is a technique which has not been reported in literature yet and can thus give new insights. The high optical surface quality of the transparent polymer also gives future potential for the application of the intermediate mold as an end product.

Figure 5-2 illustrates the concept of the complete procedure of making concrete elements. This concept will be elaborated in the following chapters.

1. Penalization of computer model

2. CNC configuration of the flexible mold

3. Production of intermediate mold

4. Casting concrete on intermediate mold. Multiple intermediate molds can be produced during curing of the concrete.

5. Concrete panel can be demolded and the intermediate mold can be recycled.

Fig 5-2 Manufacturing process concept for the production of DCC panels
6 Thermoforming

Thermoforming is a shaping technique that utilizes heat to deform thermoplastic polymers. Three aspects will be further elaborated: heating methods, shaping techniques and the thermoplastic material properties.
Flexible Mold - an innovative production method to produce precast DCC panels

6.1 Heating methods

Heating methods can be divided into three categories: convection heating, radiant heating and conduction heating (Gruenwald, 1998).

6.1.1 Convection heating

Convection heating is originally the most common heating technique. This is still preferred for thick sheets and for distributing heat uniformly where free forming techniques are used. Long heating cycles, minimum of 15 minutes, are necessary to obtain a uniformly distribution of heat. To obtain adequate heat transfer, forced circulation is necessary. Sheets cannot be overheated if the temperature is set correctly. A long heating cycle ensures a uniform distribution of heat over the surface and thickness of the sheet.

6.1.2 Radiant heating

Infrared radiant heating is the fastest way of heating a plastic sheet. The chemical composition of the plastic sheet determines the sensitivity to the radiant heating. In most cases direct radiation heating is limited to the outer tenths of a millimeter. The temperature at the center will only be heated through conduction. The surface temperature of the sheets will be heated up to 10 to 25 degrees Celsius higher than the thermoforming temperature. When the heater is turned off, thin sheets drop in temperature within seconds, whereas thicker sheets can remain in transit for a few minutes. A longer transit time enables a more uniform distribution of heat (conduction to center) and reduces mark-offs imperfections (cooling of surface) due to the mold surface roughness, see figure 6-1. Clamped sheets are more difficult to heat uniformly because of the reflection of the clamping frame.

6.1.3 Conduction heating

Conduction heating is when the sheet has physical contact with the heating element. This method is mainly used for continuous processes. If the temperature is set correctly, the sheet cannot be overheated. Furthermore, the heat loss is minimal for this heating method. A disadvantage is the direct contact which can leave imprints on the polymer sheet or may even stick to the heater.

![Fig 6-1 Heat distribution over thickness after time interval](image-url)
6.2 **Shaping techniques**

The polymer sheets are either shaped by air pressure or mechanical force. Air pressure forming enables more detailed formed parts. Mechanical forming is more low-tech and can be more economical for simple geometries. The shaping techniques have been divided into two categories: forming with mold and free forming.

6.2.1 **Forming with mold**

Essentially, this category is the shaping of a heated polymer sheet into a particular mold. In many cases either over-pressure or under-pressure (vacuum) is applied to deform the sheet into the mold. Mechanical deformation can also be utilized for a sub-forming step such as a plug assist, or for the complete forming process such as slip forming, see figure 6-3 and 6-4.

Many different mold setups exist with varying properties, mainly influencing the sheet thickness. Depending on the desired end product, one production method is favored over the other. As can be seen in figure 6-2, cavity forming utilizes a female mold which causes the material to thin out more the deeper the cavity. This is ideal for shallow parts or products that require a sturdy frame. Drape forming on the other hand utilizes a male mold. The wall thickness is distributed in an opposite manner to cavity forming. Other often used forming techniques are plug assist forming, billow drape forming, snap-back forming, air slip forming and twin sheet forming. Some forming techniques are illustrated in the following figures (Gruenwald, 1998)

---

**Fig 6-2** Cavity and drape forming

**Fig 6-3** Billow drape forming

**Fig 6-4** Slip forming

---

Thermoforming
6.2.2 Free forming

The free forming technique shapes a polymer sheet without a mold. Either over-pressure or under-pressure (vacuum) is applied to shape the sheet. The main advantage of this forming technique is that friction between the polymer sheet and a mold is avoided. This is beneficial for the surface quality; it produces sheets with high optical quality. Therefore this technique is used for purposes which require optimal transparency such as wind shields or skylights, see figure 6-6.

Figure 6-5 shows a standard setup for free forming. The main disadvantage is that only spherical shapes can be produced (Gruenwald, 1998). No other free forming techniques have been identified by the author.

Preliminary experiments have been carried out to test whether other shapes than synclastic curvature can be produced with the free forming technique. The idea is to deform a polymer sheet into an anticlastic shape without using a mold. The procedure consists of three steps. First a polymer sheet is fixed with two edges onto a timber board. Subsequently, the timber board with the sheet is heated in the oven. Finally, the heated sheet is taken out of the oven and the two unfixed edges are heightened by two wooden blocks and tensioned with weights. The amount of tension applied determines the curvature, see figure 6-7.

In fact, the heated polymer sheet behaves like a nylon stocking. The membrane can be manipulated by tensile stresses and in combination with air pressure both syn- and anticlastic curvature can be produced. The following chapter explores which polymer is most suitable for this free forming technique.

Fig 6-5 Free forming technique

Fig 6-6 Skylights

Fig 6-7 Free forming with pretension
6.3 Thermoplastic properties

As discussed in the previous sub-chapter, free forming of plastic sheets is done only with pretension and air pressure, the plastic does not contact any mold surface. Some polymers are more suitable than others, this will be elaborated in the following sections.

The polymer is required to stretch uniformly by constant applied force or tension to be able to control the tension and deformation behavior. The forces need to be high enough to resist the dead weight and prevent sagging.

6.3.1 Viscoelastic properties

Polymers consist of long molecules that are entangled which form a network. When a chain has more than ten entanglements, the individual chains cannot be separated which makes it a solid material. The bonding force between the molecules will decrease with increasing temperature. Above the glass transition temperature ($T_g$), the chains are able to slide along each other. The viscosity just above the $T_g$ is still very high, thus a high force is needed to separate the chains.

A polymer is viscoelastic which means that the strain rate influences the necessary forces. A high strain rate requires higher tension. In other words, higher tension will cause higher strain rate. This is applies to both above and below the glass transition temperature.

The diagram below illustrates a typical stress strain curve at room temperature. Even below the glass transition temperature, the polymer will show plastic deformation beyond the yield point. When a polymer is deformed below the $T_g$, the molecular network stays intact and solely the bonding between the chains of the molecular network is altered. This means that a polymer which is heated up to, or just above the glass transition temperature, will deform back into its original shape even with high stretch deformations. If heated above glass transition temperature, a plastic cup will form back to a round plate.

The mechanical model illustrated in figure 6-9 shows the underlying mechanisms. The left mechanism illustrates the intermolecular interactions. The spring-damper combination represents the viscoelastic character of high tensions and high strain rates. The damper is stress-activated, this means that below a critical stress, the yield point, the viscosity is endless high, thus the material behaves solely elastic. The material will keep flowing beyond the yield point until the stress is taken away; the deformation will stop. The material will flow until the point of rupture is reached.
The right mechanism illustrates the contribution of the network. Molecular relaxation is negligible below the glass transition temperature. In that case the damper will remain fixed and the contribution of the network is solely represented by the spring. The spring enables reversibility and pulls back the deformed network to the original state when the intermolecular forces (left mechanism) diminish through heating above the \( T_g \). Vacuum deep-draw takes place above the \( T_g \), because otherwise the required forces are too high and the strains are to limited. The viscosity needs to be sufficiently high to carry its dead weight. The molecular relaxation, damper in the right mechanism, is not negligible, thus stretching is a permanent deformation in this case (Vegt, 1996).

### 6.3.2 Strain hardening

For a stable uniform deformation, strain-hardening and strain-softening are determining factors. Strain-softening is the decline right after the yield point in a stress-strain diagram. Strain-hardening is subsequently the ascending of the curve, see figure 6-10.

When forces are applied to a polymer sheet, the stress will rise at the imperfections. Those areas will flow earlier and reach the strain-softening. These areas will stretch until the stress is high enough for other parts to reach the yield point. When the strain-softening has a small slope and the strain-hardening curve is steep, the polymer will deform stable and uniform. This is the case for PMMA and PC. PS on the other hand has a steep strain-softening with a small strain-hardening slope. Therefore, PS will deform less stable (Melick, Govaert & Meijer, 2003).

For PMMA, both the strain-softening and strain-hardening will reduce at elevated temperatures. Above the glass transition temperature at 132 °C, no strain-
softening can be observed, see figure 6-11. The advantage is that at constant stress, the polymer will deform stable and uniformly, but even the smallest stress variations will have an influence on the stretch-behavior. Even at elevated temperatures, the strain-softening is still present for PS, see figure 6-12. This means that for PS will deform unstable and non-uniformly above the glass transition temperature.

PETG, sold under the brand name Vivak, shows at lower temperatures a similar stress strain behavior as PS. At temperatures above the glass transition temperature, the strain-softening gradually diminishes like PMMA or PC, which contributes to a positive stretch-behavior, see figure 6-13.

### 6.3.3 E-modulus

The temperature determines the E-modulus of the polymer. As can be seen in figure 6-14, the E-modulus decreases drastically around the glass transition temperature. The less steep slope is the so-called rubber-plateau. Temperature variations on the rubber-plateau will have a small effect on the E-modulus. This is a suitable thermoforming range because a stable E-modulus is prerequisite for uniform stretch-behavior.

![E-modulus at various temperatures](image)

**Fig 6-14 E-modulus at various temperatures**

### 6.4 Conclusion

For a uniform distribution of heat, a convection oven is recommended. Radiant heating can be chosen to speed up the production cycle. The free forming technique can be used to form a polymer sheet into anti- and synclastic shapes with only the use of pretension and air pressure, without using a mold.

Considering the E-modulus, it is recommendable to form the polymer at temperatures around the rubber-plateau. In that case temperature variations will only have small effect on the stretch-behavior.

At those temperature PMMA, PC and also PETG have suitable properties for free forming.
7 Design

The design for the flexible mold, intermediate mold and prototype will be elaborated in detail in this chapter.
7.1 Introduction

The E-mould (tensioned membrane), designed by Schinkel and Rooy (2009), is used as a starting point for the design of the new mold technique. The E-mould will be analyzed to improve its functionality and will be adjusted to resist high temperatures for the thermoforming process.

Figure 7-1 and 7-2 show the E-mould in start position and deformed position. A polyurethane membrane is tensioned in flat position (1) and subsequently deformed by pushing the curved edges from both sides into the membrane (2). The polyurethane membrane will be exchanged for a thermoplastic polymer which will be deformed in a similar way using thermoforming.

This chapter is divided into three sub-chapters: the design for the flexible mold, the intermediate mold and the prototype.

Fig 7-1 E-mould in flat position

Fig 7-2 E-mould in deformed position
7.2 Flexible mold

The flexible mold consists of configurable edges, a heating system, the thermoplastic sheet and a system for pretension. Those four aspects will be elaborated in the following sub-chapters.

7.2.1 Edge

The controlling of the edge position of the mold is an important aspect because it determines the accuracy of the panel connections and fluidity of the panel transitions. The following paragraphs look into more detail of the edge mechanism.

7.2.1.1 Density of actuators

Four actuators is the minimum amount of control points needed for sufficient form freedom. Three actuators can only generate arches, four or more control points are able to define a freeform curve, see figure 7-3. The spacing of the actuators also depends on the stiffness of the edge material. A spacing of approximately 20cm is used for the existing flexible mold systems.

![Design](design.png)

Fig 7-3 Density of actuators, a minimum of four control points define freeform spline

7.2.1.2 Angle of membrane towards the edge

To assure a fluid transition between two panels, the membrane needs to approach the angle of the edge fluidly. The E-mould uses a flexible rubber which will guide the membrane towards the intended angle assuring that no ‘kink’ will appear. This concept will also be used for the new design.

![Design](design.png)

Fig 7-4 Flexible rubber to guide the membrane (E-mould)
7.2.1.3 Angle of edge

The angle of the edge needs to be adjustable so that the edge can be aligned to the tangent of the grid, see figure 7-5. This allows a fluid transition between the panels. The E-mould is designed with a rotating disk that can be adjusted into the desired angle. The rotation axis is approximately 50mm below the top of the edge. When the edge is positioned into an angle, the reference point in figure 7-6 will displace in the x- and y-direction. The displacement in y-direction can be compensated by adjusting the actuator, but the displacement of the x-direction is uncontrollable. To produce panels with the same orthogonal-grid size, the edges will inevitably have a flat segment which disturbs the fluid transition between two panels. If the curvature is relatively low, this imperfection may be unnoticeable. But with increasing curvature, the ‘kink’ will increase as well. Furthermore, this rotation system limits the degree in which the angle can be set. As figure 7-7 shows, 30 degrees is the maximum angle the disc can be set to. If greater, the membrane cannot be clamped by the two opposing actuators.

![Fig 7-5 Angle of mold edge is adjusted to tangent (green line) at the section (red point) of two panels](image)

![Fig 7-6 Displacement of mold edge](image)

![Fig 7-7 Maximum angle of mold edge](image)

The solution to these constraints is to position the rotation axis to the top. In that case, the reference point as indicated in figure 7-8 will remain at the same position, independent of the angle. Furthermore, the contact surface between the two opposing actuators will as well remain the same with all angle positions, see figure 7-9. The rotation axis is in fact a virtual axis, thus two points are needed for fixation of the edge.
7.2.1.4 Materialization of edge

Three properties are important for the materialization of the edge: flexibility, flexural strength and heat resistance. First of all, the edge should be flexible enough to be shaped into the desired spline. On the other hand, it should be stiff enough to follow the spline fluidly without sagging in between the actuators. Furthermore, the flexural strength should be high enough to resist the forces that are needed to push the membrane into the desired position. The material should resist high temperatures during the thermoforming process (+ 120 °C).

Three materials are suitable for this purpose: spring steel, bending triplex and elastomer. A constraint of spring steel and bending triplex is that it can only be bend in one direction; the direction of the spline. When the edge is fixated in different angles, torsion will take place. A straight strip of spring steel and bending triplex can be torsioned. But when a curved strip is torsioned, the material needs to be flexible in all directions, in which case elastomer is a suitable material.

Most elastomers such as polyurethane and EPDM cannot resist high temperatures. Although for example EPDM has a temperature range up to 120 °C, which is much higher than PUR (80°C) or natural rubber (70 °C), the mechanical strength will rapidly decrease when approaching the maximum service temperature. Silicone rubber is the only elastomer that can be used for high operating temperatures. Conventional silicone rubber can be exposed to maximum 180°C, and more advanced silicone rubbers can exceed 300°C. Because of the fact that silicone rubbers have a very low flexural strength, they need to be stiffened by for example glass fibers. Figure 7-10 shows three test samples: 1. Silicone without glass fibers, 2. Silicone with glass fibers in between, 3. Silicone with glass fibers on top. It is clearly illustrated that the glass fibers glued on the upper side of the silicone contributes the most to the stiffness of the material. The second sample with the glass fibers in between the silicone is an available product. This product is used for dimensional stability of the rubber and not for flexural strength. In this case the glass fibers are positioned at the neutral layer of the tension curve. For a higher flexural strength, the material should be strengthened on the outside. To achieve a satisfying result concerning flexibility and stiffness, the spacing of the actuators should also be taken into account.

Fig 7-8 Rotation axis at the top

Fig 7-9 Constant contact surface

Fig 7-10 Variable reinforcement
7.2.1.5 Edge elongation

When the actuators are adjusted in height, the length between the two actuators will increase. This means that length difference has to be compensated by either stretching or elongating the edge. By stretching the edge, the spline will be flattened and in worst case even create kinks at the position of the actuators. Thus elongation of the edge is a better solution. The actuators of the E-mould are connected with a sliding system so that the edge can slide over the actuators to compensate for the length difference, see figure 7-11. It is necessary for the sliding system to be flexible, so that it can follow the curvature of the spline. The E-mould has therefore been designed with a plastic slider which is easily pliable. The new mold system requires a heat resistant elongation mechanism. To make this system heat resistant, it could be made of steel or aluminum. Because it wouldn’t be pliable enough, the rail should be segmented to be able to follow the curvature of the spline. Subsequently, a sliding strip would be integrated in the rail to smoothly slide the edge over the actuator, see figure 7-12. A disadvantage of this sliding system (either plastic or steel variant), is that the connection will always create an unwanted space of motion which decreases the accuracy of the edge configuration.

An alternative solution is to use hinged plates to connect the actuators to the edge. In that case, the hinged plates will move sideways and thereby elongate the edge, see figure 7-13. The hinged plates should be long enough to ensure that the force transfer of the edge to the actuators will not make an angle of more than 45 degrees to avoid a high bending moment of the actuators, see figure 7-14.
7.2.1.6 Positioning of actuators

The edges of the flexible mold will vary in length depending on the curvature. This means that the edge should have the freedom to move, without the other two adjacent edges obstructing the movement. The same method as has been used for the E-mould will be used for the new mold system, see figure 7-15.

![Fig 7-15 Positioning of actuators, fixed position (red point), variable edge length (green arrows)](image)

7.2.2 Heating system

In chapter 6, several heating systems for thermoforming have been discussed. For this purpose, either radiant or convection heating is possible. Radiant heating is in most thermoforming processes preferable because it is more economical; the thermoplastic sheets are heated within minutes which increase the production cycle speed. Heating by convection on the other hand takes much more time, more than 15 minutes, but is preferable for thick sheet (+ 4cm). Moreover, convection heating contributes to an uniformly heated sheet, which is more difficult to achieve for radiant heating.

To ensure a rapid production cycle, the radiant heating technique is preferred for the new mold system. The thermoplastic sheet can only be heated by radiation in flat position. Once the sheet is deformed, the radiation intensity per net surface area of the sheet will vary which contributes to an unevenly heat distribution, see figure 7-16. When the radiant heating system is turned off after the sheet is heated in flat position, the sheet needs to be deformed within seconds. When the thermoplastic sheet needs to be manipulated during a more extended amount of time, a combination of radiant and convection heating offers an interesting solution. In that case, the radiant heating ensures rapid heating, while the hot air flow prevents cooling of the sheet which gives time to further manipulate the sheet.

![Fig 7-16 Radiant heating, uneven intensity](image)
7.2.3 Thermoplastic sheet
Polystyrene (PS) and most other thermoplastics have a high strain softening and low strain hardening. This results in unstable and uncontrollable deformation of the sheet during thermoforming and causes a non-uniform sheet thickness. Polycarbonate (PC) and Polymethyl methacrylate (PMMA) on the other hand show a limited strain softening and a higher strain hardening. This results in a more uniform sheet thickness and more predictable deformation behavior. Those materials are more suitable for deformation under tension because of the more stable deformation, but are also much more expensive. Polyethylene terephthalate (PETG) also shows a suitable strain hardening for elevated temperatures. PETG, sold under the brand name Vivak, is easily available in different dimensions and thicknesses. For this reasons, PETG has been chosen to be used for the experiments. As mentioned before, PC and PMMA are also suitable for this production technique. See chapter 6 for more background on the properties of polymers.

7.2.4 Manipulation of membrane
In the paper ‘84 ways of manipulation membranes’, Pronk and Dominicus (2012) present four matrixes containing 84 ways to manipulate membranes. Five form-active structures are distinguished: prestressed membrane with an anticlastic surface, prestressed membrane with a zeroclastic surface, inflatable with a monoclastic surface, inflatable with a synclastic surface and an inflatable with an anticlastic surface. Mainly the anticlastic and synclastic surfaces will be produced.

Fig 7-17 Matrix of prestress manipulation techniques
with the new mold system. By using overpressure or drawing vacuum in the mold system, the synclastic surfaces of the inflatable structures can be created. The manipulation methods are categorized in prestress, external load, pushing form-active surfaces into the membrane and pushing rigid elements into the membrane. These manipulation techniques can also be used for the new mold system. Prestressing and pushing synclastic shaped inflatables or rigid round elements into the form-active structure are most likely the main methods for manipulating the membrane for the mold technique. The manipulation matrix for prestress is given in figure 7-17. An alternative to pushing synclastic shaped objects into the membrane is by locally heating the thermoplastic sheet and deform it by over- or under-pressure. A certain amount of prestress of the thermoplastic sheet is necessary to compensate for the sagging of the sheet. Subsequently, applying prestress to certain areas, or even just lines, gives a lot of form freedom. Finally, by using overpressure or pushing (synclastic shaped) inflatables into the sheet will give sufficient shape possibilities to create free form panels for architectural façade use. The method to apply prestress to the sheet will be discussed in the following chapter.

7.3 Intermediate mould

The concrete will be cast on the intermediate mold, thus the mold needs to be stiff and stable enough to withstand the weight of the concrete. In this chapter, the shape and support of the intermediate mold and the preferred concrete casting technique will be elaborated.

7.3.1 Fixation of surface

The deformed polymer sheet, which is produced on the flexible mold, functions as the surface for the intermediate mold. This sheet needs to be fixated on a support to form a stable intermediate mold. The polymer sheet can be shaped on the flexible mold in basically two ways. In the first way, the polymer sheet which is pressed between the edges of the flexible mold during thermoforming, moves downward simultaneously with the actuators. The dynamic fixation of the polymer sheet is a difficult aspect, but the least amount of stretching will occur. This means that the deformed polymer sheet can be reused instantly for a new production cycle. Another disadvantage is the difficulty to apply prestress on moveable edges, see figure 7-18 and 7-19.

![Fig 7-18 Moveable fixation frame](image1.png)

![Fig 7-19 Moveable fixation frame test](image2.png)
The second way to shape the polymer sheet on the flexible mold is to clamp the sheet in an orthogonal frame. The edges of the flexible mold will be pressed on the sheet, like the deep drawing technique. The main advantage of this technique is that the sheet can be fixated very easily on the flexible mold and that the resulting deformed sheet can be fixated on a support very easily for the intermediate mold. Furthermore, prestress can be applied in a horizontal plane which is an easier process as well. More detail on this procedure will be given in chapter 9 ‘tests’. A disadvantage is that the sheet may be over-stretched which prevents it to be reused instantly for a new production cycle. None the less, the sheet can always be 100% recycled which contributes to an environmental friendly production process. This ‘frame’ method is chosen to be used for the mold system. In figure 7-20 a photograph is shown for the frame method.

![Fixed frame method](image1)

**7.3.2 Support**

Although the strength of most polymers is high enough to withstand the weight of the concrete, the deflection of the sheet is the main issue. Thicknesses of approximately 40mm are necessary to reduce the maximum deflection to 1mm, see appendix E. Such thick sheets are not preferable because of the long heating temperatures and investment costs. Thus thinner sheets are more economical for the thermoforming process. Thinner sheets need to be additionally supported which can be done in several ways:

*Surface support*
- Gas (over pressure)
- Granular (sand, balls, vacuums)
- Fluid (water)

*Point support*
- Edge
- Grid

Figure 7-22 illustrates the different support options. For the category surface support, the space below the mold surface needs to be enclosed to prevent leaking of the filling substance. This does naturally not apply to the vacuums method. Experiments show that when the deformed sheet has only been manipulated by tension, support on the edges solely is sufficient to prevent deflection of the sheet.
For instance hypar shells, used for the Philips Pavilion can be produced by only applying tension. The intermediate mold can then be fixated on a frame on which the actuators will be adjusted manually until they touch the surface. The spacing of the supporting actuators depends on the sheet thickness. For thickness of 3mm, a spacing of 150mm is required (see appendix E).

7.3.3 Concrete casting

In chapter 2 it is reasoned that it is preferred to have a torsioned edge for the concrete panel. This can be realized by using flexible foam as the border for the mold. The foam should be flexible enough to follow the curvature of the spline and stiff enough to resist the pressure of the cast concrete. The foam should be coated with flexible polyurethane. This prevents the concrete from sticking to the foam and makes the border reusable for several castings. Double sided tape can be used to fixate the foam to the mold. This tape can be easily separated from the mold and foam. The foam border can be positioned with the same method as the edges of the flexible mold, see fig 7-23.

The concrete can either be cast on an open or in a closed mold. The closed mold requires two similar intermediate molds. The concrete will be cast in vertical position, see figure 7-24. Both pieces can be produced with the flexible mold. Or instead, one is produced with the flexible mold and the second one by vacuum forming. This method would speed up the production cycle and is more accurate. The closed mold also gives the possibility to produce concrete elements

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**Fig 7-22** Support systems for intermediate mold

**Fig 7-23** Foam positioning

**Fig 7-24** Closed mold casting
Flexible Mold - an innovative production method to produce precast DCC panels

with varying thicknesses. This could be beneficial for structural façade elements. The closed mold produces concrete panels with two smooth surfaces.

For the open mold, the concrete can be applied onto the surface in three ways.

- Spraying
- Viscous casting
- Delayed deforming

Spraying of concrete, or shotcrete, is mentioned for completeness. Although it is used for many freeform in-situ instances, this technique is not desirable for prefabrication because of the inferior aesthetic and mechanical properties in comparison to other casting techniques.

Viscous casting is a technique where the concrete is applied in two steps (Huyghe&Schoof, 2009). In the first step, a layer of concrete is applied which is subsequently compacted for better mechanical properties and surface quality. The concrete is applied in two instances because during the process of compacting, the concrete may flow creating an unequal thickness distribution. The second step is to restore the concrete distribution. Viscous casting is a good technique for single curved or ruled surfaces. In that way the surface can be smoothened with a batten which ensures a uniform thickness distribution. Other freeform surface cannot be smoothened with a batten, which makes it more difficult to achieve a uniform distributed thickness. See figure 7-25 for the viscous casting process.

Delayed deforming means that the concrete is cast in flat position, and deformed after a time interval after gaining enough viscous strength. The occurring cracks will heal by themselves which results in two smooth surfaces. The method that Schipper (2011) uses, see chapter 2, is not possible for this mold because the surface consists of one piece. An alternative would be to cast the concrete on a flat prestressed membrane which will be untensioned upon lowering the membrane on the mold, see figure 7-26. A disadvantage of the delayed casting method is that the position of the foam strip needs to be corrected for the displacement it will make during the lowering on the mold.

7.4 Prototype

The previously described design for the new mold technique has been translated into a prototype. The prototype that has been built is a simplified design with special focus on producing hyperbolic paraboloids for testing purposes. Furthermore it has been downscaled to 1:3 of the intended size; this is done for practical reason. The prototype consists of a separate wooden bottom and top frame that can glide vertically up and down. Two struts keep the top and bottom frame 150mm separated. When the sheet is heated, the struts are removed. The top frame will
move down on to the bottom frame, see figure 7-27. The actuators and the frame to fixate the polymer sheet are attached to the frames.

![Diagram](Fig 7-27 Mold mechanism, support struts (green), heated polymer sheet (red))

The edge mechanism is designed as follows. Threaded ends are used for the actuators which are connected to the frame with nuts, wide diameter washers to assure a ninety degree angle and spring washers for a firm and easily adjustable connection. The rotation plate is connected to the actuator and flexible strip with hinges. The top hinge is connected to the flexible strip with a spacer to minimize the contact surface.

Instead of using silicone for the flexible strip, bending triplex is used, see figure 7-28. This is six times cheaper and is still suitable to form the edges for hyperbolic paraboloids. A silicone strip is glued to the bending triplex to guide the membrane to the edges. Figures 7-29 and 7-30 show the edge mechanism in detail.

The shape of the rotation plate had to be adjusted to prevent it from touching the polymer sheet and connection frame, see figure 7-31. It is preferable to position the frame close to the edge to minimize material consumption. A good stiffness is obtained when the actuators are spaced 100mm. In figure 7-32 the layout of the bottom frame is shown.

![Image](Fig 7-28 Bending triplex)

![Image](Fig 7-29 Edge detail front view)

![Image](Fig 7-30 Edge detail side view)
Instead of using a combination of radiant and convection heating, only convection heating will be used; the production speed is not important for the tests. The membrane will be manipulated by tension only. The four corners of the sheet will be tensioned by a cord that is connected to a weight. Because the produced surface is solely formed by tension, it can be supported by the flexible mold itself for the casting process. Figure 7-33 shows the mold in the convection oven. A close up of the mechanism of the mold is given in figure 7-34.

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**Fig 7-31** Adjusted rotation plate to avoid obstruction

**Fig 7-32** Layout bottom frame
Fig 7-33 Prototype in convection oven

Fig 7-34 Close-up prototype
8 Generative modeling

A generative model to adjust the actuators of the flexible mold is elaborated in this chapter.
8.1 Introduction

The aim of making a generative model of the mold system is to easily retrieve the necessary data from the computer model to configure the flexible mold. For the scope of this thesis, a generative model is useful to configure the flexible mold according to a computer model to subsequently compare it with the produced surface. In that way the configuration data for several surfaces can be retrieved quickly without manual calculation. Especially the height positioning of the actuators cannot be determined easily because of the displacement of the hinged plates.

For the automation of the production process, a generative model or script is indispensable for CNC. This CNC process consists of three steps: first a free form surface will be divided into a grid (panels), subsequently the necessary data is extracted from the model (angle and curvature), and finally the flexible mold is configured according to the data.

Numerous programs are available for scripting. For this case the Grasshopper plugin for Rhinoceros has been chosen to use for the modeling. Grasshopper is in fact not a scripting program; it is a visual generative modeling program. It is an easy to learn program featuring all the necessary operations for this case. However, because of the fact that some operations, such as projecting of points, is (yet) not available in Grasshopper, some operations had to be carried out differently. Nonetheless, the aimed generative model could be programmed. The following sub-chapters will go through the principle of the generative model, which is divided into the panelization of the facade and the configuration of the mold. The complete Grasshopper model is presented in appendix F.

8.2 Panelization of façade

First a flat grid is generated which should be bigger than the freeform surface, see figure 8-1. A element of the grid represents a panel thus the edge configuration of the mold. The geometry of the grid is restricted to the adjustability of the borders of the flexible mold. In this case a grid of 0.48x0.48m² has been used. Subsequently

![Fig 8-1 Grid of mold dimension](image1)
![Fig 8-2 Projection of grid on surface](image2)
the grid is projected onto the freeform surface, see figure 8-2. The next step is to extract the data of the panel. All four edges of a panel, or in this case only one edge is selected to be analyzed. The positioning of the actuators (every 120mm on the flat grid) is projected onto the selected curve, see figure 8-3. The height of the curvature at the position of the actuators can now be determined by using the x-coordinates. The angle of the curvature at the position of the actuators is determined by the tangent at that point. The data that has been extracted from this step is the angle and height position of the specified points of the curve.

### 8.3 Configuration of mold edge

The curved edge of the panel, which is determined in the previous step, needs to be configured by the flexible mold. Because of the use of hinged plates for the configuration of the flexible mold edge, the angle of the hinged plates depends on the curvature of the edge which subsequently determines the height position of the actuators. To find the correct height of the actuators, first the curve of the panel is generated using the earlier retrieved data of the points, see figure 8-5. Next, the position of the hinged plate on the curve is determined. The hinged plates are connected with a fixed distance along the curve. The more curvature,
the more the hinged plate connection on the curve will displace horizontally from the actuator. The angle of the hinged plate, see figure 8-7, is determined by using the Pythagorean Theorem. When the position and angle of the hinged plate are known, the height of the actuator can be determined, see figure 8-8. For the above elaborated panel, grasshopper generated the following output data per actuator for this specific edge:

1. Angle of edge (see figure 8-9)
2. Height actuators (see figure 8-10)
3. Height difference edge (see figure 8-11)
4. Angle of hinged plate (see figure 8-12)

The angle of edge and the height of the actuators are output data which can be used to adjust the flexible mold. The other output data is for verification. The hinged plates are for example not allowed to tilt more than 45 degrees. Figure 8-12 shows that the maximum angle of this specific edge is 13.4 degrees, thus it meets the requirements.
8.4 Conclusion

The Grasshopper plugin for Rhinoceros is a relative easy tool for making generative models. Especially for the use of the flexible mold, it is an effective tool to quickly extract the data from the free form surface needed to configure the flexible mold. This tool has been designed to determine the height and angle of the actuators, but it does not include output data for the membrane manipulation techniques such as pretension. If the membrane manipulation techniques can be modelled, the Grasshopper model can be extended including this feature. The Gaussian curvature analysis of the freeform surface, see figure 8-13, shows the anti- and synclastic curvature forming the basis for modeling the membrane manipulation techniques.

![Gaussian analysis free form surface](image)

Fig 8-13 Gaussian analysis free form surface
9 Tests

The purpose of the developed prototype is to test the new production method. This chapter shows the test results of the polymer sheet deforming process and the casting of the double curved concrete panels. Both sub-chapters begin with defining the goal of the tests and indicating the measuring method.
9.1 Test of plastic panels

The main emphasize of these tests is to get a better understanding of the polymer free forming technique. In specific the stretch-behavior of the sheet is an important aspect. Other points for evaluation are the shape accuracy, edge transition, reusability and prestress-behavior. Table 9-1 shows the aspects and methods for evaluation.

Table 9-1 Measuring methods

<table>
<thead>
<tr>
<th>Evaluation aspect</th>
<th>Measuring method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prestress behavior</td>
<td>Visual (fluidity curvature)</td>
</tr>
<tr>
<td>Stretch behavior</td>
<td>Measure length (Compare before and after of grid lines)</td>
</tr>
<tr>
<td>Shape accuracy</td>
<td>Measuring height (compare product with computer model)</td>
</tr>
<tr>
<td></td>
<td>Visual (Placing two sheets on top of each other)</td>
</tr>
<tr>
<td>Edge transition</td>
<td>Visual (Placing two sheets next to each other)</td>
</tr>
<tr>
<td>Reusability</td>
<td>Visual (re-heat a deformed polymer sheet)</td>
</tr>
</tbody>
</table>

The first step is to determine the correct oven-temperature. The following subchapters discuss the test results of the experiments per evaluation aspect.

9.1.1 Sheet Temperature

As noted in many literature (e.g. Gruenwald, 1998), finding the correct temperature for thermoforming can only be determined experimentally. Table 9-2 shows the test samples with the variables temperature and heating time.

Table 9-2 Temperature and heating time

<table>
<thead>
<tr>
<th>Test</th>
<th>Temperature [°C]</th>
<th>Heating time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>120</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>130</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>15</td>
</tr>
<tr>
<td>4</td>
<td>110</td>
<td>15</td>
</tr>
<tr>
<td>5</td>
<td>120</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>120</td>
<td>10</td>
</tr>
</tbody>
</table>

The heating time starts counting from the moment the programmed temperature has been reached. This takes about 10 minutes. During that time, energy will already be transferred to the sheet. The experiments show that a heating duration of 10 minutes (20 minutes in total) is enough to uniformly heat a 0.75mm PETG sheet. The sheet temperature determines in fact two things: the magnitude of force needed to close the mold and the guiding capacity of the silicone rubber. If the polymer sheet is very soft, the mold can be closed with little force, but the polymer may be too soft to be guided to the edge by the silicone rubber. In that case the silicone rubber won’t bend and an imprint of the edge will be visible in the sheet, see figure 9-1. So a good balance ought to be found. The experiments show that a sheet temperature of 120 °C is ideal for pressing the shape, but the silicone rubber leaves an imprint. Using a lower temperature (110°C) results in a smooth surface without a silicone rubber imprint, but the mold cannot be closed completely.

This means that either a bigger force needs to be applied to close the mold, or
that the silicone rubber needs to be replaced by a thinner thus less stiff elastomer. Applying a bigger force also means that the mold needs to be built accordingly, increasing forces also means increasing deformations for the actuators and the flexible edge material. The friction between the silicone rubber and polymer sheet can also leave imprints at elevated temperatures, see figure 9-2.

9.1.2 Prestress-behaviour

The prestress is applied on four corners through a cord with weight, see figures 9-3 and 9-4. Without prestress, the sheet will have bad curvature or wrinkles, see figure 9-5. Figure 9-6 and 9-7 show the fluidity of curvature of a test sample with and without prestress. The polymer sheet is clamped between wooden laths for fixation on the frame, see figure 9-8. The wooden lath cannot be clamped over the complete length of the sheet because the flexible edge would otherwise be obstructed by the frame, see figure 9-9. The flexible edge has deliberately been oversized in length to test this specific situation. The idea behind this is discussed in the next chapter. The consequence of this setup is that the cord with the weight moves down with the mold frame. The flexible edge will be additionally loaded and will deform accordingly, see figure 9-10. This deformation could be avoided by using a moveable prestress system.
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Fig 9-5  Wrinkled vs smooth surface

Fig 9-6  No prestress, bad curvature
Fig 9-7  Prestress, fluid curvature

Fig 9-8  Fixation frame

Fig 9-9  Fixation frame opening for mold edge

Fig 9-10  Deformation of flexible edge
9.1.3 Stretch behavior

A grid of lines is drawn on the polymer sheet to be able to measure the stretch behavior, see figure 9-8. The measurements show that the main deformation takes place at the edge, see figure 9-11. This is caused by the friction between the mold edge and the polymer sheet during the lowering of the mold frame. Figure 9-12 illustrates this principle. This means that the prestress has to be applied in flat position. Furthermore, the prestress cannot be altered when the mold is closed, because it will only elongate the material at the edges.

![Fig 9-11 Stretch near edge](image1)

![Fig 9-12 Stretch (red line) only near frame because of friction at mold edge](image2)

9.1.4 Shape accuracy

The intended accuracy could not be achieved because of several factors. First of all, the silicone rubber is too stiff which prevents it from guiding the polymer to the edge. Secondly, the prestress-system is not optimal which deforms the mold edge too much. Thirdly, the edge-system of the mold has too much play. This play is induced by too thin dimensioned actuators and poor hinges with play, see figure 9-13. Furthermore, the wooden mold frame worked and warped because of the drying process in the oven. This had influence on the geometry of the wooden frame on which the actuators are connected and on the bolt and screw connections of the wood. This added to the play of the mold.

The center point of hyperbolic paraboloids is at \( \frac{1}{2} \) height. The middle point of the surface has been measured to verify this and determine whether more or less pretension is needed. Because the silicone rubber altered the geometry, the height has been determined at the imprint of the silicone rubber. The mold should have 100 mm height difference, but measured from the end of the silicone rubber it’s 50 mm. The measured heights are 19 mm and 31 mm. This means that the middle point of the surface is not at \( \frac{1}{2} \) height and more pretension is required.

![Fig 9-13 Play of hinges, displacement increases with larger hinged plate](image3)
9.1.5 Edge transition
As described in the previous section, the intended shape could not be reproduced because of several factors. Specifically the edges show irregularities because of the imprint of the silicone rubber which inevitably makes it impossible to achieve a fluid edge transition. Therefore it has not been evaluated any further.

9.1.6 Reusability
The deformed polymer surface has been re-heated to form back into its original shape. Figure 9-14 shows that the polymer sheet is wrinkled rather than a smooth surfaced sheet. This is due to the permanent relocation of molecule strings during the stretching process. This means that the sheet cannot be reused immediately for a new production cycle. It can be recycled 100% nevertheless. Permanent stretching can be prevented by either using a larger polymer sheet or by thermoforming near the glass temperature, see chapter 6 for more background.

9.2 Tests of concrete casting
The end goal of the new mold technique is to produce concrete panels. The emphasis of this thesis is on the production technique for the intermediate mold, rather than the actual casting process of concrete. No experiments have been conducted to find the best suitable concrete mix; instead a standard premix has been used. The goal of these tests is to prove the suitability of two casting techniques and show preliminary test results. The samples are solely evaluated for geometric and surface quality.

9.2.1 Closed mold
Two equally shaped polymer surfaces are offset 50mm from each other with wooden laths. The resulting cavity is filled with concrete, see figure 9-15 and 9-16. A thicker thermoplastic sheet has been used to make sure that the mold would not deflect by the pressure caused by the concrete. Figure 9-17 shows the resulting concrete panel. Both sides of the concrete element are smooth because the concrete is completely enclosed by the mold.
The surface shows some irregularities which are caused by air-bells. This can be prevented by either using compacting methods such as vibrating, or using self-compacting concrete instead of ordinary concrete mix. The concrete panel thickness is solely dependent on the geometry of the mold. Thus the resulting concrete element is an accurate ‘copy’ of the mold.
9.2.2 Open mold

The viscous casting method has been used for the open mold. The polymer surface is supported on the edges with a wooden frame, see figure 9-18. As discussed in chapter 7.3.2. support, supporting the surface on the edges only is stable enough to prevent deflection. Foam strips have been taped on the surface to form torsioned edges. The concrete paste is applied on the surface by hand. Just enough water has been mixed to form a paste which is workable enough with a minimal slump. Figure 19-19 shows that the concrete sticks to the foam strips. This can be prevented by coating the foam with polyurethane. The resulting panel, see figure 9-20, only has one smooth surface. This is due to the inability of smoothing the concrete paste at the top side. For architectural use, in most cases only one smooth surface is required. Although the panel thickness depends completely on the manual casting process, a relative constant thickness is observed for the test sample.

Fig 9-15 Two surfaces seperated with spacer

Fig 9-16 Pouring of concrete in mold

Fig 9-17 Concrete panel produced with closed mold
9.3 Conclusion

The test results show that the silicone rubber is too stiff which causes imprints in the polymer surface. Smooth curvatures can be obtained by prestressing the polymer sheet. The prestress needs to be applied in flat sheet position; otherwise only the edges will be tensioned instead of the complete surface. The method to prestress the sheet needs to be vertically moveable because it deforms the flexible edge. The fluidity of the edge transition between two panels could not be evaluated. This is due to the fact that too much play has been observed in the edge system of the mold. Because of the permanent strain of the polymer, it cannot be reused for immediate production, but it can be recycled for 100%.

The open and closed mold casting techniques prove to be suitable for the new mold method. The advantage of the closed mold is that the concrete panel will have two smooth surfaces with a constant thickness. Furthermore, ordinary concrete and known compacting techniques can be used for this method which makes it an attractive production method.
10 Conclusion and evaluation
10.1 Conclusion

The goal of this thesis is to develop a mold technique to produce non-repetitive double curved concrete elements in an economical and sustainable manner. The design resulted in an innovative technique that can provide an economical and waste free alternative to existing mold techniques. The approach of using a recyclable intermediate mold for casting concrete drastically increases the productivity. A production cycle of such an intermediate mold takes approximately 15 minutes, which means that it can produce 32 intermediate molds in one work shift of 8 hours. This means that this flexible mold can produce 32 concrete elements in one day, instead of one element per day which is the case for the other reconfigurable mold techniques. Literature about free forming of a polymer sheet by prestress has not been found by the author. This indicates the innovative character of the mold technique. Experiments have shown that the free forming of polymers by tension is possible, but it is a delicate process. Furthermore, the prototype used for the experiments needs to be further developed. The mold can be optimized in several aspects to produce more accurate intermediate molds; this will be discussed under optimization.

Apart from the production of concrete panels, the intermediate mold can also be used as an end product. The advantage of the free forming technique is that the polymer surface will not undergo any friction and thus results in a maximum transparency. PMMA, which is used as an alternative for glazing, can now be shaped in any desirable free form without compromising the optical quality.

The progress of the graduation project went in general according to the prior planned scheme. The delay of one month can be attributed to the underestimation of the needed time for the design and building of the mold. The planned time turned out to be too little for the complete development of the mold. The additional time gave me the possibility to complete the testing phase and evaluate the prototype. The following paragraphs identify some points for optimization.

10.2 Optimization

Mold frame
The mold frame has been constructed with wood. This warps too much when it is exposed to high temperatures in the oven for long durations. To obtain a more dimensional stable material for fluctuating temperatures, a steel frame is recommended.

The lowering of the top frame should be simplified by for example having to pull only one handle to lower the frame. Furthermore, the top frame should not be able to displace in horizontal plane so that the upper flexible edge touches the bottom edge accurately.

Edge system
The actuators have a diameter of 8mm, which is too small to resist the occurring bending forces with no deflection. Thus an actuator with a higher moment of inertia is preferred. A little play in the hinges has a huge effect on the position of the flexible edge. Hinges of better quality, no play, are required.

The silicone rubber is too stiff to guide the polymer to edge. Either a thinner strip of the same silicone must be used, or a more flexible silicone has to be used. As proposed in chapter 7 ‘Design’, the bending triplex has to be exchanged for a reinforced silicone rubber strip to be to able have a curved and torsioned edge.
The angle plate system is preferable made of steel to avoid warping of wood. The prototype has been built with manual height and angle adjustment of the actuators. Manual adjustment means high labor costs but low investment costs. For commercial use, the mold needs to be automated. This means that the height and angle adjustments will be CNC adjusted. Although it will increase the investment costs significantly, the productivity will increase as well.

Actuator positioning
The positioning of the actuators is fixed. That means that the mold system is limited to the given dimensions. If the actuators could move sideways, the geometry can change from square to rectangular in different dimensions, see figure 10-1. For this reason, the prototype test used sheets that were not clamped entirely over the length to anticipate for this optimization, see chapter 9.1.2. By making the edges in horizontal plane rotatable, it is even possible to produce skewed shapes. The advantage of repositioning the edges is that different shapes and dimensions can be produced with high geometric accuracy at the edges.

![Variable positioning of edges](image)

Figure 10-1 Variable positioning of edges

Manipulation of membrane
The prestress system is obstructing the flexible edge which gives undesirable deformations of the flexible edge. A vertically moveable system would prevent this. Furthermore, a clamping method to connect the prestressed cord to the membrane, instead of using a hole, would transfer the forces better.

Heating system
As discussed in chapter 7 ‘design’, a combination of radiant and convection heating will increase the production cycle and still give enough time to manually manipulate the membrane. So the mold should be equipped with a radiant heating system.

Casting
To increase the surface and mechanical quality of the concrete, the paste should be compacted. This can either be done by vibrating or by using self-compacting concrete. The foam strip used for the edge should be coated with polyurethane to prevent it from sticking to the concrete. The foam can then be reused several times.
10.3 Further research

The above mentioned optimizations can be applied to make a new better functioning prototype. Those improvements will increase the performance of the mold significantly and most likely result in an accurate mold technique.

The mold technique is in its infancy and can be developed further. Some interesting aspects for further research will be noted briefly.

A smart method to apply variable tension over the complete surface of the membrane is an important aspect to further develop. Special attention is required to the open edge where no frame is attached. Other manipulation methods of the membrane such as pressing inflatables into the membrane have to be researched.

An interesting research topic is the manipulation of the membrane by air pressure and local heating. In that case air pressure could be exerted and only the surface that is heated will deform. Using air pressure instead of inflatables to deform the membrane has the advantage of avoiding friction, which preserves the high optical quality of the surface.

By extensively observing the stretching behavior of the polymer membrane, a model can be developed to predict the necessary tension needed to achieve the desired curvature.

The support system of the intermediate mold can be developed to an easily storable package.

The casting techniques, including concrete technology, could be further researched and experimented to ensure high quality end products.

Related topics include panel connections (on frame or mutually), transportation and storage of double curved elements and mechanical properties of concrete panels.

Many research topics are yet open to be explored to contribute to frontier technology.
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Figure 6-13. Dupaix, R.B., Boyce, M.C. (2007) Stress-strain curve PETG at various temperatures [Graph]. In Constitutive modeling of the finite strain behavior of amorphous polymers in and above the glass transition. Elsevier Ltd.


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Appendix B. Reconstruction Philips Pavilion

Two building methods have been developed for the reconstruction of the Philips Pavilion (Riemersma, 2012).

Method A:
- Paint and spray mortar
- XPS insulation
- Roofing
- Shotcrete and concrete core activation on membrane
- Acoustic mortar
Flexible Mold - an innovative production method to produce precast DCC panels

Method B:
- Paint + panels
- U profiles
- Roofing
- XPS insulation
- Shotcrete and concrete core activation on membrane
- Acoustic mortar
### Appendix C. Mold techniques comparison

The table is based on data presented in literature written by the mold designers, which can be found in the reference list. The costs of the mold systems are not an accurate representation of the actual costs. The prices that S. Oesterle has provided are used for a reference to estimate roughly the cost ratios between the mold systems.

<table>
<thead>
<tr>
<th>Variables</th>
<th>System</th>
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<tbody>
<tr>
<td></td>
<td>Vollers, Rietbergen</td>
</tr>
<tr>
<td>1. Function</td>
<td>mold</td>
</tr>
<tr>
<td>2. Products</td>
<td>all</td>
</tr>
<tr>
<td>3. Configuration principle</td>
<td>actuator</td>
</tr>
<tr>
<td>4. Top layer principle</td>
<td>one element</td>
</tr>
<tr>
<td>5. Connection of top layer</td>
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<tr>
<td>6. Material top layer</td>
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<tr>
<td>7. Geometry</td>
<td>fluid, r ?</td>
</tr>
<tr>
<td>8. CNC connection</td>
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</tr>
<tr>
<td>9. CNC information processing</td>
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</tr>
<tr>
<td>10. Configuration time</td>
<td>15 min</td>
</tr>
<tr>
<td>11. Cost (R=robot, M=mold)</td>
<td>R=150.000 R, M=15.000</td>
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</table>

#### Relative costs per panel with original mold systems

<table>
<thead>
<tr>
<th>Relative costs per panel with original mold systems</th>
<th>12. Productivity (products/day / mold)</th>
<th>13. cost/ productivity</th>
<th>14. factor</th>
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<tbody>
<tr>
<td></td>
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<td>1 product</td>
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<td></td>
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<td>16.563</td>
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<td></td>
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#### Relative costs per panel with temporary contra mold for all mold systems (4 hours per wax mold)

<table>
<thead>
<tr>
<th>Relative costs per panel with temporary contra mold for all mold systems</th>
<th>12. Productivity (products/day / mold)</th>
<th>13. Cost/ productivity</th>
<th>14. Factor</th>
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<td>1.3</td>
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#### Relative costs per panel with temporary contra mold for all mold systems (1 hour per wax mold)

<table>
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<th>14. Factor</th>
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<td>1.1</td>
<td>3.2</td>
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1. Function: mold = cast end product directly on mold. Contra mold = cast temporary mold on flexible mold
2. Products that the mold is designed for. All = concrete, gypsum, polymer, composites
3. Fluid = fluid shape with no kicks. All = all geometries can be reproduced
4. Robot = separate robot which can configure multiple molds; step motor = integrated motor in every single actuator; machine = integrated configuration machine in mold system
5. CNC information processing is the complexity of analysing and translating the freeform shape for the mold
6. Hypothetical productivity for concrete elements which are demoulded after 24 h.
7. The systems using a robot are deployed with maximum operation capacity. The amount of molds that can be configured by one robot is calculated by time of product hardening: concrete 24 h; wax 4 h)/configuration time
Appendix D. Material and technique selection

Data is based on Ashby (2011).

<table>
<thead>
<tr>
<th>Material</th>
<th>Vacuumatics</th>
<th>Pressing</th>
<th>Cast moulding</th>
<th>Injection moulding</th>
<th>Thermoforming</th>
<th>Spray-up</th>
<th>Stretch forming</th>
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<tbody>
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<td></td>
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<td>1000</td>
<td>240</td>
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<td>Composite</td>
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<tr>
<td>Composite</td>
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<td>1500</td>
<td>1000</td>
<td>240</td>
<td>2</td>
<td>2000</td>
</tr>
</tbody>
</table>
Appendix E. Deflection calculation

Calculation to find minimum sheet thickness or maximum spacing supports of intermediate mold. Tensile strength of PMMA is 50 N/mm².

Line load of concrete

\[ q = \frac{F}{l} \]
\[ F = \rho \cdot V \cdot a \]

substitute
\[ l = 1000\text{mm} \]
\[ b = 1000\text{mm} \]
\[ h = 5\text{mm} \]

\[ \rho = 2,3 \cdot 10^3 \text{kg/m}^3 \]
\[ a = 9.8\text{m/s}^2 \]

result
\[ q = \frac{F}{l} = 1.15\text{N/mm} \]

Formulas for deflection and stresses

\[ M = \frac{1}{8}ql^2 \]
\[ W = \frac{1}{6}bh^2 \]
\[ I = \frac{1}{12}bh^3 \]
\[ \sigma = \frac{M}{W} \]
\[ u = \frac{5}{384} \cdot \frac{q \cdot l^4}{E \cdot I} \]

Minimum sheet thickness for a maximum deflection of 1mm

substitute
\[ u = 1\text{mm} \]
\[ l = 1000\text{mm} \]
\[ b = 1000\text{mm} \]
\[ h = x \]
\[ E = 3100\text{N/mm}^2 \]
\[ q = 1.15\text{N/mm} \]

result
\[ u = \frac{5}{384} \cdot \frac{q \cdot l^4}{E \cdot I} = 1 \rightarrow h = 39\text{mm} \]
\[ \sigma = \frac{M}{W} = 0.6\text{N/mm}^2 \]
Maximum spacing of support for a maximum deflection of 1mm

substitute
\[ u = 1 \text{mm} \]
\[ l = x \]
\[ b = 1000 \text{mm} \]
\[ h = 5 \text{mm} \]
\[ E = 3100 \text{N/mm}^2 \]
\[ q = 1.15 \text{N/mm} \]

result
\[ u = \frac{5}{384} \frac{q \cdot l^4}{E \cdot I} = 1 \rightarrow l = 215 \text{mm} \]
\[ \sigma = \frac{M}{W} = 1.6 \text{N/mm}^2 \]
Appendix F. Generative model

The generative model programmed in Grasshopper Rhinoceros is illustrated in 4 parts.
Flexible Mold - an innovative production method to produce precast DCC panels
selection and x-coordinate of the edge points

sort list of x-coordinates

height difference of edge

height of points on curve with lowest point set to 0