MASTER

The VaCo Mould
a research about a new moulding technique for fluid architecture

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Summary

Since the early nineties there is a trend of fluid double curved architectural design. This trend has been rising due to the developments in three-dimensional Computer Aided Design (CAD). This brought new life into architecture in terms of organic shapes and fluid forms that can be interpreted as the smoothened follow-up of 'Deconstructivist Architecture'. For the constructions of for example the congress centre in Brasilia, high labour intensity was needed. At that time labour was relatively cheap and time was less important. Nowadays more precast concrete elements are used and formwork and labour is more expensive. This is the reason for searching new production methods to create single or double curved elements. Recently used methods are Computer Numerical Controlled (CNC) machines that precisely cut or mill a designed object. This technique, with polystyrene or wood as material, can be used as a formwork for complex shaped buildings. One of the disadvantages is that for each panel or segment a different mould is needed. To make this moulding principle profitable the formwork must have a certain repetition. Besides that, the waste of the mould is also a problem. New research investigates the possibilities of a reconfigurable mould that can be used to produce different elements.

The goal of this research is to optimize the production speed and surface quality using an adaptable surface of spring-steel. We found the curing time of the product to be the most critical aspect. To deal with this it is possible to make vacuum formed boxes with the adjustable mould in high speed. The boxes will be filled with concrete for the production of the final product. The technique can be divided into the (Va)cuum mould and the (Co)unter pressure mould. The idea is to use plastic sheets that are heated and vacuumed towards an adjustable rubber covered surface. With the curved sheets boxes are made. The box is used as a mould. Casting the mould needs a counter pressure to avoid the deformation of the thin surface of the plastic boxes. The plastic boxes provide a good surface quality of the concrete elements and a fast production process.

The adjustable flexible surface of the vacuum mould is based on a woven spring-steel mesh that can return to its original shape. The spring steel mesh is connected with a grid of adjustable pistons. The pistons are moved into different positions to form a point grid part of the demanded curved surface. The properties of the woven mesh make it possible to form double curved surfaces.

The vacuum formed Polystyrene sheets are clamped between wooden sheets, which are lasered in the designed shape. The fixation ensures that the deviation at the edges is limited. During the casting process, clay granulates are used as counter pressure. To avoid deformations in the surface the clay granulates and concrete are casted at the same time. In this research many different kind of concrete is tested. The most important factor of the concrete is the workability. This makes it possible to cast a thin and smooth panel. The workability is obtained with a plasticiser that is added to the concrete. The proportion of the plasticiser needs a high accuracy. After all tests still some blow holes or colour differences occur.

With the developed VaCo Mould products are made that show the maximum capabilities of the mould for fluid architecture. The goal of the end product is to integrate this system for the production of a building component, a concrete panel. Therefore problems for fixation methods, thickness and smooth curved panels are solved. The maximum curvature and thickness is guaranteed with local thickening for the fixation method. Water jet cutting makes it possible to produces elements in different shapes, for example topographical. The validation of the concrete panels shows deviation of approximately 3 mm and an extreme value of 6 mm. These results are acceptable for the production of façade panels.

Finally it can be concluded that the designed production process complies with a faster production process. A disadvantage is that the production of the box takes a lot of time; this is a point of improvement. The curvature of the panel is within the tolerances of the design, but the concrete mixture must be improved. The investment cost of a flexible mould is expensive, but it eliminates the production of the static moulds. The future should show whether this system is cheaper or not. More detailed information can be found in appendix A: "Paper ISOFF symposium 2015". This paper is presented at the ISOFF symposium 2015 in Amsterdam.

Preface

This master thesis is written by Tobi Lusing and Robin Versteeg as final part of our graduation project for the mastertrack "Building Technology" at the Eindhoven University of Technology. The thesis shows our work from the past year. We have chosen to work together on this graduation project, because we have the same interests in the subject of free form building elements.

After one year of hard work, we are very happy with the end result of our graduation project. However, this result could not have been obtained without the help of some people.

First of all, we would like to thank our graduation committee, Patrick Teuffel, Arno Pronk and Gerald Lindner for sharing their knowledge and assistance during the course of our master thesis. Especially, we want to thank Arno Pronk, who was intensively involved with this graduation project.

Further we want to thank the staff of student workplace and the Pieter van Musschenbroek laboratory, with Hans Lamers in particular, for making it possible to produce the VaCo Mould.

And finally we would like to thank Richard van Vliet (Cugla B.V.), Ton Cornelis (Hakron B.V.), Marc Pustjens (Prodim International B.V.) and Jeroen Stam (Cebo Holland B.V.) for sharing their knowledge and providing us materials for producing our end product.

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1. Introduction

This research is about the trend of Free Form within architectural design. Blob Architecture, a type of wavy, curvy designs without traditional edges or symmetric form, is one of these styles. This new architectural style is made possible by Computer-Aided-Design (CAD) software. Blob means Binary Large Object, which is a software feature. This brings a new life in architecture in terms of organic shapes and flowing forms. This is the next generation of design that is inspired by 'Deconstructivist Architecture', with examples of Frank Gehry (figure 1) or Zaha Hadid (TED, 2005).

Figure 1: The Guggenheim Museum by Frank Gehry (Guggenheim, 2014)

Before Computer Aided Design (CAD) software belongs to the possibilities, architects like Oscar Niemeyer were key figures in the development of modern architecture. The inspiration of Oscar Niemeyer about modern architecture is (Niemeyer, 2000):

"I am not attracted to straight angles or to the straight line, hard and inflexible, created by man. I am attracted to free-flowing, sensual curves. The curves that I find in the mountains of my country, in the sinuousness of its rivers, in the waves of the ocean, and on the body of the beloved woman. Curves make up the entire Universe, the curved Universe of Einstein"

For the construction of these buildings, high labour intensity was needed. In figure 2 the construction of the National Congress in Brasilia 1958 is showed. At that time labour was relatively cheap and time was less important. The formwork was a temporary support for the construction of the inverted dome (Andreoli & Forty, 2004). Until now the building techniques for the construction of such free form buildings are quite primitive. This is the reason why Universities are searching for new production methods to create, single or double curved elements.

Recently used methods are Computer Numerical Controlled (CNC) machines, that precisely cut or mill a designed object. This technique, with Polystyrene or Wood as material, can be used as a formwork for complex shaped buildings. One of the disadvantages is that for each panel or segment a different mall is needed. To make this moulding principle profitable the formwork must have a certain repetition. Besides that the waste of the mould is also a problem. New research investigates the possibilities of a reconfigurable mould that can be used to produce different elements.

Figure 2: The construction of the National Congress in Brasilia (Cultural Institute, 2014)

In this research new production techniques, for double curved elements in concrete, are investigated with the goal to answer the demand for Free Form Designs.

1.1 Structure of report

1.1.1 Literature study

Reference projects
Reference projects of double curved buildings of concrete will be discussed. The goal is to find out which manufacturing and construction methods are used in these projects.

Case study OV-Terminal Arnhem
The case study describes different design alternatives of the contractor. The goal is to get more understanding about factors that play an important role for the decision of the manufacturing and construction method.

Moulding principles
This part gives an overview of the moulding principles that are used in the past and upcoming developments for reconfigurable moulding. The goal is to understand these techniques and find out which moulding technique could be improved or used to develop a better moulding principle for future demands.

The combination of vacuum forming and hydrostatic pressure
This paragraph describes the techniques and manufacturing techniques that will be used in the development of a new mould principle.

1.1.2 Plan of Approach
Based on the information gathered in the paragraphs above the plan of approach will be discussed for the total project. It consists of the problem description, research objective, research questions and the planning.

1.1.3 Research

Vacuum forming
This chapter describes the research phase of vacuum forming. Based on different experiments at the university of Eindhoven and at Bas Hesselink IDAP. The question is if it is possible to produce a plastic sheet, which smoothly follows the curvature of a reconfigurable spring steel mesh. The research in Texas showed that with small spaces of 2,5 mm waviness still exists, but it cannot be seen with the naked eye. This problem could be solved with larger pin diameters, changing the pressure or a stiffer interpolation sheet.

Mould with counter pressure
In this chapter the mould with counter pressure will be discussed. First the ways of machining of the vacuum formed sheets will be explained. There are two methods of pouring a concrete panel with a plastic sheet. The first method is by lowering a mould into a basin with fluid. This method was an idea by Frank Omloo. The other method is to fixate the two plastic sheets in the basin with counter pressure. The materials that can be used as counter pressure will be discussed first and substantiated with experiments. After that the method will be explained and tested.

Design of the mould
Based on the experiments in the previous chapter, in this chapter choices will be made as regards the design of the mould for double curved panels of 500x500 mm. This chapter is divided into two parts, namely: vacuum forming machine and mould with counter pressure. To evaluate all the possible solutions for each part a morphological overview is used. In this way the choices will be substantiated.

Production process
In this chapter the production process of a double curved concrete panel, made with de VaCo Mould will be discussed. This process will be based on five main steps, namely: setting the VaCo Mould, vacuum forming, create a mould, casting concrete and recycling.

Building applications of the VaCo Mould
In this chapter the design and production process of different building applications for a facade are presented with an existing building method and future possibilities. Especially the freedom in form and the advantage of surfaces smoothness on both sides should attract the attention.

Validation
For the validation process of the designed model a comparison is made between the produced concrete element and the design. To get a better understanding of the deviations according the production process each step is validated with the goal to minimize the overall deviations. Therefore the mould is compared with the design and the plastic sheet and the counter mould is compared with the concrete panel. The validation process is realized with a scanner, the Proliner IS Series, and Cloud Compare.

Future prospects & Market potential
In the paragraph "Future prospects" the future process of the VaCo Mould will be discussed. On which parts could the VaCo Mould be optimized. Based on these future prospects a good comparison can be made between the VaCo Mould and the existing moulding techniques. This will be done in the paragraph "Market potential".

1.1.4 Conclusions & Recommendations
In this chapter the conclusion and recommendations will be discussed based on a SWOT-analysis.

2. Reference projects

In this chapter some reference projects of Fluid Architecture are mentioned. It gives an overview of buildings with double curved shapes of concrete. The buildings that will be mentioned are:

- Philips Pavilion
- Der Neue Zollhof
- Jubilee Church
- Rolex Learning Centre
- Heydar Aliyev Centre
- OV-Terminal

Diagram 1: Timeline reference projects

2.1 Phillips Pavilion – 1958

Architect: Le Corbusier

Place: Brussels, Belgium

The Philips Pavilion was built for the international exhibition that took place in Brussels (figure 3a). In this pavilion, Phillips showed the visitors a performance of light and sound, with the attention to demonstrate the capability of the company Philips. The pavilion consists of 2000 prefab panels of concrete between on-site casted concrete columns. The panels were tensioned by 3000 steel cables. These cables were placed on the outside of the construction. The moulding technique that was used for the concrete panels was a sand hill mould. First the sand hill will be shaped in the right form. After that the shape of formwork will be placed on the sand hill by the use of shuttering boards. Next, the concrete can be poured between the shuttering boards (figure 3b). The finishing of the prefab panels was done by an aluminium coating (Nijsse, 2008).

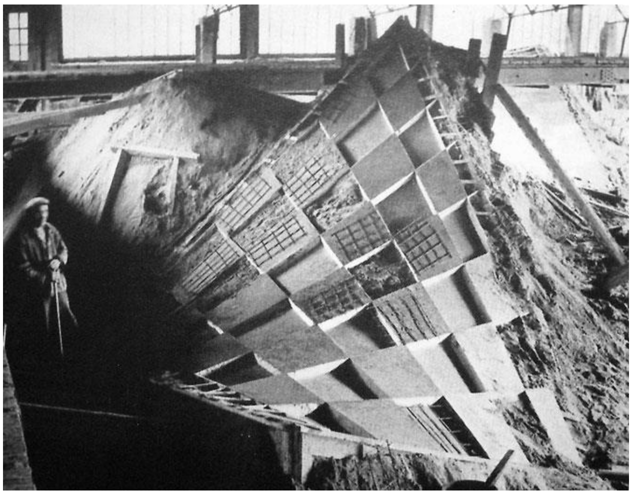


Figure 3a: Philips Pavilion (Wikipedia, 2014) & Figure 3b: Philips Pavilion under construction (McGill, n.d.)

2.2 Der Neue Zollhof – 1999

Architect: Frank Owen Gehry

Place: Düsseldorf, Germany

The Neue Zollhof consists of three separate building complexes. All three buildings are constructed of a concrete slab. The formwork of this concrete slab is milled with the CNC technique. When the polystyrene was milled, the reinforcement is placed and the concrete can be poured in the milled mould (figure 4a). Due to the open mould, the thickness of the panel could only be controlled approximately (Cohen & Ragheb, 2001). The deference between the three buildings is the finishing material (figure 4b). The finishing of left tower consists of bricks; the office building in the middle is clad with metal panels and right tower is finished in plaster (Arcspace.com, 2013).


Figure 4a: Der Neue Zollhof under construction (Cohen & Ragheb, 2001) & Figure 4b: Der Neue Zollhof (Architravel, 2013)

2.3 Jubilee Church – 2004

Architect: Richard Meier

Place: Rome, Italy

The Jubilee Church (also known as Chiesa di Dio Padre Misercordioso) is a catholic church and community centre in Rome (figure 5a). The goal of this project was to highlight the basic role that architecture has in religious spaces and to demonstrate that the connection with contemporary architecture is the key to improve quality of life in suburban areas. For this research the three double curved shells are the most interesting parts of the building. These three shells consist of prefab concrete panels with dimensions of 400x400 mm. Because all panels has the same shape, only one mould has to be made. For these panels of the Jubilee Church a steel mould was chosen. The panels are held together by a steel structure with post-tensioned cables horizontally and vertically (figure 5b). The cement that is used for the panels has self-cleaning properties. In this way the brightness of the color will not degrade over time (Hart, n.d.).


Figure 5a: Jubilee Church (Arch Daily, 2009) & Figure 5b: Jubilee Church under construction (WordPress.com, 2000)

2.4 Rolex Learning Centre – 2010

Architect: SANAA

Place: Lausanne, Switzerland

The Rolex Learning Centre is a building that it is made for the technical university EPFL (École Polytechnique Federale de Lausanne) (figure 6a). In the building there are student facilities, like a meeting area, restaurant and a library. The goal of this project was to create more communication between the students of the different study disciplines. The architect achieved this by creating a building without any walls. Also the hilly landscape offers the possibility to study quietly, but also invites to meet other people. The floor and the roof have the same shape, but they are not made of the same material. The roof is made of steel, while the floor is made of concrete. To make the concrete floor, temporary scaffolding with a CNC milled wooden formwork was needed to support the concrete (figure 6b) (ArchiTravel, 2013).


Figure 6a: Rolex Learning Centre (Eikongraphia, 2008) & Figure 6b: Rolex Learning Centre under construction (Busalto, 2013)

2.5 Haydar Aliyev Centre – 2012

Architect: Zaha Hadid

Place: Baku, Azerbaijan

The Haydar Aliyev Center is a building complex that is built to play an important role in the intellectual life of the city Baku (figure 7a). The building houses a gallery hall, a museum and a conference hall. The building is named after Haydar Aliyev. He was the leader of the Soviet-era in Azerbaijan from 1969 till 1982 and he was also the president of Azerbaijan form 1993 till 2003. The main structure of the building is a steel frame. On this steel frame GFRC (Glass Fiber Reinforced Concrete) panels are placed (figure 7b). By eliminating the need for steel reinforcement, the panels offer a lightweight construction method, and they can be individually moulded to form the curved shapes required by the design. The moulds that are used for the panels are partly from CNC cut 2D Ribs (like a hull of a boat) and partly from 3D Styrofoam blocks (Dispenza, 2011).


Figure 7a: Haydar Aliyev Centre (Frearson, 2013) & Figure 7b: Haydar Aliyev Centre under construction (Williams, 2014)

2.6 OV-Terminal – Under construction

Architect: UNStudio

Place: Arnhem, The Netherlands

The OV-Terminal is the new station for public transport in Arnhem that has to be completed in 2015 (figure 8a). Under the roof of the OV-Terminal different forms of transport are brought together, like a car parking garage, a bicycle parking, a bus station and a railway station. The OV-Terminal will be built in two phases. The first phase is the bicycle parking and the platform tunnel. In this phase the double curved elements are made of concrete "on-site" in a traditional way. That means it is made with a static wooden formwork. The second phase is the terminal. The contractor chose to build the double curved elements out of steel instead of concrete, because there islack of experience of building with double curved shapes out of concrete with such immense complexity and size. The way of construction with steel comes from the shipbuilding industry (figure 8b). The roof panels of the OV-Terminal are made of a mould with a supported membrane (Arnhem Centraal, n.d.).

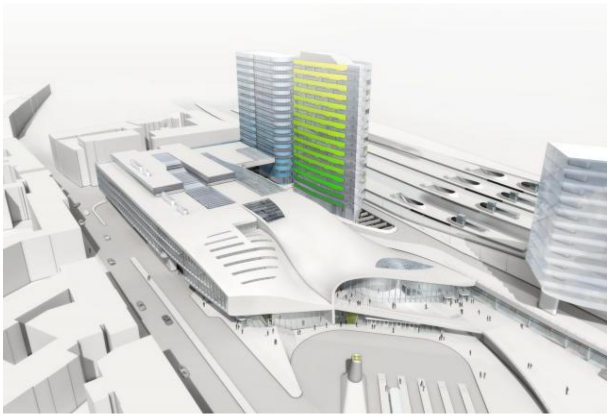



Figure 8a: OV-Terminal (Citypics.nl, n.d.) & Figure 8b: OV-Terminal under construction (Dibec, 2014)

3. Case study OV-Terminal Arnhem

For this research the project OV-Terminal in Arnhem will be discussed in more detail. The goal is to find out why certain decisions in construction methods are made. This can be for instance cost savings, lowering risk or reliability. The outcome would generate information, about the level of potency in product development, for production methods in Free Form Design.

3.1 The OV-Terminal

The OV-Terminal is under construction to answer the growth in passenger amount at one of the most important rail crossings in The Netherlands (figure 9). The master plan for this project is designed by UNStudio in 1996 and is one of the biggest projects for Arnhem after the Second World War. Until now a large amount of subprojects has been realized: a parking place, a roofed bus station, two high rise office building, a low rice office building, a bicycle parking and a platform tunnel. At this moment the most important part, the terminal, is under construction. This building brings all functions of the master plan together. This project is separated in two project phases. The terminal will be made on foundations that were realized in the first phase. Interesting is the difference in construction method that is used. In phase one mainly all elements were made in concrete, where the main construction material for the second phase is steel (Cement, 2013).

Figure 9: OV-Terminal (Publinfra, 2011)

3.2 Construction methods used in phase one

In phase one concrete is used as construction material. Traditional wooden formwork is used to build the slabs or double curved segments. It is also used for the construction of a double curved concrete stairs (figure 10a and 10b). The wooden formwork was prefabricated in a workplace, before it is assembled and supported on-site. When the wooden segments of the formwork are connected, the reinforcement can be placed. The reinforcement is a labour intensive work (figure 10c). After that the concrete can be casted.

Figure 10a & 10b: Traditional wooden formwork & Figure 10c Reinforcement (Arnhem Centraal, 2010)

3.3 Brainstorm: construction method OV-Terminal

For the construction of the OV-Terminal three possible options were investigated at BAM Advise & Engineering. These different methods are discussed during the tendering procedure. The first is made of concrete and the other two out of steel. The steel structures are prefabricated in the workplace, with a steel plate placed on the inside and the structure on top of it. It is possible to spray the steel plates with shotcrete, but for both options a coating is chosen. The steel alternatives consist of a wooden roof layer, with on top of it insulation, roofing covering and concrete panelling. The panels are made of a reconfigurable mould of mbX, which is similar to the moulding principle of Roel Schipper (Falger, 2013). The concrete option is based on traditional casting on-site. The three options are discussed below (Cement, 2013).

3.3.1 Concrete

In the utility construction it is very common to use concrete as construction material. This means that the contractor is familiar with the construction process. During research the design seems to be too difficult. The lack in experience for constructing double curved surfaces, with traditional formwork, therefore seems to result in a high risk for using this method.

To get more understanding about double curved buildings contact is made with Steiner Bau from Graz, who was responsible for the realization of the University theatre in Graz (figure 11a & 11b). In this project CNC milled formwork is used for the casting of concrete elements. The doubts about the solutions on financial and technical feasibility were confirmed by the experience of Steiner Bau. For the reinforcement of double curved vertical elements auxiliary constructions are needed to support and give the reinforcement the right curvature. Again the lack in experience with a similar project makes it difficult to make good assumptions for costs, required quality and building time. The sequence of operations, including production, positioning of the formwork, the construction of the support, difficult bar bending and phased, in a variety of conditions, casting of the concrete contribute to a high risk. Also the amount of stakeholders that are involved makes it a high risk (Cement, 2013).

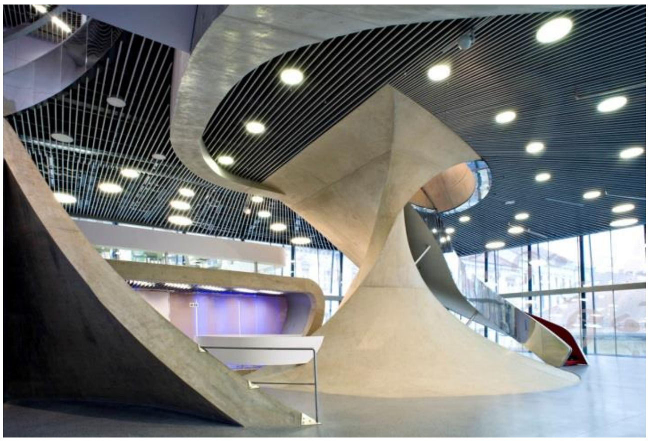


Figure 11a: Double curved element of University theatre in Graz (Theatre Architecture, 2014) & Figure 11b: The double curved element under construction (Cement, 2013)

3.3.2 Space frame

This is one of the alternatives in steel. The space frame with a steel plate on the inside has a construction height of approximately 800 to 1000 mm. The thickness of the inner plate is 4 mm. The extra space that is needed for the construction of the space frame is a disadvantage, for the integration in the design and the connections that have to be made on existing parts of the construction. This is the reason why this option is not chosen.

Another famous project is the 'Heydar Aliyev Cultural Centre' in Baku, Azerbaijan, designed by Zaha Hadid (figure 12a). This fluid design is built with a Space frame (MERO-TSK structure) and a concrete structure (figure 12b). The external skin is made of glass fibre reinforced concrete and follows the structure of the space frame. The result is an extremely thin slab of 8-13 mm thickness that is very light-weight and has a high flexural strength. The interior surface of the walls and ceiling will be constructed of composite gypsum boards with white matt paint finish. The main advantage is the flexibility of connecting the tubular members with different diameters and length at the spherical connectors by means of bolts. (University of Technology Delft, 2010).

Figure 12a: Heyder Aliyev Centre (Designboom, 2013) & Figure 12b: Space frame of Heyder Aliyev Centre (Majid, 2013)

3.3.3 Shipbuilding technology

This option can be seen as a turned inside ship. This is done to use the steel skin as a finishing material on the inside (figure 13). On top of this 10 mm steel plate stiffening ribs are placed, which result in a construction height of 550 mm. The advantage of steel is that it retains shape and in can be made in controlled conditions of a factory. This building method consists of only three operations; the production of the elements, applying of a relatively lightweight support structure and the assembly on-site. This is better in comparison with a lot of operations that have to be made for the concrete alternative. The shipbuilding technology is also a faster method of construction, in this case five months. One of the main advantages of a steel alternative is that all operations, from production until assembly, will be done by one company. This reduces the risk, which is one of the most important factors for the decision of the building method. Another advantage is a light weight construction method compared to concrete. This results that for phase two of the OV-Terminal, the shipbuilding technology is used as main construction method (Cement, 2013).

Figure 13: Inside steel structure of the OV-Terminal (Arnhem Centraal, 2014)

The biggest part of the OV-Terminal that uses the shipbuilding technique is the roof (figure 14a). On top of the steel roof Betopor is poured, which is an insulation material that consists of concrete and EPS grains. Within the betopor wooden blocks with aluminium caps are set to the right height. After that EPDM- roofing is applied on top of the roof. Inside the wooden blocks threaded ends are placed for the attachment of the concrete panels. The combination between the steel structure and the concrete panel's makes the project financially feasible compared to the designed roof that should be casted on-site. Mbx from Bergen op Zoom produces the panels with a flexible mould. The use of a flexible mould is, according to Bjorn van Overveld from Mbx, the only feasible method to produce the panels for a roof of 4500 m². For these elements high pressure concrete is used, because traditional reinforcement is practically not feasible. With 1450 different double curved panels a traditional moulding principle would be unfeasible (Bouwwereld, 2015). Besides the roof also other elements are constructed in steel, such as the twist (figure 14b). This strongly curved element is positioned right in the middle of the hall. Approximately 20% of the weight of the roof will be carried by the twist. In comparison to the roof the steel plates can have a thickness up to 50 mm instead of 10 mm, which is still possible to bend into the right curvature (Cement, 2013).

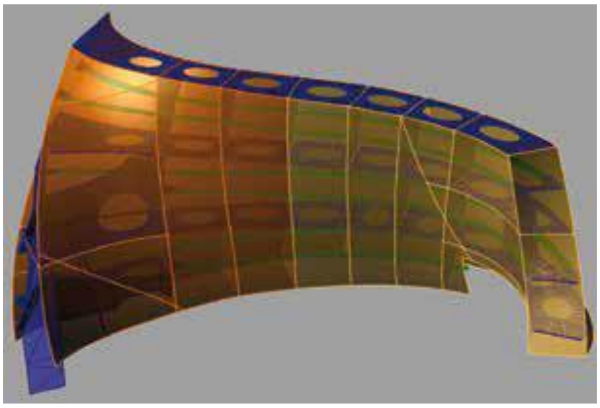


Figure 14a: The roof of the OV-Terminal (Skyscrapercity.com, 2014) & Figure 14b: The twist of the OV-Terminal (Cement, 2013)

Within the connections large horizontal and normal forces occur in different directions, caused by the angle of the joints. The combination of forces ensures that a normal steel plate as connection is not strong enough. The solution is relatively easy, whereby the shipbuilding technology is used. The vertical forces are transferred by a steel plate under the ribs. The horizontal force is transferred through steel brackets between the ribs. After the element is placed into the right position it is casted with concrete up to one meter (figure 15). An advantage of this system is that no anchors are needed to make the connection between the steel and the concrete (Cement, 2013).

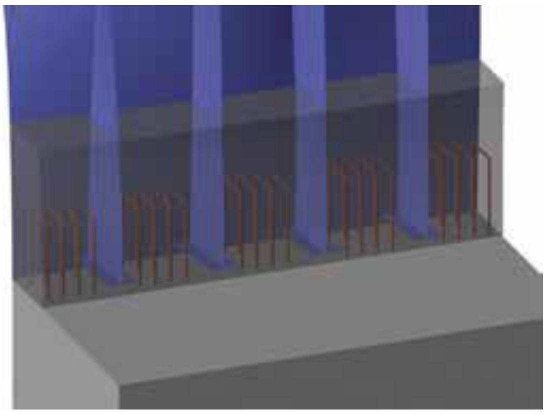


Figure 15: Connection of consisting concrete structure with the steel frame (Cement, 2013)

3.4 Conclusion

The goal of this research was to get understanding about criteria that are important for the contractor, in making a decision for the building method to be used. In this case they had to connect to an existing structure, which influenced the decision. Important for the contractor is that, the building method meets the requirements for the design, it can be built within time schedule and budget and that quality can be guaranteed. To establish that experience and risk management is necessary. In this case study the risk was lowered by making one experienced company, in double curved elements, responsible for the steel construction. Based on those reasons they decided to build the roof out of steel and concrete panels instead of casting concrete onsite. The product design for this project should meet those requirements, as much as possible, to get market potential. For instance prefabricating elements could lower the risk for the contractor. Based on this knowledge, the development of reconfigurable moulding for the production of the double curved elements took our interest and will be the start point for further research. With this system only one mould is needed to produce different double curved elements.

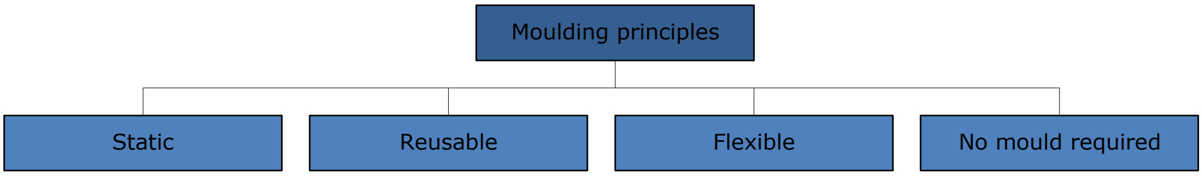
4. Moulding principles

For this research, flexible moulds for Fluid Architecture, it is important to have knowledge about different moulding principles. The definition of a mould according to The American Heritage is (The American Heritage Dictionaries, 2005):

A hollow form or matrix for shaping a fluid or plastic substance.

Moulds are used in different industries, such as: Automotive, Packaging, Buildings or others. The focus of this project is on concrete moulds for the building industry. These moulds can be divided in three categories: static, reusable, flexible and no mould required (diagram 2). The most interesting part is the development in flexible moulds. One of these moulds or a combination can be the starting point of our research.

Diagram 2: Overview moulding principles



4.1 Static moulds

Static moulds are moulds that cannot be deformed. The methods of moulding can only be reused to make several of the same products. Another disadvantage of a static mould is that the production of the mould is labour intensive. At this moment static moulds are the most commonly used moulding techniques. The different types of static moulds will be explained in the next paragraphs.

4.1.1 Timber

At the moment timber is still one of the most used moulding techniques in the building industry and is ideal for single curved moulds. The construction is mainly built up with plywood sheets, timber or metal soldiers and purlins, ties and tie plates. With this method almost every shape can be made. The quality of the shapes can be achieved by using a CNC milling machine, sometimes an additional finish layer is necessary to obtain a smooth surface (figure 16a). The disadvantage will be a more expensive mould. After the support is constructed in the correct shape the plywood can be heated and bended over it, to create the right form. For traditional buildings a timber mould has a good market potential. This is due the repetition of straight and single curved walls, an example is shown in figure 16b. The timber moulds can then be reused. Besides that it has the advantage to be reliable. When repetition is limited and Free Form is used, the labour intensity will increase, because for every element a new mould needs to be fabricated (Schipper & Janssen, Manufacturing Double-Curved Elements in Precast Concrete Using a Flexible Mould, 2011).

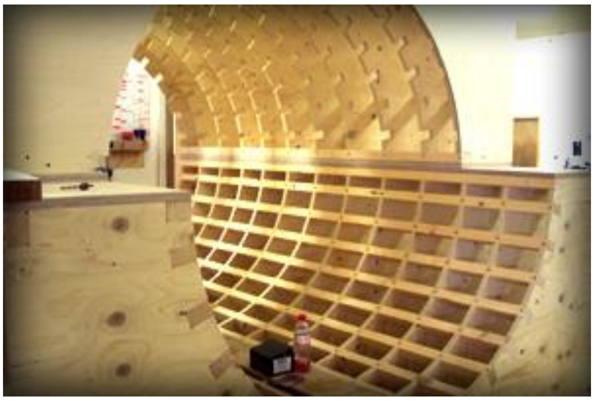



Figure 16a: CNC Milling machine (Direct Industry, 2014) & Figure 16b: Mould for single curved walls (3D Pattern & Mouldmakers Ltd, 2012)

4.1.2 Steel

The construction of a steel mould is more or less the same as a timber mould. The only difference is the production method. For the curving of steel plates more expansive metallurgy machinery is needed. The industry for building ships is specialized in the field of Free form (figure 17a) (Cement, 2013). A disadvantage compared to timber is the price, but it is more durable. This makes it possible to reuse the mould many times (figure 17b). Many precast projects use steel moulds for the highly repetitive elements, often in combination with configurable edges or inserts for customized modifications per element. This makes the system financial feasible. The potential for Fluid architecture could be interesting when it is used as construction material itself, but not as a mould (Schipper & Janssen, Manufacturing Double-Curved Elements in Precast Concrete Using a Flexible Mould, 2011).


Figure 17a: Steel structure from the ship building industry (Skyscrapercity.com, 2014) & Figure 17b: Repetition moulds (MNO Caribbean, n.d.)

4.1.3 CNC foam milling / wire cutting

CNC (Computer Numerical Control) milling is a technique to cut a foam block in a desired form. The material used for milling the mould is most of the time EPS or XPS. The method of milling a foam block makes it possible to create almost every desired form. When the same form is required the mould can be reused. The process becomes expensive when a lot of different mould types are needed. It is possible to reuse the foam block, but most of the time some residues of concrete can be found in the material. The foam block can also be produced into a form by using wire cutting. This system is limited in form. Only surfaces can be produced by a rotating and translating line, the so-called "ruled surface". In figure 18a the EPS formwork is used for the construction of Spencer Dock Bridge and figure 18b shows the application in Der Neu Zollhoff (Schipper & Janssen, Manufacturing Double-Curved Elements in Precast Concrete Using a Flexible Mould, 2011).


Figure 18a: EPS formwork of Spencer Dock Bridge (Huyghe & Schoofs, Precast Double Curved Concrete Panels, 2009) & Figure 18b: EPS fromwork of Der Neue Zollhoff (Janssen, 2011)

4.1.4 Hydrostatic Equilibrium Moulding

Nowadays 3D printing is an upcoming hype. Almost everything can be printed with a 3D printer, such as food, organs and cars. A moulding technique in combination with a 3D printer is at this moment not so much applied. An example of this combination is the moulding principle of Frank Omloo (figure 19a). The idea of his technique is to lowering a 3D printed mould, by putting concrete into a basin of non-hardening slurry (figure 19b). When both fluids are on the same level, the hydrostatic pressure of the fluids ensures that there will be no forces on the wall of the mould. In this way the wall of the mould can be made with a material, such as plastic that is printed with a 3D printer. The advantage of 3D printing is that all shapes can be made, either synclastic as anti-clastic or monoclastic. Another advantage of 3D printing as compared to other static moulds is the low labour intensity. Besides the disadvantage of the low reusability of all static moulds, are the high investment costs of a 3D printer (Omloo, 2014).

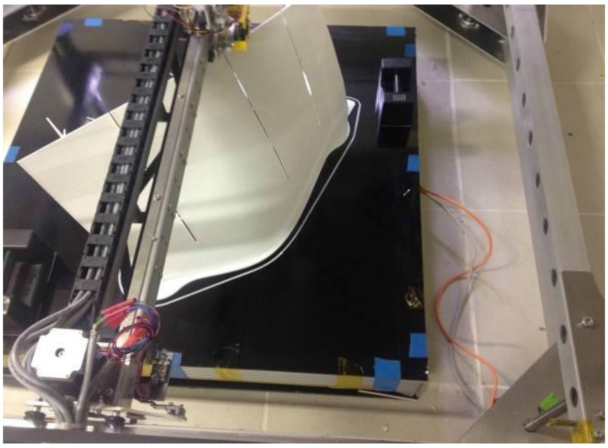


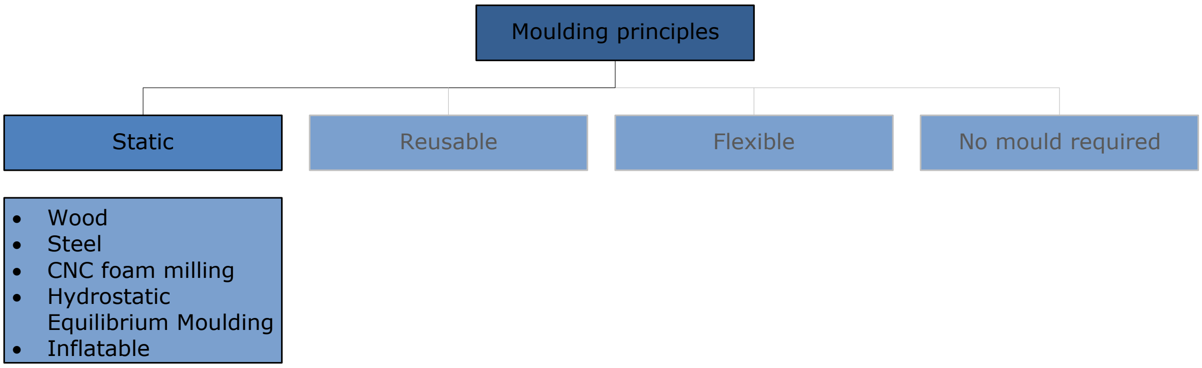

Figure 19a: Printing a mould & Figure 19b: Lowering the 3D printed mould in a basin with slurry (Omloo, 2014)

4.1.5 Inflatable

Another static mould is an inflatable mould. This mould consists of an elastic material, such as textile or a foil, that will be inflated. When the material is inflated it will be covered by a concrete layer. It is also possible to place steel rebar on it to make the concrete shell stronger. The disadvantage of using steel rebar is that the thin inflatable material could easily be damaged. Inflatable moulds are mostly used to make synclastic curvatures. When other forms have to be made the inflatable material has to be separated into different parts. Besides that cutting process is expensive, the weight of the concrete layer has to be controlled. An advantage of this technique is that the formwork can be reused, but still every sheet of the formwork has to be cut down to the right size and mounted together precisely. Examples of this technique are shown in figure 20a and 20b (Huyghe & Schoofs, Precast Double Curved Concrete Panels, 2009).


Figure 20a: Kenway Bridge (Kenway Corporation, 2014) & Figure 20b: Pykretedome of the Eindhoven University of Technology (Van Overbeeke, 2014)

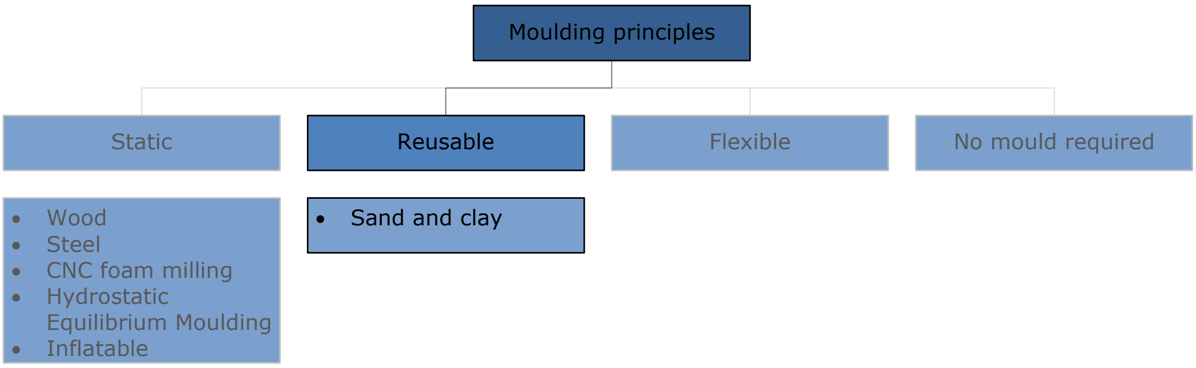
Diagram 3: Scope static moulds



4.2 Reusable moulds

Reusable moulds are moulds that are made of materials that can be reused. The advantage of this type of moulds is that there is no waste material and that means that it is a sustainable principle. The disadvantage of these moulds is the production. It is very labour intensive and in this way it is not competitive with the other moulding techniques. An example of a reusable mould is al mould of sand or clay. This method was mainly used in ancient times (Philips Pavilion), that is the reason that these types of moulding will be not further discussed in this research report.

Diagram 4: Scope reusable moulds



4.3 Flexible moulds

Flexible moulds are according to (Schipper & Janssen, Manufacturing Double-Curved Elements in Precast Concrete Using a Flexible Mould, 2011):

An adjustable formwork consisting of an elastic material that can be formed into the desired curved surface by the use of pistons, actuators, gravity, pin beds or other means.

The advantage of this system is that it can create different shapes with no waste of materials. The disadvantage of the flexible moulds is the high investment costs compared to the static and reusable moulds. The different types of flexible moulds will be explained in the next paragraphs.

4.3.1 Pinbed

The surface of this mould is a high density pinbed on which the desired material can be formed directly. Based on this principle, Sebastian Boers has designed the Fleximold in 2006. The pins of the Fleximold can be adjusted in height to create the right curvature. This will be done by a computer program. After the pins are set in the right position, a plastic sheet is heated and shaped into the mold by air pressure (vacuum forming). By developing the system nowadays the Fleximold could make concrete panels with dimensions of 1x1x0,5 m^3. The advantage of this system is the high accuracy, because the pins are placed close to each other. Another advantage of this moulding technique is that all shapes can be made, either synclastic as anti-clastic or monoclastic. A disadvantage of this system is the high investment costs. This system is therefore mostly used to produce polymer castings for special objects. Examples of forms that can be made with a pinbed are shown in figure 21a and 21b (Boers, Snel en efficiënt fabriceren met flexibele FlexiMould-mal, 2012).

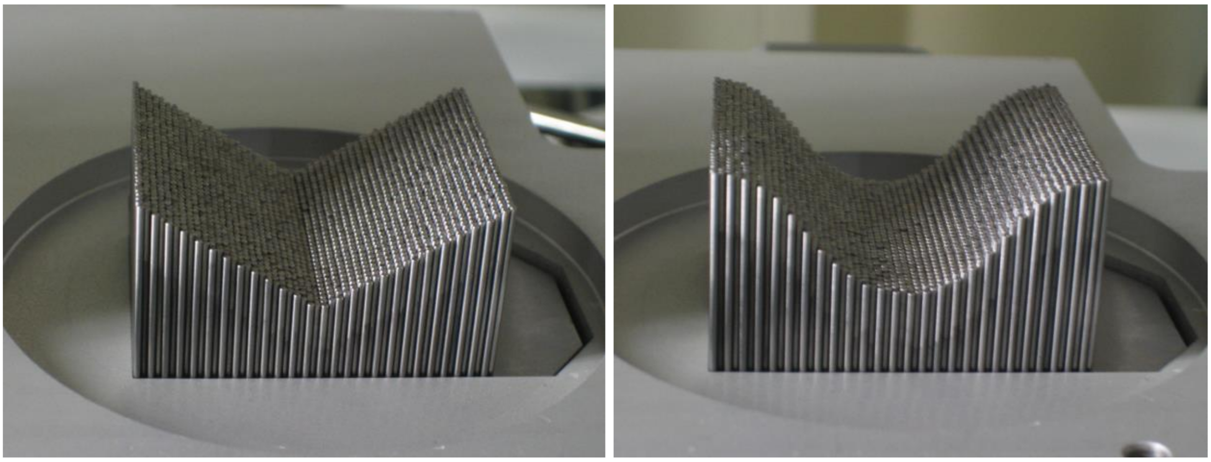


Figure 21a: Example of a pinbed with an angler form & Figure 21b: Example of a pinbed with a round form (Boers, FlexiMold, n.d.)

4.3.2 Supported membrane

The supported membrane principal is a combination of the pinbed system with an intermediate membrane on top of it. As already mentioned, consists the pinbed out of actuators which can be set in place for the right curvature. An advantage of this system is that there are less actuators needed in comparison with the pinbed system. The intermediate layer is fixed on top of the pinbed to create a smooth surface for the prefabricated concrete element. The choice of the stiffness or elasticity of the intermediate layer depends on the amount of curvature that is needed. How smaller the radius the thinner and more flexible the material needs to be. The market potential for this system is focused on panels for the building industry. The pinbed system is a more precise mould, which can be used for packaging or other detailed products. The panels can be produced in almost every curvature, while the intensity and size depends on how the mould is constructed (Gard, 2013).

Flex-rod system

The mould of Rietbergen and Vollers is built for double curved glass panels (figure 22a & 22b). The adjustable mould consists of four parts: base, sheet supports for the rods, lifting system with two main resting bars, and mould surface rods. The surface of the mould is defined by CNC cut plates, connected to the base frame. This system is made of stainless steel, to minimize weight and easy transport. To create different forms the CNC sheets need to be exchanged, the other parts of the mould can be reused. In the next phase of their research a flexible surface on computer driven actuators was created, which will decrease the manufacturing costs. This mould can also be used for concrete panels. The casting takes place in the horizontal position. When the yield strength is high enough it can be set in position. This system makes it possible to control the thickness of the element (Vollers & Rietbergen, 2007).

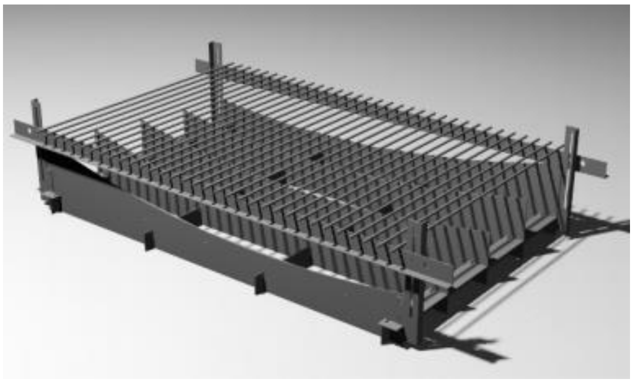
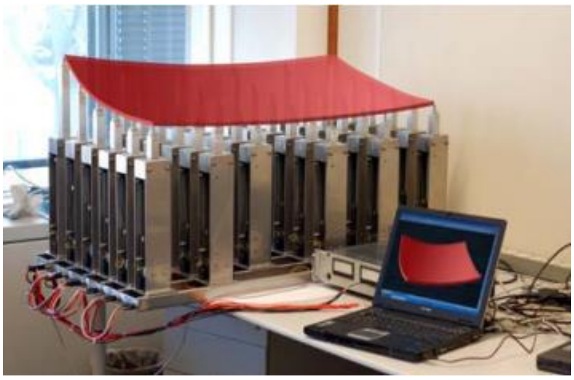
 

Figure 22a: A 3D model of the Flex-rod system & Figure 22b: The computerized version of the Flex-rod system (Vollers & Rietbergen, 2007)

Fabric Formwork system

The system of Rob Verhaegh is based on hydrostatic pressure (figure 23a). The pressure is used to set a fabric into the right curvature. The mould consists out of three parts; a bottom mould, middle mould and a top mould. The concrete panel is casted between the two fabrics and the edges of the middle mould. The counter pressure is realized by filling the bottom mould with water. By releasing the water, the fabric is pulled into the desired shape. Until now this mould can only make convex shapes, which seems to be not very flexible. This flexibility can be found in adjusting the intensity of the mould. The thickness of the segment will be approximately the same over the whole segment; this is done by adding sand in the top mould to divide the concrete. The idea behind the total system is to connect the constructed shapes to create more complex shapes. This method can also be used as a mould for construction elements on-site. The main advantage of this system is the perfect surface quality created with the bottom mould (figure 23b) (Verhaegh, 2010).

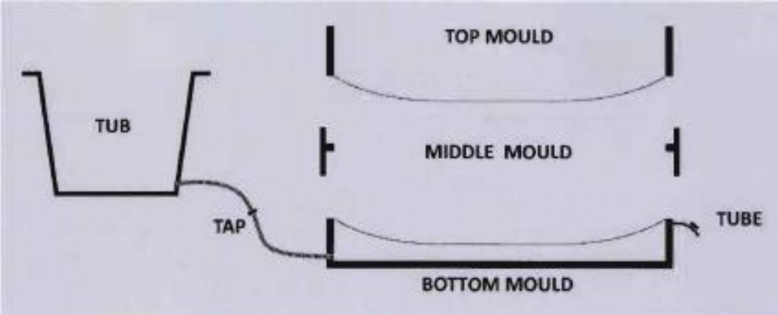


Figure 23a: Fabric Formwork system & Figure 23b: The perfect surface quality of an element (Verhaegh, 2010)

Zero Waste Free-Form Formwork

This mould is designed for use on the construction site of complex buildings. The form of the mould is realized with reusable wax, which can achieve the necessary strength and stiffness required for concrete casting when hardened (Figure 24a & 24b). For this process the reusable wax is used to create a counter mould, constructed with a reconfigurable mould made out of spaced actuators and a rubber top layer. The back of the counter mould is flat and will be fixed to a standard support structure on-site. Two oppositely placed wax moulds can be used to cast concrete on-site. The wax elements are inexpensive in comparison to other Free Form formwork inlays and the wax material is fully reusable. The wax can be shaped into any form, which makes it a good competitive solution for nowadays static in-situ mould techniques (Oesterle, Mirjan, & Vansteenkiste, 2012).

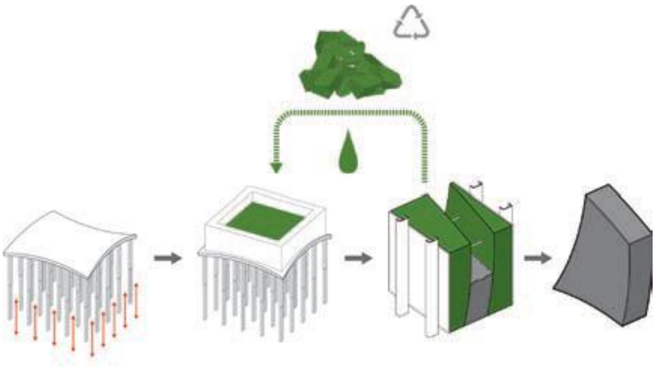
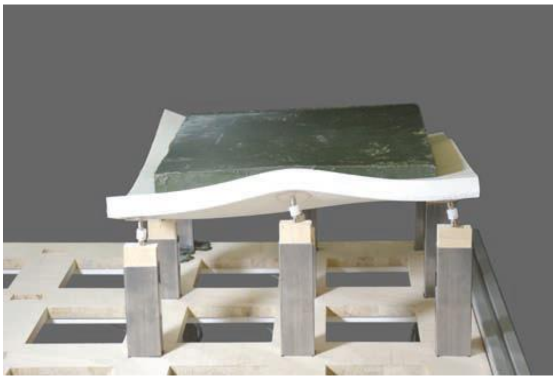



Figure 24a: Waste-free wax formwork process cycle & Figure 24b: Formed wax element on mold (Oesterle, Mirjan, & Vansteenkiste, 2012)

Flexible mould

The designed mould of Schipper uses a flexible membrane that is supported by actuators placed in a certain grid (figure 25a). On top of the membrane a flexible silicone foam, constructed to the form of the element, is placed. The goal of this flexible silicone foam is easy to deform into the curvature that is needed. The first step in the process for creating a double curved element, is to fill the rubber frame with self-compacting concrete (SCC), when it is positioned horizontally. Fibres or textiles can be used as reinforcement. During a short period of structural build-up, the yield strength of concrete increases. Then the mould will be carefully positioned into the right position. The positioning is realized by a ‘flex-rod’ system in combination with weights. In this designed shape the concrete will harden and can finally be demoulded (figure 25b). The mould can be reused to construct other elements, which increases the market potential for this system (Schipper, Grünewald, Eigenraam, Raghunath, & Kok, 2014).


Figure 25a: The principle of the moulding technique (Schipper, Grünewald, Eigenraam, Raghunath, & Kok, 2014) & Figure 25b: Poured concrete on the flexible mould (Janssen, 2011)

4.3.3 Tensioned membrane

In contrast to the supported membrane the actuators of a tensioned membrane are only positioned at the edges of the mould. A top and bottom frame clamp the tensioned membrane for creating a double curved surface. It is also possible to manipulate the membrane by using inflatables. There are two types of moulding principles that are based on a tensioned membrane, namely the E-Mould by Schinkel and Van Rooij and the Flexible Mould by Gard. These two principles will be explained in the next paragraphs.

E-Mould

The E-Mould consists of a tensioned textile membrane which is shaped by manually setting the actuators and by pushing inflatables into the textile membrane (figure 26a). The actuators are positioned on top and on the bottom of the membrane. Next the membrane will be pre-tensioned. This ensures the progressive flowing form of the membrane. Without the use of inflatables, only anticlastic shapes can be made. This mould is made for the production of polyester panels with a low cost method (figure 26b). The advantage of this system in contrast to supported membrane moulds is the amount of actuators. This means that the investment costs are much lower compared to a mould with a supported membrane (Schinkel & Van Rooij, 2009).

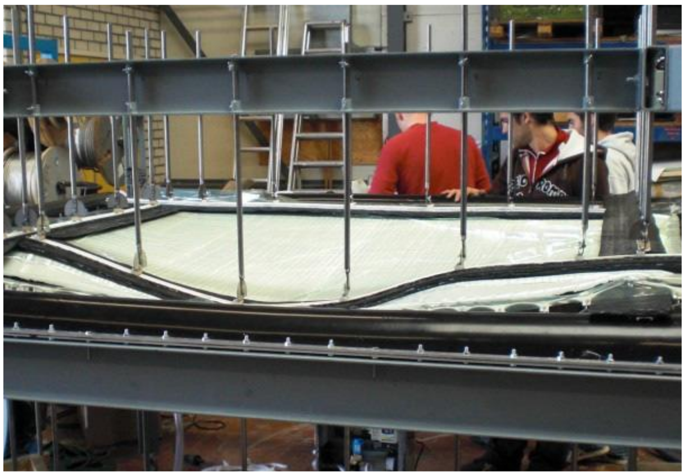
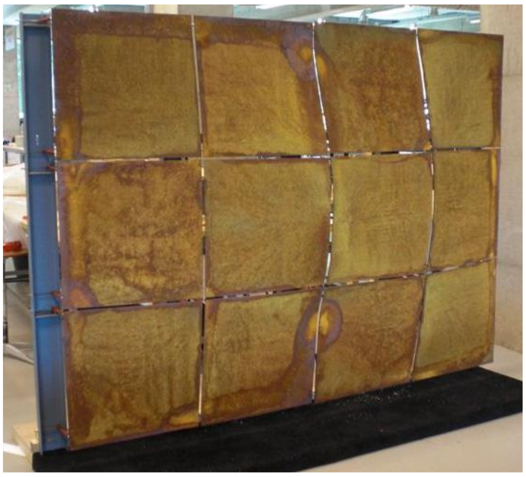



Figure 26a: The E-Mould & Figure 26b: Panels that are made with the E-Mould (Schinkel & Van Rooij, 2009)

Flexible mould

Fritz Gard designed a flexible mould in 2013 that is based on the principle of the E-Mould by Schinkel and Van Rooij. This technique focuses mainly on the edge connection of the panels to obtain a fluid transition. The similarities with the E-Mould are the actuators that are used on the edges and to manipulate the membrane pre-tension is used (figure 27a & 27b). The difference between the flexible mould of Gard with the E-Mould is that the membrane of the mould is replaced by a thermoplastic. When the thermoplastic is fixed on the edges the membrane will be heated up in an oven. The advantage of this technique is the same as the E-Mould, namely the investment costs are lower compared to a mould with a supported membrane (Gard, 2013).

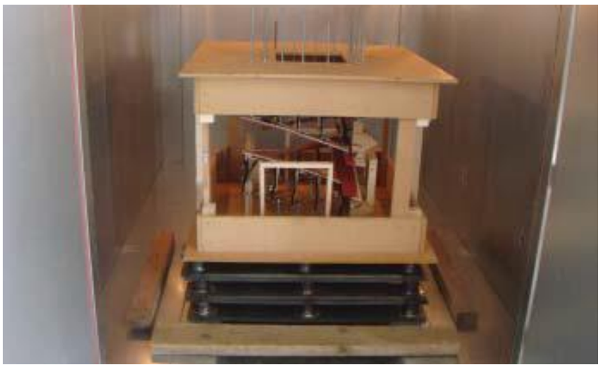


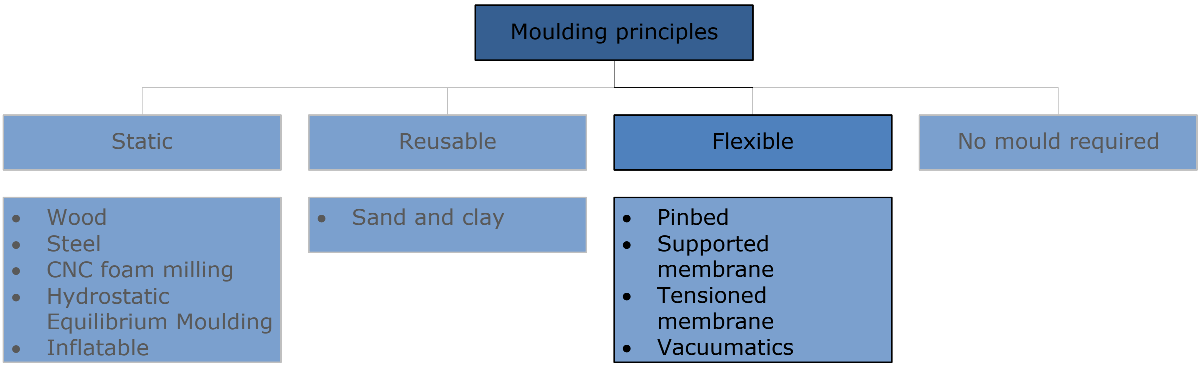

Figure 27a: Prototype of the Flexible Mould & Figure 27b: The actuators of the Flexible Mould (Gard, 2013)

4.3.4 Vacuumatics

Vacuumatics is designed by Frank Huijben in 2012. His technique is based on the principle of enclosed structural filler elements (granules) that utilises atmospheric pressure as a rigidifying tool by extracting the air within the foils (vacuum pulling) (figure 28a). Once the bag has been formed in the desired shape, vacuum will be drawn. The filler elements will be compressed and secured into the right position, leading to a fixed shape with strength, stiffness and consistency. The advantage of this technique are the low investment costs. A disadvantage of this technique is the form freedom. At this moment the only shape that can be made are arches. Another disadvantage is that the bag can only be shaped by hand and not with a computer program. In this way it is difficult to create the right shape that is designed with a computer program. Figure 28b shows a concrete element that is made with the technique of Frank Huijben (Huijben, n.d.).

Figure 28a: The principle of Vacuumatics & Figure 28b: A concrete element that is made with the technique of Vacuumatics (Huijben, n.d.)

Diagram 5: Scope flexible moulds

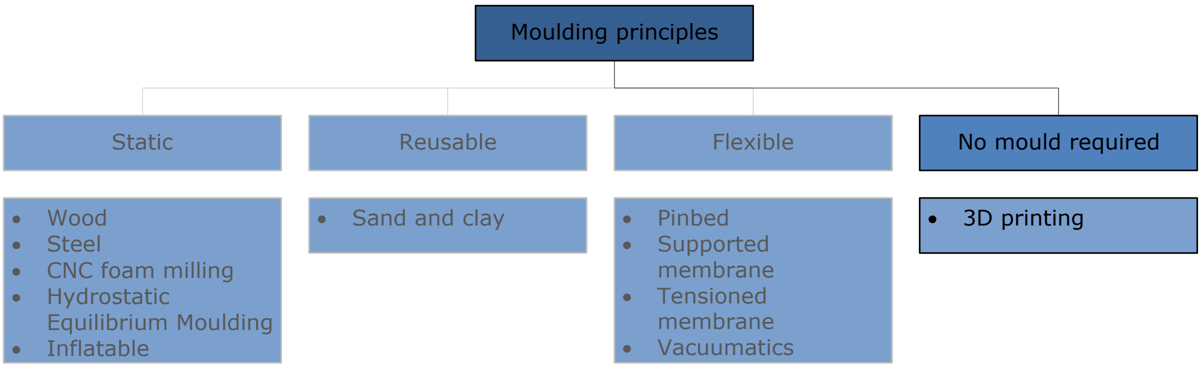


4.4 No mould required

A new upcoming moulding principle of the last years is the principle were no mould is needed. An example of this moulding principle is 3D printing. As mentioned earlier 3D printing is nowadays a popular technique. It is even possible to build a complete house in just one day with a 3D printer based on X-, Y- and Z-axis (figure 29a & 29b). On a cleared and levelled site, workers would lay down two rails a few feet further apart than the eventual building's width and a computer-controlled contour crafter would take over from there. A gantry-type crane with a hanging nozzle and a components-placing arm would travel along the rails. The nozzle would spit out concrete in layers to create hollow walls, and then fill in the walls with additional concrete (Discover, 2005). The advantage of this system, besides the production speed, is the form freedom and the accuracy. The disadvantage of this system is the surface quality, because the concrete layers that are printed with the 3D printer are visible.

Figure 29a & Figure 29b: 3D printing of a house (VOBN, 2015) (Kelin Koerkamp, 2014)

Diagram 6: Scope no mould required



5. The combination of vacuum forming and hydrostatic pressure

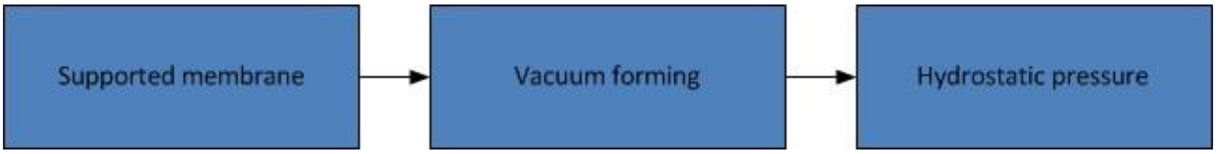
This research, about reconfigurable moulding for concrete elements, makes use of vacuum forming and hydrostatic pressure as basic principles for the production of double curved elements. The idea behind these two basic principles is:

- To separate the casting process from the flexible mould, with the goal to improve the production time;
- To use a plastic sheet to guarantee an optimal surface quality;
- To pour vertical with counter pressure to realise a smooth surface on both sides.

This production process is based on the literature of Sebastiaan Boers, Henry Kleespies and Richard H. Craford and Frank Omloo.

The first step in the production process is setting the supported membrane in the right curvature. The designed shape will be obtained through vacuum forming of thermoplastic sheets over the supported membrane. These sheets are used as a counter mould for the production of the concrete elements. To overcome deflections during the casting of concrete, hydrostatic pressure with the same density is used. When the concrete is cured the element can be demoulded. Diagram 7 shows an overview of the production process. The goal is to optimize this process and limit the deformations according to the design.

Diagram 7: Production process



5.1 Vacuum forming

Vacuum forming is one of the most common methods of processing plastic materials. It is a process used to manufacture a wide range of products from simple packaging trays to high impact aircraft cockpit covers. It is also used extensively to make design prototypes of products to be produced by other processes (Formech International Ltd, n.d.). The definition of vacuum forming is according to (Collins, 2014):

A process in which a sheet of warmed thermoplastic is shaped by placing it in a mould and applying suction.

The materials that can be vacuum formed are the following plastics: ABS (Acrylonitrile Butadiene Styrene), PC (Polycarbonate), PE (Polyethylene), PETG (Polyethylene Terephthalate Glycol), PMMA (Polymethylmethacrylate), PS (Polystyrene), PP (Polypropylene) & PVC (Polyvinyl Chloride) (Formech International Ltd, n.d.).

Types of moulds

The most used materials of moulds for vacuum forming are: wood, aluminium and synthetic resin (figure 30a, 30b & 30c). The choice of the mould material depends on the desired end product and the proposed batch size. Moulds of wood (MDF) are most of the time used for making of prototypes. A mould of synthetic resin is a cost-effective solution for a small batch. While an aluminium mould will be usually used for larger and recurring batches. The moulds will be produced with a CNC milling machine (Akaplast Thermoforming, n.d.).

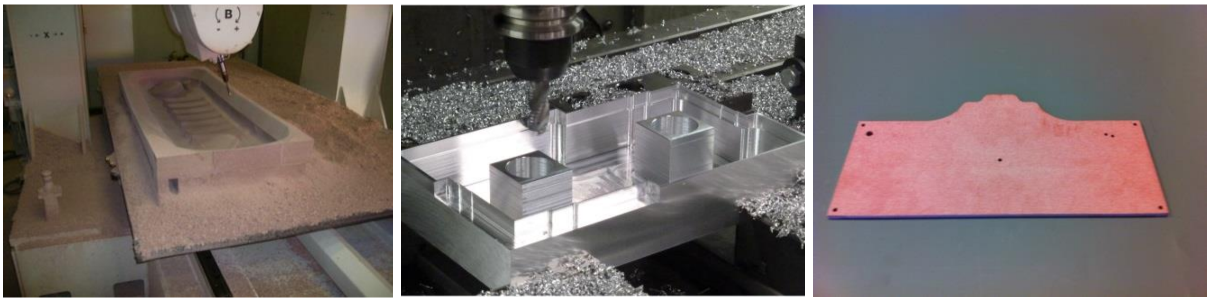


Figure 30a: A wooden mould (Van Leeuwen Modelmakerij, n.d.), Figure 30b: An aluminium mould (Machinefabriek De Wilde, 2011) & Figure 30c: A mould of synthetic resin (Schreinemacher Kunststoffen B.V., 2014)

5.1.1 Process of vacuum forming

The process of vacuum forming takes a few seconds with a thin sheet and a couple of minutes when using thicker sheets. In figure 31 an example of a vacuum forming machine is illustrated. After the shape is vacuum formed, the shape has to be finished into the right form. There are different ways to do this, namely: cutting, milling, stamping, bending and gluing. In the following figures the process of vacuum forming will be explained (Agulon Kunststoffen, n.d.).

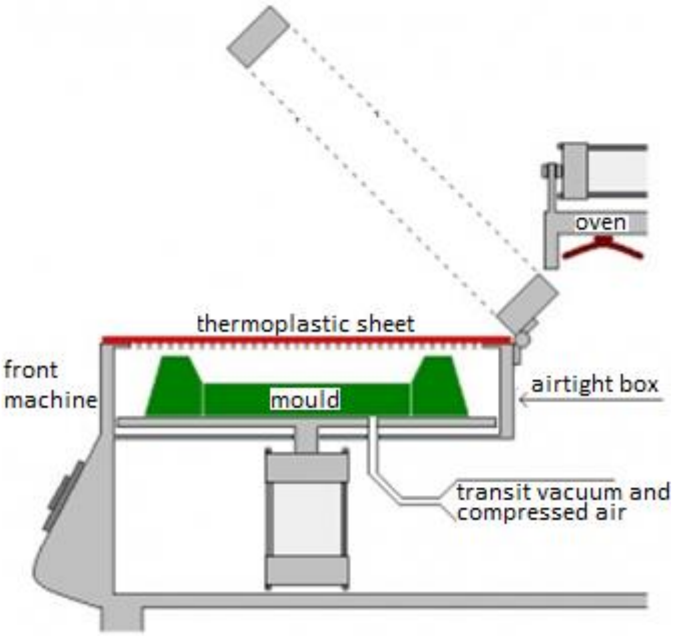


Figure 31: An example of a vacuum forming machine (Agulon Kunststoffen, n.d.)

First the mould is placed in the vacuum forming machine. After that the thermoplastic sheet will be closed airtight with a clamping frame (figure 32a). Then, the oven will be placed above the thermoplastic sheet and heated until the processing temperature is reached (figure 32b). When the oven is removed above the thermoplastic sheet, the sheet will be blown spherical (figure 32c) (Agulon Kunststoffen, n.d.).

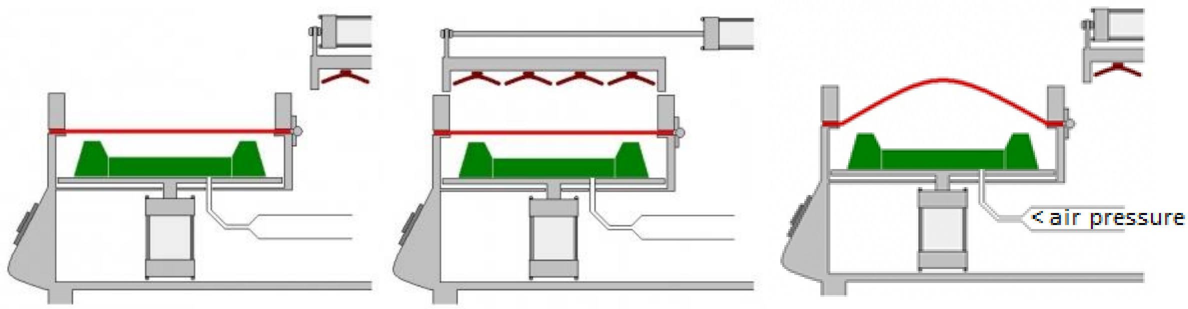


Figure 32a: The mould and the thermoplastic sheet is placed in the vacuum forming machine, Figure 32b: The sheet will be heated up & Figure 32c: The sheet is blown spherical (Agulon Kunststoffen, n.d.)

Then, the mould will be pressed in the hot plastically sheet (figure 33a). After that the air between the thermoplastic sheet and the mould will be vacuumed (figure 33b). The shape that is obtained will be cooled. This will be done by blowing air above the shape and/or by water cooling in the mould. When the vacuum formed shape is cooled down, the shape will be released by blowing air pressure in the box (figure 33c) (Agulon Kunststoffen, n.d.).

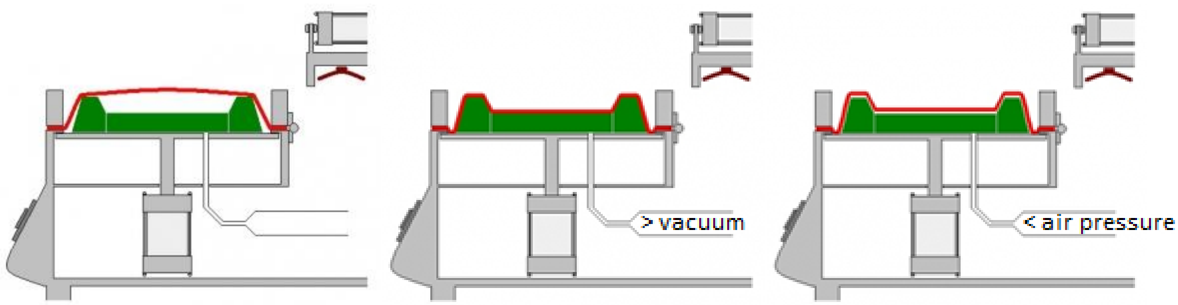


Figure 33a: The mould will be pressed in the sheet, Figure 33b: The sheet will be vacuumed on the mould & Figure 33c: The shape will be released by blowing air (Agulon Kunststoffen, n.d.)

When the mould is loose of the shape, the mould will be placed down (figure 34a). The clamping frame can be opened and the vacuum formed shape can be taken out of the vacuum forming machine (figure 34b) (Agulon Kunststoffen, n.d.).

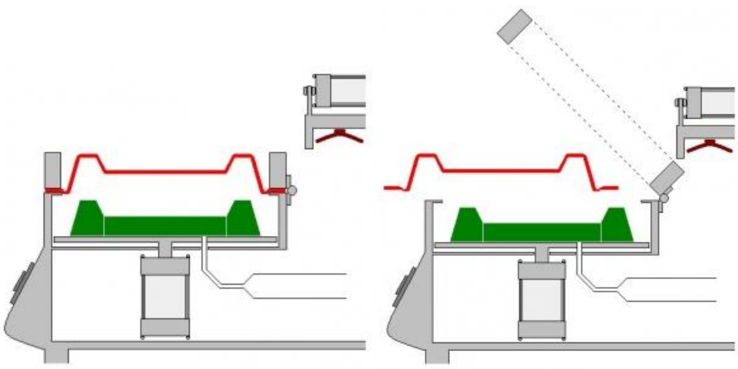


Figure 34a: The mould is placed down & Figure 34b: The vacuum formed shape can be taken out (Agulon Kunststoffen, n.d.)

5.1.2 Pinbed

The Fleximould of Sebastiaan Boers is a reconfigurable mould for small scale customized products (figure 35). The pinbed system sets every actuator (pin) at the exact height according to the digital information. All the actuators together create a solid form. When the shape is set into place, it can be vacuum formed. This idea is similar to the production process used in this research. The only difference is that the actuators in this research are supported with a membrane. The advantage is that less actuators are needed, which results in more space between the actuators. The fact that the mould of this system is not solid for vacuum forming could be a problem and should be investigated (Boers, Snel en efficiënt fabriceren met flexibele FlexiMould-mal, 2012).

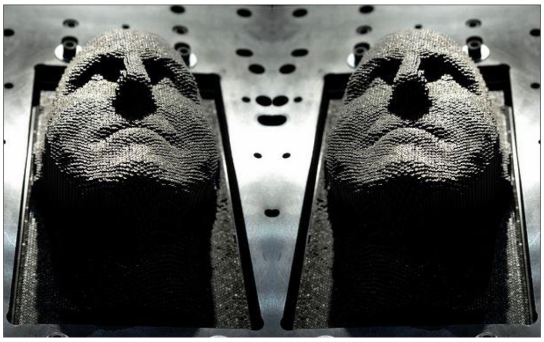


Figure 35: Small scale customized products (Jan Laugs, n.d.)

5.1.3 Supported membrane

In Texas they also studied vacuum forming of compound curved surfaces with a variable geometry mould. This study is focused on a method for producing prototypes of compound curved surfaces with a variable configuration vacuum forming mould composed of a number of discrete pins and a rubber interpolation sheet. This system is nearly the system that will be used in this research only on small scale. In Texas they mentioned rapid prototyping with a variable geometry vacuum forming mould as a feasible process, but with limitation of surface smoothness and achievable curvatures. It is important to understand which factors are involved or need to be controlled to create a smooth surface within the limitations for a particular project. In figure 36a and 36b the construction principle of the reconfigurable mould based on vacuum forming is shown (Kleespies & Crawford, 1998).

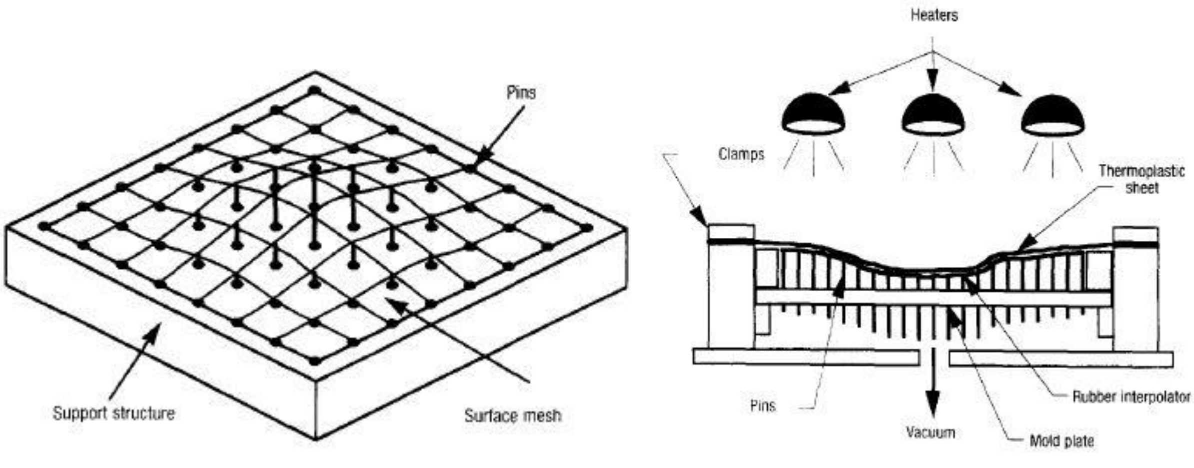


Figure 36a: 3D overview of the reconfigurable mould & Figure 36b: Section of the reconfigurable mould (Kleespies & Crawford, 1998)

The inspiration for this mould is on PinArt and Impressions, that uses a pin screen concept to reproduce three dimensional images. The mould for this research is constructed as a vacuum forming box. This machine consists of a vacuum forming plenum that houses the mould plate and adjustable mould pins. The pins (actuators) are covered with an elastic rubber interpolation sheet that provides the forming surface for a thermoplastic sheet. Radiant heaters above the vacuum box soften a thermoplastic sheet to allow vacuum forming onto the rubber surface.

During the vacuum cycle, atmospheric pressure pushes the hot thermoplastic onto the rubber sheet and down to the mould pins. The thermoplastic sheet is then cooled in the desired shape. The dimensions of these pins and the set up are quite small, 43 mm long, 1.1 mm in diameter, and spaced at 2.5 mm. The rubber membrane is 1.1 mm thick. The rubber sheet is used to prevent the pin tips from contacting the mould plastic. The result after vacuum forming was a surface that displayed a rough or bumpy appearance similar to a golf ball. This effect is given by a range of design and process parameters (Kleespies & Crawford, 1998):

- Pin diameter (D)
- Pin spacing (b)
- Forming pressure (P)
- Interpolation sheet thickness (t)
- Interpolator stiffness (E)
- Pin shape.

When these parameters can be controlled vacuum forming with a supported membrane of spaced pins or actuators can be feasible as a part of the production process for a concrete element. The mould in Texas shows a pinbed with pins that are placed very close to each other. The resulting roughness of the surface is represented with the parameter waviness as shown in figure 37a. The waviness is very small and cannot be seen with the naked eye. The waviness for our project could be a bigger problem, because the spacing between the actuators is around 100-150 mm instead of 2.5 mm. To solve this problem the already discussed parameters should be adjusted.

In this case it is important to make the interpolating layer stiffer. This can be realized with for instance a steel mesh. Adjustment of the air pressure will also be an important factor. In figure 37b results of changing parameters for the reconfigurable vacuum mould of Texas are shown. This plot represents thickness-to-span ratios with curves for different ratios. The thickness ratios range from thin (1/20) to borderline thin (1/10), to very thick (1/5 an 1/3). The vertical axis are determined by reasonable values for the vacuum forming pressure of 0,069 Mpa and the stiffness of a soft rubber (2.76 Mpa). The horizontal axis is determined by a deflection-to-span ratio. From the plot it can be concluded which effect the changing of different factors has on the deflection of the membrane. For instance a thick and stiff sheet can be set under higher pressure with less deformation than a thin sheet that is less stiff. If for our project the waviness is too high, it is necessary to create a counter pressure with for instance water, air or oil. The advantage of the research in Texas is the fact that it gives understanding about the possibilities of vacuum forming with a reconfigurable mould (Kleespies & Crawford, 1998).

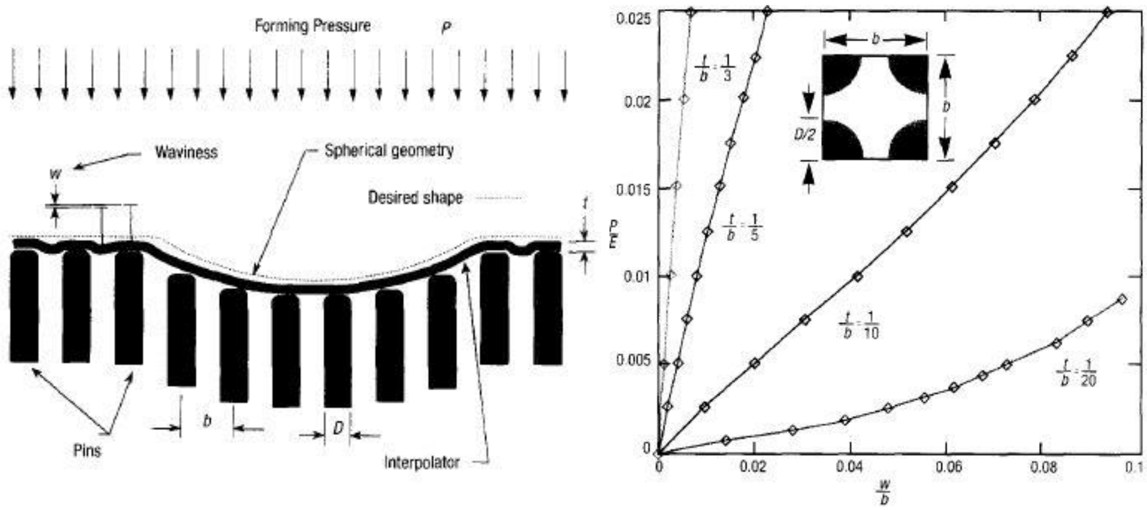


Figure 37a: The resulting roughness of the surface & Figure 37b: Results of changing parameters for the reconfigurable vacuum mould (Kleespies & Crawford, 1998)

5.2 Hydrostatic Pressure

The next step in the production process is based on hydrostatic pressure. The definition of hydrostatic pressure is according to (The American Heritage Dictionaries, 2005):

The pressure exerted by a fluid at equilibrium at a given point within the fluid, due to the force of gravity. Hydrostatic pressure increases in proportion to depth measured from the surface because of the increasing weight of fluid exerting downward force from above.

In figure 38 an example is illustrated of the principle of hydrostatic pressure. One of the main functions of traditional formwork is that it can stand the hydrostatic pressure of wet concrete. This hydrostatic pressure will be managed by a thick plywood on a wooden or steel framework. One of the disadvantages of these materials is that they are inflexible. With the hydrostatic moulding technique the withstanding of the hydrostatic pressure of the concrete will be arranged by a fluid (Omloo, 2014). Hydrostatic Equilibrium Moulding by Frank Omloo is based on this principle and will be explained in the next paragraph.

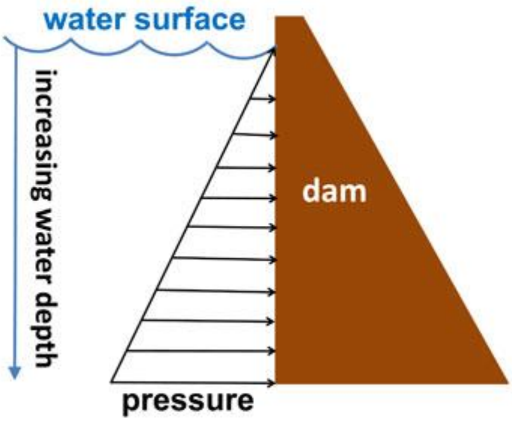


Figure 38: An example of the working of hydrostatic pressure of a dam (Teachenengineering, 2014)

5.2.1 Hydrostatic Equilibrium Moulding

The Hydrostatic Equilibrium Moulding technique of Frank Omloo is based on the Pascal's Law. The definition of this law confirm (The American Heritage Dictionaries, 2005) is:

The principle is that external static pressure exerted on a fluid is distributed evenly throughout the fluid. Differences in static pressure within a fluid thus arise only from sources within the fluid (such as the fluid's own weight, as in the case of atmospheric pressure).

In case of the technique by Frank Omloo, there is a fluid of wet concrete and a fluid of non-hardening slurry. Both fluids have the same density, fluid column height and viscous characteristics. The idea of the technique is to lowering a mould into a basin of non-hardening slurry. By lowering the mould in the basin the level of the concrete and the level of the non-hardening slurry will be equalized. The mould separates the wet concrete from the non-hardening slurry. By the hydrostatic pressure of both fluids there will be no forces on this wall. Hereby the thickness of the wall can be reduced (Omloo, 2014).

Fabrication method

Because of the opportunity of reducing the thickness of the mould, the material of the mould does not have to consist of wood or steel. And when other materials can be applied there will be also new methods of fabrication. Frank Omloo has chosen for 3D printing as fabrication method. The reason for this fabrication method is that 3D printing is suitable when dimensioning gets complicated and building tolerances become narrow. For example, when an architect has designed a building with double curved concrete elements (Omloo, 2014). The definition of 3D printing confirm (BusinessDictionary.com, 2014) is:

The manufacturing of a three-dimensional product from a computer-driven digital model. This process is additive, where multiple layers from CAD (computer-aided design) drawings are laid down one after another to create different shapes.

The material that is 3D printed by Frank Omloo is Polylactic Acid. Polylactic Acid is according to (Techopedia, 2014):

Polylactic acid is primarily created using renewable or green sources such as sugar cane, starch and corn. As a result, it can easily be recycled. It is used in most additive manufacturing processes that design 3-D models and prototypes through plastic-based materials. In fused deposition modelling (FDM) technology, the molten polymer filament, which is extruded from the controller nozzle, is polylactic acid.

This means that when using Polylactic Acid as a mould it has the potential of a waste free fabrication.

Experimental shell

Frank Omloo has produced a model based on the design of el Colegio en Monesterio (figure 39). El Colegio en Monesterio is designed by the Spanish architect Justo Garcia Rubio (Justo Garcia Rubio. Architects., 2011). This architect is well known with Free Form architecture. El Colegio en Monesterio consist of several double curved concrete elements.

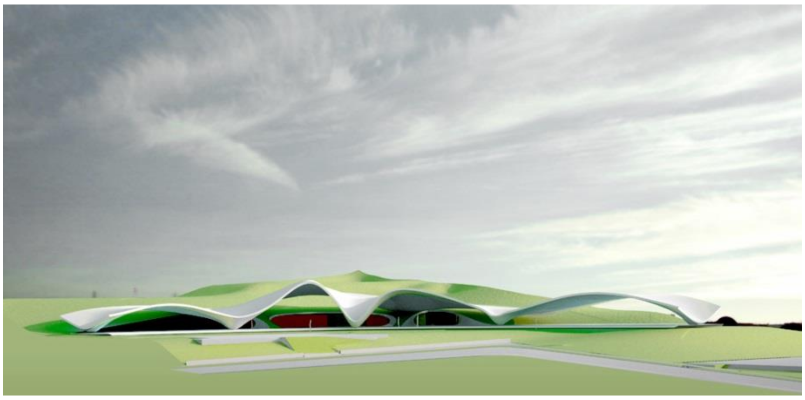


Figure 39: El Colegio en Monesterio (Justo Garcia Rubio. Architects., 2011)

The experimental shell of Frank Omloo is divided into eight pieces and has the following dimensions: length 2.7 m, the span between the supports is about 2m, the width varying from 0.9 m to 1.6 m (figure 40). The maximum height of the shell is 0.5 m. Besides that the shell has three supporting points. The different segments will be assembled on-site with bolted connections. The advantage of this way of assembling is that it is demountable (Omloo, 2014).

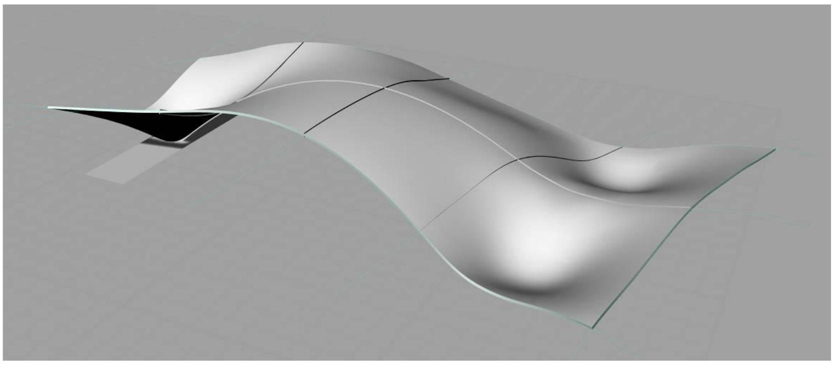


Figure 40: 3D model of the experimental shell (Omloo, 2014)

From modeling to production

The modeling of the separate pieces of el Colegio en Monesterio is done with the designing program Rhinoceros (figure 41). This program is ideal for making models with double curved elements. When the model is made in Rhinoceros it is put in the program Slic3r. Slic3r is a tool to convert a digital 3D model into printing instructions for a 3D printer. It cuts the model into horizontal layers, generates tool paths to fill them and calculates the amount of material to be extruded (Slic3r, 2014).

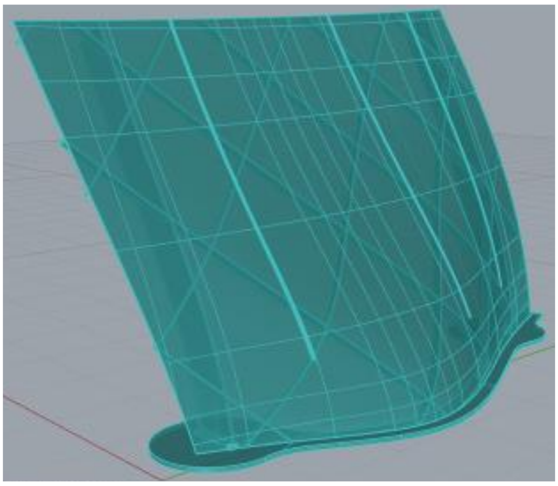


Figure 41: 3D model of a piece of el Colegio en Monesterio (Omloo, 2014)

When the modelling was finished it was printed with a BigRepOne 3D-printer (figure 42). For printing of the mould the Polylactic Acid has to be heated up till 190 °C. During this printing some problems occur. One of the problems is shrinking. This means that the dimensional accuracy was lost. Another thing was that after cooling the element was deflecting, because it became under tensional stress. These two problems were in the end solved by introducing vertical dilations into the shell of the mould. In this way the shrinkage and the deflections were acceptable. The vertical edges of the mould must be firmly positioned settled by reinforcing the edges with flanges (Omloo, 2014).

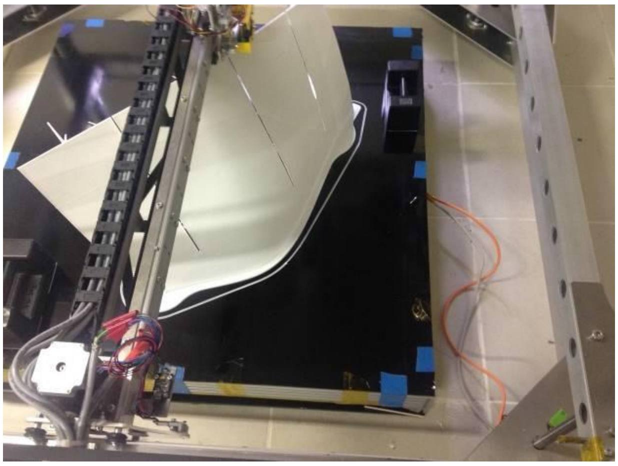


Figure 42: 3D printing of the mould (Omloo, 2014)

Pouring concrete

After the 3D printer had printed the mould the process of pouring concrete could start. Very soon it became clear that the mould was not watertight, because small parts of the cavity were filled with slurry. This problem was solved by pouring concrete in the mould before it was dipped in the basin with slurry. This ensures that the slurry does not enter the mould. The concrete that was used for this mould has a gravity of 2000 kg/m^3. Because both fluids must have the same properties, the slurry was matched with this gravity.

Besides that it is important during the pouring that both levels are on the same height. This guaranties that the mould does not deflect, because the pressure is zero on the thin 3D printed walls.

Frank Omloo indicated at the outside of the mould the inside volume levels for equalizing the liquid levels (figure 43) (Omloo, 2014).

Figure 43: Indication of the volume levels (Omloo, 2014)

For accelerating the hardening process of the concrete the slurry basin was preheated up to 35 °C. When the mould was filled with concrete it had to stay in the slurry basin for twelve hours. After that the mould could be lifted out of the basin. The hardening process then continues another twelve hours, until the concrete could be demoulded. After demoulding the printed surface was visible in the surface of the concrete. This is in the end solved by a surface lining of a thin latex sheeting. Frank Omloo has chosen for latex, because it is an elastic material. Whereby it is an ideal material to cover the leaving folds on the surface. The result of two poured concrete elements is shown in figure 44 (Omloo, 2014).

Figure 44: The result of two poured concrete elements (Omloo, 2014)

Conclusions

This research technique of Frank Omloo has some interesting starting points. The combination of the hydrostatic pressure of a fluid with a mould with thin walls has some opportunities. One of those opportunities is pouring vertically. In this way it is possible to create complete walls for buildings, when the process is scaled up. Besides the advantages there are also some problems. One of the problems is the surface quality of the concrete by the 3D printed walls, this could be solved by using another technique than 3D printing. Besides the surface quality 3D printing is also an expensive way of fabrication of a mould. There are perhaps opportunities to control the process of pouring concrete. At this moment the shape cannot be controlled (Omloo, 2014).

6. Plan of approach

In this chapter the plan of approach will be explained based on the following parts: problem description, research objective, research questions, research strategy, assumptions, preconditions.

6.1 Problem description

With the rise of the computer programs (CAD) it became possible to design complex double curved elements. With the computer programs it is easy to create a 3D design of a curved element. The designing is not the problem in this case, but converting this model into a building element certainly is. There is a demand for more efficient production methods that meets this new form of design.

Buildings with curved elements are not a new phenomenon. For example in 1958 the National Congress was built in Brasilia. This National Congress was designed by the architect Oscar Niemeyer. The fabrication of the concrete shell was built on a temporary support formwork. This was a labour intensive construction method. However, the fabrications costs were not high. This is because the wages of the Brazilian workers were very low. In this time the fabrication costs are more expensive, because the minimal wages of workers are higher than around 1958.

Nowadays there are also other production methods, like CNC (Computerized Numerical Control) foam milling. This method is used in the Heydar Aliyev Center in Baku, Azerbaijan (figure 45). The production and the costs of the fabrication of CNC foam milling are competitive with the fabrication of a timber or steel framework. This is because the labour intensity is lower. But even then, it is only competitive when it is used several times. In case of double curved elements this does not occur very often. Another disadvantage of the CNC technique is that it creates a lot of waste (Gard, 2013).

Within this research a competitive mould for CNC foam milling is investigated. Important factors will be reconfigurable and a fast production process.

Figure 45: Construction of the Heydar Aliyev Center in Baku, Azerbaijan (Skyscrapercity.com, 2010)

6.2 Research objective

With this research a solution for the production of double curved elements will be investigated. One panel can be seen in (figure 46). The goal is to improve a hydrostatic mould, with a vacuum pulled sheet, to produce panels for a façade. The main focus is to implement the panels on the building site. The elements will be made with a reconfigurable mould. This is necessary to avoid the problem of repetition that was required to save costs in existing moulding principles.

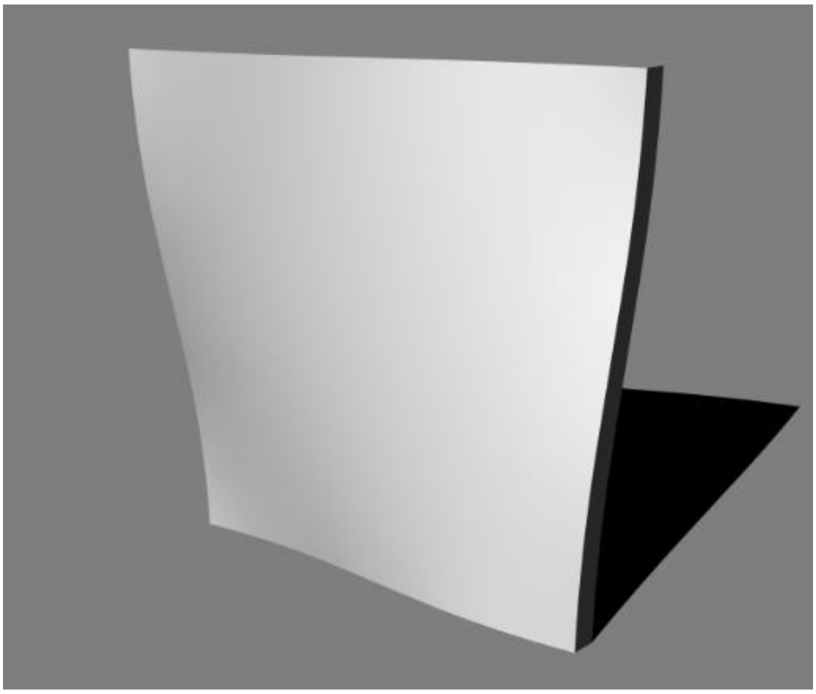


Figure 46: Double curved façade panel

6.3 Research questions

On the occasion of the research objective the following main question is formulated:

Can a double curved concrete panel, made with a reconfigurable mould based on vacuum forming in combination with hydrostatic pressure, compete with existing moulding techniques?

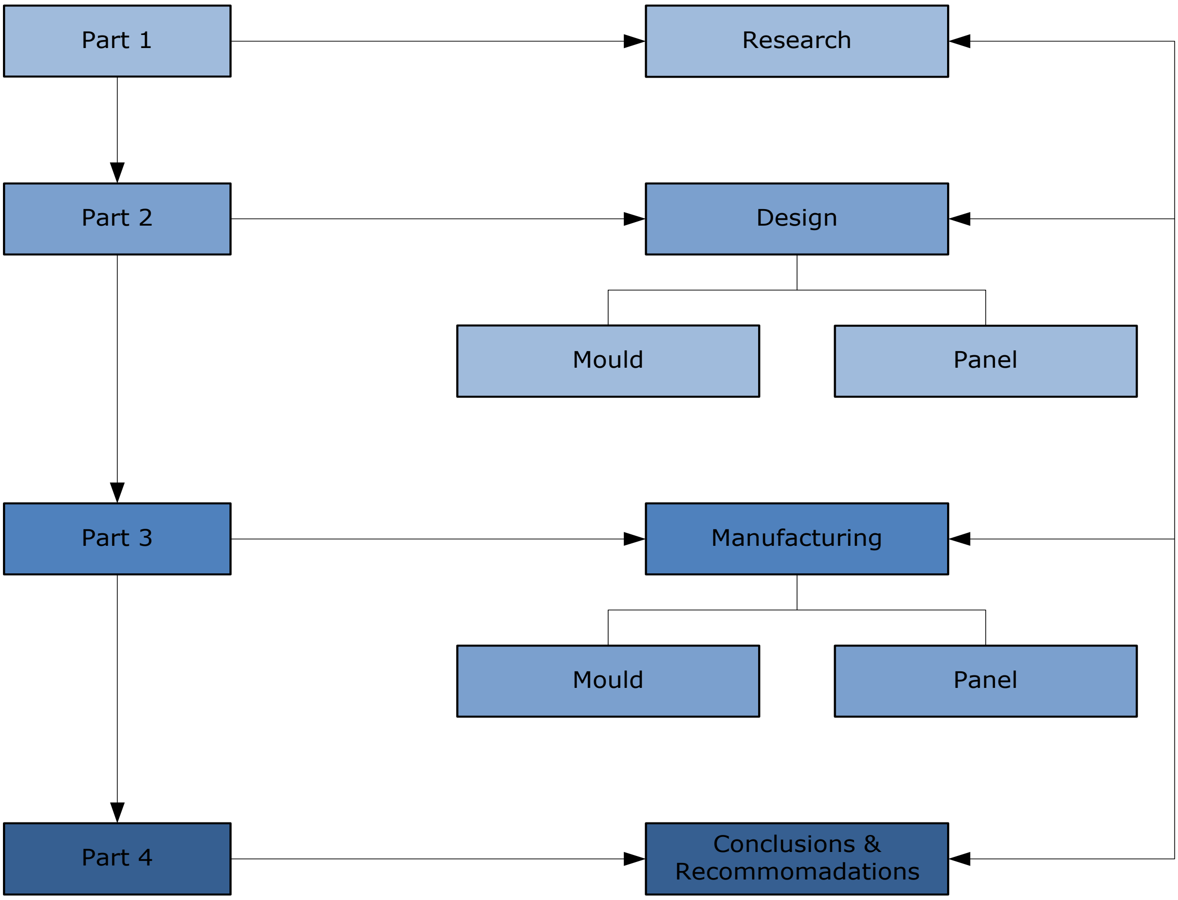
To answer this main question, the following sub-questions are formulated:

- Can the separation of the casting process and the flexible mould be an improvement to a faster production process?
- Can a plastic sheet guarantee a good surface quality?
- What are the limitations in form by using this moulding technique?
- How can a façade panel be produced within the tolerances of the design?
- What are the future possibilities of the VaCo Mould?

6.4 Research strategy

The research can be divided in four parts; below diagram 8 shows the components. Part 1 focuses on the research of the process and investigates aspects related to the production process. In this phase also experiments for the improvement of the moulding principle will be done. Part 2 contains the designing process of the mould and the facade. In part 3 the manufacturing of the mould and facade will be elaborated. Part 4 will give a conclusion and recommendations of the end result.

Diagram 8: Research strategy



6.5 Assumptions & preconditions

For this graduation project it is important to bring research, done in reconfigurable moulding principles, into real practise. This means: design or improve a moulding principle and produce façade panels. The preconditions to reach this goal are that a mould with a flexible membrane of 500x500mm is designed and will be used for the production of vacuum pulled sheets. These sheets are used in a moulding principle, which creates hydrostatic pressure on both sides when concrete is casted in between. When this production method is optimized, double curved panels can be realized within the restricted dimensions of the so far produced flexible mould. The focus in the production of the façade panels is based on building technology rather then on construction technology.

7. Vacuum forming

This chapter describes the research phase of vacuum forming. Based on different experiments at the university of Eindhoven and at Bas Hesselink IDAP. The question is if it is possible to produce a plastic sheet, which smoothly follows the curvature of a reconfigurable spring steel mesh. The research in Texas showed that with small spaces of 2,5 mm waviness still exists, but it cannot be seen with the naked eye. This problem could be solved with larger pin diameters, changing the pressure or a stiffer interpolation sheet.

7.1 Material

In paragraph 5.1 "Vacuum Forming" the plastics, that are suitable for vacuum forming, are listed. These materials were: ABS (Acrylonitrile Butadiene Styrene), PC (Polycarbonate), PE (Polyethylene), PETG (Polyethylene Terephthalate Glycol), PMMA (Polymethylmethacrylate), PS (Polystyrene), PP (Polypropylene) & PVC (Polyvinyl Chloride). In this paragraph the different plastics will be compared with each other and one plastic will be chosen for the experiments of vacuum forming.

7.1.1 General

In general plastics can be divided in two groups, namely: thermoset and thermoplastic (figure 47). A thermosetting plastic is a plastic that relating to a compound that softens when initially heated, but hardens permanently once it has cooled. Thermosetting materials are made of long-chain polymers that cross-link with each other after they have been heated, rendering the substance permanently hard (The American Heritage Dictionaries, 2005). Thermoplastic materials are materials that have the property of softening repeatedly when heated and hardening once cooled. Thermoplastics also have what is known as a 'memory' enabling a formed part to revert to its original state when reheated (Formech International Ltd, n.d.). Because thermosetting materials are not suitable for vacuum forming, the further part of the research will be concentrated at thermoplastics.

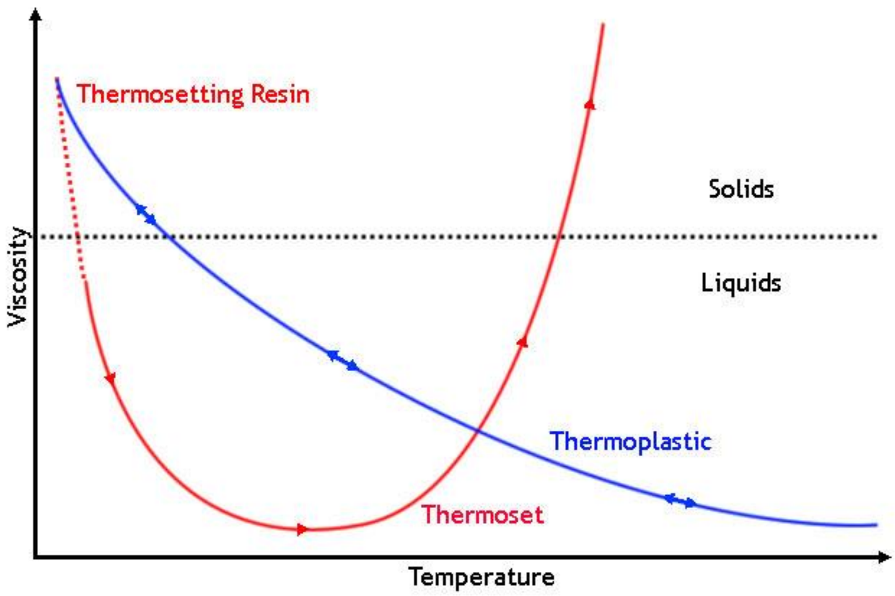


Figure 47: The difference in viscosity between thermoset and thermoplastic (+Composites, 2014)

7.1.2 Thermoplastics

The thermoplastics can also be divided into two groups: amorphous and crystalline. Amorphous thermoplastics are easier to vacuum form as they do not have such a critical forming temperature. When heat is applied amorphous materials become soft and pliable (Glass Transition Temperature (Tg)) (figure 48). If heated to a higher temperature it reaches a Viscous state (Tv). The changes occur over a range of temperatures and enable the operator to have a fairly wide forming range. Amorphous thermoplastics are: ABS, PC, PETG, PMMA, PS and PVC (Formech International Ltd, n.d.).

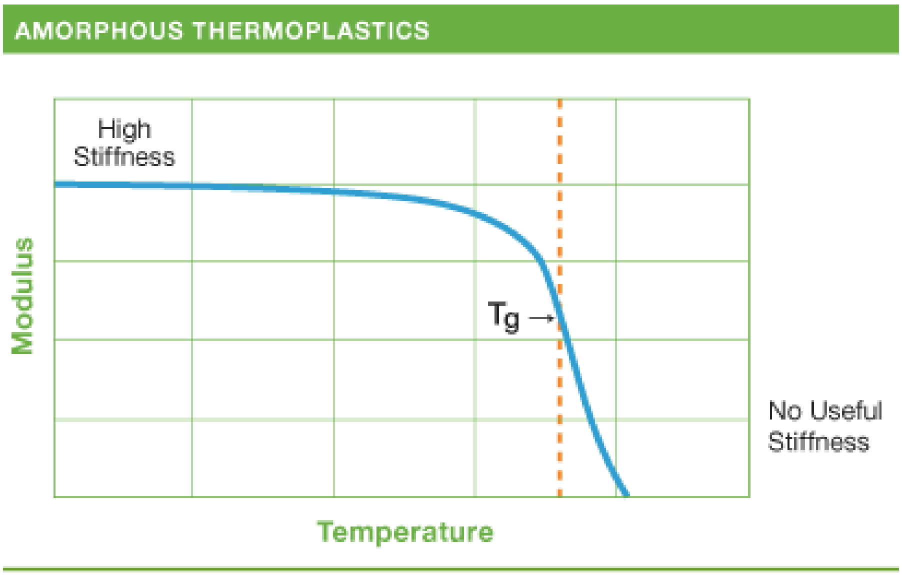


Figure 48: The change of the modulus for amorphous thermoplastics when the temperature changes (Solvay Plastics, 2015)

ABS (Acrylonitrile Butadiene Styrene)

Hard, rigid amorphous thermoplastic with good impact strength and weather resistance. It contains a rubber content which gives it an improved impact resistance. Available with different textures and finishes in a range of thickness. Needs drying. Available in Fire Retardant and UV stabilised grades. The glass transition temperature of ABS is 88-120 °C The applications of ABS are: Luggage, Caravan Parts, Vehicular Parts, Sanitary Parts, Electrical Enclosures (Formech International Ltd, n.d.).

PC (Polycarbonate)

Hard, rigid clear amorphous material with high impact resistance and good fire rating. Self-extinguishing. Requires high forming temperatures. Needs drying. Excellent clarity. The glass transition temperature of PC is 150 °C. The applications of PC are: Light diffusers, Signs, Machine Guards, Aircraft trim, Skylights, Riot Shields, Guards and Visors (Formech International Ltd, n.d.).

PETG (Polyethylene Terephthalate Glycol)

An easy forming amorphous thermoplastic. FDA approved for food applications. Optically very good with excellent fabricating performance. Thermoforms with ease utilising low temperatures and fast cycle times. Can be sterilised and is resilient to a wide range of acid oils and alcohols. Not recommended for use with highly alkaline solutions. The glass transition temperature of PETG is 80 °C. The applications of PETG are: Point of Sale and Displays, Medical Applications (Formech International Ltd, n.d.).

PMMA (Polymethylmethacrylate)

A high quality hard amorphous plastic with good clarity that can be worked after forming. Only extruded sheet is suitable for vacuum forming effectively. Cast PMMA will not respond well as it displays a very small usable plastic zone. As a result it will only produce general contours with large drape radii. Needs drying. The glass transition temperature of PMMA is 105 °C. The applications of PMMA are: Signs, Roof Lights and Domes, Baths and Sanitary Ware, Light Diffusers (Formech International Ltd, n.d.).

PS (Polystyrene)

One of the most widely used materials. An easy forming amorphous thermoplastic. Thermoforms with ease utilising low temperatures and fast cycle times. Available with different textures and patterns. No pre drying required. Poor UV resistance and not suitable for outdoor applications. The glass transition temperature of PS is 94 °C. The applications of PS are: Low cost and disposable items, toys and models, packaging and presentation, displays (Formech International Ltd, n.d.).

PVC (Polyvinyl Chloride)

Strong, tough thermoplastic with good transparency in thinner gauges. Good chemical and fire retardant properties. Highly resistant to solvents. Thicker materials are rigid with good impact strength ideally suited to outdoor industrial applications. The glass transition temperature of PVC is 105 °C. The applications of PVC are: Packaging, Machine Guards and Car Trim (Formech International Ltd, n.d.).

Semi-crystalline and Crystalline thermoplastics have a far more critical forming temperature as they go rapidly from the Tg state to Tv, a change known as the Melt Transition Temperature (Tm) (figure 49). When using crystalline materials is imperative that accurate temperature control is used to monitor the heating process. Crystalline thermoplastics are: PE and PP (Formech International Ltd, n.d.).

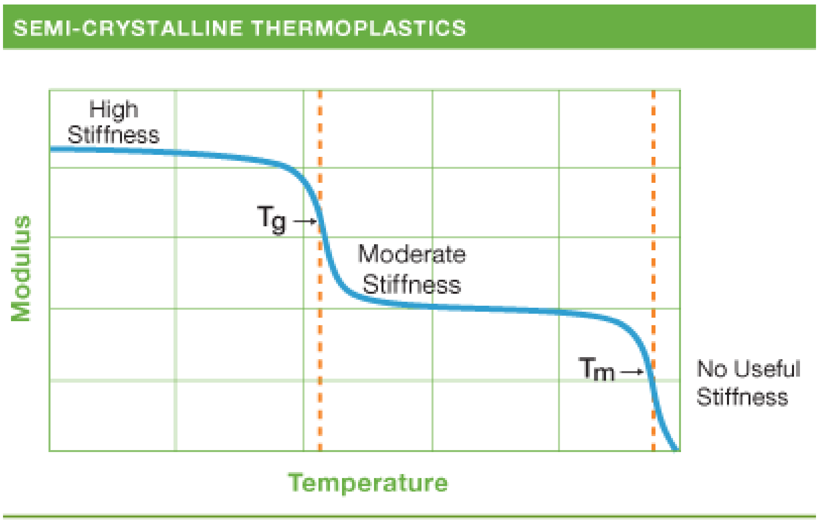


Figure 49: The change of the modulus for semi-crystalline thermoplastics when temperature changes (Solvay Plastics, 2015)

PE (Polyethylene)

PE is a semi-crystalline thermoplastic that has a good heat control with sheet level required for successful forming. High shrinkage rates but good chemical resistance and strength. Available also as a cross linked closed cell foam. The glass transition temperature of PE is 125 °C. The applications of PE are: Caravan Parts, Vehicular Parts, Enclosures and Housings (Formech International Ltd, n.d.).

PP (Polypropylene)

PP is a semi-crystalline thermoplastic which has difficult form characteristics with sheet sag inevitable. Chemically inert and very flexible with minimum moisture absorption make it suitable for a wide range of applications. High forming temperature but no drying required. Many grades of PP are available containing fillers and additives. Co-polymer as opposed to homo-polymer PP is recommended for vacuum forming, as the copolymerisation process helps reduce stiffness and broaden the melt and glass transition temperatures increasing thermoforming ability. The glass transition temperature of PE is 5 °C. The applications of PP are: Luggage, Food Containers, Toys, Enclosures, Medical Applications, Chemical Tanks (Formech International Ltd, n.d.).

7.1.3 Criteria

To make the right decision, for the plastic sheet, a comparison can be made between the different plastics. This comparison will be based on six criteria, namely: formability, hygroscopic, finishing, strength, shrinkage and price. The most important criteria is formability. Formability is how easy the plastic sheet will be formed on the mould. Hygroscopic is that plastic sheets absorb moisture which if not pre-dried prior to forming will result in moisture blisters which will pit the surface of the sheet resulting in a reject part (Formech International Ltd, n.d.). Finishing is how easy the material can be edited with machines. Strength and shrinkage are how strong the material is and if the plastic shrinks. End at last the price if the material is cheap or expensive.

Each plastic will be rated with scores as follows: 2 = very good, 1 = good, 0 = medium, -1 = bad and -2 = very bad. At the end all scores will be added together and the plastic sheet with the highest score is the best material for the vacuum forming process.

7.1.4 Conclusion

In the comparison scores of diagram 9 there are three plastics that meet our requirements, namely: PE, PETG and PS. All three plastics have a total score of five . The formability is the most important criteria of the comparison, that's why the choice will be made between PETG and PS. The plastics PETG and PS do not differ much. PETG scores better on the criteria strength and shrinkage, but PS on the other hand is cheaper than PETG. Because the material PETG is available in the workplace of the Eindhoven University of Technology the choice was easy to make. So for the experiments PETG is chosen as the material.

Diagram 9: Comparison of thermoplastics

	Formability	Hygroscopic	Strength	Shrinkage	Finishing	Price	Total
ABS	1	-1	1	0	1	0	2
PC	1	-1	2	0	1	-1	2
PE	-1	1	2	1	1	1	5
PETG	2	1	1	1	1	-1	5
PMMA	-1	-1	0	0	-1	-1	-4
PS	2	1	0	0	1	1	5
PP	-1	1	2	-1	1	1	3
PVC	0	1	1	0	1	1	4

7.2 Vacuum forming machine – Eindhoven University of Technology

In paragraph 5.1 of the literature study about vacuum forming the process is described in genaral. The next step of the research is to get more experience with vacuum forming. This will be done by experiments performed with the vacuum forming machine of Eindhoven University of Technology. The goal of the experiments is to produce a PETG sheet that smoothly follows the surface curvature of a spring steel mesh with a silicon layer.

7.2.1 Process

The fabrication of the co-polyester plate can be divided in the realization of the mould and the vacuum process. For the mould a steel mesh (spring steel) is set into place with two fixation points on a wooden plate. The open spaces underneath the edges of the membrane will be supported with wood plates. To avoid that the structure of the spring steel is printed into the co-polyester plate it is covered with silicone (figure 50a). The experiments will be done with the vacuum forming machine of Eindhoven University of Technology. This vacuum forming machine is the 686 of the German company Formech (figure 50b).

Figure 50a: Spring steel mesh in a silicon layer & Figure 50b: The Formech 686 vacuum forming machine (Scouten Group, 2015)

7.2.2 Results

The first result of the experiment is the deformation of the form. The wooden support was pushed to the outside and the spring steel was pushed downwards, which resulted in large deformation according to the original mould design (figure 51a & figure 51b). This problem can be solved if the pressure of the vacuum forming machine can be controlled.. The vacuum machine that was used in the workspace did not have this function. Another result of the experiment is that every irregularity will be seen in the PETG sheet. For example the silicone did not fully cover the spring steel, which is directly noticeable in the sheet. On the other places the results of the PETG sheet were quite smooth. The complete experiment can be found in Appendix B, Experiment 1.1: Vacuum forming machine – Eindhoven University of Technology.

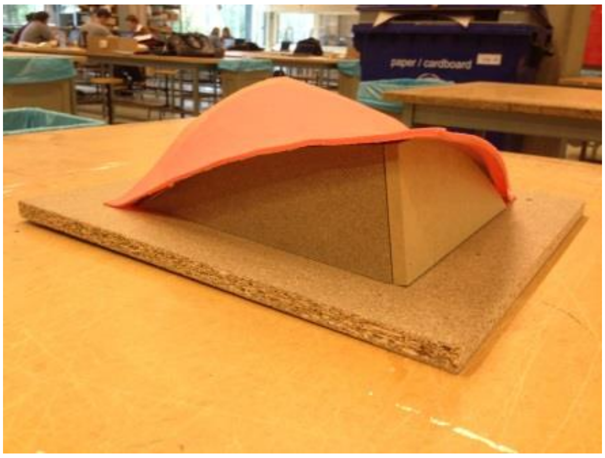


Figure 51a: The form before vacuum forming & Figure 51b: The form after vacuum forming

To ensure that the spring steel, with the silicon top layer, will not deform, sand will be used in the second experiment. The sand will be placed between the wooden edges under the spring steel (figure 52a). The result of the mould after vacuum forming was better than experiment 1. Because there was sand under the spring steel, the PETG sheet was not pulled down to the ground. In this way the form was gradually, such as the edges of the wooden plates (figure 52b). At one end there where some bubbles. This could be because there was some sand underneath, because the sand was not completely closed off. The complete experiment can be found in Appendix B, Experiment 1.2: Vacuum forming machine – Eindhoven University of Technology.

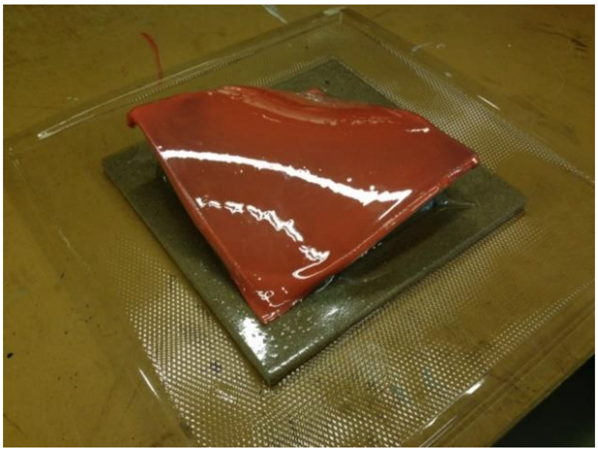


Figure 52a: Supported by sand & Figure 52b: No deformation

7.3 Vacuum forming machine – Bas Hesselink IDAP

The experiments with the vacuum forming machine of the University show that the pressure of the machine was too high for making the right curvature without any support. The supposition is that if the pressure is adjustable the right curvature can be reached without supporting sand. With this thought several companies were approached with the question if they have a vacuum forming machine that can adapt the pressure. Mr. Hesselink of the company Bas Hesselink IDAP responded positive. Beginning of January an appointment was made to do some experiments. The goal of these experiments was to produce a 1 mm PETG sheet that smoothly follows the surface curvature.

7.3.1 Process

The vacuum forming machine of Bas Hesselink IDAP is made by the company itself (figure 53a). The process of vacuum forming is the same as described in paragraph 5.1.1 (Process of vacuum forming). The difference between that process and the process at Bas Hesselink IDAP is that they use a buffer tank to control the pressure (figure 53b). The heating time of the PETG sheet at the experiment was 2.50 minutes. When the PETG sheet was heated up, the sheet was blown up to create more material. After that the mould was pressed into the PETG sheet and the pressure is controlled by the buffer tank. By releasing air bit by bit, the sheet is smoothly pulled down on the mould.


Figure 53a: Vacuum forming machine of Bas Hesselink IDAP & Figure 53b: Buffertank to control the pressure

7.3.2 Results

The result of the experiment is that changing the pressure worked well. The span of 30 cm was no problem and did not deform (figure 54a). The pressure used for vacuum forming this co-polyester sheet was approximately 0,1 bar. This means that no vacuum was used. The silicone of the membrane resulted in a smooth surface (figure 54b). The only disadvantage is that the PETG sheet could not be moved again when it came in contact with the membrane. This problem could be solved by using felt instead of silicone. The complete experiment can be found in Appendix B, Experiment 2.1: Vacuum forming machine – Bas Hesselink IDAP.


Figure 54a: No deformation & Figure 54b: Smooth surface

7.3.3 Validation

The validation of the vacuum forming process is done with Autodesk's 123D Catch and CloudCompare. First 70 pictures are made around the PETG sheet and the silicone mould to create a 3D scan of the objects. Within 123D Catch the scale of both objects is set to 1:1. For both scans excess material is removed, with the goal that only the surfaces can be compared to each other. For the accuracy of 123D Catch there is an average error of 0.8 mm in the x and y-direction, and an average error of 0.9 mm in the z-direction (Van Rijbroek & Verboord, 2015). After the surfaces are correctly scanned, both surfaces can be loaded into CloudCompare. In this program the two surfaces can be seen as point clouds, which can be compared. The two surfaces are presented together to compare the variation in dimension. From figure 55 it can be concluded that the highest difference in distance can be found at the corners and the centre of the PETG-sheet. The extreme value of 24,44 mm on the edge of the sheet is not part of the surface that is needed. This point, consisting of overhang steel mesh, is bended downwards due to the under pressure. The deformation in the middle is not more than 8 mm, which is quite good for a span of 30 cm. When more pins are used the deformations will be less, but the mould will be more expensive.

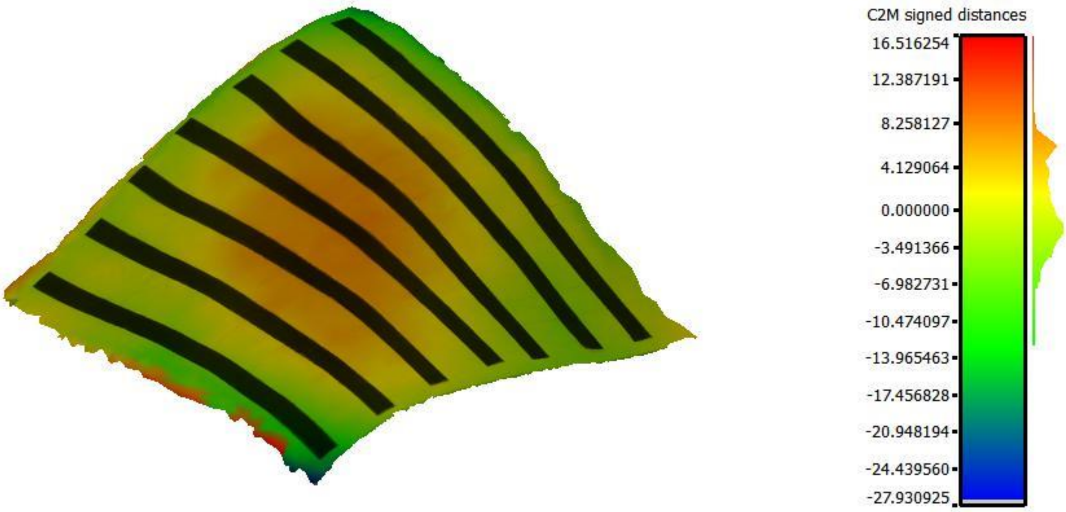
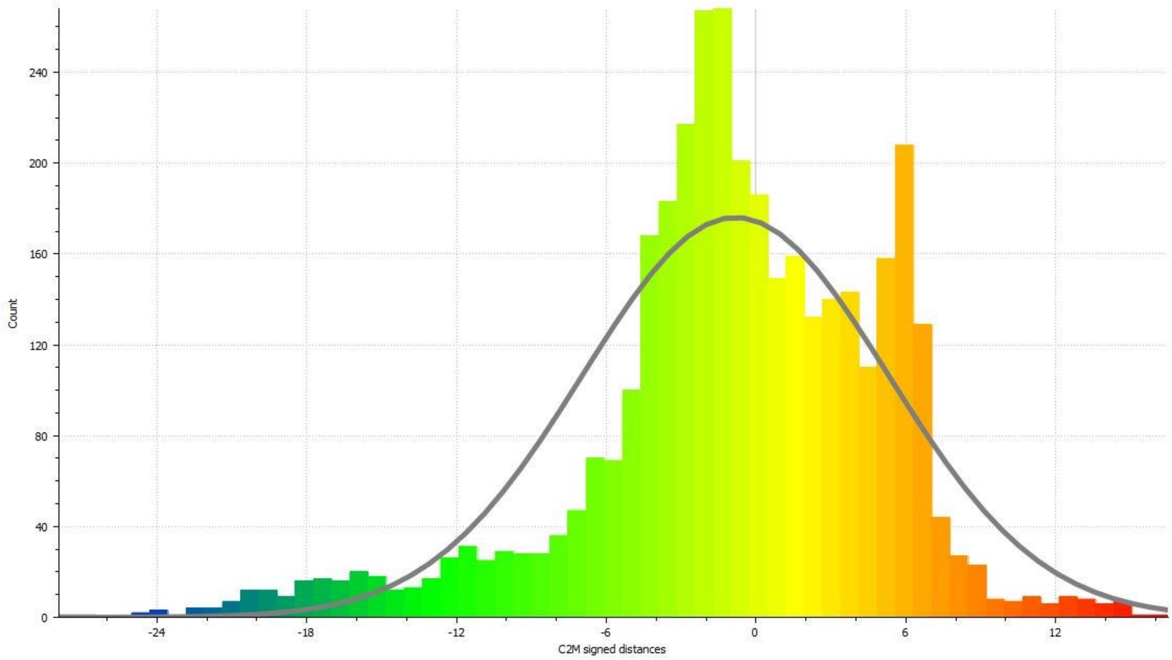


Figure 55: Cloud Compare model of the vacuum formed PETG sheet

Based on the Gauss curvature, see diagram 10 below, it can be concluded that the mean is less than 1 mm and the standard deviation 6 mm.

Diagram 10: Gauss curvature of the vacuum formed PETG sheet



7.4 Vacuum forming machine – Custom-made

After the experiments done by Bas Hesselink IDAP in Arnhem, it can be concluded that vacuum forming is an achievable method to deform plastic sheets into the desired shape we designed. Up front there were doubts if changing the pressure has the right result, but it did. Based on these experiments explained in paragraph 7.3, we built our own vacuum forming machine. The plastic sheet will be heated with a hot air gun and formed on the reconfigurable mould by little pressure controlled by a vacuum cleaner. This vacuum forming machine is made for a mould with the dimensions of 300x300 mm and will be used for further experiments. In the next paragraphs the different test with this vacuum forming machine will be discussed. When everything is working correctly it will be built in a larger scale.

7.4.1 Design & production

The design of the mould is based on the same principles that were used at the company Bas Hesselink IDAP. The construction of the mould consists of a flexible mould, a guide, a frame and a heating box (figure 56a & 56b). For this prototype, the flexible mould consist of four or six pins, that set a spring steel mesh (membrane) on the right height by using nuts. This steel mesh (type: WNFE3) has a plain weave, with apertures of 2 mm and a wire thickness of 1,25 mm. This mesh is quite stiff, which results in less deformation, and is restricted to form compared to a more flexible steel mesh. For the test described in this paragraph only the stiff membrane is tested. The flexible mould is made airtight and is connected to a vacuum cleaner that creates under pressure for the vacuum process. The frame is made to clamp the PETG sheet in between and make an airtight connection with the airtight box. This construction is made of MDF, screws, bolts and nuts. There is no rubber used to create a better airtight connection. On top of the frame a heating box is placed, with the goal that all the heat is transferred to the PETG sheet and not to the surroundings. For equal circulation of hot air a plate of fire resistant material (Pyrogel XT Plus – 5 mm) is placed underneath the hot air gun to avoid overheating at one spot. When the PETG sheet reaches the right temperature the frame should be pressed down on top of the flexible mould. To avoid movement of the frame it is moved downwards via guides.

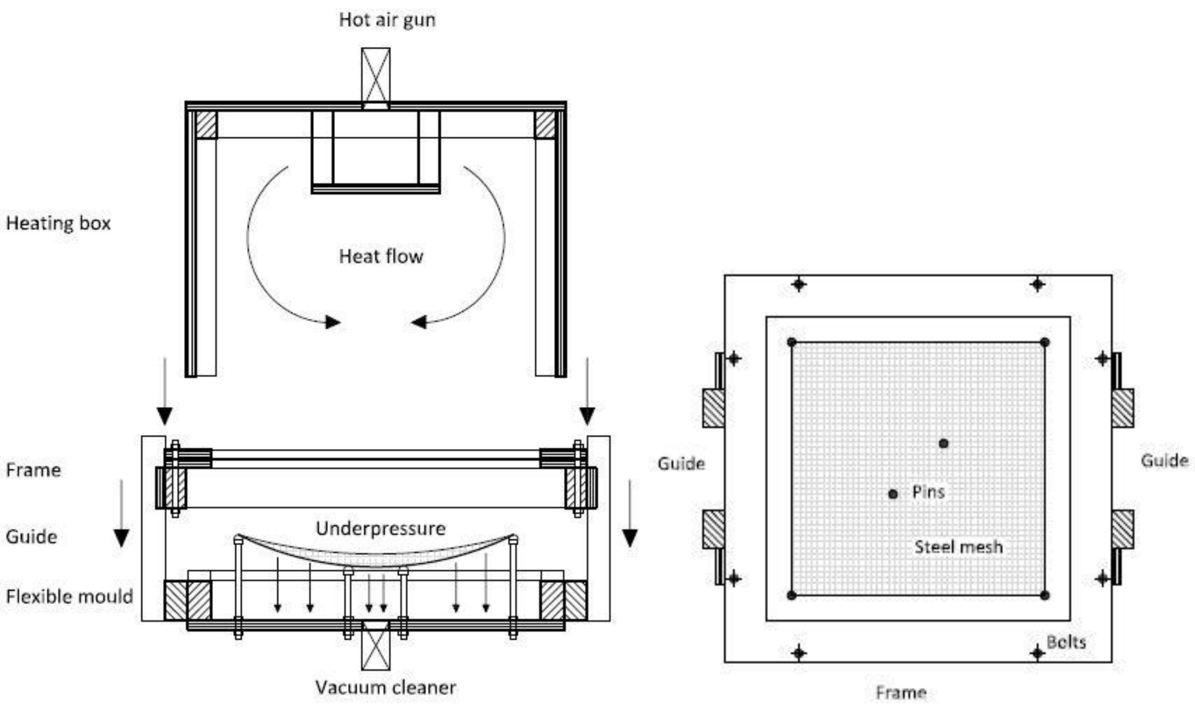


Figure 56a: Section of the vacuum forming machine & Figure 56b: Top view of the vacuum forming machine

7.4.2 Process

The First step in the process of vacuum forming is adjusting the flexible membrane into the designed curvature. Then the preparations can be done for vacuum forming. For these experiments PETG sheets of 1 mm are used for vacuum forming. When this sheet is cut into the correct size it can be clamped in between the frame using bolts. The frame is then placed in a guide to ensure that the frame is moved straight downwards on top of the flexible mould. Before the frame is pushed over the flexible membrane, the sheet is heated with a hot air gun that is normally used to release paint from wood. To avoid losses of heat, the sheet is fully covered within a box. The heating time is approximately 20 min. The material is then flexible enough to follow the curvature of the membrane. The frame connects with an airtight box, which is connected to a vacuum cleaner. The vacuum cleaner then creates an under pressure underneath the flexible membrane, which results in a smooth curvature that follows the membrane. After the right form is reached the plastic sheet is cooled and demoulded. This sheet will be used as a counter mould for concrete elements.

7.4.3 Experiments

The performance of the mould worked fine for the tests. The main goal was, if a simple forming machine made of MDF, a vacuum cleaner and a hot air gun can produce a PETG sheet that is curved on a reconfigurable mould. After a few tests, with varying temperatures and pressure, the results were quite good. The bolds that are used as pins were connected with only two nuts, so that causes a little bending inaccuracy. The connection between the frame and the flexible mould was good enough to create the under pressure that was needed. The guides for the frame helped to speed up the process for an airtight situation and resulted in a sheet that was hot enough to use under pressure. The number of operations are limited after the heating time is finished, the frame can be pulled over the formed steel mesh and set under pressure with the vacuum machine. After the sheet is cooled it is ready to be used in the hydrostatic mould. If the form of the mould has to be changed, the nuts must be replaced. The flexibility in height is not as easy as in the mould for glass. Figure 57a & 57b show the custom-made vacuum forming machine.

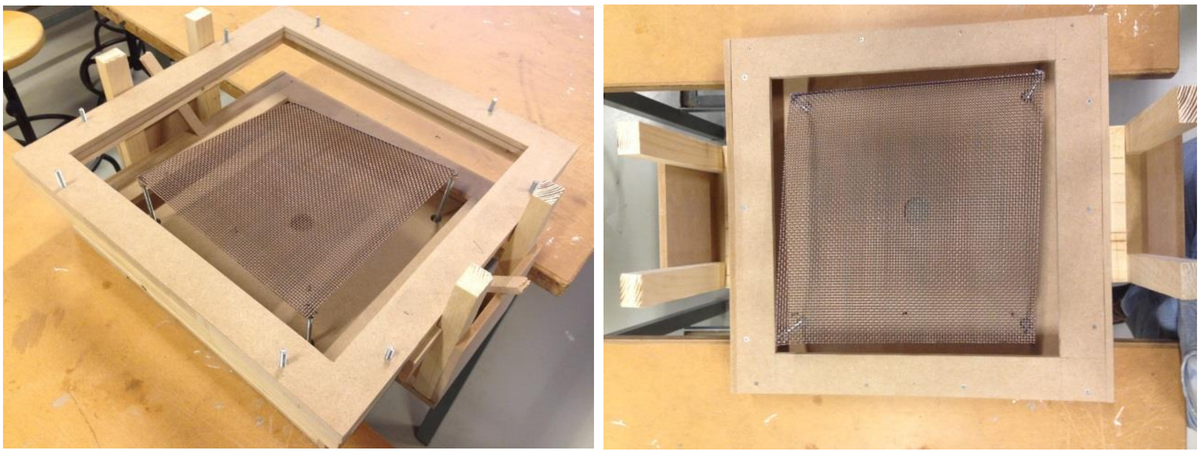


Figure 57a: Custom-made vacuum forming machine & Figure 57b: Top view of the vacuum forming machine

In total 6 experiments for vacuum forming are done with PETG to get the right result (appendix B). The main bottleneck was getting the right temperature equal over the entire surface. The first test resulted into centralized flexibility in the middle of the sheet, that causes a wrinkle as shown in figure 58a. The reason is too much material at one single spot. To avoid this problem a plate covered with fire proof material (Pyrogel XT Plus – 5 mm) was placed in front of the hot air gun. This resulted in an equally spread heat flow and solved the problem of wrinkling (figure 58b). This problem is already added in the drawing of paragraph 7.4.1. Besides the way of heating also the duration of heating influences the flexibility of the sheet andthe final surface quality.

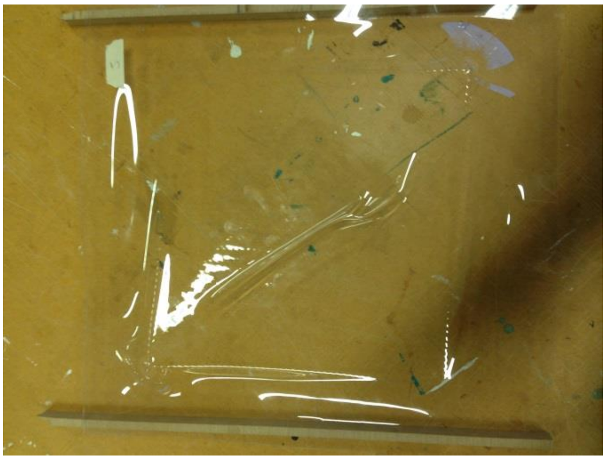
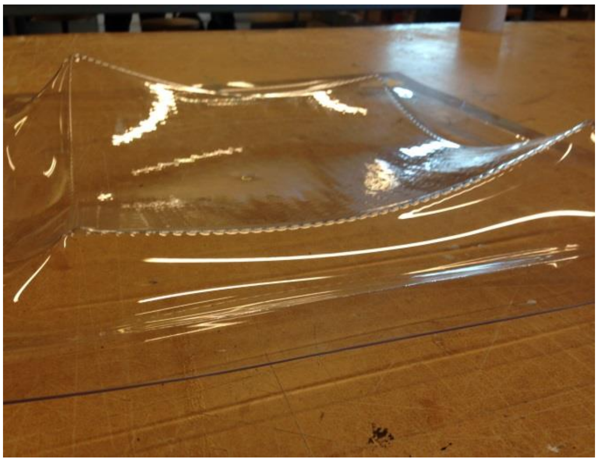
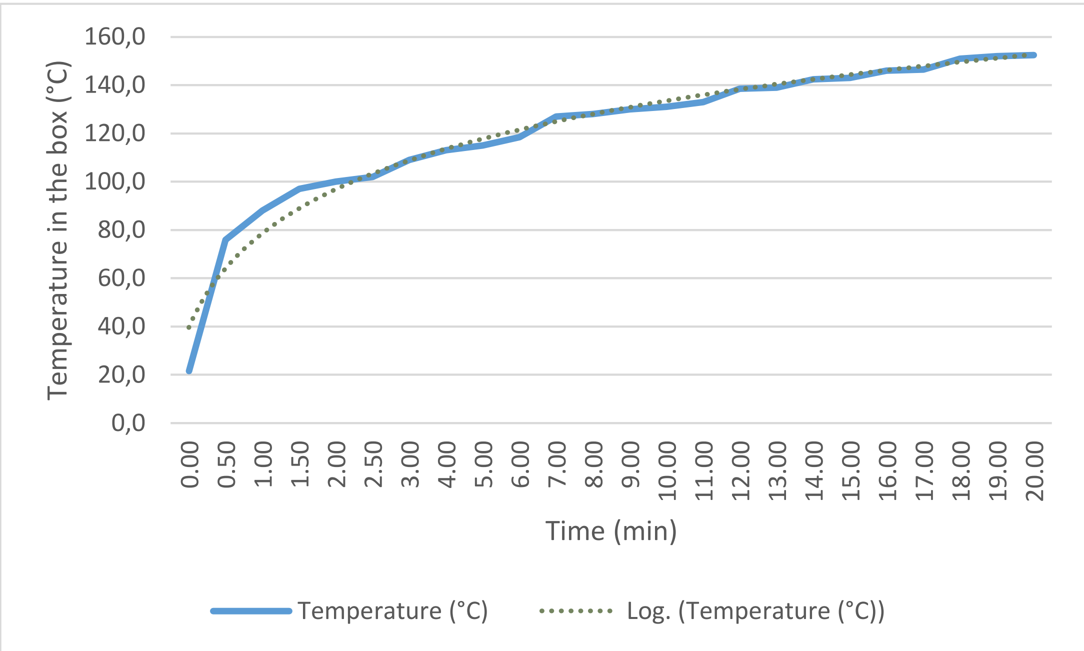


Figure 58a: Wrinkle in the middle of the sheet & figure 58b: Smooth surface

Temperature

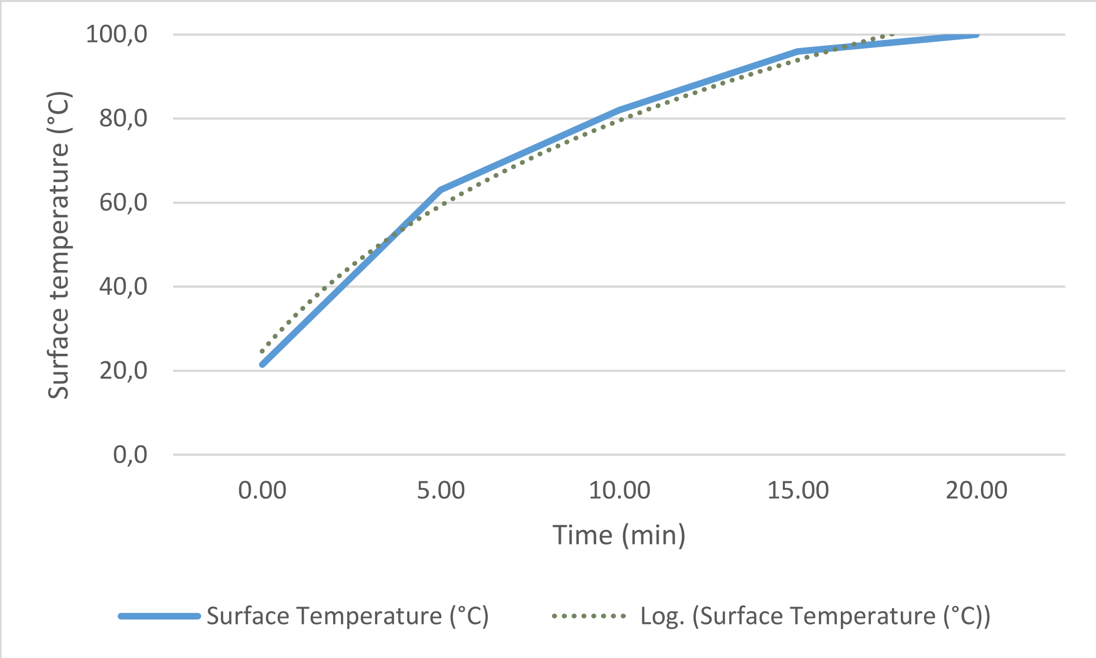
Two temperature measurements were made. One of the temperature in the box and one of the surface of the PETG sheet. The temperature inside the box is measured with a Yokogama heating sensor (model: 2455). A 1 mm PETG sheet will be heated up by a Bosch hot air gun (model: PHG 490-2) till the sheet is plastically enough for vacuum forming. The heating time of the PETG sheet varies if the box is already used shortly before. When the measurement took place the box was not used shortly before. So the temperature at the start was the same as the room temperature, namely 21,5 °C. The first three minutes are measured every 30 seconds, because the temperature rises faster in the beginning. From 100 °C the increase in temperature rise is at a lower speed (diagram 11). The total time till the PETG gets fully plastically was 20 minutes.

Diagram 11: Measurement temperature inside the box



The surface temperature of the PETG sheet is measured with a Therm heating sensor (model: 2260-2). The temperature of the sheet in the beginning was the same as the temperature in the box (21,5 °C). After five minutes the temperature of the surface was 63 °C (diagram 12) and there was some local sagging. After five minutes the temperature of the surface increases slowly. When the temperature became higher the sagging evolved from locally till all over the sheet. The temperature of the surface after 20 minutes, when the PETG sheet was fully plastically, was 100 °C.

Diagram 12: Measurement surface temperature of the PETG sheet



The result of these measurements is that it takes at least 20 minutes to make a 1 mm PETG sheet fully plastically with a hot air gun. To accelerate the vacuum forming process a heating lamp could be used. In this way the heating will be spread evenly.

Under pressure

The pressure was also changed during different experiments. The conclusion is that the pressure should run up slowly until the maximum level and switched of when the continuity of form is reached. The pressure will be around 0.1 bar. This means that no vacuum is applied to the membrane, which ensures continuity of the surface. During the design phase it was not sure if the box for vacuum forming was air tight enough, but now it can be concluded that there is no problem with this low pressure. Figure 59 shows how the PETG sheet is formed under pressure.

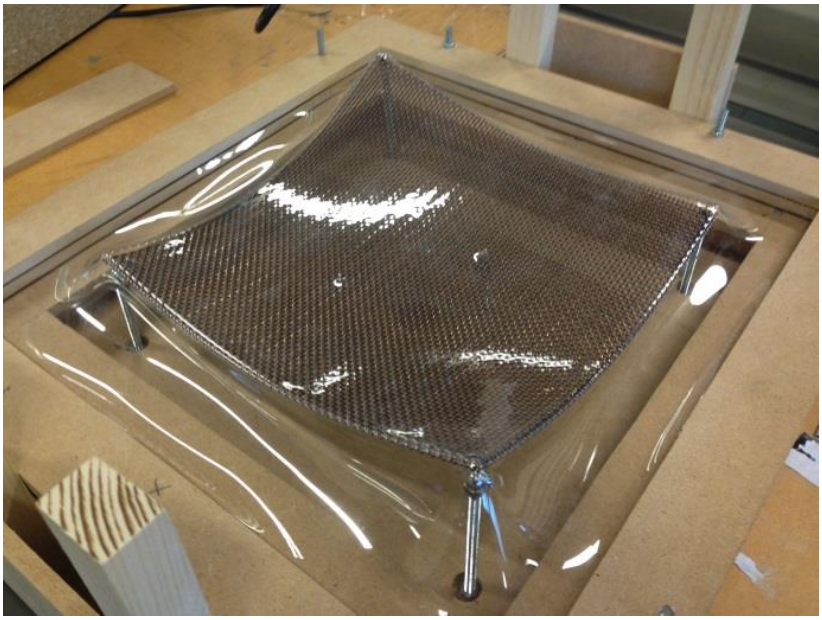


Figure 59: A vacuum formed PETG sheet

Form

For the experiments that were done, the type of form was not important. The main goal was getting experience with vacuum forming. The form was set into an anticlastic shape, this is the most difficult shape for vacuum forming. When a synclastic shape is used it forms directly over the shape, which is not possible with an anticlastic shape. That is why under pressure is needed to create an anticlastic curvature. As a result the surface quality is good. The pattern of the steel mesh is however well printed in the PETG sheet. The final concrete element needs to be smooth and therefore a silicone or vilt layer should be used in between. The continuity of the form is tested with 123D Sketch in combination with Cloud Compare. With this program the difference in the form of the mould and the sheet can be compared (figure 60). From this comparison it can be concluded that the largest deformation is approximately 16 – 1 = 15 mm. The positive under value of 1 mm is given, because the PETG sheet is placed 1 mm above the mould. This is realized by picking four points in the middle of the PETG sheet and align that with the opposite located points of the mould. After that the lowest point of the sheet was lifted just above the mould to avoid negative values.

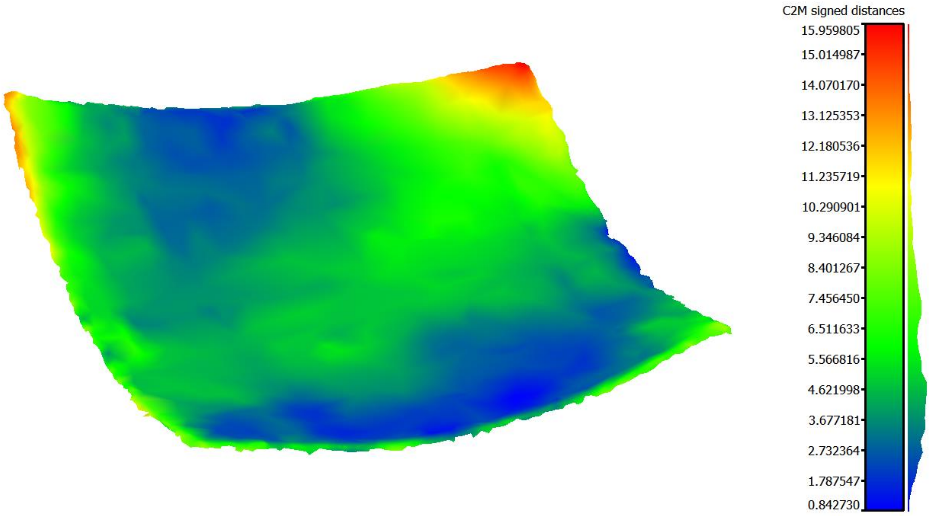


Figure 60: Cloud Compare model of the vacuum formed PETG sheet

The reason for the largest value of 15 mm at the corner could be a too short cooling time or bending of the steel mesh caused by too high under pressure. The mean deformation of the sheet compared to the mould is 6mm, with a standard deviation of 3 as can be seen in diagram 13.

Diagram 13: Gauss curvature of the vacuum formed PETG sheet

The edge quality is good, but not straight. The correct size is needed for the hydrostatic mould and the final element. Control of the dimensions is needed for the connections in the construction phase. The quality of the layer is good. There are no bubbles, cracks or other discontinuity. The thickness of surface area is thin, which makes it quite flexible. The fact if it is too flexible will be tested with a mould of hydrostatic pressure. When the edges perpendicular to the surface can be used, it will strengthen the surface. When the plate is too flexible, thicker plates, or other types of plates can be considered.

7.4.4 Possible improvements

The membrane used for this mould is too stiff to create extreme double curved forms. When less curvature is accepted, stiff material has the advantage of less deformation. For more flexible forms a thinner wire diameter or aperture of spring steel is needed. Possible deformations can be avoided with more actuators/pins. Besides the material properties it is important that the mesh is cut straight and in correct size to be sure that the element has the right shape and size. It is also important for the connections between elements.

For this mould a vacuum cleaner is placed underneath the centre of the PETG sheet to create under pressure. Better surface results of the PETG sheet could be established by spreading the under pressure at different points. This can be a consideration for the final mould, at this moment centralized under pressure works fine. The cooling time for the sheet of this prototype is equal to the time the vacuum cleaner is running. When the sheet is not cooled enough during under pressure it can cause deformations. Improvements can be made with a separate cooling system or a longer cooling time.

The next step is integrating these principles in a flexible mould with a larger dimension. Other students are involved with a project about double curved glass and made a larger flexible mould based on the same principle (El Ghazi & Schuijers, 2015). There are possibilities to design our vacuum machine based on that design. In this mould the used spring steel is less stiff, which can give advantage for more flexibility in form. For the adjustment of this mould for vacuum forming, the temperature of glass must be taken into account.

For the final design of the mould other possible solutions for connections will be considered. Besides the construction it is also import to limit the amount of operations and the time that is needed to produce these PETG sheets. One big improvement can be another heating solution that brings the heating time back from 15 min to approximately 2 min. Based on the research of plastic sheets PS could also be a good option. This material is cheaper, but needs another processing method.

8. Mould with counter pressure

In this chapter the mould with counter pressure will be discussed. First the ways of machining of the vacuum formed sheets will be explained. There are two methods of pouring a concrete panel with a plastic sheet. The first method is by lowering a mould into a basin with fluid. This method was an idea by Frank Omloo (figure 61a). The other method is to fixate the two plastic sheets in the basin with counter pressure (figure 61b). The materials that can be used as counter pressure will be discussed first and substantiated with experiments. After that the method will be explained en tested.

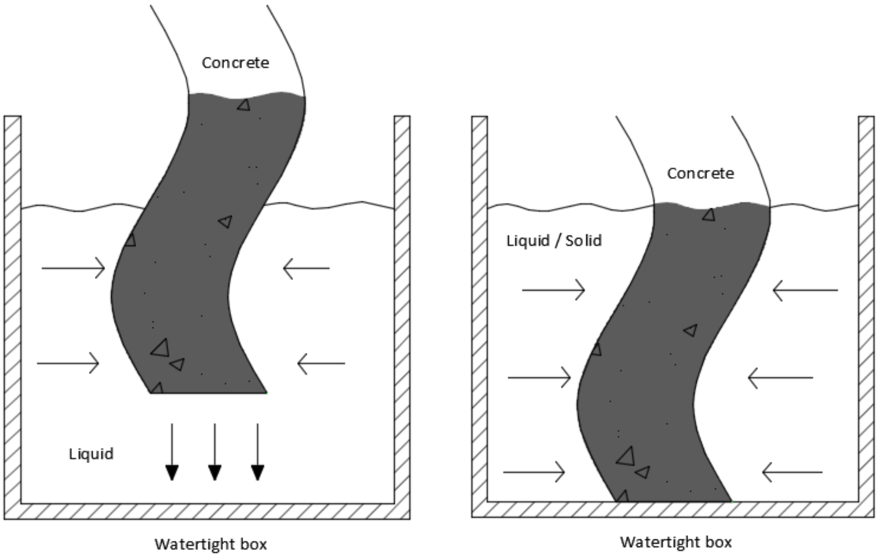


Figure 61a: Lowering & Figure 61b: Fixation

8.1 Machining of sheets

The machining of the sheets can be compared with wood and metal. This makes it possible to saw, mill, cut, laser cut, punch or drill the sheet. During machining it is necessary to be aware that the sheet can easily brake. This means that for sawing hard metal is needed and a fine tooth pitch should be used for thin plates and a rough tooth pitch for thicker plates. The following types of saws can be used: handsaw, buzz saw or a belt saw. It is also possible to protect the sheet with protection foil. Sheets with a thickness up to 3 mm can be easily cut or punched without losing quality of the material. The punching knife should be 30°, with clearance between the tool and the cutting surface of 0.01 to 0.03 mm (figure 62a & 62b). When smooth edges are important, sheets thicker than 1.5 mm can better be machined by sawing or milling. Drilling can be done with sharp metal drills. Most of the time cooling is not needed. Milling and laser cutting is also a good option to create the right shape for the sheet. Especially for difficult shapes a laser cutter is very helpful (Bayer, n.d.).

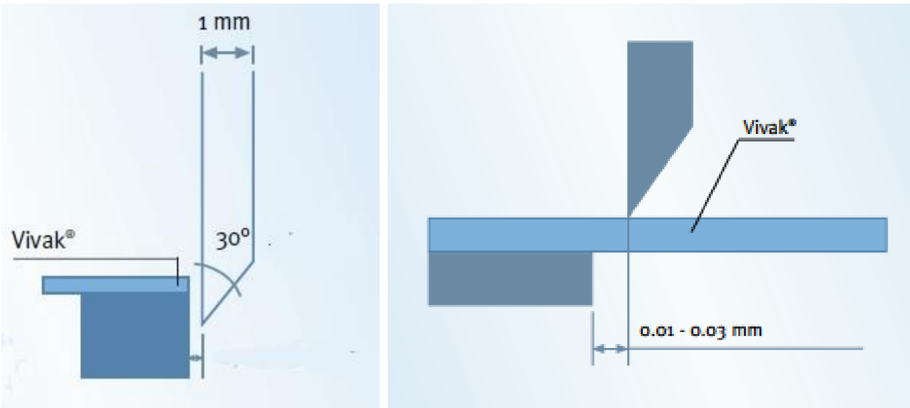


Figure 62a: The punching knife must be max. 30° & Figure 62b: A clearance of 0.01 to 0.03 mm (Bayer, n.d.)

8.2 Materials for counter pressure

In this chapter different kinds of materials were tested as counter pressure for the pouring process. The materials will be divided in two groups: materials for lowering process (figure 63a) and materials for fixation process (figure 63b). The concrete that is used for these experiments is lightweight concrete (Beamix beton 111 comfort) and the material of the plastic sheet that used is PETG (thickness: 1 mm).

Figure 63a: Counter pressure for lowering process & Figure 63b: Counter pressure for fixating process

In figure 64a and figure 64b it can be seen what happens when no counter pressure used. The thin plastic sheet is not strong enough to hold the concrete together. That is why the concrete is deformed instead of straight.

Figure 64a & Figure 64b: Concrete panel without any support

8.2.1 Lowering process

For the lowering process a fluid is needed. In this case not the counter pressure but the hydrostatic pressure is relevant. The definition and principle of hydrostatic pressure was already mentioned in chapter 5.2 "Hydrostatic Pressure". The density of both fluids has to be the same, because otherwise the concrete will deform the plastic sheets. The lightweight concrete that is used for the experiments has a density around 1.8 kg/dm^3. This means that the density of the other fluid must also have a density around 1.8 kg/dm^3. Diagram 14 shows the density of some common fluids. The only fluid which comes close to the density of lightweight concrete is sulphuric. The disadvantage of sulphuric is that it is a dangerous liquid. When sulphuric comes in contact with the skin it causes burns. So this liquid is not suitable to work with (SoortelijkGewicht.com, n.d.).

Diagram 14: Density of common fluids

Liquid	Density (kg/dm3)
Water	1.0
Sea water	1.02
Alcohol	0.79
Milk	1.03
Diesel	0.84
Oil	0.9
Gasoline	0.7
Sulphuric	1.84

Bentonite

In the civil industry also liquids are used for hydrostatic pressure. For instance bentonite, in combination with water, used as a temporary support of the ground for the construction of diaphragm walls (figure 65a). Bentonite is a clay generated frequently from the alteration of volcanic ash, consisting predominantly of smectite minerals, usually montmorillonite (figure 65b). Montmorillonite is a clay mineral with a layered structure. The physical properties are largely determined by the structure of the crystal lattice of the clay mineral ($4SiO_2Al_2O_3H_2O$) , and not by the chemical composition. There are two kinds of bentonite, namely: sodium-bentonite and calcium-bentonite. The difference between these two types is the swelling capacity. For sodium-bentonite this is five times higher than for calcium-bentonite. Economically sodium-bentonite is better than calcium-bentonite (de Vries, 1992). Other properties of bentonite are good viscosity, absorbency and plasticity. The applications of bentonite, beside as support fluid in diaphragm walls, are (Cebo Holland, 2015):

A. Sealer in non-permeable liners for landfill sites;
B. Binder in the production of iron-ore pellet;
C. Retention-aid in the paper manufacture;
D. In wine production for the clarification;
E. In fertilisers;
F. In waste water treatments.

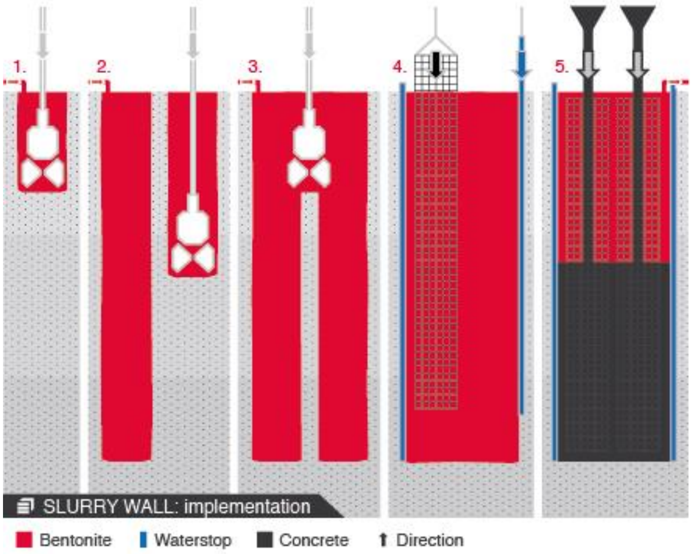


Figure 65a: Bentonite as a temporary support for a diaphragm wall (Fondedile, n.d.) & Figure 65b: Bentonite powder (Qingdao New Continent Minerals, n.d.)

Mixture of bentonite

The density of bentonite powder (Cebogel CSR) is around 2.3kg/dm^3, but then it is not a fluid. To make bentonite a fluid it has to be combined with water. The density of this mixture depends on the amount of bentonite in it (diagram 15). The limit of the amount of bentonite is 115 gr per liter, to make the mixture still workable (after that it becomes a solid).

It then has a density of 1.094 kg/dm^3 after four hours (recommend waiting time from Cebo Holland). To increase the density of the bentonite mixture, dolomite or barite could be added. Both materials are well known as materials with a high density. Dolomite has a density of 2.8 kg/dm^3 and barite has a density of 4.2 kg/dm^3. Because barite has the highest density, this material is chosen as an additive to the mixture. The mixture of 115 gr bentonite is already very thick, and therefore sufficient barite (Cebo Baryte) is added to 85 gr bentonite and 1 L water. Diagram 15 shows the different densities with 500, 1.000 and 1.500 gr barite. After four hours the density of the mixture with 1.500 gr of barite has a density of 1.79 kg/dm^3. This mixture is suitable for using it as counter pressure for the lightweight concrete described above. The experiments with pouring concrete with bentonite as counter pressure are shown in the next chapter.

Figure 66a: The mixer that is used for the experiments (Hobart, Type N-50) & Figure 66b: The balance that is used for the experiments (Mettler PE3600)

Diagram 15: Experiments mixture with bentonite and barite

Density after pouring				Density after four hours		
Material	Weight (kg)	Volume (dm3)	Density (kg/dm3)	Weight (kg)	Volume (dm3)	Density (kg/dm3)
Bentonite (45gr)	0.972	0.975	0.997	0.952	0.975	0.977
Bentonite (85gr)	0.875	0.875	1.000	0.864	0.875	0.987
Bentonite (115gr)	0.83	0.75	1.107	0.821	0.75	1.094
Density after pouring				Density after four hours		
Materiaal	Weight (kg)	Volume (dm3)	Density (kg/dm3)	Weight (kg)	Volume (dm3)	Density (kg/dm3)
Bentonite (85gr) + Barite (500gr)	1.390	1	1.390	1.377	1	1.377
Bentonite (85gr) + Barite (1000gr)	1.747	1.075	1.625	1.612	1	1.612
Bentonite (85gr) + Barite (1500gr)	1.803	1	1.803	1.790	1	1.790

8.2.2 Fixation process

Besides the bentonite/barite mixture also solid materials could be used as counter pressure for the fixation process. Materials were chosen that were available in the Pieter van Musschenbroek Laboratory of the University, namely: sand, fly ash (coarse) and clay granulate. Also the use of pins is tested. For every test the material for counter pressure is placed in the mould first and after that the concrete is poured. The plastic sheet that is used between the counter pressure material and the concrete is a 1 mm PETG sheet. The goal of these tests was to create a straight panel. Then it can be concluded that the material/pin as counter pressure works or not.

Sand / Fly Ash (coarse)

Because the results of sand (Gamma metselzand) and coarse fly ash are the same they are brought together in this paragraph. Figures 67a & figure 68a show that the plastic sheet is not strong enough to hold the sand/fly ash. The sand/fly ash counter pressure is too high, so that the plastic sheet was already deformed before the concrete was poured. This is also visible in the two results (figure 67b & 68b). A solution to this problem is to pour the concrete and the counter pressure material in the mould, at the same time.


Figure 67a: Test sand as counter pressure material & Figure 67b: Result after demoulding


Figure 68a: Test fly ash as counter pressure material & Figure 68b: Result after demoulding

Clay granulate

The result of counter pressure with clay granulate (Viano Granules Hydro) is very good. Because of the low weight of the clay granulate the plastic sheet was not deformed before pouring the concrete. It resulted in a straight panel (figure 69a & 69b). The only question is if the plastic deforms when it is made on a bigger scale, because this was just a small scale test.


Figure 69a: Test clay granulate as counter pressure material & Figure 69b: Result after demoulding

Pins

At last a pin as counter pressure is tested (figure 70a). In this way the plastic sheet was also not deformed before pouring the concrete. But from the result it can be concluded that the pin only supports the plastic sheet locally (figure 70b). To solve this problem more pins will be needed. The disadvantage of this solution is that it takes more time to set all the pins in the right place.

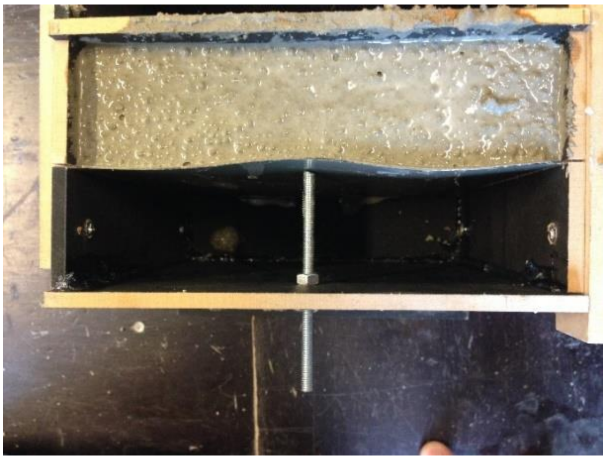


Figure 70a: Test pin as counter pressure & Figure 70b: Result after demoulding

8.2.3 Conclusion

The results of the different materials were various. Sand and fly Ash were too heavy, the pin solution not practical. In this way the plastic sheet does not maintain their original shape. The result with Clay granulate was very good, because it is a lightweight material. The only question is if the plastic deforms when making a sample on a bigger scale. At first sight the bentonite looks like a good material because it is a fluid (easy to pour) and the density can be raised to the density of concrete by adding the Barite. In this last option there will be no deformation of the plastic sheet. This will be tested in the next chapter.

8.3 Method

In this chapter both methods of lowering and fixation will be explained and substantiated with experiments. The experiments will be done with lightweight concrete (Beamix beton 111 comfort). Also the same mixer (Hobart, Type N-50) and balance (Mettler PE3600) will be used for these experiments. The bentonite that is used for these experiments is the one with a density of 1.79 kg/dm^3 (Chapter 8.2.1: Lowering process).

8.3.1 Lowering

The difficulty of the mould, that is used for the lowering process, is how to separate the two plastic sheets that need to be fabricated into one mould. This can be done by the use of a middle piece to which the plastic sheets will be fixed (figure 71). This middle piece can be made of the same material as the sheets, or a different material may be chosen like wood or foam. A critical point of the mould will be the water tightness.

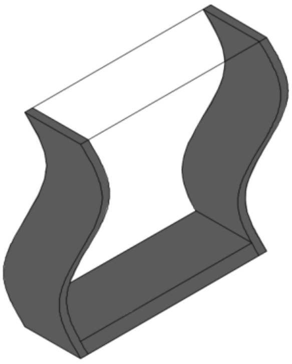


Figure 71: Middle piece (grey)

Plastic

If plastic is chosen for the middle piece, the sheets can be fixed to the middle piece in the following ways: gluing, adhesive tape, mechanical fixation or welding.

By gluing the sheets on the middle piece two types of glue can be used, namely adhesive glue that is solvent based or normal adhesive glue. Solvent based glue is the easiest and most economical method. The addition of 8% plastic chips provides a solution adhesive with reduced evaporation speed and increased viscosity, which makes it much easier to apply and handle. A further advantage of this solution adhesive is that it is gap-filling, meaning that the surfaces to be bonded do not need to be so flush as when using a pure solvent-type adhesive. This glue is specially made for fixing two PETG sheets together. Normal adhesive glue is a good alternative if this glue is tolerant to PETG. The advantage of this type of glue is that it can be bought in every DIY shop (Bayer, n.d.).

Another method of fixing two plastic sheets together is the use of transparent, double-sided adhesive tape (figure 72). This tape is acrylic based and is ideal for rapid bonding. These tapes are elastic and particularly suitable for bonding thin PETG sheets to other plastics, glass or metal. A disadvantage of the tape is the water tightness. It is difficult to make the mould watertight with only double-sided tape (Bayer, n.d.).

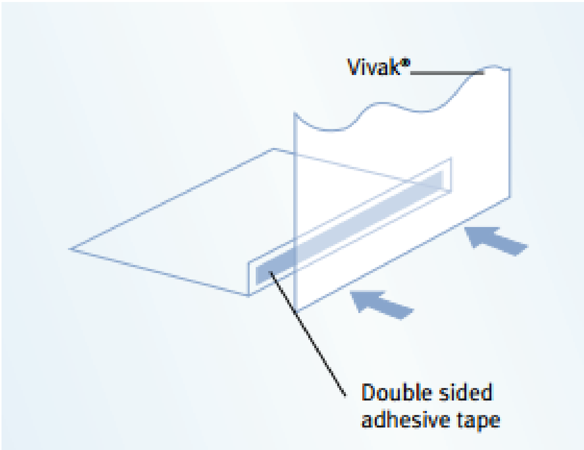
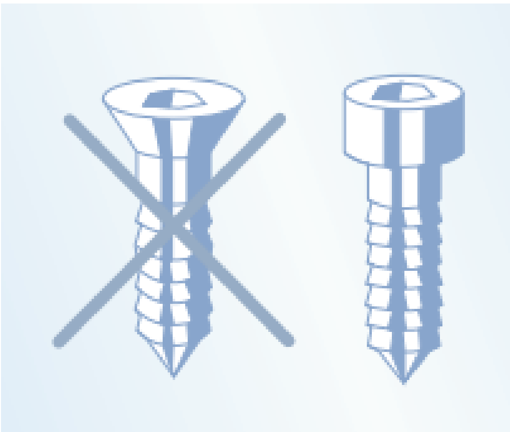


Figure 72: Double sided adhesive tape (Bayer, n.d.)

Due to its good impact resistance, PETG can also be fastened mechanically using any method. When using screws, opt for screws with a cylindrical head to bond various parts further and avoid any with beveled heads, as these can cause cracking (figure 73a). Drill holes should be measured to allow for expansion and shrinkage (figure 73b). All plastic screws are suitable. When using metal screws a suitable plastic underlay is required. Avoid over-tightening screws. Use a through bolt rather than cutting a thread in the sheet (Bayer, n.d.).



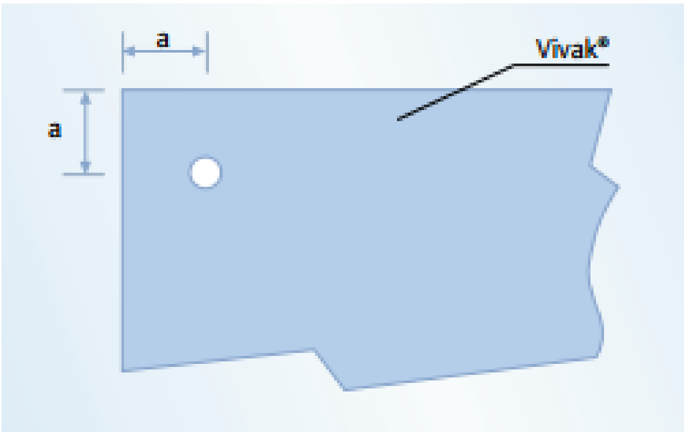


Figure 73a: Only screws with beveled heads are suitable & Figure 73b: The holes for fastening have to be made minimal 10mm outside the edges (Bayer, n.d.)

Welding is mainly performed on opaque sheets. It does not produce optimum optical quality, and should therefore be carefully considered. The most used type of welding is hot-gas welding. For hot-gas welding an air volume of 50–100 l/min and an air temperature of 250–300 °C is recommended, measured 5 mm in front of the nozzle. Rounds or profiled extruded rods, or even narrow strips cut from a sheet, can be employed as welding rods (Bayer, n.d.).

Other materials

Besides plastic also wood can be used in combination with the PETG sheets. If the middle piece is made of wood it is easy to attach the sheet by screws. Also sealant can be used as a connection method with wood. When the panels are double curved it can be useful to make the middle piece with a laser cutter. The laser cutter is based on the CAD/CAM principle. In this way it is easy to create the right form out of the AutoCAD file.

Experiment

For the experiment of lowering the mould in bentonite two moulds were made (250x100x30 mm). One with the middle piece of plastic and one of wood. The complete plastic mould is glued together with Hard Plastic Glue of Bison. The plastic sheets at the wooden mould were fixed with kit. The box with the bentonite is made of 6 mm MDF sheets and roof battens of 25x35 mm. The pouring process was difficult because the concrete was not fluid enough for a 30 mm panel (figure 74a). This could be solved by the use of an other type of concrete, like self-compacting concrete. The concrete that is poured in the complete plastic mould has a smooth surface on five sides (figure 74b). There are also some bubbles in the concrete, this can also be solved by using self-compacting concrete. The concrete that is poured into the wooden/plastic mould only has a smooth surface on two sides (the sides of the plastic sheets). This mould was beforehand coated with formwork oil. But still the concrete came in contact with the wood (figure 74c). This problem could be solved by painting the MDF with special MDF paint.

Figure 74a: Difficult to pour lightweight concrete in a small mould, Figure 74b: Result of pouring concrete in complete plastic mould & Figure 74c: Result of pouring concrete in wooden/plastic mould.

8.3.2 Fixation

The mould of the fixation process looks like the mould of the lowering process, with the difference that the plastic sheets will be clamped by wooden plates (figure 75). These wooden plates have the same shape as the vacuum formed plastic sheets. These shapes will be made with a laser cutter that is based on the CAD/CAM principle. The other difference is that the mould will be placed in the basin first and then the bentonite or an other material will be poured together with the concrete.

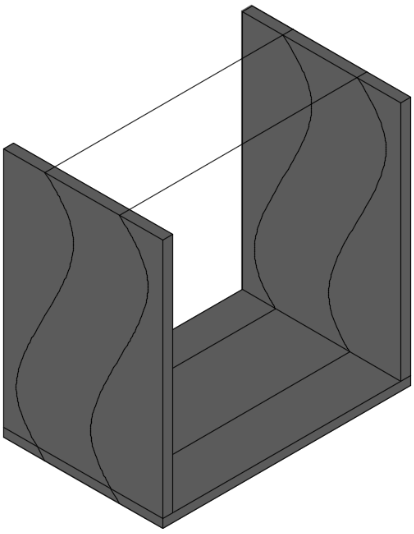


Figure 75: Fixation principle

Experiment

For the experiment of fixation the mould in the basin is made of one double curved mould (250x250x30 mm). This mould consists of two vacuum formed PETG sheets that are clamped with 6 mm MDF sheets of the same shape (figure 76a). These MDF shapes are screwed on another MDF sheet. The basin was made in the same way as the basin of the lowering test, only this time 9 mm MDF sheets are used instead of 6 mm. In this experiment also the pouring process was difficult, because the concrete was not fluid enough. The result of the concrete element is shown in figure 76b. The problems of the bubbles and the contacting between concrete and wood were the same as for the experiment of the lowering principle, because it was poured at the same time. The plastic sheets ensure that the double curved panel has a smooth surface.

Figure 76a: Clamped plastic sheets in a basin & Figure 76b: The result of casting a double curved concrete element with lightweight concrete

8.3.3 Conclusion

Either lowering as fixation are working principles. The only problem is the concrete. The lightweight concrete that is used for the experiments is not fluid enough for pouring thin panels and leaves bubbles on the surface. This problem can be solved by the use of self-compacting concrete. In the next chapter self-compacting concrete will be discussed and tested.

8.4 Self-compacting concrete

The concrete mixture will be designed based on the requirements for the facade panels. The panels should be light and thin to meet the requirement op lifting the panel by hand on building site. The concrete will be casted between to plastic sheets with an offset around 30 mm. The plastic sheets are vulnerable for heavy equipment and should be held in place by counter pressure. The thickness of the panel and vulnerability of the sheets requires a concrete mixture with a high workability. This type of concrete is called Self-Compacting Concrete (SCC) also referred as "Self-Consolidating Concrete" and "high performance concrete". This type of concrete can flow through and fill gaps of reinforcement and corners of moulds without any need of vibration and compaction during pouring process. SCC results in durable concrete, and saves labour and consolidating noise. SCC is obtained with a High Range Water Reducing (HRWRA) admixture. HRWRA are synthetic, water-soluble organic chemicals, usually polymers, which significantly reduce the amount of water required to achieve a given consistency in plastic concrete. The use of HRWRA can effect in two ways; reduce water to achieve strength and reduced permeability / improved durability or to achieve increased workability (Cement Admixtures Association, 2012).

For the research of Self-compacting concrete a mixture of H.J.H. Brouwers & H.J. Radix is used as a starting point (Brouwers & Radix, 2005). This mixture has a density of 2360 kg/m³, which is the density of regular concrete (diagram 16). For this mixture the Chinese method is used. This method starts with the packing of all aggregates (sand and gravel together), and later the filling of the aggregates voids with paste (diagram 17) (Lotfy, 2012). The standard mixing sequence gives the time to mix at after a curtain material is added. After 5.5 minutes mixing the edges will be scraped to be sure that all aggregates will be mixed. Next the binder can be added and mixed for 1 minute. For this research high-performance superplasticizer (SP) "Glenium 51" is used as HRWRA. This will be mixed together with ¼ litre water for another 30 seconds. After that the total mixture is mixed 15 minutes before it can be casted. The total duration is 22 minutes. The method is easier to carry out and results in less paste. This saves the most expensive constituents, namely cement and filler. The purpose of this mix design was to investigate the maximum packing that can be achieved (Brouwers & Radix, 2005).

Diagram 16: Self-compacting concrete mixture

Required quantity per liter			
Mix B	**kg**	**(kg/dm³)**	**dm³**
Cement	0.315	2.950	0.107
Limestone	0.164	2.750	0.060
Sand 0 – 1 mm	-	2.650	-
Sand 0 – 2 mm	0.306	2.650	0.115
Sand 0 – 4 mm	0.719	2.650	0.271
Gravel 4 –16 mm	0.673	2.650	0.254
Water	0.173	1.000	0.173
Superplasticizer	0.0055	1.045	0.005
Total amount	**2.356**	-	**0.985**

Diagram 17: Standard mixing sequence of self-compacting concrete

Mixing sequance				
Sand + Course LW aggregate	3/4 water	Binder	1/4 water + SP	Mixing
0:30 min	5:00 min	1:00 min	0:30 min	15:00 min

8.4.1 Experiment 1

For experiment 1 mixture B, see diagram 16, is made in the laboratory. The aggregates are put together inside a mixer (figure 77a). During mixing it became clear that gravel was too coarse for the mixer. To overcome that problem the concrete is mixed in a mortar tube. During mixing it was hard labour, which gave us doubt about the quality of the concrete. Because of difficult mixing some extra SP was added. After a few minutes the workability was improved. On top of the mixture a thin reflected layer occurred with small blow holes. The concrete is casted in a plastic box made of double curved polystyrene sheets, which sacks into bentonite due to the weight (figure 77b). The casting process was quite difficult because the concrete was very sticky and hardened quickly.

Figure 77a: Hobart (Type A-200) mixer & Figure 77b: Lowering process in the bentonite

After demoulding some errors can be seen. The panel shows difference in colour (figure 78a) and it shows stripes and water scouring visible on the concrete surface (figure 78b). The reason of the colour difference could be a too high slump flow and a too low viscosity. The viscosity can be increased by adding VMA (Viscosity Modifying Admixture) or reduce the amount of SP. Other reasons could be a wet mould, too low temperature or change in rate of pour. The primary reason of water scouring is bleeding of water and fines. The reason for this is a too high water to powder ratio or a too low viscosity (The Self-Compacting Concrete European Project Group, 2005). Because two errors leads to a too low viscosity it can be concluded that too much SP was added. It is strange to see that the front side of the panel is very smooth and the back side shows water scouring. But the quality of the front side is better than the quality of lightweight concrete.

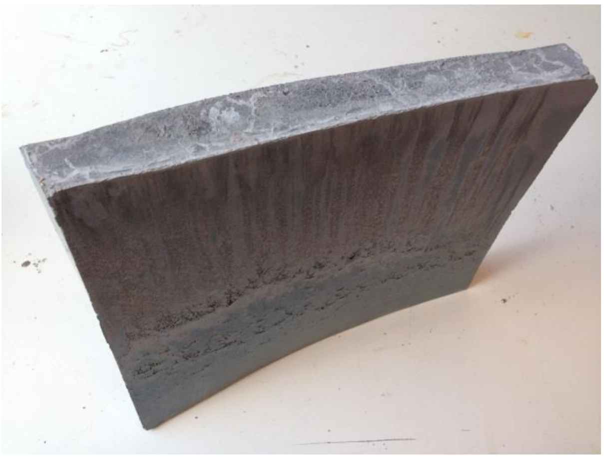


Figure 78a: Colour difference & Figure 78b: Visibility of stripes and water scouring

8.4.2 Experiment 2

The goal of the second experiment is to find the right amount of SP for the SCC. Three types of concrete will be mixed. Besides the adjustment of SP the gravel of 4-16 mm is left out the mixture (diagram 18). This is done because finer aggregates create a smoother panel. When gravel is not included the density and volume changes. The mixing sequence can also affect the end result of concrete. For this experiment the binder is mixed together with the other aggregates (diagram 19). Besides that also the mixing time is reduced. The total mixing time is between seven and nine minutes.

Diagram 18: Changed mixture

Required quantity per liter			
Mix B	**kg**	**(kg/dm³)**	**dm³**
Cement	0.315	2.950	0.107
Limestone	0.164	2.750	0.060
Sand 0 – 1 mm	-	2.650	-
Sand 0 – 2 mm	0.306	2.650	0.115
Sand 0 – 4 mm	0.719	2.650	0.271
Gravel 4 –16 mm		2.650	-
Water	0.173	1.000	0.173
Superplasticizer	Var.	1.045	
Total amount	**1.677**	-	**0.726**

Diagram 19: Changed mixing sequence

Mixing sequance		
Sand + Course LW aggregate + Binder	3/4 water	1/4 water + SP
1:00 min	3:00 min	3:00/ 5:00 min

Amount of SP per mixture and type of defect is shown in (diagram 20). The quality of each element can be seen in figure 79a, 79b and 79c. The experiments showed that the amount of SP needs to be very accurate. The viscosity was better, but there were still blow holes on the surface. Blow holes can have a few meanings; too high viscosity, unsuitable aggregate grading, rough mould surface, excessive fines, concrete temperature is too high, too long mixing time induces air. The conditions could have affected the result, because it was quite warm. The concrete was warm and hardened very quickly. Mixture 3 had the highest viscosity and was the most difficult to cast. Strange is that mixture 2 shows more blow holes than mixture 3. This can indicate to another problem, such as a too long mixing time. During mixing there is a curtain point in time where it becomes very fluid, maybe it is needed to stop before that point. The problem can also have something to do with skipping the gravel. Instead of gravel there could be an excessive of fines and an unsuitable aggregate grading. The colour difference is caused by a too low viscosity, which means that too much SP is added inside mixture 2 and 3. The little damage and the fact that it is not very smooth could be caused by too early demoulding.

Diagram 20: Type of defect in combination with the amount of SP

	Amount of SP (kg)	**Type of defect**
Mixture 1	0.050	Blow holes, colour difference.
Mixture 2	0.045	Vertical stripes or water scouring visible on concrete surface, blow holes, not very smooth, little damage on the edge and colour difference.
Mixture 3	0.040	Smaller blow holes (still visible), not very smooth.

Figure 79a: Result with mixture 1, Figure 79b: Result with mixture 2 & Figure 79c: Result with mixture 3

For further improvement the amount of SP will be estimated around 0,0425 kg/dm³. This is between mixture 2 and 3, also the mixing time will be watched very closely. When this does not give the solution, the grading of aggregates should be changed.

9. Design of the mould

Based on the experiments in the previous chapter, in this chapter choices will be made as regards the design of the mould for double curved panels of 500x500 mm. This chapter is divided into two parts, namely: vacuum forming machine and mould with counter pressure. To evaluate all the possible solutions for each part a morphological overview is used. In this way the choices will be substantiated.

9.1 Vacuum forming machine

Before the design phase of the mould some tests and research was done to get experience with vacuum forming. The most important factors that came out of this research were:

- The needed pressure for vacuum forming on top of a flexible layer is around 0.3 bar, which is lower than the atmospheric pressure.
- Airtightness has not to be very accurate, because there is no vacuum.
- The use of silicone rubber around the spring steel mesh results in good surface quality.

With these factors in mind a morphological analysis can be made for the final design of the mould.

9.1.1 Morphological overview

This chapter shows the morphological overview that is made as a head start for the final design of the vacuum forming machine. The morphological overview is divided into five parts:

A. General
B. Flexible layer
C. Pins
D. Heating
E. Vacuum Forming

The different parts were derived from literature and experimental study. Each part has several solutions for the design of the vacuum forming machine. All solutions are compared with each other and the best principle will be developed. The vacuum forming machine must meet the following requirements:

- Double curved forms with dimensions of 500x500 mm can be made
- The double curved forms must have a smooth surface
- It must be user friendly
- It must be a quick process

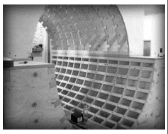
The complete morphological overview can be found in appendix C.

A General

This part was already mentioned in chapter 4 "Moulding principles". To make the overview complete also this part is taken in account to see in which category this new method belongs.

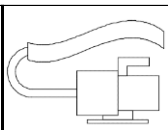
A1 Mould technique

The vacuum forming machine has to make all different kinds of double curved panels without any repetition. That is way the vacuum forming machine belongs in the flexible mould category.

A1	Mould technique						
		A1A	A1B	A1C			
		Static	Reusable	Flexible			

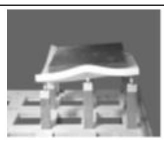
A2 Flexible mould technique

Because the vacuum forming machine consists of pins with a flexible layer, it belongs in the category "Supported Membrane".

A2	Flexible mould technique						
		A2A	A2B	A2C	A2D		
		Pinbed	Supported membrane	Tensioned Membrane	Vacuumed Membrane		

A3 Supported membrane technique

Maybe the vacuum forming machine will be placed in the future in this list.

A3	Supported membrane technique				?		
		A3A	A3B	A3C	A3D		
		Rubber frame - pouring directly (Schipper, 2014)	Hydrostatic - pouring directly (Verhaegh, 2010)	Wax formwork - countermould (Oesterle, 2012)	Vacuum forming - countermould (Lusing & Versteeg, 2015)		

B Flexible layer

Part B "Flexible layer" is divided in four components, namely: material, stiffness, material top layer and if this top layer is attached or loose. The goal of the supported flexible layer is that it can be formed in any possible surface. These surfaces can be categorized according the Gaussian curvature. The explanation of the Gaussian curvature is illustrated in figure 80. The normal vector can be placed on every given point on the curvature. From that point the different principal curvatures follow the normal planes. The sections created with the normal planes are called normal sections and the curvature is called normal curvature. When complex surfaces are used, different sections will have different curvatures. The minimum and maximum of these curvatures are called the principal curvatures (k1, k2). The Gaussian curvature is the product of both principal curvatures (Van Rijbroek & Verboord, 2015).

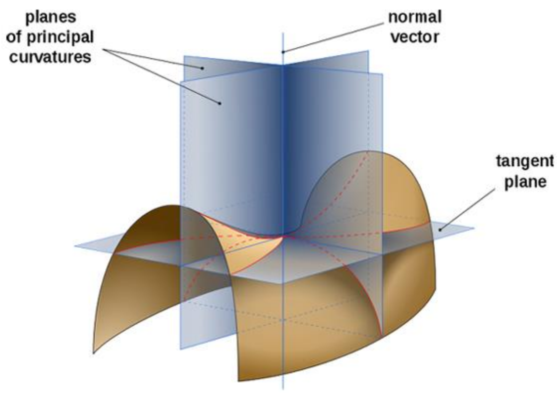


Figure 80: Explanation of the Gaussian curvature (Wikipedia, 2015)

Surface curvatures can be classified in four categories according to is Gaussian curvature (figure 81) (Pronk & Dominicus, 2013):

1. If the Gaussian curvature is zero (k1k2=0) and both principal curvatures are zero, the surface is zeroclastic.
2. If the Gaussian curvature is zero (k1k2=0) and only one curvature is equal to zero, the surface is monoclastic at that point.
3. If the Gaussian curvature is positive (k1k2>0), both principle curves are same. This means the surface is synclastic.
4. If the Gaussian curvature is negative (k1k2<0), the principal curvatures are different. This means the surface is anticlastic.

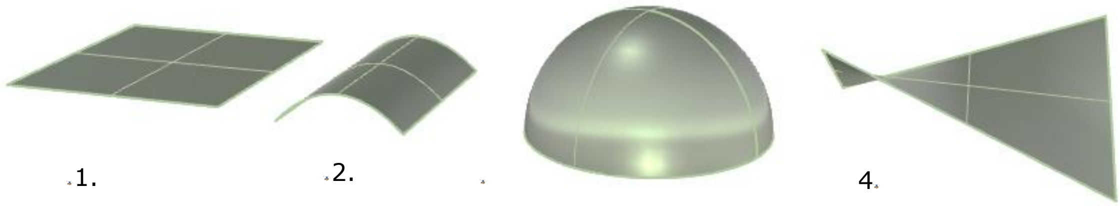
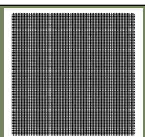


Figure 81: Surface curvatures according to the Gaussian curvature (Pronk & Dominicus, 2013)

B1 Material

The adjustable flexible surface of the vacuum mould is based on a woven spring-steel (figure 82a). The properties of the woven mesh makes it possible to form double curved surfaces. A well-known example proving the adjustable properties of a woven steel mesh is a synclastic tea-strainer (figure 82b). The only disadvantage of the material is that spring steel loses its flexible properties when it reaches a temperature above 200 °C. This disadvantage is not a problem, because such high temperatures will not be reached with vacuum forming. Another disadvantage is the surface of spring steel. The openings of the mesh will be seen on the plastic sheet and thereby also in the surface of the concrete panel.


Figure 82a: Close up of spring steel & Figure 82b: Synclastic tea-strainer (Soothing Sip, 2015)

B1	Material						
		B1A					
		Spring steel					

B2 Stiffness

There are different kinds of spring steel on the market. In this morphological overview a comparison is made between a flexible and a stiff spring steel mesh.

B2A Flexible

The flexible spring steel mesh has a wire diameter of 0.8 mm with openings of 1.75 mm (Omnimesh, WNFE3). It is easy to form double curved shapes through the 0.8 mm wire diameter. An experiment with this type of spring steel shows that this sheet has the same shape as the steel mesh that is set in the right position (figure 83a & 83b). The opinion, before this experiment, was that maybe the mesh was not strong enough for the pressure of the vacuum cleaner. The result of the experiment shows that this was not a problem.

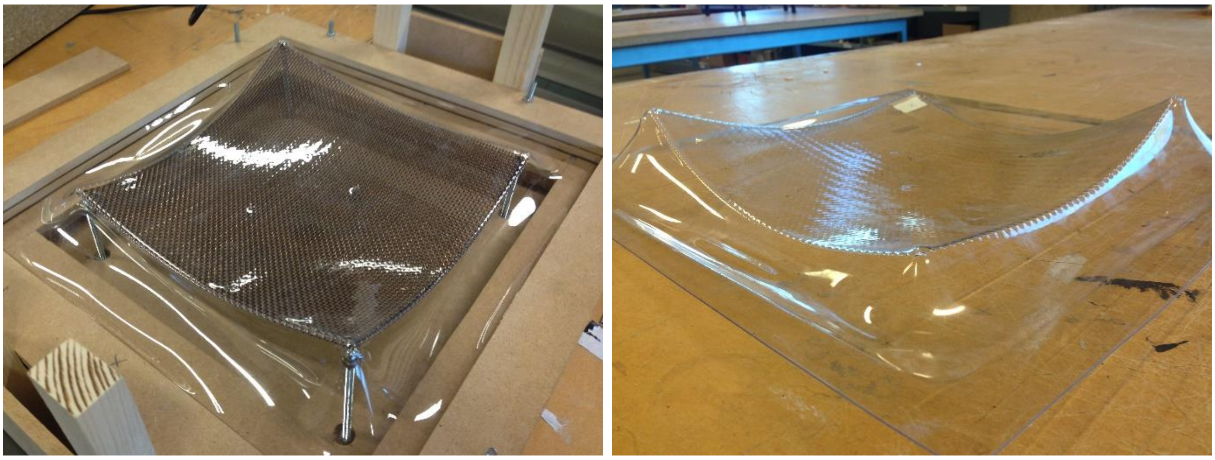


Figure 83a & 83b: Experiment with flexible spring steel

B2B Stiff

The stiff spring steel mesh has a wire diameter of 1.25 mm with openings of 2 mm (Omnimesh, WNFE3). Also an experiment with the stiff spring steel is done. The result of this experiment was the same as the one with the flexible spring steel (figure 84a & 84b). The disadvantages of this spring steel compared to the flexible spring steel is that it is more difficult to set the pins in the right position (wire diameter of 1.25 mm) and the investment costs are higher.

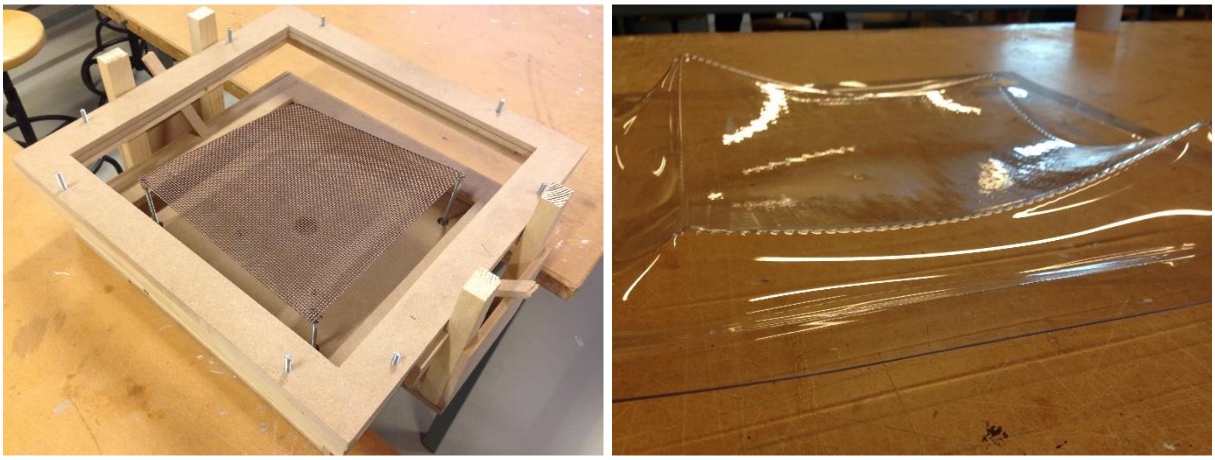


Figure 84a & 84b: Experiment with stiff spring steel

Final choice:

B2	Stifness						
		B2A	B2B				
		Flexible	Stiff				

B3 Material top layer

To avoid the imprint of the spring steel a top layer could be used. Because spring style is a hard material thin and soft materials are not suitable as top layer. Two materials that have better properties for this problem are silicone and felt. Both materials were tested by means of an experiment.

B3A Silicone

Silicone is an elastomer with properties non-reactive, stable, and resistant to extreme environments and temperatures from -55 °C to 300 °C (Kremer & Richtering, 2011). For the experiment a two components silicone top layer is used with a hardness of shore A10 and the mixing ratio of the two components (hardener and rubber) is 1:1 (Poly-Service, 2015). The silicone on the membrane resulted in a smooth surface (figure 85a & 85b), but the disadvantage is that the PETG sheet (thickness: 1 mm) cannot be moved again when it came in contact with the membrane. Because the PETG sheet is extendable when it is plastically, this is not a problem.

Figure 85a & 85b: Experiment with silicone

B3B Felt

Another solution is using felt as top layer material (figure 86a). Felt is a fabric which is usually made of wool or other animal hair, often mixed with natural or synthetic fibres. The loose fibres are connected to each other by the action of heat, moisture, chemicals and pressure, without spinning, weaving or knitting (Encyclo.nl, 2015). The felt that is used for the experiment is construction felt (Vilton 22 bouwvilt). The result of vacuum forming of a 1 mm PS sheet over the felt was not very good, because the pins were visible on the surface of the PS sheet (figure 86b). Also the extensibility of the felt is not so good, this could be a problem when other double curved forms have to be made.

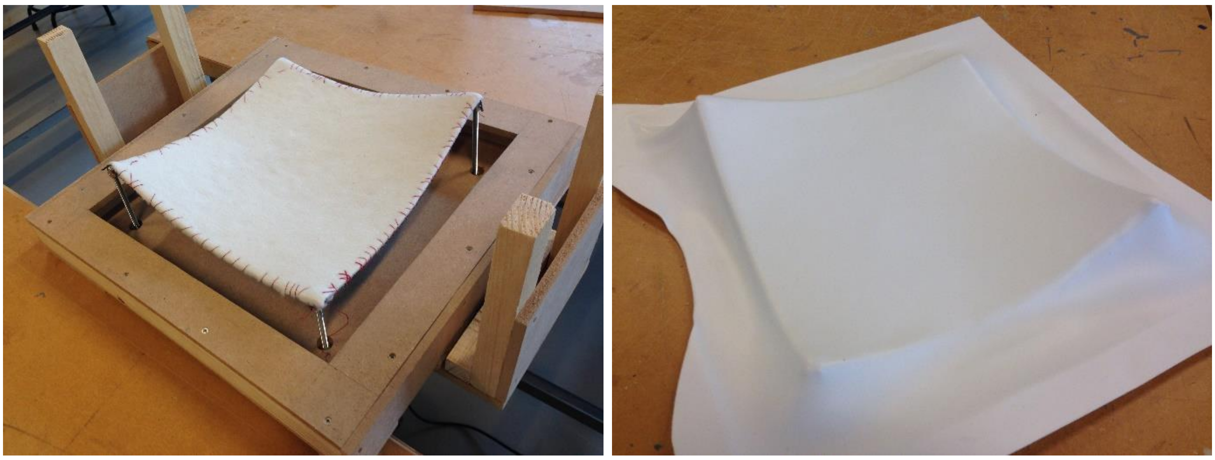


Figure 86a: Experiment with felt as top layer & Figure 86b: Result of the experiment

Final choice:

B3	Material top layer						
		B3A	B3B				
		Silicone	Felt				

B4 Top layer

The top layer of silicone can be used in two ways: loose on the spring steel mesh or attached at the spring steel mesh.

B4A Loose

The disadvantage of a loose top layer is that it could move on top of the spring steel mesh. Besides that silicone is an ideal material to combine with the spring steel mesh, as one flexible and extendible layer with a smooth surface. This is the reason that this method is not tested.

B4B Attached

For this experiment a wooden mould is made. The spring steel mesh will be kept at a distance by spacers (figure 87a). In these spacers holes are drilled for the steel wire, which can be used for connecting the mesh with the actuators. For this experiment also a two components silicone rubber is used, but this time with a hardness of shore A30. The hardness of shore A30 is a little bit stiffer than the silicone with a hardness of shore A10. The mixing ratio of the two components (hardener and rubber) is the same, namely 1:1 (Poly-Service, 2015). The result of the experiment was a good smooth and flexible top layer (figure 87b). A critical point is that coverage on top of the spring steel mesh has to be enough, because otherwise the pins can be seen through the surface of the flexible layer.

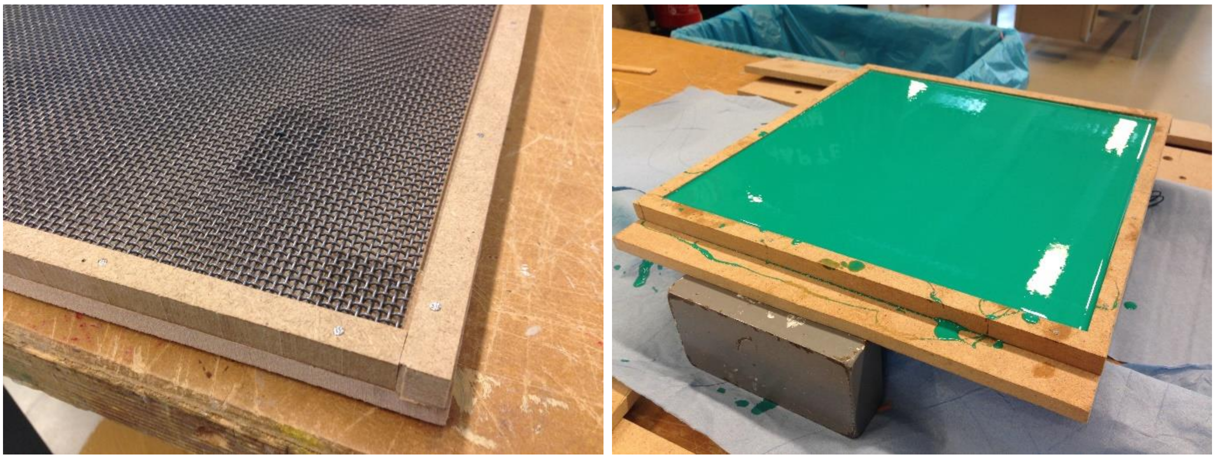
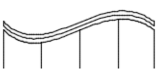


Figure 87a & 87b: Spring steel casted in silicone

Final choice:

B4	Top layer						
		B4A	B4B				
		Loose	Attached				

C Pins

The component "pins" is divided into six parts: spacing, type, joint at flexible layer, prevent axial rotation, set height and lifting.

C1 Spacing

The pin spacing depends on how extreme the forms can be made with the mould. The radius of existing double curved constructions varies between 0,75 m and 45 m. This implies the use of many actuators is unnecessary (Schipper, Grünewald, Eigenraam, Raghunath, & Kok, 2014). With nine pins less extreme forms can be made than with 25 pins. The mould must be suitable for double curved panels with dimensions of 500x500 mm. To create smooth curves and surfaces NURBS can be used.

NURBS (Non-Uniform Rational Basis-Splines) are mathematical representations of two- or three-dimensional objects, which can be standard shapes or free-form shapes. NURBS are used in computer graphics and the CAD/CAM industry and have come to be regarded as a standard way to create and represent complex objects. In addition to curves and surfaces, NURBS can also represent hyper surfaces. Most sophisticated graphic creation tools provide an interface for using NURBS, which are flexible enough to design a wide range of shapes. NURBS are compact expressions that can be evaluated and displayed quickly. NURBS work especially well in 3D modelling, allowing the designer to easily manipulate control vertices, called ISO curves, and control curvature and the smoothness of contours. NURBS are defined by both control points and weights. It takes very little data to define a NURB (Rouse, 2011).

Because the panels are 500x500 mm, four different pin spacing's are chosen with round numbers (figure 88). With a pin spacing of 250 mm three pins are needed. The forms that can be made with these pins are always single curved and are not suitable for making double curved forms. Double curved forms are not a problem for the other three types of pin spacing (125 mm, 100 mm & 50 mm). Then another aspect that has to be taken into account is investment costs. The more pins, the more expensive the mould will be. The pin spacing with largest dimension (125 mm) has the lowest investment costs. The pressure that will be released on the flexible layer during the vacuum forming process is not a problem for this dimension, because this will be taken care of by the flexible layer with the spring steel mesh.

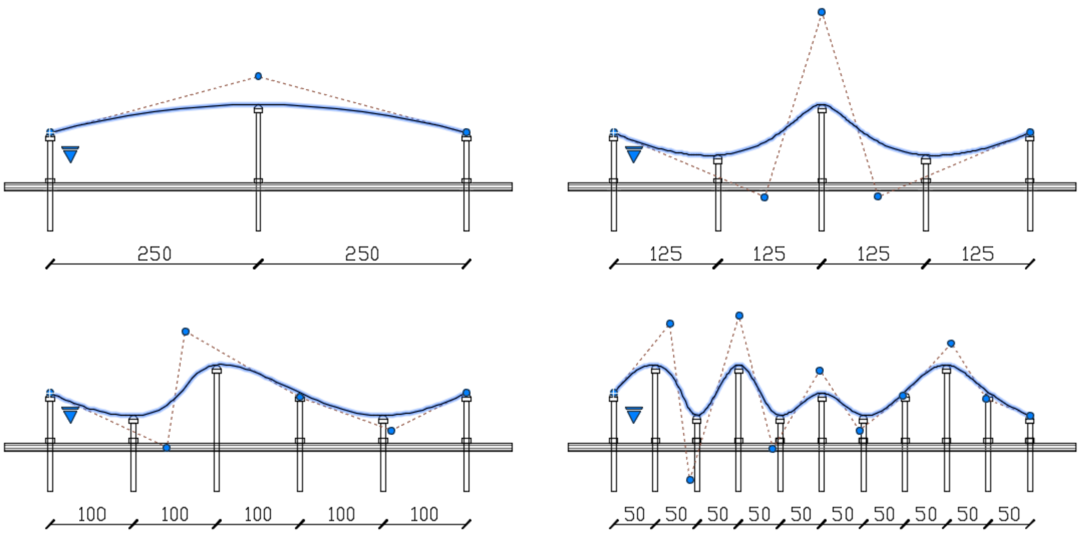
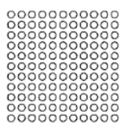
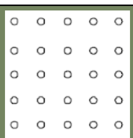
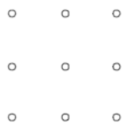


Figure 88: Possible curves with a pin spacing of 250 mm, 125 mm, 100 mm and 50 mm

Final choice:

C1	Spacing						
		C1A	C1B	C1C	C1D		
		50mm	100mm	125mm	250mm		

C2 *Type*

The pins of the Fluid Mould (Van Rijbroek & Verboord, Fluid Mould, 2015) will also be used in this new mould. These pins are made of RVS. There are three types of pins: non-pendulum pins (fixed), pins with clevis eyes connections (hinge) and pins with ball joints (ball) (figure 89).

Figure 89: Non-pendulum pin, pin with a clevis eye connection and a pin with a ball joint

The position of the pins is also an issue. Not every pin can be placed anywhere. The centre pin is always fixated. If the other pins are also fixated (figure 90a), the flexible layer has to be very elastic. The flexible layer is not that elastic. The solution is using pins with clevis eyes connections (h) or ball joints (b) or the combination of it. If the rest of pins are all with clevis eyes there could be a rotation problem (figure 90b), because the clevis eyes can only hinge at one direction. The choice will be made between all ball joints (figure 90c) or the combination of ball joints with clevis eyes connections (figure 90d). The investments costs are not a problem, because they are low-cost products. Because the amount of pins with all ball joints and one non-pendulum was not available, a combination is chosen of pins with ball joints and clevis eyes connections. The clevis eyes will be placed in the centre of each row, because they hinge in one direction. The other pins will be ball joints. These ball joints rotate 360 °C and has maximum angle of 30°. This must be taken in account (Van Rijbroek & Verboord, Fluid Mould, 2015).

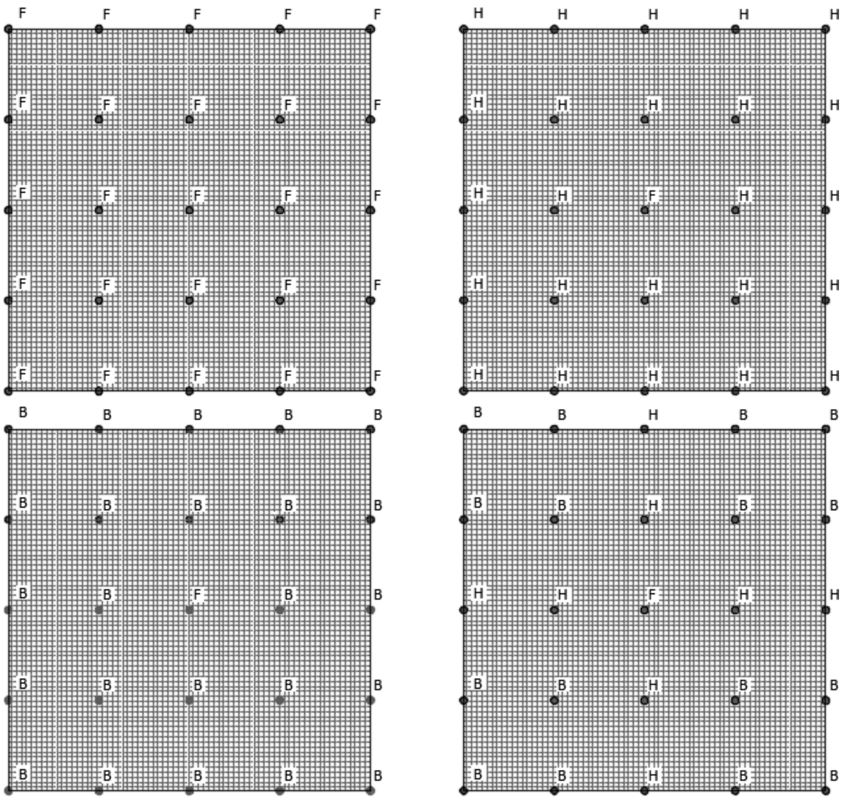


Figure 90a: All fixated, Figure 90b: Fixated with clevis eyes, Figure 90c: Fixed with ball joints & Figure 90d: Fixed with clevis eyes and ball joints

Final choice:

C2	Type	C2A Fixed	C2B Hinge	C2C Roller	C2D Fixed & Hinge	C2E Fixed & Roller	C2F Fixed, Hinge & Roller

C3 Joint at flexible layer

There are several solutions to attach the flexible layer with the pins. For instance gluing or screwing. Because a flexible layer is chosen in combination with a spring steel mesh the actuators can also be attached at the spring steel mesh. This can be done by the use of steel wire. These steel wires will be casted along with the spring steel mesh (figure 91a). When using cap nuts on top of the pins it is easy to connect the steel wire with the pins, when holes are drilled in the cap nut (figure 91b).

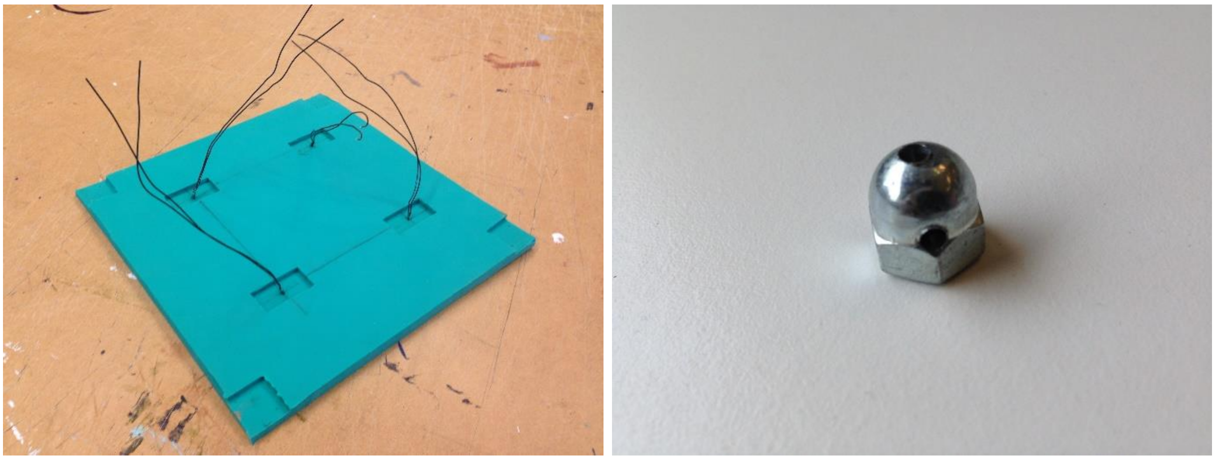


Figure 91a: Steel wire cast along with the spring steel mesh in the silicone & Figure 91b: Holes in the cap nuts ensure that it is easy to connect the flexible layer with the pins

Final choice:

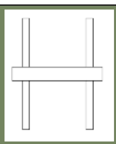
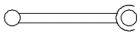
C3	Joint at flexible layer	C3A Glue	C3B Attach to spring steel	C3C Screw			

C4 Prevent axial rotations

When the pins are only fixated at the spring steel mesh axial rotation can take place. To avoid this axial rotation a squared pin or modified treated pins could be used. But both solutions lead to little deformations in the axial rotation. A good solution for this problem is using a support actuator. When one actuator will be connected to the other the axial rotation can be prevented. This can be done by the use of wooden strip (figure 92a & 92b). The wooden strip has to be fixated to one pin, to prevent torqueing and the other pin serves as a guide. In this way the arm of the point of engagement is extended (Van Rijbroek & Verboord, 2015).


Figure 92a & Figure 92b: Bottom & Top view - Wooden strip preventing axial rotation of the pin with clevis eye connection

Final choice:

C4	Prevent axial rotation						
		C4A	C4B	C4C			
		Squared	Supported	Modified treated			

C5 Set height

There are different options for setting the pins in the right heights, namely: nuts, hose clamps or by the use of step motors. The cheapest solution is setting the height by the use of nuts (figure 93a). The disadvantage of this option is the labour intensity. It takes some time to set 25 pins in the right height. The option with hose clamps is an alternative for nuts (figure 93b). The disadvantage of this solution is that it is difficult to find hose clamps with a diameter around 8 mm and it is difficult to pull on the hose clamps. The third option is the most expensive one. For the future step motors could be a good solution. But because this mould is just a prototype, setting the pins in the right height by the use of nuts is chosen.

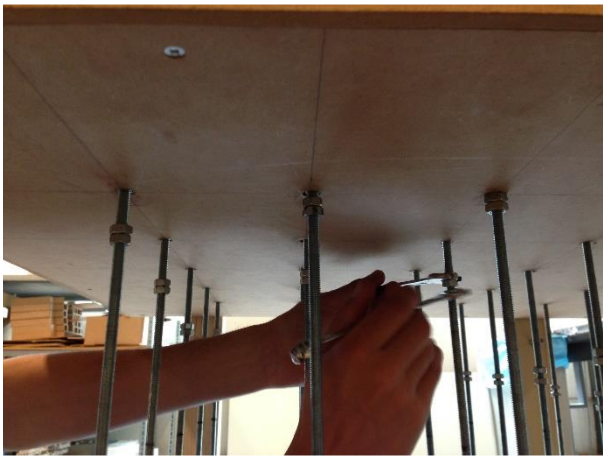
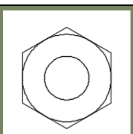
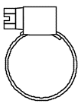
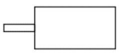



Figure 93a: Setting the height by the use of nuts & Figure 93b: Hose clamp

Final choice:

C5	Set height						
		C5A	C5B	C5C			
		Nuts	Hose clamps	Step motor			

C6 Lifting

The lifting of the pins can be done in several ways, for instance by hand, with a lifting jack and a step motor. The reason for not choosing the step motor as solution is the same as in the previous part. The disadvantage of lifting the pins with a lifting jack is the same as of the step motor, namely the investment costs. A cheaper solution is lifting the pins by hand. At this option a wooden sheet will lift to the bottom of the vacuum forming machine (figure 94). This wooden plate must then be fixated temporarily by a bolt to prevent lowering.

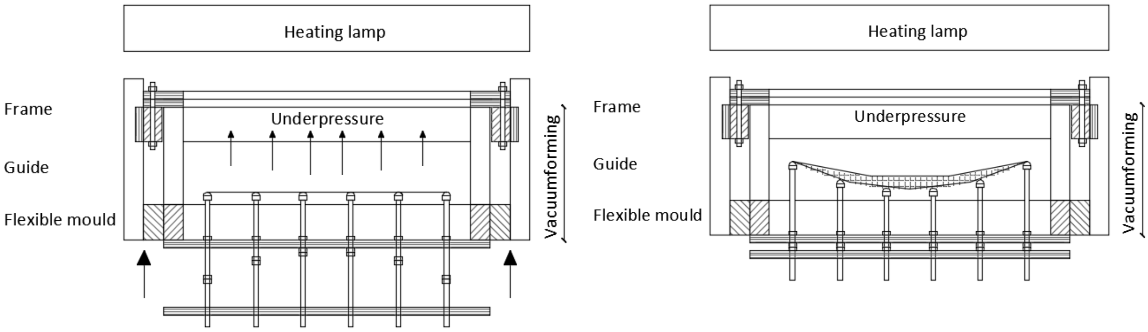
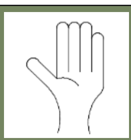
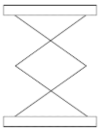
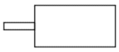


Figure 94: Lifting the pins by a wooden sheet

Final choice:

C6	Lifting						
		C6A	C6B	C6C			
		By hand	Lifting jack	Step motor			

D Heating

There are different ways of heating up a plastic sheet. In this paragraph four different options will be discussed, namely: the hot air gun, the heating lamp, the intermediate dryer and the patio heater.

DA Hot air gun

The hot air gun was already mentioned in chapter 7.4, about the experiments with vacuum forming. Spreading the heat over a plastic sheet by hand with the hot air gun does not work, because the sheet is quickly cooled down. A box is needed so that all the heat is transferred to the plastic sheet and not gets lost to the surroundings (figure 95a). For equal circulation of the hot air, a plate with a fire resistant material (Pyrogel XT Plus – 5 mm) is placed underneath the hot air gun to avoid overheating at one spot (figure 95b). Disadvantage of this process is the heating time of around 20 minutes.

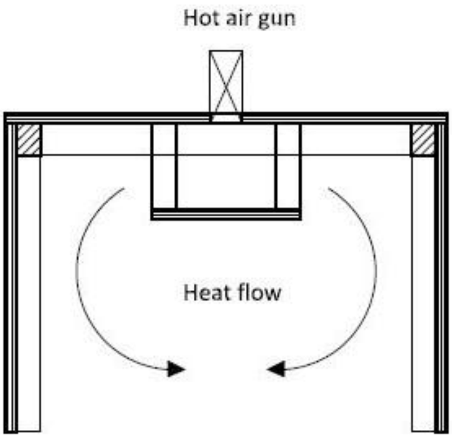


Figure 95a: Setup hot air gun & Figure 95b: Heat flow

DB Heating lamp

Another way of heating up a plastic sheet is with the use of heating lamps. In the test setup four heating lamps (Philips Infrared, R125 IR – 250W) are placed 13 cm above a PS sheet (45x45 cm). The heating lamps are placed with a centre-to-centre distance of 25 cm (figure 96a). When the heating lamps are turned on, the problem can be seen on the white PS sheet (figure 96b). The light beams of the heating lamps are too small for the plastic sheet. In this way only a small part of the sheet is heated up. This problem can be solved by adding more heating lamps in the setup, but that is also more expensive. Another solution is by placing the heating lamps further above the PS sheet, but then the process time will be longer.

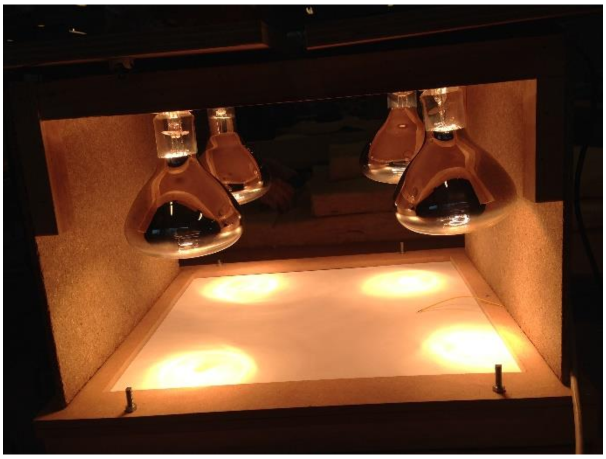
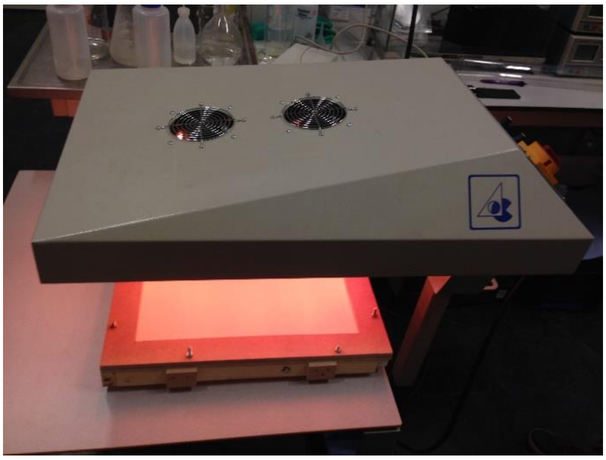


Figure 96a: Setup heating lamps & Figure 96b: Locally heated

DC Intermediate dryer

An intermediate dryer is normally used for quick drying of elements in an experimental way. The intermediate dryer that is used for the test has a power level of 6000 W (Texflash Evolution). In the test setup the intermediate dryer is placed 23 cm above a PS sheet (45x45 cm) (figure 97a & 97b). Because of the high power level of the intermediate dryer, the PS sheet is fully plastically after around five minutes. The heating sensor (Yokogama – Model 2455) measured 90 °C directly above the sheet. The main advantage of this system is the quick process. The disadvantage is that the intermediate dryer only works 20 seconds, then it has to be turned back on. Also the investment costs of the intermediate dryer are high.



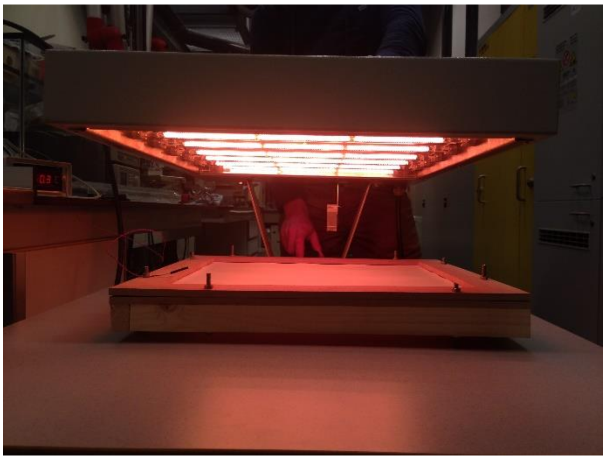


Figure 97a & 97b: Setup intermediate dryer

DD Patio heater

The patio heater is a good alternative to the intermediate dryer. The patio heater consists of three quartz lamps filled with highly pressurized halogen gas. The maximum power level of a patio heater (around 2000 W) is lower than the power level of the intermediate dryer, but the patio heater works longer and the investment costs are lower. The patio heater that is used for testing has three power level modes: 650 W, 1350 W and 2000 W (Eurom TH2003). Because the power level is lower, a choice was made for two patio heaters. To ensure that the heat will not quickly disappear the patio heaters are placed in a wooden box that is coated with aluminium foil (figure 98a & 98b). With this test setup a PS sheet with a thickness 2 mm is fully plastically in ten minutes with a power level mode of both patio heaters of 1350 W. The heating sensor (Yokogama – Model 2455) measured 80 °C directly above the sheet.

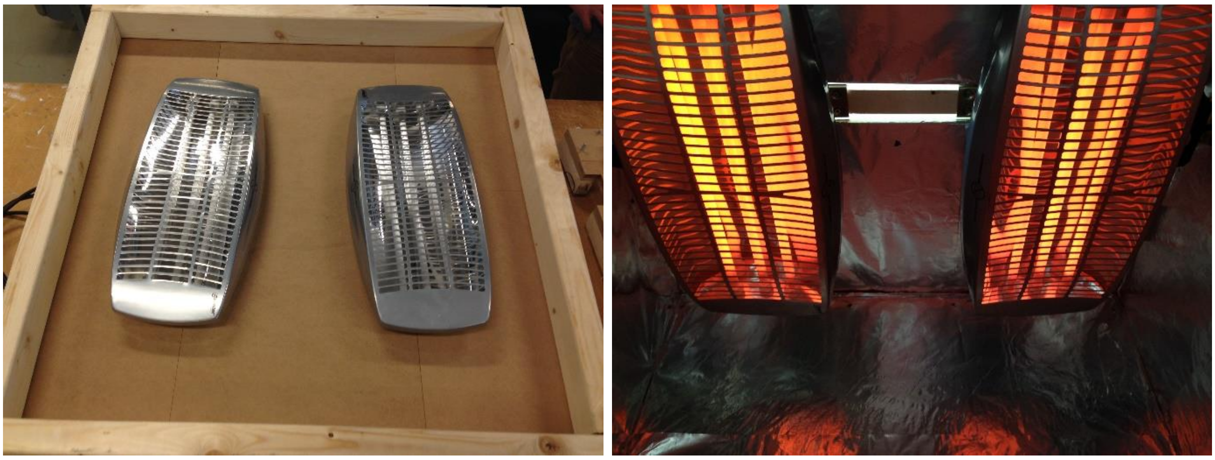
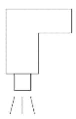
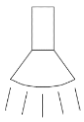
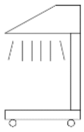
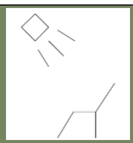


Figure 98a & 98b: Setup patio heaters

Final choice:

	Heating						
		DA	DB	DC	DD		
		Hot air gun	Heating lamp	Intermediate dryer	Patio Heater		

E Vacuum forming

This part of the morphological overview is divided in two parts: the equipment that will be used for vacuum forming and the way of vacuum forming.

E1 Equipment

There are two types of equipment that can be used for vacuum forming, namely: a vacuum pump or a vacuum cleaner.

E1A Vacuum pump

As already mentioned in chapter 7.3 "Vacuum forming machine – Bas Hesselink IDAP" the pressure of only a vacuum pump is too high for the vacuum forming process of this research. The only option to use a vacuum pump in this research is when the pressure is adaptable. This can be done by the use of a buffer tank (figure 99a). In this way the pressure can be controlled (figure 99b). The disadvantage of this solution is the high investment costs.

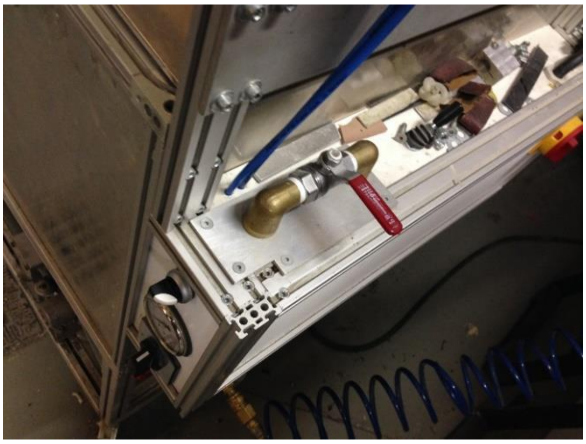


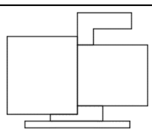
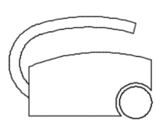
Figure 99a: Buffer tank to control the pressure & Figure 99b: Controller of the pressure

E1B Vacuum cleaner

Because the pressure does not have to be so high, it is also possible to simply use a vacuum cleaner. This is a cheaper solution then the vacuum pump and it is already used in the testing phase (chapter 7.4). The only question is whether the vacuum cleaner is powerful enough. The vacuum cleaner that was used in the testing phase has a capacity of 1800 W (Siemens, Big bag 3l) (figure 100a & 100b). If this vacuum cleaner is not powerful enough also an industrial vacuum cleaner can be used.

Figure 100a & 100b: Vacuum cleaner that is used for the testing phase

Final choice:

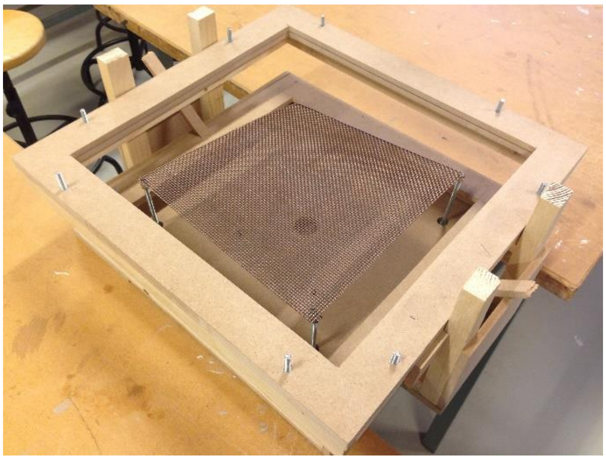
E1	Equipment						
		E1A	E1B				
		Vacuum pump	Vacuum cleaner				

E2 Way

There are two ways of vacuum forming: lowering and pulling up

E2A Lowering

The lowering principle was already mentioned in the testing phase of chapter 7.4 "Vacuum forming machine – Custom-made" (figure 101a). The advantage of this principle is that it is easy to pull the plastic sheet over the flexible membrane. Another advantage is the height of the box that will be vacuum formed. Because the box is low it is easy for the vacuum cleaner to create the under pressure quickly (figure 101b). A disadvantage of this principle is that the connection of the frame with the flexible mould has to be perfect and airtight.



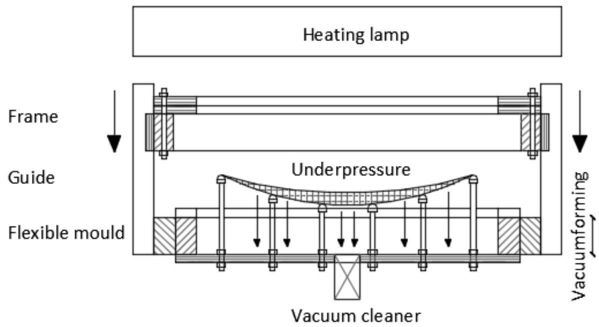
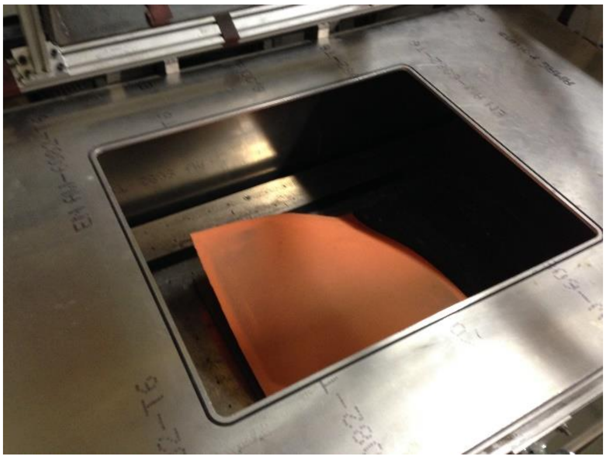


Figure 101a: Lowering principle of the testing phase & Figure 101b: It is easy to vacuum because the box is low

E2B Pulling up

The most vacuum forming machines are working this way (figure 102a). The pulling up principle means that the model is pulled through the plastic sheet. In our case this is a difficult principle, because we have many pins to be pulled up, what makes it very heavy. Also the process of making the box complete vacuum takes longer, because the box has to be much higher (figure 102b).



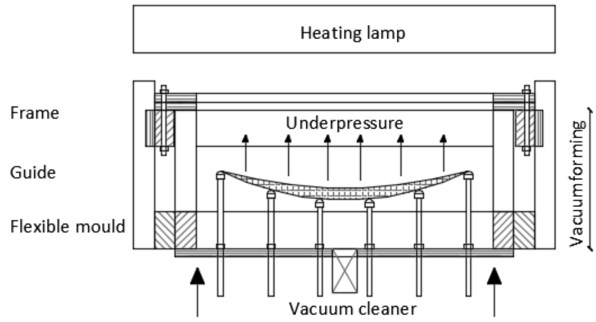
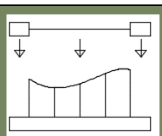
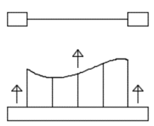


Figure 102a: Pulling up principle of the vacuum forming machine of Bas Hesselink IDAP & Figure 102b: It takes longer to vacuum because the box is higher

Final choice:

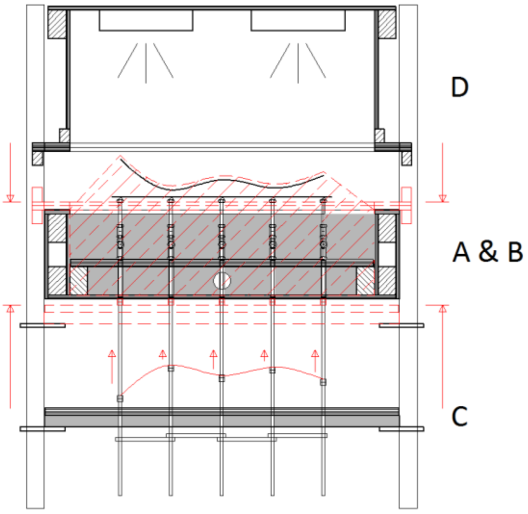
E2	Way						
		E2A	E2B				
		Lowering	Pulling up				

9.1.2 VaCo Mould – Vacuum forming machine

The VaCo Mould 'Vacuum Counter Pressure Mould' is approximately the same as for the test mould of 300x300 mm. This definitive mould can produce double curved plastic sheets with a dimension of 500x500 mm. Based upon the morphological matrix the best solution of each parameter is used to design the vacuum mould. The decisions were mainly based on the relation between material properties and costs. The mould consists of four important parts:

A. The main construction
B. The pins and interpolation sheet
C. Lifting principal
D. Heating element

These parts and the final mould can be seen in figure 103a and 103b and will be further elaborated in separate paragraphs. The figure shows the moving parts of the mould. First the pins are lifted at the correct height (which starts at *part C*). Then the heated plastic sheet moves (from *part D*) on top of the adjusted pins (*part B*) to create the final shape. *Part A* is the construction and ensures an airtight box to stimulate a good working vacuum machine. The vacuum is still provided with a vacuum cleaner that can be adjusted in different amount of pulling power. The pulling power guarantees a smooth curvature of the plastic sheet. These plastic sheets will be used later in the hydrostatic mould. The definitive drawing including dimensions and details and text are added in appendix D.



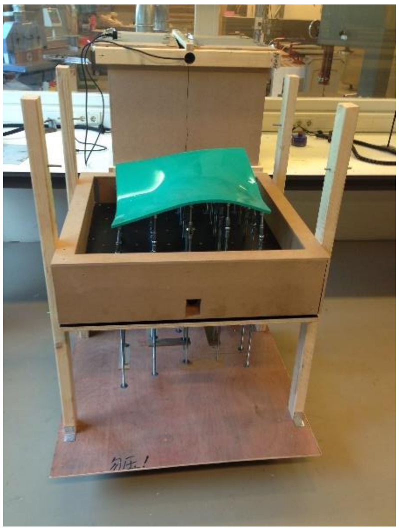


Figure 103a: Section of the final mould & Figure 103b: The final mould

A Main construction

The main construction consists of columns that transfer the loads to the ground (1), the frame for clamping the plastic sheet (2) and the airtight box to create a vacuum (3) (figure 104a). The main construction of the mould is made of wood instead of steel, because it is easier for us to manufacture, low in costs and the difference in measurement deviation will not be very high. The construction parts that have to withstand heavy loads are made of plywood for concrete purposes. The non-constructional parts are made of MDF. The dimensions of the mould are shown in diagram 21. The frame is made of separate MDF plates and is screwed together with battens (2.1) to create more rigidity. The clamping of the sheets is realized with bolds and nuts. The airtight box is used to obtain under pressure with a vacuum cleaner (figure 104b). The vacuum cleaner is attached to the side of the airtight box (3.2). The perforated sheet (3.1) is filled with tubes to guide the pins (3.3) and holes to create the vacuum. This sheet is made of plywood for concrete purposes, because it has to withstand the forces of the pins. The red hatch represents the volume that needs to be vacuum formed. The flange (3.4) is needed for the connection with the frame. The height of the flange has approximately the same height as the pins, 122 mm.

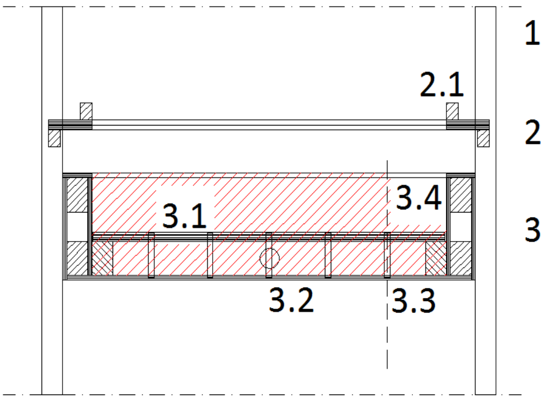


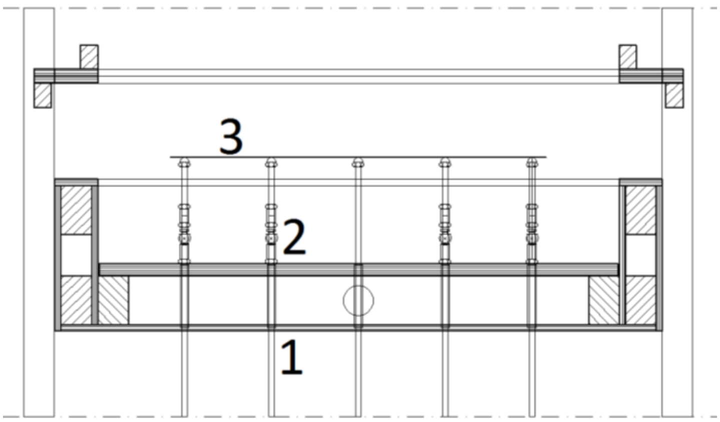
Figure 104a: Main construction & Figure 104b: Airtight box

Diagram 21: Dimensions of the mould

Compenent	Size (mm) or Amount (ps.)
Height	1500
Outer size Vacuum Forming Box	874 x 874
Including Columns	972 x 874
Outer size Frame	934 x 934
Inner size Frame	750 x 750

B The pins and interpolation sheet

The pins are made of threaded rods (1) and can move in direction by different hinges (2). The interpolation sheet (3) is placed on top of the pins and is connected with bulb shaped nuts. The form is set into place by 25 pins divided over the surface of 500x500 mm. This results in a pin spacing of 125 mm. The drawing and illustration of construction is shown in figure 105a and 105b. The amount and size of the pins and interpolation sheet are given in diagram 22.



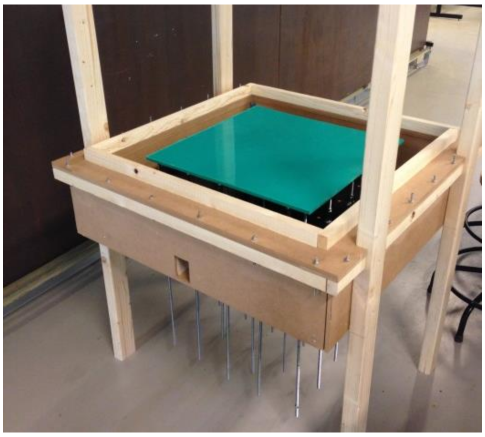


Figure 105a: Technical drawing of construction & Figure 105b: Construction of the final mould

Diagram 22: Amount & size of the pins and interpolation sheet

Compenent	Size (mm) or Amount (ps.)
Pin spacing	125
Pin diameter	8
Interpolation sheet	550x550
Final plastic sheet	500x500
Amount of ball joint connections	16
Clevis eye connections	8
Non- pendulum rods	1

The interpolation sheet is made of elastic rubber (silicone) with a spring steel mesh in the middle. The mesh ensures that after a shape is made it can return to its original shape, whereby the silicone layer is used to create a smooth surface connection with the plastic sheet. In figure 106a and 106b the manufacturing of the interpolation sheet is illustrated. The mould is made of MDF with a flange of 12 mm. This is done to create a silicone layer of 10 mm thickness. The spring steel is kept in place by spacers; to be sure the mesh will be in the middle of the silicone layer. The steel wires are attached to the steel mesh and are used for the connection with the bulb shaped nut. These nuts will be fixated to the steel mesh, which means that the pins are set from the middle of the sheet. The silicone rubber PS 8530 consists of two components a basis and a hardener. The components will be mixed 1:1 and poured in the mould. It is hardened after two hours.

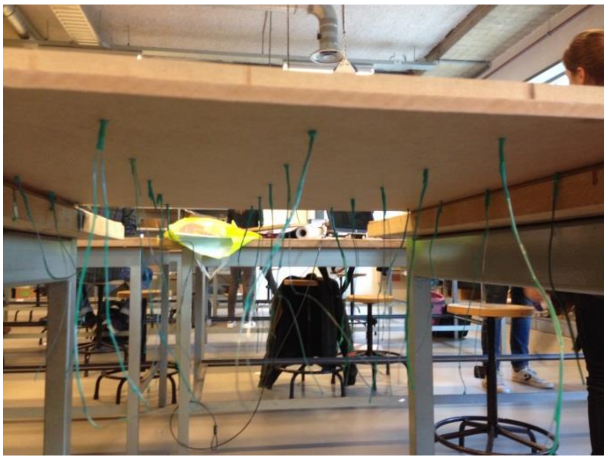
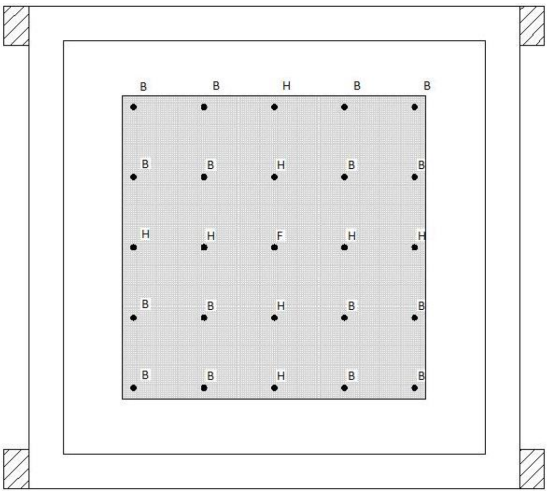



Figure 106a & Figure 106b: Manufacturing of the interpolation sheet

After demoulding of the mould the bulb nuts will be attached to the interpolation sheet. When the layer is ready it can be connected to the pins. First the pins must be placed inside the tubes of the perforated sheet. The layout of the pins can be seen in figure 107a. For this mould three kind of pins are used: non- pendulum rods, ball joint connection and the clevis eye connection. The layout shows one fixated rod (F) in the middle, which keeps the interpolation sheet into place, a cross of clevis eye connection that can only move in direction (H) and the others are ball joint connections (B), that can move in all directions. When double curved shapes are made the corners of the interpolation sheet will turn inside, which makes the area smaller from the front size. This is the reason for the oversized layer. The distance between the frame and the first pin is the same as the pin spacing, 125 mm. The space is kept to be sure that the angle to the first pin during vacuum forming will not be too big. When the space is too small it can cause failure of the plastic sheet. Between all 25 pins the plate is perforated to create an equal pulling pressure during vacuum forming. When the pins are set, the interpolation sheet can be connected (figure 107b).



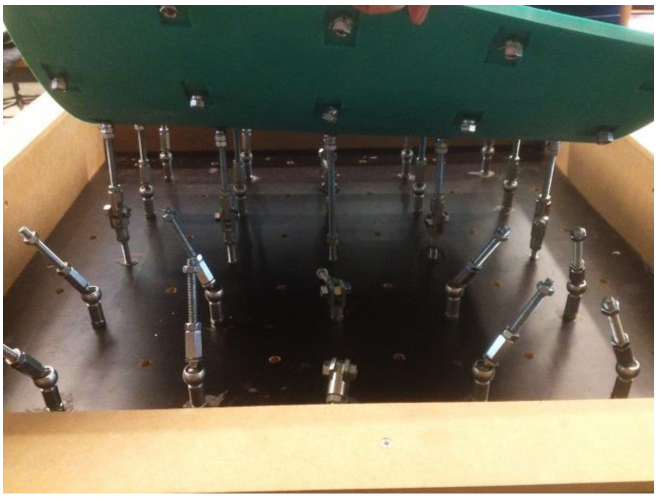
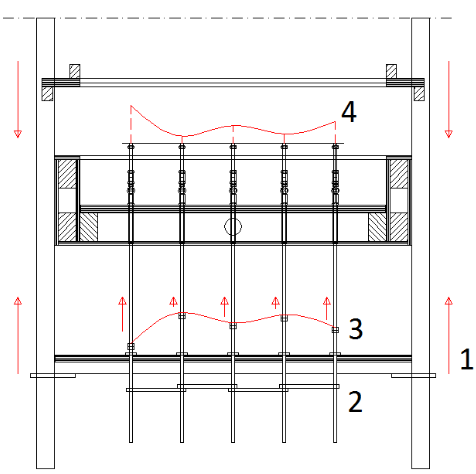


Figure 107a: Layout of the pins & Figure 107b: Connection of the interpolation sheet with the pins

C Lifting principal

The lifting principle consists of a lifting plate (1), connection pieces between the pins (2), adjusting the height (3) and the final shape after lifting (4) (figure 108a). The lifting plate is made of plywood for concrete purposes, because it should lift the pins. Underneath the edges of the plate, battens are placed for the connection with the columns. A pin can be pulled out to adjust the height of the plate. When the pins are placed through the plate, they are joined together to avoid friction of the pins (figure 108b). The nuts of the mould can be adjusted in height to create the right curvature. After that the plate is pulled up against the bottom plat of the airtight box and the final is realized.



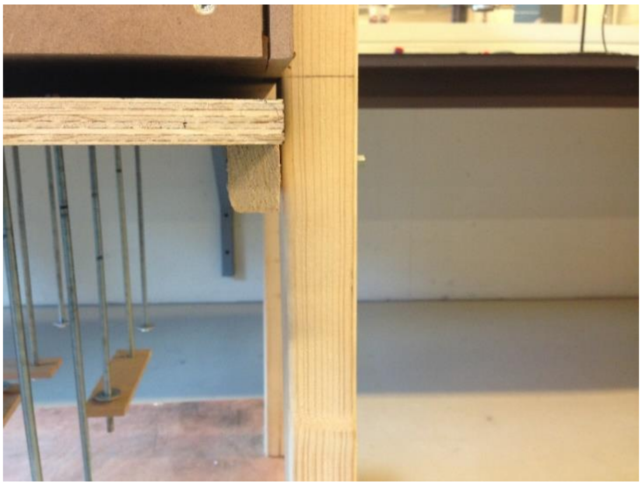


Figure 108a: Lifting principle & Figure 108b: Pins are placed through the plate

D Heating element

In this stage of the process the plastic sheet is heated (1) and pulled down on top of the pins (2) (figure 109a & 109b). The heating is realized with two Eurom TH2003 heaters. The power of this heater can be set to 650-, 1350-, 2000 W. The size of one heater is 17x49x29 cm. The goal of the heating element is to heat a plastic sheet with an area of 750x750 mm. The type of sheet that is used is described in 9.1.3, the plastic sheet. Important is that the heat is divided equally over the sheet, that is why the elements are placed inside a box. This means that the middle and the edges of the sheet reach the same temperature that is needed for vacuum forming of the sheet. When the sheet is flexible enough it can be pulled down onto the airtight box, where a vacuum is created underneath the flexible form. The vacuum is realized by using a vacuum cleaner. The vacuum cleaner will be switched of when the right curvature is obtained. After cooling the plastic sheet can be removed from the frame and used in the next step of our process, the mould with counter pressure. This part will be discussed in chapter 9.2, mould with counter pressure.

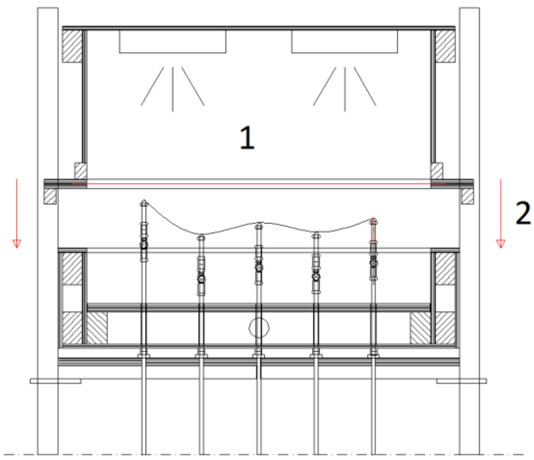


Figure 109a: Heating & lowering principle & Figure 109b: Plastic sheet clamped in the frame

9.1.3 Plastic sheet

For the choice of the type of plastic sheet for vacuum forming, it is important to have a good formability and price ratio. Based on these requirements for the sheet the formability of PETG and PS (High Impact Polystyrene (HIPS)) is tested. The experiments and literature showed that the heating time for PS takes more time than PETG, which distracts to a higher glass transition temperature. This is the temperature where the material becomes fluid. The tests on the small mould were done with 1 mm sheet of PETG or PS. Due to an increase in size of the mould the sheets are 2 mm to get more stability for the pouring process in the hydrostatic mould. The comparison of both sheets can be seen in diagram 23 (Polycasa, 2013) (Bay Plastics Ltd, n.d.).

Diagram 23: Comparison of PETG and HIPS

	PETG	PS (HIPS)
Vicat softening temperature	82 °C	89 °C
Elongation at break	54 %	50 %
Price 1 m² (2 mm thickness)	€23,60	€11,68

The conclusion of these facts is that the PS, according to the price, makes our product more feasible. Besides that it is not possible to see the difference in formability between both types of sheets. The results of both experiments can be seen in figure 110a and 110b.

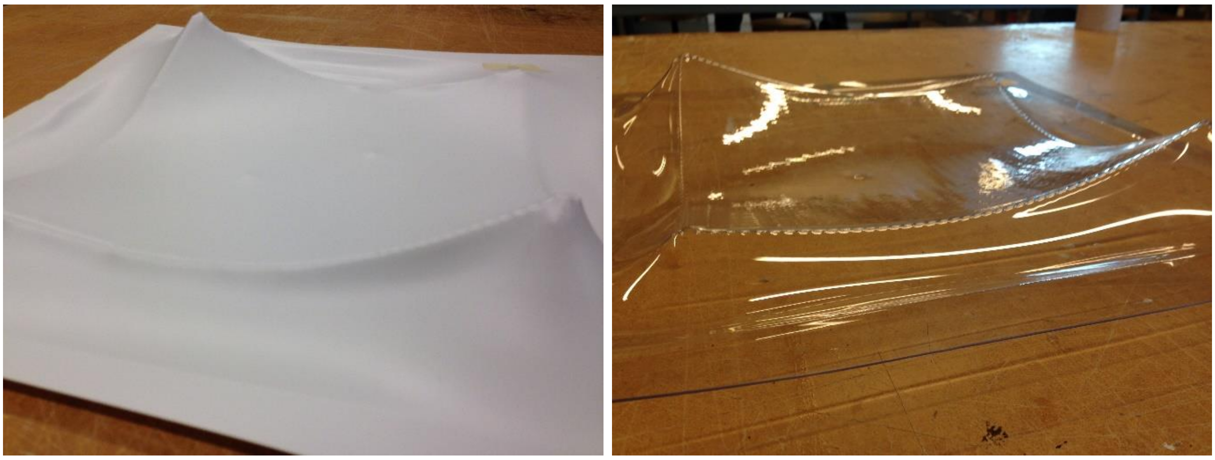


Figure 110a: Result of vacuum forming with HIPS & Figure 110b: Result of vacuum forming with PETG

The only downside of PS is that the production time is a little bit longer due to the higher glass transition temperature that is needed. In appendix B the results of the vacuum forming experiment is shown, based on the same conditions as PETG. The heating process of the prototype vacuum machine was done with a heating gun, for the final mould an infra-red heater is used to speed up the production time. In this case the glass transition temperature is reached much faster, which make the difference in heating process between the two sheets almost zero. Besides a fast production time the range of elongation at break of the material should be big enough to create the double curved form. For both sheets the elongation at break is around 50%, which is very good. This means that the sheet, clamped between the frame, can be extended from 750 mm up to 1125 mm. During the design phase the maximum needed elongation will be tested on the mould. Also the angle from the start point of the frame to the first pin could be normative.

9.2 Mould with counter pressure

This mould is used to cast the concrete. Important is that the counter pressure, given by the density of the material, is approximately the same as the concrete. Research in the first phase resulted in two possible mould designs. The differences in both designs are based on how the plastic sheets are used to create concrete element. For the first method the sheets are fixated inside the airtight box, where the second method creates a box that will be lowered down into a slurry which is used as counter pressure.

9.2.1 Morphological overview

This chapter shows the morphological overview that is made as a head start for the final design of the mould with counter pressure. This morphological overview is divided into five parts:

A. Casting method
B. Sheet connection
C. Connection method
D. Water tightness
E. Counter pressure

The complete morphological overview can be found in appendix C.

A Casting method

The casting method is divided into lowering and fixation (figure 111a & 111b). The lowering method is based on a box of polystyrene that is lowered into the mould with bentonite as counter pressure. The plastic sheets are made with the VaCo Mould. The sheets are then cut into the right size. The sheets for the thickness of the panel are cut on the right size with a laser. Therefore the design of Rhinoceros is used as an input. When the design does not fit to the set height of the edges, fixing the sheets together will be a problem. Fixation means that the plastic sheet is clamped between MDF sheets that are cut into the correct size with a laser. This principal works the same as for lowering. Fixation holds the edges into the right position. The other method is more prone to deviations at the edge. When the vacuumed sheet does not fit between the MDF lasered parts the plastic sheet will deform in another direction. This problem can be solved with the use of a 3D milling machine. This machine has the property to mill under an angle of 45°. When the fixation is realized the concrete is casted at the same time as the counter pressure material, which could be bentonite or clay granulate.

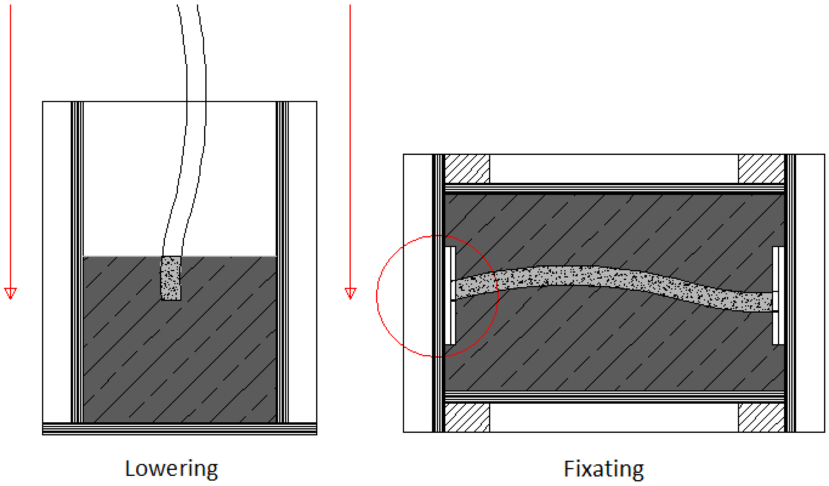
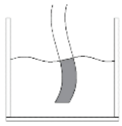
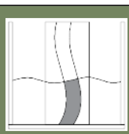


Figure 111a: Lowering method & Figure 111b: Fixation method

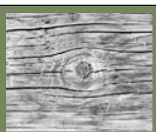
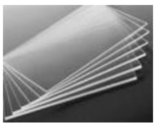
Final choice:

Method								
			AA	AB				
			Lowering	Fixation				

Sheet connection

The connection between the sheets can be made with wood, plastic or foam. Wood and foam are more focused on the fixation method. Between those two options wood is more dimensionally stable. The process of foam is easier, because the edges of the sheet are drawn on to the foam and cut exactly into the right shape. This means it does not influence the dimensions of the design. Plastic is used for the lowering method to create a box.

Final choice:

Sheet connection								
			BA	BB	BC			
			Wood	Plastic	Foam			

Connection method

The connection method gives possibilities how the different materials can be connected. The choice of connection type depends on the casting method. There are mainly two things that need to be connected, the vacuum formed sheets and the box that is meant for the counter pressure. For the connection of the box for counter pressure, screws are the best solution. For the connection of the plastic sheets two options are suitable, glue (figure 112a) or fixation with wooden plates (figure 112b). When the fixation with PS sheets is used, it needs to be bevelled into the right curvature of the panel.

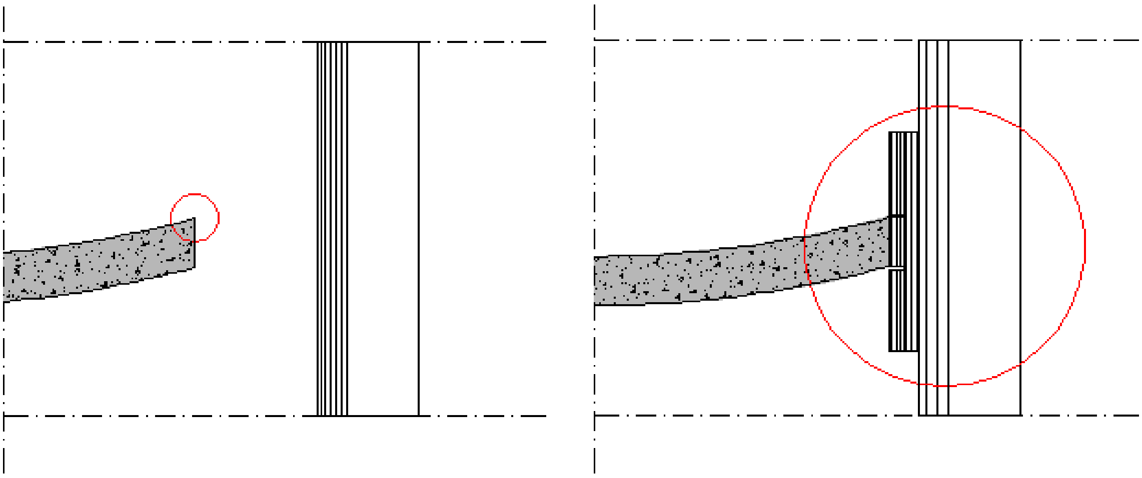
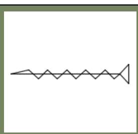
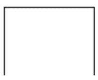
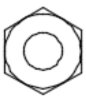
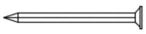
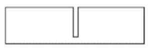


Figure 112a: Plastic sheets glued together & Figure 112b: Clamping the plastic sheets between the wooden plates

Final choice:

Connection method								
			CA	CB	CC	CD	CE	CG
			Screws	Staples	Nails	Bolts & nuts	Glue	Slot

Water tightness

Water tightness can be of great importance for the counter pressure box and the connection of the sheets. Water tightness is needed when a fluid is used as counter pressure and to avoid leakage of the concrete. Bentonite is a fluid but is not as fluid as water. This means that it is not necessary to use rubber or a sealant. A watertight connection between the plastic sheets can also be realized with glue.

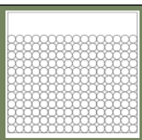
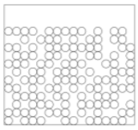
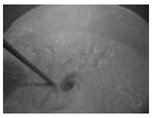
Final choice:

Watertightness								
			DA	DB	DC	DD	DE	
			Rubber	Sealant	Slot	Glue	None	

Counter pressure

Counter pressure can be delivered with a solid or fluid substance. Important for the decision of the counter pressure is the simplicity of the production and the surface quality for the concrete element. When a solid material is used as counter pressure the concrete and solid material should be casted at the same time. When a fluid is used, the plastic box can be lowered inside the counter pressure mould.

Final choice:

Counter Pressure	E1	aggregation state						
			E1A	E1B				
			Solid	Liquid				
	E2	Material						
			E2A	E2B	E2C	E2D	E2E	
			Water	Bentonite	Sand	Clay granules	Granulate	

9.2.2 VaCo Mould – Counter pressure

After testing the different materials for counter pressure, the best solution is clay granules (figure 113a). The materials bentonite and clay granules both had potential to guarantee good surface quality and less deviation, but clay granules had more advantages for the production process. When clay granules are used as counter pressure it results in a dry production method. Beside that it was difficult to release the mould from the bentonite, because it creates a suction effect. During casting the concrete and clay granules are poured at the same time, to avoid deviations of the PS sheet. The mould with PS sheet is clamped between wooden plates that are milled into the right angle and curvature of the designed panels (Figure 113b). This method ensures very minimal deviation at the edges, which is of great importance for the connection of the panels.

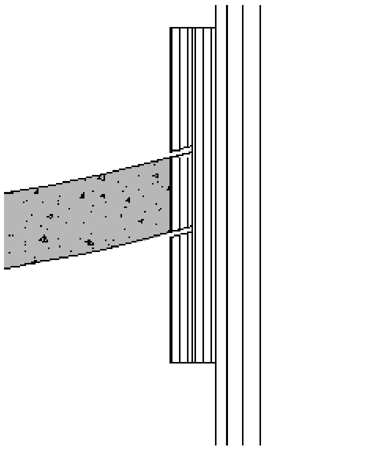


Figure 113a: Clay granules as counter pressure & Figure 113b: Clamping principle with milled wooden plates

9.2.3 Concrete

In the previous paragraph about concrete, different mixtures of SCC were tested. The main problem was to get the right workability. The workability depends on the amount of plasticizer that is added to the mixture. When the amount is not correct, it causes blow holes or colour differences on the surface. Eventually a lot of knowledge is gained according SCC, but to find the right mixture more experience is needed. One of the goals of the research is to obtain a smooth surface. To guarantee the surface quality a proven mixture is needed. Based on that reason a mixture of Cugla concrete is used. This fluid concrete consists of 4 mm aggregates. For the casting process 3,2 liter water is added to 25 kg of Cuglaton 4 mm concrete and is mixed for 3 minutes. First a test panel is casted to evaluate the surface quality of the panel (figure 114a). The test panel satisfies to the quality described in the goal. This panel is not suitable for the building industry, because it cannot withstand tensile strength. This can cause fracture to the panel, therefore steel fibres are used to reinforce the concrete panel. The calculated amount of steel fibres is 650 grams for 25 kg (Van Vliet, 2015).

After testing the difference in strength between the normal concrete and the reinforced concrete is obvious; it can be concluded that it is harder to break. Besides that it will always stick together (figure 114b). The downside of steel fibres as reinforcement is the visibility at the surface (figure 114c). Both methods are tested on a larger scale and can be seen in figure 114d. The casted panels still show same blow holes, while it is a proven concrete. The amount of water was exactly measured and mixed together with the concrete for three minutes. The problem could be that some points of the concrete sticks to the PS sheets, the workability was not good enough or it was not equally casted.

Figure 114a: Test panel, Figure 114b: The steel fibres sticks together, Figure 114c: The steel fibres are visible at the surface & Figure 114d: Result of testing the mixture on a large scale

10. Production process

In this chapter the production process of a double curved concrete panel, made with de VaCo Mould will be discussed. This process will be based on five main steps, namely: setting the VaCo Mould, vacuum forming, create a mould, casting concrete and recycling.

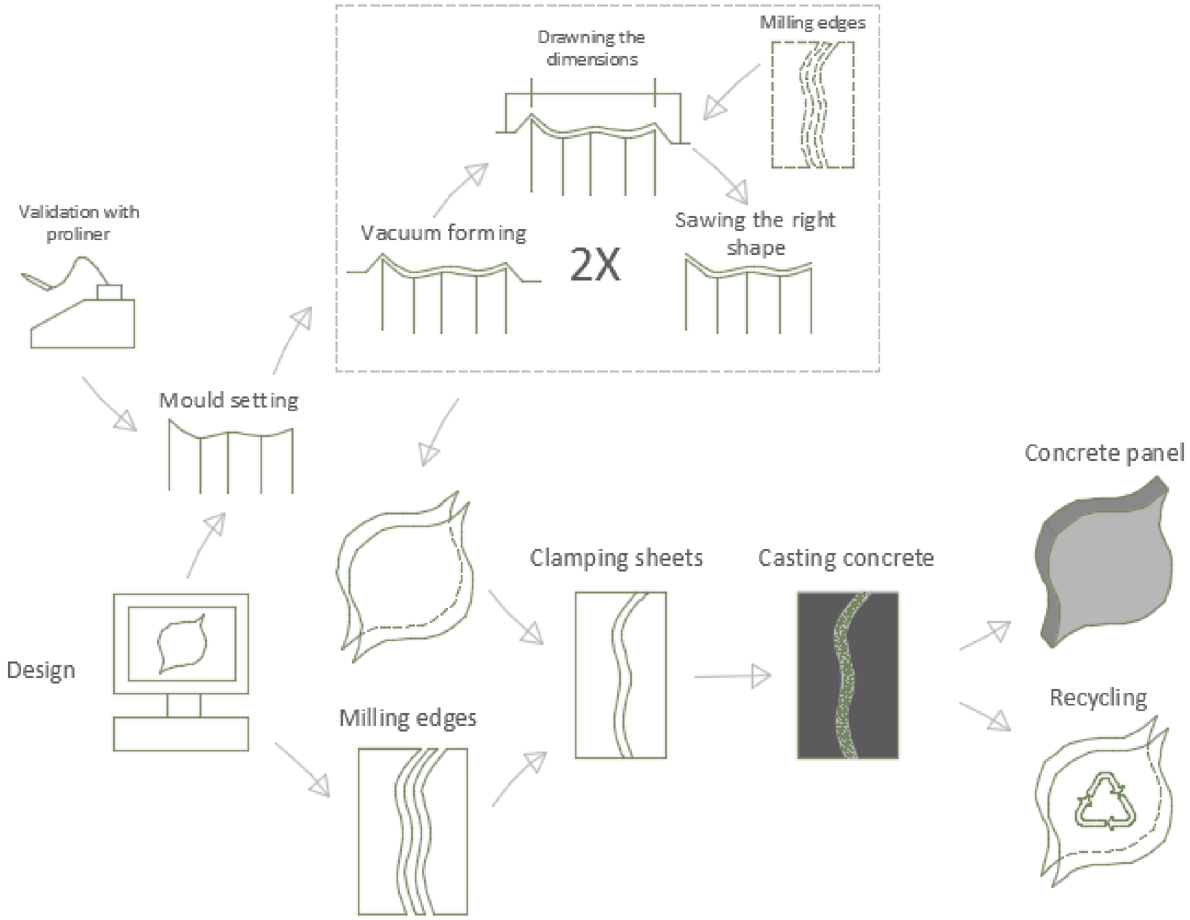


Figure 115: Production process of the VaCo Mould

10.1 Setting the VaCo Mould

Before using the VaCo Mould for the first time the flexible layer has to be calibrated. This means that the starting points of the pins are all at the same level. The calibration is to be done by the use of a level. The level is placed on top of the flexible layer and each pin will be set at the same height (figure 116a). To ensure the deviation is as small as possible the flexible layer will be scanned with a Proliner from the company Prodim (chapter 12.2 "scanning method"). The scanned result will be compared with a flat element in CloudCompare. The result shows a little deviation on the right-hand corner (yellow part) (figure 116c). Figure 116d shows the result after adapting the pins underneath the right-hand corner. The deviation of 2.5 mm is reduced to 1.2 mm. When the deviation of all pins is around 2.0 mm, the VaCo Mould can be set in the right curvature. This will be done by the use of nuts. The heights of these nuts will be obtained from the measurements in Rhinoceros, as described in chapter 12.4 "Validation 1". The heights of the nuts will be locked by turning the nuts counter-wise to each other (figure 116b).

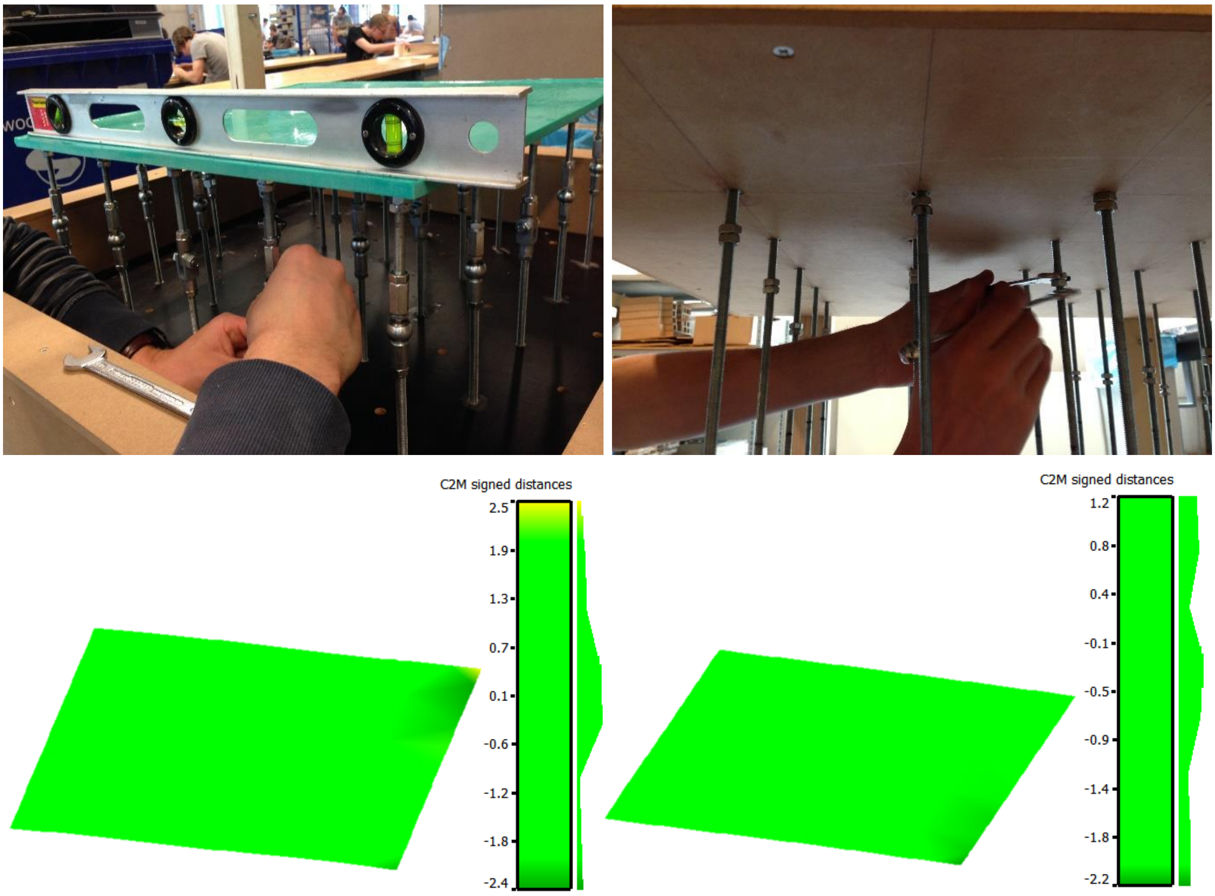


Figure 116a: Calibration of the flexible layer, Figure 116b: Setting the nuts in their desired height, Figure 116c: The deviation after calibration with a level & Figure 116d: The deviation after adapting the pins underneath the right-hand corner

When all nuts are set in the right heights for the desired curvature the lifting plate can be pulled up to the bottom of the airtight box. In this way there is no clearance between the nuts and the airtight box (figure 117a). What results in a double curved form of the flexible layer and that is similar to the designed form in Rhinoceros (figure 117b). As a final check the flexible layer will be scanned with the Proliner to ensure that the deviation is as less as possible. After that the 2 mm PS sheet can be clamped in the frame. This PS sheet is custom-made with the dimensions of 850x850 mm and will be clamped by the use of screw-threads and nuts (figure 118a). On each side there are six screw-threads with two nuts that ensure the fixation of the sheets. When this is done the frame can be placed between the columns (figure 118b). These columns are used as guide for the frame. The frame will be held at height by four rods underneath this frame.

Figure 117a: No clearance between the nuts and the airtight box, Figure 117b: The flexible layer is set in a double curved form

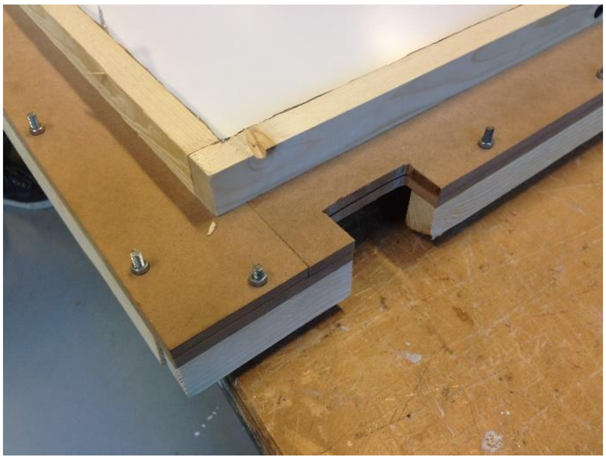


Figure 118a: Clamping the plastic sheet in the frame & Figure 118b: The frame is placed between the columns

10.2 Vacuum forming

In chapter 9.1.2 "VaCo Mould – Vacuum forming machine" is mentioned that the heating element consist of two patio heaters. During the vacuum forming process both heaters are damaged by a too high temperature in the heating element, which also caused a short circuit. To solve this problem the patio heaters were replaced by two heating spirals (Bestron barbecue AJA802T, 2000 W). When the frame with the PS sheet is placed between the columns, the vacuum forming process can begin. The heating element will be placed on top of the frame and the heating spiral will be switched on (figure 119a). The glass temperature of PS is 89 °C. The temperature inside the box is measured with a Yokogama heating sensor (model: 2455). The begin temperature of the box without heating was 22.8 °C. When the heating spirals are switched on the glass temperature of 89 °C is reached in 3.15 minutes. But then still the corners are not plastically enough. The total time till the PS sheet is fully plastically, is five minutes with a temperature of 115.2 °C (figure 119b). The total time could be shorter when the vacuum forming machine is used in short time intervals. Then the box will still be warm from the previous session.

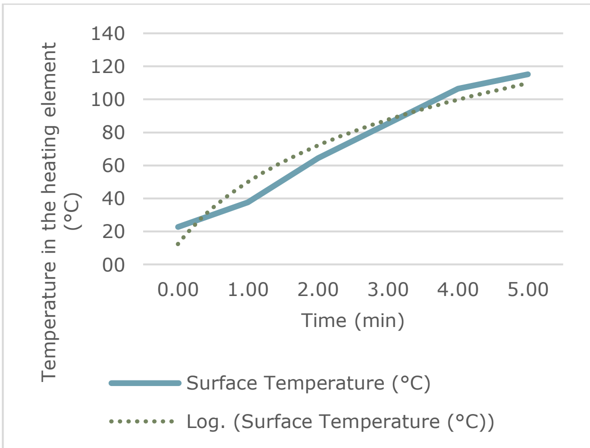


Figure 119a: The heating element consisting of two heating spirals & Figure 119b: Measurement temperature of the heating element

When the PS sheet is totally plastically, the vacuum forming process can be started (figure 120a). First the heating element will be taken off. The rods, that held the frame at height, will be pulled out and the frame with the PS sheet will be pulled down over the flexible layer (figure 120b). When the frame is attached to the airtight box the vacuum cleaner will be switched on. This vacuum cleaner ensures that the PS sheet will be pulled correctly over the surface of the flexible layer. After one minute the vacuum cleaner will be switched off and the PS sheet will be cooled down in the frame. When the PS sheet is cooled down the sheet can be taken out the frame. The end result is a vacuum formed PS sheet with a double curved shape that is equal to the adjusted flexible layer.

Figure 120a: Mould setup before vacuum forming & Figure 120b: The PS sheet is pulled down over the flexible layer

10.3 Create a mould

To create a mould two double curved PS sheets are needed. This means that the vacuum forming process has to be done two times. For making the mould only the double curved surface of the vacuum formed sheet is needed. This surface has to be cut out with a saw. To ensure that the shape has the right dimensions of a frame with these dimensions is placed on top of the plastic sheet. In this way the wooden sheets, which are cut with a laser cutter for the clamping principle, can be placed on the frame to draw the right dimensions on the surface (figure 121a & 121b). When these dimensions are drawn on the surface, the surface can be cut out. This will be done by drilling a hole in the plastic sheet, were a jig saw can be put in. Now the surface can easily be cut out (figure 121c & 121d).

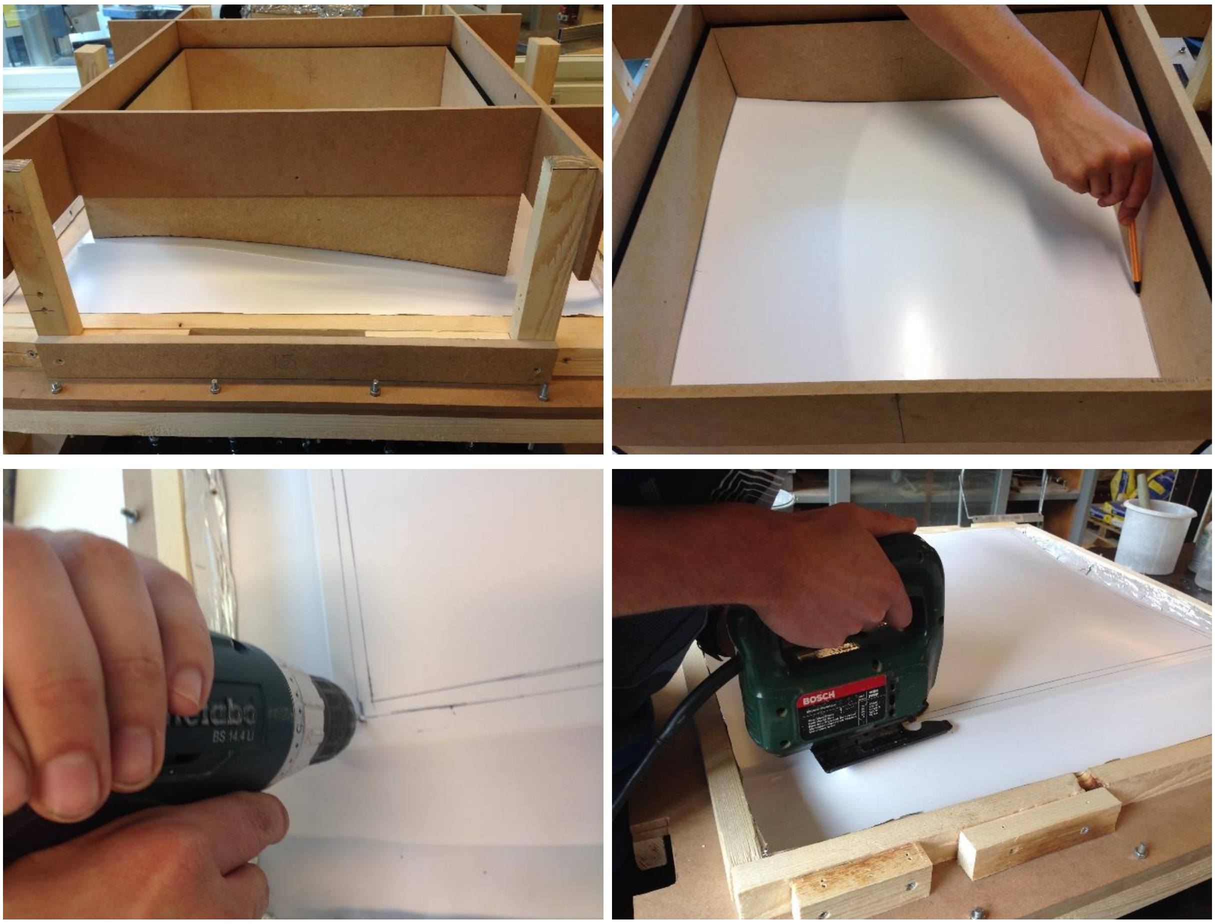


Figure 121a & 121b: The edges, which are milled, can be placed to the frame and now it is easy to draw the right dimensions, Figure 121c & 121d: Drilling and sawing the sheet

When both surfaces are cut out, the mould can be made. First three wooden plates will be sawed for the substructure. After that the first PS sheet can be clamped with the milled edges (figure 122a) and these edges will be screwed on the substructure (figure 122b).


Figure 122a: The PS sheet will be clamped one by one & Figure 122b: The milled edges will be screwed on a wooden plate

10.4 Casting concrete

When the mould is finished it will be placed in a box and the concrete can be poured (figure 123a). For one concrete panel one 25 kg bag of concrete (Cuglaton 4 mm) is needed. This bag will be mixed with 3.2 litre water and must be mixed three minutes. After these three minutes the concrete mixture is ready to be poured. The clay granulate, that is used as counter pressure, has to be poured at the same time as the concrete. Other ways the concrete will deform the plastic sheet. When the mould is fully poured with concrete, the curing process can begin (figure 123b).


Figure 123a: The mould is placed in a box & Figure 123b: The mould is fully poured with concrete and clay granulate

The curing time of the concrete panel with the concrete of Cugla is two days. After that the panel can be demoulded and it will be wrapped in shrink foil (figure 124a). After four days the panel is fully cured and can be pulled out of the shrink foil (figure 124b).

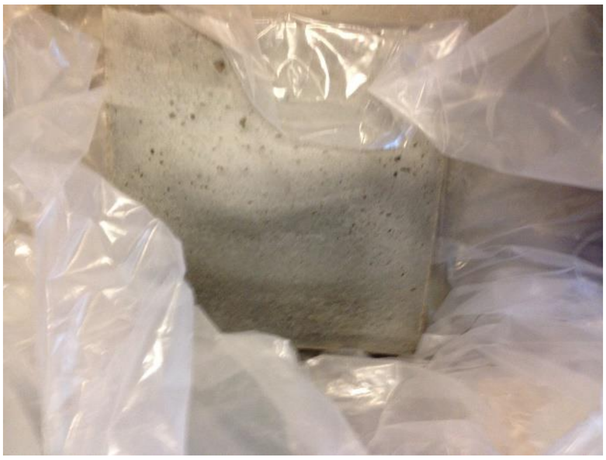
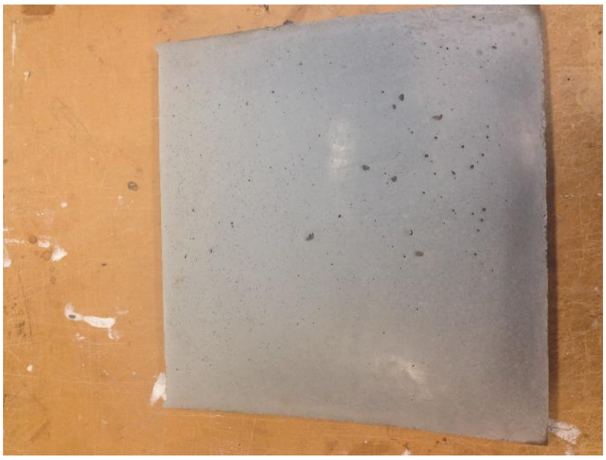



Figure 124a: A concrete panel wrapped in shrink foil & Figure 124b: The concrete panel cured after four days

10.5 Recycling

When the concrete panel is demoulded, the plastic sheets can be reused if in the design of the façade more panels are repeated. This is because the smooth surface of the PS sheets are easy to clean, as can be seen in figure 125a & 125b. Besides that, the material polystyrene (PS) is also recyclable as raw material. This is because the polystyrene is an oleaginous material. The polystyrene can easily be melted and moulded into new polystyrene sheets (SUEZ environnement, 2015).

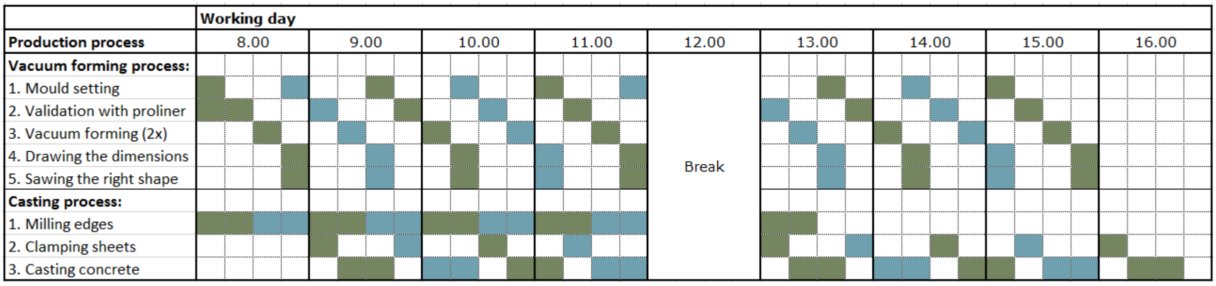

Figure 125a: The PS sheet after demoulding & Figure 125b: The PS sheet after cleaning

10.6 Time schedule

Diagram 24 shows the time schedule of a working day with the production process as described in this chapter. Setting the mould takes about 15 minutes. Meanwhile the Proliner could be prepared for the validation. This validation takes also 15 minutes. In these 30 minutes the wooden edges are milled for the first mould. This process could continue constantly. When the Proliner has validated the VaCo Mould and the mould is set in the exact form, the vacuum forming could start. Both PS sheets could be vacuum formed in 15 minutes. After that the dimensions could be drawn and the right shape could be sawn. This takes also 15 minutes. In the meantime the mould is already set in the form of the next panel. When the sheets are cut out in the right dimensions, the sheets can be clamped with the milled edges. This takes around 15 minutes to make this mould. At last the mould can be casted, which can be done in 30 minutes.

The total production time of one panel takes one hour and 45 minutes. Because the vacuum forming process of the next panel could already start when the first panel is not even casted, at the end of the day a total nine concrete panels could be casted. This production process could be faster if there were more identical panels.

Diagram 24: Time schedule of the production process



11. Building applications of the VaCo Mould

In this chapter the design and production process of different building applications for a facade are presented with an existing building method and future possibilities. Especially the freedom in form and the advantage of surfaces smoothness on both sides should attract the attention. For the existing principal a standard façade anchoring for natural stone elements is used and can be applied for renovation or facades in new buildings. The anchoring for this system is placed within the seam of the façade panels. The disadvantage of this system is that the anchoring method gives restrictions to the curvature that can be made, due to the needed concrete covering for the pins. For the future possibilities, methods are designed to use the mould at maximum capabilities. Then more extreme curvatures can be made. This is made possible by local thickening that is realized for anchoring at the back of the panel. Besides that also the possibilities for sandwich elements and production methods for different shapes of the elements will be investigated. First the exiting method will be discussed, with an introduction of a reference project.

11.1 Directly applicable

This method shows a production process of how a façade element can be made nowadays. A great example of an already constructed building is the Heydar Aliyev Centre in Baku, designed by Zaha Hadid (figure 126a). For this project double curved concrete panels are used on both sides of a spaced steel frame (figure 126b). This principle can be used for the design of new buildings, made with the VaCo Mould. For this method the supporting structure is not within the scope of our project, only a solution is given for the fixation of the panels and the way a façade is designed. Double curved panels on both sides of the façade, give the possibility to experience a different kind of architecture on the inside of the building. When this method is used for only a vertical façade, the same double curved panel can be used on the inside and outside of the façade. This gives the advantage that only two PS sheets need to be vacuum formed and can be reused for the other panel. This principal is also used for freeform buildings made nowadays, therefore the penalization and design is optimized to reduce the amount of different panels. This is done to speed up the production and reduce the investment cost of the building. The VaCo Mould makes it possible to make every panel unique by using a reconfigurable mould instead of a static mould of EPS or wood that is used for the Heydar Aliyev Centre. The designed product is a façade with four panels on the inside and outside. This product is focused on the aesthetical function of a façade with double curved concrete panels and the way it is applicable nowadays.

Figure 126a: Heydar Aliyev Centre (Zaha Hadid Architects, 2012) & Figure 126b: Spaced steel frame (News.Az, n.d.)

11.1.1 Penalization

When a double curved façade is divided into panels, it is called penalization. In regular buildings the panels could be story high and restricted in width for the transport dimensions. For freeform constructions the penalization is more difficult. Double curved elements can be split in a lot of ways. This can be different shapes or direction of the panels. The direction of the panels can for instance be set into the right angle of the design to get a fluent seam between the elements over the building (figure 127a). When the design is made there is an optimization process to minimize the differently shaped elements. This saves the amount of moulds that are needed. This optimization process requires a lot of mathematical knowledge. A solution could be the Evolute tool of Rhinoceros. The VaCo Mould is a flexible mould, which makes it possible to make every panel unique with one mould. But still it would be a cheaper solution to minimize the amount of different shapes, because the PS-sheets can be reused. The penalization for the design has no difficulties, because the face counts only four panels at each side. This means the panels all have the same size of 500 mm with a planar grid seam of 10 mm (figure 127b).

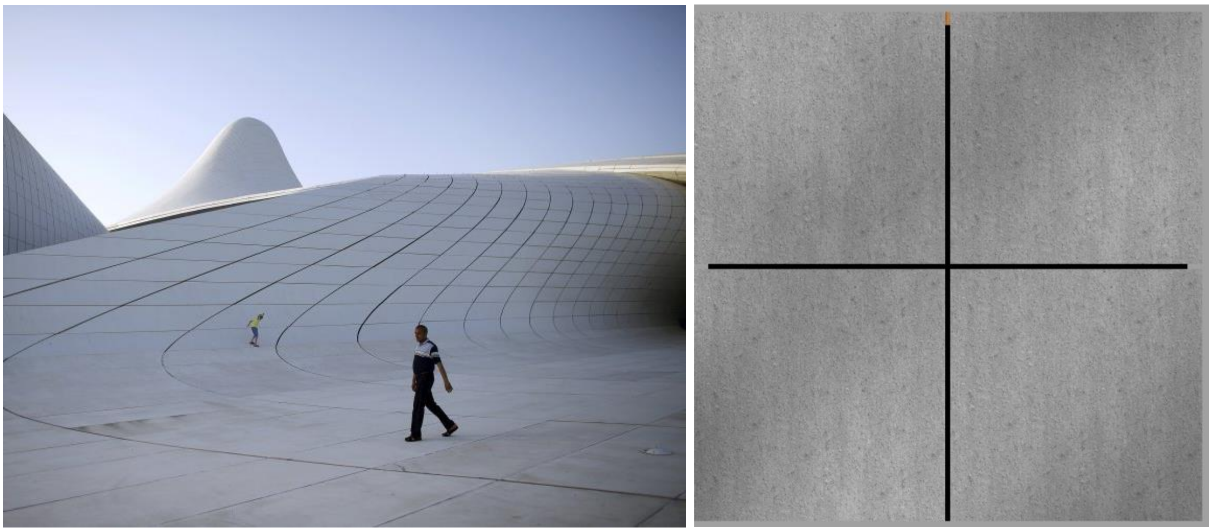


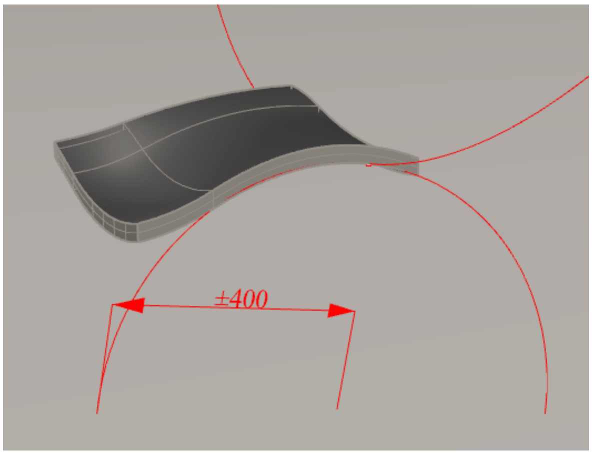
Figure 127a: Fluid seam of Heydar Aliyev (Zaha Hadid Architects, 2012) & Figure 127b: Planar grid seam

11.1.2 The design

The design for the façade is made with Rhinoceros. This design is realized based on the following preconditions of the mould and construction method:

- The size for the panels is restricted to 500x500 mm;
- The maximum curvature for vacuum forming has approximately a minimum radius of 400 mm, this test can be seen in figure 128a and 128b. This limitation depends on the amount of extra material that is used. For this process PS sheets of 750x750 mm are used. This means 125 mm extra material for all edges of the mould;
- The curvature at the edges should have a radius of >1000 mm, due to the fixation method of the façade panels;
- The designed shape must be constructed with the VaCo Mould that can make curves with five control points and a degree of four (figure 129a).

The design of the panels is constructed out of NURBS surfaces. The advantage of NURBS surfaces offer the most control over the surfaces, due to the weight that can be attached to each control point (figure 129b). The difference in shape of the surface is given with the degree of the surface. Degree 1 is flat, degree 2 is curved in one direction, while a degree 3 surface can change once form concave to convex curvature.



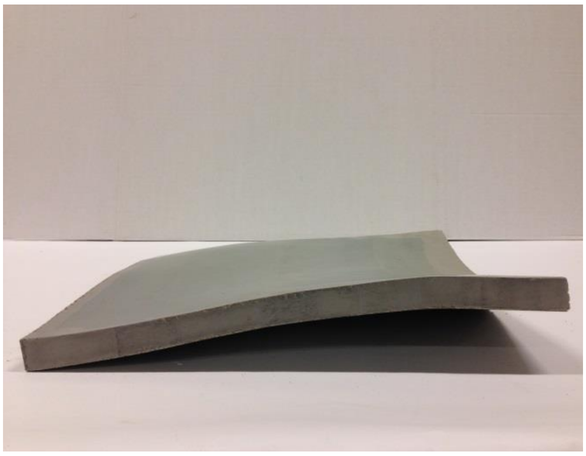
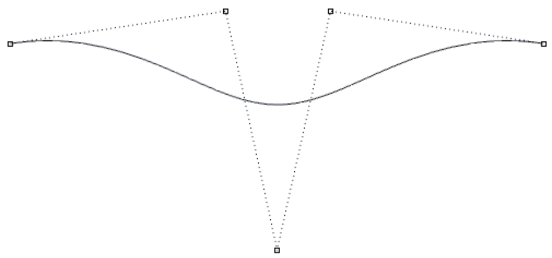


Figure 128a: Minimum radius that can be made with the mould & Figure 128b: Casted panel with extreme curvature



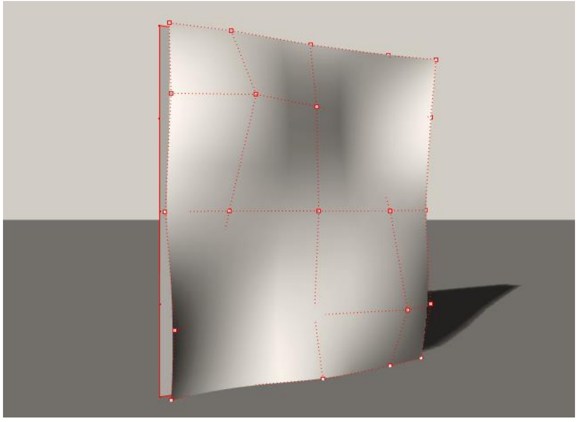


Figure 129a: Constructed curvature & Figure 129b: Adjusted NURBS surface

The dimension of the manipulated surface for the final design is four panels including a seam of 10 mm, which means 1010x1010 mm. This surface shows positive and negative values as can be seen in figure 130, meaning that the red areas are synclastic and the blue areas are anticlastic. Al the panels have different curvatures at each point, which make every panel unique. After the shape of the façade is designed, the façade is panelised into a planar grid of four panels (500x500 mm) and a seam of 10 mm. Every panel satisfies to the preconditions described in paragraph 11.1.2 "The design". The façade is closed at both sides with a side panel, to illustrate a solid wall. For this method a wooden inner construction is used with natural stone anchors. This design represents the advantage of a good surface quality on both sides of the panel.

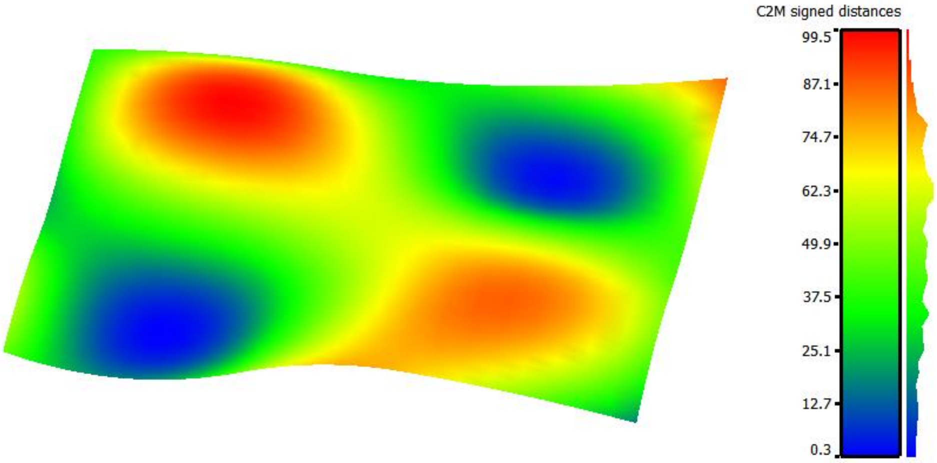


Figure 130: Curvature analysis of the design

11.1.3 The assembly method of the design

The design, which consists of eight panels and four side panels, are placed with four different kind of anchors. This system of Hakron Nunspeet is originally used for natural stone elements. Every anchor is adjustable without the anchor used on top, which are custom made on the correct size. Figure 131a shows the adjustable anchor that is used in the middle part of the façade. The dowel in combination with the pin supports the weight of the upper panel and the wind load of the bottom panel. In the concrete panel tubes were casted for the four pins (figure 131b).

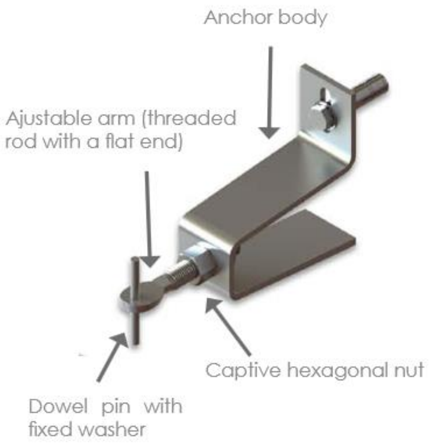
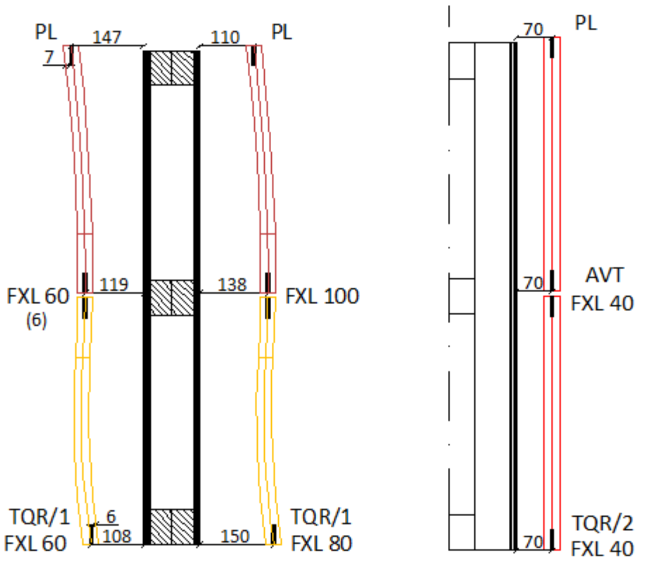


Figure 131a: Adjustable anchor (Fixinox, n.d.) & Figure 131b: Tubes fixated in mould for anchors

The cavity of the panels is 70 mm minimum and increases until 150 mm depending on the curvature of the panels (figure 132a). The final design can be seen in figure 132b. The panels of this design are, as already mentioned, restricted to a minimum radius of 1000 mm. This minimum is needed for the covering of the concrete. In the next paragraph solutions are given to use the mould at full capacity.



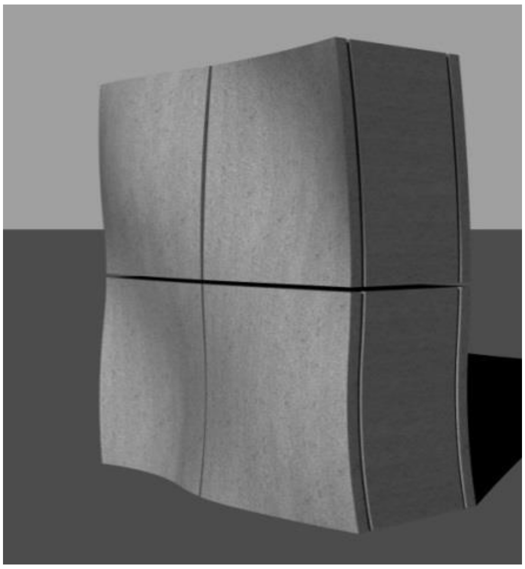


Figure 132a: Overview of used anchors & Figure 132b: The final design

11.2 Future possibilities

In this paragraph the future possibilities of the VaCo Mould will be discussed. There are opportunities in thickness, curvature, shape, form fitting and building elements.

11.2.3 Maximum capabilities of the VaCo Mould

As mentioned earlier in paragraph 11.1.3 "The assembly method of the design", the full capacity of the VaCo Mould is not used, because of the restrictions of the anchors. This problem could be solved by vacuum forming the plastic sheet with local thickening. This can be done by placing a flexible material on top of the flexible layer (figure 133a). For example the material rubber. In this way the curvature could be more extreme, because the anchors are not leading any more. The result after vacuum forming with a local thickening can be seen in figure 133b.

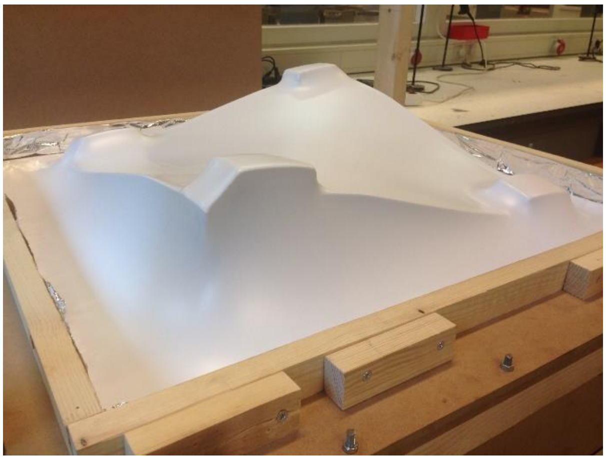



Figure 133a: Rubber on top of the flexible layer & Figure 133b: The result after vacuum forming with a local thickening

11.2.4 Different shapes of the panels

The panels that are made with the VaCo Mould are 500x500 mm square. In the future there are also possibilities with different shapes. This can be done by using a five or six-axis water jet cutting machine. Water jet cutting is a production technique which materials, for example concrete (figure 134a), will be cut by water in combination with abrasive substance (Infonu.nl, 2011). With this machine it is possible to made more organic or atlantic shapes as can be seen in figure 134b. The accuracy of the VaCo Mould must have the same accuracy as the edges, because otherwise the connection between the different panels varies.

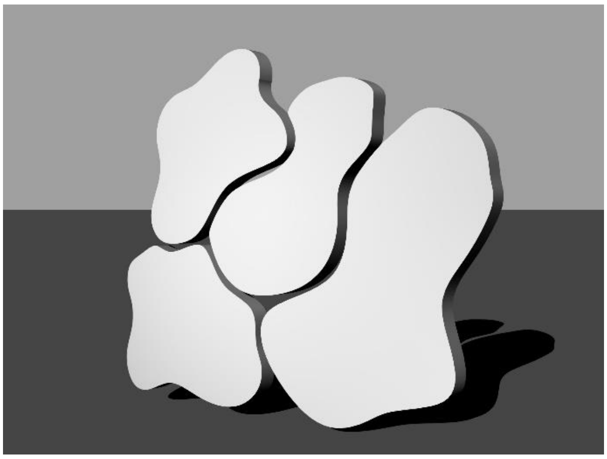



Figure 134a: Result of a six-axis water jet cutting machine (Bureaubakker, 2011) & Figure 134b: A render of concrete panels with organic/atlantic shapes

11.2.5 Form fitting

As mentioned previously it is also possible to place a flexible material, like silicone rubber, on top of the flexible layer. With this technique it is possible to vacuum form a text or logo into the plastic sheet, which after casting is visible also in the surface of the concrete panel. The result will then be the same as the form fitting principle of Frank Huijben (figure 135a). A critical point will be the pressure that is needed to visualize the object. The pressure must be higher, because otherwise the object will not be visible on the surface. A render of the concrete panel with a logo is shown in figure 135b.

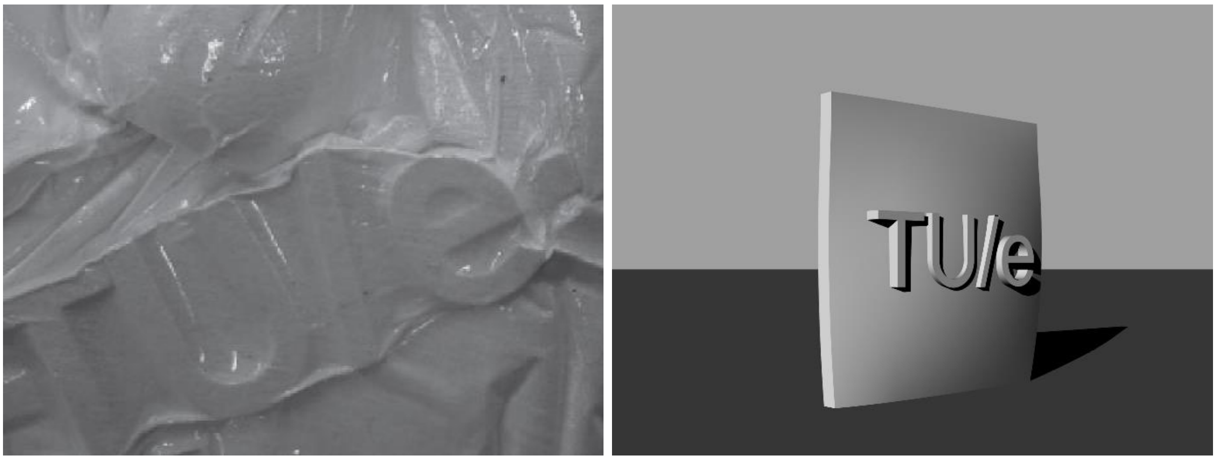


Figure 135a: Form fitting with Vacuumatics (Cement, 2009) & Figure 135b: A render of a concrete panel with the logo of Eindhoven University of Technology

12. Validation

For the validation process of the designed model a comparison is made between the produced concrete element and the design. To get a better understanding of the deviations according the production process each step is validated with the goal to minimize the overall deviations. Therefore the mould is compared with design and the plastic sheet and the counter mould is compared with the concrete panel. The validation process is realized with a scanner, the Proliner IS Series, and Cloud Compare. This process will be discussed in the following paragraphs.

12.1 Validation process

The deviation of the end product can be improved by validating every part in the production cycle. When one part of the production process is within the excepted tolerances it can be excluded for further improvement. This means that if the deviation of the end product is too much the problem should be in the other three production parts. The validations compare the difference between for example the production of the mould and the design, which is validation number 1. The following validations are made (figure 136):

- Validation 1; comparison between the mould and the design
- Validation 2; comparison between the vacuum forming and the mould
- Validation 3; comparison between casting and vacuum forming
- Validation 4; comparison of casted product with the design

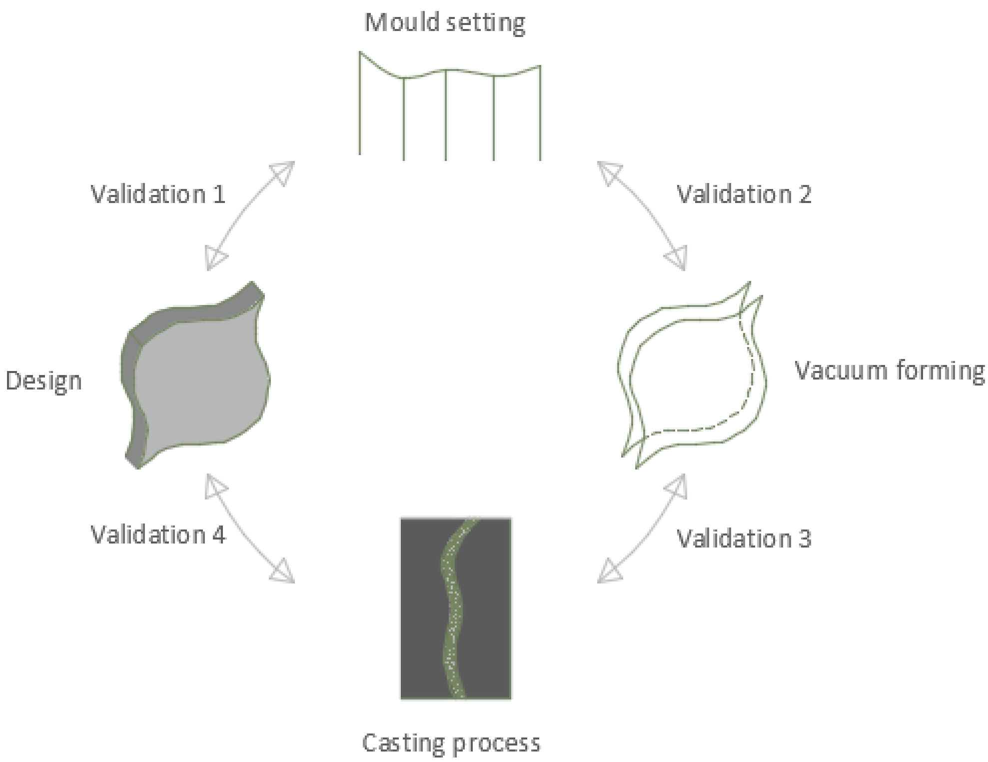


Figure 136: Validation process

For this validation process panel D of the final design is used (figure 137). This panel is convex in the middle and slightly double curved on the edges. Further information of the design can be found in chapter 11 "Building applications of the VaCo Mould".

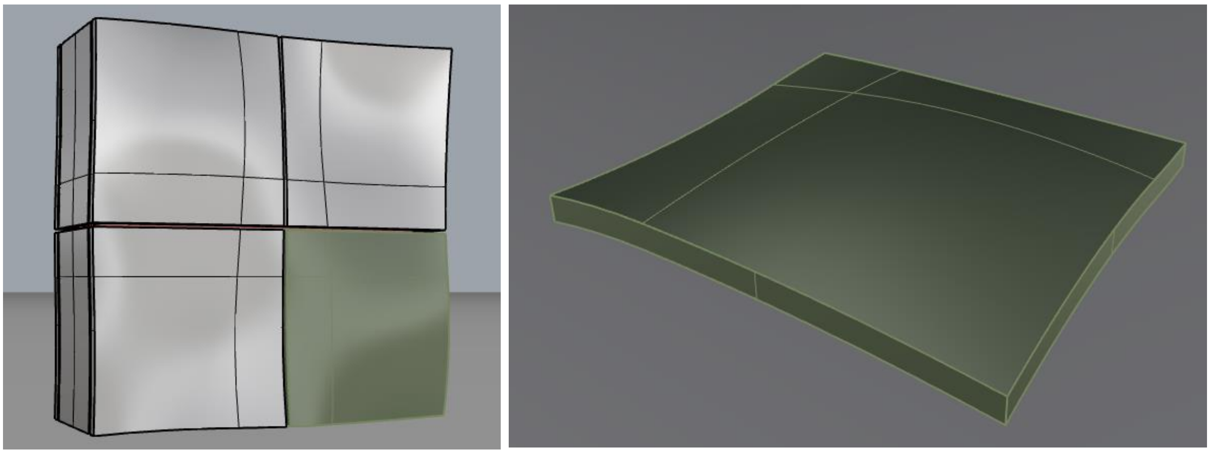


Figure 137: Panel D of the final design

12.2 Scanning method

The scans are made with a Proliner, which is different from laser scanners. The Proliner IS series, used for this project, is a high quality measurement solution for the industry. This equipment includes advanced technical wire technology, on board water level sensors and a large touch screen (figure 138a). The accuracy is >0.19 mm. This instrument is suitable for high precision and quality control (Prodim, 2013). Scanning of the product is done with a pen attached to wire, which computes a curtain point on the product by determining the angle and distance within a three- dimensional coordinate system. The first step is levelling the Proliner IS to get a good starting point. Then three reference points are picked on a flat surface from where the mesh can be constructed. The pattern and reference points, which are used as input to construct the mesh, can be seen in figure 138b. For the edges and the surface different end pieces are used for the pen (figure 139). The mesh will be constructed properly if the wire is held straight form the starting point without any obstacle in between. When the point cloud is obtained with the scanner the variations between the points can be computed to create a mesh using Prodim Host.

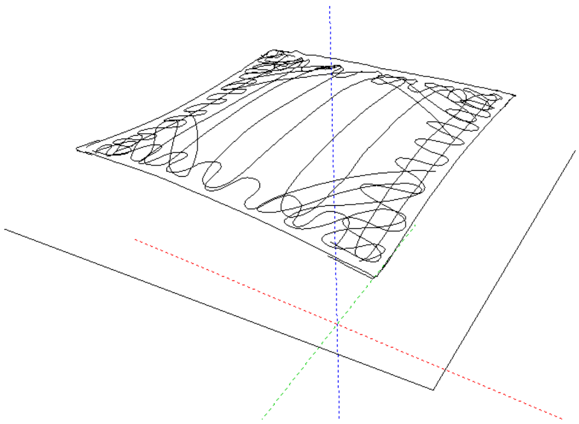


Figure 138a: The Proliner IS (Prodim, 2013) & Figure 138b: The pattern of reference points

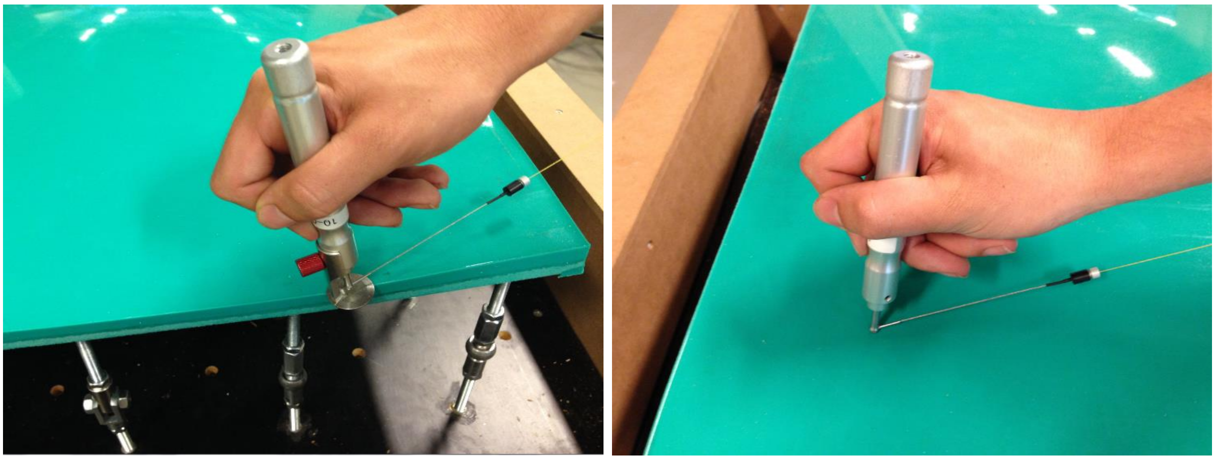
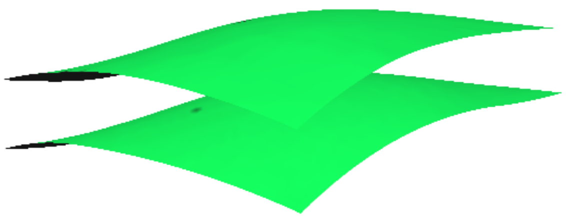


Figure 139: Different end pieces for the edges and surface

12.3 Cloud to mesh comparison

The comparison between the meshes is computed with cloud compare. Cloud compare is a 3D point cloud processing software that can calculate the variations between two meshes. The goal for the total production process is to limit the deviations between design and practice as much as possible. This can be realized by improving the design based on the variation noticed during validation. For the VaCo Mould it is quite unrealistic to have a deviation of approximately zero, because then dimensional stable materials should be used and the mould must be automated to reduce personal mistakes. The deviation can be computed in cloud compare when the meshes are aligned properly. Therefore the meshes are rotated and moved until the same curvature of the two meshes is placed on the right position (figure 140a). When the deviations between both meshes are calculated, the colour scale gives information about variations at certain locations (figure 140b). For a better comparison the colours represents the same value for every part of the validation process. For instance green represents -2 until 2 mm, which means a total green mesh stays within the tolerances of -2 and 2 mm (diagram 25). The mean and standard deviation are statistical values to get a clear overview of the variations.



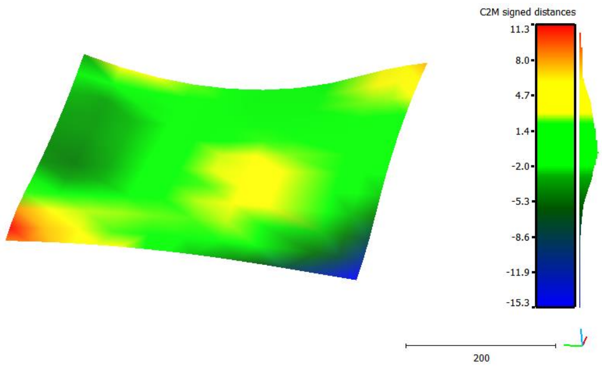


Figure 140a: Two meshes are placed above each other & Figure 140b: The variation based on colours

Diagram 25: Colour scale

Colour	Blue	Green	Light green	Yellow	red
Deviation	- ∞/-6	-6/-2	-2/+2	+2/6	+ / ∞

12.4 Validation 1

For this validation a comparison is made between the mould and the design. Before this validation the silicone layer of the VaCo Mould is levelled (chapter 10 "Production process"), to be sure that the deviations are not too much. This validation was also done with the Proliner and Cloud Compare. The deviation was within the -2 and 2 mm. The setting of the mould is based on straight lines starting from a grid of 25 pins towards the curvature of the panel (figure 141a). This method is not reliable, because the rotation of the ball joints is not taken into account (figure 141b). Therefore the Proliner is used to readjust the pins that are not set correctly. Other deformations more to the middle of the mould could be a wrong setting of the mould. For small curvatures, like this panel, the variation between straight measurement and the design is very critical. This problem can be solved with a 'graphic algorithm' editor grasshopper or a 3D laser scanner with live data.

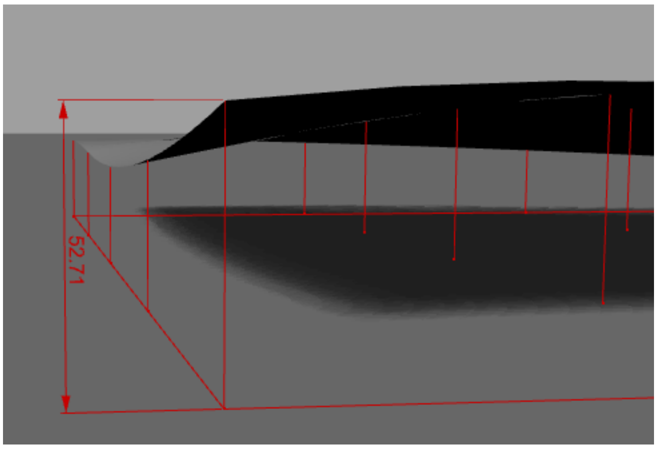
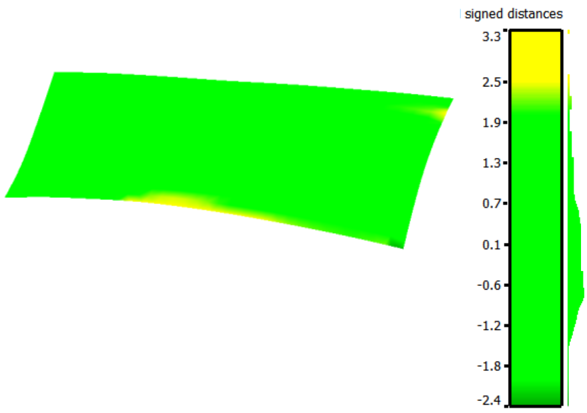


Figure 141a: Measurements in Rhinoceros & Figure 141b: Rotations of the ball joints

The validation is done in two steps. First the mould is set with the input data (straight measurement) of the design. The results show an almost green picture, within the deviations of -2 and 2 mm (figure 142a). The yellow part in the colour scale means that the pin must be adjusted to lower the silicone layer. For the readjustment, step 2, the edges for the counter mould are used to see if it connects well, if not it is compared with the scan of the Proliner (figure 142b). The readjustment made the scan green, which means that the deviation is approximately between -2 and 2 mm.



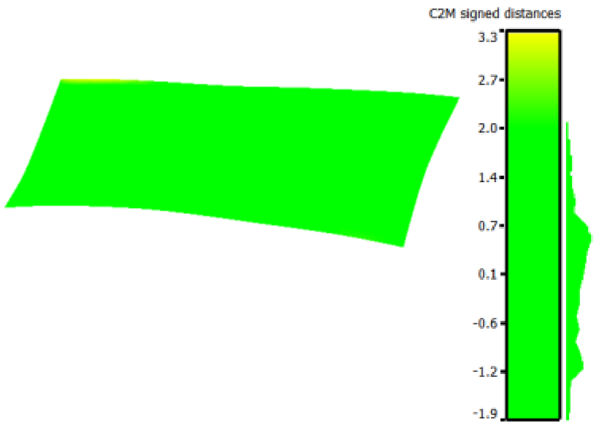


Figure 142a: The validation of the mould setting with the input data & Figure 142b: The validation of the mould after scanning with the Proliner

12.5 Validation 2

The validation between the PS sheet and the mould was done before sawing (figure 143a). Most of the area stays within the -2 and 2 mm. The extreme value of -4.7 mm at the bottom of the panel is an area that is pushed down too far during vacuum forming. This could be a tolerance in the ball joint connection or the mesh. After sawing the sheet bended back in the natural shape of the form (figure 143b). The problem of the edges will be less during the casting process; because it is forced into the right curvature with MDF milled edges.

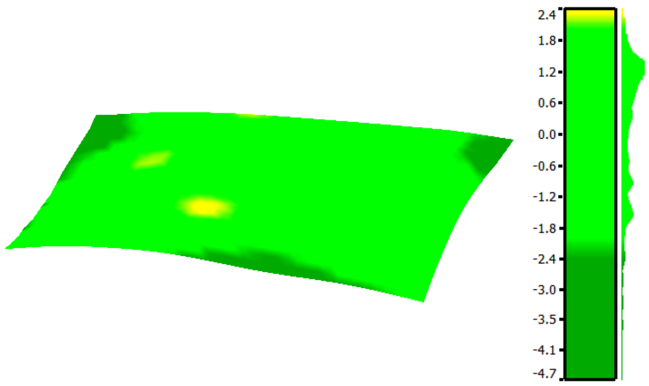
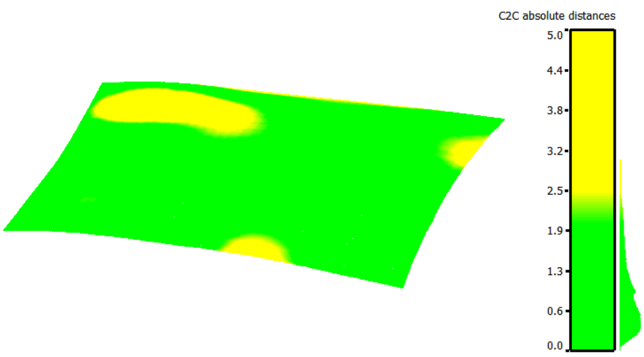


Figure 143a: The validation between the PS sheet and the mould & Figure 143b: Bending of the sheet

12.6 Validation 3

Validation 3 gives the comparison between casting and vacuum forming (figure 144a). For this validation the edges are aligned to each other, because the deviation of the edges should be reduced to a minimum by the use of a clamping method. This means that larger deviations are obtained in the middle section of the panel. Most of the area stays within the -2 and 2 mm. The most extreme deviation is at the top of the panel, which is +5 mm. The reason could be that the counter pressure was not strong enough to withstand the pressure of the concrete (figure 144b).



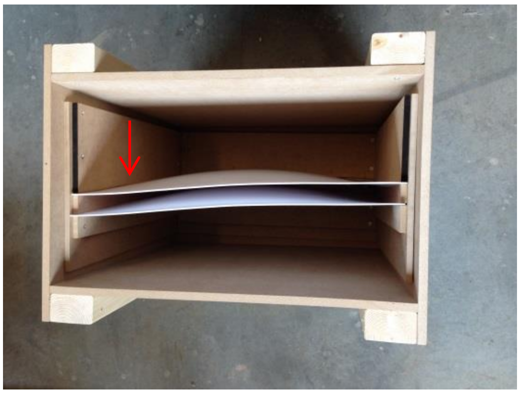


Figure 144a: The validation between casting and vacuum forming & Figure 144b: The red arrow shows the place of the most extreme deviation

12.7 Validation 4

For this validation the same method of validation 3 is used. The comparison of the concrete panel with the design shows approximately the same values as validation three, which means that the casting method could be improved (figure 145). This deviation can be avoided by clamping the sheets at the top of the mould. The majority of the deviations are within 3 mm. The extreme value is 6.1 mm at the left top of the panel. The variations at the edges must be as less as possible, because the connection with the next panel should be smooth. The differences in the middle section are less important, it only can disturb the designed shape. For this design 6 mm is not that much and it can be concluded that the production process of the elements is quite accurate.

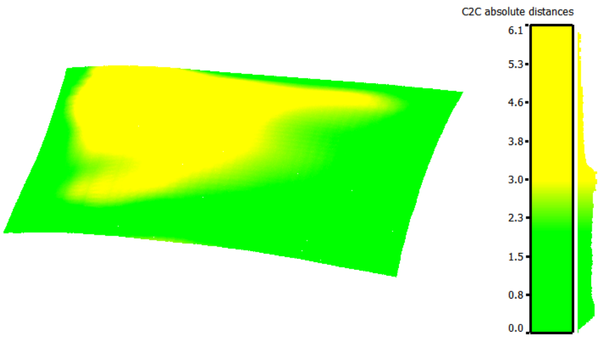


Figure 145: The comparison of the concrete panel with the design

13. Future prospects & Market potential

In this chapter the future prospects and the market potential of the VaCo Mould will be described. In the paragraph "Future prospects" the future process of the VaCo Mould will be discussed and which parts the VaCo Mould could be optimized. Based on these future prospects a good comparison can be made between the VaCo Mould and the existing moulding techniques. This will be done in the paragraph "Market potential".

13.1 Future prospects

In this paragraph the future prospects will be described. In which way the VaCo Mould, nowadays a prototype, will be developed to a principle that can compete with the existing moulding principles.

13.1.1 Dimensionally stable materials

At this moment the VaCo Mould is made of MDF board and wooden beams (figure 146a). One of the characteristics of wood is that it works. This property is not useful for a moulding principle where the deviation should be as small as possible. Dimensionally stable materials like steel or aluminium could be used as main construction material of the VaCo Mould. For example in the future the VaCo Mould could be a combination of the 3Dflexmould (figure 146b) (El Ghazi & Schuijers, 3Dflexmould, 2015) and the vacuum forming machine of Bas Hesselink IDAP (figure 146c).

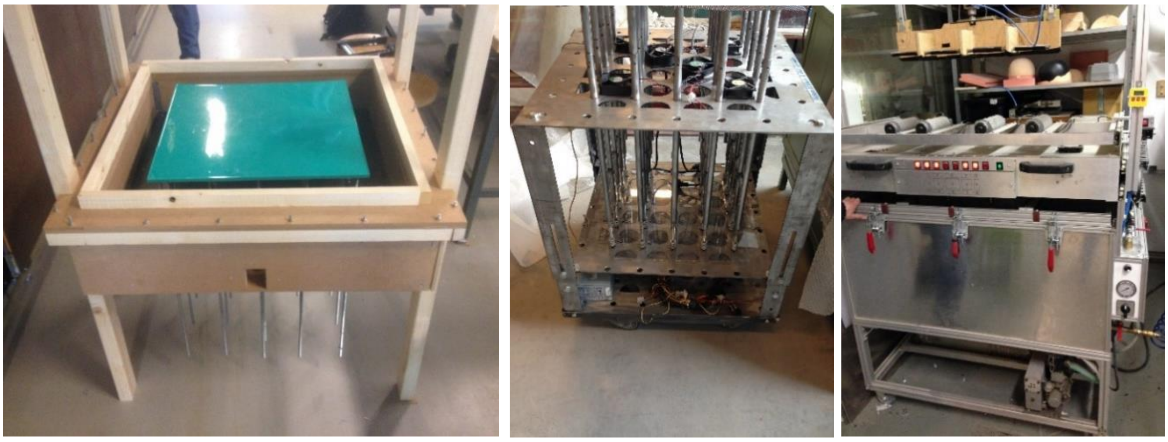


Figure 146a: The VaCo Mould nowadays, Figure 146b & 146c: The VaCo Mould in the future: A combination of the 3Dflexmould and a vacuum forming machine

13.1.2 Automated process

Another important modification is that the VaCo Mould has to be automated. At this moment the heights are measured in Rhinoceros and are set by adjusting nuts in the VaCo Mould (figure 147a). This is a labour intensive and time-consuming process. To speed up this process a step motor or a servo motor could be used to make this process automated (figure 147b). The step motor or servo motor will then be controlled by an Arduino, which is a microcontroller board.

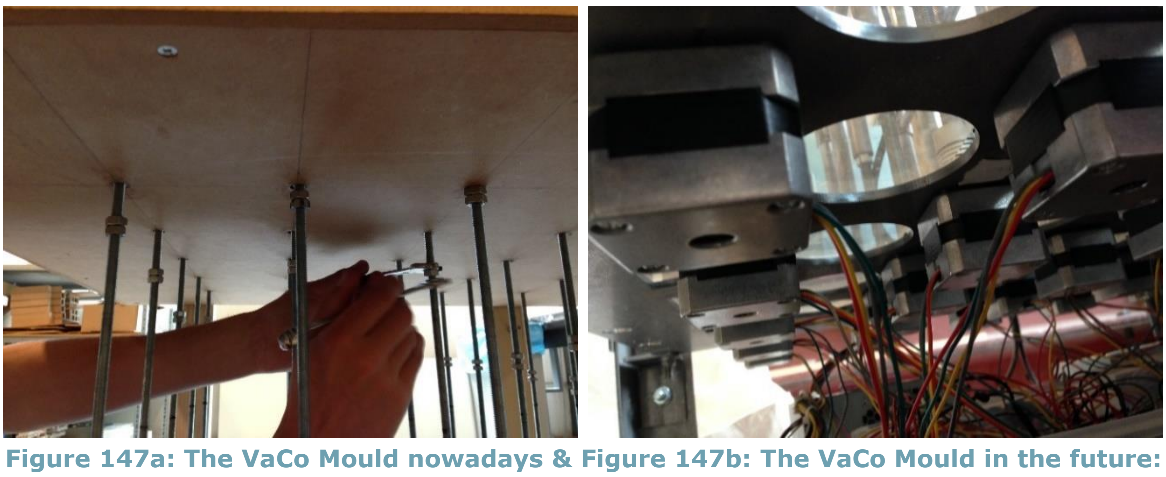
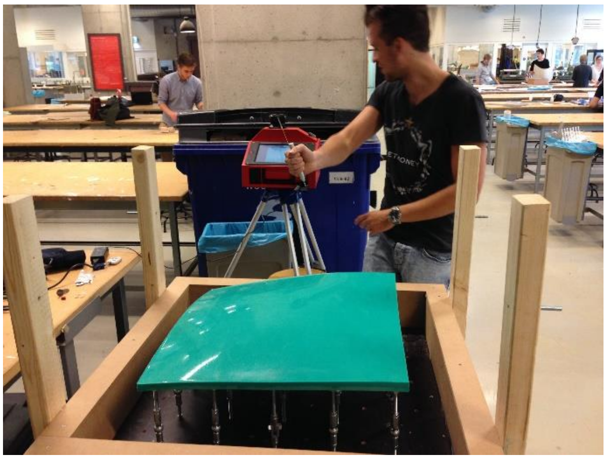


Figure 147a: The VaCo Mould nowadays & Figure 147b: The VaCo Mould in the future: controlled by a step motor

13.1.3 Built-in validation process

For the validation process of the VaCo Mould at this moment a Proliner is used (figure 148a). The process of first setting the flexible layer in the right curvature and after that scanning this flexible layer, is also a time-consuming process. This process must be made faster in the future. If a 3D laser scanner (figure 148b) is connected with Rhinoceros, the mould could be automatically set in the right curvature. In this way the curvature can also be directly validated. Another option is using a Grasshopper model. This Grasshopper model is linked with the design in Rhinoceros. Grasshopper automatically calculates the height of the pins and sends the information to the step motor. Both options are suitable for the VaCo Mould, but the preference goes to the laser scanner, because it also controls a the deviation in the mould.



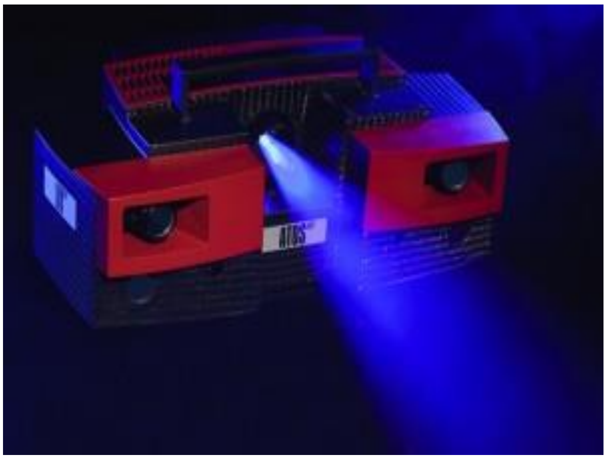


Figure 148a: The validation process of the VaCo Mould & Figure 148b: The VaCo Mould in the future: Built-in 3D laser scanner (Pelser Hartman, 2015)

13.1.4 Optimization vacuum forming process

One of the things that could be optimized in the vacuum forming process is the frame with screw-threads and bolts (figure 149a). For the fixation of the 2 mm PS sheet, 25 screw-threads are used. This means that it is a labour intensive job, what needs to be done faster in the future. At vacuum forming company Bas Hesselink IDAP they used clamps to fixate the plastic sheet (figure 149b). Based on this principle two clamps have to be placed on each side of the mould. This application will optimize the production speed.

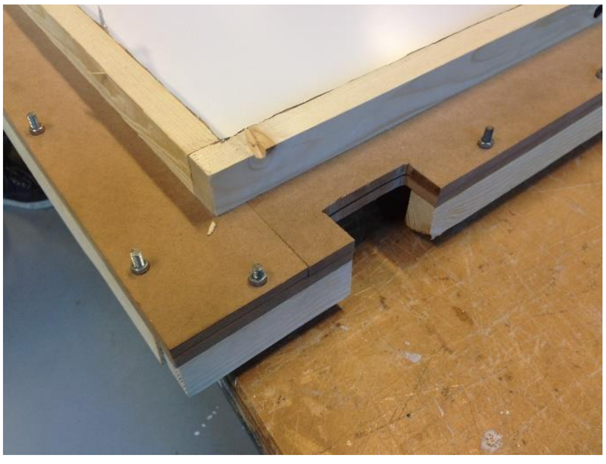


Figure 149a: Clamping the frame nowadays & Figure 149b: The VaCo Mould in the future: clamps to fixate the PS sheet

Another aspect of the VaCo Mould that could be improved is the heating element. The use of two heating spirals in the prototype works fine for heating up the PS sheets (figure 150a). This process could be faster by a better distribution of the heat generated by the heating spirals and adding more heating spirals. This improvement makes it possible to place the PS sheet closer to the surface. In this way the plastic sheet will be plastically much quicker. At the company Bas Hesselink IDAP they used such kind of heating spirals (figure 150b).

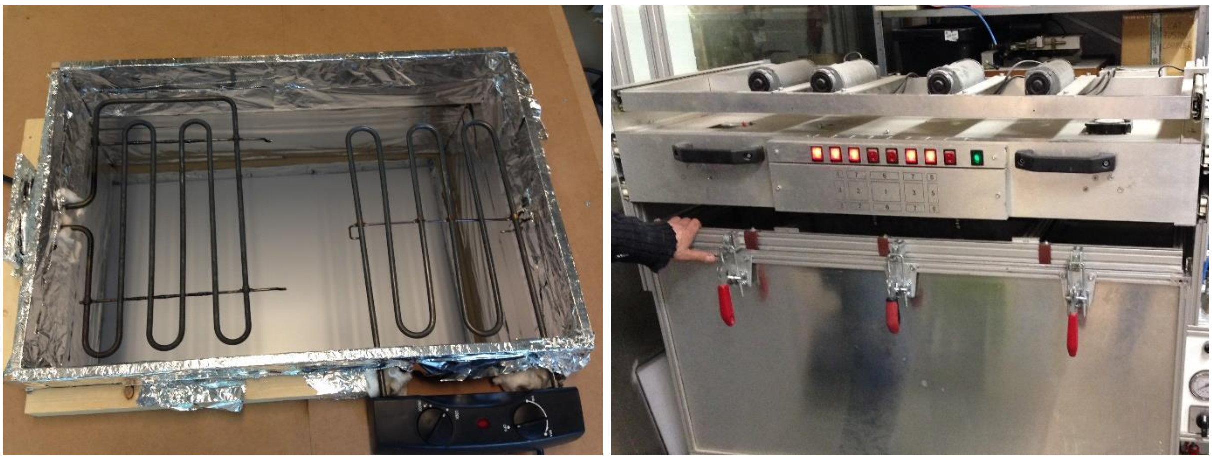


Figure 150a: The heating element of the VaCo Mould & Figure 150b: The VaCo Mould in the future: a heating element with heating spirals

The last part of the vacuum process that has to be optimized is the machine that creates the vacuum. At the VaCo Mould a vacuum cleaner is used for this process (figure 151a). In the future this has to be a more professional machine, namely a vacuum pump. The most vacuum forming companies using this kind of machine. The vacuum pump must be equipped with a buffer tank to control the pressure, as mentioned earlier (figure 151b).

Figure 151a: The vacuum cleaner of the VaCo Mould & Figure 151b: The VaCo Mould in the future: equipped with a vacuum pump with a buffer tank

13.1.5 Optimization mould manufacturing

The optimization of the mould manufacturing is mainly in the area of sawing principles. At this moment first a frame with the panel dimensions is placed on top of the vacuum formed sheet (chapter 10.3 "Create a mould"). In this way it is easy to draw the dimensions of the panel on the PS sheet. After that a hole will be drilled at each corner. In these holes a jig saw be placed and then it is easy to saw the correct dimensions (figure 152a). But in the future this process has to be much faster. A solution for this problem could be a 3D laser cutter (figure 152b). When this 3D laser cutter is connected with the Rhinoceros model, it can easy cut the right surface. A condition for the laser cutter is that it is flexible in the Z-direction, so it can follow the fluid form of the vacuum formed PS sheet. Then the whole manual process of drawing the dimensions, drilling the holes and sawing the right form can be skipped.

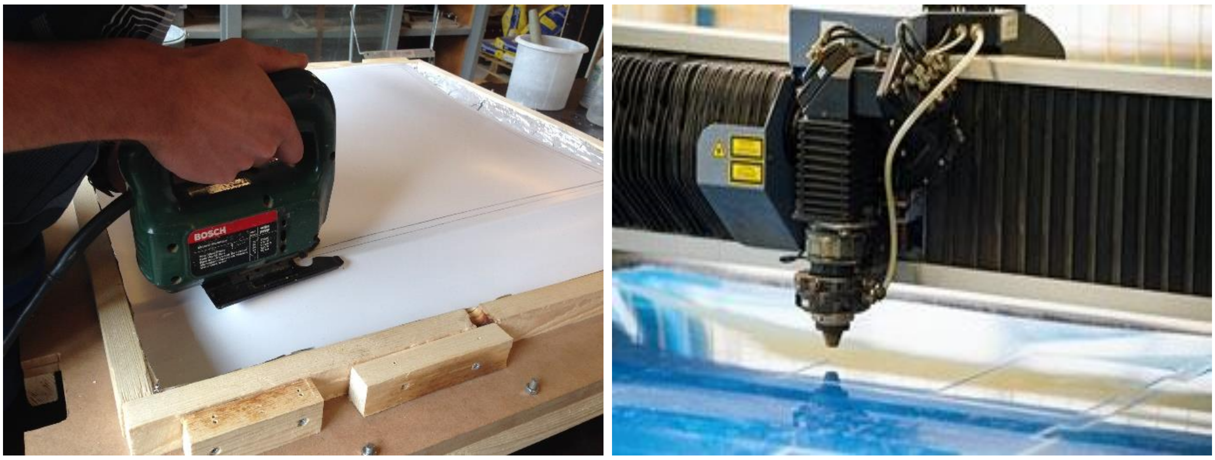


Figure 152a: The VaCo Mould nowadays & Figure 152b: The VaCo Mould in the future: Built-in 3D laser cutter (Schuerman, n.d.)

Also a five axis milling machine (figure 153a), instead of a three axis (figure 153b), could optimize the process of milling the edge. With this milling machine every edge can be perfectly milled and post processing is not needed.

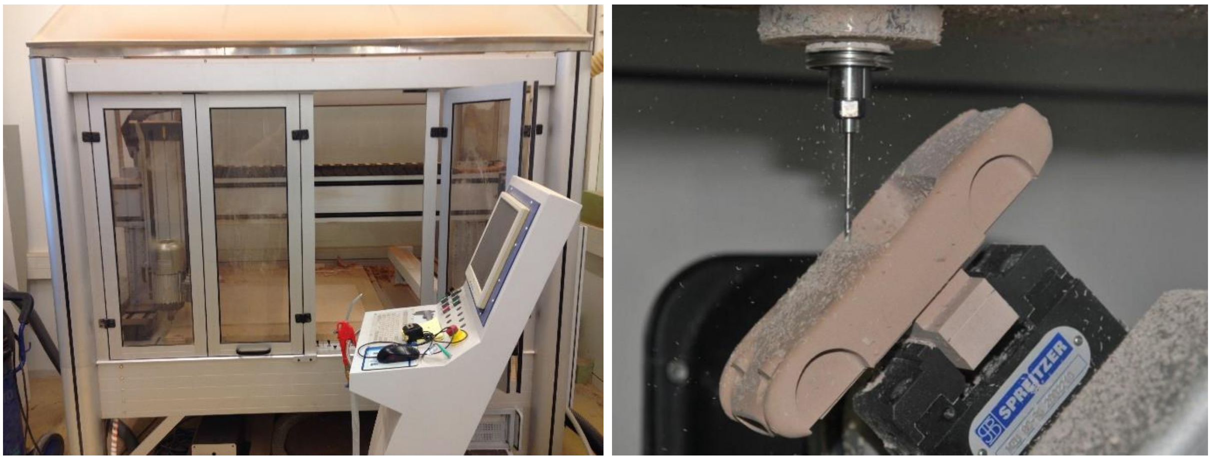


Figure 153a: The three axis milling machine of Eindhoven University of Technolgy & Figure 153b: A five axis milling machine (Vraagenaanbod.nl, 2011)

13.1.6 Optimization pouring process

The pouring process could also be optimized. At this moment the concrete and clay granualte will be poured at the same time by hand. So every time two people are needed to pour one concrete panel. In the future this could be solved by using a machine with three spray nozzles. Two nozzles pour clay granulate and the other one pours concrete. In this way only one person is needed for the pouring process.

Another point of discussion is the amount of pouring panels. For the prototype of the VaCo Mould one wooden box is made (figure 154a). This means that only one panel can be poured at the same time. This process must also be made faster, because otherwise there is also no need for a quicker vacuum forming process. A solution to this problem is using a battery mould (figure 154b). At this moment a battery mould is mainly used for walls in prefabricated houses.

Figure 154a: The pouring process of the VaCo Mould & Figure 154b: A battery mould for prefabricated houses (Hendriks Precon, 2015)

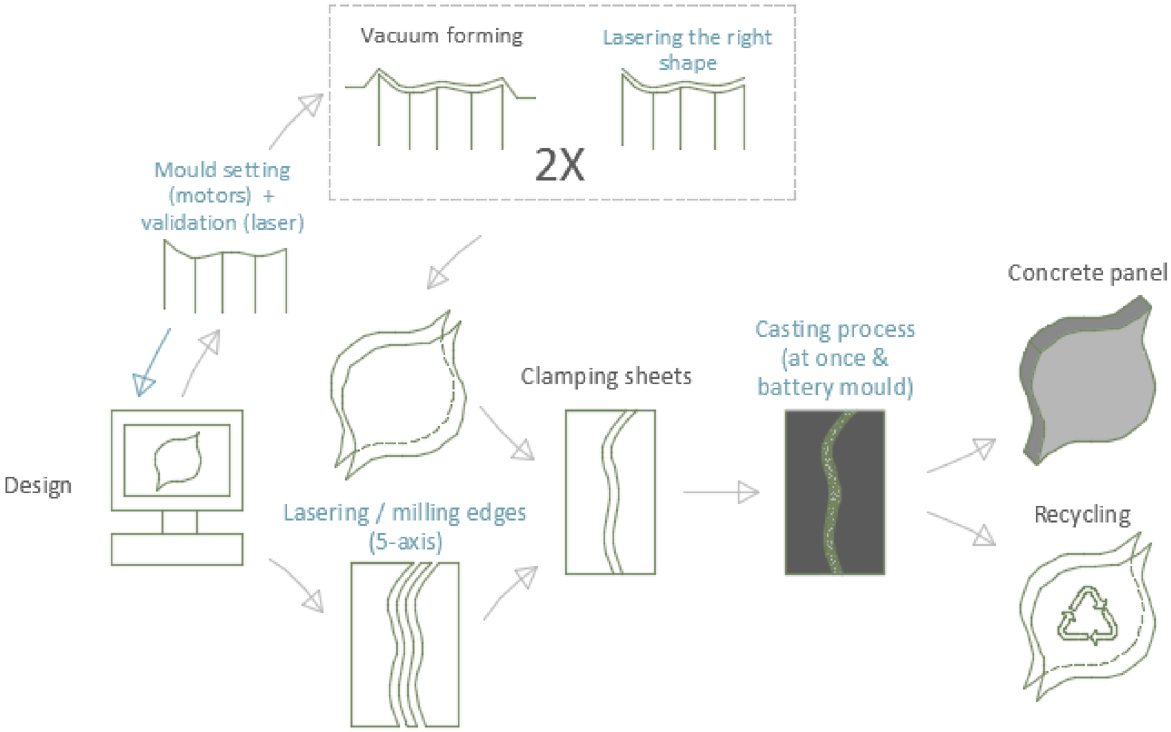
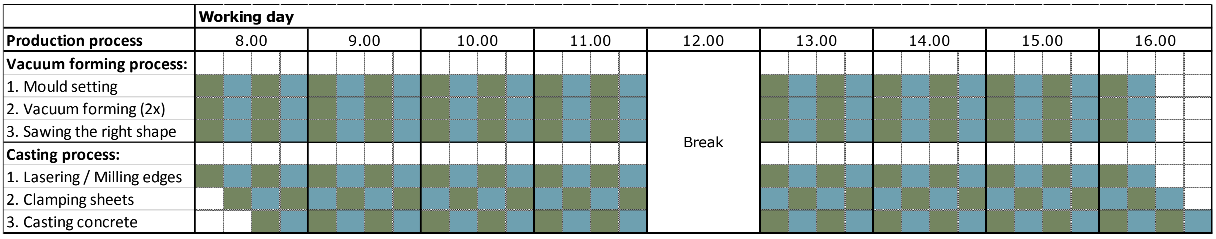


Figure 155: Production process in the future

13.1.7 Production time

Diagram 26 shows an assumption of a time schedule for a working day with the optimized production process. If the whole process is automated, the vacuum forming process of two PS sheets can be done in 15 minutes. At the same time a laser or milling machine can cut or mill the edges for the clamping principle. This clamping can be done in 15 minutes. At the same time the sheets are clamped, the vacuum forming process of the next panel could be started. The last part of the casting process for the first panel is casting the concrete. This can also be done in 15 minutes. This means that the production process of one panel takes 45 minutes. Because the vacuum forming process of the next panel could already start when the first panel is not yet casted, at the end of the day 30 concrete panels could be fabricated.

Diagram 26: Production schedule of one working day



13.2 Market potential

The market potential of the VaCo Mould could be determined by making a comparison with existing moulding principles. These moulding principles have already been described in chapter 4 "Moulding principles". To make a clear comparison between the different moulding principles, the comparison is divided into nine parameters, namely: form freedom, reusability, accuracy, production speed, no counter mould is needed, surface quality, surface quality on two sides, labour intensive and costs.

13.2.1 Parameters

The parameter "Form freedom" indicates the amount of possible forms each moulding technique can make. Parameter "Reusability" indicates if the mould can be reused for other productions. The parameter "Accuracy" expresses the accuracy of the mould compared to the designed model. The "Production speed" indicates how fast the production process is. The parameter "No counter mould is needed" expresses if a counter mould is needed or the concrete can be poured directly without a counter mould. The "Surface quality" indicates the quality of the surface of the produced element before post-processing. Parameter "Surface quality of the produced panel" expresses if the quality of the surface is on one side or both sides of the produced element. The parameter "Labour intensive" indicates if the labour intensity is high for producing elements with this moulding technique. And at last the parameter "Costs", this parameter expresses if the moulding principle is a cheap or expensive principle.

13.2.2 Validation existing moulding principles

The moulding principles are validated for producing a concrete panel with dimensions 500x500 mm and a thickness of 30 mm. Each moulding principle will be rated with points as follows: 2 = very good, 1 = good, 0 = medium, -1 = bad and -2 = very bad. At the end all points will be added together and the moulding principle with the highest score could be called the "best" moulding principle. But this was not the goal of the research. The goal of the research was to design a moulding principle that has a quick production process and produce panels with a smooth surface on both sides. These important parameters are highlighted in green in diagram 27.

Wood

Wooden moulds score the worst on the nine parameters. This moulding principle is also one of the reasons that new moulding techniques have been developed. Because it is a labour intensive process, the production speed is low and the costs of wages are very high. The surface quality is good of a wooden mould, but only on one side. This is because the panels are poured horizontal.

Production speed: -2 **Surface quality: 1** **Surface quality on two sides: -2**

Steel

The steel moulds score good on the parameters "Accuracy" and "No counter mould is needed". With a steel mould the accuracy is very good, because the steel is casted on a foam mould which is CNC milled. The smooth surface of the steel ensures that the concrete panel also has a smooth surface. The other two important parameters are rated with -1 (production speed) and -2 (surface quality on two sides), because different moulds have to be made for a double curved façade and with this mould the concrete will also be poured horizontally.

Production speed: -1 **Surface quality: 2** **Surface quality on two sides: -2**

CNC Foam Milling

The CNC Foam Milling technique is one of the most used moulding techniques for double curved concrete panels. The EPS foam blocks will be milled by a five axis milling machine which ensures a good accuracy, enough freedom in geometry and it reduces the labour intensity. On the other hand the investment costs are very high by using a milling machine. The surface quality is very good, because a polyurea layer is placed on top of the milled foam blocks, which ensures a smooth surface. The production speed is good. A mould for a double curved panel of 500x500 mm with a thickness of 30 mm takes around 50 minutes to mill with a five axis milling machine. The surface quality on two sides is, as with the other moulds, not good, because the concrete is l poured horizontally.

Production speed: 1 **Surface quality: 2** **Surface quality on two sides: -2**

Hydrostatic Equilibrium Moulding

The hydrostatic equilibrium moulding technique of Frank Omloo is rated very good on the parameters "Form Freedom", "Accuracy" and "Labour intensive". By using a 3D printer it is easy to make a double curved mould, that also ensures a good accuracy. The labour intensity is low, because when the mould is printed, only the concrete has to be poured in the mould by using hydrostatic pressure. That is why the production speed is also rated as good. A disadvantage of this moulding principle is the high investments costs by using a 3D printer. The surface quality could be better, because the printed surface of the mould was visible in the surface of the concrete.

Production speed: 1 **Surface quality: 0** **Surface quality on two sides: 0**

Inflatable

The inflatable moulds scores the best on the parameters "Form freedom" and "No counter mould is needed". The form freedom is high, because the fabric is a flexible material. The good score of the "No counter mould is needed" is because the air in the fabric is used as counter mould. The lowest score is on the parameters "Reusability" and "Surface quality on two sides". The material fabric is by itself a reusable material, but for other forms the fabric has to be adjusted. The pouring principle for this mould is also horizontal, which ensures the lowest score at the parameter "surface quality on two sides". On the other important parameters, "Production speed" and "Surface quality", the inflatable mould scores good and very good. No counter mould has to be made and the fabric ensures a very smooth surface.

Production speed: 1 **Surface quality: 2** **Surface quality on two sides: -2**

Sand / Clay

The sand or clay moulds score the second worst on the nine parameters. Only on the parameter "Reusability" these moulds have a good score, because sand and clay are reusable materials. The parameter "Surface quality" scores medium when sand or clay is used for the mould. The other two parameters, production speed and surface quality on two sides, are very bad. It is a labour intensive process that results in a slow production speed. The panels are poured horizontally and that is why on only one side the surface can be rated average.

Production speed: -2 **Surface quality: 0** **Surface quality on two sides: -2**

Pinbed

The pinbed of Sebastian Boers scores very good on the first four parameters (form freedom, reusability, accuracy and production speed). Every form can be made with a pinbed. Because the pinbed is a flexible mould the mould is reusable. The amount of pins ensures that the accuracy is very good and the production speed is quick by the use of vacuum forming. The score on the other parameters are not so good. The surface quality is very bad, because the pins leave spots on the surface and the amount of pins ensures that the investment costs are very high.

Production speed: -2 **Surface quality: -2** **Surface quality on two sides: -2**

Supported membrane

The best rated moulding technique is the supported membrane, for example the Flexible Mould by Roel Schipper. Depending on the amount of pins, almost every form can be made. The supported membrane is a flexible mould which means the mould is reusable. The mould is less accurate as the pinbed, but it is still good enough. The production speed is quick and not labour intensive by pouring concrete directly on the flexible layer, but several moulds are needed because the concrete has to be cured. The surface quality of the concrete panel is very good, because the flexible layer has a smooth surface. A disadvantage is that the smooth surface is only on one side, because the concrete is poured horizontally. The investments costs are lower compared to the pinbed, because less pins are needed, but still too high.

Production speed: 1 **Surface quality: 2** **Surface quality on two sides: -2**

Tensioned membrane

The second best rated principle is the tensioned membrane, for example the Fluid Mould by Erwin van Rijbroek and Martijn Verboord. This technique is rated as very good on the important parameters “surface quality” and “surface quality on two sides”. This is because the pouring method is not horizontal but vertical. The plastic sheets ensures a smooth surface. The production speed is also rated as “good”. The investment costs are lower as for the pinbed and supported membrane techniques, because only the edges are supported with pins. The disadvantage of this technique is that a counter mould is needed.

Production speed: 1 **Surface quality: 2** **Surface quality on two sides: 2**

Vacuumatics

Vacuumatics of Frank Huijben is rated ‘very good’ for the parameters “Form Freedom”, “Labour intensive” and “Costs”, because every form can be made and the pressurized membranes are low cost materials which are simple to control. The disadvantage of the vacuumatics technique is the surface quality, because the granular material causes an imprint in the concrete panel.

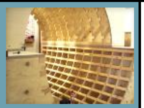
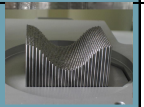
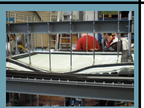
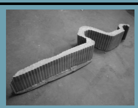
Production speed: 1 **Surface quality: -2** **Surface quality on two sides: -2**

3D Printing

The 3D printing technique scores ‘very good’ for the parameters “Form freedom”, “Reusability”, “Accuracy”, “Production speed” and “Labour intensive”. The 3D printer ensures a good accuracy, enough freedom in geometry and it reduces the labour intensity. On the other hand the investment costs are very high by using a 3D printer. Another disadvantage is the surface quality. It is very bad rated, because the concrete layers that are printed with the 3D printer are visible. This does not provide a smooth surface.

Production speed: 2 **Surface quality: -2** **Surface quality on two sides: -2**

Diagram 27: Validation moulding principles

			Form freedom	Reusability	Accuracy	Production speed	No counter mould is needed	Surface quality	Surface quality on two sides	Labour intensive	Costs	Total
Static Moulds	Wood		1	-1	0	-2	1	1	-2	-2	-2	**-6**
Static Moulds	Steel		1	-2	2	-1	2	2	-2	0	-1	**1**
Static Moulds	CNC foam milling		2	-2	2	1	2	2	-2	2	-2	**5**
Static Moulds	Hydrostatic Equilibrium Moulding		2	-1	2	1	-2	0	0	2	-2	**2**
Static Moulds	Inflatable		2	-2	0	1	2	2	-2	-1	-1	**1**
Reusable Moulds	Sand / Clay		1	2	0	-2	2	0	-2	-2	-2	**-3**
Flexible Moulds	Pinbed		2	2	2	2	-2	-2	-2	1	-2	**1**
Flexible Moulds	Supported membrane		2	2	1	1	2	2	-2	2	-1	**9**
Flexible Moulds	Tensioned membrane		1	2	0	1	-2	2	2	1	0	**7**
Flexible Moulds	Vacuumatics		2	1	0	1	0	-2	-2	2	2	**4**
No mould required	3D Printing		2	2	2	2	1	-2	-2	2	-2	**5**

13.2.3 Validation VaCo Mould

The VaCo Mould can only compete with the existing moulding techniques if the recommended improvements, as described in chapter 14.1 “Future Prospects”, are applied. The validation of the VaCo Mould is also based on these future prospects. In diagram 28 the VaCo mould is added to the validation of the moulding principles. Below the score for each parameter will be explained.

Form freedom – Score: 2

The 25 pins ensure that every possible form can be made with the VaCo Mould.

Reusability – Score: 2

The parameter “Reusability” is also very good. This is because the flexible layer always returns to its original form. Besides that also the PS sheet is a recyclable material.

Accuracy – Score: 1

The accuracy is good, but it is not so good as the pinbed technique. The amount of pins determine how accurate the form will be. The more pins, the more accuracy.

Production speed – Score: 2
The production speed is very high by using the vacuum forming process. A PS sheet with a thickness of 2 mm could be vacuum formed in five minutes. The production speed of 3D printing is faster, because no mould is needed.

No counter mould is needed – Score: -2
The whole principle of the VaCo Mould is based on using a counter mould. That is why on this parameter the score is -2.

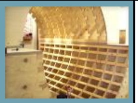
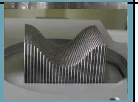
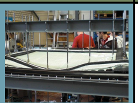
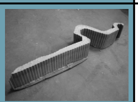
Surface quality – Score: 2
The surface quality on the other hand is very smooth. This is because the PS sheet provides a concrete panel with a very smooth surface. On the parameter "Production speed" the 3D printing is faster than the VaCo Mould, but on the surface quality the VaCo Mould scores much better.

Surface quality on two sides – Score: 2
Another very good rated parameter is the "Surface quality on two sides". By using the vertical pouring process, in combination with clay granulate as counter pressure material, the two PS sheets provide a smooth surface on both sides of the concrete panel.

Labour intensive – Score: 1
The only labour intensive part of the VaCo Mould is making the plastic mould. At this point the 3D printing technique, supported membrane and the CNC foam milling have a better score.

Costs – Score: -2
Besides that a counter mould is needed, also the material costs are high of the VaCo Mould. For a panel of 500x500 mm, a PS sheet is needed with dimensions of 850x850 mm. These dimensions are needed because for vacuum forming the extensions are extracted from the excess of the sides. The price of a PS sheet with dimensions of 500x500 mm, with a thickness of 2 mm, is around twelve EURO. Once the VaCo Mould will be scaled up, this price will be also higher. Another cost item is the laser machine, for cutting the right shape out of the PS sheet, and the five axis milling machine for milling the bevelled edges, for the clamping principle. But this could also be outsourced to other companies.

Diagram 28: Validation moulding principles with VaCo Mould

Category	Type	Subtype	Image	Form freedom	Reusability	Accuracy	Production speed	No counter mould is needed	Surface quality	Surface quality on two sides	Labour intensive	Costs	Total
Static Moulds	Wood			1	-1	0	-2	1	1	-2	-2	-2	**-6**
	Steel			1	-2	2	-1	2	2	-2	0	-1	**1**
	CNC foam milling			2	-2	2	1	2	2	-2	2	-2	**5**
	Hydrostatic Equilibrium Moulding			2	-1	2	1	-2	0	0	2	-2	**2**
	Inflatable			2	-2	0	1	2	2	-2	-1	-1	**1**
Reusable Moulds	Sand / Clay			1	2	0	-2	2	0	-2	-2	-2	**-3**
Flexible Moulds	Pinbed			2	2	2	2	-2	-2	-2	1	-2	**1**
	Supported membrane	Existing Moulds		2	2	1	1	2	2	-2	2	-1	**9**
		VaCo Mould		2	2	1	2	-2	2	2	1	-2	**8**
	Tensioned membrane			1	2	0	1	-2	2	2	1	0	**7**
	Vacuumatics			2	1	0	1	0	-2	-2	2	2	**4**
No mould required	3D Printing			2	2	2	2	1	-2	-2	2	-2	**5**

14. Conclusions & Recommendations

The last chapter "Conclusion & Recommendations" is divided in three parts: SWOT-analysis, conclusion and recommendations.

14.1 SWOT-analysis

To have a clear picture of the potential of the VaCo Mould, this technique is subjected to a SWOT-analysis (diagram 29). The SWOT-analysis is divided into two parts, namely: internal origin and external origin. The internal origin are the strengths and weaknesses of this moulding technique and the external origin are the opportunities and threats presented by the environment. Based on this evaluation a good conclusion and recommendation can be described.

Diagram 29: SWOT-analysis of the VaCo Mould

		Helpful To achieving the objective	Harmful To achieving the objective
Internal origin	Attributes of the moulding technique	**Strengths** - Fast production cycle - Relatively low-cost production method - Smooth surface quality on both sides - Accuracy of flexible membrane - Recyclable mould material - Simple manual configuration - All forms can be made	**Weaknesses** - Depending on a non automated scanning method, to set the mould - 3D milling or laser machine needed to produce the edges - Manual configuration
External origin	Attributes of the environment	**Opportunities** - Trends in freeform design - High costs of current moulding techniques - Scale up VaCo Mould - Industrialized production process - Additional manipulation methods - Interactive process between laser scanning and designed geometry for higher accuracy	**Threats** - Input for mould setting - Inaccuracy of the pins - The production of the counter mould with PS sheets - Correlation simulation with production process - Deviation in deformed thermoplastic sheets - Imprints in thermoplastic sheet - Mixture of SCC

14.2 Conclusion

The goal of this research was designing a moulding technique that has a quick and low cost production process and creates façade panels with a smooth surface on both sides of the element. This new moulding technique is based on vacuum forming in combination with counter pressure. The idea behind the vacuum forming and counter pressure:

- Separating the casting process from the flexible mould, with the goal to improve the production time;
- By improving the production time also the costs will be reduced;
- To use a plastic sheet to guarantee an optimal surface quality;
- To pour vertical with counter pressure to realise a smooth surface on both sides.

Another important goal of this research is that this moulding technique can compete with existing moulding techniques. Based on these predictions the following research question is formulated:

Can a double curved concrete panel, made with a reconfigurable mould based on vacuum forming in combination with counter pressure, compete with existing moulding techniques?

Based on the four important parameters (production time, low cost process, surface quality and casting process) the following conclusions are formulated:

Production time

The advantage of the technique of vacuum forming with counter pressure is the production time. Separating the vacuum forming process from the casting process creates a continuous cycle. The vacuum forming process of one panel takes around one hour. In the meantime the edges for the clamping principle will be milled. When two plastic sheets are vacuum formed, these sheets will be clamped with the milled edges. After that the mould can be casted, which can be done in 30 minutes. The total production time of one panel takes one hour and 45 minutes. Because the vacuum forming process of the next panel could already start when the first panel is not casted yet, at the end of the day nine different concrete panels could be casted.

This production time is based on the prototype of the VaCo Mould. When this mould will be updated as described in chapter 13.1 ”future prospects”, the total production time of one concrete panel takes 45 minutes. By the separated steps of the process of this moulding, at the end of the day 30 different concrete panels could be casted.

Low cost process

The surface quality of each casted concrete panels show different result. There are several mixture of concrete tested during this research. The main problem was to get the right workability. The workability depends on the amount of plasticizer that is added to the mixture. When there is too much plasticizer in the mixture, it causes colour differences on the surface. When there is a lack of plasticizer, it will cause blowholes on the surface. Eventually a lot of knowledge is gained according SCC, but designing a proper mixture needs more experience. With this knowledge further a proven mixture of Cugla chosen. The first experiment with this mixture on a small flat panel was very good. Based on this experiment the mixture of Cugla is chosen for the panels of the final design. After demoulding of the final concrete panels still some blowholes where visible on the surface, while it is a proven concrete. The problem could be that some points of the concrete sticks to the PS sheets or the mixture is not suitable for double curved shapes. This will be an important recommendation for further research.

Surface quality

The surface quality of the casted concrete panels are different. Several mixtures of concrete were tested during this research. The main problem was to get the right workability. The workability depends on the amount of plasticizer that is added to the mixture. When there is too much plasticizer in the mixture, it causes colour differences on the surface. When there is a lack of plasticizer, it will cause blowholes on the surface. Eventually a lot of knowledge is gained about the SCC, but designing a proper mixture needs more experience. With this knowledge the choice is made for using a proven mixture of Cugla. The first experiment with this mixture on a small flat panel was very good. Based on this experiment the mixture of Cugla is chosen for the panels of the final design. After demoulding of the final concrete panels still some blowholes were visible on the surface, while it is a proven concrete. The problem could be that some points of the concrete sticks to the PS sheets or the mixture is not suitable for double curved shapes. This will be an important recommendation for further research.

Casting process

To create a smooth surface on both sides a proper counter pressure material was needed. Different counter pressure materials were tested in the experimental phase. The best results are achieved when using the counter pressure materials clay granulate and bentonite. Both materials were tested on a bigger scale. The materials bentonite and clay granules both had potential to guarantee good surface quality and less deviation, but clay granules had more advantages for the production process.

An important fact is that during casting the concrete and clay granules have to be poured at the same time, to avoid deviations of the PS sheet. The validation of the concrete panel with the casting process shows an extreme deviation at the top of the panel. The reason could be that the counter pressure was not strong enough to withstand the pressure of the concrete. This deviation is avoided by clamping the sheets at the top of the mould.

General

In the beginning there were some question marks if vacuum forming with a flexible mould is a working principle, because the pressure that will be realized during vacuum forming is very high. Most of the companies that are spooking with this, did not think this would be possible, because they used only static moulds. After this research it can be concluded that the vacuum forming process in combination with the supported membrane is a good working principle, when the pressure is adjustable.

Another conclusion is that with the flexible layer of spring steel and silicone, all kinds of forms can be made. This is also confirmed by the validation, which shows that most of the area of the validated parts stays within the -2 and 2 mm tolerance. This means that the spring steel is an ideal material for flexible moulding techniques.

14.3 Recommendations

The recommendations are mainly based on the improvement of the production process as mentioned in chapter 13 "future prospects and market potential". Besides that some recommendations are given for building applications. The goal for the future is to translate this idea to an industrialized production process. To establish this, the following steps can be taken.

For the vacuum forming process it can be recommended to design a mould with dimensionally stable materials and a full automated process. This modification limits the amount of proceedings and improves the production speed. The automation process should be designed as an interactive process between the designed model and the projection to the production of the element. This can be achieved by translating the data of the design to a laser placed above the flexible membrane, which calculates the deviations between the mould pins that are automatically set with a motor or hydraulic system. The heating element in the prototype is placed 500 mm above the plastic sheet, because the PS sheet must be heated equally to avoid wrinkles. When spirals are placed over the entire surface of the PS sheet, it can be placed closer to the surface and save approximately four minutes in production time. The vacuum cleaner to create the pressure can be replaced with a vacuum pump and a buffer tank to control the pressure. For applications in the build environment it is advisable to scale up the mould. Vacuum forming machines nowadays exist in a size of 4000x2500x1000 mm. This means that scaling up the system will not give problems for vacuum forming. For more freedom in form more pins can be used, but the question is if this will be worth the investment. Local deformation can also be realised by adding different forms of silicone on top of the mesh.

The counter mould still brings a lot of effort in the production process. The PS sheet must be cut in the right size, clamped between wooden sheets and put together to create the counter mould.

At the moment the sheets are sawed, after the correct size is drawn on the sheet. This process can be improved by using a laser that cuts the right shape. The wooden sheets for clamping the PS sheets are lasered perpendicular, which can cause deviation in the PS sheets. A solution would be a laser or drilling method that can cut or drill under an angle. The most labour intensive part is the clamping method itself, for this part every plate must be fitted with screws. It is recommended to research other methods to eliminate this process. It might be possible to develop an automated process. The produced mould uses clay granulates as counter pressure and must be poured at the same time as the concrete. This process can be automated when different tubes under pressure cast the materials equally. The casting process can be accelerated with a battery mould. The different concrete mixtures tested still show some colour deviation or blow holes. For further research other mixtures must be tested.

The building application for this mould is large. Within this research only the application for concrete is investigated, but also other materials as glass or wood have a big potential. The goal was to produce a concrete panel, which shows the possibilities of the VaCo Mould. Local thickening is used to produce a concrete panel with the maximum curvature that is not dependent on the fixation method. Other innovative technologies as water jet cutting make it possible to produce every kind of shape. This gives the opportunity to design facades with a topographic view. The VaCo mould can also be optimized to produce sandwich elements. This requires a systematic way of using the counter mould and anchoring methods, but this was not the objective of this research.

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Appendix A: Paper ISOFF symposium 2015

ISOFF AMSTERDAM 2015

The VaCo Mould, a new moulding technique for fluid architecture

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Abstract

The VaCo Mould is a new moulding technique to answer the demand for more efficient production methods of double curved elements in fluid architecture. The goal is to design an efficient production process resulting in high-quality panels. The VaCo Mould is a combination of vacuum forming and counter pressure. Vacuum forming is used to produce plastic sheets that are deformed according to the designed surface. This form is obtained by a supported mesh; pistons are used to deform the mesh. The plastic sheets are used to create a mould for the vertical casting process. The curved sheets are kept in place with counter pressure, due to the hydrostatic pressure that is exerted by wet concrete during the casting.

Keywords: adjustable surfaces, free from, vacuum forming, counter pressure, fluid architecture

1. Introduction

Since the early nineties there is a trend of fluid double curved architectural design. This trend has been rising due to the developments in three-dimensional Computer Aided Design (CAD). This brought new life into architecture in terms of organic shapes and fluid forms that can be interpreted as the smoothened follow-up of ‘Deconstructivist Architecture’, with examples of Frank Gehry (figure 1) or Zaha Hadid [1].

Figure 1: The Guggenheim museum, Frank Gehry [2]

Before CAD software belonged to the possibilities, architects like Oscar Niemeyer also designed buildings with curved surfaces. An example is the congress centre in Brasilia, which is designed as an inverted dome. For the construction of these buildings, high labour intensity was needed. At that time labour was relatively cheap and time was less important. Until now the building techniques for the construction of such free-form buildings were quite primitive. Nowadays more precast concrete elements are used and formwork and labour is more expensive. This is the reason for searching new production methods to create single or double curved elements.

Recently used methods are Computer Numerical Controlled (CNC) machines that precisely cut or mill a designed object. This technique, with polystyrene or wood as material, can be used as a formwork for complex shaped buildings. One of the disadvantages is that for each panel or segment a different mould is needed. To make this moulding principle profitable the formwork must have a certain repetition. Besides that, the waste of the mould is also a problem. New research investigates the possibilities of a reconfigurable mould that can be used to produce different elements.

2. Flexible moulds

A flexible mould is a mould that can be set into different shapes. With this method it is possible to create different concrete panels, with less labour intensity, material waste and costs of formwork. The disadvantage of a flexible mould is the high investment costs. Examples of flexible moulds are:

- pinbed - a system with high density adjustable pins for accurate products (figure 2a) [3].
- zero-waste free-form formwork - reusable wax is used to produce a counter mould and is constructed on a reconfigurable mould (see figure 2b) [4].
- flexible mould - the concrete is poured horizontally on a supported membrane and set into the right curvature after the concrete has created enough yield strength (figure 2c) [5].

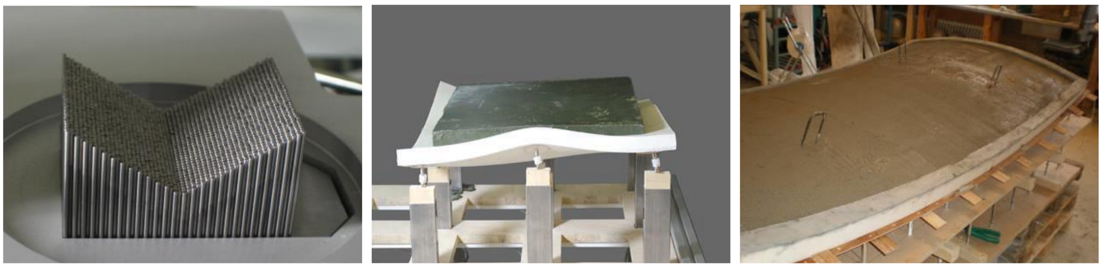


Figure 2a: Pinbed [3], Figure 2b: Zero-waste free-form formwork [4] & Figure 2c: Flexible mould [5]

Based on literature it can be concluded that a flexible moulding technique makes it possible to create an efficient building method for double curved elements. Most of the systems are still in development and need further research.

3. The VaCo Mould

The goal of this research is to optimize the production speed and surface quality using an adaptable surface of spring-steel. We found the curing time of the product to be the most critical aspect. To deal with this it is possible to make vacuum formed boxes with the adjustable mould in high speed. The boxes will be filled with concrete for the production of the final product. The technique can be divided into the (Va)cuum mould and the (Co)unter pressure mould. The idea is to use plastic sheets that are heated and vacuumed towards the adjustable surface of the rubber covered. With the curved sheets boxes are made. The box is used as a mould. Casting the mould needs a counter pressure to avoid the deformation of the thin surface of the plastic boxes. The plastic boxes give a good surface quality of the concrete elements and a fast production process.

3.1. The vacuum mould

The adjustable flexible surface of the vacuum mould is based on a woven spring-steel. The spring steel mesh is connected with a grid of adjustable pistons. The pistons are moved into different positions to form a point grid part of the demanded curved surface. The properties of the woven mesh makes it possible to form doubly curved surfaces. A well-known example proving the adjustable properties of a woven steel mesh is a synclastic tea-strainer (figure 3).

Figure 3: Synclastic tea strainer

The stiff properties of the spring-steel deviates the mesh in to an equilibrium with a smooth curved surface connecting the point mesh formed by the grid of adjustable points. To smoothen the tactility of the mesh it is casted in an elastic silicone rubber. The advantage of this system is its simplicity, robustness and therefore feasibility compared to other adjustable moulding techniques. More about the working of the spring steel mesh is published in the paper *Flexible mould by the use of spring steel mesh* by Pronk et al. 2015.

This mould is designed to produce elements with a dimension of 500x500mm. A section of the mould can be seen in figure 4a and the final mould in figure 4b. The mesh used for this mould is supported with 25 pins, with a pin spacing of 125mm. Three different types of pins are used: one fixated pin in the middle, clevis eye connections in a cross and at the edges ball joints. The ball joints make it possible for the spring steel mesh to deform into the designed curvature. These deformations makes the planer projection of the surface smaller than 500x500mm; therefore the spring steel mesh is oversized to the dimension of 550x550mm.

The mesh is enclosed with a wooden box, which together with the frame for the plastic sheets, creates an airtight volume for vacuum forming. A vacuum cleaner is used to realize the under pressure. This is suitable because a low pressure of approximately 0.1 bar is needed. The frame is used to clamp the plastic sheets. On top of this frame the heater is placed, which heats up the plastic sheet in 5 minutes and reaches a temperature of 115˚C. The heater is made with heating spirals. Polystyrene sheets are used for vacuum forming. When the sheet is heated it becomes plastic enough to be pulled over the mesh. The mesh is set into the right shape by adjusting the pins to the right height. These input settings are measured from a Rhinoceros model.

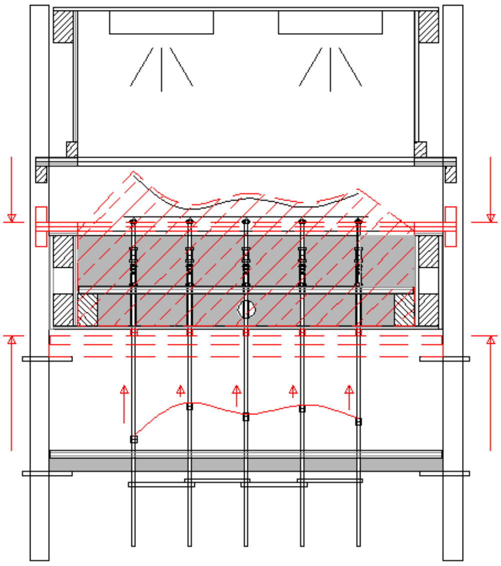
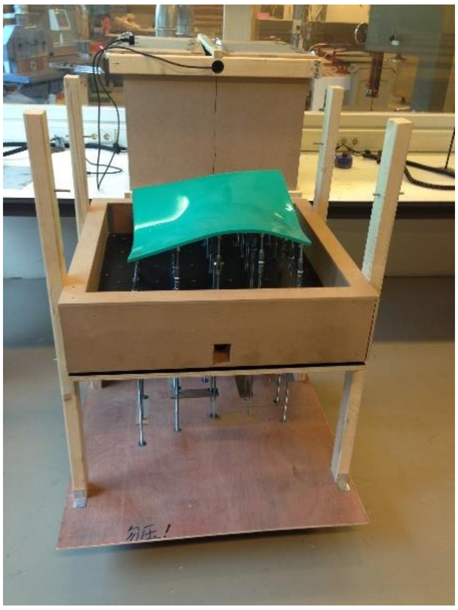



Figure 4a: Section of vacuum mould & Figure 4b: The final vacuum mould

With this mould it is possible to create synclastic and anticlastic shapes. The possibilities for local deformation are limited by the amount of pins. In this case we realized a grid of 25 pins. The maximum curvature is given with a minimum radius of 400mm. This limitation depends on the amount of extra PS material that is used. For this process, PS sheets of 750x750mm are used. This means that 125mm extra material can be used to produce the curvature.

3.2. The counter mould

When the plastic sheets are formed into the right curved surface with the vacuum mould, the mould for the casting process can be produced. The top view of the mould can be seen in figure 4a and the final counter mould in figure 4b. The plastic sheets are clamped between wooden sheets, which are laser-cut according the design. The mould is placed inside a box, which is used to realize counter pressure. The material used for counter pressure is a clay granulate. Compared to other tested materials such as bentonite, this dry method is easier to use. During the casting process the concrete and clay granulates are casted at the same time, to avoid the deformations of the plastic sheet.

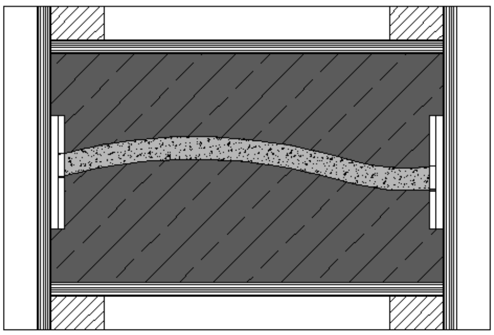



Figure 5a: Top view of the counter mould & Figure 5b: The final counter mould

4. Production process

The production process of a double curved concrete panel is divided into four steps:

1. mould setting,
2. vacuum forming,
3. create a mould, and
4. casting concrete.

The total process of creating a double curved concrete panel is visualised in figure 6.

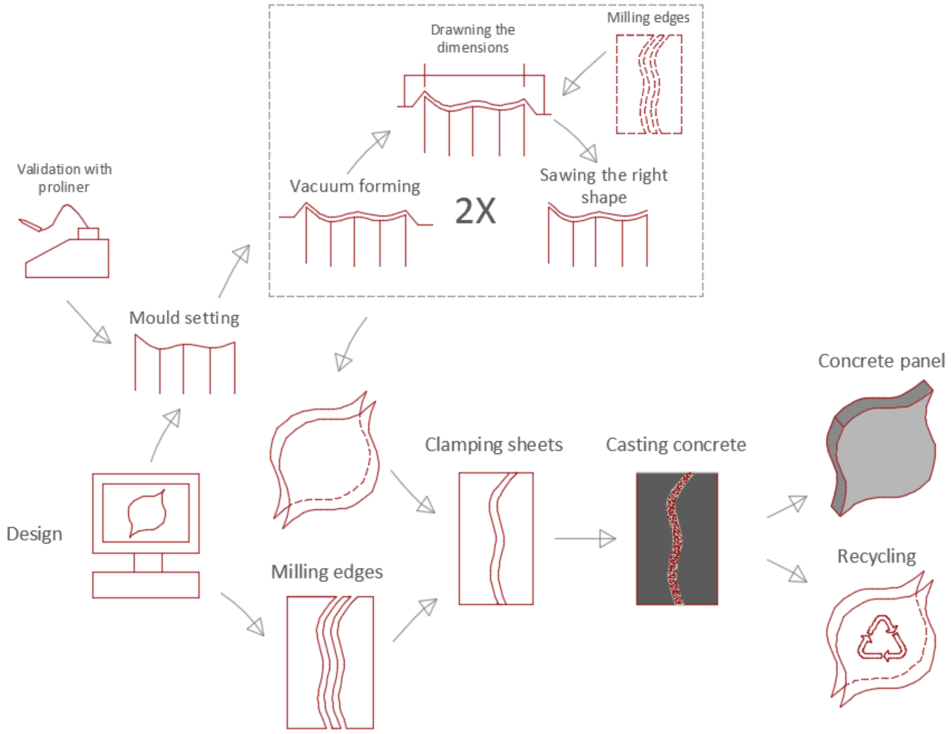
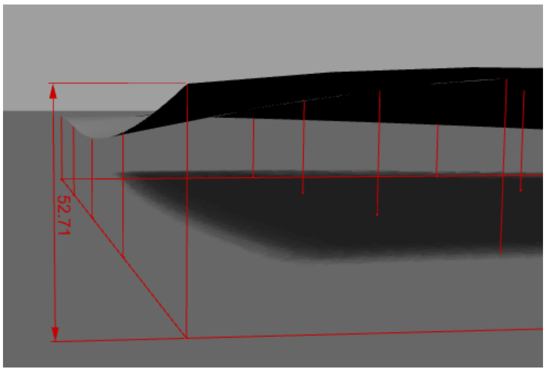


Figure 6: The total production process

4.1. Mould setting

When a panel is designed in Rhinoceros the VaCo Mould could be set in the almost the same surface. The heights of the pins will be measured in Rhinoceros and are based on straight lines starting from a grid of 25 pins towards the curvature of the panel (figure 7a). When all heights are obtained, the VaCo Mould will be set into the right curvature by sliding the pins in the right position. The pins consist of bolts with threaded ends. To lock the heights of the bolts nuts will be brought in position and turned counter-wise to each other. When all nuts are set in the right heights, a lifting plate can be pulled up to the bottom of the airtight box. In this way the pins are sliding in position, which results in a double curved surface of the flexible layer similar to the designed form in Rhinoceros (figure 6b). The manual sliding system for the pins we have used is developed by Roel Schipper and Peter van Eigenraam of the TU Delft [5]. It is possible to automate this system, as we have done for a glass mould [6].

As a final check the flexible layer will be scanned with the Proliner by the company Prodim to ensure that the deviation is within the tolerances. After that the 2mm PS sheet is clamped in a frame.



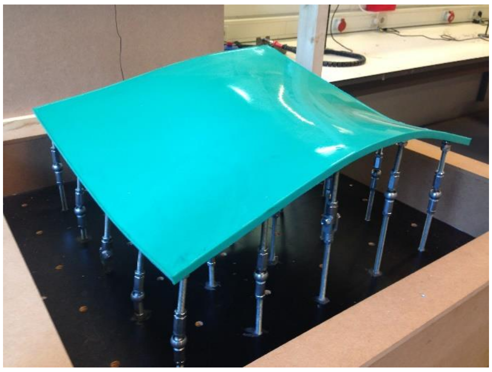


Figure 7a: Measuring the heights in Rhinoceros & Figure 7b: The flexible layer is set in the right position.

4.2. Vacuum forming

The heating element will be placed on top of the clamped sheet and the heating elements will be switched on. When the PS sheet is total plastic, the vacuum forming process can be started. First the heating element will be taken off. The rods that held the frame at height, will be pulled out and the frame with the PS sheet will be pulled down over the flexible layer (figure 8b). When the frame is attached to the airtight box the vacuum cleaner will be switched on. This vacuum cleaner ensures that the PS sheet will be pulled on the surface of the flexible layer. When the PS sheet is cooled down the sheet can be taken out the frame. The end result is a vacuum formed PS sheet with a double curved shape that is equal to the adjusted flexible layer.

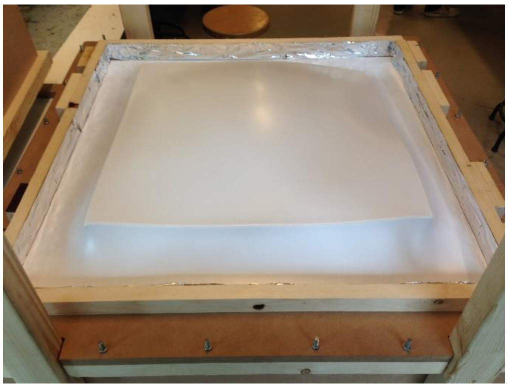



Figure 8a: The PS sheet is placed between the columns & Figure 8b: The PS sheet is pulled down over the flexible layer

4.3. Create a mould

To create the box for the mould two double curved PS sheets are needed. This means that the vacuum forming process has to be done twice. For making the mould only the double curved surface of the vacuum formed sheet is needed. This surface has to be cut out. To ensure the cutting edges of 500x500mm a frame is placed on top of the plastic sheets. This frame has been cut in the right shape with a laser cutter. After cutting the sheets (figure 9a) the wooden frame and sheets are assembled to boxes (figure 9b). The laser cutting of the edges and the clamping of the sheets make it possible to have very low tolerances at the edges of the elements to be made.


Figure 9a: Drawing the right dimensions & Figure 9b: Clamping the sheets with the milled edges

4.4. Casting concrete

When the moulding box is finished it will be placed in a bigger box. The concrete is poured in the moulding box and at the same time the clay granulates are poured in the bigger box to give counter pressure. This is to avoid that the hydraulic pressure of the concrete will deform the plastic sheet. When the mould is fully poured with concrete (figure 10a), the curing process can begin. When the panel is fully cured it can be de-moulded (figure 10b) and the plastic sheets and wood could be recycled. The total production time of one panel takes one hour and 45 minutes. Because the vacuum forming process of the next panel could already start when the first panel is not casted, at the end of the day nine concrete panels could be casted.

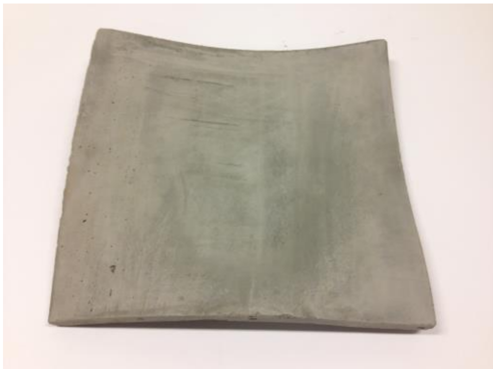



Figure 10a: The mould is fully poured with concrete & Figure 10b: The end result of a concrete casted panel

4.5. Future prospects

In this research we realized some panels with a prototype of the VaCo Mould. In the future the VaCo Mould can be improved to a principle that can compete with the existing moulding principles. This can be done by improving the mould by using dimensional stable materials, like steel or aluminium instead of the wooden prototype we made. Another important modification is to scale up and automate the the VaCo Muld. Automation will speed up the process with the help of a step motor or a servo motor to adjust the pins. We have researched and realized this in another project [6]. The validation process could also be automated, for instance by the use of a laser measurement. Laser cutting could be used for cutting the right surface of the vacuum formed sheet. A condition for the laser cutter is to be able to cut under an angle. In his way it will be possible to clamp the fluid form of the vacuum formed PS sheet more precise at the edges of the moulding box. The casting process could also speed up by using a battery mould. The improved process of creating a double curved concrete panel is visualised in figure 11.

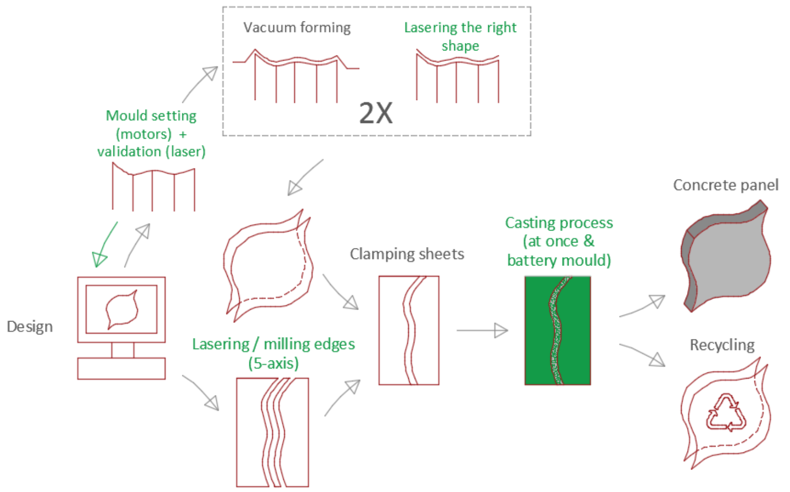


Figure 4: Improved production process

5. Validation process

The validation process is used to limit the deviations of the design compared with the end product. The deviation of the end product can be improved by validating every part in the production cycle. When one part of the production process is within the excepted tolerances it can be excluded for further improvement. This means that if the deviation of the end product is too much, the problem should be in the other three production parts. The validations compare the difference between for example the surface of the mould and the design, which is validation number 1 that is visualized in figure 12. The following validations are made:

- Validation 1: comparison between the mould and the design
- Validation 2: comparison between the vacuum forming and the mould
- Validation 3: comparison between casting and vacuum forming
- Validation 4: comparison of casted product with the design

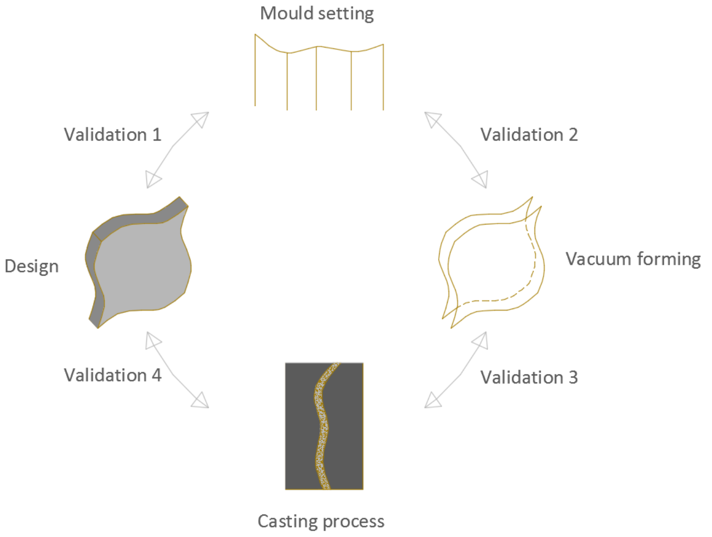


Figure 12: Validation process

The results of validation 1, 2 and 3 are generally within the deviations of ±2mm. Validation 4 is the overall validation and can be seen in figure 13. For this validation the edges of the design and the concrete panel are aligned, because these deviations should be minimal with the clamping method that is used. The average deviation is 2.4mm and the standard deviation is 1.4mm. The extreme value of 6.1 at the left top of the concrete panel could be caused by a too high pressure of the concrete. This means that there was not enough counter pressure.

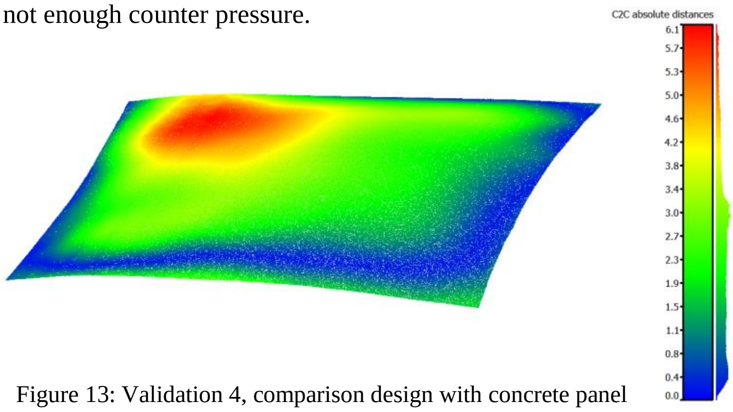


Figure 13: Validation 4, comparison design with concrete panel

6. Conclusions and recommendations

The conclusions and recommendations are based on a SWOT analysis and the market potential of the VaCo Mould. One of the strengths of the VaCo Mould is the fast production cycle by separating the vacuum forming process from the casting process. Also the smooth surface quality of the concrete panels, by using plastic sheets as mould material, is a strong feature of the VaCo Mould. The disadvantages of the VaCo Mould are the inaccuracy of the pins and the production time of the counter mould with the plastic sheets. The important recommendations for the VaCo Mould are: scaling up in size and speed the VaCo Mould, industrializing the production process and improving the accuracy.

Acknowledgement

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Appendix B: Experiments vacuum forming

Experiment 1.1: Vacuum forming machine – Eindhoven University of Technology

Goal: To produce a PETG sheet that smoothly follows the surface curvature of a spring steel mesh with a silicon layer.

Vacuum forming machine

Type:	Formech 686
Forming Area:	646x620 mm
Sheet size:	686x660 mm
Max depth of draw:	325 mm
Max material thickness:	6 mm
Heating zones / Heater type:	6 / Quartz
Power consumption:	8 kW
Air requirements:	80 PSI / 5 Bar

Mould

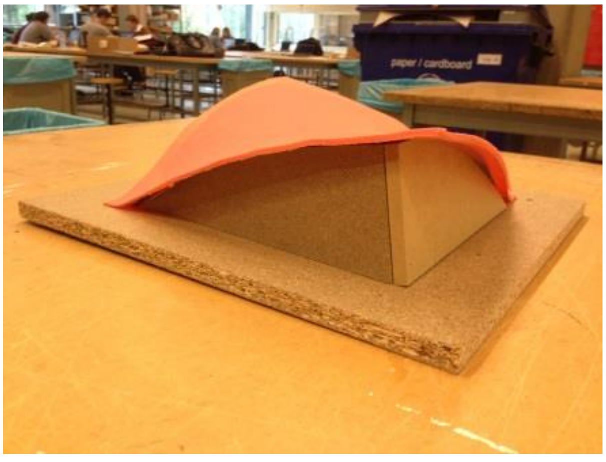
Construction:	Made of chipboard
Support:	Under the edges
Steel mesh:	Spring steel: WNFE3 – 1.75x0.8
Top layer:	Silicon
Size:	300x300 mm

Variables

Time:	Not measured
Max. temperature:	Not measured
Type / thickness of sheet:	PETG / 1 mm
Pressure:	Approximately 3-4 Bar

Results

In this prototype the wooden support was pushed to the outside and the spring steel was pushed downwards, which resulted in large deformation according to the original mould design. The vacuum machine that was used in the workspace did not have the ability to decrease the force of vacuum forming. Another option to solve this problem is to put sand, clay granules or other materials underneath the membrane as counter pressure.




Experiment 1.2: Vacuum forming machine – Eindhoven University of Technology

Goal: To produce a PETG sheet that smoothly follows the surface curvature of a spring steel mesh with a silicon layer.

Vacuum forming machine

Type:	Formech 686
Forming Area:	646x620 mm
Sheet size:	686x660 mm
Max depth of draw:	325 mm
Max material thickness:	6 mm
Heating zones / Heater type:	6 / Quartz
Power consumption:	8 kW
Air requirements:	80 PSI / 5 Bar

Mould

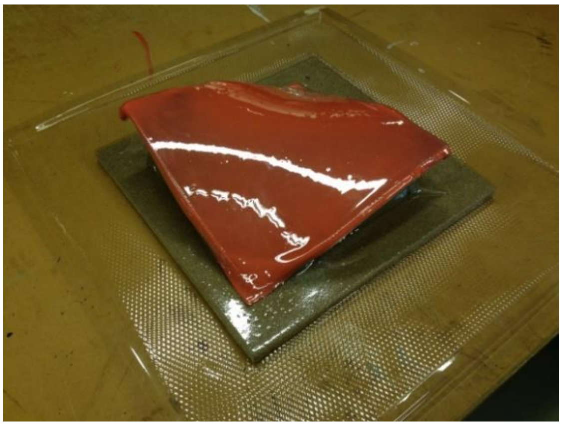
Construction:	Made of chipboard
Support:	Sand
Steel mesh:	Spring steel: WNFE3 – 1.75x0.8
Top layer:	Silicon
Size:	300x300 mm

Variables

Time:	Not measured
Max. temperature:	Not measured
Type / thickness of sheet:	PETG / 1 mm
Pressure:	Approximately 3-4 Bar

Results

The result of the mould after vacuum forming was better than experiment 1.1. Because there was sand under the spring steel, the PETG was not pulled down to the ground. In this way the form was gradually, such as the edges of the wooden plates. At one end there where some bubbles. This could be because there was some sand underneath, probably because the sand was not completely closed off. Another result of the experiment is that when there is an overhang, the co-polyester will be pulled over this overhang by the high air pressure. This makes it difficult to pull the co-polyester off the wooden mould.



Experiment 2.1: Vacuum forming machine – Bas Hesselink IDAP

Goal: The PETG sheet should follow the curvature of the supported membrane. This was the bottleneck of previous experiments, where the membrane deformed under the high pressure.

Vacuum forming machine

Type:	Custom-made

Mould

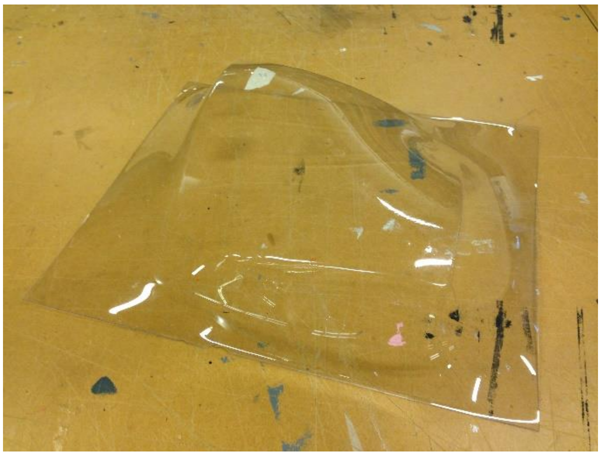
Construction:	Made of chipboard
Support:	Under the edges
Steel mesh:	Spring steel: WNFE3 – 1.75x0.8
Top layer:	Silicon
Size:	300x300 mm

Variables

Time:	2.50 min
Max. temperature:	Not measured
Type / thickness of sheet:	PETG / 1 mm
Pressure:	Approximately 0.1 Bar (no vacuum)

Results

From this experiment it can be concluded that changing pressure worked well. The span of 30 cm was no problem and did not deform. The PETG sheet was slowly pulled into the membrane, by releasing air bit by bit. The silicone of the membrane resulted in a smooth surface, but the disadvantage is that the PETG sheet cannot be moved again when it came in contact with the membrane accidentally. This problem could be solved by using felt instead of silicone. The wooden support for the membrane was placed too far inside the mould, which caused a small deformation.

Experiment 3.1: Test vacuum forming machine

Goal: To produce a PETG sheet that smoothly follows the surface curvature of the spring steel mesh.

Vacuum forming machine

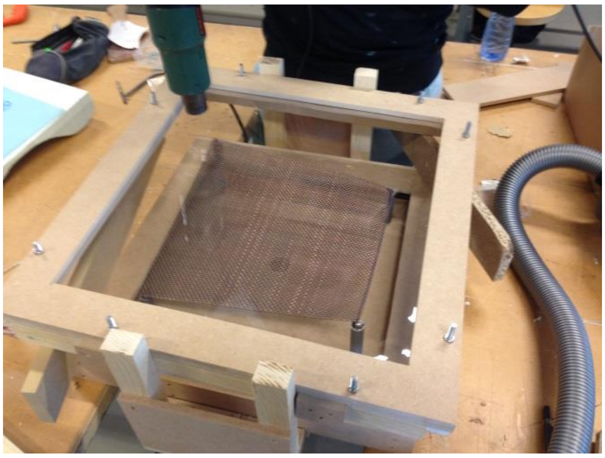
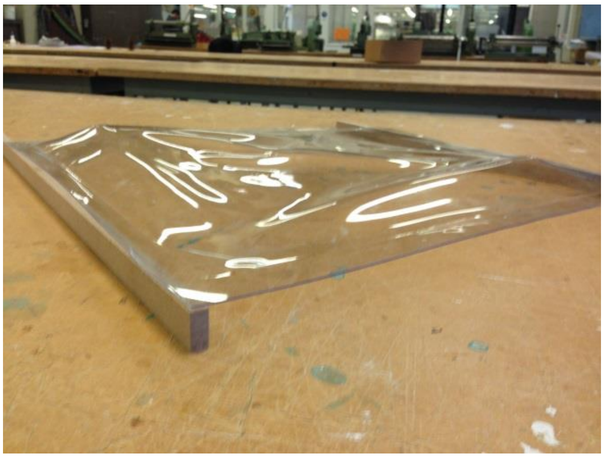
Type hot air gun:	Bosch PHG 490-2, 1400 W – Temp. 300-500 °C
Type of vacuum cleaner:	Siemens Big Bag 3L, 1800 W
Construction:	Made of MDF
Covering:	No
Fire resisting material:	No

Variables

Time:	Not measured
Max. temperature:	Not measured
Level of hot air gun:	2
Way of heating:	Moving by hand
Type / thickness of sheet:	PETG / 1 mm
Steel mesh:	Spring steel: WNFE3 - 2x1.25
Size:	300x300 mm
Distance between actuators:	300 mm
Pressure:	Approximately 0.1 Bar (no vacuum). The pressure is raised slowly.

Results

For this experiment the temperature of the PETG sheet was too low for vacuum forming. Heating without covering seems not to be an option. The heat must be divided equally over the sheet to get the best results. This means that it should be avoided that curtain spots get hotter or colder than other spots, tis can cause wrinkling.

Experiment 3.2: Test vacuum forming machine

Goal: To produce a PETG sheet that smoothly follows the surface curvature of the spring steel mesh.

Vacuum forming machine

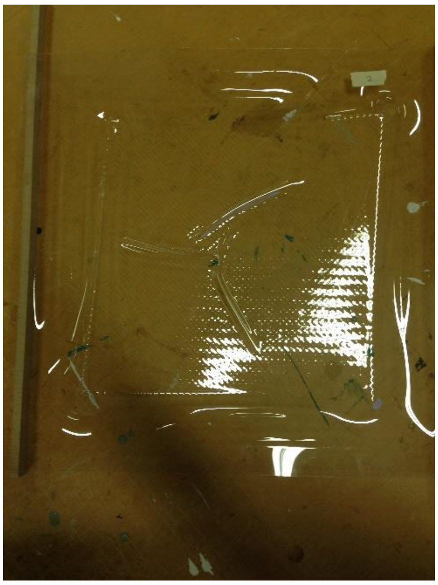
Type hot air gun:	Bosch PHG 490-2, 1400 W – Temp. 300-500 °C
Type of vacuum cleaner:	Siemens Big Bag 3L, 1800 W
Construction:	Made of MDF
Covering:	Yes
Fire resisting material:	No
Heating sensor:	Yokogama – Model 2455

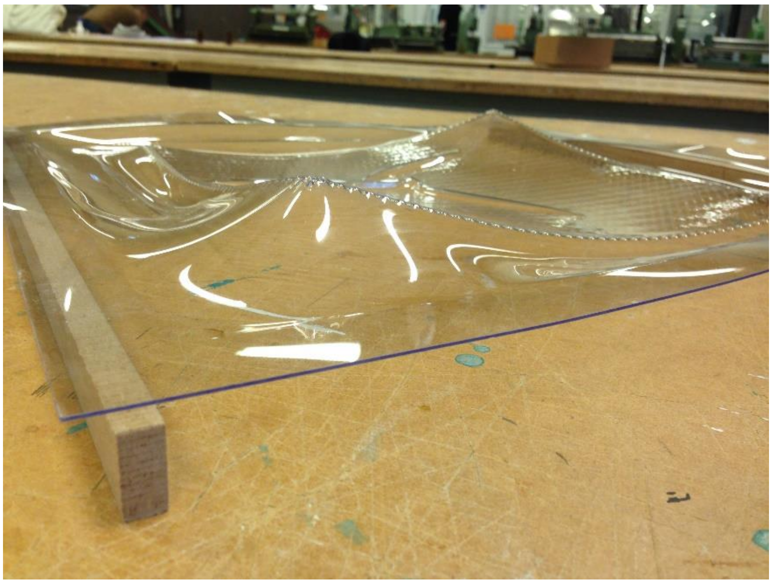
Variables

Time:	4.25 min
Max. temperature:	124°C
Level of hot air gun:	2
Way of heating:	Centralized
Type / thickness of sheet:	PETG / 1 mm
Steel mesh:	Spring steel: WNFE3 - 2x1.25
Size:	300x300 mm
Distance between actuators:	300mm
Pressure:	Approximately 0.1 Bar (no vacuum). The pressure is raised slowly.

Results

For this experiment a box is made around the hot air gun to avoid loss of temperature and too centralize heating. The sheet bended enough in the middle, but at the edges it was less flexible. The vacuum forming worked. The only problem was a wrinkle in the middle of the sheet. This problem could be caused by too high pressure of the vacuum cleaner, the pressure was gained to early or the sheet was not heated equally.





Experiment 3.3: Test vacuum forming machine

Goal: To produce a PETG sheet that smoothly follows the surface curvature of the spring steel mesh.

Vacuum forming machine

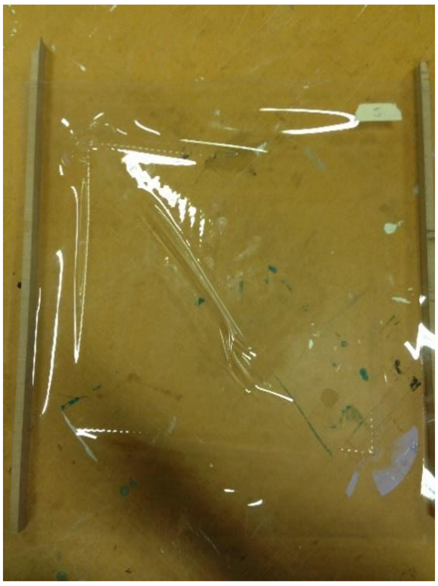
Type hot air gun:	Bosch PHG 490-2, 1400 W – Temp. 300-500 °C
Type of vacuum cleaner:	Siemens Big Bag 3L, 1800 W
Construction:	Made of MDF
Covering:	Yes
Fire resisting material:	No
Heating sensor:	Yokogama – Model 2455

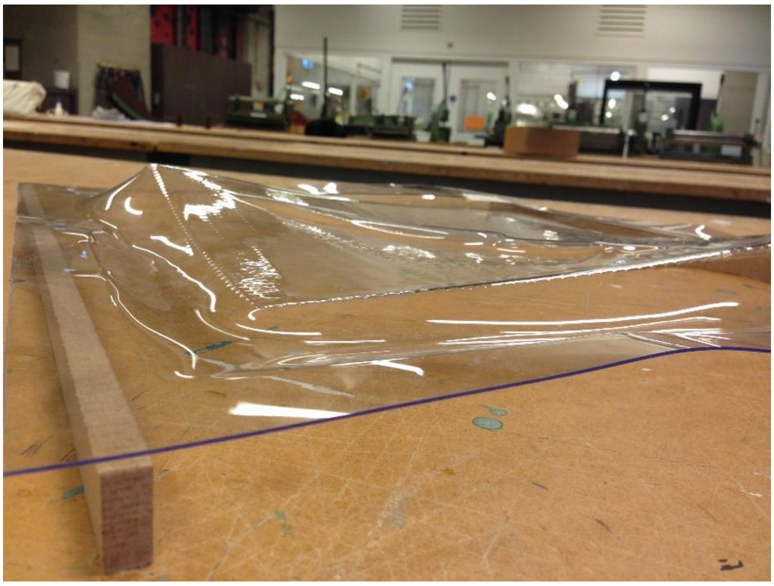
Variables

Time:	4.25 min
Max. temperature:	124 °C
Level of hot air gun:	2
Way of heating:	Centralized
Type / thickness of sheet:	PETG / 1 mm
Steel mesh:	Spring steel: WNFE3 - 2x1.25
Size:	300x300 mm
Distance between actuators:	300 mm
Pressure:	Approximately 0.1 Bar (no vacuum). The pressure is raised slowly.

Results

For this experiment the temperature, construction of the mould and the time is held the same. The only difference is that the vacuum cleaner is set on the lowest value. We can conclude that the pressure was not the problem, because approximately the same wrinkle as in experiment 3.2 occurred.





Experiment 3.4: Test vacuum forming machine

Goal: To produce a PETG sheet that smoothly follows the surface curvature of the spring steel mesh.

Vacuum forming machine

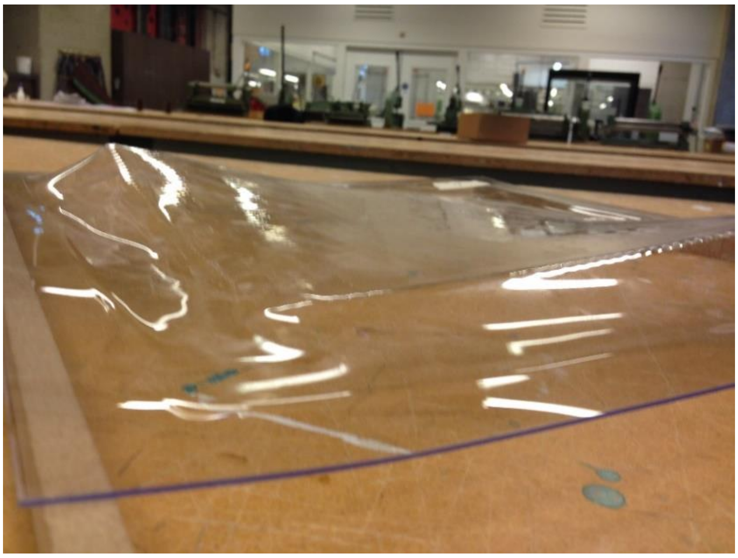
Type hot air gun:	Bosch PHG 490-2, 1400 W – Temp. 300-500 °C
Type of vacuum cleaner:	Siemens Big Bag 3L, 1800 W
Construction:	Made of MDF
Covering:	Yes
Fire resisting material:	Pyrogel XT Plus – 5 mm
Heating sensor:	Yokogama – Model 2455

Variables

Time:	15 min
Max. temperature:	175 °C
Level of hot air gun:	2
Way of heating:	Spread over surface
Type / thickness of sheet:	PETG / 1 mm
Steel mesh:	Spring steel: WNFE3 - 2x1,25
Size:	300x300 mm
Distance between actuators:	300 mm
Pressure:	Approximately 0.1 bar (no vacuum). The pressure is raised slowly.

Results

According to the above experiments in clause 3 so far, the form of the mould or the temperature difference in the sheet can cause the wrinkle. Because the flexibility in design of the mould is very important, the form was held the same for the time being. To solve the temperature problem a wooden plate was set in front of the hair dryer, because the heat is the highest in the centre region. The wooden plate moves the heat in different directions, which will result in a more equal distribution of the heat above the sheet. The wooden plate was prevented from burning by using a fire resistant material. As a result of the inserted wooden plate, more time was needed to heat up the sheet. This change in the design solved the problem of the wrinkle. From this last experiment it can be concluded that the principle works well. The vacuum cleaner easily pulls the sheet into the right curvature.



Experiment 3.5: Test vacuum forming machine

Goal: To produce a PETG sheet with a mark (for optimizing the cutting process) that smoothly follows the surface curvature of the spring steel mesh. Also an edge will be created for the use inside the hydrostatic mould.

Vacuum forming machine

Type hot air gun:	Bosch PHG 490-2, 1400 W – Temp. 300-500 °C
TWype of vacuum cleaner:	Siemens Big Bag 3L, 1800 W
Construction:	Made of MDF
Covering:	Yes
Fire resisting material:	Pyrogel XT Plus – 5 mm
Heating sensor:	Yokogama – Model 2455

Variables

Time:	15 min
Max. temperature:	175 °C
Level of hot air gun:	2
Way of heating:	Spread over surface
Type / thickness of sheet:	PETG / 1 mm
Steel mesh:	Spring steel: WNFE3 - 2x1.25
Size:	300x300 mm
Distance between actuators:	300 mm
Pressure:	Approximately 0.1 Bar (no vacuum). The pressure is raised slowly.

Results

The PETG sheet was not flexible, because the cover was not heated enough. This means that the heating time of the PETG sheet must be longer when the vacuum forming machine is used for the first time that day. This is also a reason why the mark, for optimizing the cutting process, on the surface was not clearly visible. This might also be caused by the pressure of the vacuum cleaner. When the pressure is higher, the PETG sheet is pressed harder on to the spring steel mesh, so the visibility of the mark will be better. For a better finishing of all edges the membrane must be placed higher. The edges that were created in this experiment, cannot be used in the hydrostatic mould. The idea was to press a frame in the PETG sheet by hand. But the cooling time was too fast to press a frame into the PETG sheet at the right time.


Experiment 3.6: Test vacuum forming machine

Goal: To produce a PETG sheet that smoothly follows the surface curvature of the spring steel mesh. With this experiment the spring steel mesh is placed in a more extreme position.

Vacuum forming machine

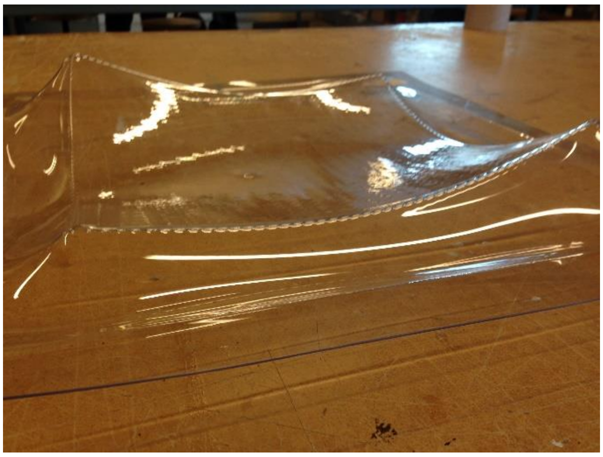
Type hot air gun:	Bosch PHG 490-2, 1400 W – Temp. 300-500 °C
Type of vacuum cleaner:	Siemens Big Bag 3L, 1800 W
Construction:	Made of MDF
Covering:	Yes
Fire resisting material:	Pyrogel XT Plus – 5 mm
Heating sensor:	Yokogama – Model 2455

Variables

Time:	15 min
Max. temperature:	175 °C
Level of hot air gun:	2
Way of heating:	Spread over surface
Type / thickness of sheet:	PETG / 1 mm
Steel mesh:	Spring steel: WNFE3 - 2x1.25
Size:	300x300 mm
Distance between actuators:	300 mm
Pressure:	Approximately 0.1 Bar (no vacuum). The pressure is raised slowly.

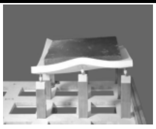
Results

Because experiment 3.5 was done one hour earlier the cover was still warm (28 °C). Hereby 15 minutes of heating time was enough to make the PETG plastically. The form of the shaped of the mesh was excellent for vacuum forming. Also the edges of the PETG were formed quite well. There were only two marks in the middle of the surface. These marks were caused by the steel wire of the actuator. This problem can be solved by placing a silicone layer on top of the spring steel mesh.

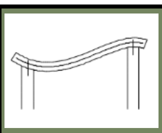
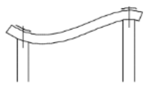
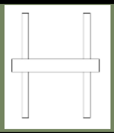
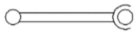
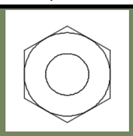
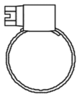
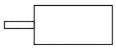
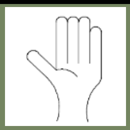
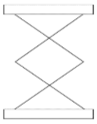
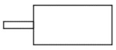
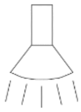
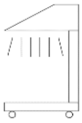
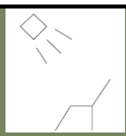
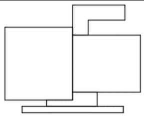
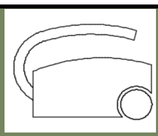
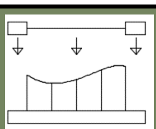
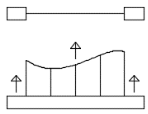


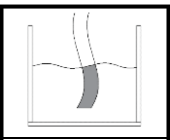
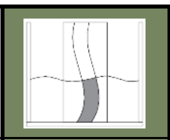
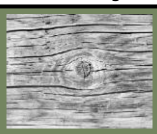
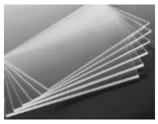
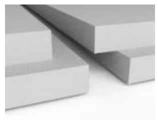
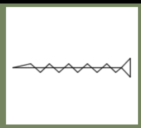
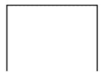
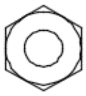
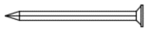
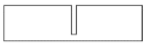
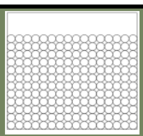
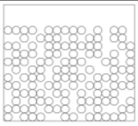
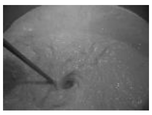
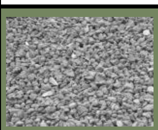
Appendix C: Morphological overviews

Morphologically Overview - VaCo Mould

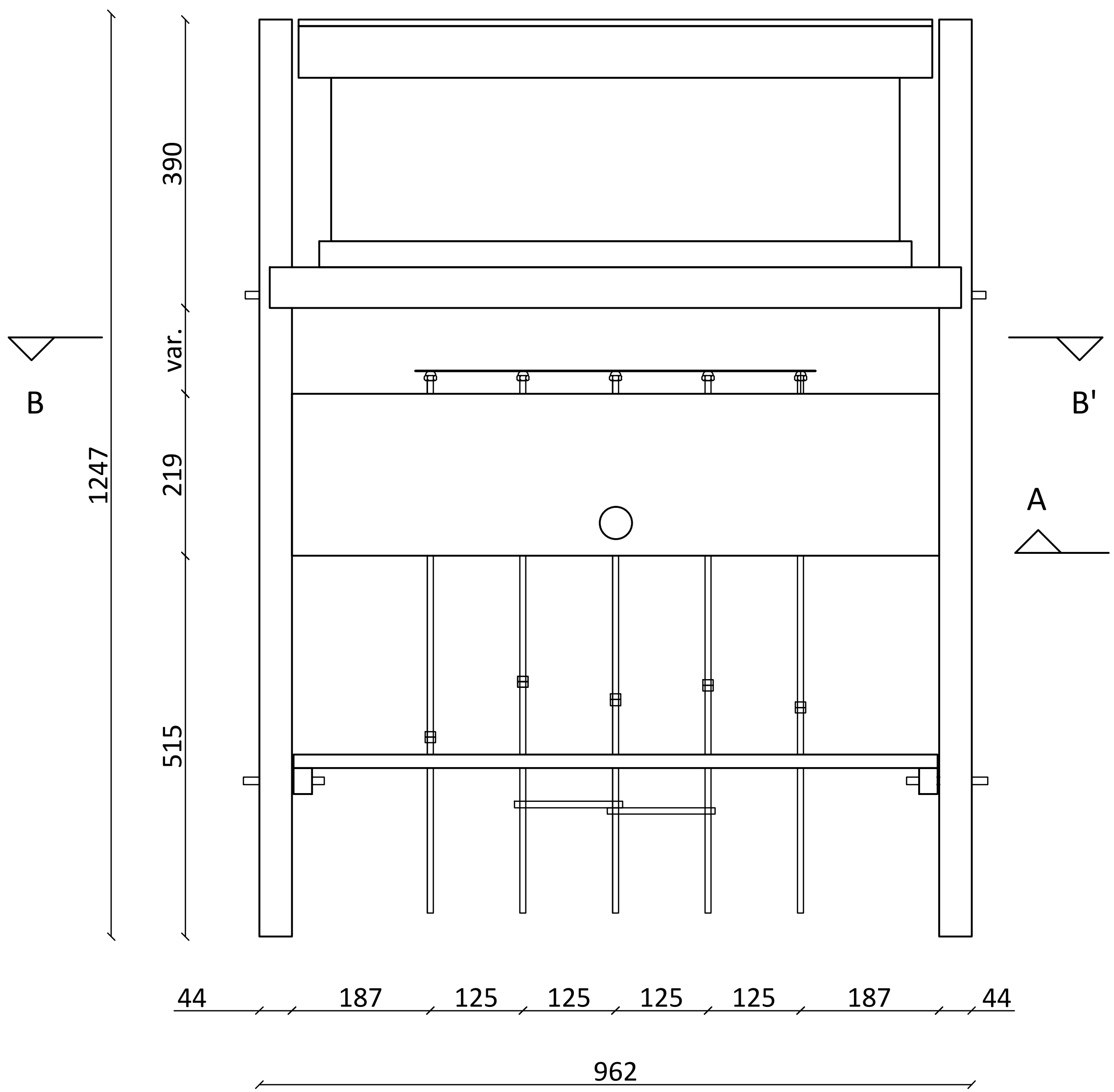
A	General	A1	Mould technique	 A1A Static	 A1B Reusable	 A1C Flexible		
		A2	Flexible mould technique	A2A Pinbed	A2B Supported membrane	A2C Tensioned Membrane	A2D Vacuumed Membrane		
		A3	Supported membrane technique	 A3A Rubber frame - pouring directly (Schipper, 2014)	 A3B Hydrostatic - pouring directly (Verhaegh, 2010)	 A3C Wax formwork - countermould (Oesterle, 2012)	? A3D Vacuum forming - countermould (Lusing & Versteeg, 2015)		
B	Flexible layer	B1	Material	B1A Spring steel					
		B2	Stifness	B2A Flexible	B2B Stiff				
		B3	Material top layer	B3A Silicone	B3B Felt				
		B4	Top layer	B4A Loose	B4B Attached				
C	Pins	C1	Spacing	C1A 50mm	C1B 100mm	C1C 125mm	C1D 250mm		
		C2	Type	C2A Fixed	C2B Hinge	C2C Ball	C2D Fixed & Hinge	C2E Fixed & Ball	C2F Fixed, Hinge & Ball

Morphologically Overview - VaCo Mould

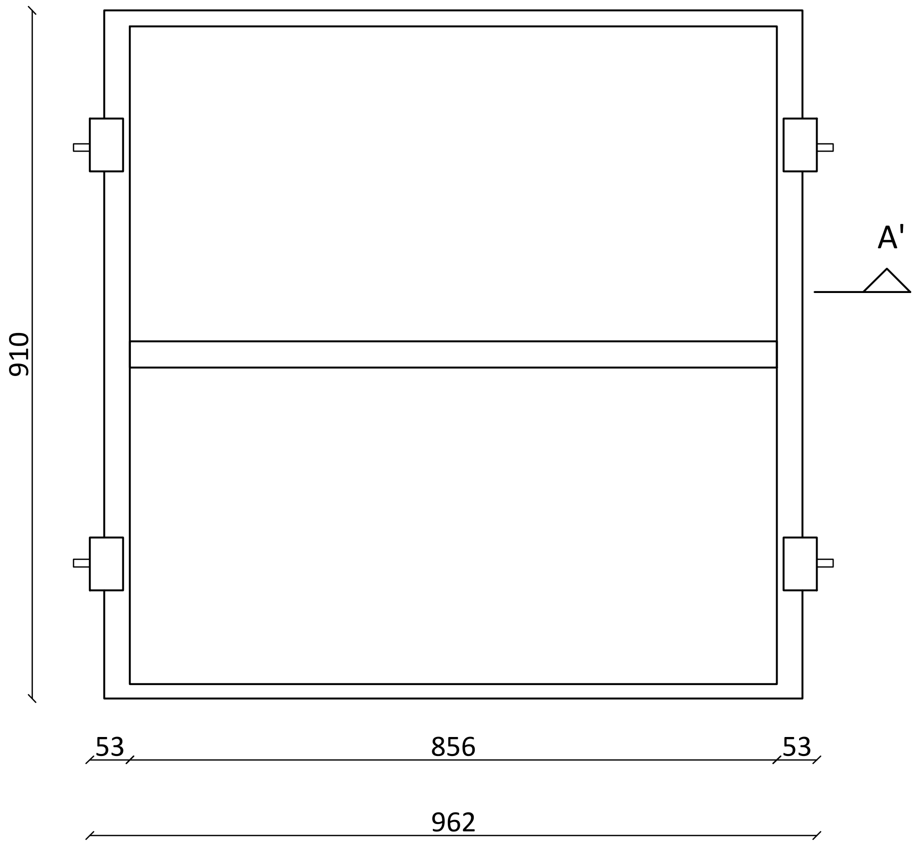
C	Pins	C3	Joint at flexible layer	 C3A Glue	 C3B Attach to spring steel	 C3C Screw			
C	Pins	C4	Prevent axial rotation	 C4A Squared	 C4B Supported	 C4C Modified treated			
C	Pins	C5	Set height	 C5A Nuts	 C5B Hose clamps	 C5C Step motor			
C	Pins	C6	Lifting	 C6A By hand	 C6B Lifting jack	 C6C Step motor			
D	Heating		Heating	 DA Hot air gun	 DB Heating lamp	 DC Intermediate dryer	 DD Patio Heater		
E	Vacuum forming	E1	Equipment	 E1A Vacuum pump	 E1B Vacuum cleaner				
E	Vacuum forming	E2	Way	 E2A Lowering	 E2B Pulling up				

Morphologically Overview - VaCo Mould	A	Method								
					AA	AB				
					Lowering	Fixation				
	B	Sheet connection								
					BA	BB	BC			
					Wood	Plastic	Foam			
	C	Connection method								
					CA	CB	CC	CD	CE	CG
					Screws	Staples	Nails	Bolts & nuts	Glue	Slot
	D	Watertightness								
					DA	DB	DC	DD	DE	
					Rubber	Sealant	Slot	Glue	None	
	E	Counter Pressure	E1	aggregation state						
					E1A	E1B				
					Solid	Liquid				
			E2	Material						
					E2A	E2B	E2C	E2D	E2E	
					Water	Bentonite	Sand	Clay granules	Granulate	

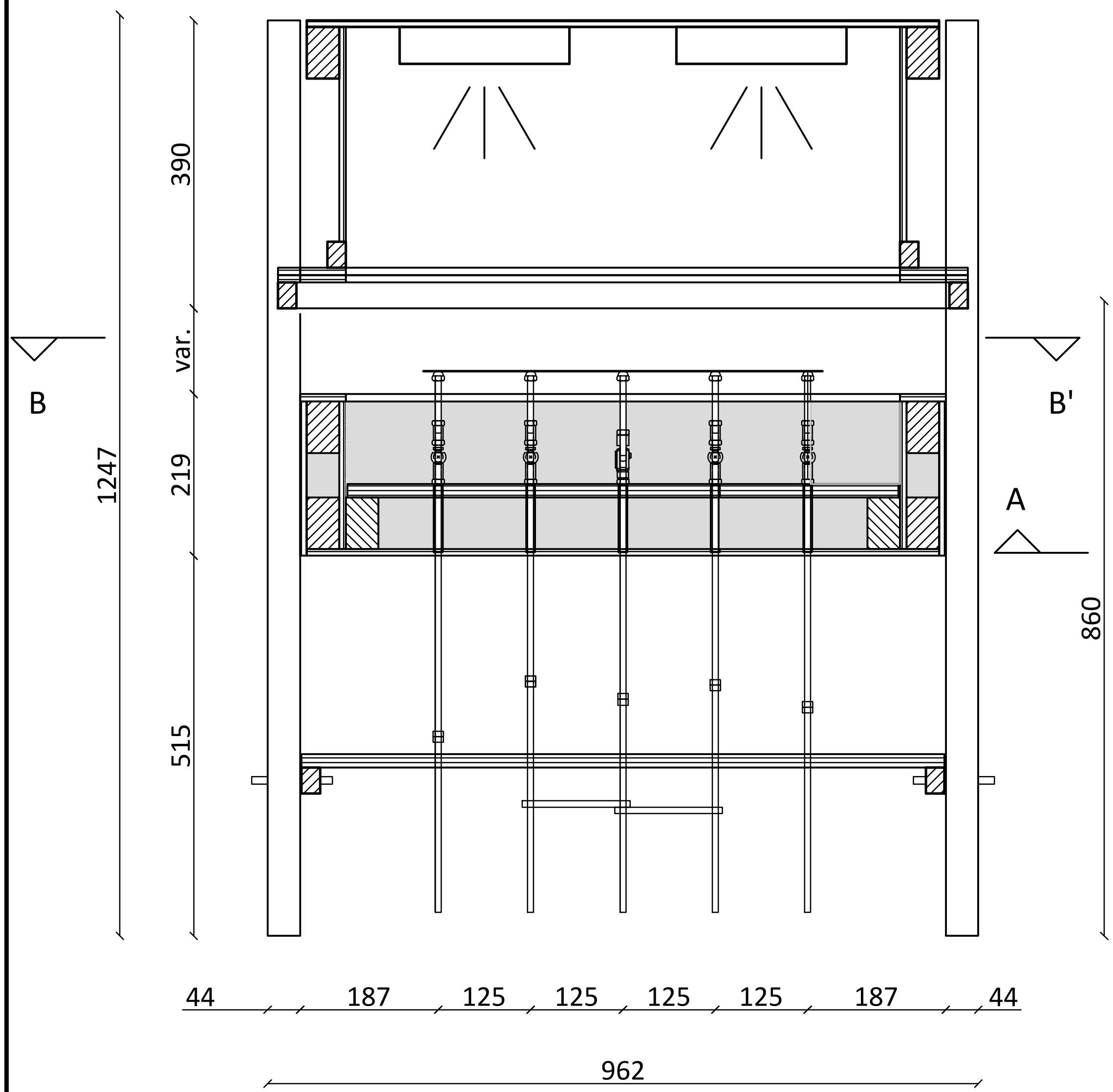
Appendix D: Technical drawings



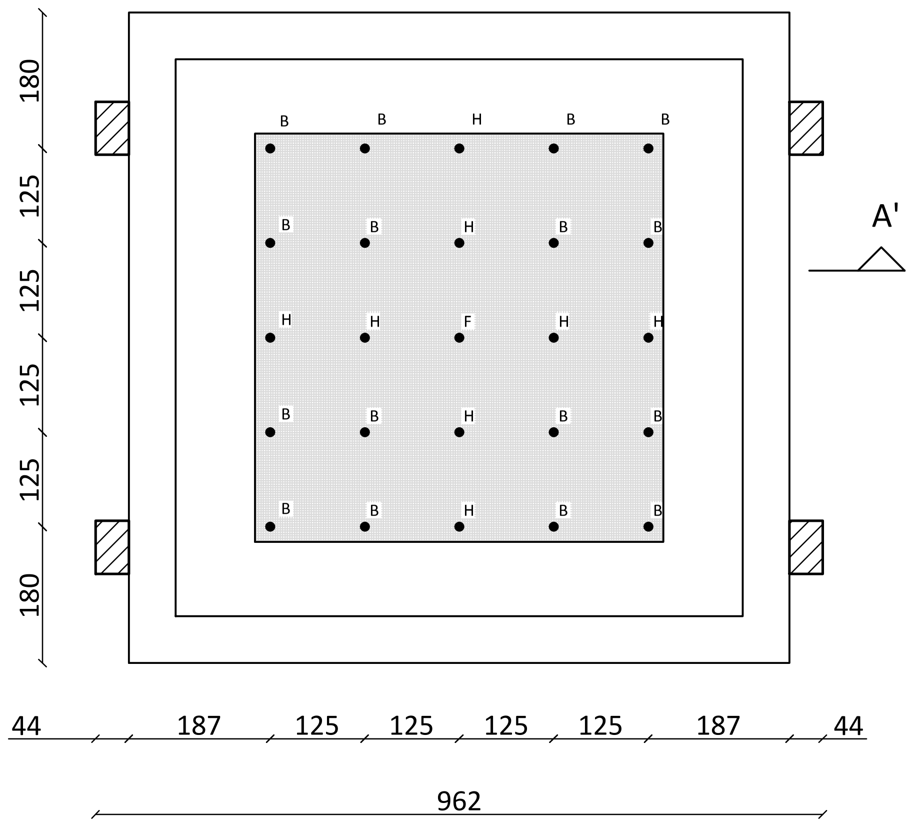
Front view 1:10



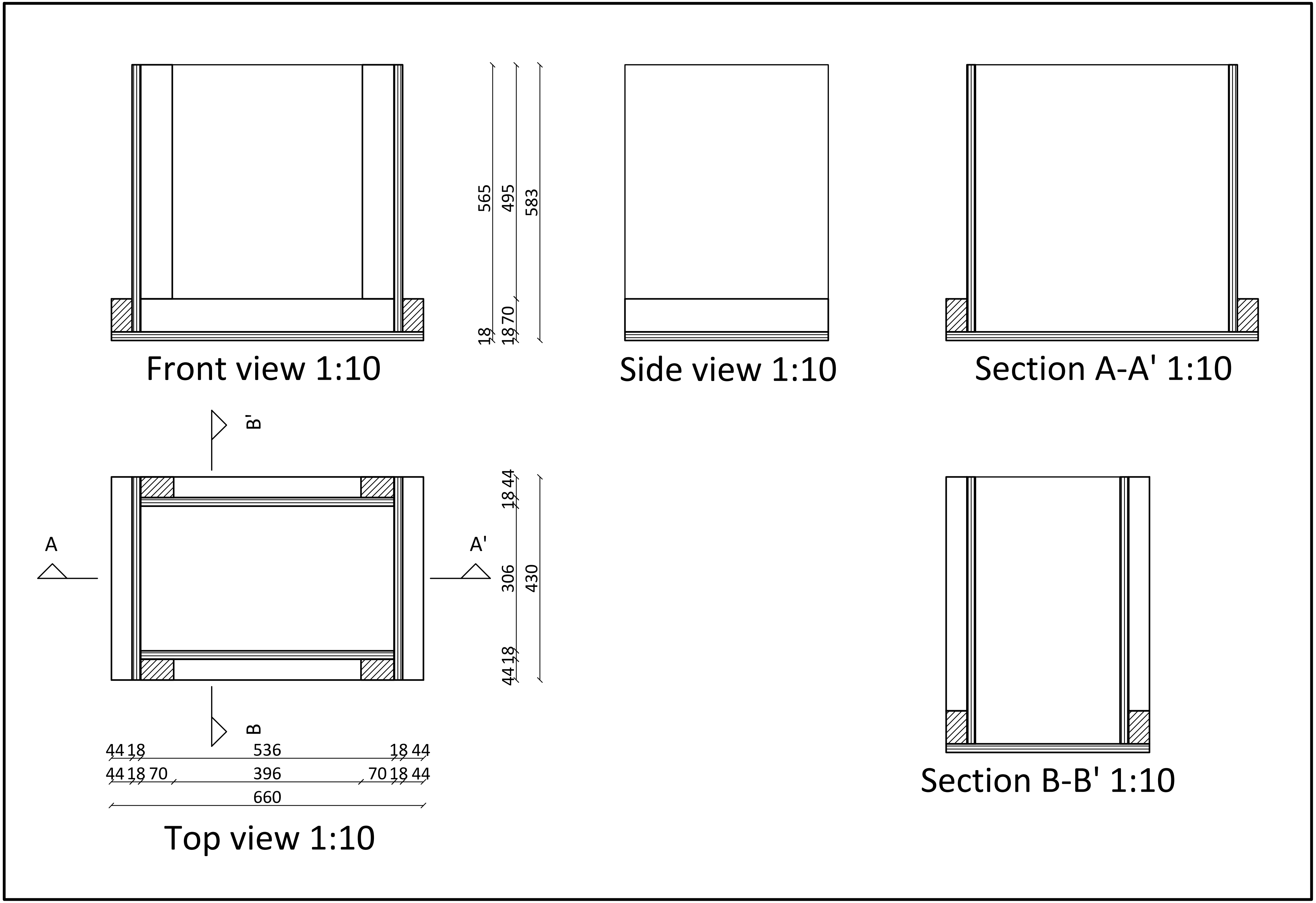
Top view 1:10



Section A-A'



Section B-B'


Front view 1:10
565
495
583
18
18 70
Side view 1:10
Section A-A' 1:10
B'
A
A'
B
18 44
306
430
44 18
44 18
536
18 44
44 18 70
396
70 18 44
660
Top view 1:10
Section B-B' 1:10