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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](image-url)
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]](image)

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](image)

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.
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.
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.

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 in 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.
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.

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.
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 expected 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
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.

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