Robotic Hot-Wire Cutting & Casting

DEVELOPING A DIGITAL DESIGN TOOL TO ASSIST IN THE DESIGN OF A SMALL PAVILION USING ROBOTIC HOT-WIRE CUTTING AND ULTRA-HIGH PERFORMANCE CONCRETE.

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SUMMARY

This paper investigates the inherent relationship between shape, material and process for the process of casting ultra high performance concrete into robotic hot-wire cut EPS moulds, and how constraints from this relationship can be communicated towards the designer through a digital design tool. Through practical and literature research clear constraints have been defined. These constraints have been tested in a digital design tool with the design of two pavilions. The observations show that the complexity and differences in geometry make the parametric design tool insufficiently flexible and only suitable for specific project-related geometries and the repetitive task of preliminary mould making.

CONTENTS

1. BACKGROUND

This chapter contains and introduction to the context of the research question. In this way the relevance of the project for the architectural discourse is shown in a wider context of society.

This research paper is the first half of the graduation project at the Architectural Engineering studio at TU Delft and forms the basis for the second part, the design project.

1.1. NEW MEANS IN ARCHITECTURE

Since decades digital design tools have become an integral part of the architectural practice. With CAD software, architects have been able to accurately describe and optimize increasingly complex designs. The supposed downsides (Riedijk, 2009) of this development are that, because of its lack of scale and materiality, CAD alienates architects from the inherent relationship between shape, material and production technique. This is seen as the degeneration of the architect in the role of master-builder to that of a mere stylist.

With the democratization of production technology, digital fabrication has become a process which joins the increasing capabilities of CAD software with the constraints and capabilities of manufacturing techniques. Although many firms and students have been using digital fabrication to produce models and prototypes for years through 3D printing, CNC milling or laser cutting, the use of digital fabrication for the production of the architectural object itself is relatively new. Experiments, like the 3D-printed façades by DUS-architects, haven't been picked up by industry because of the non-scalability of the production techniques (Scheurer, 2009) which results in tremendous production times or unreliable material properties.

1.2. ROBOTIC MANUFACTURING

As a next step, robotic manufacturing has been picked up by architectural researchers and students from institutes such as Princeton University, Harvard Graduate School of Design and the ETH Zurich to directly link CAD modelling to full scale production in architecture. Robotic arms have been used in serial production in automotive and product manufacturing to save costs, increase precision and speed up the production process

Figure 1. Challenging non-scalability of 3D-printing by DUS Architects ©DUS Architects

since the mid-1980s. In the construction industry robotic manufacturing has not been implemented on a large scale mainly because of the low level of repetition. In serial prefabrication robots can be implemented quite easily in addition to or replacement of CNC machines, but the building site itself is still very much unexplored. The unique advantages of robotic arms over CNC machines are their large reach, myriad of end-effectors, automatic tool-changing and the ability to execute if and goto statements. This last ability allows for the implementation of machine vision and decisions to be made while the machine is in operation while being part of a larger, automated process. This is the most powerful aspect of the robot and why it has been widely used in other industries.

1.3. ARCHITECTURAL DISCOURSE

Although the means have changed, architecture's goal is still to add value and meaning to materials. To allow the architect to re-establish his comprehension of the dependencies between process, material and shape, the architect could be able to reinvent the associated aesthetic and internalize the constraints and possibilities such that his improved design reduces engineering and failure costs and maximizes the value added.

Taking an active stance within the production process can allow the architect to master the possibilities of certain material-shape-process combinations, which could, in turn, lead to a new stance on the supposed dichotomy between structure and ornament.

1.4. RESEARCH QUESTION

The goal of this research is to investigate the relationship between shape, material and production process in relation to robotic manufacturing. Therefore, a specific material and production method are essential parts of the research question. For this technical research the production process of concrete casting, a technique used since Roman times, is infused with the modern-day technology of robotic hot-wire cutting of expanded polystyrene (EPS) moulds. To be able to use these constraints in a digital design process,
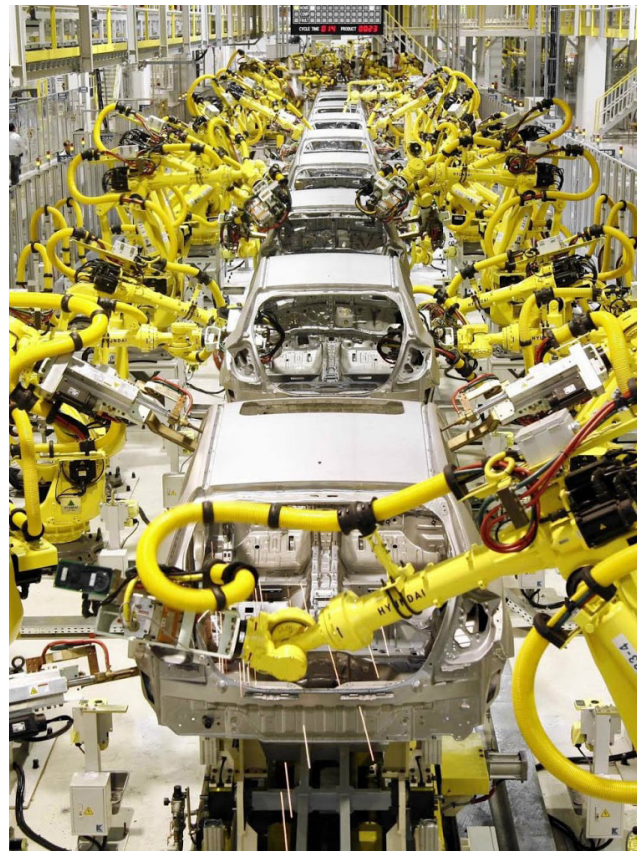

Figure 2. Robots in production line © Youngester.com
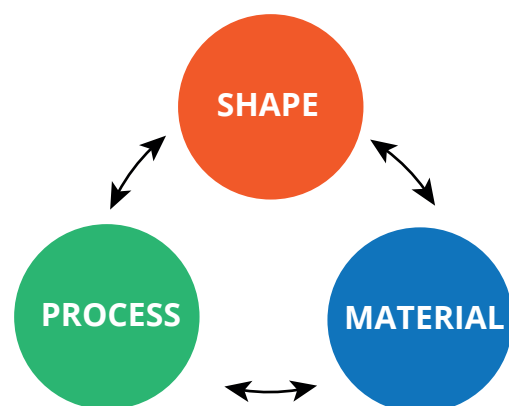

Figure 3. The interdependency between n S,P en M.

the resulting constraints and possibilities will be combined in a digital tool. To test this tool, two small pavilions will be designed. This results in the following research question:

"In what way can a <u>digital design tool</u> assist in the design of a <u>ultra-high performance concrete</u> pavilion using <u>robotic hot-wire cut EPS moulds</u>?"

1.5. A DIGITAL DESIGN TOOL

Within architectural research it is common to produce guidelines or tools to bring attained knowledge into practice. The possibilities and constraints that are related to the production process and material and will influence the design should be communicated to the designer during the design process. To bring this knowledge into the digital design process of contemporary architectural practice, the digital tool should give direct or incremental feedback on the design. In that way, the relevant constraints can inform the geometry of the building.

1.6. ULTRA-HIGH PERFORMANCE CONCRETE (UHPC)

There are many different kinds of concrete. They contain different types of aggregate, chemical admixtures or reinforcements and have different properties like self-compacting or pervious (frost-proof) concrete. UHPC is investigated because it is relatively new type of concrete which is defined by compressive strengths of over 200MPa. This allows for very slender concrete structures and the fine aggregate results in an unmatched surface quality.

1.7. ROBOTIC HOT-WIRE CUTTING (RHWC)

The technique of hot-wire cutting is widely used to make architectural models from foam materials like EPS. It is also used on a larger scale to cut large slices and blocks of EPS for industry. As described earlier, robotic manufacturing has been picked up by universities. The combination of these techniques at the TU Delft and other universities has already led to impressive results like Supermanoeuvre's Periscope Tower or Hyperbody's RDM-vault. These show a glimpse of the possibilities robots and smart geometry have in architectural production. ◼

Figure 4. Robot Hot-Wire Cutting at the RDM and Supermanouevre's Periscope Tower ©Supermanouevre.com

2. APPROACH

To answer the main research question (In what way can a digital design tool assist in the design of a ultra-high performance concrete pavilion using robotic hot-wire cut EPS moulds.) multiple sub questions have been formulated and a specific approach assigned to answer them.

The first subquestion is answered in the next chapter: constraints. It contains all the insights and knowledge related to RHWC, UHPC and moulding which can influence the design of the pavilion.

Subquestion 1: What factors (constraints/ properties) should the designer be aware of concerning:

◆ SQ1a: Robotic Hot-wire Cutting
Method: Literature research on robotic manufacturing and EPS hot-wire cutting, practical tests at RDM Robotlab

◆ SQ1b: Material constraints of ultra-high performance concrete
Method: literature research and reference studies

◆ SQ1c: Making moulds and the casting process
Method: Literature research and reference study (casting into EPS), extensive prototyping and testing (cutting and casting) and drawing and modelling (research by design).

To make sure these constraints are usefully applied, the role of the tool within the digital design process is defined. Next, the factors which have been discussed in SQ1 will be tested for their compatibility with the tool and ordered hierarchically. Also, the way in which these factors are communicated to the designer are discussed.

Subquestion 2: What does the digital design tool do?

◆ SQ2a: What role can the tool fulfil within the digital design process?
Method: Literature research

◆ SQ2b: Which factors should be implemented in the tool?

To test the design tool, two small pavilions are designed. The first pavilion will be designed to test a rudimentary setup of the tool after which the tool, and the way it is applied, can be improved. The resulting tool will then be tested on a more complex pavilion to see where the tool starts to lack performance. The observations and evaluation of this second process will lead to the conclusion of the paper.

Subquestion 3: Is the tool effective?

◆ SQ3a: Is the tool effective in the design of a small rain shelter?
Method: Research by design: sketching, prototyping, modelling and then evaluating.

◆ SQ3b: Is the tool effective in the design of a medium-sized pavilion?
Method: Research by design: sketching, prototyping, modelling and then evaluating. ■

3. CONSTRAINTS

Manufacturing is largely based on constraints, and so is design. The knowledge to be implemented in the cool consists of three different aspects: shape (RHWC), material (UHPC) and process (casting).

3.1. ROBOTIC HOT-WIRE CUTTING CONSTRAINTS

The robotic hot-wire cutting process within this chapter is defined by the facilities at hand at the RDM Robotlab of the TU Delft in Rotterdam. The robot available is an ABB IRB6400 robotic arm equipped with a custom-built hot-wire tool. The constraints are based on this setup.

3.1.1. GEOMETRY

The hot-wire cutter cuts EPS foam with a tensioned metal wire which is heated to about 200 °C. The resulting geometry from a cut with a straight wire is always ruled. This means that it can be described (locally) by a straight line sweeping through points.

The wire length is about 840mm. in between the aluminium brackets. This means that when the tool is moving through the EPS the ends should be outside of the EPS volume.

Another limitation of the hot-wire tool is that it can easily cut convex shapes but has difficulties cutting concave ones. This means that, since we're cutting

Figure 6. Single moulds versus assembled moulds

the moulds/negatives, components are generally easier to make (i.e. consisting of fewer parts) when they are concave. This guideline should be clear to the designer because small design decisions can sharply increase the complexity and expense of the mould.

For a visual take on the possibilities of the hot-wire cutter there is a vocabulary of forms in the attachments.

3.1.2. VOLUME

The volumetric constraints are related to the type of construction which is being built. Concentrating on a relatively small scale pavilion there are two possible scenarios; to use every cut block as a single mould or to use multiple blocks as a mould for a larger component or even the entire pavilion.

The volume that this robot can cut is limited by its geometric properties and fixed position (compared
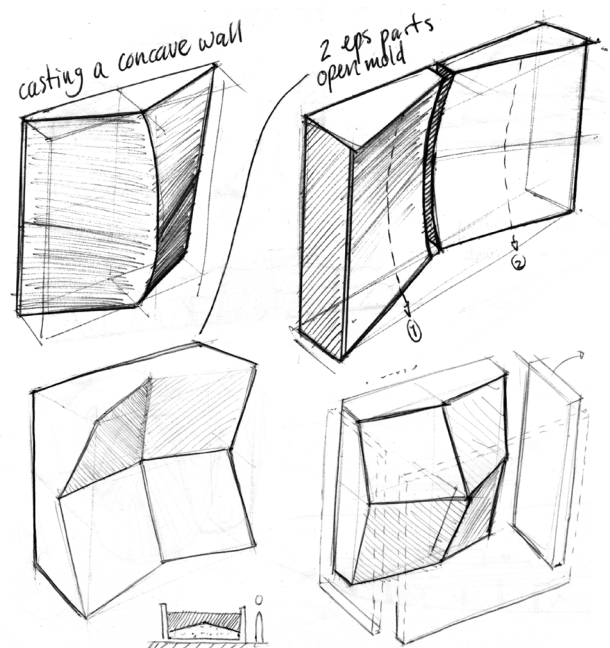

Figure 5. 6-axis movement allows for flexibility ©ABB

Figure 7. Concave objects are difficult! Convex not so.
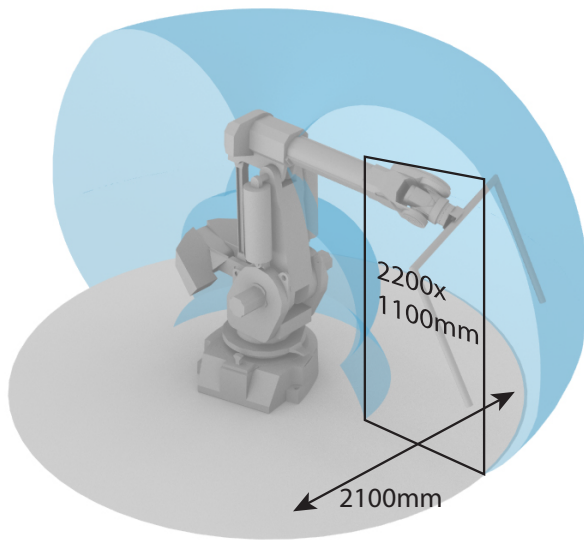
Figure 8. Robot envelope and stock size

Figure 9. Relationshipschedule for RHWC ©Bain (2011)

to a robot on a track). When we look at the envelope which the robot can reach without its end-effector, this is the domain in which the orthogonal stock EPS has to fit. These are the same constraints into which the components will have to fit (scenario 1) or in which the component or entire pavilion will have to be divided (scenario 2). The volume should have the maximum dimensions of a 2200*1100mm groundplane and a maximum height of 2100mm.

3.1.3. SPEED AND MATERIAL

One of the interesting things about CAD is the ability to optimize shapes based on manufacturing data, like manufacturing speed. A benefit of hot-wire cutting compared to traditional CNC-milling is its low production times. This is due to the fact that a CNC mill needs to mill through all the material around the desired shape while a hot-wire can easily trace its surfaces (McGee et al., 2013). The downside of this machine is that the geometry it can describe is only a small part of what a CNC-mill can describe, ruled surfaces being the most apparent.

To be able to estimate the production time of the object requires the length of the tool-path and the tool speed. Although not implemented on the current setup, the speed of the robot could be adjusted to the amount of material it is cutting through and the desired surface quality. Unfortunately, these are extremely complex thermomechanical calculations involving factor inter-dependencies as shown in figure 9. (Bain, 2011) To make a rough estimation of the required manufacturing time, the tool-path length can
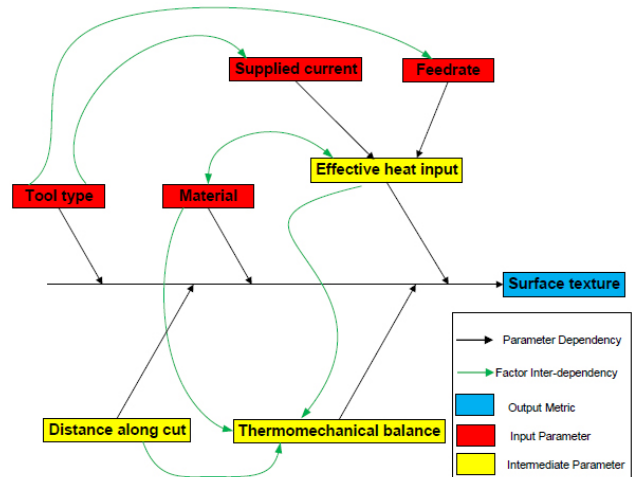
be divided by the average speed. Based on observations during cuts at the RDM Robotlab, where measurements varied between 1,5m/min and 2,5m/min, these have been determined at a conservative 1,5m/min. This has been tested with EPS200 and will have to be determined for different densities.

3.1.4. FIXTURES AND JIGS

Manufacturing robots rely heavily on reference positions. This is the position of the tool (TCP) from which all movements and actions are calculated. Because the robot at the RDM is not equipped with machine vision or sensors to detect where the EPS block is, it is essential that the position and orientation of the physical EPS block is exactly as the block that is defined in the software.

To be able to produce with accuracy, fixtures are used to put the block in place and keep it there. Because some cut cannot be made with the block in the same position, the block will often need to be rotated around one of its edges. For this a rotation jig can be used. Although fixtures can improve production accuracy, repositioning of the block adds time and complexity to the manufacturing job. Therefore, reorientation of the block should be kept to a minimum.

3.1.5. FACTORS TO BE CONSIDERED FOR THE TOOL

To summarize this paragraph, here is a short list of the relevant factors from RHWC:
◆ Geometry: ruled
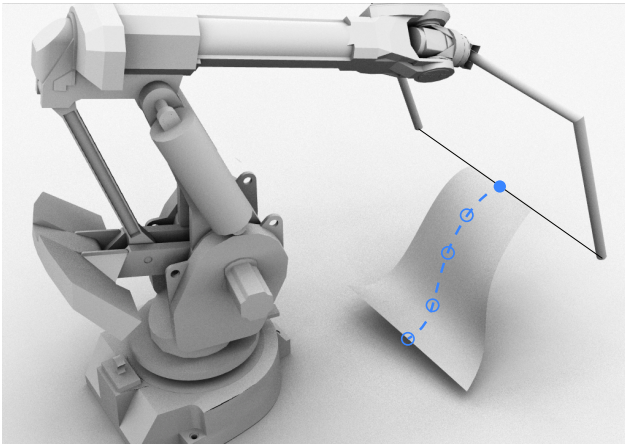◆ Geometry: 840mm wide surface
◆ Geometry: concave vs. convex

Figure 10. Robot's ToolCenterPoint and Tool-Path

◆ Volume: one block-one mould or assembled mould
◆ Volume: max. 2,2x1,1x2,1m
◆ Speed & material: production time indication
◆ Fixtures & jigs: Minimum of reorientations

3.2. MATERIAL CONSTRAINTS

Now it is known what constraints and possibilities RHWC introduces to the design of the pavilion, the focus shifts to the material which should take these forms. Although the backgrounds section shortly hinted at the reasons for choosing concrete, these will be elaborated upon shortly here. Also, the specific choice for ultra-high performance concrete and the resulting constraints and possibilities will be expressed.

3.2.1. CONCRETE AND FORM

A common image of concrete is that of orthogonal columns, beams and slabs which are visible only during construction and which are hidden from view by other building components during the functional lifespan of the building. But concrete, being capable of taking any shape, texture and surface quality the mould gives it, can be used in much more expressive ways while still fulfilling its role as a structural component. This has been shown throughout history by masters like August Perret, Frank Lloyd Wright, Le Corbusier and Felix Candela. The relationship between ornament and structure which we are touching upon here is a far too delicate and meaningful architectural

discussion to be covered in this paragraph, but the role which concrete can play in expressing a position within this discourse is evident and will be explored in the design project related to this paper.

Next to being the perfect medium for such an architectural statement, it is also one of the few construction materials (among which the structurally inferior EPS) which can almost effortlessly compose a volume instead of encasing it, see figure .

In short, concrete allows for exploration in different aspects of architectural expression: in its form (from thin and planar to wildly organic and volumetric) and in scale (from its dominant shape to surface pattern and surface quality).

Figure 11. UN Studio's Burningham Pavilion: simulating volume. ©UN Studio

3.2.2. ULTRA-HIGH PERFORMANCE CONCRETE

There are many different types of concrete composed of different aggregates, chemical admixtures or reinforcements. The 'recipe' is being changed constantly to produce concrete with different properties. One of the most recent outcomes of this ongoing innovation is ultra-high

performance concrete (UHPC). UHPC is defined as concrete which has a compressive strength of over 150MPa – 250 MPa (Schmidt et. al, 2004), compared to 10-40MPa for regular concrete. It is made up of a finer and different mix than standard concrete (cement, sand, stone and water) namely: fine-grained sand (filtered), silica fume, small steel fibres and high-strength Portland cement. It lacks the rough aggregate that makes up lower-strength concretes. UHPC is produced by different brands like Ductal, Taktl or Gtecz' Quantz. Gtecz also makes special mixes based on your location to make the mix as environmentally friendly and cost-efficient as possible (Gtecz UHPC, 2013) Local sand or aggregates can be also added to the mix to make the material blend in with its environment.

3.2.3. PROPERTIES OF UHPC
Because of the use of filtered sand, UHPC is capable of accurately taking up the texture of the mould in contrast to regular concrete where the aggregate makes the surface more porous. This surface quality is often combined with steel fibres to prevent brittle failure and make is less in need of maintenance and give it a longer usage life. The steel fibres can sometimes replace static reinforcement.

Figure 12. Foster's Queen Alia Airport in Jordan contains local sand for it's local feel. ©Foster+Partners

Because UHPC is more fluid it is also easier to cast, although adding fibres can make it more complex and sometimes require it to be pumped into the mould with pressure instead of being poured. Otherwise the fibres align and make the structure fail in the perpendicular direction. UHPC does not harden as fast as concrete which allows for a longer processing time (Schmidt et. al, 2004).

Figure 13. Het Hoge Hert is one of the pilot projects to introduce UHPC in the Netherlands. ©UNStudio

One of the downsides of UHPC is that it is more costly than regular concrete. On the other hand, because of its superior structural qualities, a smaller volume can be used to take the same compression force. This can influence the design by allowing for much more slender components.

3.2.4. FACTORS TO BE CONSIDERED FOR THE TOOL
This short list summarizes the most relevant factors from UHPC:
◆ Slender compression components (200MPa compared to 50MPa)
◆ High level of detail in surface
◆ More costly than regular concrete

3.3. MOULDING CONSTRAINTS
Now that it's clear what shapes we can make in what material, it becomes essential to consider the interface between the two: the mould. Casting concrete, like any other production method, has some has some very specific constraints and demands which it puts on the design of the component. To be aware of these and have them communicated to you during the design process can ease the iteration process of production preparation. First, the process of casting will be explained, followed by how specific aspects of this process influence the design.

3.3.1. CASTING PROCESS
Concrete can be cast into many types of moulds

Figure 14. Gehry's Zollhoftowers of '98 used EPS moulds for their unique shape.

Figure 15. Future Systems' Spencerdock bridge: cast using milled EPS form-work ©NOE Betonvormgeving

as long as they are not too porous to let water out of the mixture while curing. These can be timber or steel but also rubber, fabric or even inflatable moulds (Schipper et. al, 2011)

EPS has been used for casting concrete occasionally since the end of the previous century and has been used in several high-profile projects. EPS is mostly used when projects are made up of complex geometry within which there is hardly any repetition. EPS has some downsides which make contractors hesitant in accepting it as a moulding material: it is quite fragile and flammable. On the other hand, it is extremely light and easily recyclable. EPS can also be used as a stub (positive shape) for a more durable resin mould for repetitive casting.

The main principle of the casting/moulding process can be defined roughly as follows:

1. Make mould

To cast a component, a mould needs to be manufactured first. For EPS this means its parts are either CNC milled or cut (hot-wire or blade) into the desired shape.

After that, the porous surface of the mould can be sealed off using a primer (e.g. acrylic) or a coating (e.g. polyurea). This can be done to improve the surface quality and make sure that water stays in the mixture.

The final preparation before casting is assembling the mould (if it consists out of multiple parts)

either by clamping or gluing the parts together and adding a release agent. The release agent is often sprayed on and forms a thin barrier between the wet concrete and the mould to make it release more easily when it has cured.

2. Pour concrete

When the mould is ready and the concrete has been mixed, the concrete can be poured into the mould.

Figure 16. Bubbles got stuck under almost horizontal faces of the mould during tests at the RDM.

Figure 17. This mould needed gluing because it was not produced precisely enough,

Figure 18. The mould is wedged in to cope with the volumetric pressure.

This means the mould needs a spot where the concrete can be cast into the mould (this is called a feeder). For an open mould this would be the entire top but for complex shapes in a closed mould the positioning of the opening is quite essential to the final product. All the little edges and holes should be filled with concrete and no air-pockets should be trapped inside the shape. Therefore, the component should be re-oriented so that no air-bubbles get stuck underneath the geometry.
After casting, the mould can be vibrated with a vibration needle or table to get the small bubbles trapped in the mixture out.

UHPC can also be injected into moulds because of its fluidity but this requires additional strengthening of the mould and is unreliable with EPS (S. Gelderman, NOE Betonvormgeving, personal communication, December 10, 2013). It was not feasible to test this within this research because there were no machines at the RDM Robotlab to facilitate this.

3. Open mould
After 5 to 7 days the concrete will have cured enough to open the mould, considering no external heating has been applied to speed up the process. When glue was used to keep the mould together some force may be required to open it up. This will also decrease the chance of being able to use the mould again. It might be necessary to rotate the

mould to make sure the component doesn't fall out once it is opened. The mould would need little cleaning or repairing if it was properly coated and could be used again. The concrete will need another 20 days to get to reach its full structural potential.
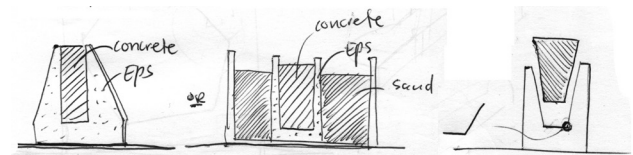
Figure 19. Coping with volumetric pressure and drafting angles.

3.3.2. DRAFTING ANGLES
An important factor for any casting or moulding process is the use of draft angles. It can be close to impossible to get an object out of its mould when the component is not tapered. Depending on both the geometry of the component, the surface quality and the release agent a drafting angle of 1 to 2 degrees should be considered.

3.3.3. MOULD PARTS AND SEAMS
If changing the geometry is not an option then the mould can be split-up into multiple parts, but this leaves more room for errors in sealing and clamping the mould parts together. Therefore a minimum of mould parts is recommended especially when re-use of the mould is not necessary.

Also, the mould parts need a certain thickness. This could be in relation to the volumetric pressure. To save on material and complexity sand can be used to take most of the pressure. When pressure has been taken care of, the fragility of the mould becomes a concern. Therefore a standard minimum should be assigned. It should be capable of withstanding the application of acrylic and rough handling during casting or transportation. A minimum thickness of 10cm is considered sufficient and the object can be positioned in such a way that it fits the smallest possible EPS block.

3.3.4. INSERTS AND CONNECTIONS
When producing prefabricated components the interface between them is essential. There are two main ways of joining pre-fabricated elements.

1. Using connectors
There are many different types of metal or composite connections that can be used to transfer forces or allow for expansion or shrinkage. These connections can be cast into place but can also attached later-on with drilled-in thread. The metal connections can then be welded or bolted together. Another way of connecting two components is through a dowel/anchor method (NPCA, 2012).

2. In-situ pour
When components have been placed on their designated locations a small mould can be used to pour concrete in between them. This is most effective when they are already connected by steel or composite connections which are then protected by the cast-on concrete. Optionally, when no fibre-reinforcement is used, this is when rebar can be attached to the mould.

3.3.5. FACTORS TO BE CONSIDERED FOR THE TOOL
The factors which follow from the casting process and can influence the design are:
◆ The mould is a <u>negative</u> of the desired component.
◆ The mould has a minimum wall thickness (approx. 10cm) but minimize EPS use.
◆ The mould should avoid air-pockets and horizontal faces (where air gets trapped) and have a
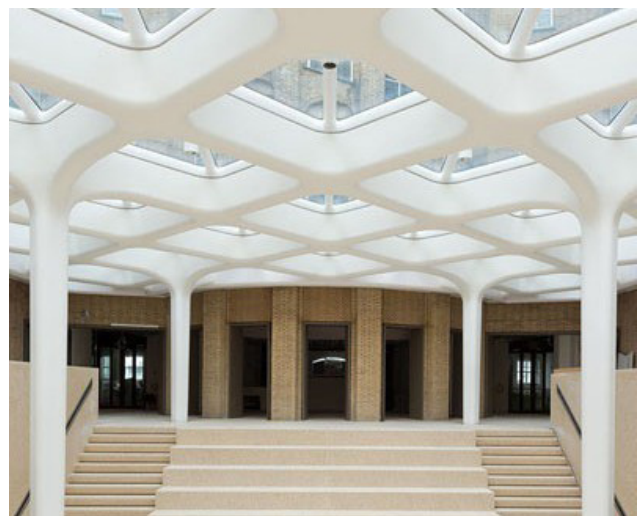
Figure 20. The roof of the Ministry of Defence, by Sander Architecten, in The Hague uses in-situ cast elements on top of pre-cast columns. ©Nedcam

feeder to allow the concrete to go in.
◆ Minimize mould parts
◆ Consider drafting angles and surface quality for a smooth release.
◆ Consider appropriate connections

4. TOOL DEVELOPMENT

Although the practical and literature research and reference studies have resulted in a base of knowledge, it would be useful to be able to apply this onto design projects directly. Therefore, the possible role and effect of the digital tool within the digital design process will be explored. Subsequently, the previously determined factors will be examined for implementation in the chosen design process and environment.

4.1. THE TOOL WITHIN THE DIGITAL DESIGN PROCESS

The use of digital tools can be divided in roughly three methodologies (Kotnik, 2010): representational, parametric and algorithmic. Within the representational methodology, software is used to merely describe and control complex geometry and can be seen as a digital modelling method, while a parametric approach leaves room for variations because the interplay between elements is described parametrically (adjustable within a certain domain). But where on a parametric level the function stays the same and the input changes to produce different outcomes, an algorithmic approach is focused on the function. This function takes a model of reality as input and through manipulations delivers an optimal architectural geometry as output. The main
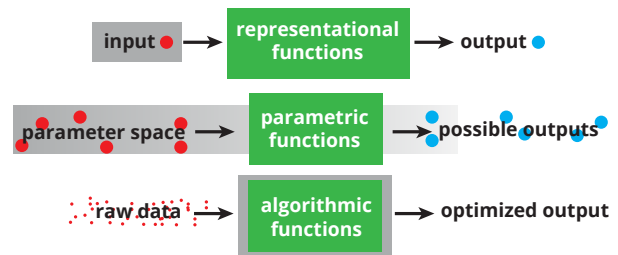
Figure 21. Digital methodologies in architecture

difference is in the focus on the computational process and digital literacy which increases from the first to the last.

Although the algorithmic approach is the most powerful because of its customizability, it will also require deep knowledge about programming languages and a complex framework before anything can be tested. Therefore, the tool will be developed within a parametric design approach. This allows it to be tested on two pavilions and preferably used in the design project related to this research. Also, it could be flexible enough to cope with changes in constraints like different EPS block sizes or smaller surface widths.

Because the digital tool is focused on assessing the manufacturing constraints and possibilities of a certain geometry, it can only be effective once that
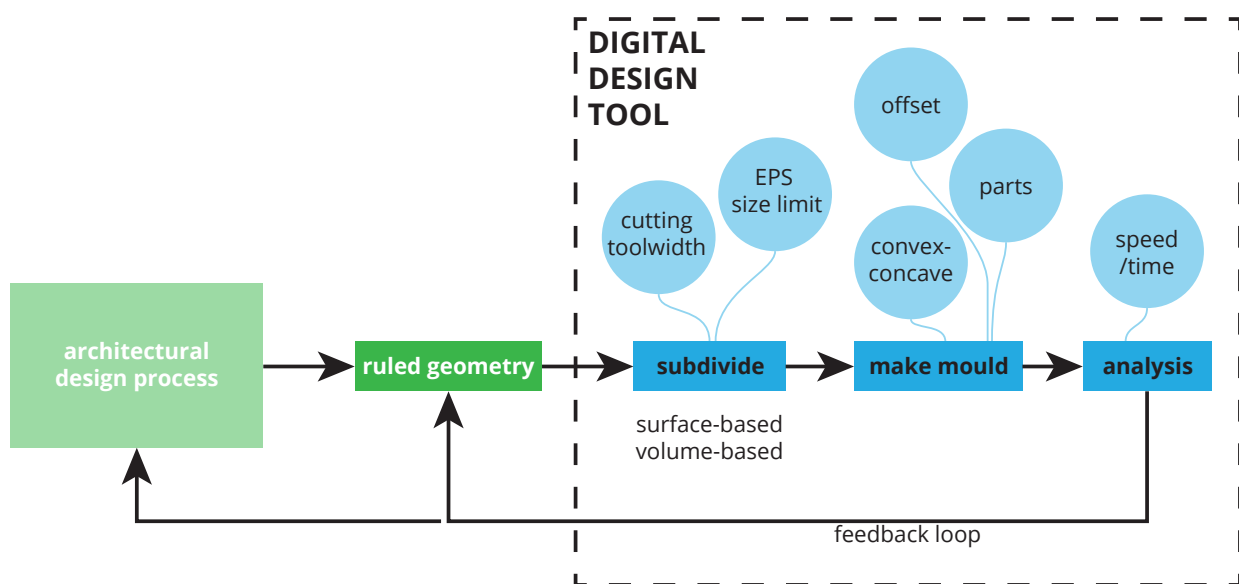
Figure 22. Predefined place of the design tool within this research paper.

geometry has been created within CAD software. The essential part of this assessment is that its results, for this specific manufacturing method, are fed back into the design through a manual or automatic feedback loop until the results are satisfactory. In that way it makes a difference compared to regular moulding software like RhinoMold or Expert Mold Designer, which are too elaborate and require too many settings to be used for quick iterations.

4.2. IMPLEMENTING FACTORS INTO THE TOOL
To make sure that almost any geometry can be checked for its manufacturing properties, the tool will be developed in Grasshopper, a graphical algorithm editor, which is integrated with Rhinoceros 3D, a common 3D modelling program.

The digital tool, or script, that will run in Grasshopper should be able to incorporate certain factors into the iterative design process. Therefore, a short list of the factors and why they will, or will not, be tried to integrate within the tool is written below:

1. RHWC – Detect non-ruled geometry / transform into ruled geometry:
Not implemented: when designing for RHWC it is essential to use ruled geometry, but the approximation of such a shape is very complex (Cohen-Steiner et. al, 2004). The experiments in ruled geometry as described earlier (Ch.3.1.1.) give an indication of the possibilities of ruled geometries and can be used as an inspiration during the design process.

2. RHWC - 840mm wide surfaces / max. volume of 2,2x1,1x2,1m
For a design to be constructed out of components, the geometry needs to be subdivided. For primarily surface-based constructions this can be quite easy as long as the curvature is low and it is of limited thickness. For volume-based geometry with no dominant planar direction (like a column or joint based structure) this might mean splitting the mould up into multiple parts.
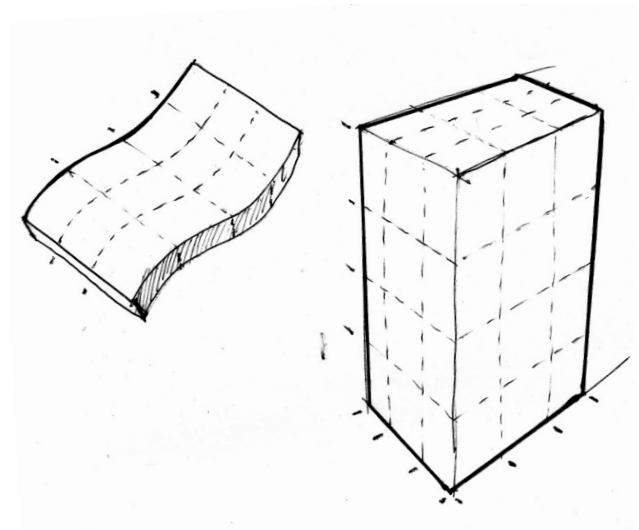
Figure 23. Surface-based and volume-based division

3. Geometry: concave vs. convex / division of mould parts
Based on the geometric properties of every individual part, a negative shape has to be made and subdivided based on the limitations of the RHWC.

4. One block/one mould or assembled mould
As an extra feature which can add to the flexibility of the system, the ability to generate large moulds (larger than 2,2x1,1x2,1m) out of smaller parts could be added. This is however considered a less important feature because it doesn't increase the feedback of the tool, just the scale of components this tool could serve.

5. Performance measurements: cutting time indication
To give the designer an indication of the total production time and costs, a cutting time indication would be useful to add.

6. UHPC constraints
The possibilities of UHPC for architectural design are very interesting but can only be validated through finite element analysis. Although this is possible within Grasshopper, it is outside of the scope of the research and could be seen as the next step in the design process.

7. Mould constraints

The rotation and optimization of the subdivision of the mould is essential for the tool's success. Because the quality of the mould is dependent on many factors (e.g. drafting angles, air pockets, wall thickness) this will be a breaking point for the tool and reserved for testing the second pavilion.

5. TESTING THE TOOL: DESIGN OF 2 PAVILIONS

5.1. ASSIGNMENT: DUNE PAVILIONS

The assignment for the pavilions is related to the design project in their materiality but because of time constraints the complexity and scale is limited.

The first pavilion is to be a cantilevered rain shelter which is mostly surface-driven. This will be used to test the subdivision algorithm and mould-generation.

The second, slightly larger, pavilion is a monocoque structure on columns to test both the surface- and volumetric subdivision. Here, the tool will be implemented on different types of geometries to test its flexibility.

5.2. PROCESS DESCRIPTION

Because the limitations and possibilities that the tool offered will be discussed more thoroughly in conclusion this paragraph will mostly serve as an illustration of the design process.

5.2.1. PAVILION 1: RAIN-SHELTER

The focus of this evaluation is on the tool, so there will not be too much attention on the initial design. Because the pavilion was designed symmetrical this immediately showed the difficulty of making concave, or angled inward, shapes. Therefore, the symmetry-axis was chosen to separate the design since the solution method would be the same for both sides. The division by EPS size
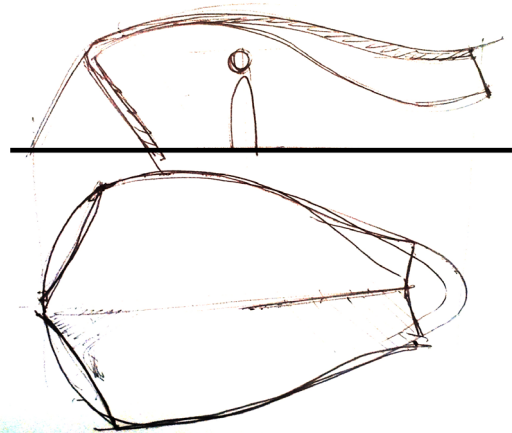
Figure 24. First sketch of rain-shelter pavilion
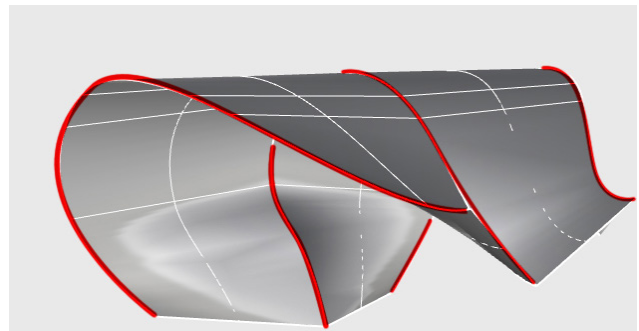
Figure 25. Symmetry: ruled surface between 3 curves
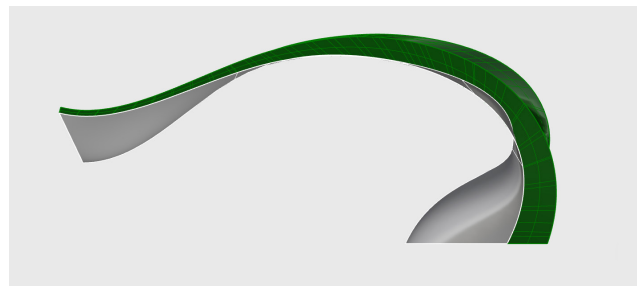
Figure 26. Non-uniform thickness was applied
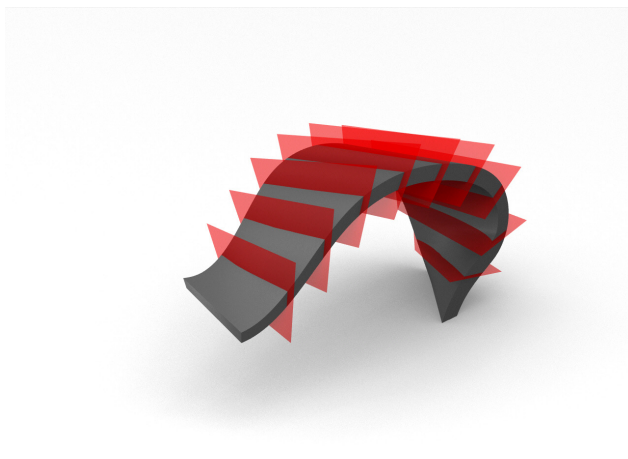
Figure 27. Subdivision based on maximum cut-width

Figure 28. Thickened surface separated
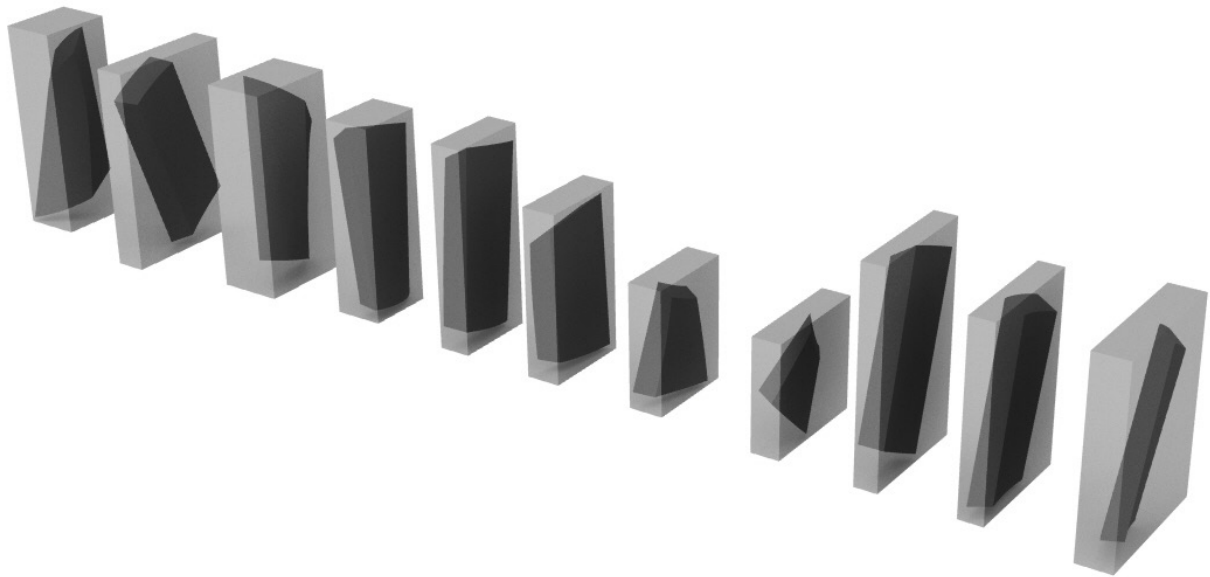
Figure 29. Pavilion 1 parts into optimized, offset boxes

(2100*2200mm) worked well, and adjusting it later on to the tool-width (smaller, at 850mm) proved the flexibility of the surface division method. Also the reorientation (genetically optimized using Galapagos for Grasshopper) of the object to fit it in moulds worked perfectly, except for the fact that it wasn't possible to have it automatically generate the mould parts. Although it would work on one part, because the topology on other mould differs, the script doesn't work on those. This is because of the parametric approach picked which isn't as powerful as an algorithmic one where one could write an efficient recursive function for this. Also, some functions that normally perform well in CAD (like splitting a surface) don't work well when used in the (free) plug-in Grasshopper. Therefore, the geometry had to be taken out of the plug-in, hard-edited in Rhino and then plugged back into the parametric editor. This disrupts the information flow and speed of iterations drastically. The tool did show however that it is perfectly capable of subdividing a surface-driven geometry and packing it into EPS stock-sizes, although some parametric alterations were done to make sure there were no horizontal planes within the mould (because of bubbles). The feedback loop and ease of changing the input geometry was completely absent because of the interruptions in the information flow. One of the major setbacks was the lack of topology analysis where a ready-made component analyses the main curvature direction. Because of this the slight curvature the components had in them had to be reduced.

5.2.2. PAVILION 2: ICE-CREAM SHACK

The ice-cream pavilion was to be a monocoque on small columns. By making it an enclosure with only one window the would be tested on completely different geometry, although this still had a clear main direction (lengthwise). Along its length the surface was defined by some randomly defined points which make up the wavy surface. It was clear that the design had to be separated into 3 distinct parts because of their inherently different topologies: an extrusion over 6m, the walls on both ends and the feet.
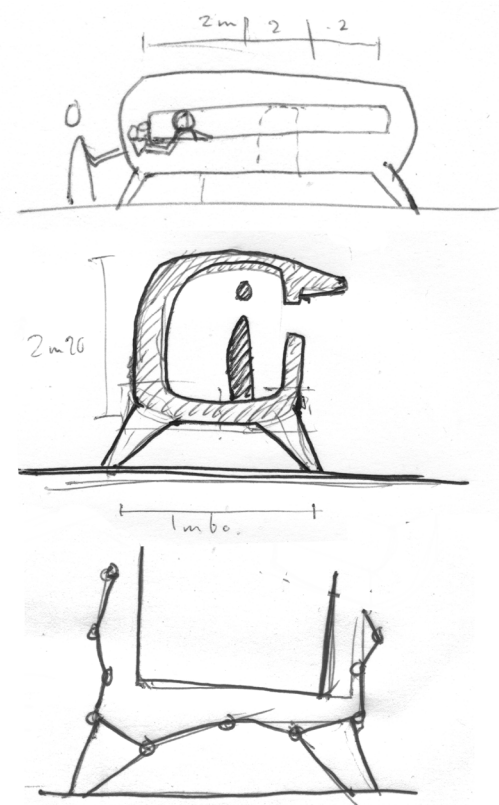
Figure 30. Concept of ice-cream pavilion
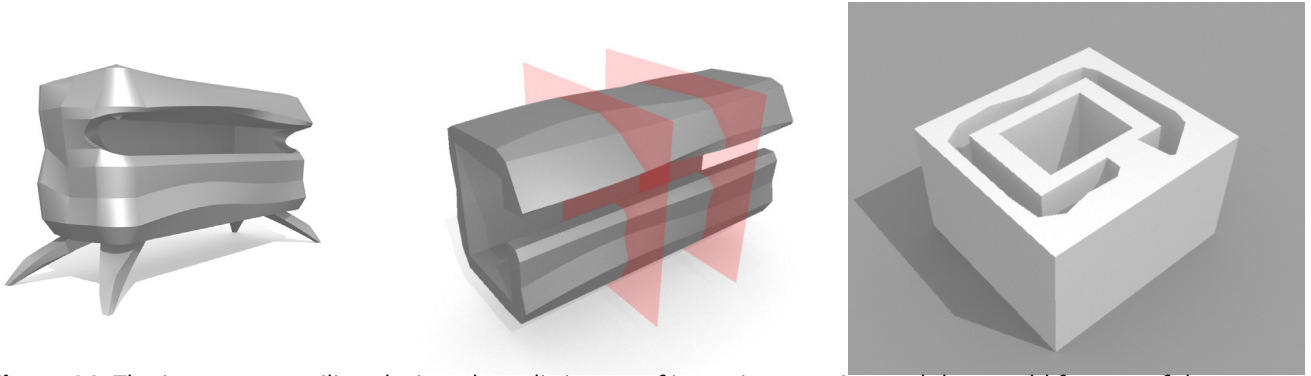
Figure 31. The ice-cream pavilion design, the splitting up of its main extrusion and the mould for one of those parts.

This was the first reason why the previously utilized script couldn't be used; it wasn't capable of making this distinction. Here, the knowledge from the constraints helped to make separations but couldn't be made internal to the script. Although the parametric editor was used to automatize slow tasks (like making the boxes around the complex shapes) it wasn't used to subdivide any part. Even the symmetrical part on both end, which seemed quite flat, was too complex because it had to be split across it's convex lines. Although, eventually, moulds were made for every part, this proved to be so difficult that is was not to be automatized.
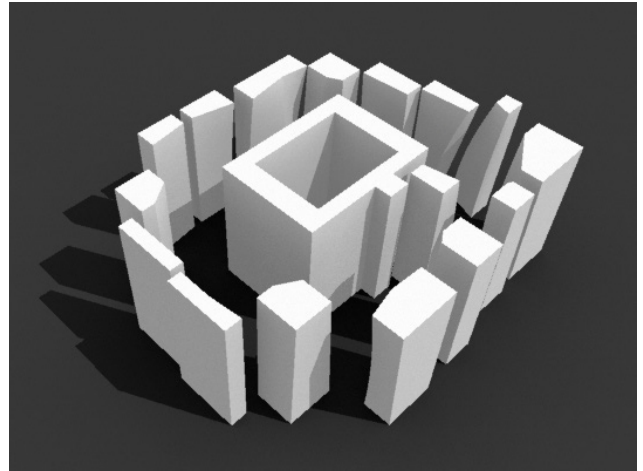
Figure 32. Subdivision based on constraints.
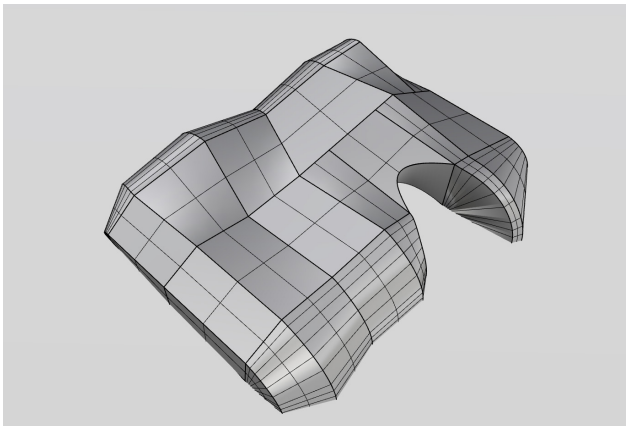
Figure 33. End part of the pavilion with flat backside
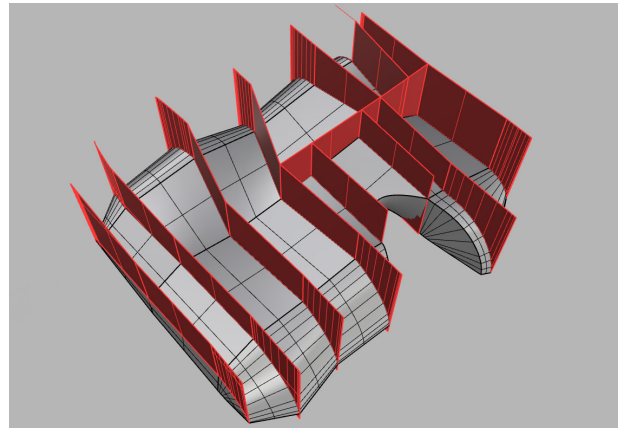
Figure 34. Subdivision based on concave folds
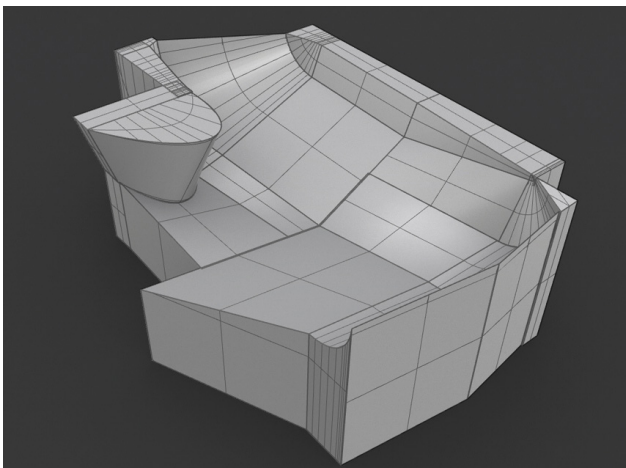
Figure 35. Complexity of end part mould.
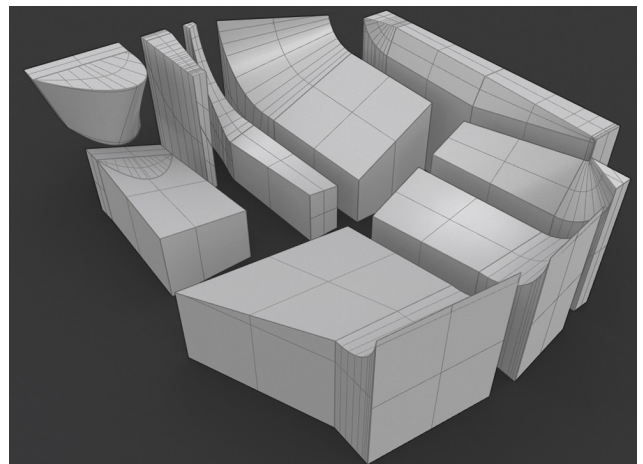
Figure 36. Different parts because of concave folds

6. CONCLUSION

Since the beginning of this paper, the complexity of mould making for concrete has been apparent. The goal of this research paper was to investigate the contribution a digital design tool could have on the design of a pavilion, made out of UHPC cast into RHWC EPS moulds.

It must be concluded that the development of a good mould requires expertise and time which can't be replaced by a piece of software, although it can help improve insight in the geometries unique problems. Recognizing opportunities and problems during the design process and trying to optimize the mould for a smooth cutting, casting and releasing process requires experience. Although this was experience during the design of the second pavilion, the limitations of this fabrication process have become painfully aware. The subset of geometries that the RHWC can make in contrast to a CNC mill is relatively small and requires the mould to be split up into numerous parts (as seen in pavilion 2).

The digital design tool can be used to automatize processes for moulds but has to be developed for very specific geometries to be efficient. In that way, it could fit a component-based approach to complex geometry. It was also incapable of incorporating material constraints of UHPC or specific, and important, moulding aspects.

The limitations of this technical research are also in it's focus on topology. Practice with the RHWC and moulding and developing the vocabulary of forms have created a solid background to approach the aesthetic aspects of the subsequent design project, but lack any building physics related aspects. Therefore, the incorporation of insulation, windows and reinforcement has to be investigated. Also the structural efficiency and incorporation of these concrete components in a larger building system should be looked into.

Further research can also be done into the effectiveness of a digital design tool in the development and optimization of component-based geometry.
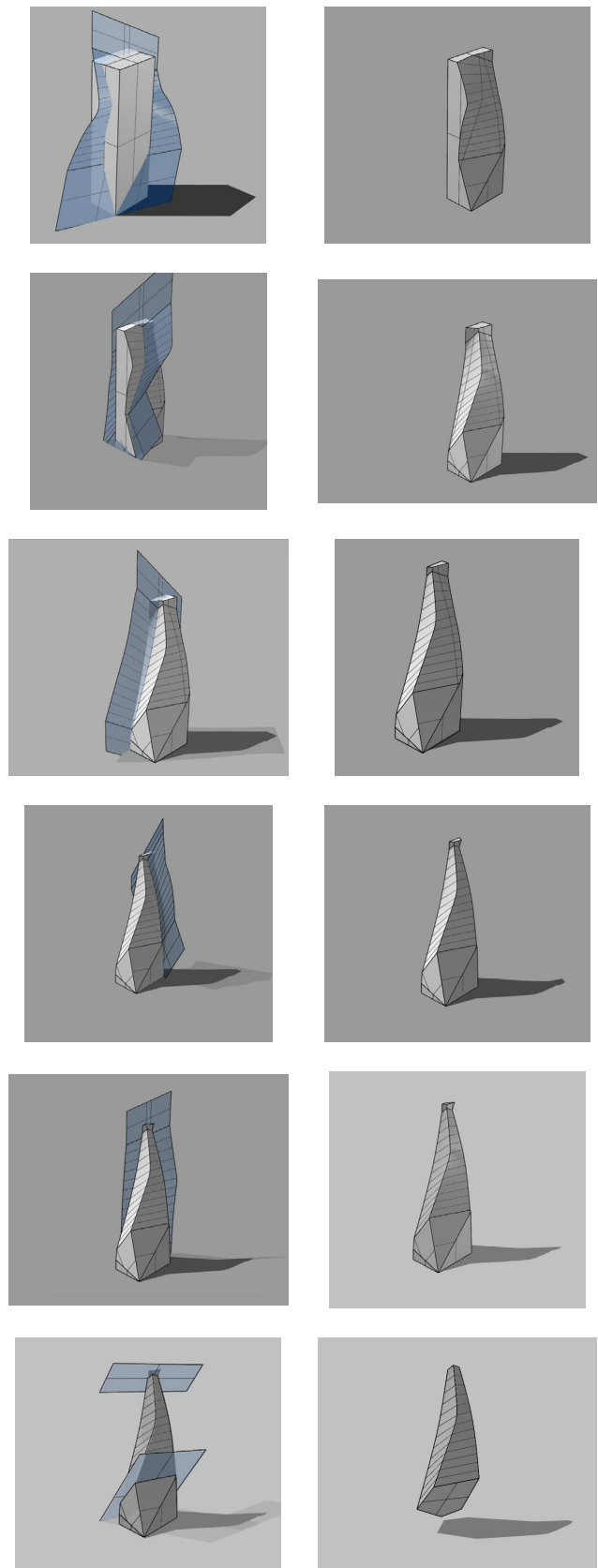
Figure 37. Six cuts to make the leg of pavilion 2.

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8. ATTACHMENTS

8.1. VOCABULARY OF FORMS
For this research, a small exploration into the specific possibilities of RHWC was done. This resulted in drawings and models of ruled geometry to inspire the design of the pavilions and the design project.

8.2. OBSERVATIONS AT THE RDM
During this research, much time was spent at the Robotlab at the RDM in Rotterdam to get familiar with the RHWC and the moulding process. Pictures from that research have been added to show the current state of affairs at the Robotlab and to illustrate the research into RHWC and casting.

VOCABULARY OF FORMS
-robotic hot-wire cutting-

d< tool width

1 cut

1 cut

2 cuts

sharp edges

Rounded corners
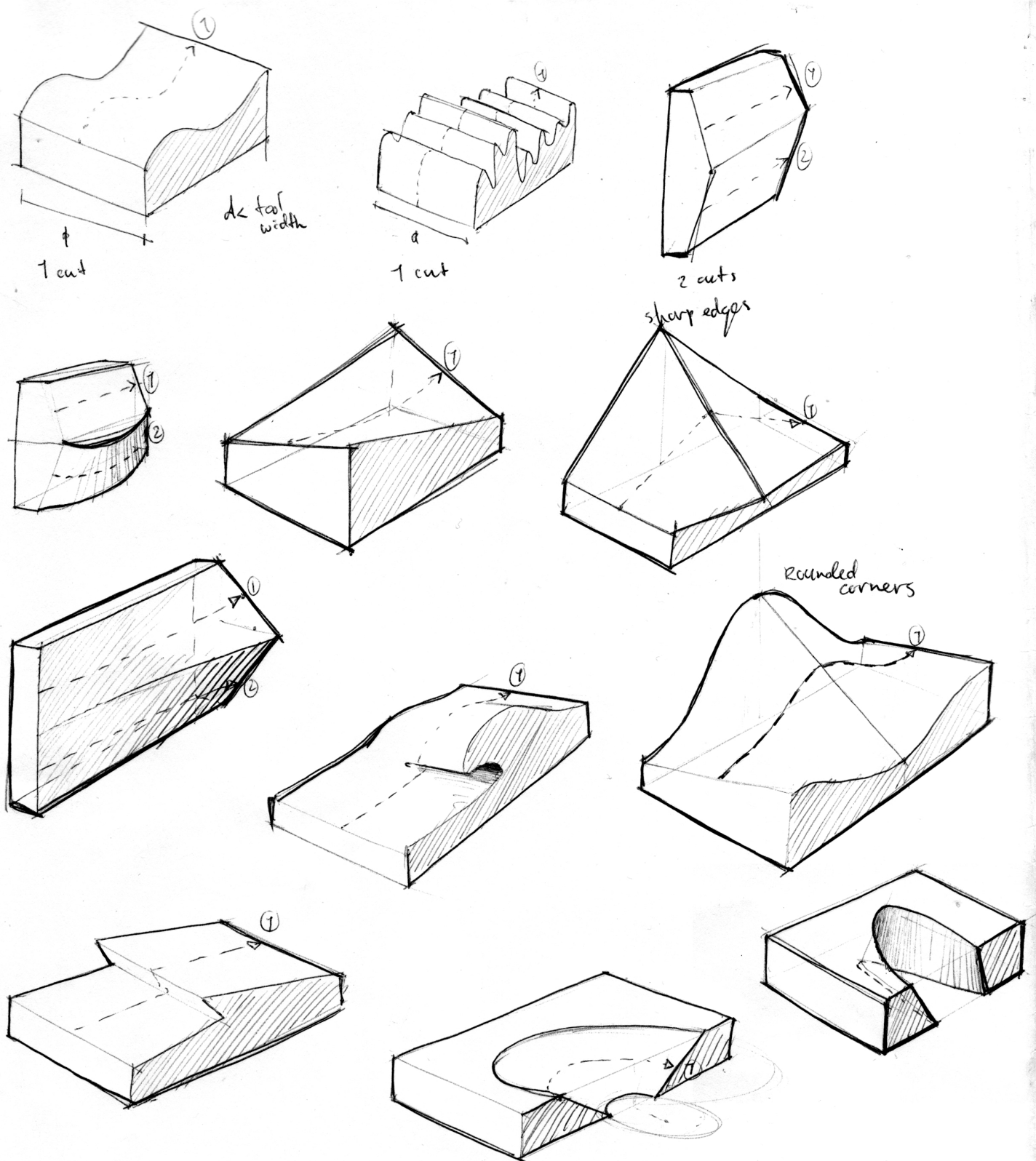
VOCABULARY OF FORMS
-robotic hot-wire cutting-

casting a cube:

open
1-part.

①
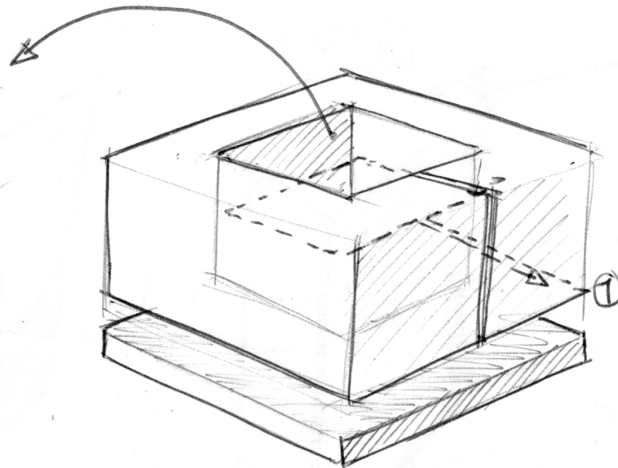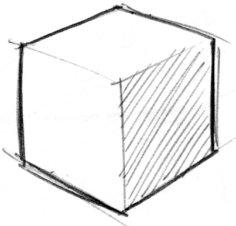
casting a column:

open, **1**-part.

bigger:

①
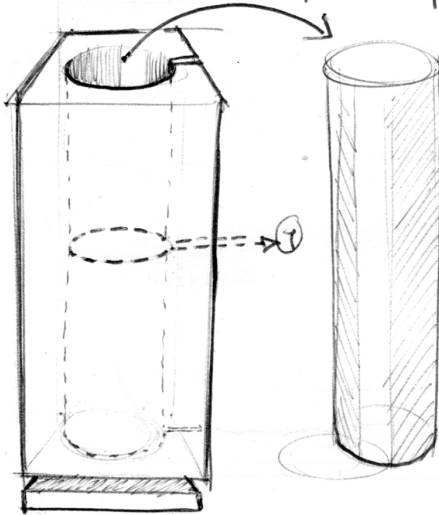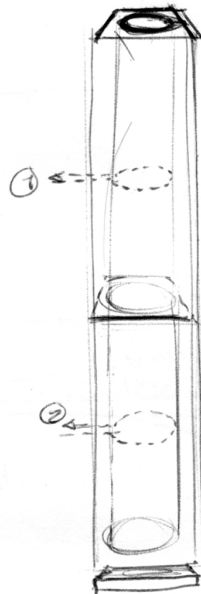
2-part
larger than 84 cm

①

②

casting a concave wall
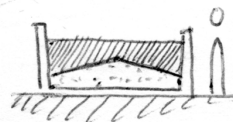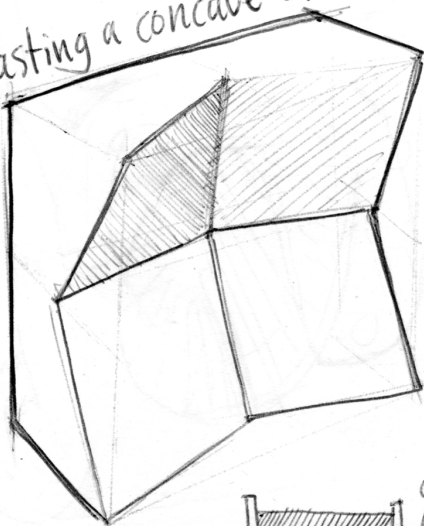
4 cuts
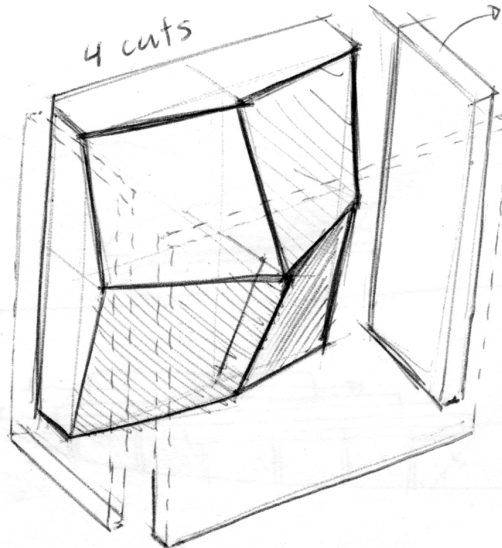
coated
standard
wall system.

VOCABULARY OF FORMS
-robotic hot-wire cutting-

casting a concave wall

2 eps parts
open mold

①

②
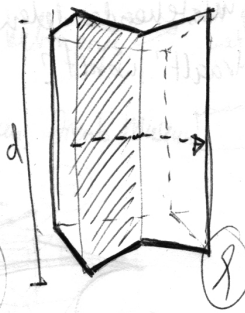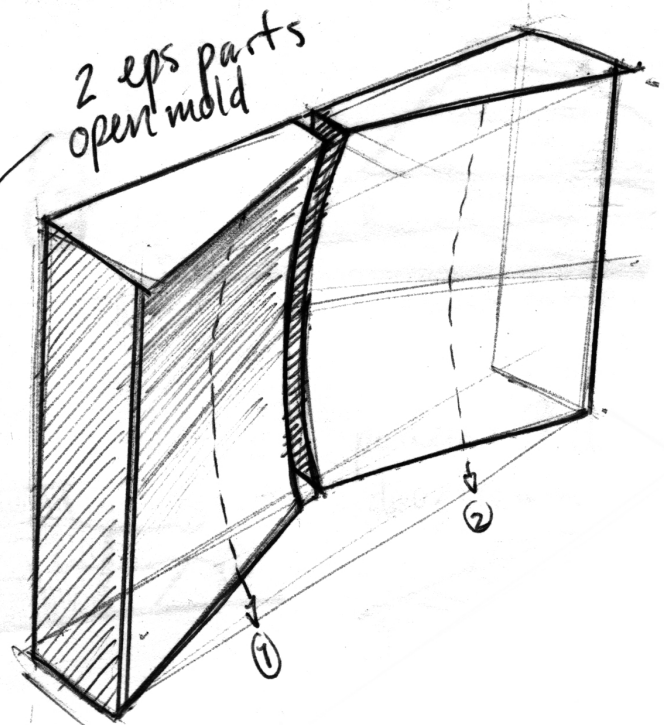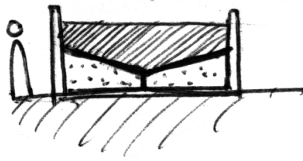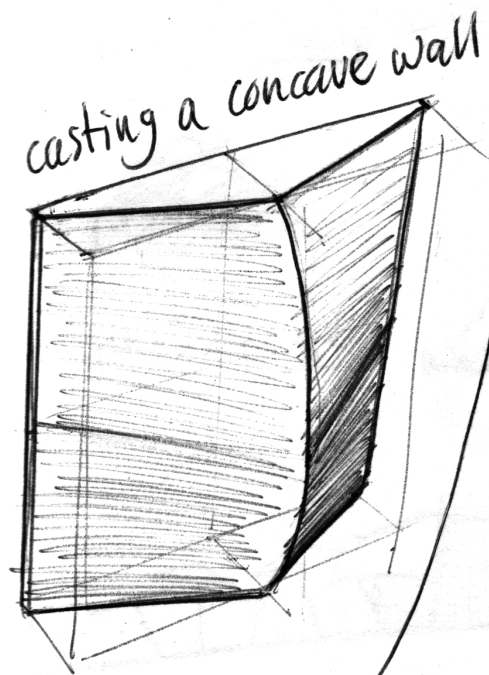
if d < toolwidth
toolwidth =

d

δ

δ
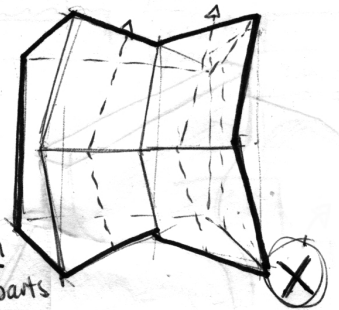
tool-collision
make into 2 parts

✗
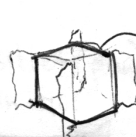
→ a convex corner means a seam in the mould?
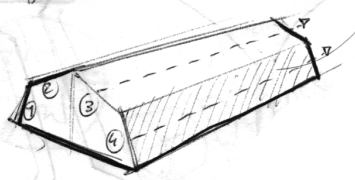
4 cuts
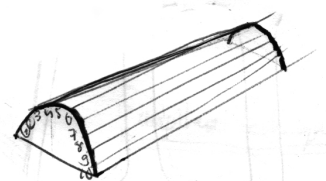
10 cuts

parts | convex | concave
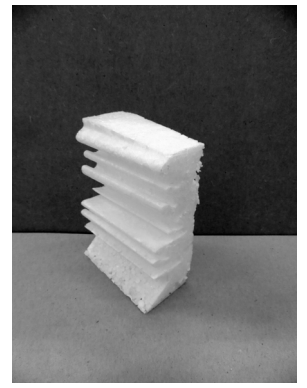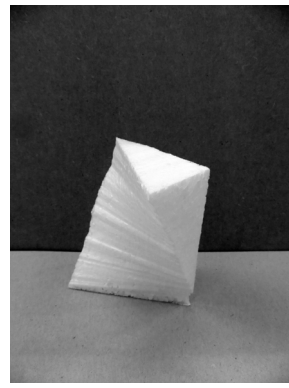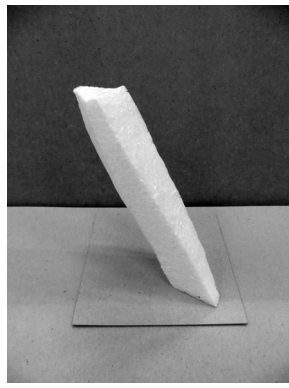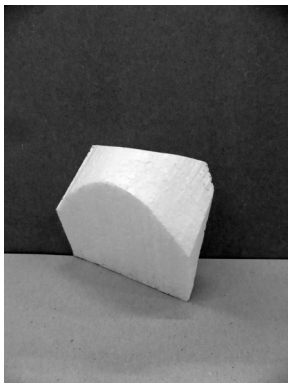mold

d < 84 cm

①

1 cut

VOCABULARY OF FORMS
-robotic hot-wire cutting-

raam

OBSERVATIONS AT THE RDM