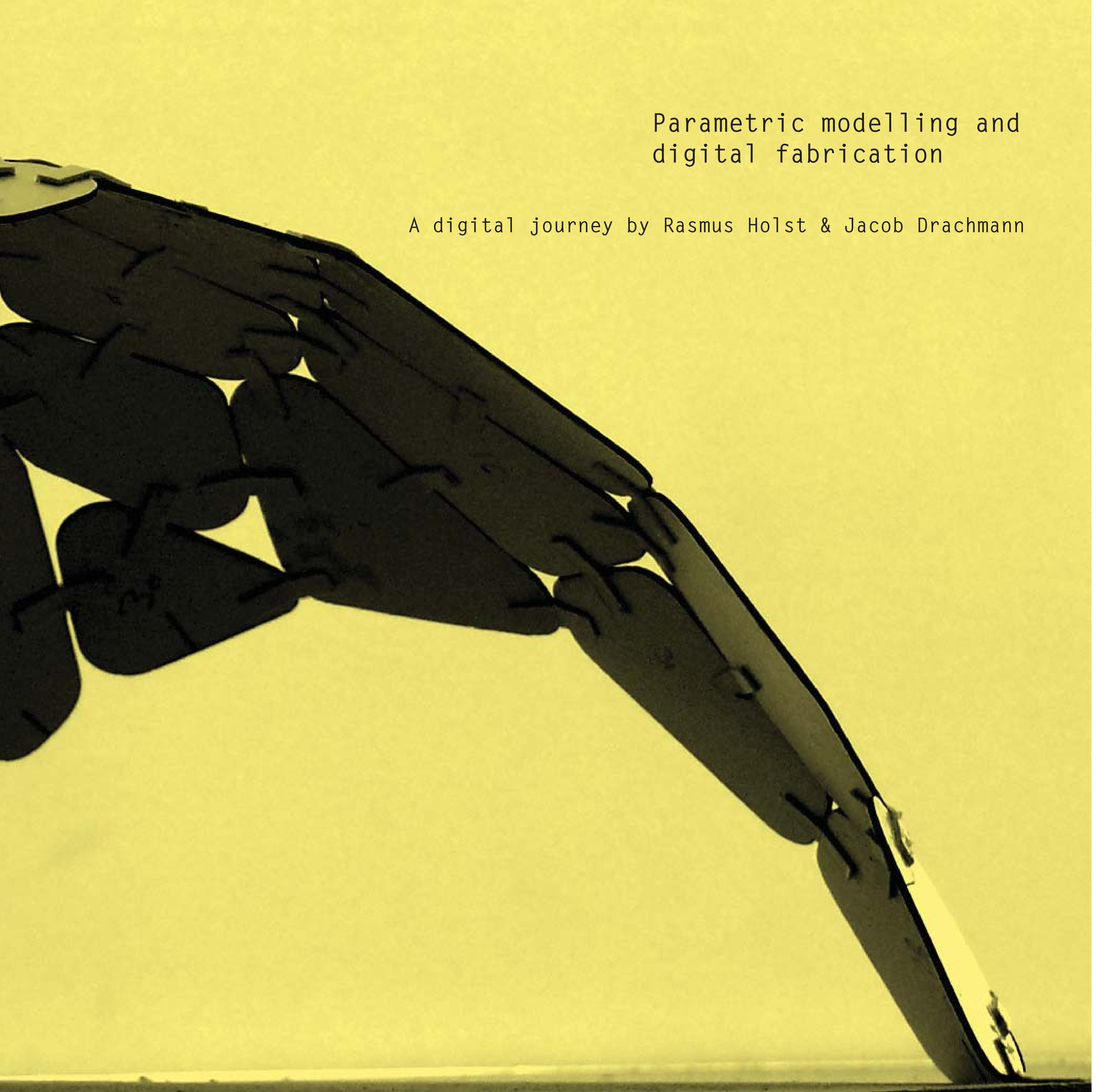
Parametric modelling and digital fabrication

A digital journey by Rasmus Holst & Jacob Drachmann



Titlepage

Parametric modelling and digital fabrication is the product of a 5 ECTS special course in the thirteen-week period at BYG.DTU in the autumn 2010.

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Thanks..

During the making of this project we have collaborated with various institutes and people.
In this connection we wish to thank:

- Jan Karlshøj
- Henrik Almegaard
- BYG.DTU
- Steen Markvorsen, MAT.DTU
- Rambøll
- Tim Nøhr, Danish Design School
- CITA , KARCH

Abstract

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In the realm of architectural geometry many disciplines are present. In this interdisciplinary field, different aspects and demands come together. Architects, engineers, mathematicians and computer scientist all have different ways of looking at the field, but they share the same need of control ,to be able to test their ideas and visions for further progress.

This project looks into the need for build-ability that especially engineers and architects have. It shows how far the limits can be pushed in order to obtain and build almost any shape using digital methods.

The digital methods for the modelling phase as well as in the production phase are introduced - hence the title "*Parametric modelling and digital fabrication".*

Parametric modelling is essential to be able to see how different design choices will affect the project and give the designer the needed control even when dealing with complex geometries.

Digital fabrication is the future and the arrival of new possibilities and less limitations. All ready today, most production processes are automated, but most have certain restrictions of shape. So to keep a healthy project economy, this needs to be considered in the design phase. But as the news methods as; laser-cutting, CNC milling, 3D printing etc. become more feasible, these restrictions seem to slowly vanish.
This project focus on a architectural geometry design case in order to go through the three main new fabrication methods:

- Laser cutting - CNC milling - 3D printing

and looks at the different demands and possibilities that follows

Content

Introduction

Generating visually attractive double-curved surfaces can be done using any 3D CAD software and seems to be part of a new paradigm in architecture. This creates a need for development of new production and construction methods, which will meet the demands from clients and architects. Large double-curved surfaces can either be built as a continuum; being e.g. a membrane structure or a concrete shell. It can also be built by dividing the surface into elements, which can be produced industrially off-site, and assembled on-site.

Dividing a complex shape into elements has been done in various projects. This technique has mostly been used for panelization, using glass as cladding material. Creating a logic and repetitive tiling of a given surface has been a major aspect, due to economic and practical reasons.
The thesis of this project is, that the use of digital fabrication techniques, will eventually remove the economic need for creating similar structural elements for large structures of complex geometry. What is expected to happen in the building industry, is what happened in the car industry 60 years ago.

The standard automated methods all ready used today in production of building components does not care about quantity and size, but it cares about shape and similarity.

A robot does not care about any of these things. If it is able to cut in all three dimensions or more, it will if told to. This means that if the wanted panelization of a surface causes many unique pieces, it is no problem.

What is needed is the right understanding of required inputs and outputs throughout the design- and production phase.

Project goal

The goal is to design a room-sized freefrom shell structure using Rhino[1] to interpret sketches in to a 3D model, and using Grasshopper[2] to work out a definition for working on the project from different parameters. To produce the structure using different digital fabrication tools each tool creates the demand for a different approach.

This project will focus on three digital fabrication methods, which we have chosen to divide into three generations.

1. generation: 2D laser cutter
2. generation: CNC milling machine
3. generation: 3D-printer.

A scaled model is produced using a laser-cutter at CITA at the Royal Academy of Arts.

1 Rhinoceros - www.rhino3d.com
2 Rhino plugin - www.grasshopper3d.com

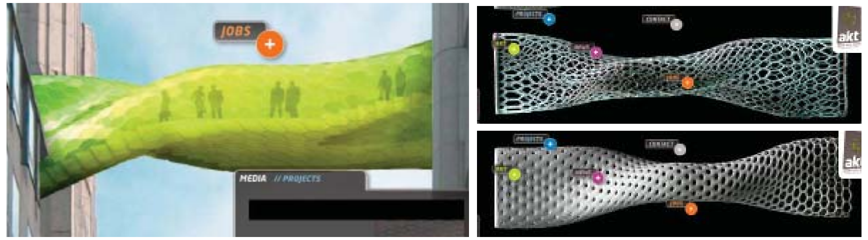
If possible, within the time frame of this project, a full scale structure is to be assembled and exhibited at DTU campus.

A single detailed full scale element is produced, preferably in wood, using a CNC milling machine at the Danish Design School.

Finally a scale model is produced using a 3D-printer at MEK-DTU.

DuPont by Corian design studio

Vossoir cloud by Iwamoto-Scott Architecture



Land securyties bridge by Future Systems and consultants Adams, Kara, Taylor

Parametric design and digital fabrication - Introduction

In this section, the world of parametric design and digital fabrication is introduced and investigated. We will introduce what have been done, what is being done, what are the perspectives and what are the possibilities.

Parametric design can be defined as a method where all informations in a project are linked. I.e. for a simple house, the placement of a window is linked to the placement of a door which is linked to the corner of the house. If the length of the wall is changed in the model, the door will follow and the window will too. This speeds up the design process, and gives a visual feedback to the designer whenever a change is made.

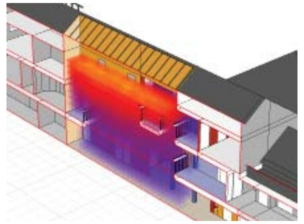
Digital fabrication is in this project defined as a fabrication technique where the production tool is directly linked to a digital model of a design. In the case of the house - i.e. the wall with cutouts, can be directly produced with only one step between the digital model and the produced elements. Linking the digital parametric model to the fabrication tool, can therefore give the designer the opportunity to produce a physical model very quickly.

This working method has been widely used by designers of small scale objects, where a physical model can be used to test ergonomic qualities, visual appearance etc.

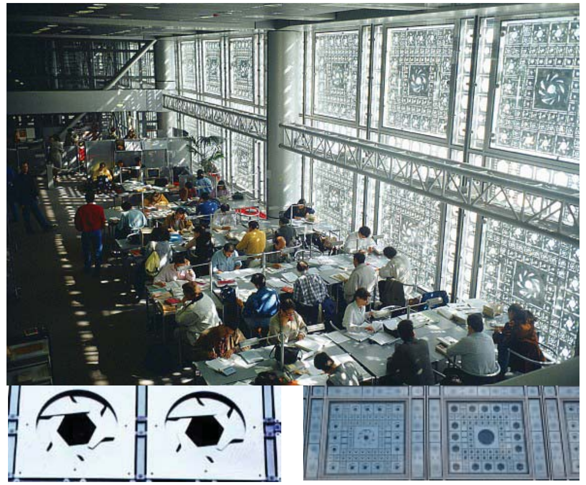
In an architectural scale, the link between parametric modelling and digital fabrication has mostly been used to create parts of a large structure.
Vossoir cloud by Iwamoto-Scott (see picture above) is an example of this. The workflow from idea to production is as follows:

In order to experiment with the light for the Louvre Museum in Abu Dhabi Jean Nouvel had a light lab build.

Elephant house, Norman Foster.
The lighting in the elephant house resembles the lighting in nature..



Example of daylight analysis performed in Ecotect



L'Institut du Monde Arabe, Jean Nouvel.
The elements of the facade operates like a camera lens to control the sun's penetration into the interior of the building.

- A digital hanging-model is created
- A surface is parametrically linked to the hanging-model
- The surface is triangulated
- The triangles are represented by a spatial element which is linked to the curvature of the surface
- A cutting pattern is produced for each element
- The elements are produced using a laser-cutter
- The final structure is assembled.

A change made in the shape of the hanging model will therefore result in changes down through the different steps of the model and eventually in the geometry of the cutting pattern for the elements. It is very hard to imagine how a piece of architecture like this could be realized without the use of parametric modelling and the link to digital fabrication tools.

A perspective in parametric modelling is the ability link to other digital tools, for analysis of 3D-geometries. For daylight-analysis a software like Ecotect can analyze any given geometry. If the daylight is not sufficient, the size of the windows can quickly be changed and analyzed again until the result is satisfactory.
This method could also be used for structural analysis, cost analysis, aesthetic evaluation etc.

For engineers this might be the most important aspect.

Research

To get into the world of this subject we attended two events.

Digital Crafting 18-20.08.2010:
Our research started in the research network *Digital Crafting*[1]. Here we attended a three day workshop/seminar at the Danish Technological Institute.

Here people with an interest in the field from different places of the world and with different backgrounds came together to learn and discuss. The workshop was about topology optimization and processing using Rhino3d. After finishing the optimized model in Rhino, a negative shape was milled in polystyrene and used as a concrete mould.
Several speakers spoke on the subject; topology optimization and digital tools. Amongst these Neil Leach (University of Southern California) and Ole Sigmund (DTU).

1 http://www.digitalcrafting.dk

This led to the very interesting discussion; in which direction to take this.

Advances in Architectural Geometry Vienna 18-21.09.2010:
This conference brings together researches and interests from the fields of architecture and geometry to discuss recent advances in research and practice.

We attended this 4-day workshop and conference at Vienna, together with people from Saha Hadid architects, Forster and partners architects, Autodesk etc. Here we were introduced to the most cutting edge digital calculation software in panelization of freeform surfaces from the people of *Evolute*[2].

We also saw the way that the big engineering and architecture firms used programming and parametric modelling as

2 http://www.evolute.at/

must-have tools in finding solutions for their advanced projects. [3]

From the workshop and the speakers we realized that the tools for panelization of free-form surfaces and optimization of regular and similar facets was very far ahead. So our interest in the unique facetting and the use of unique elements became even more interesting. This was a field with very little research in at this conference. For more information see also the book *Advances in Architectural Geometry 2010 (AAG2010)*[4]

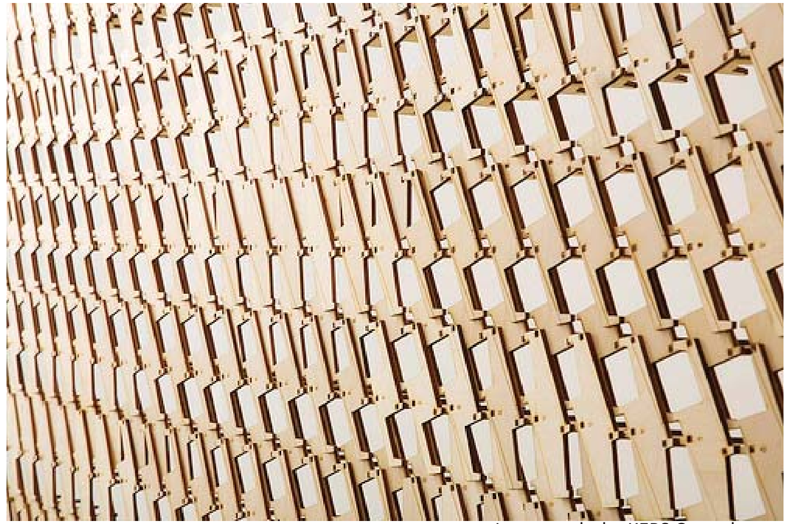
But even to make something unsystematic and seemingly randomized, a system is needed. We discovered that the three different generation of production-tools mentioned

3 http://www.architecturalgeometry.at/aag10/program.php
4 AAG2010 - Ceccato, Hesselgren, Pauly, Pottmann and Wallner.

previously all needed a different degree of work. To create a flat panelization of a surface, and produce the elements with a lasercutter, is definitely what needs the most work on from the designer. The idea of shell structure quickly arose.

The following will hold chapters on inspiration sources and references, introductions to the three generations of digital tools and the theory of shell structures.

http://www.flickr.com/photos/49368664@N05/4711435802/sizes/o/in/photostream/



Laser works by KEPS Copenhagen

Tools for digital fabrication

Many modern production facilities are based on digital fabrication. For this project we have focused on three tools:

1. Lasercutter
2. 3D mill
3. 3D-printer

These are introduced in the following section, since the understanding of them has been important in the later design process.

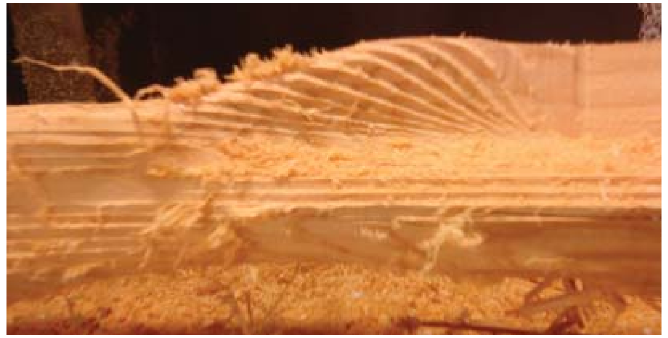
The Lasercutter

A lasercutter can be used for various materials, from cardboard to steel, and can cut a given pattern in a plate material. The precision of the tool is what makes the lasercutter ideal for objects where connections are a part of the elements. Ornamentations can also be burned into the surface of i.e. wood plates.
The cut edges will be perpendicular to the plate, which is one limitation. Another constrain is the size of the plates which are used to cut out the subjects.

This goes for the 2D laser cutter, however newer machines has the ability to work with skew angles, enabled by a laser head on a rotating axis.

http://www.vancemetal.com/NewPages/OurCapabilities2.html





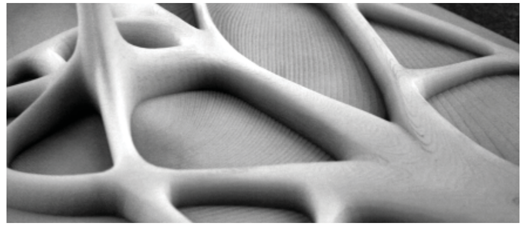
Images from the milling workshop at the Danish Design School

CNC-mill

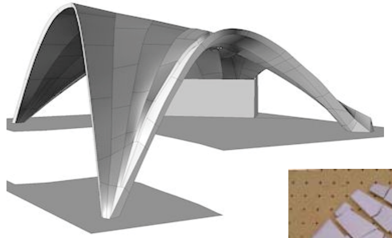
A CNC mill is similar to a regular handheld mill used to smoothen edges, cut holes etc. Mounted on a 5-axed robot, as the ones used in the automotive industry - it can produce a subject from a cubic element by simply milling away material until the desired shape is reached. The shape can typically only be created from one side, so in order to create an object of any shape, it requires rotation of the object. This can be done by rotating the object while milling or by flipping the object 180 deg. manually, when one side of the object is finished.

A 2-days 3D milling workshop was attended at the Danish Design School.

Rough edges. Wood milling by Alex Myers



Multi-axial milling robot



Shell elements

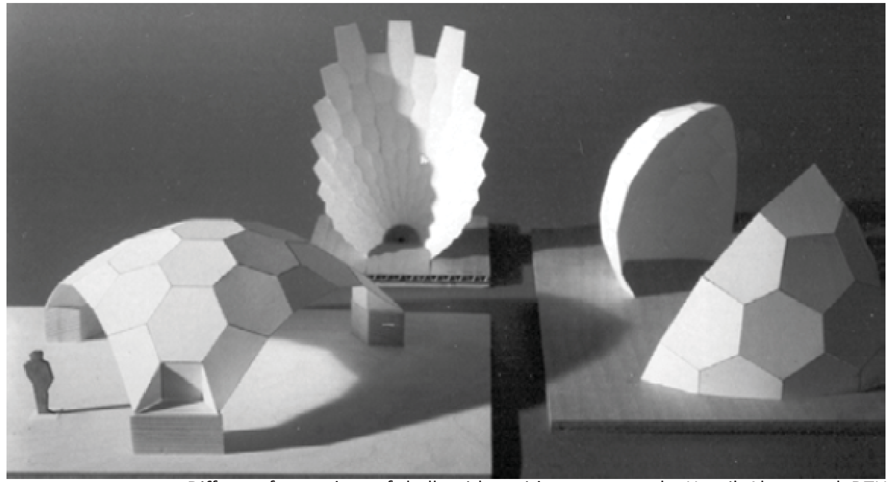
Enrico Dini prints large scale cement based structures

Gaudi Stool by Bram Greenen

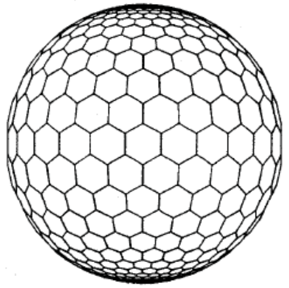
3D-printer

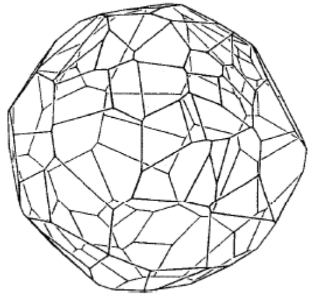
The 3D-printer is based on additive fabrication. A printer head moves in three dimensions within a domain varying in size from printer to printer. Within this cubic boundary given by the size of the printer, a subject of any given geometry can be produced.
Main constraints are size and material.

Possible materials are gypsum, PVC and even metal.
Gypsum is today the most common and available, this is treated with some kind of hardener in the end, to make it less fragile.



Different facettations of shells with positive curvature, by Henrik Almegaard, DTU





Shell structures

“A shell structure which is designed correctly only obtains normalforces in its own plane, and is therefore potentially a minimal-structure”[1]

Shell structures can i.e. be build by plane facets or cast in one piece to create a smooth surface.
Economically and practically building shells in elements has opportunities. Gridshells covered by planar glass must be based on a facettation, and generally planar elements are easier and cheaper to produce.

Facettation - Tangent plane method

A planar facettation of a surface, can be obtained by using the tangent plane method described by Almegaard[1], which includes the following steps:

1. Generation of points on a surface
2. Generation of tangent planes in points
3. Extrusion of tangent planes -> tangent boxes
4. Subtraction of tangent boxes from a volume containing the initial surface
5. The facetted surface can now be used to build the shell structure

The shape of the facets, and thereby the properties of the final shell structure, depends on the position of tangent points and the curvature of the surface.

1 [1] HAL - Skalkonstruktioner. By og Byg + SBi 2003

Concrete shell by Felix candela - thickness 30 mm!

Plywood shell by Henrik Almegaard, Hørsholm

Gridshell - British museum, London

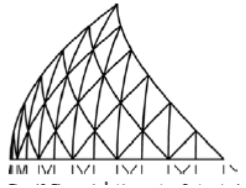
Stability - Stringer Method

To ensure stability of a facetted shell structure based on the tangent plane method, the stringer method described by Almegaard[1] can be used to create the tangent points.
The method is an extension of the stringer method used for disks, where a plane element is represented by a system of linear stringers. In general the spatial stability of a shell structure depend on the following:

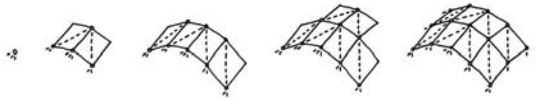
- Support conditions
- Facettation

The stringer method has been used to build a full scale shell structure in Hørsholm, which still stands after 20 years. See picture above.

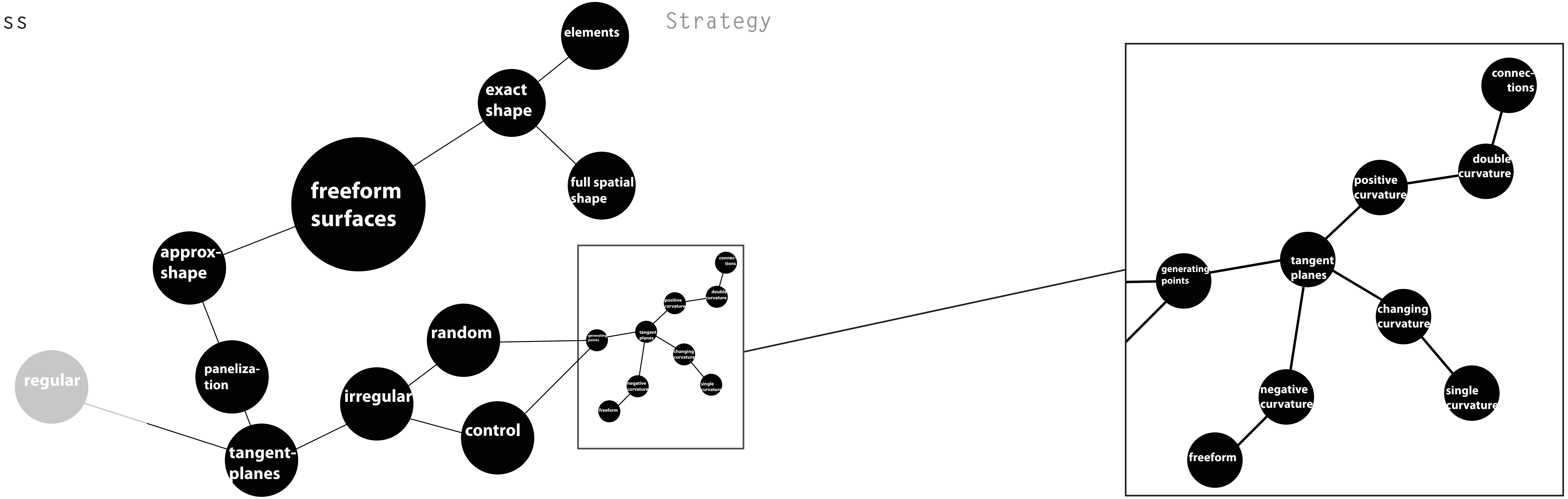
Instead of using the stringer method, a shell can be successively built and thus become stabile.



Stringersytem [1]



Successively built shell structure [6] (Stability of shell structures, Almegaard)



Program map

In this section we describe how we work in order to reach the project goal.

From the first freeform surface there are two ways to go. First an approximate shape can be obtained from planar elements, through panelization.
The other way is to try and obtain the exact shape through elements with curvature or a full size spatial shape.

First step:
On the program map above it seams clear that the way that requires the most of the programming tool is the way of the panelization. The first step on this freeform surface survey is to create the program for modelling panelization of a freeform positive curved surface.

At this point we are looking at non-standard panel elements, meaning that we are not aiming for similar panels, rather having an interesting random pattern and possibly be able to control this, as mentioned in the introduction.
We are looking at how to interact between randomness and control. The theory used for the panelization is the tangent plane method mentioned in a previous chapter. This method demands the generation of points on the surface for the tangent planes.

The algorithms that needs to be worked out differs a bit, depending on the curvature of the freeform surface. If taking it in the direction of the surfaces with positive Gaussian curvature all over, the changes needed in order to make the definition work on shapes with changing Gaussian curvature and finally negative Gaussian curvature also, is foreseeable. This only calls for more programming steps.

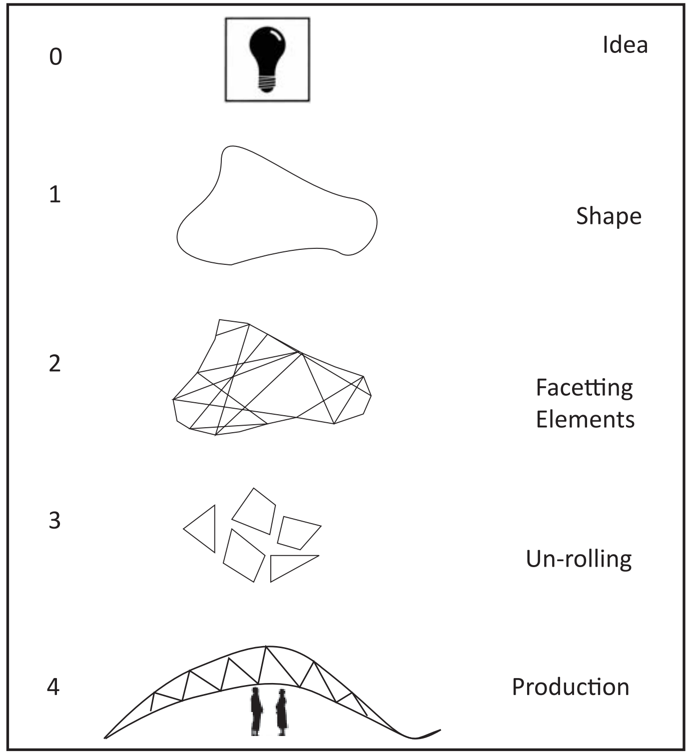
For this reason, within the scope of this project, we are focusing on the detailing of shapes with positive double curvature, to be able to look at the very important aspect of the connections between the facets.

Second step:
Secondly we are looking at how to obtain the exact shape. If dealing with buildings and larger structures, construction elements will normally be needed. So we will look at the different ways to divided the surface into elements, how to connect them and the aesthetics of these.

Third step:
The future perspective of a full scale 3D printer, would allow for the precise construction of full spatial shapes. The technology is here already, but with great limitations of materials and size.

This allows for fine and exact detailing of the full shape structure, where only the imagination and shape stability set the limits.

The method will be explained in the following.



Method

As mentioned the choice of fabrication method determines the basic program. The different possibilities and limits for the methods are listed below:

Generation 1: Lasercutter
+ No limitations of different shapes
- Have to be plane elements
  Modelling: Plane facettation, un-rolling production system.

Generation 2 : CNC-mill
+ Does not have to be plane elements anymore
- High material usage (by cut-out)
  Element repetation (by moulding)
  Modelling: Cut elements - system

Generation 3 : 3D Print
+ Precise shape
  Material optimized
  Modelling: Division of shape into elements if need-ed.

This depends on the size of the printer cabinet.

These are the things to consider, when building the program.

Program

We are building the program/definition starting out by working in a pretty simple method. Then more layers can be added to increase the complexity to the program.
See the figure above:

Level 0.
The idea from design case.

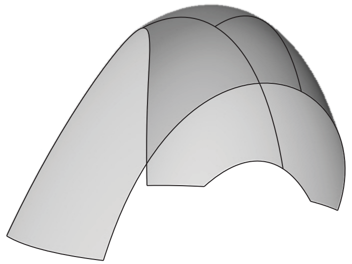
Level 1.
The shape - in this case a smooth surface.

Level 2.
Facetting and optimization - Optimizing the facetting and detailing the connections.

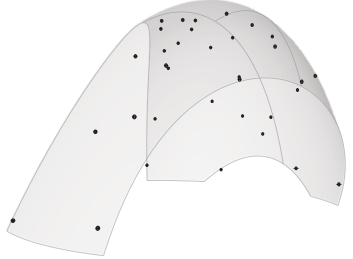
Level 3.
Production preperation and optimization - Optimizing the un-rolling of the facettes.

Level 4.
Production and construction

Each of these are connected iterative and experiences from level 4 can easily trigger changes in level 1. E.g. optimization of the basic shape, after e.g. static- and/or energy concerns etc.



1



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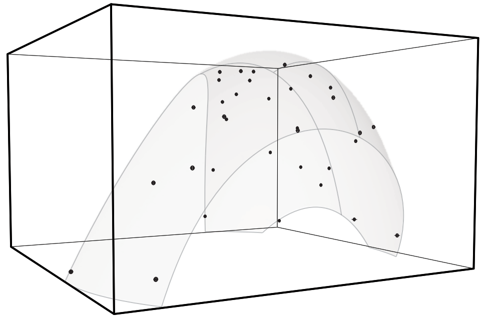

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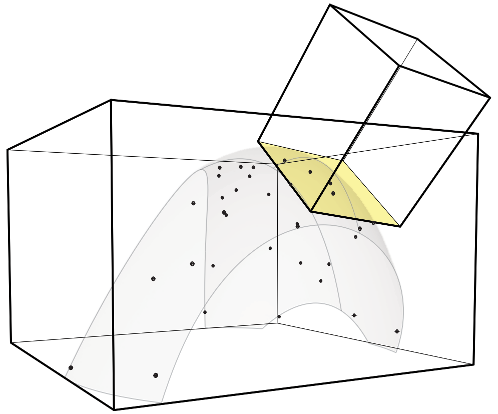

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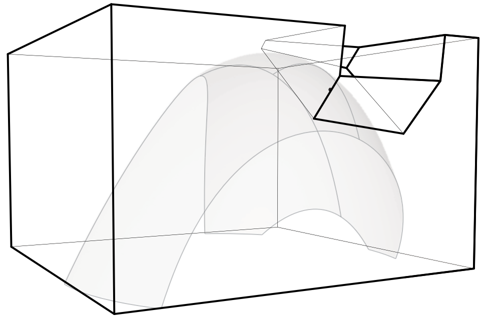

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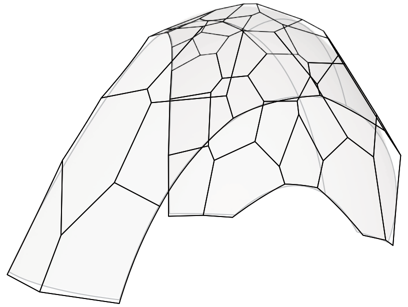


6

Facetting a surface

The series of drawings here, represent the process from smooth surface to a facetted shell. The tangent-plane method, as described in the previous description of shell structures, is applied.

The surface shown here is also used later on in the design of a pavilion. It is important to stress, that it could be any smooth surface with positive curvature.

1. A smooth surface with positive curvature is loaded into the Grasshopper-definition.

2. Points are generated on the surface

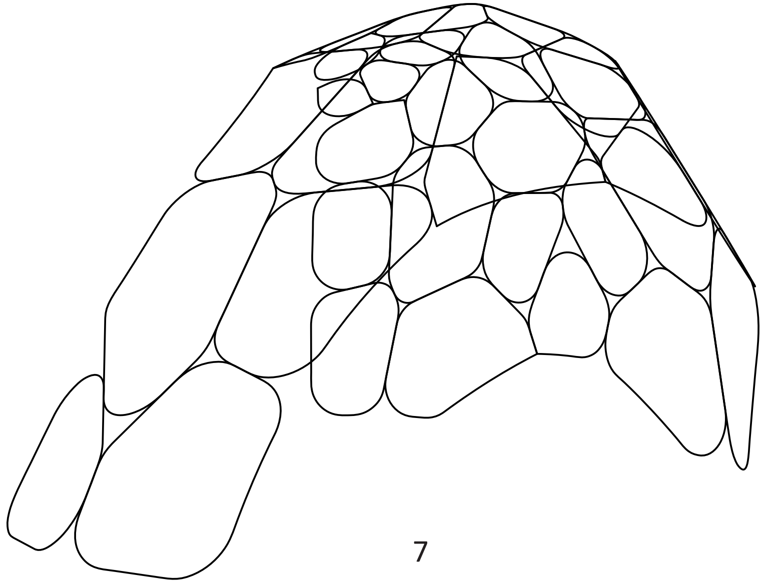
3. A bounding box containing the surface is created

4. All points on the surface are evaluated and tangent planes (yellow) are created and extruded

5. Each “tangent-solid” is subtracted from the bounding box

6. After subtracting all “tangent-solids” an approximation of the initial surface appear - now as a facetted shell

7. The geometry of the facets can be further manipulated



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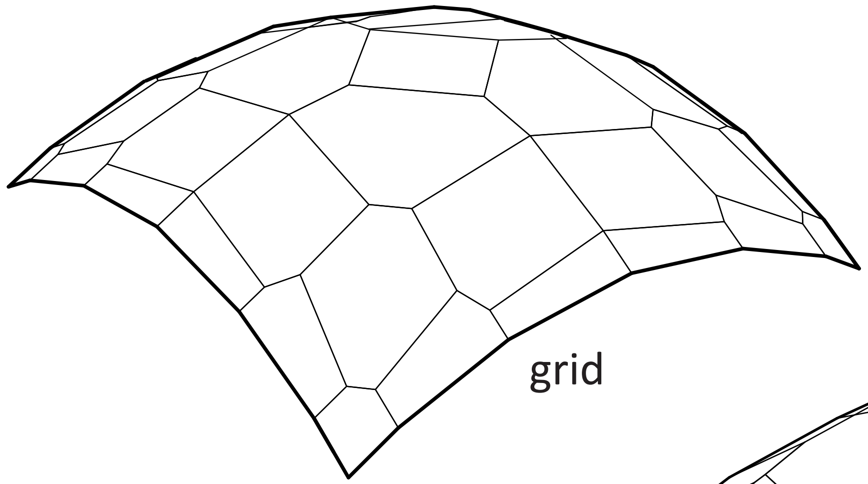
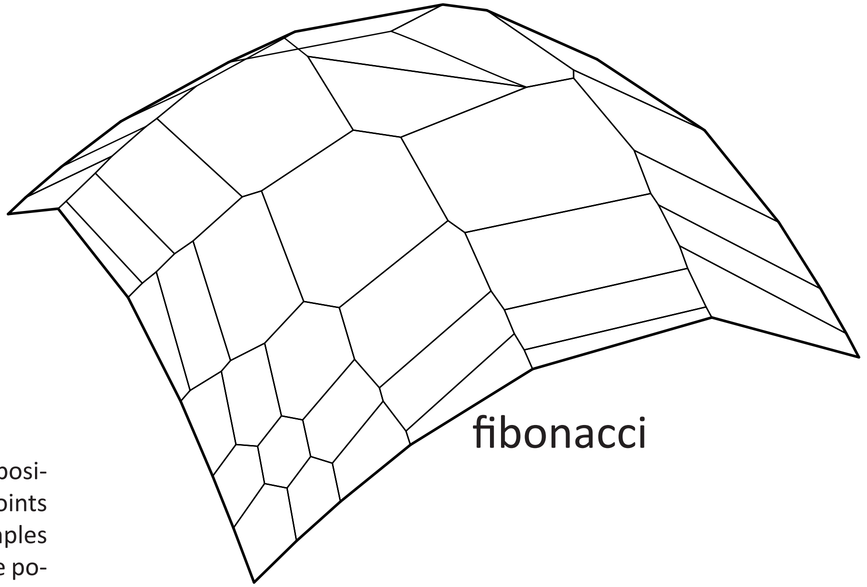


grid



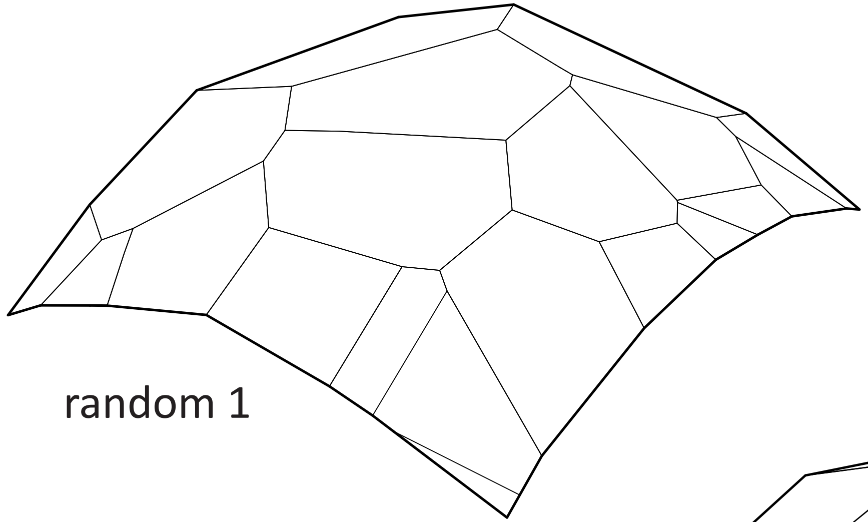
fibonacci

Controlling the facettation

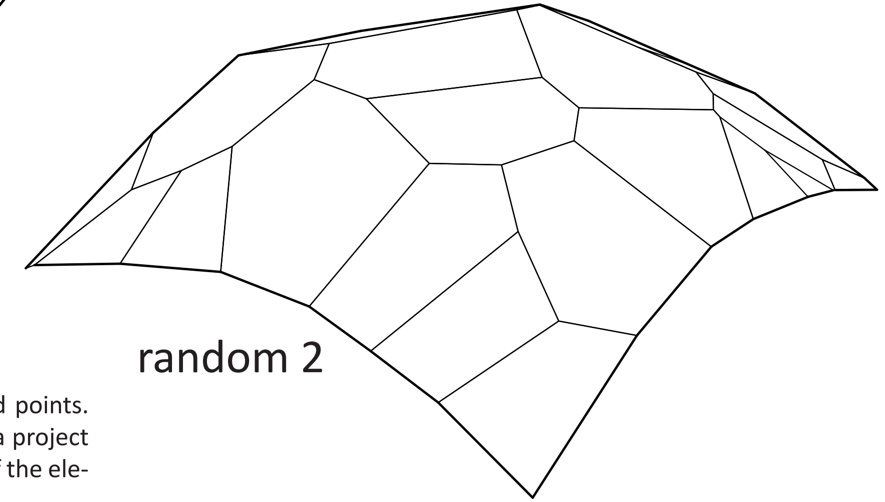
The shape of the facets created, solely depend on the position of the tangent-solids - thus on the position of the points in which the tangent-planes are created. These examples show how different the shells become, depending on the position of the tangent-planes.

The above images show a controlled approach to the generation of the points - from a grid and from fibonacci numbers.

Both produce shells with a certain degree of symmetry. This appears due to the shape of the surface. A similar grid of points on a non-symmetric surface would produce a facettation which is non-symmetric.



random 1

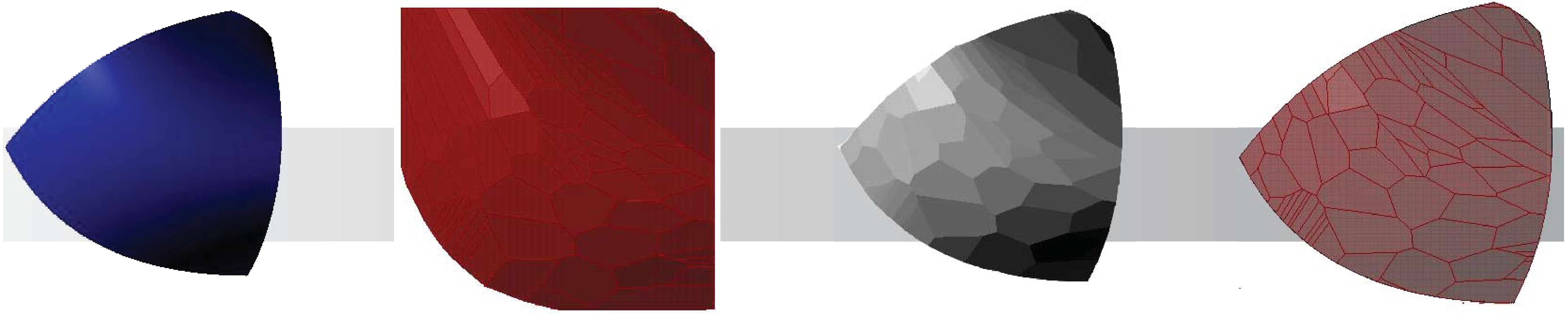


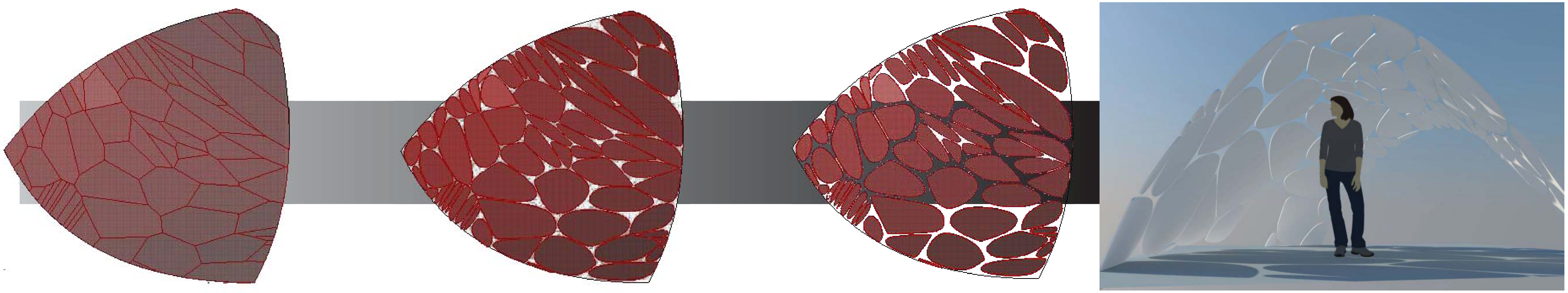
random 2

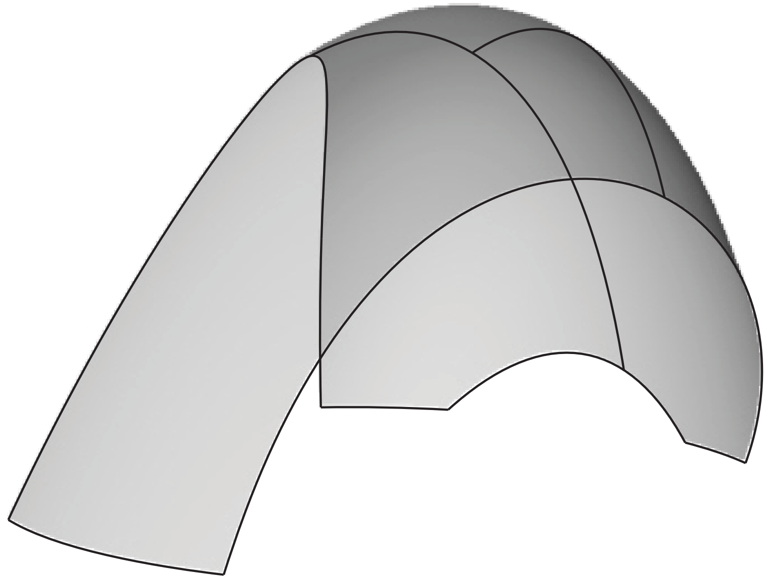
The shells above are based on randomly generated points. We found the patterns fascinating and suitable for a project where the production tools do not limit the shape of the elements.

The following two pages show a test of the definition where a set of randomly generated points are used to create a shell-proposal.

Tangent planes are defined as having the points as centriods, but one could also find it interesting to play with the placement of the planes in respect to their points. This would mean a change in the intersection between the planes.







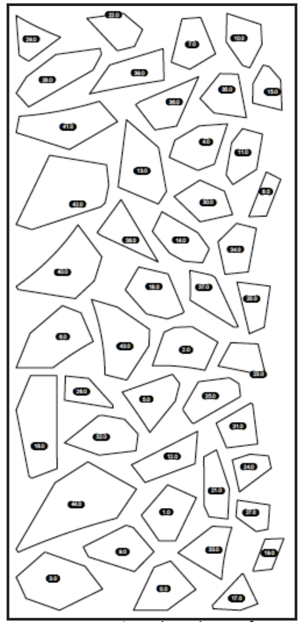
Design case

After developing and exploring the grasshopper-definition, we use it in a design case project - winter pavilion at DTU campus. The site is a 3.8 X 3.8 meter paved square, fit in the rigidly planned landscape between building 116 and 117. The design has evolved from model studies and shape-optimization in Grasshopper, in the following steps:

1. Finding a surface for the design
2. Model review, test of stability
3. Verification of design
4. Creation of 3 different designs based on 3 different production methods.

1. Surface

The grasshopper definition can create a facettation of a surface with positive gaussian curvature. The chosen surface is a part of an ellipsoid which has been tweaked in Rhino. The surface has been cut to create an open space.


Nesting the planar facets


Model 1

2. model review

The facettation method is not based on the stringer method described by Almegaard[1], and the shell is therefore not necessarily stabile. Model nr. 1 easily deforms from the touch of hand, and is not considered to be stabile. To make the shell stabile, there are according to Almegaard the following three options:

1. Change the surface
2. Choose another facettation
3. Design solutions

We have sought to stay true to the randomly generated facettation for aesthetic reasons. This limits solution nr. 1 to be a adjustment of the shape - we have enlarged the supports, since this is the most critical point in the design.

Because of the randomness in the creation of tangent points, there is no control with the final facettation. We therefore manually manipulate the facettation to create a more stabile design.
Firstly we ensure as much curvature as possible near supports. This adds stiffness to the design, and is clearly felt in model nr. 2.
Secondly we ensure that there are no vertices where 4 edges meet. This maximizes the number of connections in the shell, and therefore enlarges the stiffness. Getting rid of vertices with four edges is done by applying a check in the definition, which locates edges smaller than a given number. The tangent points near the located vertice, are then manipulated to create an extra vertice.

These topological manipulations improve the stability of the shell - but does not make it spatially stable.

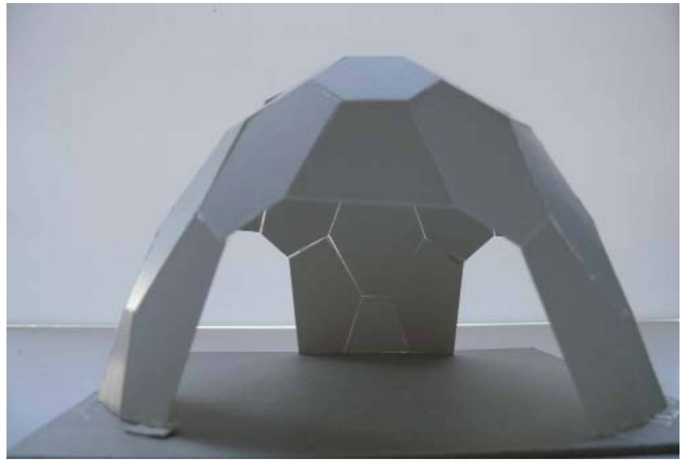
1 HAL - Skalkonstruktioner. By og Byg + SBi 2003


Model 2

3. Verification of design

The third approach is to design solutions which will make the shell stable. One approach is to transfer moment throughout the shell structure. To do this two things are necessary; the elements must be stiff enough to withstand the moments they are subjected to and the connections between them should be equally stiff.

Different connection types are discussed in the following section.

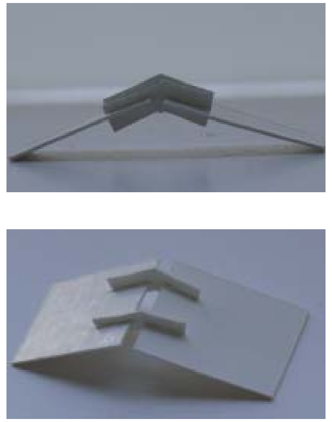


Reference model

To have an idea of the stability of the cardboard models, a reference model of a shell structure, which is known to be stabile, is needed. Using our grasshopper definition, the stringer model was created and the stability can be compared. The conditions of the shells are of course not the same, but have a great deal of similarities. Both have three supporting edges, three openings and the shells have approximately the same size.

The stringer method, as used in this project, can easily be transferred to a given surface using our definition and this show the strength of having a parametric model definition that can be used for various purposes.

Comparison of the reference model and the case models, confirmed our design reviews, where we concluded that moment stiff joints between the facets are needed.



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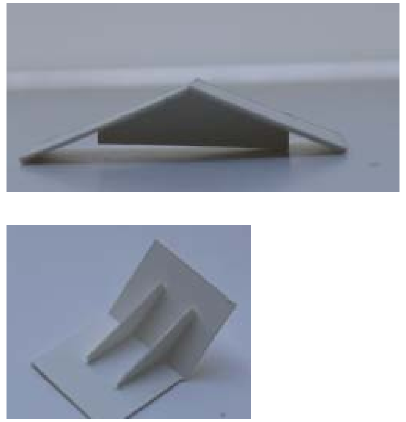

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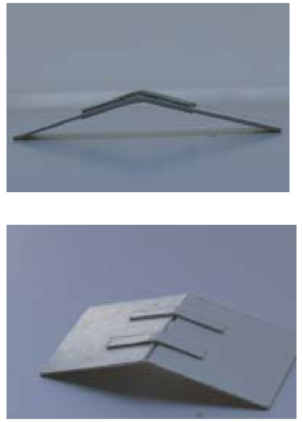


3

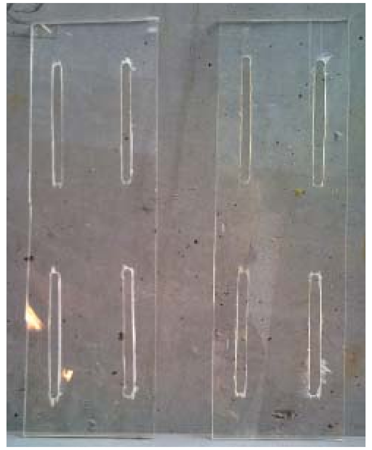
Connection design

The first idea was to use hinged joints. Hinges has a high degree of flexibility and makes the assembly process smooth. The first design review model showed that the wanted shape would be obtained using hinges. Here we used glued edges in the model. Since no moment could be transferred, the structure was not stabile. For this reason we looked at other ways of making the joints.

Figure 1 shows a connection consisting of two joint pieces, in which the facets can be placed. This gives a moment stiff connection and uses the moment of inertia around the strong axis for the main bending moment. Also it allows for a gap between the elements, allowing a play of light in the structure. A joint like this, would be unique for each different angle between the elements, and the lack of flexibility in it, would make the later assembly process difficult, if not impossible.

Figure 2 shows a somewhat similar connection. This connection is very well known from boat building. Depending on the demand for this joint, it takes up space inside the structure, but could be used aesthetically in an interesting way. Again the joint would have to be unique and cannot be standardized.

Figure 3 is somewhat of a double hinged joint. This joint fulfills a large part of the parameters that needs to be fulfilled for this structure. It can be produced in various ways. One of these ways would be to connect e.g. the insides with a hinge and obtain something similar to design review 1 or 2. When all the elements are then connected and the structure is shaped, the outside hinges can be connected. This will make a stiff connection, since the rotation axis of the two sets of hinges are not the same, and therefore the elements cannot rotate. Because of the big potential, it is this connection principle that we chose to go on with.



Connection design - full scale

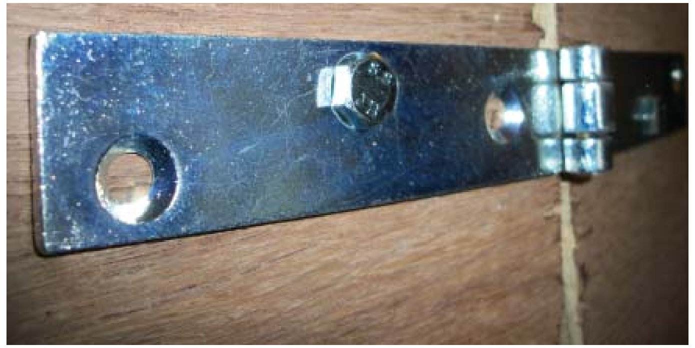
To make the assembly process flexible, we suggest oblong holes in the plates. So before tightening the bolts, bending in the plates and thereby rotation of the elements are possible. When the correct shape is obtained, the bolts are fastened and the elements can no longer rotate.
If the corners of the elements are to be cut out and some elements edges might not meet, the holes for the bolts are placed parametrically in the 3d model and can be fabricated digitally, as the respective placement will differ from element to element.

Plexi-glass
The connection with plexi-glass looks are very elegant and creates almost invisible connections. Plexi-glass is a material that is easily obtained in any builders merchant. That is why we chose to use this material. The bending strength is pretty high, but is very friable, which makes a hard material to experiment with. Another kind of polymer material that was less friable and even more flexible might be preferred in this connection, but it comes to show that the connection is very stabile up until fracture of the plexi-glass.
This would have to be investigated further to estimate an optimal solution. The distance between the oblong holes might have a big influence.




Metal strips
The same connecting concept is investigated in this joint experiment. Here the plexi-glass are replaced with metal strips. Because of a limited set of tools for his investigation, oblong holes could not be applied to the strips. This created some pretty big inaccuracies which made the joint less stiff, but it was clear that it could definitely be a possibility, since the material is able to bend much more, has a high tensile strength. The ability to transfer shear forces in the joint is decreased in this case, when using the two sets of narrow strips, and therefore a combination of this and the previous connection would be very interesting. The investigation also showed that it is very important that the strips are completely tensioned. So for assembly reasons a material with a higher bending strength must be preferred, but the tensile strength and the yielding fracture of the metal is very preferable.

Plastic strip
Here another material with a higher degree of the bending is investigated. A transparent plastic rail, with a special cross-section is used. With the chosen placement of bolts in this case, the joint can only transfer little shear force, but moment is transferred. The profile of the rails increases the moment of inertia, but the joint is not at stiff as the first joint with plexi-glass. It is clear that buckling appears in parts of the cross section.

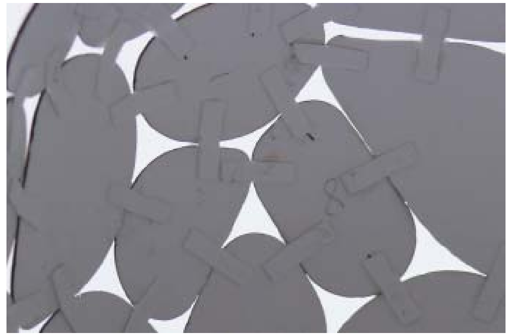


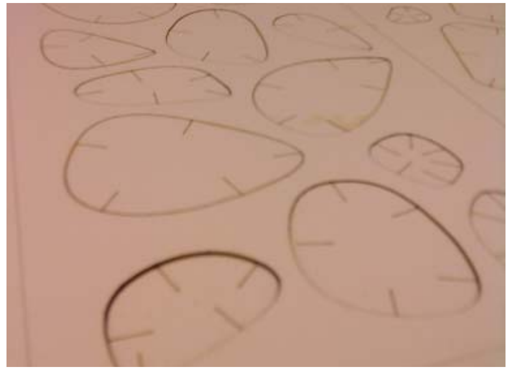

Steel hinges
At last the basic idea is investigated. The idea of the two sides of hinges is directly transferred to the project in this case. Again oblong holes in the hinges are required. As expected this solution works very well, but the small spacing between the cylinders in the hinge, makes smaller movements possible, which is not wanted.

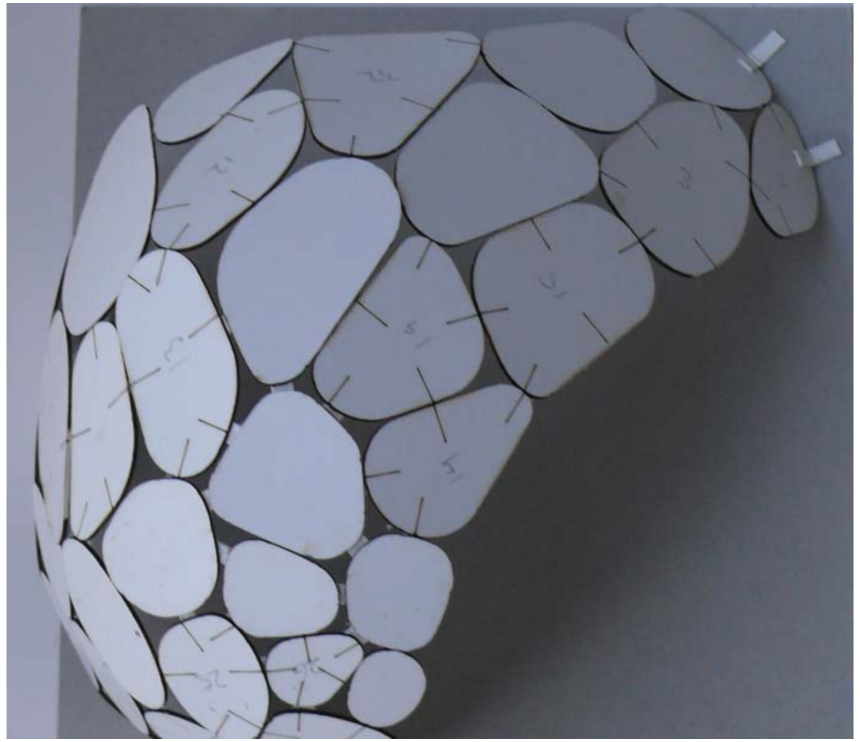
A common thing for these connections is that the connection parts are universal. This makes the assembly process easier. These investigations have shown that the connection is definitely possible, but FEM calculations of the moment transfers have to be carried out. Then materials with sufficient strengths can be found and tested.

Digital fabrication

After reviewing the first carboard models, we thought we were ready to produce scale models. In the following section we present the pavillion design produced with the lasercutter, a 3D mill and a 3D printer.
The different tools all take the design in specific directions with respect to tectonics, materials, aestetics etc. We have translated the patterns produced by facet edges, to the designs where a facettation actually isn´t needed. This is chosen to get consistency through the designs.
We will go through each of them and discuss qualities and limitations and practical issues.





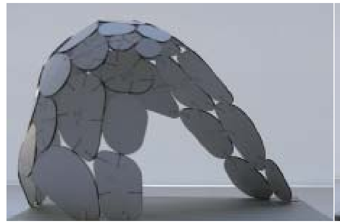
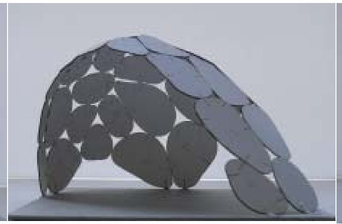
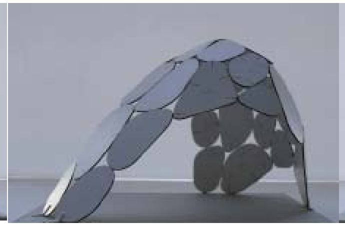
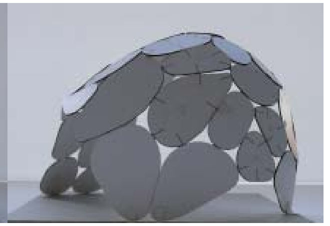


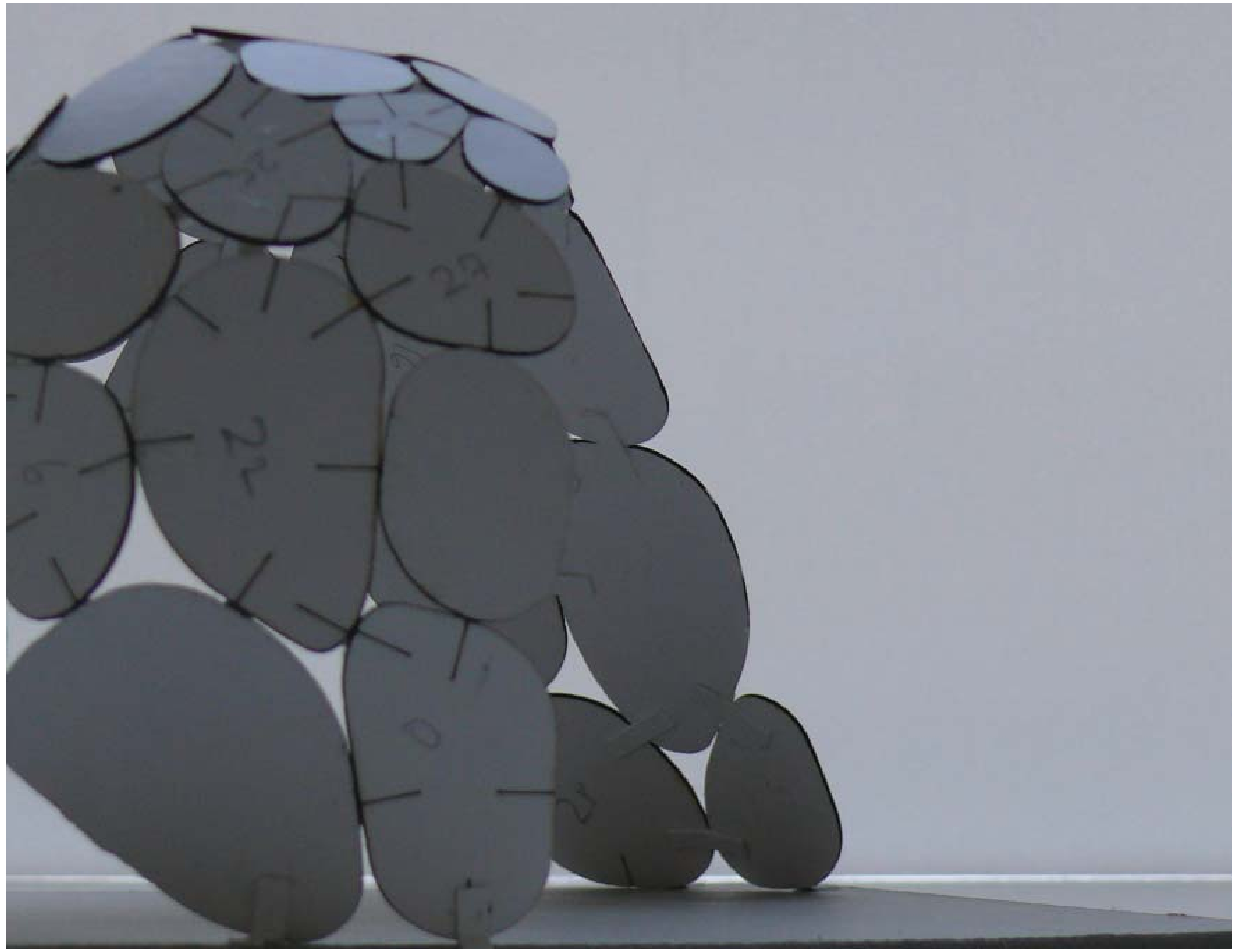
Lasercut - model 1

Two important factors have influenced the lasercut designs;
1. Stresses at corners are small and forces between elements are, ideally, transfered as normal and shear forces via hinges.
2. The precission of the lasercutter allows the elements to have curved edges – this model would have lasted a weekend to cut by a hobbyknife.

The pattern that appears allows light to shine through and changes the normal perception of a ”shell structure” as a closed structure.

The radius of the corners, and thus the size of the openings, can be changed parametrically in the Grasshopper definition. As shown in the review of models this design is not stable due to the hinge connection. In the second lasercut model, the moment stiff connection is implemented.

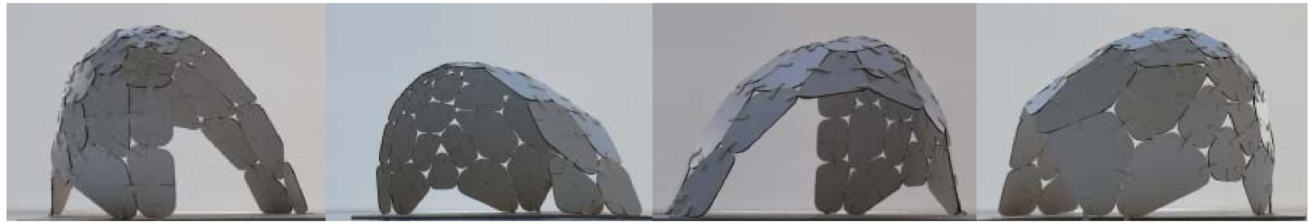


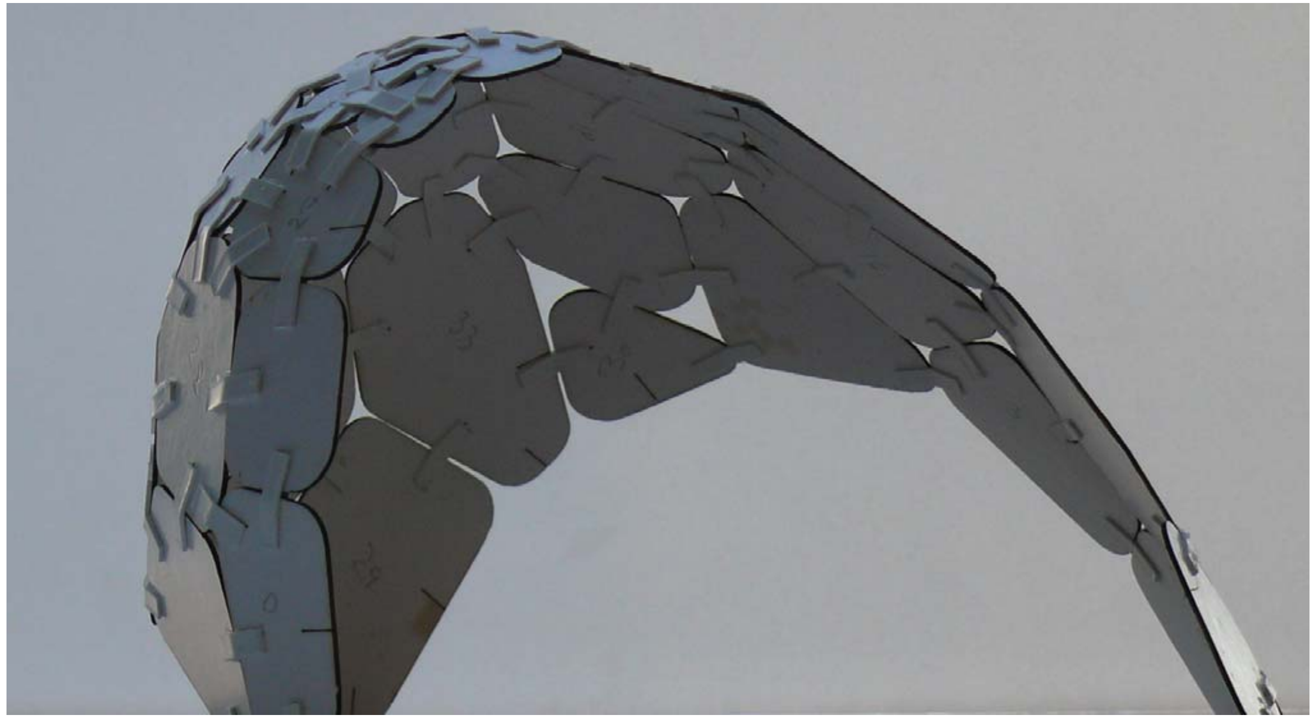
Lasercut - model 2

This design is created the same way as the previous. There are two main differences:

The radius of corner curves has been made smaller, which makes the light-holes smaller. The elements are now visually somewhere in between polygons and the more organic shapes in the first lasercut model.

The stiff connection has been implemented and the model shows to be relatively stiff. It is not as stiff as the reference model, but by increasing thicknesses of plates and connections we assume that a stable design can be achieved.





3D milled

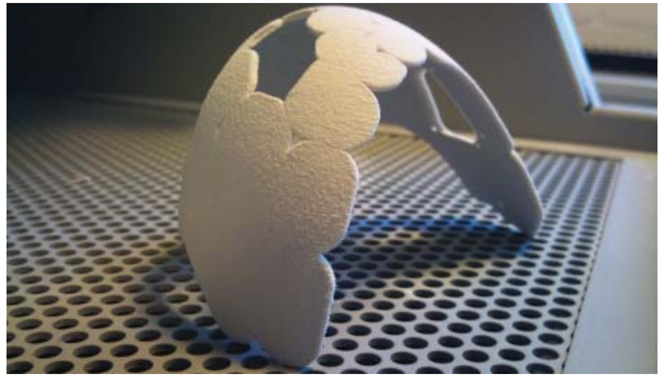
During a two day workshop at the Danish School of design, we were introduced to different 3D milling machines. There are two interesting perspectives in the 3D-mill in relation to this project:

1. The mill can be used to create individually shaped polystyrene molds for casting concrete elements.

2. Wood elements can be produced in any given shape

We have produced one 1:1 curved element to show a perspective. Wood is light and strong and would be ideal for such a structure. The connections between elements could be milled into edges for easy assembly.

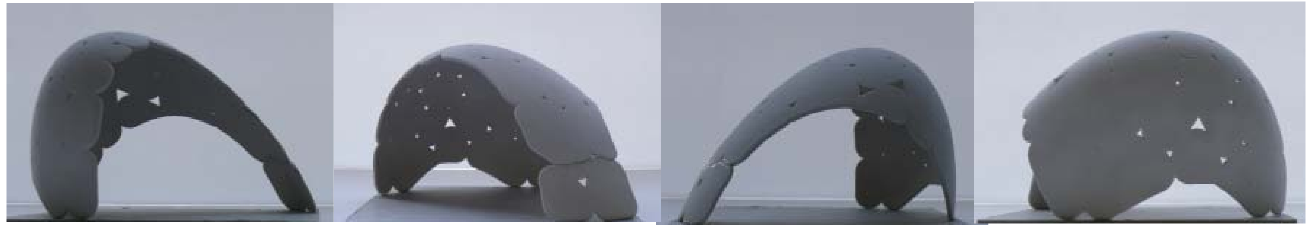
In the present design, where a stiff connection is needed, a connection like the ones used for the plane facets could be implemented.



3D Print

The 3D-printed model was produced using a gypsum-printer at MAT-DTU. With the 3D-printer, we wanted to get closer to the original surface from which the facetted shell emerged. To keep a clear reference to the rest of the project we used the planar facets as basis of the curved elements.
To test our digital model and get a feeling of the printer, we did a 1:40 model. It showed that a few facets were not printed. This was corrected and the 1:20 model turned out fine. The leg-support broke during the printing due to the dead load of the shell. The crack was at the presumably most fragile part of the structure.

In a 1:1 situation, it is utopian to imagine the shell to be printed in one piece – however this could easily be a scenario in the future. Creating a similar structure in one piece would obviously be done using in-situ cast concrete. Scaffolding would be a shell structure by itself, but it would be buildable and the more likely way to build it.



Conclusion

With this project we wanted to go from ideas to the computer and into reality again. We wanted to translate theory into praxis. By working parametrically and systematically we have been able to create a program that allows for control of detailing of the structure for a free-form shape.

From a free-form shape to a structure that is actually possible to build there is a great process in between. This process needed the use of new tools. The parametric model allows us to fit our model to the demands of the fabrication method.

The fabrication methods utilized and investigated in this report, are methods of the future that is already here. Most of us have heard about the 3D-printer, the CNC milling machine and the laser cutter, but we tend to use the conventional method. Even though a lot of these are possible in the industry, e.g. in the car industry where robots has been used for a long time.
In this project we have researched on the methods, adapted our program to be able to explore these and in the end actually used them.

To go from the paper sketch, through the 3D-model in the computer, the scale model, to the actual construction, many changes will occur all of the time. Without a parametric system, this process would have taken forever and has been an absolute must.

When most of this designing and investigation is automated, why not look at the technology to make the production go faster as well. During this thirteen week period that this project has lasted, we have been able to pretty quickly translate the theory of faceting of shell structures into a real-time parametric definition, to be used on any surface with positive curvature.

This is a parametric definition which also lets the designer take the next step and get the model out of the computer.

All the necessary steps are accounted for, including scaling of the model, projection of the elements to the plane and numbering. We have shown how nesting software can be used to create completely ready element-sheets for production with optimized material use.

We have discovered what the possibilities and perspectives, aesthetically and practically, the 3D printer and the CNC cutter hold. We have been confirmed in our believe in the value of unique elements in architectural projects, and we now know that when using a parametric model together with digital tool, there is no practical necessity in having identical elements.

A big wish from the beginning was to be able to build the full scale structure at DTU campus. We have discovered that the stability of free-form shell structure can be hard to obtain, and therefore investigations and testing is needed. From these results, most changes can easily be made. The scaled models have given us a good impression of the stability of the structure, but since this has never been a main subject of this project we do not feel that we have entirely sufficient knowledge of the behavior of the structure. Therefore we have chosen not the make the full scale structure, but we believe that we would be able to relatively easily if the we where sure of the stability. For the production part, the exact same procedure would be used as the scaled model, only a larger laser cutter at the Royal Academy would be used and the cardboard replaced with plywood.

Perspective

The analysis of the structure is definitely the next step and could mean adding additional layers to the definition/program. The model that is obtained from the definition as it is now, could be transferred to a FEM program, and the interaction between the parametric model and the FEM model would allow us to approach an optimized solution.
The program that we have done here can be used with surfaces with positive curvature, so another next step would be to expand the definition to all surfaces with negative curvature as well.

Finally the joints that will be chosen for a project could be incorporated in the 3D model.

Considering the fabrication methods, there is no doubt that this is going to be a very useful tool in the future. When size goes up and price goes down it is going to be even more interesting in the construction industry. Also the ability to use different materials and create whole composite structure materials will increase the potential.

Our program could be added extra layers of information regarding a expanded stringer method, looking at how the theory can be transformed to a more random grid. Also the theory of successive building of shells could be implemented. This has not been in the scope of this project, but could be a future project, to work upon ours, for people with an interest.

"Geometry lies at the core of the architectural design process. It is omnipresent, form the initial form-finding to the final construction."

\- AAG 2010