Faculty of Architecture
Department of Building Technology
Façade Master Design Program

Graduation Report

Standard Principles:
Double Curved Facades

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Preface

This research is my graduation project on the international façade master track at the University of Delft. The graduation is in cooperation with a facade engineering company Oskomera. The benefit of this is that it allows me to get information and guidance from both the industry and university. The goal of the graduation is to learn more about facades construction, development and planning. Also at the end of the graduation the result should give new insights in the topic and create general knowledge usable by others. I have chosen the subject as I’m interested in optimizations and new production techniques in the façade sector. Also I had done previous research in double curved facades.
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Summary
This research pursues to find a form of standardization in the field of double curved system facades. At the moment the engineering and construction of a double curved façade is time consuming and high in costs. A form of standardization would reduce both and make the façade type more applicable in the ‘regular’ building domain. The methodology of the research is based on research by design. Instead of looking at the numerous possibilities a double curved façade could possibly be constructed, a single design is made based on the outcome of an analysis to the current façade systems and solution.

The research started with a literature study to existing double curved facades. A categorization table was made to categorize the different façade types.

The main research is split into 3 main sections: analysis, design and process analysis.

Analysis
The analysis acts as basis for the design. A façade has to provide basic demand for the user and client regarding user comfort and building protection. Standardized aluminum profiles called mullions and transoms are used to provide a systemic way of constructing a façade system and providing the protection proscribed in the building regulations. In the existing façade systems there are two main concepts to overcome a single rotation: one to take up the rotation in the joints and two take up the rations in the profiles. Option one allows for straight profiles and thus panels, option two has curved profiles and thus bended panels. For the design option one is chosen as it has the best opportunity for standardization, the profiles and panels remain straight allowing regular façade profiles to be used. The geometrical problems of the double rotation are now centered in the nodes. It allows the possibility to use standard façade profiles for the straight sections.

Design
The nodes are based on a single concept, but unique outcome. The design starts with a transformation from an architectural 3d model to an engineering model. This translates the architectural geometry into a wireframe on which the profiles are situated. The alignment of the profiles to the wireframe is very important to make sure they make a flat surface and seal for the panels (in this case double glazing). As this involves a lot of modeling time to generate the geometry for an entire façade, a generative modeling tool is used called grasshopper that can generate geometry based on input parameters and wire flow diagrams. The created wire flow diagram makes it possible to apply a single concept design on numerous nodes all with different input parameters (angles of alignment). The generated nodes are complex to produce. Two main production concepts where explored: single node element and the multi node element. The single node elements consist out of a single one element node that connect to standard system profiles, the multi element node consist out of multiple standard system profiles that are cut into such manner that they fit together exactly to form the desired node. From a comparison the choice was made for the single element node to, although it looks more complex in nature and requires less traditional production techniques it allows for the best precision and easiest manufacturing. The consequence of this choice is that the node itself should be created using rapid prototyping techniques like milling or 3d printing. The costs for milling is depending machine time while for 3d printing it is related to the material use.
3d printing allows larger geometrical freedom, which is why it is chosen for the design. At the moment 3d printing is still more expensive, but the trend is that the price will get lower over time.

From this production model an exploration to the basic demand like strength, insulation and water management was done. There were no hard calculation made, but based on analysis’s some assumption and recommendation could be made:
- For strength and structural integrity one has to watch out how the standard regular façade profiles are used, normally they are checked using the moment of inertia based on forces that act on 2 axis (x,y) in a double curved façade as proposed the forces on the profile could act on any axis in a 360 degree domain of the section.
- For insulation one can argument that the façade performs slightly lower that a regular system façade due to a relative higher percentage of surface area and a slightly larger amounts of profiles used.
- For water management one can use the regular water management system used in standard façade system, still the water has to be drained from the system, therefore around the node the water should be drained with special brackets. This allows only small amounts of water over the nodes and it connection points.

To design and produce the nodes new tools are used: generative modeling saves time and allow for changes based on the input parameters. To produce the models rapid prototyping techniques should be used. This can be 3D printing or milling, where 3d printing allows for better geometrical detailing. Although the price of 3d printing is relatively high at the moment, it is expected to drop in the coming years.

To summarize, the following steps are involved:
- Transform the architectural model to a wireframe
- Design the concept node using generative modeling software
- The influence of structural capabilities on the shape
- Find nodes that exceed limitations and adjust the wireframe
- Make a production model for all nodes
- Make a cam model for all nodes
- Print the models using 3d printing techniques
- Construct the façade on the building side

**Process Analysis**
The proposed design is using new techniques and will alter processes within a company like Oskomera. The task of the engineer in the building processes is extended from the normal engineering task to some involvement in both the geometrical design process and the production of the nodes. The opportunities you can have with these new engineering tools are:
- Repetitive manufacturing for non repetitive elements
- Possibility to price/time savings: using a single concept on a wide variety of elements
- Have a single 3d model for calculation, like structure, insulation etc
- New design techniques: Material efficient design with 3D printing
The possible threads and points to keep in mind with these new engineering tools are:

- 3D print is costly at the moment (but there is a steady decline in price over time)
- Change in the work processes of the engineer and production employer
- 3D printing is a new technique and untested in façade engineering, more research is needed to find limitations and design rules.

For an architect the design concept has certain opportunities, but he also has to take in account some geometrical limitations of the concept. The general concept to standardize double curved façade would be beneficial to architects as it will eventually drop the costs, making the façade applicable on a more ‘regular’ basis rather than only at high budget projects. It will give the architect a new tool to shape the architectural domain into a more fluent space and less constricted by the rectangular shapes. The concept has also some geometrical limits to take in account. The architect has to take in account the relation of the height of the building and the depth of curvature. The higher a building to larger the depth should be to create a visual effect noticeable. Some limitation are derived from the concept design:

- The maximum angle of rotation in the standard profiles ( +/- 20 degrees)
- Limits and deflections defined by structural calculations
- The minimum edge length of a panel ( +/- 1,5 meter)

Conclusive from the research we can argument that it is plausible to design a double curved façade, based on a mesh and standard component. Making it possible to have a production process is in a reparative manner. Still this research is only the start of an exploration to the possibilities in engineering and producing a double curved façade from standard components. It will need a lot of additive research before it could be in anyway taken in real production.
Research Topic
General
Subject and Internship
The façade research group at the University of Delft, consisting out of several tutors and PHD researchers, has multiple contacts with the industry. The University of Delft has lots of information and knowledge to share related to the research in façade technology. But there are always limits in the amount and type of information that can be transferred to the student. Therefore I personally find it interesting and helpful to get in touch with the industry to support my work. It not only adds new information to the topic, they offer also another view of perspective to the subject and can bring problems faced in the field of work.

A list with possible graduations topics was proposed by the companies participating. As a student you are free to choose a topic from this or propose your own, in general there is a broad spectrum to choose from. I was happy to pick several topics of my interest as I preferred to work with the industry. After some visits and some initial reconnaissance I made a choice on the topic. In combination with the Oskomera Group I started a research on ‘Standard principles of Double Curved facades’. My choice is founded on personal interests and my belief that in the future building domain double curved surfaces will play more and more an important role.

The Oskomera Group
Oskomera is a company that is specialized in engineering and producing façades, steel constructions and solar techniques. Oskomera engineers and produces a variety of facades, but their main type is aluminum curtain wall systems. Oskomera is hiring Trainees on a regular basis to extend their own knowledge and transfer their experience to the new ‘generation’ of façade engineers. My graduation research is the collaboration between me, Oskomera and the Technical University of Delft in which the intension is to share information to support this research. The subject of double curved facades is interesting for Oskomera as there is in the current industry the double curved façade is an exceptional facade type. In general it is a façade type on which a lot still can be learned and explored.
Research
Field of research
The research topic ‘Standard principles of Double Curved facades’ is the quest for some sort of standardization in the field of double curved facades. The subject can related to buildings totally encapsulated in a curved façade better known as blob design, but also to buildings with a roof or single façade with this curvature. It is a broad domain, lots of research is already done and some actually build.

Still there is the need by architects to use more and more double curved elements in their building. It can be seen as the ultimate expression and an enlargement of the architects design freedom. Not only architects fancy of using this type of facades, also the public is attracted and fascinated by it. If you look at one of the early adopters of double curved façades, Frank O. Gehry with it Guggenheim Museum in Bilbao, it is seen that the expressional character of the building alone attracted numerous tourist to the therefore unpopular region.

Double curved facades created these days are usually completely designed and engineered for the specific building it is applied to. Almost no standardization is used for this type of façade, which makes sense in some way as the projects are usually very different and complicated in nature. The consequence of this is buildings with double curved are relatively expensive in nature. So there are lots of improvements possible: trying to find a way of standardization could reduce cost, time and might even improve the market penetration of double curved facades.

To create some sort of simplification and standardization in this process it is a good idea to work with a ‘façade system’. A façade system is a collection of standardized elements and connection details, limited by the condition set to the system, that together make up a preset curtain wall façade. These (existing) systems come in different types but will in essence fulfill the initial step of standardization and simplify the engineering process.

Till now the ‘regular’ standard façade systems are not able to cope with double curved facades, but are more suitable for straight and single curved facades. To make double curved surfaces with these systems a new approach is needed.
Aims and objectives
The research is trying to pursue the aim of introducing the double curved facade more into the regular building domain. Till now the development and engineering of a double curved facade is really project based and therefore exclusive and expensive. It is expected that by use of standardized facade systems in design more effective’s methods for engineering and production methods can be found. The objective is to develop a double curved facade system and possibly the tools needed to design a complicated facade with this system. The result gives the architect a new design freedom by adding an extra dimension to the facade and Oskomera an addition to their catalogue.

Design Process
The design process, from architect till assembly, is important in this research as it plays a central role in the development of a new facade system. The choices made in the development stage of the facade system will have a direct influence on the design process. When the outcome of these choices will create a more complicated or time consuming design process, the result can have direct effects on market usage of the system. Therefore this process should be carefully taken in account during the development of a new system and should aim at integration and optimization solutions.

Diagram 1: General design process

The process can be very complicated and has lots of variables included. In a rudimentary way is described as seen in diagram 1. The design process starts with a design given by the architect. For a complex facade that has 3d surfaces it is important to define the design, this is done by transferring it to the computer into geometry. From this point the geometry is analyzed by an engineer to fit the boundary conditions of the facade system and meet requirements like building law and physical load. When all is checked and approved the production of the separate elements can start. For some parts there will be a preassembly depending on the type of system used and when all is ready it can be transported to the building site. Here the elements are assembled by the workers to complete the facade as whole.

Facade System
An ideal situation would be to design a completely new facades system that can cope with double curved surfaces. But as the research has a limited time span another approach is needed. Instead an upgrade of a system currently on the market has a higher potential, as it can be quickly adopted by the market. Looking at the strengths of such a system additional components can be added to make it compatible and optimized for double curved surfaces. The current system can already make a single curvature, so there is much potential.
Research Question
During the start of my research project the research question was intentionally kept a bit broad to leave the possibility for different solutions and ideas. Over time I was able to refine it to its final state.

Main question
How to design a double curved facade using standardized façade components?

Sub questions
- How do regular façade systems take up rotations?
- How to transform a standardized single curved façade to a double curved facade?
- How to integrate the double curved façade into the design process?

Figure 3: Possible system enhancements

Figure 4: Possible design tool output
Methodology

Double curved facades have a broad architectural domain, for my research I therefore a guide to determine my focus point. I was able to do this by making an initial reconnaissance study to the overall current double curved buildings/facades. Looking at case studies in the overall domain different types of solution could be analyzed and explored. The gained knowledge would allow me to set a focus point in agreement with Oskomera and my mentors. From the focus the research was further refined. (Diagram 2)

Diagram 2: initial research setup

The research is divided into three main sections. The first is an initial analysis, followed by a design stage and concluded with a process analysis. (Diagram 3) These sections refer also back to the 3 major sub questions in the last chapter.

Diagram 3: global research process

The analysis acts as a reconnaissance to the subject: how does it work? What are possible manufacturing possibilities? What strategies are already been realized? What to learn from this? Etc. When this is clear a decision can be made to set a starting point for the second stage, the design. This starting point should be documented like a set of boundary conditions to have a method of validation for the rest of the research.
The second design stage is about the development of the façade system given the boundary condition from the analysis. How are the problems like water tightness solved? How will different element work together and what will they look like? This part is all about engineering and there should be a good interacting between the domain of manufacturing and materialization. All are interrelated and can be manipulated by different tools. The end result is a façade system product where all aspect of materialization, materialization and construction are clear. (Diagram 4)

Diagram 4: Engineering diagram [design stage]

The final step is about the integration of the new developed system into the general design (implementation) process, from architect till assembly. How can this façade be build with the engineering and production capabilities of Oskomera? This involves in mapping and analyzing the current processes and tools used at Oskomera. Conclusive from this it might be possible that new tools are needed, when for example new production techniques are used. Another option would be to adapt or optimize current tools if possible. (Diagram 5)

Diagram 5: Process integration diagram [optimization stage]
Tools

The research topic asked for some tools to help me answer the research question. These tools could be related to the supply of information or to get a better understanding in the research material and/or geometries involved. When we think of tools helpful to the research, we can get them from different domains.

For the optimization of geometry, the panel shape and understanding of the system it should be clear that the use of 3D computer graphics is beneficial. For the optimization also parametric design can be used, as this technique offers the possibility to change geometry and produce different study shapes in a short time span. An example of such program could be Rhinoceros in combination with Grasshopper as generative tool. Next to that Rhinoceros can be used as a tool to make preparation model for rapid manufacturing. For building physics and static loads there other software available like iDiana and Trisco.

It is important not to look only at the digital tools. There are a lot of specialists available at the university and Oskomera that can give valuable advice and opinions on the subject. Without them it would not be possible to collect the necessary knowledge to proceed with this research. The specialist can be divided in 4 main groups.

- In first there is TUD Façade Group where I’m guided by Tillmann Klein my first mentor. The Façade Group has specific information regarding façade solutions and innovative ideas.
- Second is Oskomera Group where I’m guided by Rene Blok. Oskomera has lots of information regarding façade engineering, production, manufacturing and general industry knowledge.
- Third is TUD Computation and Performance Group where I’m guided by Rudi Stouffs. The Computation and performance group has specific information regarding computer optimizations, parametric design and general research.
- Fourth is TUD Blob Group guided by Karel Vollers. The Blob group has several members that have lots of knowledge about blob architecture and double curved architectural designs.

Diagram 6: Supporting specialists
1. Analysis
Basics of a façade system

Introduction
The transformation from a flat façade to a double curved façade brings lots of different problems. To find the right solutions for these problems it is wise to take a step back and look at what basic function a façade should actually fulfill and how a façade system actually works. This basic knowledge can be seen as the foundations on which the design can be developed and to tackle complicated problems.

Functions
In essence the function of the face in relation to the building can be described as following:
“It provides the architectural appearance, provides views to the inside and outside, absorbs push and pull forces from wind loads, bears its self-weight as well of that of other building components. The façade allows sunlight to penetrate into the building while usually providing protection from the sun at the same time. It resists the penetration of rainwater and has to handle humidity from within and without. The façade provides insulation against heat, cold and noise and can facilitate energy generation.” These functions are basic demands on what a façade should do and behave like. It is important to take these in account during the design and research process.

Figure 5: Overview of the basic façade functions

Sources:
(Knaack, et al., 2007) Blz 36
Components

A façade is buildup with distinctive components, they are linked together by an interface which bonds them together so they act in union. Façades can be categorized in groups with different component layout. In general one can speak of one leading group in façade construction: the metal glass façade. The buildup principle (Figure 6) of a metal glass façade can be defined in 3 areas:

- The primary structure (shell of building) forming the main load bearing structure of the building.
- Secondary structure, which is the load bearing structure for the façade and constitutes the connecting element between levels one and three.
- Infill elements.

The primary purpose of this assembly lies in the separation of the functional requirements that the façade needs to fulfill. The layout simplifies the connection of individual façade components and provides options to compensate for moving parts and tolerances. For the double curved façade this allows a breakdown of the complexity in multiple smaller problems. Still when too much layers are applied it will come at the cost of visibility and user comfort so an optimum has to be found.

![Figure 6: Basic metal glass facade layout](image)

The principle described above can be seen as main principle. There are of course others, for example a façade constructions where the primary and secondary structures form one component. The secondary structure is then part of the load bearing structure of the building. Although not very common, when used it is important to closely examine this version. Tolerances, deflection and building physics can be critical as there are fewer places to overcome these.

Sources:
(Knaack, et al., 2007) Blz 37
**Loads and construction**

A façade has to cope with a variety of loads. These loads are related to different conditions and usages. Usually they do not occur not all at once, but in the design stage they should all be taken in account. In general the loads can be separated into 5 groups:

- Self-weight
- Weight of snow and water
- Wind load (push and pull)
- Live loads (person colliding with inside of the façade)
- Stress loads (component deflection due to temperature or humidity)

The make a constructively stable façade the loads need to be guided back to the main construction and foundation. For the regular glazed façade the main dead loads act downwards, parallel to the façade. This is contradictory to the wind loads and other dynamic loads, which act horizontally on the façade. Both horizontal loads and vertical loads need to be taken from the infill component to the secondary component layer. From here it can be taken to the main construction and foundation. There are many ways how to guide the forces downwards as this can be subjective to not only restrictive parameters but also the esthetical view. Some example how the secondary structure and infill panels can be organized is seen in Figure 7:

![Figure 7: Structural organization examples](image)

**Sources:**
(Knaack, et al., 2007) Blz 38
**Systems**

Nowadays almost all buildings use systemized facades. This means that specific parts of the structure are standard components provided by façade suppliers. The necessity for systemizing the facades becomes clear when looked at the high demands of building performance today, making the façade a rather complex building component. In addition to ease the design, systemized solutions offer a clear and controllable process from the design stage till assembly. The system have to fulfill building law and therefore are pretested for resistance to wind-driven rain, thermal insulation, air permeability, sound insulation, fire and building safety.

Within the array of façade systems two main types can be distinguished, the ‘post and beam’ system and the ‘unitized’ system:

The *post and beam* façade has a base structural element consisting out of sections made out of timber, steel or aluminum. The sealing system on the interior is mounted onto this structure. Next would be the layer of the infill elements, these can be glass panes, windows or doors. An interface of for example rubber moldings around the infill panels guarantee the water and air tightness of the connections. The post and beam façade is constructed on site by building up the individual elements.

The *unitized façade* is different compared to the post and beam structure as it is made out of highly prefabricated façade elements that makeup units. This gives and advantages as most of the construction can be in factory without outside weather conditions. The units in itself usually are a storey high and already provide in most of the facades function. A disadvantage can be that the units need to have an all around sealant which will result in double -splice profiles increasing the visibility of the connection.

Sources:

(Knaack, et al., 2007) Blz 39-40
Building law

According to the Dutch building law and European standards a façade has to fulfill a set a criteria to fulfill safe use of the building. During the design process these requirements should be taken in account, but it could be possible that there is no time or priority to make the official calculations and checks. It is good to keep them in mind

Constructive:
- Deflection:
  The construction should not have too much deformation
  \[ w_c < w_r \text{ mm} \]
- Strength:
  The construction has to be safe under extreme loading
  \[ W_c < W_r \text{ mm}^3 \]
- Stiffness:
  The construction has to be functional under normal loading
  \[ l_c < l_r \text{ mm}^4 \]

Building physical:
- Thermal insulation:
  The façade should be thermal insulated with a minimum of cold bridges
  \[ U_c < U_r \text{ W/(m}^2\text{·K)} \]
- Sound insulation:
  Inside -> outside
  Outside - > Inside
- Light admittance:
  Minimal Daylight
  Overheating
- Air tightness:
  The façade should be airtight, to prevent energy loss, moisture problems and user discomfort
- Water tightness:
  There should be water accumulation inside façade and a proper water management should be applied to drain the water

Safety:
- Injury protection
- Burglar protection
- Escape prevention (optional)
- Explosion protection (optional)
Influence of a curvature

Introduction

As we have seen in the first chapter the current curtain walling systems are generally build in two types: the post and beam system and the unitized system. These systems are a way to standardize the façade simplifying the design process, control quality and reduce costs. The systems are built out of straight post/beam elements and flat panels. A major part in the success of the systems is the way they are repetitive. Not only in macro level but also on the element level. This makes extrusion extremely suitable as main production technique.

This all applies to flat facades, when a curvature is added the façade will get more complicated. In essence a curved façade should follow a curved line setup by the architect in horizontal or vertical direction. This curvature requires an adaption of the façade system as these are only made out of straight elements.

Curvature

A curvature in the façade means that there is a rotation in the plane of the façade that has to be taken by the façade system. In general one can say that a rotation can be solved in the connections leaving the elements straight or by bending the elements so that the connections stay perpendicular. When the rotation is taken up in the connections it will leave little adaptation to the rest of the façade and it can be easily transformed from the flat state. Bending the elements will have more influence, in particular in production techniques. Regular extrusion techniques will not be sufficient to produce the curvature making extra production steps necessary; also controlling the degree of deferment in the paneling is hard to control.

The choice will also have an effect on the appearance of the façade. When using curved elements in the structure the façade will follow the direct line setup by the architect. When using straight elements it will only be an approximation of that curvature. This approximation is acquired by segmentation of straight elements; it should mimic the original curvature. It should be closely watched that the original cure is not lost in the segmentation process. A balance has to be found to trick the human eye; making it believing the shape is round well in fact it is based out of straight elements. When the amount of segmentation is increased it will have a better approximation of the curvature and it becomes less obvious that straight elements are used. (Figure 10)

![Figure 10: Segment a curve in straight elements](image)

Sources:
(Pottmann, et al., 2007) Blz 226
System solutions
Solution to overcome the problem of rotation are different for the post and beam system and unitized system as they are different in general setup. Still both systems tackle the problem in similar fashion.

There are two ways of solving this in a post and beam system:
1. Take up the rotation in the joints (connections)
2. Take up the rotation in the elements (post/beam)

Figure 11: Take up rotation in post and beam system
For a unitized façade the solution are as following:

1. Take up the rotation in the joints between the units
2. Take up the rotation in the units: Connections
3. Take up the rotation in the units: Post/beams

Figure 12: Take up rotation in unitized system
Reference Projects

Introduction

As there is large variety in solutions to design and produce a double curved surface, it can be beneficial to look at several example projects. The benefit of analyzing and gathering these case studies is creating a knowledge base on which several problems and solution are explored.

To maintain an overview of the wide variety of case study projects with a double curved façade I made a category map to categories them to their different characteristics. These categories are setup to refer to different façade and building properties. An example is a general material or a fixation method. Using these categories makes it easier to identify a case study project, but more important gives it a degree of relation with the research project. If there are problems faced in the research it can now easily be compared to similar case study projects.

Categories

There are numerous characteristics that can be used to categorize a façade or building. From analysis of the different case studies a collection of categories and properties is produced. From this a selection is made to make an indexation. This selection consist out of the 6 most important façade related characteristics 3 more are added to cover the general building properties. It is important to have these last 3 more general characteristics as the façade has an inextricably relation to the overall building.

The main categories used to are: material, mesh, panels, watertight, fixing, construction, function, building type and orientation. Each of these categories has a set of properties that together form the category domain. Table 1 and table 2 show an overview map of the generated categories and properties. In essence every case study project is bound to at least one property per category.
### Category Map

#### Façade Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Glass</th>
<th>Polymer</th>
<th>Ceramics</th>
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**Table 1:** Category map: façade properties

#### Building Properties

<table>
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<td>Roof</td>
<td>Facade</td>
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</table>

**Table 2:** Category map: building properties
Projects

Project name: **Cable Railway Station**
Architect: Zaha Hadid Architects
Location: Innsbruck
Completion: 2007

Properties:
- **Material**: Glass
- **Mesh**: Quadrangle
- **Panels**: Curved
- **Watertight**: None
- **Fixing**: Adhesives
- **Construction**: Separated [aligned]

Function: Public
Building type: Low Rise
Orientation: Roof & facade

Description:
The construction of the cable station is built up from steel ribs of 8 and 12mm thickness and follows the lines on the surface. The panels are made of glass with a resin on the backside that provides the ‘milky’ color and break failure safety. The glass panels have a standard width of 1.25 meter with a variable length; this is due to massive snow loads of up to 300 kg/m² that have to be taken into account. The glass is hot pressed in a mold where a laser scanner checks if the deviations are within the limits. The panels are fixed with adhesives to polyurethane profiles that are bolted to the steel frame. Using polyurethane profiles made it possible to work with a smaller deviation factor.

Photos:
Details:

1. Rendering Deschaufler Station Hungerburg, Aufhellung der Glasfassaden
2. bemalte Stehhäppchen-Dachscheibwerk
3. Stahlfachwerk mit aufgeschraubten PE-Profilen zur Glasfassung
4. Freischneid-PE-Profil, computergenerierte Anordnung der Segmente auf eine Fläche
5. Optimierung der Glashämmertechnik durch variable Verankerung von pulverisierten Ödolins bis zur Halterung mit Edelstahlblech und PE-Profil

1. Rendering of Hungerburg station roof shell, division of glazed elements
2. Isometric of steel-rib roof structure
3. Steel ribs with polythene sections bolted on for fixing glass
4. Cutting diagram for polythene sections: computer-generated layout of segments on a panel
5. Optimization of glass design: progressive simplification from adjustable hinged mounting to standard stainless-steel fixing with polythene section

Sources:

(Detail, 2007) blz 1458-1463 (Urbarama.com)
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</table>
Project name: **Kunsthaus Graz**
Architect: Peter Cook / Colin Fournier
Location: Graz
Completion: 2003
Properties:

- **Material**: Plastic
- **Mesh**: Quadrangle
- **Panels**: Curved
- **Watertight**: Second layer
- **Fixing**: Mechanical [spider]
- **Construction**: Separated [aligned]

Function: Public
Building type: Mid Rise
Orientation: Roof & Facade

Description:
The construction of is made out of a steel grid framework resting on concrete pillars. The steel is encapsulated with grey insulation foil where on top the acrylic panels are placed using a spider system. Each of the 1500 3D panels are individually shaped and fitted with a light to create a media facade.

Photos:
Exploded view:

Sources:
(Detail, 2003) blz 1252-1253  
(Flickr)  
(Schmal., 2004) blz 87
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</table>
Project name: Blob Eindhoven
Architect: Massimiliano Fuksas
Location: Eindhoven
Completion: 2010
Properties:
- **Material**: Glass
- **Mesh**: Triangle
- **Panels**: Flat
- **Watertight**: Silicon
- **Fixing**: Mechanical [profile]
- **Construction**: Integrated

Function: Public
Building type: Mid Rise
Orientation: Roof & Facade

Description:
The facade on the Eindhoven blob is self-supporting from the foundation and made out of steel trusses. Wind forces are directed to the concrete floors by steel bars. The geometry is developed by using a mesh of interlocking triangles. On these triangles rubber strip are placed where the glass is resting on. The joints are then sealed with silicon and fitted with fixing cabs to hold the glass in place. It is a mechanical fix.

Photos:
Principle details:

Sources:
(BouwiQ, 2010) blz 8-13  
(Bouwwereld, 2010)  
(Flickr)  
(Geveltechniek)
### Façade Properties

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</table>
**Project name:** BMW Welt  
**Architect:** Coop Himmelb(l)au  
**Location:** Munchen  
**Completion:** 2007  

**Properties:**  
- Material: Glass  
- Mesh: Triangle  
- Panels: Flat  
- Watertight: Silicon  
- Fixing: Mechanical [profile]  
- Construction: Integrated  

**Description:**  
Condensation, the associated moisture damage and unsatisfactory internal climates are common problems facing large steel-and-glass structures, and are normally counteracted by the application of floor-level convectors, facade radiators or high strength ventilation systems. A more architecturally appealing solution is that of providing heating directly at the facade level, by the use of temperature controlled fluids within the steel facade elements: the integrated facade. The advantages of such a system, where the heating system is more or less invisible, are not restricted to the purely aesthetic. In particularly complex spatial situations, sections of the facade which are in “wind shadows” may not be sufficiently heated by conventional convection heating systems. An integrated facade heating system combats the situation where it occurs. The most well known building of the day using this form of technology is the BMW World in Munich, the steel and glass facade of which is illustrated and discussed in detail.

**Photos:**

[Image of BMW Welt facade]
Sources:
(Compfight)
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</table>
**Project name:** Noise Wall and Car Showroom

**Architect:** ONL Oosterhuis lenard

**Location:** Utrecht

**Completion:** 2007

**Properties:**
- Material: Glass
- Mesh: Triangle
- Panels: Flat
- Watertight: Rubber strips
- Fixing: Mechanical [profile]
- Construction: Separated [aligned]

**Function:** Commercial

**Building type:** Mid Rise

**Orientation:** Roof & Facade

**Description:**

This luxury car showroom is integrated into a 1.5-km long noise wall separating an industrial district from the A2 motorway near Utrecht. Motorists driving past at 120 km/h can catch a glimpse of the 5,000 m² display space inside through its all-glass front. The automotive theme is also exploited in the dynamic lines of the building. To keep the number of foundation piles down to a minimum, the architects developed a space frame spanning 9 m from pile to pile. The money saved was then spent on the visible upper parts of the building. The steel profiles of the space frame were fitted with overlapping panes of toughened glass sealed with hard rubber profiles, an arrangement which accommodates any temperature-related changes in the support frame. Where the noise wall develops into the showroom, the individual panes gradually double in size towards the centre. The facade of this main section, with its diagonal frame, is thermally separated and double-glazed. Unusually the 42-mm thick double glazing units are fitted directly to the supporting steel frame. This is only possible because the frame here is very stiff and displays virtually no deformation. From the base of the building up to the 133-m long ridge, the glass has a solar coating, increasing in performance towards the ridge. In strong contrast to this glass front is the rear of the building, clad almost entirely in sheet metal.

**Photos:**
Details:

Sources:
(Detail, 2007) (oosterhuis.nl)
## Façade Properties

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</table>
Holiday House

Architect: 24H-architecture
Location: Övre Gla
Completion: 2004

Properties:

- Material: Wood
- Mesh: None
- Panels: Flat
- Watertight: Overlap
- Fixing: Mechanical
- Function: Private
- Building type: Low Rise
- Orientation: Roof & Facade
- Construction: Integrated

Description:

The house is located on the shores of a Swedish lake in a nature reserve. The only new buildings allowed in this area are extensions to existing structures. In the present scheme, an unconventional method of construction was used, in the form of a room that can be extended telescopically out of its basic “cocoon” in summer in little more than 20 seconds. Templates were supplied by the architects for the prefabrication of the curved load-bearing plywood structure. After a period of weathering, the red-cedar shingle cladding acquires the color of the grey granite rock of the surroundings. The few glazed areas in the facade were located so as to avoid reflections that would be visible from the lake.
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</table>
Project name: Walt Disney Concert Hall
Architect: Frank O. Gehry
Location: Los Angeles
Completion: 2003
Properties:

- **Material:** Steel (stainless)
- **Mesh:** None
- **Panels:** Curved
- **Watertight:** Overlap
- **Fixing:** Mechanical
- **Construction:** Separated[Aligned]

**Function:** Public/Commercial
**Building type:** Mid Rise
**Orientation:** Facade

Description:

Designed by architect Frank Gehry, Walt Disney Concert Hall, new home of the Los Angeles Philharmonic, is designed to be one of the most acoustically sophisticated concert halls in the world, providing both visual and aural intimacy for an unparalleled musical experience. Through the vision and generosity of Lillian Disney, the Disney family, and many other individual and corporate donors, the city will enjoy one of the finest concert halls in the world, as well as an internationally recognized architectural landmark. From the stainless steel curves of its striking exterior to the state-of-the-art acoustics of the hardwood-paneled main auditorium, the 3.6-acre complex embodies the unique energy and creative spirit of the city of Los Angeles and its orchestra.

Photos:
### Façade Properties

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### Building Properties

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**Project name:** Multi Tenant building  
**Architect:** Paul de Ruiter  
**Location:** Schiphol  
**Completion:** 2010

**Properties:**
- **Material:** Glass  
- **Mesh:** None/Solid  
- **Panels:** Flat  
- **Watertight:** Rubber Strips  
- **Fixing:** Mechanical [Profile]  
- **Construction:** Integrated  
- **Function:** Offices  
- **Building type:** Mid Rise  
- **Orientation:** Facade

**Description:**
The facade of the Multi Tenant building is engineered and produced by Oskomera. The photos you see are from their personal photo archive. In this case they have used a traditional post/beam curtain walling system, but with special additives like the sun shading profiles. The windows are just a flat surface where the rotation of the façade is taken at the joint of the profile.

*Figure 13: Multi Tenant – Paul de Ruiter, Schiphol*

**Sources:**
(Oskomera, 2010)
### Façade Properties

<table>
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<tr>
<th>Material</th>
<th>Glass</th>
<th>Polymer</th>
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<td>Roof &amp; facade</td>
<td>Roof</td>
<td>Facade</td>
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</table>
Project name: Jinso Paviljon  
Architect: Cepezed  
Location: Amsterdam  
Completion: 2009  
Properties:  

- Material: Glass
- Mesh: Quadrangle
- Panels: Curved
- Watertight: Rubber Strips
- Fixing: Mechanical [Profile]
- Construction: Integrated

Function: Public  
Building type: Low Rise  
Orientation: Facade

Description:

This is a special project in Amsterdam where also a post/beam system is used. The rotation is not taken in the joints, but the actual profiles and glass is curved. For this project the glass manufacturer designed a special installation mechanism to cold bend the glass in place, fixating it on the pre-curved façade profiles. Glass can be curved in a cold state if the curvature is relatively small.

Figure 14: Jinso Paviljon – Cepezed, Amsterdam 2009

Sources:
(Bouwwereld) (Steelconstruct)
### Façade Properties

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<tr>
<th>Material</th>
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Project name: Altitude 25
Architect: Devereux Architects
Location: London
Completion: 2007

Properties:
- Material: Glass
- Function: Private
- Mesh: None
- Building type: High Rise
- Panels: Flat
- Orientation: Facade
- Watertight: Rubber Strips
- Fixing: Mechanical [Unitized]
- Construction: Integrated

Description:
This project is a project in Dubai, where large unitized curved elements are used. This type is not seen that often as it is a very complex solution. Every unit is unique and the engineer has to make sure the unit fits perfectly, within a small tolerance, with the other units.

Figure 15: Altitude 25 – Devereux Architects, London 2007
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Sources:  
(Oskomera, 2010)
Project name: **Capital Gate tower**
Architect: RMJM Architects
Location: Abu Dhabi
Completion: Expected 2011

**Properties:**
- **Material:** Glass
- **Mesh:** Triangle
- **Panels:** Flat
- **Watertight:** Rubber Strips
- **Fixing:** Mechanical [Unitized]
- **Construction:** Integrated
- **Function:** Private / Commercial
- **Building type:** High Rise
- **Orientation:** Facade

**Description:**
This project is a project in Dubai, where large unitized curved elements are used. This type is not seen that often as it is a very complex solution. Every unit is unique and the engineer has to make sure the unit fits perfectly, within a small tolerance, with the other units.

*Figure 16: Capital Gate tower – RMJM Architects, Abu Dhabi*
### Façade Properties

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<tr>
<th>Material</th>
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### Building Properties

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Sources:
(Designboom)
Single curved to double curved

Introduction

A double curved façade would be a single curved façade with an addition of another curvature. In comparison a flat façade has 0 axes of rotation, a single curved façade has 1 axes of rotation and a double curved façade has 2 axes of rotation. (Figure 17) The addition of the extra rotation axis gives a possibility for architects to design more dynamic and fluent facades.

![Figure 17: Flat, single curved and double curved façade](image)

Typologies

The double curved a façade cannot be seen as a single typology, there are actually two intermediate types between a single curved façade and a freely double curved façade. These two intermediate types have in technically terms a double curved surface, having a two axes rotation on the surface, but in practice follow a predictable geometrical shape. This because they are based on a single curved façade added by an additional geometrical translation. This translation can be seen as a movement or rotation of one outer side in relation to the opposite side, for example top and bottom.

The first intermediate type would that be of an ‘inclined’ façade. An inclined façade is based on a single curvature where one side is translated sideways parallel to the façade.

The second intermediate type would that be of the ‘twisted’ façade. The twisted façade starts also with a single curvature but in this case one side is rotated making 2 corner points move in opposite direction perpendicular to the façade. A combination of the two types is also possible. The difference with a truly freeform façade is that the inclined and twisted façade have a predictable geometrical shape, consisting out of more repetitive elements, making design and production easier. A freely double curved façade follows in general not a regular geometrical shape like an inclination or a single twisted surface. It consists out of a more complex composition of regular and irregular shapes, translations and forms. (Figure 18)

Sources:
(Vollers, 2001) blz 34 (Wikipedia)
Free form architecture
A double curved façade techniques makes it possible to design freeform architecture also called ‘blob’ architecture. Blob architecture can be seen as a movement in architecture in which buildings have an organic, curved-shaped, bulging form. Not only is the shape different also the buildings are generally very spacious: the space is modeled first followed by the material. It is in contradiction to the more traditional buildings where the building follows out of standard elements and the construction. The origin can be found in the developments in new computer and façade technologies, these are the building blocks from which this movement has been erected. The name ‘blob’ is also derived from the computer world, it stands for ‘binary large object’, or in normal terms a large collection of digital data.

![Figure 18: Single curved, inclined twisted and freely double curved facade](image)

Blobs are in definition freeform architecture, but freeform architecture should not directly mean blob designs. Freeform architecture has a wider definition, but is not very defined. A square building with a big double curved façade or roof can be seen as freeform architecture, as well as a free spanning twisted roof. It is the relation between the parts of the building that have de deformation in comparison to the more typical building appearance that makes the difference. In general if the double curved or twisted surfaces give a building its main character it can be called freeform architecture.
Freeform architecture stretches the boundaries of the meaning façade. Usually a large part of the building is enclosed in the façade, creating a uniform and amorphous shape. In this case the façade does not only act as façade anymore but blends over to a roof. This adds complexity to the case as a roof has to fulfill in general a different set of demands then a façade. For example water can collect on a roof, but also on a free form façade, appropriate measures needs to be taken to prevent water entering the building. It also has to withstand a different set of loads as snow can collect on top of it. Adding more complicity the architect in general wants to give the freeform façade a uniform appearance, it is important to look at all aspects to make a good design.

*Figure 20: Fading between roof and façade in freeform architecture*

Sources:
10. (Schilperoort, 2010)
Mesh
The mesh of the double curved façade plays an important role in the construction and appearance of the building. A mesh is an approximation of an intended shape by points and lines and is generally used in computer models to mimic a shape or structure. One of the early known meshes used for both architecture and construction is from Antoni Gaudi (1852-1926). He made a chain mesh to gain insight in the optimal structural lines for the cathedral ‘Sagrada Familia’ in Barcelona.

A mesh is by definition a collection of points and connecting lines arranged into a basic shape that forms geometrical faces. The intersecting edges of the faces connect together to form a grid like approximation of the shape. In architecture the edges are usually described by building construction like metal post or beams. The faces represent usually infill panels like glass or plate material.

There are different types of meshes; all are distinguishable by the geometrical shape the faces make. The faces can for example describe a quadrangle, a triangle or a hexagon. Although the last one is less common each has its own advantages and disadvantages. Meshes are used in 3d drawing programs to mimic the shape of (double) curved surfaces with flat (planar) faces and come in lots of different types.

The current way of building double curved facades is using triangle shape elements. Examples can be found in a lot of structures like the Fiera Milano complex of Massimiliano Fuksas or the Great Court at the British Museum from Norman Foster. All can be reduced to a triangle like shape. What is the reason behind the triangle? There are several explanations for it. The first is shape and form. The main point is that with current production methods it is really hard and expensive to make actually double curved surfaces. Single curved surfaces in glass, metal and wood are seen more regularly, but for double curved surfaces it gets difficult. Metal for example can be formed in 3d shapes with the use explosion techniques where a plate is pressed into a mould due to the fore of the explosion.
Glass can actually be bended a little in cold state with some pressure and there are several more of these techniques. All is still development, and there is no definitive answer what can be used best.

With the need of architects to make more and more transparent facades, glass becomes an important material to work with. The current solution to prevent the curvature of materials is to use straight elements and divide it in segments. It is an approximation of the curvature, but in overall it looks like it is a continuous surface. There are several shapes that can be used to mimic the curvature depending on the angle and size, but the shape most optimized is the triangle. This is also related to the construction.

One of the first architectural projects that had double curved surfaces was the Guggenheim museum in Bilbao by Frank O. Gehry. It had actually a straight post and beam steel frame behind the outer surface. You can’t see it as the cladding is hiding it, but would you replace the cladding with glass it would reveal the massive structure. In glass curtain walling systems it is therefore common to the have the construction integrate and make the system thin to optimize transparency.

Architects usually prefer a facade system as lean as possible, so that construction and cladding really are merging into one as seen in the example of Foster and Fuksas. The advantage of the triangle in a system like this is that the shape of a triangle is already structural stable. In essence you wouldn’t need extra reinforcements as the 3 sides of a triangle make a rigid frame. Depending on the need there are also possibilities the even further enhance the rigidity by fixing the glass in such a way that it can act as stiffing plate fixing the 3 sides of a triangle.

Sources:
10. (Schilperoort, 2010)
2. Design

Introduction
The previous chapters have shown the basics of a façade system and the complexity a curvature can add to a façade system. The knowledge collected can now be transformed into a design assignment. There are different ways in which the design assignment can be routed. One idea is that of global reconnaissance. By developing a lot of different concept designs, one creates an orientation in the subjected and will have a better basis on which a good design concept can be chosen. Still the outcome of this would be very vague/global and hard to validate without any real deeper research results. Considering the limited time span I have chosen a different approach. I want to use the already collected knowledge in this analysis and experience of Oskomera to develop a single design concept and work it out in detail. The results and conclusions collected during this design process would make a usable advice on possible further research, adaptations needed on the concept and which production techniques are usable and which not.

An ideal situation would be to start a design for a double curved façade completely from scratch. But considering the time span and technology already available at Oskomera, I defined the topic to base the design on existing elements. Starting off with a system currently on the market has a higher potential, the initial building regulation is already fulfilled by the system and there is always a possibility for change. By looking at the strengths of such a system additional components can be added to make it compatible and optimized for double curved surfaces. Important is to choose a system that can already make a variety of single curvatures as this makes the transformation to a double curvature easier.
Demands
The idea of this chapter is to setup the design rules on which a design can be based. It is a way to restrict the topic and give a possible base for discussion. The idea is that the concept design should give an answer and more insights in the double curved façade systems.

Building
When designing a façade it is always good to look at the larger picture, the building. The building determines a lot of the general aspects of a façade. How should it look like? What typical function should it fulfill? Where are the structural connection points? Etc.

//Function
Important is to make a decision what function the building should be designed for. A distinction is made between three main building functions: office use, public use and residential use. There is an important difference between these functions regarding to building regulations like building safety, energy performance, fire prevention etc as seen in chapter 1. An example is given in table 5.1 where a comparison is given for the energy performance coefficient (E.P.C.) of Dutch building law. A lower number stands for higher the demands regarding energy saving.

<p>| | |</p>
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<td>Public</td>
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*Table 5.1: EPC of different building types*

One can argument a basis for the choice of selecting the right building function can be made by choosing the function type with the most restrictive building regulation. If necessary it could be fitted to any other function type as they would have less strict regulation. Unfortunately this distinction cannot be made that clearly. For example residential buildings have by Dutch law stricter regulations regarding energy performance if compared to offices. But when looked to a topic of fire safety offices have more strict regulations compared to residential buildings. So there is no conclusive ‘best’ choice as in general one can say that by Dutch law residential buildings and office have high standards. A decision can be made by looking at the current use of façade systems. In the Netherlands residential buildings are still usually build using traditional building methods using brick and concrete. Where public buildings are usually a mix, office building stand out where a large percentage uses a facade system. Conclusive form this, the choice is made to focus on the offices as main building type.

//Construction Material
There is a wide spread of materials that can serve as main material for a buildings construction. Still one can distinguish 2 main materials: Concrete and steel. As our façade should be connected to the construction it is important to determine the main construction material as this will influence detailing. The use of steel and concrete construction differs. In the USA there is a tradition to build steel construction where in Europe in general concrete is used more often. Still a façade is usually connected to the construction on the floor level. As floors are most commonly made out of concrete I will use concrete as main building construction material.

Sources:
11. (VROM) Afd 5.3, Art 5.11

//Floor height

As the facade is in general constructively connected at floor level, see also chapter 1, it is important to determine the floor height to be used in the design stage. I’m using an office as reference building so a logical step to make would be to use the regular floor height used in office. As the regular floor height for offices most commonly corresponds to the minimal floor height stated in the building degree we take it as the standard. For an office building the current minimal floor height for buildings is 2,6 meter, adding floor construction and ceiling systems makes it general 3,5 meters. Conclusive to this a floor height of 3,5 meters will be used for the design.

//Type

There are 3 main building types of building regarding the height. Low-rise is between 3 and 12 meters (1-4 floors), mid-rise is between 12 and 24 meters (5-8 floors) and high-rise is 24 meters and above (9 floors and above). As the double curved façade should have some relation with the extension of the façade outwards/inwards it is best to choose a midrise building type, this is also a common type in the current office buildings.

Sources:
**Facade**
Adding some design restrictions to the façade in general is important. There will be demands to façade generated by building law or chosen in the previous paragraph. But to focus the design some extra restrictions are necessary to push it in the right direction. All is not fixed, but give an initial guideline for the concept.

**Material**
There are numerous type of material that can be used for the façade elements. It could be aluminum, steel, wood, you name it as it has the right properties it can be used. Still the building regulation prescribes there should be a minimal type of transparency in the façade for an office building. Therefore automatically glass comes in the picture. Glass is also one of the hardest materials to use as infill panels as it is pretty have in nature and also needs good sealant against moisture and water vapor. In general speaking if a façade can be fitted with glass panels, almost any panel will fit in to replace it. The concept design should therefore be fitted with glass infill panels.

**Façade Type**
As shown in chapter 1 there are different façade types. Most commonly used is the single skin façade. Another possibility would be double skin façade. With a double skin only the outer skin could have the double curvature and there rest could be plain normal, also the outer skin should not necessary be thermal insulated. Therefore it is much more interesting to work with a single skin façade. There are a lot more problems to overcome, but it makes it much more interesting. Also a single skin façade is in general cheaper as only one skin is applied. A single skin curtain wall system is therefore used for the design. Next to that to reduce complexity, there will initially be no use of unitized elements.

**Panels**
As discussed before there are several ways of creating a double curved façade. In chapter 3 we can see 2 options for regular system solutions. Take up the rotation in the beams or take up the rotation in the joints. The consequence of taking up the rotation in the beams would mean also a curvature in the panels; this will actually result in a double curved panel. This adds extra complicity to production methods. Working with flat panels is possible by fluent segmentations and bring the rotation problems back to one point, the knots. Therefore the flat panels should be used in the design.

**Construction**
I will be working with a regular office building structure with floor heights of 3.5 meter. This span is normally overcome with façade system and therefore need no extra structure for support. The façade should just carry its own weight and wind forces.

**Orientation**
It is seen that there is a problem with double curved facades for the case that the façade blend over to roof and backward. There is no clear distinction anymore. As this created extra problems it is important to take this into account in the design and therefore the reference building used should have in some form a double curved surface that faces the same problems.
The type choice of system is really important. There are lots of different existing systems on the market and all have their specific advantages and disadvantages. As discussed before the idea is to use partially an existing system and modify it to a double curved system. The beams of the existing system are used to cope with most of the demands so the focus is at the connecting knots, where all problems meet. It is possible to make a double curved surface with the profile of a single curved façade system because the double curvature is solved in the connecting knots. The profiles only have to handle a single curvature as you can see in Figure 24. The goal is to create a fully glazed façade by adapting a standard curtain wall system with double glazing.

![Figure 24: Example of rotations in the system](image)

Most system manufactures have a system that can cope with some degree of rotation. This rotation creates a single curvature in the façade and is usually taken up by the rubber sealant. As these rubbers also provide sealing against water the rotation is often limited. Creating larger rotation in the façade requires specialized elements. (Figure 25) One should make a difference here in rotation towards the façade and a rotation away from the façade as the parts will differ.

![Figure 25: Possible system enhancements](image)
To prevent the use of too much specialized parts and a lot of different connections a preference would be to use the regular profiles. The downside of this is that the rotation with these profiles is limited, making it a contradiction to the need of large rotation angles to supply flexibility to the system. To get a better understanding of the different angles possible with these systems I have done a small research seen in table 5.2

<table>
<thead>
<tr>
<th>Supplier</th>
<th>System</th>
<th>Rotation inwards</th>
<th>Rotation outwards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynaers</td>
<td>CW50</td>
<td>20°</td>
<td>30°</td>
</tr>
<tr>
<td>Reynaers</td>
<td>CW60</td>
<td>15°</td>
<td>15°</td>
</tr>
<tr>
<td>TKI</td>
<td>252</td>
<td>15°</td>
<td>15°</td>
</tr>
<tr>
<td>Schueco</td>
<td>FW50</td>
<td>20°</td>
<td>20°</td>
</tr>
<tr>
<td>Schueco</td>
<td>FW60</td>
<td>20°</td>
<td>20°</td>
</tr>
</tbody>
</table>

*Table 5.2: Max angle of rotation with regular system components for different suppliers*

Conclusive from this table one can argument that Reynaers CW50 system profiles are the best option to choose at the moment as they provide the largest rotation of 30 degrees. Using aluminum standard façade elements in other ways as designed will have effect on structural integrity of the profiles and is should be closely monitored and checked in the design stage.

**Mesh**

//Minimum Size
The mesh openings should have a minimum size to allow transparency and light in the building. Small mesh sizes will create a lot of profile and construction material blocking the light and lowering user comfort.

//Maximum size
The mesh openings should have a maximum size to allow the mesh to mimic the curvature. Large panels would not follow a curvature smoothly which will prevent the use to see the optimal shape. It also creates other problems like as fire regulations are present in between floors.

//Maximum angle
There is a maximum angle between the profile and the panels set by the system supplier.
Geometry

Introduction
When designing the geometry of a double curved façade systems there are several geometrical design problems to face. A reduction is already made by the choices in the program of demands. An example of that would be the choice to take up the double curved rotation in the nodes, resulting in flat segments. The geometry outline of a double curved façade/building is usually given in a 3d model containing the information of the basic geometry. So it is important to understand and translate this information to an actual design. How to interpret this architect’s model as an engineer and make sure it fulfills all demands given. This in relation to statics, insulation and building degree so that it the architects idea can be transformed into a model/drawings ready for production.

Architects Model
The data received from the architect will always be different for every architectural bureau. For a double curved façade the most common way off delivering the geometry data is by use of a 3D model. This 3D model will at minimum supply a geometry that describes the contours of the façade.

In technical terms there are 2 general ways how this geometry can be delivered:
1 Using a Surface
2 Using a Wireframe

Architect’s tents to have mostly surface models as these are used to generated/render the concept pictures and give an easy to understand picture for the client. The façade engineer will need a wireframe model to position to location of the façade transoms and mullions. Therefore a wireframe needs to be created from the surface model in cooperation with the architect.

As a notation to the computer models you should know there are multiple types of surfaces in 3D computer modeling. The 2 most used are a NURBS surface and polygon surface. Both use a different technique to describe a surface in a 3D environment. There are multiple technical differences between to two, but the most important one is that a NURB surface is build up out of a mathematical model, while a Polygon surface is only an estimation of the curvature using flat segments. The preference to use would be the NURB surface as this describes the curvature more accurate than a polygon surface.

Sources:
12. (Wikipedia)
**Engineer model**

Compared with an architectural 3D model the engineer’s model is very different, this difference becomes clear when you look at the goal the architect/engineer wants to achieve. The architect mainly focuses on the visualization part. He wants to pursue the client in selling the building with nice images. He also needs to communicate his ideas to the engineer that will make the technical drawings and calculation. (In this case façade drawings) So the model will usually contain some technical outline. In common terms the architects has a more visual approach to modeling. He has no need to put in all the hidden elements of you don’t see it in a rendering.

The use of an engineering model is therefore not to make nice pictures or renderings, but to make accurate calculations and measurements for production. It usually mimics the real product 1:1. Still most engineers work commonly with 2D drawings, which have its benefits and downfalls.

For perpendicular system facades the façade is in commonly in one plane or on other terms following a straight line. The façade elements are usually repetitively positioned and spaced along the façade so that most of them are aligned in their own plane when seen in a 3D model. This creates the advantage for the façade engineer as he can describe the façade in 2D drawings. The 3th dimension is just an extrusion of 2D.

Some advantages of 2D drawings are: it is relatively fast to draw, you can print it on paper and you can focus on the problematic points (details) rather than drawing every inch of the building. The main disadvantages of 2D: the readers needs to have a good 3D imagination, it becomes much harder to describe complex 3D objects and you need a lots of drawings for non repetitive elements.

As façades become more geometrical complicated the 2D drawing becomes much less efficient to describe the façade. To the point where there are no repetitive elements and every node has to be described separately. If this would be drawn in 2D it would ask a vast amount of imagination from the reader to understand and will have therefore a high error rate in production. In the case of designing a double curved façade it is therefore much more convenient to use a 3D model or a combination of 2D drawings with a 3D model.

The next step in 3D modeling at the moment is generative modeling. With generative modeling you do not shape the objects by hand, but instead they are generated by a computer script. It is a very methodological way of creating a 3D model; you define every step you make and make a relationship between the geometrical shapes and modifications to it.

A generative model has the advantage that you can really quickly change the model so it makes good use for research. It allows you to define every step in de modeling process and allows much more complicated relations between object and positioning such as mathematical formulas. A disadvantage would be that it is maybe a bit less flexible as you are bound to the script, soothe object has to fulfill the rules that has been set.
The work experience between manual modeling and generative modeling is best seen in an example: in table 4 you see 4 actions performed by a user in a 3D model. Let’s assume we have 2 users. One is using a generative model to put in the 4 actions and the other is putting them in by hand. Now we want to change the action to move the sphere 20 mm to 30 mm. The user who has put the information in by hand has to undo 3 steps, make the change and action the last 2 steps again. He makes a total of 5 actions. The advantage of a script is that you can change variables or parameters directly. So the user goes to the section in the script where it states ‘move 20 mm’ and changes it directly to ‘move 30 mm’. It only costs 1 action. The benefit of this will only extend towards the tendency to more complicated models.

**Example model actions**

**Example Actions**

1. Create a sphere  
2. Move: +20 mm X-axis  
3. Array: 20 units  
4. Scale: factor 2

**Manual modification**

**Undo 3 Steps**

1. Create a sphere  

**Action new move**

1. Create a sphere  
2. Move: +30 mm X-axis

**Action last 2**

1. Create a sphere  
2. Move: +30 mm X-axis  
3. Array: 20 units  
4. Scale: factor 2

**Generative modeling modification**

**Direct change value**

1. Create a sphere  
2. Move: +30 mm X-axis  
3. Array: 20 units  
4. Scale: factor 2

Due to the rapid way of modeling with generative model tools it is rely suitable for designing a concept like ideas as you can quickly change the outcome model. Also it creates a clear methodological overview as it defines every step in the process.
Positioning
The positioning of the main façade system elements (mullions and transoms) to the architect’s wireframe model is important as it will define how they meet in the connecting nodes. The profiles are extruded along the wireframe from the architect’s model. Let’s take a simple rectangle profile as example. You can extrude this rectangle profile over a wireframe model so that the wireframe line is in the exact center of the profile. See also the section in Figure 29 where the wireframe line is marked as a red dot and the 3d example in Figure 30.

When you see these example images it becomes clear the profile has a relative dimension to the wireframe. This also has an influence on the position of the glass panes and all the other façade elements connected. Especially the way how to profiles meet in connecting nodes. This makes the positioning of the profiles in relation to the wireframe very important.

For a perpendicular in plane connection all is pretty clear as seen, when you angle the transom in relation to the mullion you will get a geometrical problem. This can be seen at the angled illustration of Figure 31. Due to the angled connection the mullion and transom will not meet in the top and bottom part of the profile. There is a small difference in height. This is due to the geometrical fact that the angled size of a triangle is longer than the straight size (see pythagoras $a^2 + b^2 = c^2$) and the chosen point of positioning the profiles center in relation to the wireframe.
You can use another approach by positioning the profiles not center in relation to the wireframe but on top. Still the effect remains the same, see Figure 32. In geometrical terms the best way to solve this is the offset the transoms slightly different in relation to the mullions, aligning the outer faces. (Figure 33)

The geometrical solution is used in the industry, although they use a little cheat. In the above examples I presumed all the profiles were the same. In the current facade industry they are actually using 2 different types of profiles, one specific for a mullion and one specific for a transom. There are several differences between these profiles, but in geometrical the terms the mullion profiles are always a bit higher / deeper. Also the faces of the profiles are always aligned on the outer face to make sure it has a tight seal with the cladding, which could be a panel or glass. The connection is secured by rubber profiles that have a type for a specific range in interval of the angle made.

For the concept we need to align the profiles from the top surface with the wireframe to make the correct alignment for the glass window panes.
We now have looked at the profiles from a side view. The glass panes are leading regarding the alignment of the profiles in reference to the wireframe and become the zero line. (Figure 34) To translate this into perspective; a triangle surface, described by 3 lines from the wireframe, defines the bottom position of a glass window pane. Two section views, with inward and outward angles, give also an interesting point of attention. Figure 35 shows two section views, the red lines are the fixed zero lines, based on the wireframe model. From Figure 35 we can see that the point where the two glass panes meet, relative to the section profile, is not the same for the two sections. It can be explained by the different angles involved. Indirectly also the width of the profile has influence as the window will be place on the rubbers on the both sides.

For the design we should take in account this displacement. We already agreed that the windows panes are on a fixed plane, which should results in changing the profiles accordingly along their length axis to compensate.
**Fixation**

In our design we should somehow also make connection between the ‘standard’ profiles. It is a very complicated node where 6 wireframe lines will join. All the lines will have different angles on 3 axes, which make the node and possible connection pretty complicated. To work to a solution/concept I will first look at the some existing connection techniques in the curtain wailing systems.

Within façade systems there are several possibilities to connect the profiles (mullions and transoms) with each other. The mullion is the standing profile and is continuous over the facade height. The transom is the horizontal profile and is cut every time it meets a mullion. The most common way to connect a transom and mullion is with a t-connector shown in Figure 37. The t-connector is a ‘U’ shaped profile that is mounted on a mullion. The t-connector is mounted on the side of the mullion and the transform is slit over it to fix the two. It makes use of the hollow space inside the profile.

![Figure 37: T-connector Fixation](image)

When the maximum height of a mullion is reach (usually 6 meters) or it needs a dilatation the mullion is connected using a special dilatation profile. (Figure 36) This profile is more or like a negative of the cavity and is slit in both the top and bottom profile. It acts as an insert. The insert can take over perpendicular forces acting on the profile (like wind forces); both can take non in the parallel direction. One point of the insert is usually fixed so that the other can slide over it. This is useful to cope with the extension of the mullions due to temperature difference or forces that work on it. The insert can take up moments, but it is usually not used in such fashion.

Sources:

(Schuco, 2009)
It gets interesting when multiple profiles connect together in a node and have all different angles. In essence for a complicated double curved façade a cost effective solution will need a design that is in concept for every node the same, but will be unique in a physical way to fulfill the demands of the double curved façade. There are several examples of a similar setup of this in the space frame technology.

Space frames are structural frames based on 2 simple elements, (steel) tubes and (steel) node connectors. Put together they can form rigid frames to support all kind of structures, including roofs, facades and more. With space frames you can also build almost any kind of geometrical structure you want, which brings it in relation to the double curved facades. Depending on the system the space frames are usually bound to certain geometrical limits or mount angles. This can be due to production techniques and/or the need for repetition.

As an example I’ll be looking at a system of the manufacturer Octatube. They have developed a special node (Tuball) to connect steel tubes into a space frame. The nodes in the space frame are very flexible. They all have the same spherical shape with and a hollow cavity that can be opened by a special cap. (Figure 38) Still the steel tubes can be connected in a big variety of angles as the holes of the connecting bold can be drilled in different for every sphere. This makes it possible the produce every sphere as a unique element and still have it based on a single concept. There is a difference as these nodes are only used structurally, while my design includes all façade functions.

![Figure 38: Octatube Tuball connector](image)

![Figure 39: Tuball Examples](image)

Sources:
(Ramaswamy, et al., 2002)  (Bouwwereld)
Concept

Derived from the information gathered I have come to the point where I can start with an initial proposal for a concept. Summarizing the design task: the concept should house a design proposal for a double curved façade; build out of a mesh of flat panels, using standardized façade system elements. The problems are concentrated in the mesh nodes, which ask for a new solution/approach.

My initial inspiration is based on the space frame solutions like the Tuball where a single geometrical concept is transformed in a very flexible node system. The difference is that the Tuball system only incorporates structure and this concept should house all façade functions. The idea is to apply a comparable concept to the double curved façade system.

The approach starts from the architect’s model. This would be a wireframe of the façade as seen in [figure]. The wireframe has 6 members per node so that all panels consist out of triangles making sure they are based on flat panels. Due to the design choices the main technical problem are concentrated in the nodes. Due to the choice to use standard façade profiles for the straight members of the façade most problems such as wind and water tightness are already solved.

I want to use generative modeling and rapid manufacturing techniques to create a geometrical unique node for every node in the double curved façade. The generative modeling allows me to create a script that has several variable input variables. These variables should be linked to the architect’s wireframe model. The outcome of the script is shaped into a format that will directly be usable for a production department, referring to 2D or 3D drawings/models. So in fact the script defines a concept shape that only has be calculated and designed once by an engineer. The result is a variety of geometrical outcomes within a certain set of defined limits based on a single concept design. The outcome can be produced using rapid prototyping techniques. It creates the possibility to produce unique members on a repetitive manner on a relative short timescale.
Generative Model
Introduction
I started the development of the generative model with the use of the 3D program Rhinoceros. The choice of 3D software was relatively simple as Rhinoceros is a program I have good experience in. It has also the advantage that Rhinoceros can prepare created models directly for production use in rapid prototype machining. Rhinoceros has capabilities for generative modeling, using rhino script, but it is rather complex, instead I used a plug-in called Grasshopper. Grasshopper is a tool that uses dataflow diagrams to build generative scripts in a visual manner, which makes it really user-friendly.

Case Study
Based on the concept and the given parameters set at the start of this chapter I started off by creating a case study project in 3d to act as a starting point for the design. I therefore took a facade section of a building 5 stories high (3,5 meter floor span) and generated a random nurb surface mimicking the façade like in an architectural model. (Figure 40) I then used a grasshopper model, from my previous research, to generate a triangle mesh from this surface, making the first step from the architectonic to engineering model. (Figure 41) As I now have a global wireframe example mesh I can zoom, to the level and problems of a single node.

Figure 40: Architectural Facade - Nurb surface

Figure 41: Initial transformation to engineering model - Wireframe Mesh
**Wireframe Translation**

The idea is to use a wireframe as architectural input model. This means the script has to transform the lines from the wireframe into extruded members. It will also give an initial insight how the profile join up in the nodes. The keep things simple I started with designing a script for a single node instead an entire wireframe façade. This node consists out of 6 lines that come together in a single point under different angles. The members are extruded parallel to the 6 wireframe lines. See Figure 42.

![Figure 42: Initial node extrusion](image)

The grasshopper model requires an input to work with. These import parameters are important as they form the basis of the model and give it the ability to modify by changing the values. For the creation of the node model I started with 3 main parameters:

1. The wireframe model (6 lines node)
2. 2D section of the façade system profile
3. Point of extrusion of the facade system model

I faced several obstacles during this extrusion. Rhino and grasshopper have a broad set of tools to do geometrical operations to the model. The first obstacle is that not all 6 wireframes are aligned in the same manner. In 3d modeling a line has a start point and an end point, the computer then generates a line in between. This line represents a vector that has a direction. To process the node so that mathematical calculations can be correctly applied it is important that all vectors face all outwards or inwards. The difference does not really matter as long as the alignment is the same. The solution I found is to strip of the starting points of the wireframe lines. Then I compared the xyz coordinates with each other. A way to this is to use the normal distribution from probability theory and calculate the standard deviation from the values.
It should be mentioned that you can correctly determine the ‘wrong’ orientated profiles as long as there are not an even amount of wrong a good orientated members. So you can detect with this method 1 wrong member out of 5 correct ones, or 4 wrong out of 2 good, but not 3 wrong members and 3 good members as the difference with the variation will indicate this.

Figure 43: Grasshopper - different orientation on wireframe

A visual example of the script is shown in Figure 44. This is a simplified version where only the difference of the two squared average is withdrawn from the squared value. The outcome has a positive number for the wrong members and a negative number for the good members. This could also be reversed depending if the node would be positive/negative. The outcome is related back to points, a new orientation of the points is created and new lines are drawn.

Figure 44: Grasshopper - Reorient the wireframe lines
Now I have the 6 lines of the node in good orientation it is time to extrude the profiles over the lines to give a god visual impression of the 3D node. This is done by defining the section lines of the profile in 2D and extrudes it along the wireframe lines. It is important to take in account the mathematical displacement discussed in the ‘positioning’ paragraph, you can see what happens without it in Figure 45. The faces towards the outside do not match up and there would be no way to fix a glass panel on this uneven surface.

![Figure 45: Uneven profile members - out of alignment](image)

To align the profiles probably two things should be done. First the members have to have a displacement over their local axis to compensate for the different angles the glass panels are connecting. (Seen in paragraph ‘positioning’) Second the member should be aligned (rotated) to each other so that the panels, shown red in Figure 46, are in plane with the profiles. When this is done correctly the angle point of the panel should be the point where the 2 related profiles meet in space, shown as a black dot in Figure 47. In this figure we can also see the dotted lines are spaced from the initial wireframe, we have to make this offset as the glass windows are resting on rubbers that connect to the outer side of the profiles.

![Figure 46: Example profiles with infill panels](image) ![Figure 47: The point of intersection between 2 member](image)
To solve this problem a separate grasshopper script has to be made. This script should have 3 input parameters.
1 The 6 wireframe lines
2 The point of extrusion
3 The point on which the (glass) panel is connected to the profiles (using rubbers)

First we focus on the correct alignment. From the input parameters we can create an extrusion of tubes along input wireframe lines. The tubes represent the distance between the point of extrusion and the point of connection. The output is seen in Figure 49. We can also make a planer surface between the wireframe lines representing the panels seen in Figure 48.

When we now intersect the two, we can distinguish a point where both two tubular members and a panel meets. This point is the same point as seen in Figure 51 and is very important to determine the alignment of the panel. When connecting all the points you will get to local horizontal axis of the extruded members, seen in Figure 50.
This all is molded into a grasshopper script outputting the horizontal axis as lines. You can see the visual aspect of the script in Figure 52, a more detailed view can be found in the appendixes.

![Figure 52: Alignment grasshopper script](image1)

Now we have our alignment correct we have to reposition the wireframe to be aligned with the newly found local horizontal axis. This second step requires to measure the perpendicular distance between the wireframe lines and the axis lines. Grasshopper has a tool for this to measure the shortage distance between two lines. Not only gives this distance the displacement of the wireframe and the extruded profile, but also it gives us the vertical axis of the local axis systems. See Figure 53 for the script.

![Figure 53: Displacement script grasshopper](image2)

The result is that we now have a local x and y axis for every wireframe lines and we also know the displacement over this vertical axis. (Figure 54 and Figure 55) In other word we can now align the panels with each other and can reposition them to be in line with the glass panels. The outcome 3D model can be seen in Figure 56 and Figure 57, where Figure 57 is showing also the rubber profiles the glass pane can be fixed on. As you can see the rubber perfectly match up in the point of intersection.

![Figure 55: Found local axes](image3)  ![Figure 54: Displacement distances](image4)
**Figure 56:** 3D model outcome of the alignment script - Blank

**Figure 57:** 3D model outcome of the alignment script: Rubbers added
**Model Evaluation**

An important point to think of when we see the node in the 3d model is how to find a way to translate this into a production concept. From what we have seen in the above figures it is a very complex geometry and it needs good attention.

A problem occurs on the intersection between the intersecting geometrical surfaces. When two profile members meet they intersect with each other on certain spots, but are not ended at that point. The intersection often creates unexpected geometrical spaces inside the profiles, which make it quite a mess inside. (Figure 58) A solution is to cut to profiles the point where it meets another profile. This will result in a more clean geometry.

![Intersecting profiles](image)

**Figure 58: Intersecting profiles**

There would be multiple ways of trimming each profile so that it stops at the point of intersection with its neighbor. One could mathematically calculate the point of intersection and create a plane of intersection to cut the model. But another way is to use a neighbor profile to act as trimming template, so trim the profile at the point where it meets its neighbor. The last solution was the easiest to bring in practice as all the elements where on different angles and had different trim angles which would make calculating it a difficult task.

To bring this in practice every profile member should be cut by its right and left neighbor. So for the 6 profiles you need $6 \times 2 = 12$ trim elements. Unfortunately this will not solve all geometry problems. As sometimes the profiles do not intersect over the entire height. This will result in some geometrical residue, mainly blocking the profiles edges and rain gutters on the top. To clear this I made a template following the outer contours of the profile and also duplicated this into another 12 trimming templates replacing to original trimming profiles. For the script I now had to do some complicate sorting to assign every profile member with the right (left and right) trimming geometry. The combing effort resulted in a much cleaner geometry. You can see the above steps in Figure 59.
Figure 59: Steps to clean up the geometry
Concept development

Introduction
A basic model is now created using generative modeling. It gives great insights in how the structure might look like and possible complications. Still it is not clear how it can be produced and how it will work compared to other systems.

Production concept
For production we need a general concept how a sample node like we have seen in the model can be made. There are of course several ways, but in general terms you can split a production concept in two possibilities:

1. Single element node
Create the node out of a single unique object to which the façade profiles attach to. This will mean that the node object should be created in a unique way, probably by use of rapid manufacturing techniques.

![Figure 60: Single node element](image)

2. Multiple element node
Create the node out of separate elements and connect them using insert/spider elements. This would allow the possibility to more common production techniques in façade design. An example would be cutting the system profiles up and welding them together.

![Figure 61: Multi node element](image)
If we look at the two concepts they will require different production techniques with their advantages and disadvantages. A good comparison is needed to determine which solution should be the best choice to proceed with at the moment.

We start with the single element node. This concept has the advantage that it has a sense of simplicity. You prevent difficult connections between the façade profiles and the node as they can be on a single angle (machine cut). This will also have an advantage if you look at water drainage and air tightness as it will more easily integrate standard solutions from current façade systems. It will require the use of rapid manufacturing techniques (possible 3d milling or 3d Print) which can be seen as a disadvantage. They are non common techniques in façade engineering and not always will need more testing to be used in practice. But it will make it possible to produce a complicated node out of a single object.

The multiple element nodes are created out of separate elements linked to each other. They can be connected using welds or inserts/spiders. The advantage is that regular production techniques can be applied, like extrusion and cutting techniques, which are common in the façade building. A disadvantage would be that the node exists out of a lot of separate elements. Increasing the margin of error, where we need a high precision with this 3d façade.

If we compare the single and multi node concept it seems that the single node concept is simpler in nature, but using more untested techniques compared to the multi element node. The multimode element uses more common techniques, but is these common techniques actually an advantage? When we look at the profiles for the multi node concept, they first need be cut the precise match of the neighbored element. If you look at [figure 31 above] then we need at least 6 machine cuts for every element on a single node side. This is the simplest approach as there might be added extra parameters when we look at water drainage, insulation etc. Next that if you use for example welding, it will need a very complex setup to make sure all elements have the right angle. In overall the error margin for the multi node concept would be much bigger compared to the single node concept. There for the choice production concept would be that of the single node.
Demands regarding production and usages

Introduction
The concept model should of course not only be produced in a correct fashion, it should also be checked for demand regarding building degree. This is regarding structural strength, insulation, water management etc. For the concept we can look at it in two different views. We can determine a macro level where we considered the demands on the entire façade and a micro level where we look more deeply into the node itself.

The model is a representation of a case study project. The outcome can be different on other projects with a different set of parameters and boundary conditions. (floor height, profile choice, largest span etc) Due to the complexity of the model I was not always in the state to make the actual calculation. Instead I tried to find a general approach and look for critical points to keep in mind.

Strength
Strength is about structural stability and the forces that act on the structure. First we have to look to the macro level of the façade. The façade as whole is build out of a mesh framework that is build out of triangles. Triangles are structurally very stable geometries. This has advantages when we look at the structural strength of a façade. A regular facade system has a specific outline as seen in the ‘analysis’ chapter. The regular façade system is build out of a rectangular framework, but the forces are guided along the gravitational lines to the construction. There is also a difference between the façade profiles in the form of a transom and a mullion. On the transom the dead loads act parallel on the section plane and for the mullion the forces act perpendicular on the section plane. Due to this the profiles can be adjusted to a specific load.

The forces on the triangle mesh façade system are much more irregular and it will be very hard to calculate by hand. You can distinguish something else from Figure 63 and Figure 62. Compared to the rectangular façade system the triangle mesh system has not the regularity between mullion and transom. The force on the profiles in the mesh system can working on a lot of different angles.
A problem arises as it is very hard to setup a good reference project. Double curved façade will have little similarity with other double curved facades as the shape is always different. Therefore the mesh structure will always be different as the forces involved. A computer program like iDiana is needed to exactly calculate the forces involved.

In the Netherlands the façade is checked for its structural integrity by calculating the minimal acceptable moment of inertia. The moment of inertia is a factor that represents the resistance a material has to allow a rotation around its axis. By calculating the minimal moment of inertia that is needed, a profile can be chosen with a higher factor than the minimum and so fulfilling the regulation demands for safety. The minimum moment of inertia can be calculated by adding the wind forces and dead loads, but should also be checked for maximum deflection. If the deflection of the façade has reached its maximum before the loads do it should be used as the norm.

Facades not bear the same loads as the building structure itself. The forces are smaller but consist out of two main elements: wind loads, dead loads and for the roof possible temporary load like water and snow. The wind loads are always calculated from a perpendicular viewpoint in relation to the façade plane. The dead load not, they are always in aligned with the gravitational lines.

If we zoom in more at the micro level we can distinguish two problems, one for the standardized profiles and the other for the node.

The standardized elements are designed for a specific load usually based on a fixed angle on which the dead loads work. For regular façade system this was always perpendicular or parallel to the section plane of the system profile. Let call these directions x and y. To find the correct profile we had to find the minimal moment of inertia in x direction and y direction and apply the correct one depending on the situation. In the manufactures system manual we can look up the correct profile size as he already calculated the moment of inertia for us in x and y direction. For the triangle mesh façade the dead load can be on any angle regarding to the profile section. There is no fixed x and y axis, it is different for every profile.

In essence this would mean that every profile could have a different dimension regarding the different forces and the angle on which it is situated. This is not desirable as it would prevent repetition and add complexity. It is best to calculate the entire façade in a computer program like iDiana, find the maximum stress for all profiles and dimension one that will fulfill all profiles at once.
If the profile initially chooses would not fulfill the regulation, there would be several options to add extra strength to the profiles. One option would be to enlarge the profile in depth. This will increase the outer material distance to the center of gravity increasing the moment of inertia.

If it would not be esthetical appropriate to increase the profile dimensions then another solution could be tested. To overcome the bending stresses you can add inserts profiles over the entire length of the profile. (Figure 67) These insert profile, made from steel or aluminum can add extra material increasing the Moment of inertia in different directions. For the architect this has the advantage that the façades appearance will not change. The standard profiles are based on forces in $x$, $y$ direction. One can image that special profiles can be made to increase strength in the other direction, for example by adding extra ribs.

![Figure 66: Increase dimension](image1)

![Figure 67: Add insertion profiles](image2)

The second problem is with the node how can we make the node structurally stable? If we look at the model created in the last chapter we see that the node connects to the profile members on a variety of different angles. Depending on the angles, there can be quite large forces and moments working on the node. For the model there is still no clear concept how to overcome these stresses. Every time the profiles meet at the node they connect on a different angle and not always in a very optimal connection. To overcome this problem a solution is to found. When we look at the Tuball node from Octatube, which is only used for construction, we can see that the used a sphere to overcome the different forces on all the angles involved. The sphere is a very stable shape that can withstand many different forces, the round shapes helps to distribute the forces preventing peak loads on irregularities.
When we apply the sphere to our construction we discover that there is a problem. The profiles we use are unlike the tubes of Octatube not even in width and depth. The façade profiles are significantly deeper, more in a relation 1:2 and changes in relation with the forces involved. To overcome this we can stretch the sphere to fill in the extra depth. When we transform the spherical shape we come to a cylinder. The cylinder is less strong in all direction, but especially on the rounded surface it can take forces in different angles. Due to the limitation of the façade profile they can only handle small angles making the cylinder a sufficient geometrical shape to overcome this.

Figure 69: Spherical concept

Figure 68: Cylinder concept
**Tolerances**

Tolerances are an essential subject when constructing facades. You need tolerance for a different set of reasons. At first all elements need to be produced, cut welded etc. During production all is made as close as it can be to specification. But you cannot expect that there will be no (small) errors during this process; there is the human factor, but also machines that are off specification. This will mean a beam cut to 250 mm can actually be 251 mm or 249,6 mm. Of course the industry will do as much as it can to reduce this number, but it should be taken in account.

Next to production tolerances there are also temperature tolerances. A material contracts and expands a small amount due to temperature changes. It has usually only a measureable influence on elongated elements. The thermal expansion of aluminum is for example 0,02 mm for every rising degree in Celsius over 1 meter length. So if the temperature is increased 20 degrees for 6 meter profile, the total length of the profile will increase by: \[6 \times 60 \times 0,02 = 2,4 \text{ mm}\]. When we take a temperature difference of 40 degrees this will already be 4,8 mm. These should definitely be taken in account. There will also be a small displacement when profile members are loaded by for example wind forces.

Finally we need tolerances during the construction of the façade. The loading of the façade can create setting or displacements of the construction, which should be taken in account. Also the different building components on a building site have different tolerances. Façade engineer work regularly with millimeter precision. But for example concrete construction can have tolerance up to one centimeter. Usually special bridge construction or brackets are sued to overcome the tolerance difference between different building sections, like the concrete construction and façade profiles. These allow an offset on different axis to align the façade to specification.

The production and displacement tolerances can be overcome during the construction process. It can then be fixed, but the expansion and loading tolerance are always present. There will on micro level always be small displacements in the facades due to temperature difference and wind loading.

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**Sources:**

(Wikipedia)

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*Figure 70: Expansion due to temperature change*

*Figure 71: Displacement due to wind load*
There are two possibilities to deal with the tolerance in the façade:

1. Disconnect certain the profile members from the profiles with the nodes
2. Fix all the connecting from the profile to the node.

A logical choice is the first option to allow some movement for expansion. It will relieve the structure from stresses caused by the expansion/contractions. This method is done commonly on current façade systems. The problem is that it also lowers the structural strength due to more ‘flexible’ connections. In regular façade construction this is no problem as only the transoms are disconnected on a regular basis. The mullions are continuous ever larger length providing stability.

The framework consists out of a triangle mesh. This means that there are much more disconnection in the profile as it disconnects on each node. The nodes and profile connections are a weakness as these create are relative flexibility in the system. The mesh would become much more stable when it has rigid connection. Fixing the connections can be compared with shell like structures. There will be extra forces involved due to the expansion and contraction of the profiles, but they can be distrusted over the framework as it is working as a whole. It would therefore be best to make sure the production tolerances can be taken up during construction, but the members are fixed to enhance overall stability of the mesh. Due to the added forces from the expansion the complete mesh should be calculated in a structural program like Diana to find maximum deflection and the stresses involved.

In the ‘generative model’ chapter we defined a concept where we have a single node that connects to the standardized façade elements. Still we have to find a way to connect those elements and also take in account the tolerances. A solution can be found in the already existing systems for connecting the façade profiles with the node. We have seen in the chapter ‘fixation’ that there are currently 2 common ways of connecting a façade member. For the parallel elements an insert is used and for perpendicular connections a t-connector. The inserts are a particular interesting solution. Currently they are used to connect two profiles that are stacked on top of each other. (Façade profiles usually have a standard length of 6 meters) Then act as a point where tolerance can be taken, but can also take up loads. In a similar fashion steel profiles are sometimes inserted into the cavity of the profile to increase the bending stiffness.
Insulation
The energy performance of facades system can really vary depending on the chosen system. The trend is to use more and more energy efficient systems as the government increases the demands in the regulation. The performance of a faced can be determined by its thermal heat coefficient. This is the heat resistance of all the material of the facade combined in relation to their situation. Every material/element has its own heat resistance. Aluminum has for example a much larger conductivity then wood. The coefficient is there for determined by the percentage of surface, in contact with outside temperature; a specific material has in relation to the other materials.

Heat can be transferred in 3 ways.
1 convection
2 radiation
3 conduction

Too increase insulation performance all 3 have to be at a minimum. For a façade system the thermal resistance factor is mainly determined by the amount of glass and profiles used. In general terms the glass panes have a better insulation then the aluminum profiles, mainly because aluminum has good heat conductivity. The profile manufactures are desperately trying to find solutions for this problem by create thermal breaks between the outer glass pane and the inner aluminum construction profile. These thermal breaks usually consist out of cavities with low heat resistance plastic spacers. To increase performance special insulation material can even be added to the cavity to prevent radiant heat transfer.

For the calculation of the heat transfer coefficient we can use a computer program. The one in use at the University of Delft is called Trisco. Oskomera uses a program from the same series that is called Bisco. Bisco will allow for 2D calculations and Trisco for 3D. Unfortunately Trisco would only allow 3d models with rectangular structure. The 3D node where we are working on has at the moment too complex for the program. It might be that with other software an accurate calculation can be obtained.

Figure 73: Rectangular and triangle mesh facade
For now we can only compare the performance of the regular façade system in general terms with the double curved system. This is still very hard as it depends on the percentage of glass versus profiles used. When the glass surfaces become bigger, the performance will increase slightly.

To make a simple and fair comparison we can look at a regular façade system and a double curved façade system (with a triangle mesh) that have both the same surface area of glass. We take 2 glass panes, one triangle and one square, both with an example surface of 25m². The profile length needed for the circumference of the square panes is $5+5+5+5 = 20$ m. (Figure 75)

When we look at the triangle pane the circumference is different. An example with an isosceles triangle; we have a base of 10 and height of 5, which makes the side $5\sqrt{2} = 7,07$ and the total length $10+7,07+7,07 = 24,1$ m. (Figure 74)

(Note that this is a general comparison, the dimensions used are somewhat exaggerated and not based on production dimensions of glass)

From this equation we can see that we need approximately 20% more profiles ($24-20/20*100$). This value will increase further because:
1 not all triangles have to same surface area, while most rectangular façade pane do.
2 An equilateral triangle has the lowest circumference, if the angles decreases or increases the length will increase.

In the example we had an incensement of the profiles with 20%, this does not mean that the total heat coefficient factor is decreases by 20%. If the façade would consist out for 10% out of profiles and 90 % out of glass the percentage of profiles would increase to 12%. It will have a negative effect on the heat coefficient factor but in a much smaller scale.

The advantage of the current concept is that the same standardized profiles are used, so in their thermal heat resistance will be the same. Unfortunately we were unable to calculate the heat resistance factor of the node, but we can ban assume that it will have a slightly lower value than the profiles itself as the metal surface is bigger. Conclusive with this approximation we can predict that the concept system with the triangle mesh would perform less than the regular façade system. It will require some 3D calculation software to determine the actual numbers, but it should not be off by large amount as we are using the same standardized profiles.
Water management

We have found a solution for interconnecting the nodes and the profile by the use of inserts. Still a solution has to be found to correctly drain the water out of the system and prevent leaks. We can divide the water drainage problems in 2 sections:

1. Standardized profiles
2. The nodes and connections

In Figure 77 you can see an example section of a standard system profile. The standardized profiles have the advantage that the water drainage is already solved by the manufacturer. It can be explained by (Figure 77 and Figure 76). The initial rainfall is stopped by the first barrier. This barrier usually consists out of a rubber that is clammed against the panel. If any water leaks through due to wind forces condensation etc it will be channeled through a special gutter located on the side of the glass pane. To make the seal complete there is a secondary rubber on the bottom part of the glass. This will prevent the water from the channels to leaks inside and make the façade airtight.

![Figure 77: Drainage of the profiles](image1)

![Figure 76: Drainage of the caps](image2)

There standardize profiles have usually the same principle for their structural main profile. The top caps can differ depending to the architects wishes. Other solution can also be structural glazed façade or façade fixed by a small wig [figure 78]. Usually these types are sealed off by a special rubber profile or silicon. For double curved façades they have an advantage as you would prevent complicated connections with the caps at the node. It would be preferable to use such a solution.

The support rubbers come (2nd barrier on figure 78/79) in different types per system provider. An important thing to notice is that these rubbers allow only a small amount of rotation. So for a flat façade one uses rubber A, for an inward rotation one uses rubber B and for an outward rotation on uses rubber C. Although there are tolerances in the amount of degree a rubber can take they are usually limited to about 5/10 degrees. Meaning that for the design one should use multiple types of rubbers or design a new rubber set for the concept.
For the nodes the problem can be solved in a similar fashion as the standard profiles. The arms of
the node will have the exact same section as the standardized profiles. These will meet in a
cylindrical element. You can see in Figure 81 that the center is opened to allow free water transport
from the water channels in the profiles. These water channels need to be routed outward to prevent
too much water rushing through it. To overcome this we can route the water outward using water
breaks. The water breaks are plastic brackets that can be put into the water channels to route the
water outwards on the outside of the façade. They are part of the standard accessories list of façade
manufacturers. (Figure 80)
It would be most convenient to place them on the spots just before the point where the node and profile member meet. This will help to reduce the amount of water on the connecting surfaces.

The last point of concern is the connection between the profile and the node itself. There could be a minimal amount of water present on the connecting surfaces, so both would need to have a good seal. As we have seen in Figure 72 the node and profile are structurally connected by an insert profile. The edges of this connection still have to be sealed. The advantage with the single node solution is that we can make the connecting surface a flat pane.

One solution would be to use silicon. Silicon is flexible and can be applied in hard to reach places. It is often used in the current solutions where the insert profile is used for extending profiles. Still it will take quite some time to seal the entire connecting surface; also there will be a lot of the connection to seal. As it is not a good solution for the long term I did a new search.

At Oskomera they were familiar with another solution used in the company’s rich history. It is called a jacket and made out of a rubber like epdm. It work like a sealant ring also found in tubing systems to seal a connection, only now in a more complicated shape. The jacket is a flat rubber element that is cut to shape to exactly fit the profile. When to two profile ends meet the epdm is presses by the two elements making a seal to prevent leakage and make the connection airtight.
Model Evaluation

Looking back at the generative model we can apply some changes to make it up to date with the decision made in this chapter. These changes are regarding, strength, tolerance and water management.

For the model the important thing to change is to apply the cylinder element in the center of the node. This will clean up the geometry and allow for a clear perspective view on the model.

A problem arises that for a good connection to all the profiles we to center the cylinder element to the other profiles. To do this we first have to create an average perpendicular line in the center of the node. This line is the average line created by the 6 perpendicular lines extrapolated from the wireframe lines in this example. It gives the average plane of all 6 faces.

![Figure 82: Process of calculating the offset of a complex node - part 1](image)

From this line we can draw a cylinder that is situated in the exact center of the average perpendicular line and has the radius of half the width of a chosen system profile. For example: if a chosen system profile has a width of 50 cm the radius of the cylinder will be 25 cm.

![Figure 83: Process of calculating the offset of a complex node - part 2](image)
Now we have the cylinder we can use it to trim off the existing profile members. To do this we duplicate the cylinder 6 times, one for emery to be trimmed profile. Finally we make a hollow cylinder profile that will fit exactly in the created opening.

For the script it was also important to filter for residue geometry. If you trim an element it only remove the geometry where both the base geometry and the trim geometry meet/overlap. If the profile sticks does not overlap on all places it with the cylinder it will leave small rest geometry. To overcome this I applied a volume filter to the geometry. So I set to only pass the geometry that has a minimal amount of volume. This little trick held me to filter out the main 6 profile elements and leave out the rest. Unfortunately the volume calculations are a bit processor intensive so it slowed down the model a bit.

In Figure 86: Finished model we can see the resulting model and in Figure 87 the exploded view showing the structural cylinder core. You can see that the lengths of the profiles arms are now equal. In an actual production model this length will be variable to reduce material. The insert will slide in the end of a profile arm and connect to the standard profile. The length of the profile arm is based on the minimal insertion length of the insert profile (related to strength) and an offset distance. The offset distance is measured from the center point to the point where the insert profile can be inserted. Due to the different intersections between the arms this point will differ.
Figure 86: Finished model

Figure 87: Exploded view model
Production
Introduction
The choices made in the previous chapter have an effect on the production possibilities. For the production processes it was important to make a choice between a single node concept and a multi element node concept. When the choice was made for the single node concept it automatically ruled out several production methods like welding. In fact when we want such a complex geometry made at once we only have a few production methods left. These production methods will be known as rapid manufacturing techniques.

Rapid manufacturing
Introduction
Rapid manufacturing is often confused with rapid prototyping. Although related it is not the same. For the rapid prototyping the focus is on the process of developing prototype will rapid manufacturing is making small series of products in a fast manner. Rapid prototyping makes it possible to produce in repetitive series for non repetitive unique element. Usually a computer model is on the basis of the manufacturing process delivering the input information to the machine. Rapid manufacturing is not always 3D related; it can also refer to cutting machines that process 2D cad drawings. It is a fitting process to develop the complex node that we developed. We will try to look at the different possibilities.

To get form a cad/3d model to a real live model there is an extra step needed. It involves slicing the model in sections, so that a machine an interpreted them and machine it. This is for all rapid manufacturing techniques the same.

![Rapid manufacturing process]

Figure 88: Rapid manufacturing process

3D Printing
3D printing is a form of additive manufacturing technology where a three dimensional object is created by successive layers of material. 3D printers offer product developers the ability to print parts and assemblies made of several materials with different mechanical and physical properties in a single build process.

In recent years 3D printers have become financially accessible to all sized business, thereby taking prototyping out of the heavy industry and into the office environment. It is now also possible to simultaneously deposit different types of materials.
New machinery and production techniques are developed increasing performance, precision and speed. Also the number of materials that can be printed is extended rapidly. The material list now consists out of wide variety materials. In general the materials that can be printed are part of the following material groups: plastics, metals, glass, ceramics, and (sand) stone. Also color additions are in some situation possible.

Print techniques
Not all materials can be printed with the same technique. There are different techniques that all have advantages and disadvantages. Also the type of material choice is sometimes bound to a production technique.

The most common production techniques for 3d printing are:
- Selective laser sintering
- Fused deposit modeling
- Stereo lithography
- Inkjet 3d model printing

Selective laser sintering is a technique that uses lasers to harden a substrate. The substrate is put in very thin layer on top of the previous layer. The substrate is only fused on the spots lit by the laser, using the heat that it is generating. By building up the layers a 3d model is generated.

Fused deposit modeling is using an injection technique. A material is molted into a liquid state and injected at the model using a special syringe. As the material cools it will harden. No substrate is used, so sometimes it will need a (printed) support structure to not collapse during printing.
The stereo lithography technique is using a fluid bad, instead of a solid substrate. The fluid has hardened by the use of a laser or sometimes UV lighting (DLP) on the desired spots. Again the model is lowered a small amount the start producing the next layer.

The inkjet 3d model printing is similar to the selective laser sintering technique. It is using a solid substrate, but instead of fusing the material with a laser an inkjet print technique is to apply small droplets of binder (glue) to fuse the material.

**Project**

For this project especially the steel printing is interested. There are 3 main production techniques that can be used to machine the complex 3d node in steel.

Electron beam melting is a technique where metal powder is melted and blasted on the model layer by layer using an electron beam in a high vacuum. It is like welding a small layer by layer in a precise manner so that a 3 dimensional object can be created. A similar technique is direct metal laser sintering (DMLS) which is like selective laser sintering only using a more powerful laser to accomplish the melting of the metal.

Both methods have the disadvantage that it created large amounts of heat. Therefore the object has to be connected to a base plate to dissipate the heat out of the object. It has to be cut loose after finishing. Still due to temperature changes it seems that the tolerances are quite large, when the steel cools the materials shrinks creating difference in the printed model compared to the computer model. These can around 1 to 3 mm. usually the model is therefore afterwards post processed to accomplish the correct dimension, this can be CNC techniques or polishing techniques. As our model is quite complicated and has not always easy reachable places it would be less desirable. Still the development is quickly and it is expected that DMLS printing will be within short amount of time applicable without a secondary processing step.

Normal Selective laser sintering is possible with metals; a binder is used to bind the metal substrate. The result is that the final material is much weaker than a full metal object as structurally the binder is leading. There is a technique to remove this binder and replace it with a metal to create a fully metal object. This green model technique uses an extra step. First a ‘green’ model is printed using a regular SLS printing process with fine metal substrate. When the object is printed, it is placed inside a chamber/oven. The binder material is molted and then the empty spaces in the piece are filled with bronze, to obtain a model entirely in metal. This technique allows for very accurate tolerances.

Sources:
(Pezzini) (Wikipedia) (Economist, 2009) (Shapeways)
**Milling**

A milling machine is a machine used to machine solid materials. Milling machines can perform a vast number of operations, from simple to complex. Cutting fluid is often pumped to the cutting site to cool and lubricate the cut and to wash away the resulting rest material.

![Milling drill technique](image)

*Figure 93: Milling drill technique*

Computer Numerical Control (CNC) Milling is the most common form of CNC. CNC mills can perform the functions of drilling and often turning. CNC Mills are classified according to the number of axes that they possess. Axes are labeled as x and y for horizontal movement, and z for vertical movement, as shown in this view of a manual mill table. A standard manual light-duty mill is typically assumed to have four axes:

1. Table x.
2. Table y.
3. Table z.
4. Milling Head z.

A five-axis CNC milling machine has an extra axis in the form of a horizontal pivot for the milling head, as shown below. This allows extra flexibility for machining with the end mill at an angle with respect to the table. A six-axis CNC milling machine would have another horizontal pivot for the milling head, this time perpendicular to the fifth axis.

![Different rotations for milling machine](image)

*Figure 94: Different rotations for milling machine*
**Analysis**

When looked at the two production processes, both have their advantages and disadvantages. If we weigh these arguments we can make a suggestion which process is best to choose.

The 3d printing has a big advantage that you can make very complex geometry with it. This can even be geometry that normally would need extra production steps. An example would be a hinge or shackles. There are actually almost no geometrical limitations to the process, besides some machine limitations. This would be minimum wall thickness and maximum dimension of the object. The price of the printing process is usually depending on the amount of material. As the model is build using a substrate/injection process you only pay for the material that is actually used in the model. Any substrate left can be recycled for the next model. Still the substrate is relatively expensive, so 3d manufactures are usually charging for the model based on the amount of substrate used.

The CNC milling process can also make complex forms, but is more bound to the rotations and angles a drill can make. The more advance milling machines have a 3 axis drill; this makes it possible to reach difficult places. Still the technique can’t cope with all geometries; the problem is mainly that a drill can only reach a certain amount of points before it will collide with the model. The production price is less dependent on the material cost. You need a lot more material to start with compared with 3d printing techniques, but the raw material is less expensive. Instead the production time is the main cost factor and manufactures are usually charging in production time. CNC milling takes usually longer then 3d printing as it will have to use multiple drills to soothe a surface and thus go over the same area multiple times before it will end up with a finished product.

The material used in both techniques is different. For CNC milling regular steel or aluminum can be used. Which would allow finishing techniques like anodizing the prevent oxidation and rain protections. For 3D printing this is more unfamiliar terrain. Not all manufactures have materials that are tested on all properties and it will probably need more research. To get an overview of the general material properties per production technique I made a small table:

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>3D Printing Steel</th>
<th>Milling Aluminum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Insulation</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>UV resistance</td>
<td>?</td>
<td>+</td>
</tr>
<tr>
<td>Water Resistance</td>
<td>?</td>
<td>+</td>
</tr>
<tr>
<td>Frost</td>
<td>?</td>
<td>+</td>
</tr>
<tr>
<td>Extension</td>
<td>?</td>
<td>+</td>
</tr>
</tbody>
</table>

Sources:
(Tos) (Wikipedia) (Shapeways)
When we compare the two production processes we see that 3D printing can create more complex geometry as CNC milling is limited by the drill. 3D printing is also more material efficient. Both can produce models in a non serialized manner, where prices will differ for both. At the moment CNC milling is a relatively cheaper than 3d printing in steel, given that the model can be milled. But there is a tendency for 3d printing to get cheaper in the coming years making it even accessible for consumers.

Regarding the current model we can conclude that using CNC milling techniques would be a problem as the drill would not be able to make the complicated twists in the geometry. Therefore the choice is obvious to go with the 3D printing process.

![Figure 96: Growth of Additive Manufacturing](image)

![Figure 95: Industry division of additive manufacturing](image)

**Model Evaluation**

The model created in grasshopper needs slight modification regarding the chosen production concept. These changes are bound to the design rules of a 3d printed model. At first all closed spaces need a small cavity to drain non used substrate from the model. The remaining substrate will be locked in if this is not done. Next the wall thickness has a minimum; this will prevent the collapse or crumbling of the model during printing/hardening/baking. The limit will be different by manufacturer but in this case it is 3 mm. It can also be solved by applying extra support struts. In general one should take in account that the model is applied the regular physics and should be able to stand on its own.

It now needs to be processed by a cam program, slicing the model up and preparing it for printing. This can be done by the manufacturer, but Rhino (the program I used) has also a cam plug-in. With the right settings it will generate a model ready for production.

Sources:

(Wohlersassociates, 2008)
Construction

Introduction
We have seen the possibilities to design and manufacture a 3d node for a double curved standardized façade system. We have shown a proposal for production, but it is not clear how this can be constructed and how it will influence other engineering processes. I will try to look into these problems.

Pre manufacturing
Most parts of the façade are pre-manufactured to make sure only little production has to be done on site. We have seen in the first chapter that the unitized façade is the façade type that is almost entirely pre-manufactured. For the post and beam system there are more on-site building steps involved. Still all of the separate components are produced in facture, making sure they have the right dimension, have predrilled holes etc. This increases quality and reduces errors as usually in a factory. The components can be produced in a controlled environment, where on-site conditions are more difficult to control. Here factors like weather, reach ability, heights, temperature and so on play a role.

For the double curved façade also all the components are pre-manufactured. This will be the 3d nodes, brackets, profiles, insert etc. This will make sure the construction on-side will go as smoothly as possible.

Construction
When the nodes are designed and have been printed they need to be constructed. Although the technique allows for construction in-factory, the design I took is a post and beam system that’s need fitting on the building site. This will require some steps to mount the system to the main building structure.

The separate façade components can be produced in factory as always with a post/beam system, but the system needs to be mounted on the building site. The following steps could be considered as a general concept idea:

- Produce separate component
- Transport the components to the building site
- Align and mount the brackets for the nodes that connect to the structure (using lasers)
- Mount the first 3d nodes to the brackets (1st order)
- Use the mounted nodes as directional guide to mount the first profiles
- Mount the rest of the 3d nodes (using lasers) and possibly supported by temporary construction
- Mount the final profiles and make adjustments for production tolerances
- Fix all profiles permanently to make sure the mesh act like one structure
- Mount the rubbers and glass
- Finish the façade using sealant or caps.
3. Process

Introduction

In chapter 2 we have seen the possibilities to design and manufacture a 3d node for a double curved standardized façade system. We have shown a proposal for production, but new tools and production methods are used. In this chapter I will try to look into these methods and how these are related to current processes of Oskomera as engineering and manufacturing company. Of course a full optimization and analysis of the process within a company could be the basis of an entire new research; therefore I will keep it short and try to name a few main points of interest.

Processes

The processes within of a building construction are very complex and will include many parties. From investors, clients, architects, engineers, contractors to sub-contractors and more, sometimes one company deals with multiple roles. Oskomera for example is an engineering company, but does also have its own manufacturing.

Instead of making a complex scheme of all the different roles and parties I tried to make a simplified version with 5 general steps in the building process: design, geometry, engineering, production and assembly. During the design and geometry stages the architects defines the building, the engineering stage is the part where the engineer tries to interpret the ideas of the architect, makes the appropriate calculations and refines the ideas to production drawings. The next steps are then the actual production and assembly. If we place the position of the architect and engineer into place as seen in [diagram 7] then we see that the architects takes care of most of the design and geometry stages and the engineer for the engineering stage. Of course it will never happen within such strict boundaries, often the point on which the work of engineer starts and ends will be vague.

Diagram 7: building processes
If we look at a company like Oskomera they are not only responsible for the engineering stage, but also for production and partially assembly. Toward the architect there is also some involvement with the geometry, so the spectrum is a bit wider. [Diagram 8]

![Diagram 8: Oskomera position in the process](image)

When we want to integrate a product like a double curved façade with rapid manufacturing of the design node the influence of the engineer will need to be broader. At first we have seen in chapter 2 that an early involvement regarding the geometry is needed to guide the transformation from the architectural model to a wireframe that is optimized for the double curved façade. This means that the engineer should already be in contact with the architect in the early stages of the design. Next the engineer is now also more involved in the production process. Due to the generative modeling tools the engineer is capable of directly linking an architectural model to a production model. This makes the engineer now even more involved into multiple process stages: geometrical design, engineering and production. See also [diagram 9]

![Diagram 9: Role extension of the engineer](image)
General Analysis
When we look at the design in chapter 2; the new production techniques of rapid manufacturing and tools like generative modeling tools, it is obvious they have possible opportunities and threads to take in account when implanted for use in a company like Oskomera. I will try to point out the important ones.

Opportunities
The points that could be opposed as opportunity the discovered engineering tools and concept:

- Repetitive manufacturing for non repetitive elements
  *Due to the use of rapid manufacturing production techniques in combination with generative modeling tools one can acquire a production process that produces non standard façade elements on a reparative manner.*

- Possibility for price/time savings: using a single concept on a wide variety of elements
  *As one can make non standardized elements using repetitive process one could assume that there will be price and cost reductions. Still more research is needed.*

- Have a single 3d model for calculation, like structure, insulation etc
  *The generative models allows for a single model that should be calculated for different applications setups (angles). But when generated the model could be applied N times elements as long as they are within the setup limitations.*

- New design techniques: Material efficient design with 3D printing
  *The rapid prototyping techniques allow for geometrical modeling of elements on a cost efficient manner, one is not bound to production limitations and this can optimize the model for structural and material need.*

Threads
The points that could be opposed as thread regarding the new engineering tools and concept.

- 3D print is costly at the moment:
  *3d printing is costly at the moment between $5 and $10 dollars per cm² depending on the type of material. Thus one should only use these techniques for the elements that cannot be produced with regular techniques at lower costs.*

- Is extra training required to handle these techniques in a company like Oskomera?
  *Both the production and modeling techniques are new for Oskomera, how can Oskomera integrate these techniques and processes. Or should one outsource this at a specialized 3th party company.*

- 3D printing is a new technique and untested in façade engineering
  *As 3d printing techniques are using unfamiliar materials not used in façade engineering, they are often untested regarding to the needs of façade engineers. More research is needed to find limitations and design rules. New materials are involved that need proper testing not only for strength, but also weather influences like frost, rain, uv radiation etc. How will the material last over time?*
Opportunities for Oskomera

The concept has multiple advantages regarding to the process and engineering solutions found for a double curved façade. But if one looks at the overall picture one can see it gives some advantages for Oskomera above other companies, as such that a design strategy proposed in this research does not exists jet in the façade industry.

In the current situation if an architect wants to design a double curved façade he probably first tries to make an inventarisation to the possible design options and make an analysis of reference projects. He then tries the make a rough design and will in the mean time try to find an engineering company that is willing to take the risk of building a façade that is mostly made out of untested/non standard elements. During this search it is well possible that a lot of choices are made that will negatively influencing the design. As companies are not willing to take the risk or asking high prices, for these specialized façade, and some consensus has to be made by the different parties.

Now if this concept will be developed to a producible and sellable product Oskomera has an advantage. An architect’s does not need to make their own inventarisation and analysis of reference projects and engineering solutions. Oskomera can offer it as readymade system solution already in the very early design stages. The system allows guarantees and known facts regarding structure, insulation and environmental protection. Also it gives the architects some design limitation to take in account which will prevent the architect from designing something that could not be made. This will save time for the architect as for Oskomera and allows Oskomera to be very early connected with the architect. This in combination with the architect following the system design rules enlarges the chances to acquire the order for Oskomera vastly.
Architectural possibilities and limits

Introduction

Double curved facades are an upcoming façade type in today’s architecture. But the type is not that commonly used by the ‘common’ architect or regular projects. We see them back on the high-end project with large budgets. This is mostly caused by the complexity of double curved façade and the tremendous amounts of engineering work involved. How will the new design concept make a difference?

Benefits for architecture

The main think the concept in chapter 2 brings is some form of standardization, where conventional method would only allow non serialized production. The possibility to standardize doubled curved facades has certain benefits for Architecture. Standardization would come with possible cost reductions, with the techniques proposed less time would be involved to engineer the facade.

Unfortunately in my research I have not made hard cost analysis. But from the research and explored production methods we can assume that in time, there is a high probability to reduce cost. These cost efficiencies can be obtained by the use of 2 main tools. First the repetitive concept producing non repetitive elements, second the use of a generative model to reduce engineering and modeling time.

For architecture this has the benefit that facade type of double curved facade could become available for the ‘normal’ budgets in the more ‘regular’ building projects. This will give the architect new tools in the design of a building and it will be less constrained by the budget and cost aspects of such a façade. In the end this could have an influence on the architectonical domain and urban landscape. The double curved façade could have a more influential meaning besides the more traditional shaped buildings. At the moment our dwellings and offices consist mostly out of rectangular building envelopes, which I hope will change in a more mixed situation in the near future.

Figure 97: Rectangular street profile versus Mixed rounded street profile
**Matter of size**

Regarding a double curved façade it is really important to set have some relation between the double curvature and the height of the building. For example: if you have a building of 6 meters in height a bulge of 1 meter outward will have a dramatic effect on the appearance. The same bulge on a high-rise building of 100 meters will almost not be seen. It is the relation between the height of the building and the depth the facades moves outwards/inwards that makes the ‘effect’. See also Figure 98. In this case the most dramatic affect can be accomplished by a building lower in height. Making the building very low in height has another consequence. As the building gets lower the angles that make the double curvature are getting steeper. As the concept is based on flat segmented elements that are an approximation of a curvature they should keep a natural and fluent transition. Reducing an object in size while keeping this transition fluent will result in smaller frame sizes between the elements. In today’s offices it is preferable that window sizes will have a reasonable size. For mesh optimization a higher building would therefore preferable. As these two arguments contradict each other one should find a solution in the middle which would result that a mid-rise building would be the most optimal building type for the developed concept.

*Figure 98: Effect of relief compared to the height of a building*
**Geometrical Limits**

The designed concept has several geometrical limits to keep in mind as architect and engineer. The facade is based on standard facade components, for which we made the choice to use regular profiles to keep the concept simple. These standard profiles have a maximum positive (outward) and negative (inward) angle of connection between the panel (glass) and the actual profile, which will define the geometrical limitation of the system. The values you see in Table 11 are the sum of the angles for both panels in relation to the profiles. To get the maximum angle of one panel in relation to the profile you have to divide it by 2.

![Inward rotation](image1.png) ![Outward rotation](image2.png)

**Figure 99: Direction of rotation**

<table>
<thead>
<tr>
<th>Supplier</th>
<th>System</th>
<th>Rotation inwards</th>
<th>Rotation outwards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynaers</td>
<td>CW50</td>
<td>20°</td>
<td>30°</td>
</tr>
<tr>
<td>Reynaers</td>
<td>CW60</td>
<td>15°</td>
<td>15°</td>
</tr>
<tr>
<td>TKI</td>
<td>252</td>
<td>15°</td>
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<tr>
<td>Schueco</td>
<td>FW50</td>
<td>20°</td>
<td>20°</td>
</tr>
<tr>
<td>Schueco</td>
<td>FW60</td>
<td>20°</td>
<td>20°</td>
</tr>
</tbody>
</table>

**Table 11: Direction of rotation**

We can see that in the table that the Reynaers CW50 profiles allow the most flexibility solution regarding the maximum angles (20/30). To get more in touch what you can do with an angle of rotation of 30 degrees I made a small calculation. Say we have a facade that has panels with a width of 1 meter and the system allows us a rotation of 20 degrees. A 90 degree turn in the facade can then in theory be made within 4 elements (3 profiles) with a radius of 1.73 meters (3/√3). For an angle of 20 degrees the radius is around 2.8 meter, all within one floor height.

![Example calculation for 90 degree turn in facade using 1 m length elements](image3.png)

**Figure 100: Example calculation for 90 degree turn in facade using 1 m length elements**
So the maximum angle the curvature in the façade is defined by the system profile that is chosen at
the start of the project. But this is not the only factor. In the above calculation example we have
taken a panel width of 1 meter, or better it has an edge of 1 meter length. Of course the panels
would normally have all kind of dimension, but there should be a minimum length defined. This
length brings back the connection between the regular profile and the printed 3d node. The
connection is made by using special insert profiles that slide inside the cavity of the profile. To ensure
strength of the connection the insert length and insertion depth is defined by the structural forces
involved. For now we can define a safe depth of 30 cm of insertion. Taking in account the node
center point it will result in a total length of at least 150 cm for the edge of a panel
(4 x 30 cm + 2 x15).

Figure 101: Profile around edge of the panel; node-profile-node

The values we have found are limiting the geometrical curvature of the façade. Still the façade is also
bound to the mesh and structural connection points. A node poses a possible thread to the structural
stability as there will always be a limited amount of flexibility in the joints. To prevent a collapse of
the façade it is important to minimize the amount non supported nodes between 2 structural fixed
nodes to keep deflection within the regulation standards.

Conclusive the geometrical limits of the concept double curved façade are defined by:
- Maximum angle of rotation in the standard profiles ( +/- 20 degrees)
- Limits and deflections defined by structural calculations
- The minimum edge length of a panel ( +/- 1,5 meter)
Concept Renderings
Reflection

There were quite a few steps involved in this research project. I started off broad with a literature study to discover the different kind of façades in the double curved domain. Due to the complexity and the broadness of the subject it is really hard to get good focus on it. Also regarding to Oskomera I noticed that there was in the early stages no clear aim or goal to the subject, I had to find it somewhat myself. I think that I often wanted to explore the subject to deep and together with my tutors I sometimes had to ask myself: Is this relevant for the research? In which manner will this information contribute to the research? I noticed that I needed some guidance and found it in structuralizing the research in stages. The 3 main stages: analysis, design and process analysis gave structure.

Part of the analysis chapter is an extension of the literature study; you might see some remains of the problems I had, sometimes I went a bit too deep into the subject. For example to explain the façade systems it was good to do a step back, but I had to shorten it a bit on some point the keep in the relevant parts for my research.

My methodology was that of research by design. Of course one can find numerous solutions to design a double curved façade in some sort of standardized manner, but instead of theoretically thinking about possible solution, I just proceeded on what I thought was the best approach. The design evolved based on choice and rational decisions found during the research project, which is good. But one has to keep in mind that this just an approach of many, more roads will lead to Rome. So one should learn from it, but not necessary directly copy the results.

The process analysis stage has been kept relatively short, just pointing out the main points of attention. One can analyze the process structures in a company. But it will require a full research to make to appropriate conclusions and advice towards it. It was not in the league of this research.

Overall I’m satisfied with the results, still it is unfortunately that the real calculation where not made, they would have provided some harder evidence which would have made the results somewhat more conclusive. Still you should keep in mind how broad this topic started. For Oskomera I think it is a good lead towards a new research focused more on the technical aspects of the topic.
Conclusion

Conclusive from the research we can argue that it is plausible to design a double curved façade, based on a mesh and standard component. Making it possible to have a production process is in a repetitive manner.

This is achieved by reducing the geometrical problems back to the nodes and use traditional façade elements to solve. It allows the possibility to use standard façade profiles for the straight sections. The nodes are based on a single concept, but unique outcome.

To design and produce the nodes new tools are used: generative modeling saves time and allows for changes based on the input parameters. (A generative model for this concept has been proven in a real time model on which the included sketches where made.)

To produce the models rapid prototyping techniques should be used. This can be 3D printing or milling, where 3D printing allows for better geometrical detailing. Although the price of 3D printing is relatively high at the moment, it is expected to drop in the coming years and research to new materials extended.

It is important that the engineer should make sure it has a close relation with the architect early in the early stages of the design process. It will ensure that it can have an influence on the translation of the architectural model and the limitations of the system. This will be beneficial for Oskomera as there is a higher probability to acquire an order; when an architect works with a system specific to Oskomera.

The task of the engineer in the building processes is extended from the normal engineering task to the involvement in both the geometrical design process and the production of the nodes.

To summarize, the following steps are involved:

- Transform the architectural model to a wireframe
- Design the concept node using generative modeling software
- The influence of structural capabilities on the shape
- Find nodes that exceed limitations and adjust the wireframe
- Make a production model for all nodes
- Make a cam model for all nodes
- Print the models using 3D printing techniques
- Construct the façade on the building side
Points for further research

When we want to create a new façade product it will have to follow a long trajectory before it can actually be applied into an actual building project. This research is only the start of an exploration to the possibilities in engineering and producing a double curved façade from standard components. It will need a lot of additive research before it could be in anyway taken in production. Therefore I have formulated some points of further research that could be of interest for new research to Oskomera and the university:

- Structural calculation:
  The standard façade profile in the concept design are used in a different setup they the system supplier subscribes. How will the profiles cope with the different angles and does it need extra reinforcements? Can the nodes be structural optimized and will the insert profile be strong enough to cope with the moments?

- Calculations to the expected bulging and deflections:
  As the double curved façade is loaded it is expected that there will be a lot more bulging and deflections in the façade. What will the deflection be under load and how will the façade react to wind forces?

- Calculation to the thermal performances:
  How does this concept compare to a traditional façade and a double curved façade build with traditional methods, what are the problematic points and can they be improved?

- Material study in rapid manufacturing:
  What are the technical properties of materials used in the rapid manufacturing techniques are they applicable in façade engineering, what is their maximum strength and how will they cope with weather conditions?

- Cost Calculations:
  Production costs in relation to a regular façade and in relation to a double curved façade produced with traditional methods.

- Feasibility study to the design process, building process and market adaptation:
  The concept uses new production and engineering techniques that require early collaboration between architect and engineer in the design process. Are architects willing to work that early in the design process with a partner like Oskomera? Can the new processes easily be integrated in the current organization structure?

- Further study to the use of traditional elements in the concept:
  In the research possibilities multiple solutions and problems are explored. Sometimes the assumption was made that traditional elements could be used, without the need for specialized elements. Still most of these elements are not totally used in traditionally fashion; they probably will need further research and possible adaptations to fit a final design. This is for example regarding, brackets, rubbers, façade profiles etc.
Bibliography


Klein, T. Photo Archive.


Appendix I – Grasshopper model