Computational Mesh Geometry and Architectural Construction;

Generating Construction Aware Quadratic Meshes
Considering the Possibility of Torsion Free Nodes and Planar Faces

Thesis, M-CDC
W.S 2016-17

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2nd Advisor: Dipl. – Ing. Martin Manegold
Structure Consultant: Prof, Jens Uwe Schulz
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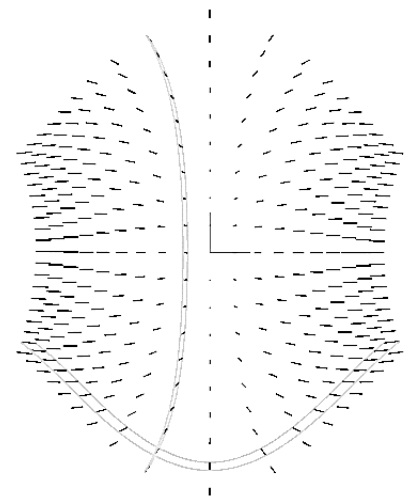


Contents

Goal

Discretizing double curved surfaces, ***Complex***, into a mesh

which is buildable with flat sheet of Material, ***Simple***

Objectives

Introducing workflow from design to construction

Explaining relationship between geometry, construction and form finding

Connecting computation tools and experimental methods

Reducing complexity of construction

Clarifying Architectural approach as emerging process

Design to Construction Process

Form finding Values

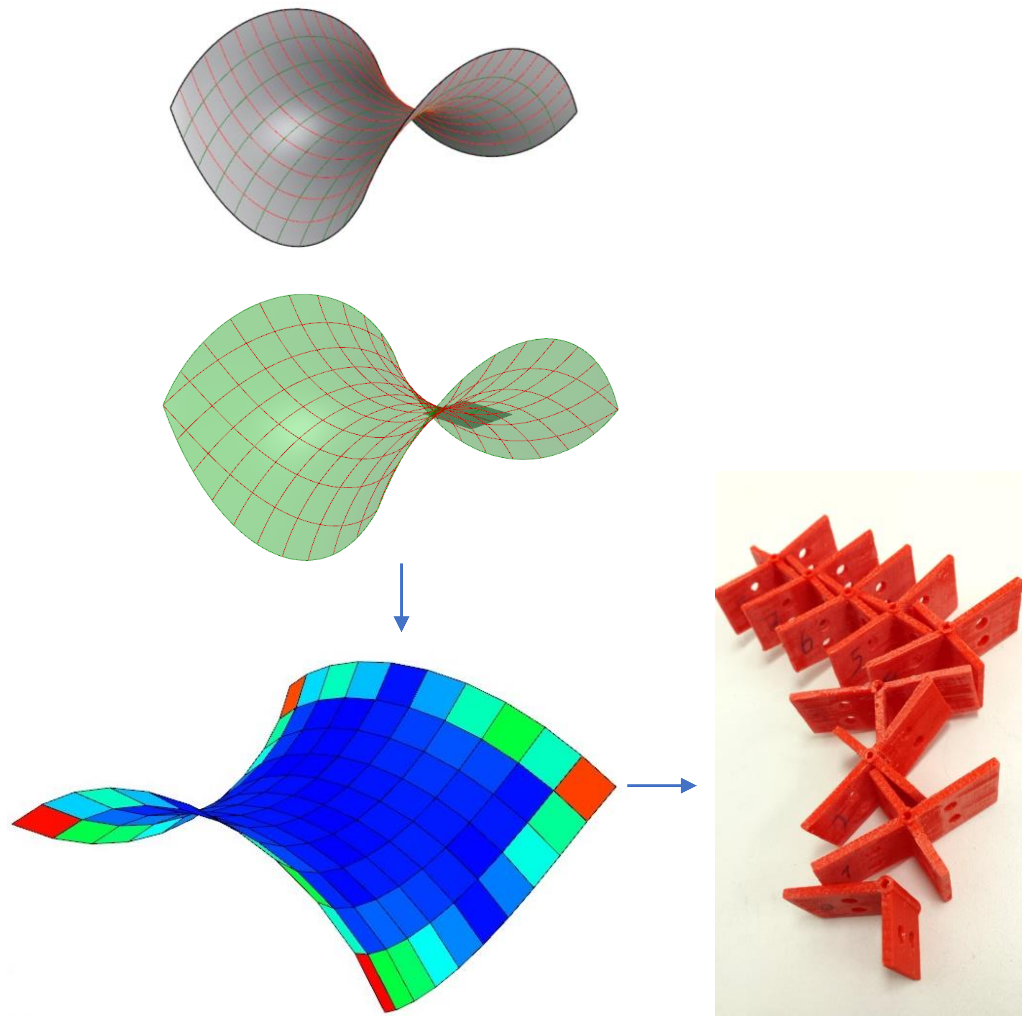
Simulation and extracting mesh

Surface from mesh

P.C lines network, P.Q mesh

Structural analysis

Executive Detailing and Construction



Surface Design and Discretization:

. Aeronautic and Manufacturing Industries

. Gaming; Game Processing

. Medical Data; MRI Scans

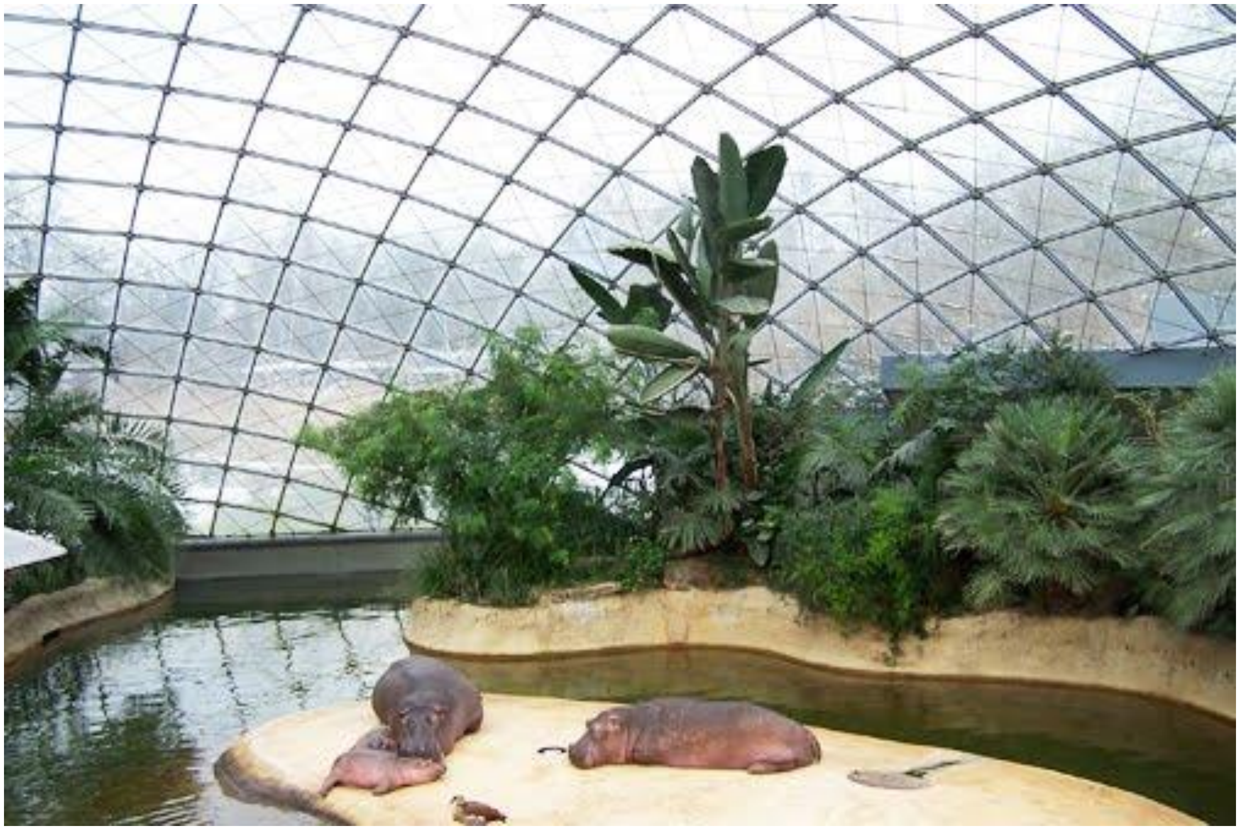
and

. **Architectural Manufacturing**

Surface Discretization in Steel and Glass Architecture

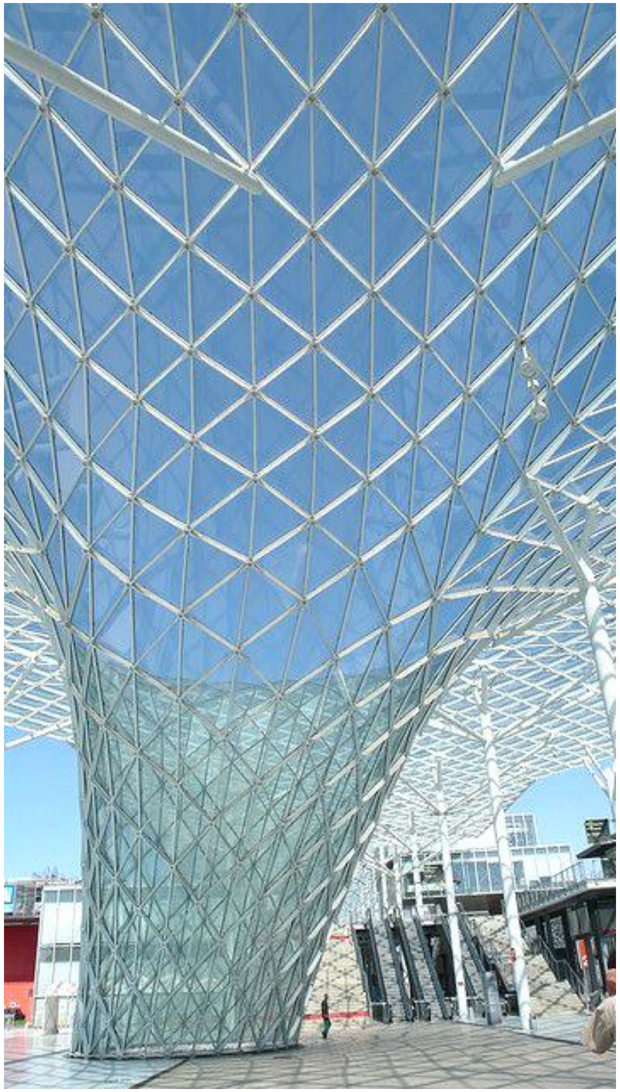
Glashaus-Pavilion by Bruno Taut in Cologne

Surface Discretization in Steel and Glass Architecture



Berlin Zoo by Schlaich Bergermann

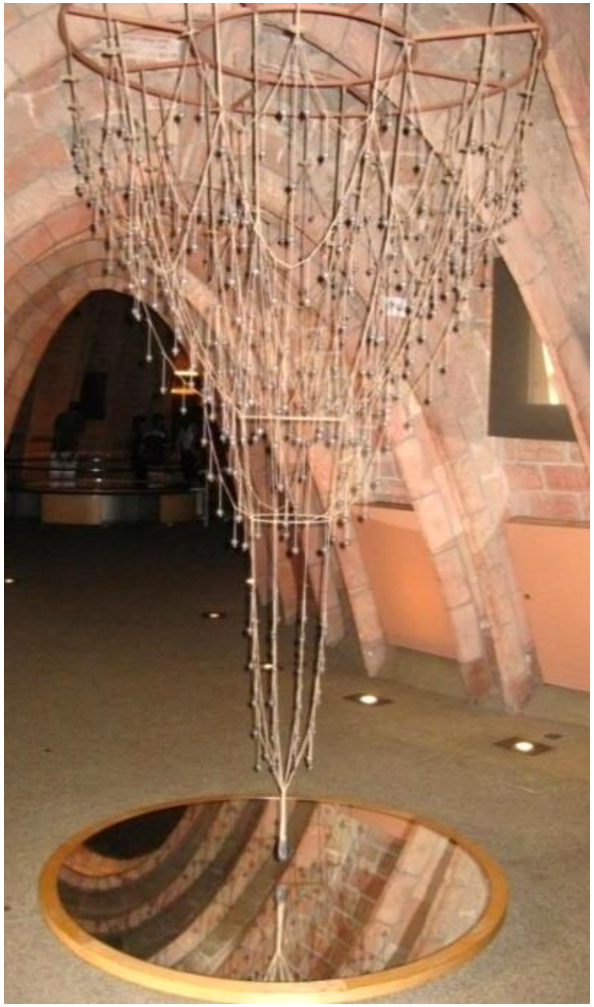
Surface Discretization in Steel and Glass Architecture



Milan trade fair, by Studio Fuksas

Form Finding Instead of Shape Drawing

Hanging Model; Force Flow



Hanging Model experimental model by Antoni Gaudi

Form Finding Instead of Shape Drawing

Soap Films; Minimum Material

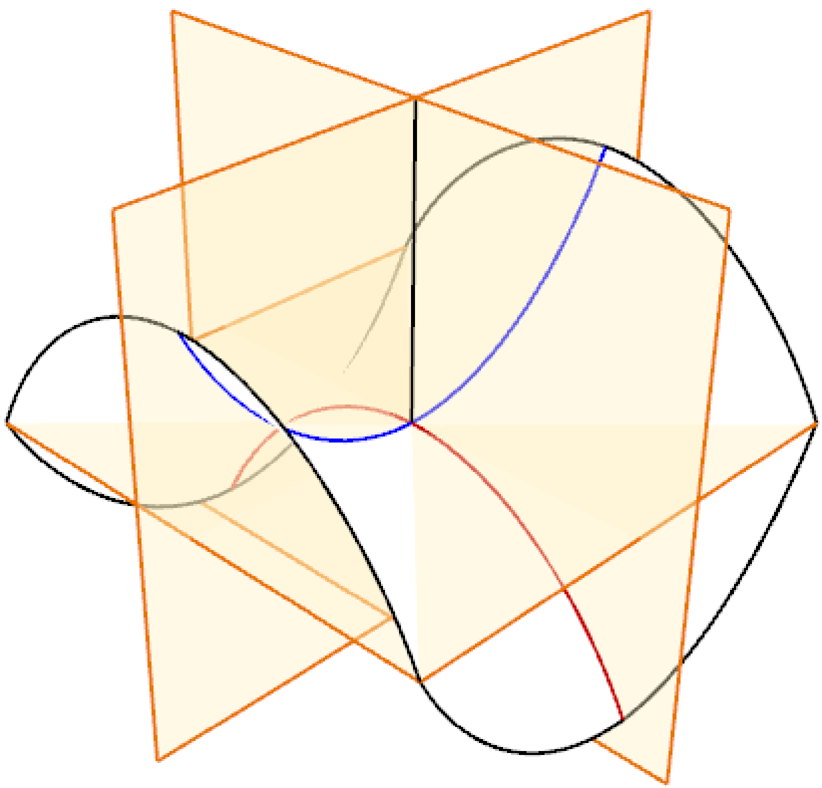
Olympic Park Munich by Frei Otto
Form Finding Based on Dynamic Relaxation and Soap Films

Form Finding Instead of Shape Drawing

Wet Fabric; Force Flow

Service station, Deitingen Sud, Switzerland
Form Finding Based Suspended Wet Fabric

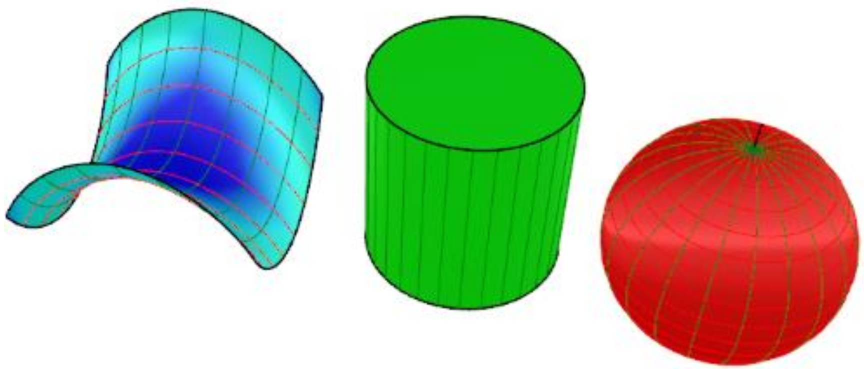
Principal Curvature



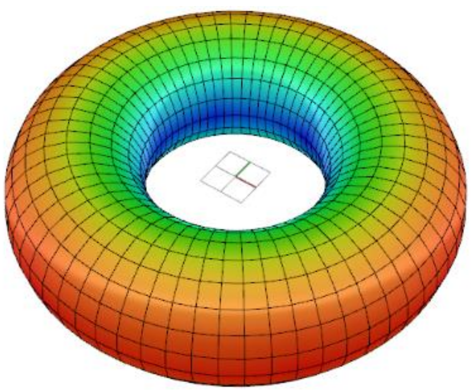
Saddle surface with principal curvatures in an Arbitrary Point

Maximum and Minimum amount of Bending
$K1 = 1/R1$, $K2 = 1/R2$

Gaussian Curvature



K(-) Blue, K(0) Green, K(+) Red



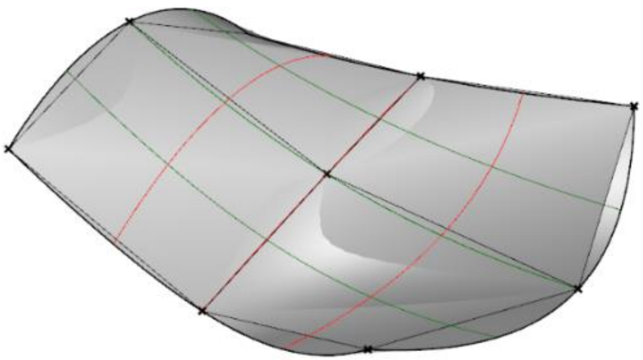
Gaussian Curvature:

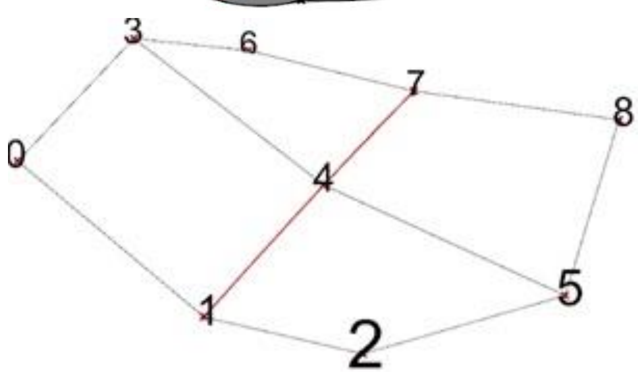
K= k1.k2

If K = 0 : Developable Surface

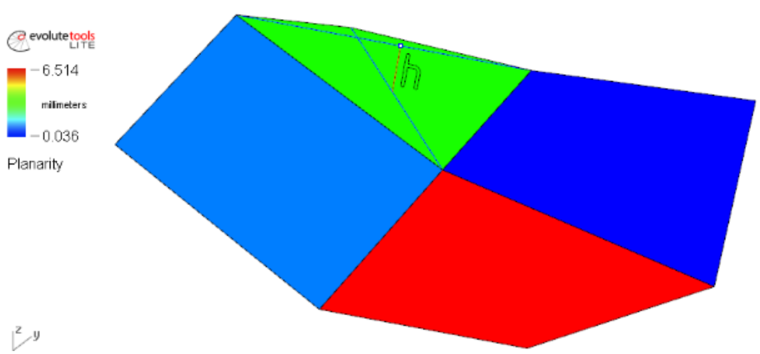
If K ≠ 0 : Double Curved Surface

Surface Discretization





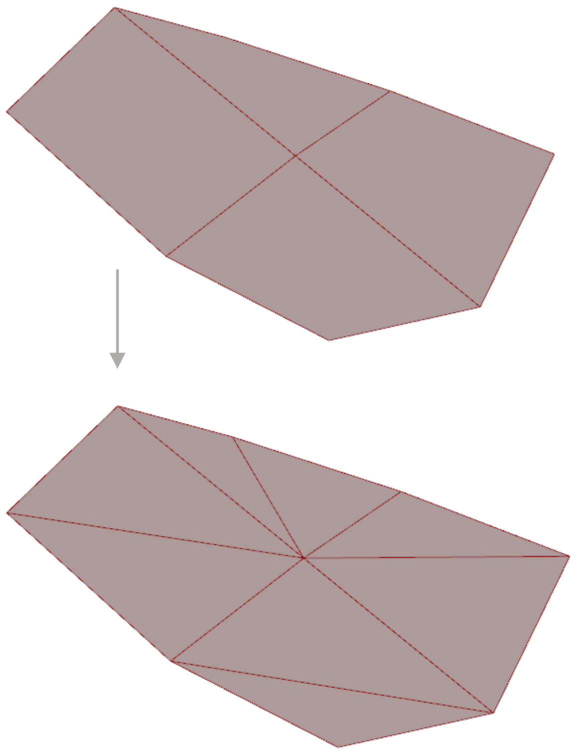
U,V Parametrization of Certain Parameters in U and V Domain on Surface and Connecting them in Certain Rule of Connection, **Mesh**



First Visible Problem
Nonplanarity

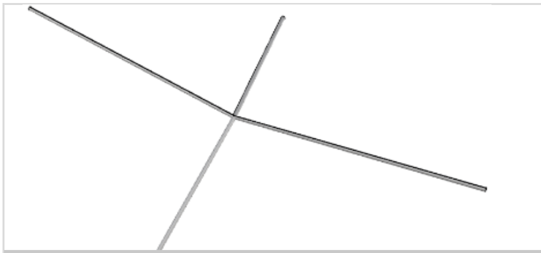
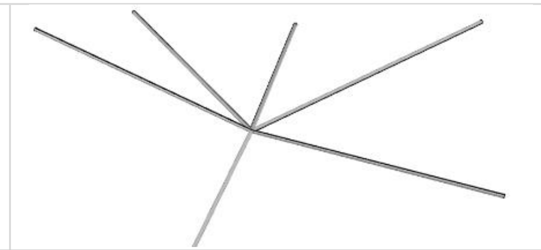
Surface Discretization

First Solution



If

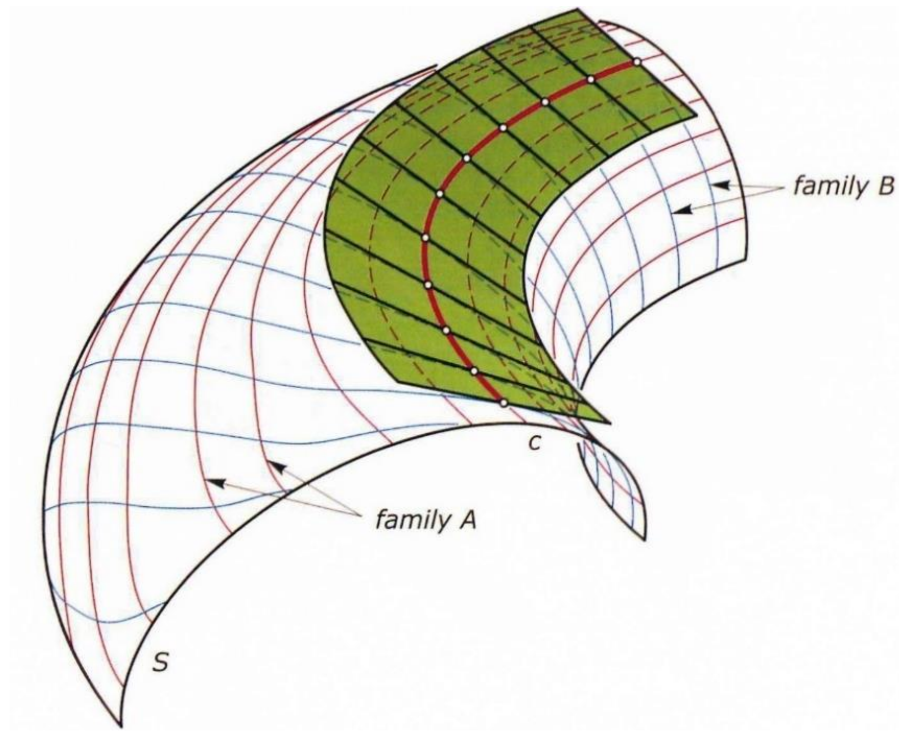
Planarity

	
Valence:4	Valence:6
Panel Cut: Easier	Panel Cut: Harder
Steel: Less	Steel: More
Glass: More	Glass: Less
Exact Offset with Normal Vector: possible	Exact Offset with Normal Vector: Impossible

Planar-Quadratic Meshes;
Conjugate Curve Network

Curve network is conjugate If:

Tangents Build a Developable Surface



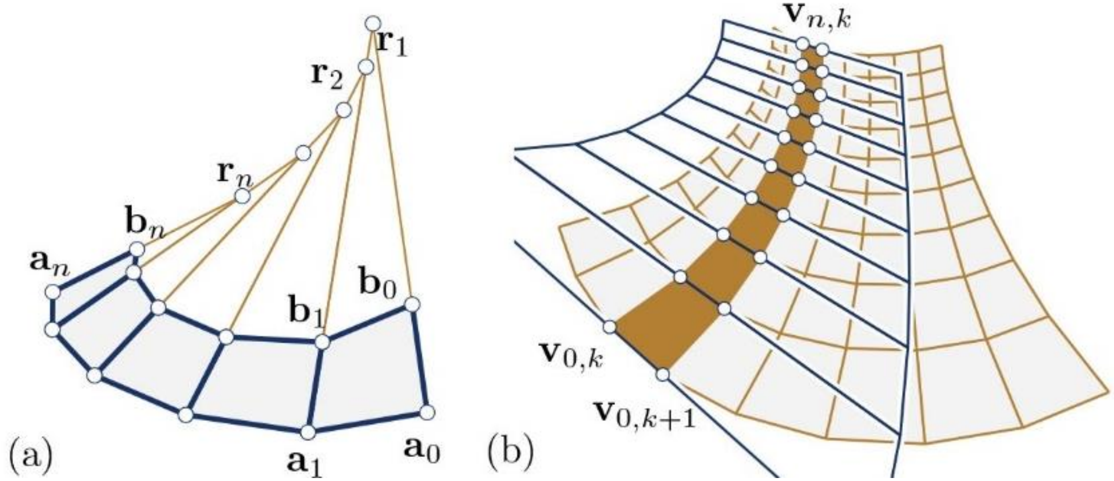
conjugate curve network of two family of A and B

Planar Quadratic Meshes;
Principal Curvature Lines Network

Conjugate and Orthogonal

Only one Possibility:

Principal Curvature Lines Network



(a) PQ strip as a discrete model of a developable surface.
(b) Discrete developable surface tangent to PQ mesh along a row of faces

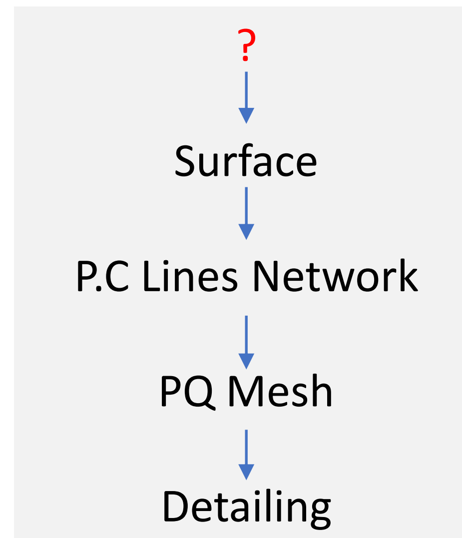
Review

PC Lines Network Process:

1. Finding Principal Directions at an arbitrary Point on **Surface**
2. Moving toward Directions in a very small Distance
3. Finding Closest Point on the Surface
4. Iteration Process
5. Finishing the Iteration Process at the edge of the Surface

PQ Mesh Generation Process:

1. Preparing Conjugate and Orthogonal Network of Curves
2. Intersection of Family A and Family B
3. Putting the Intersections in a certain Order
4. Connecting the Ordered Points; Extracting Mesh

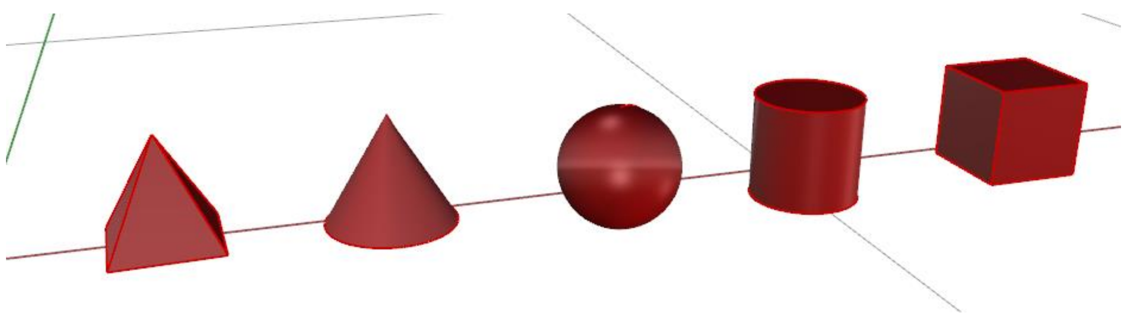


Form Finding and PQ Mesh;

Minimal Surface

Values to Find Smooth Surfaces;

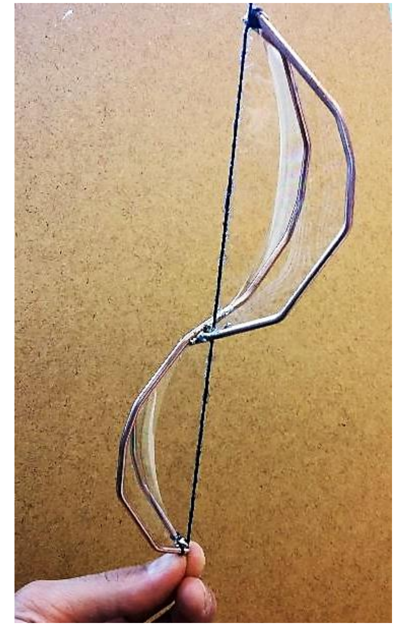
Minimum Material Usage and Force Flow



Volume: 1000 m3
Areas: 758, 729, 484, 554, 600m2

Form Finding and PQ Mesh;

Minimal Surface



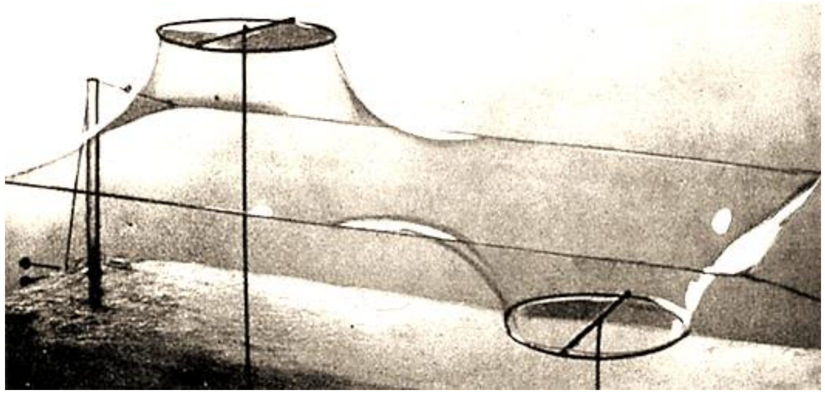
Soap Films

minimal surfaces are curvature-continuous
surfaces with vanishing mean curvature

minimizing surface area under given boundary conditions

Form Finding and PQ Mesh;

Minimal Surface



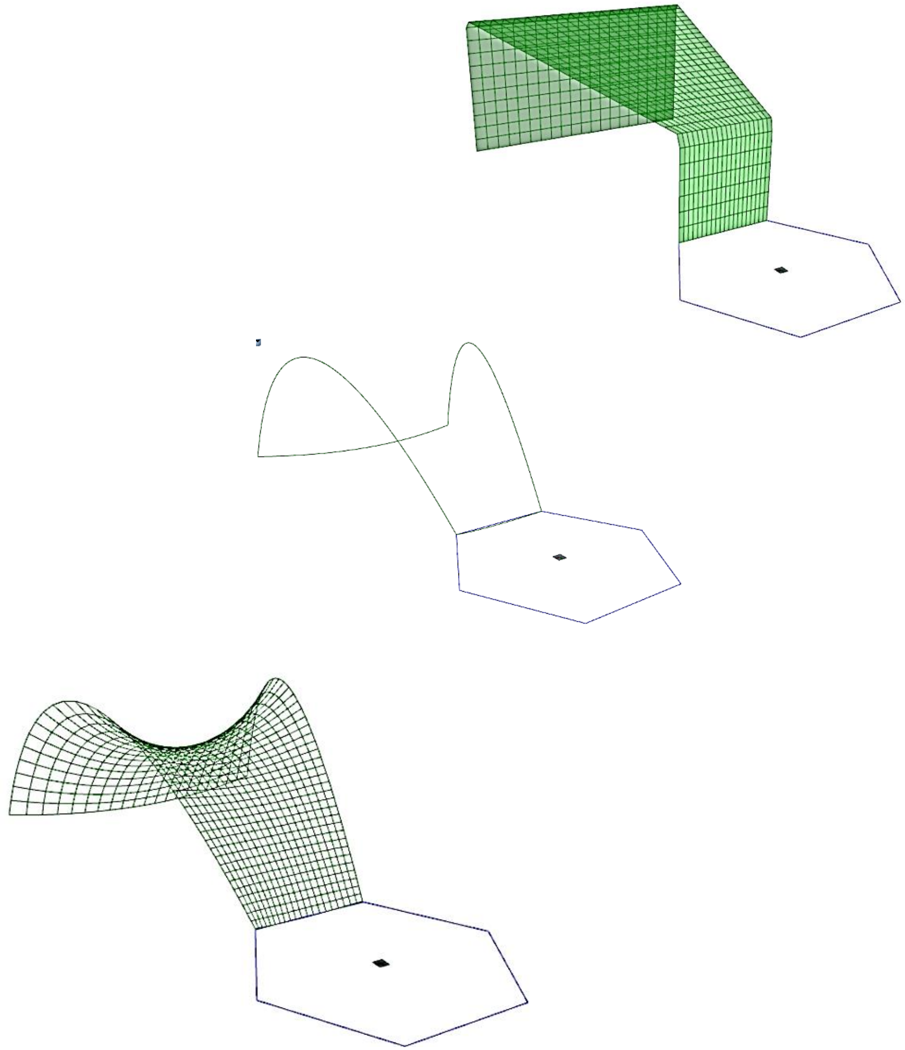
Soap Films

Frei Otto’s experimental form finding samples

Form Finding and PQ Mesh;

Minimal Surface Simulation by

Dynamic Relaxation



Procedure:

1. Base Mesh
2. Frame and Boundary Condition
3. Setting Values
4. Simulation

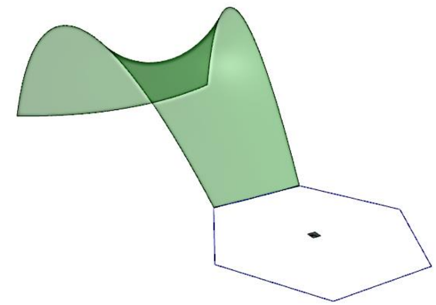
Form Finding and PQ Mesh;

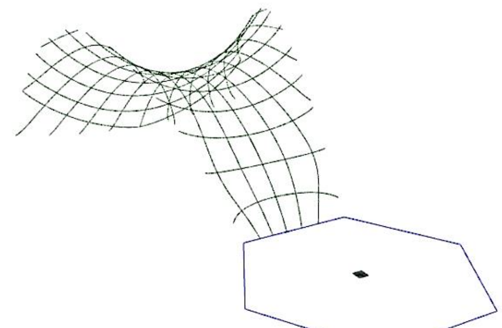
Minimal Surface Simulation by

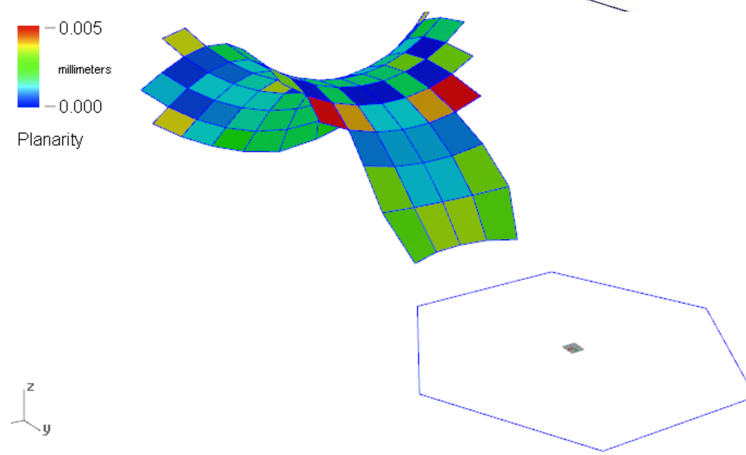
Dynamic Relaxation

Procedure:

5. Geometry out of Simulation
6. PC Lines Network
7. PQ Mesh
8. Prototype







Form Finding and PQ Mesh;

Hanging Models

Catenary

Hanging chain or cable formed under its own weight

when supported only at its ends

With good manner of force flow

And preserves materials avoiding bending

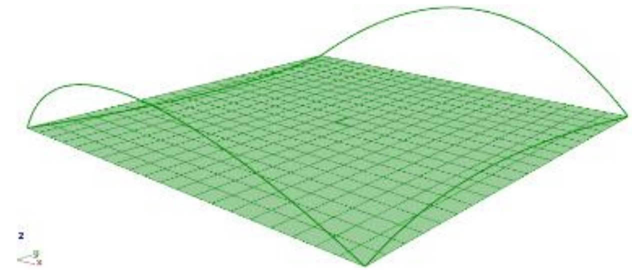
Form Finding and PQ Mesh;

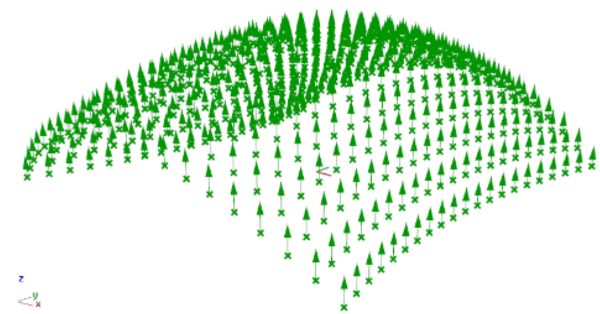
Hanging Models

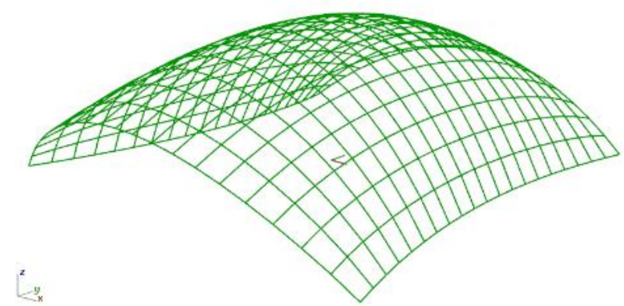
Experimental Hanging Model Form Finding

Form Finding and PQ Mesh;

Hanging Models







Procedure:

1. Base Mesh

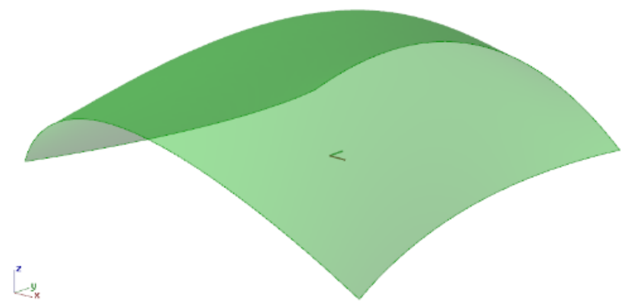
2. Frame and Boundary Condition

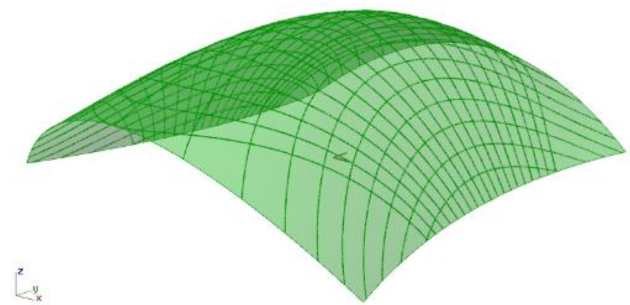
3. Setting Values

4. Simulation

Form Finding and PQ Mesh;

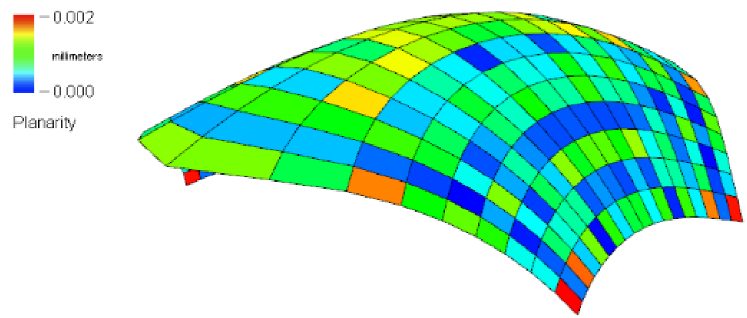
Hanging Models





Procedure:

5. Geometry out of Simulation
6. PC Lines Network
7. PQ Mesh
8. Prototype



Structural Simulation

Anticlastic Beam

Preprocessing:

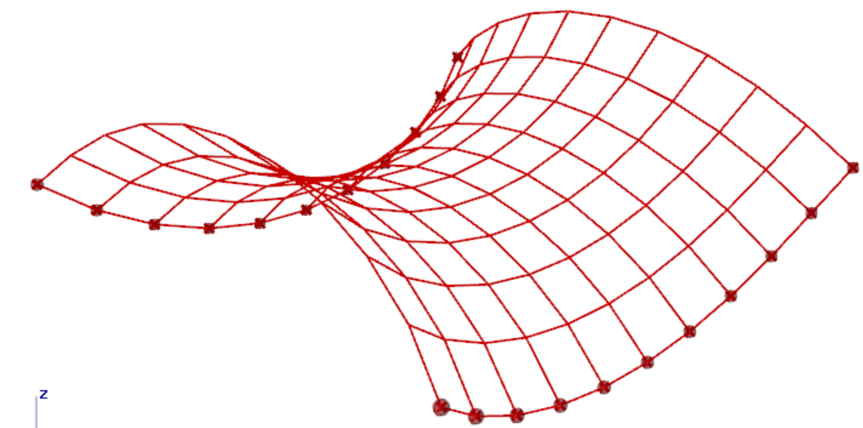
Rhino Geometry (Nodes and Curves- Structural)

&

Border Condition

&

Material and Cross Section Properties



Material:

Structural Steel; S-355

Material Properties:

Self-weight: 78.5 [kN/m^3]

Density: 7850 [kg/m^3]

Elastic modulus: 2.100e+5[N/mm^2]

Poisson ratio: 0.300

Cross Section:

Rectangular; B/H = 75^{mm}/120^{mm}

Structural Simulation

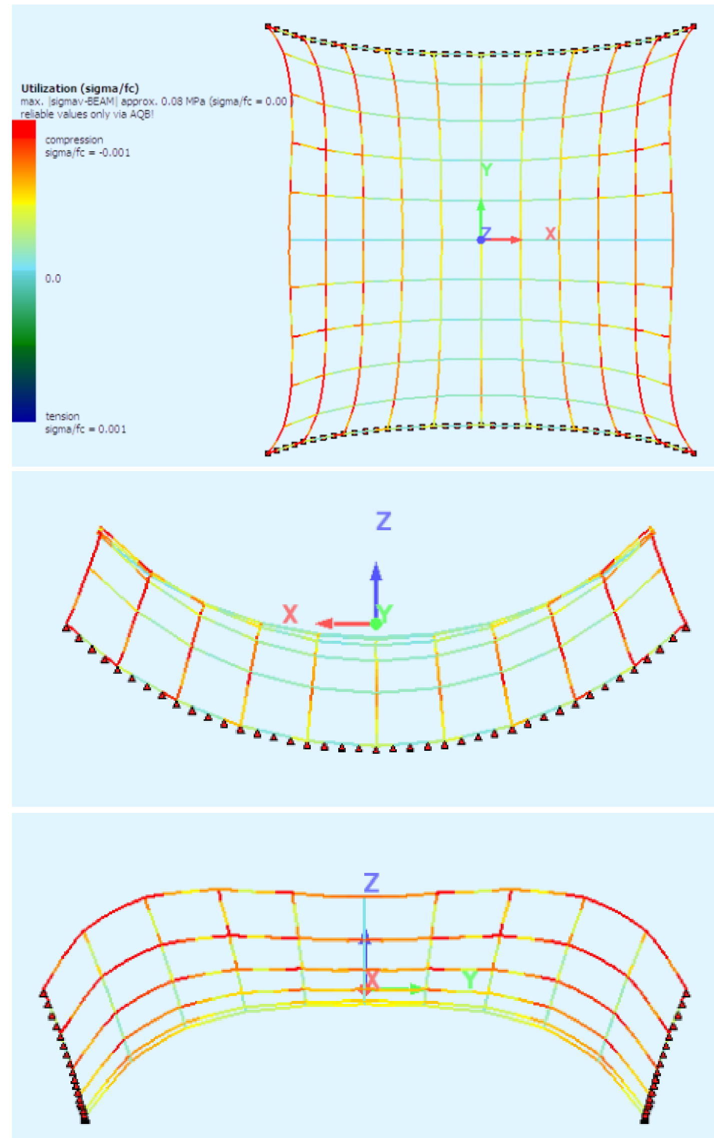
Anticlastic Beam

Processing:

FEM – Sofistik

Solvers:

Load, ASE



Structural Simulation

Synclastic Beam

Preprocessing:

Rhino Geometry

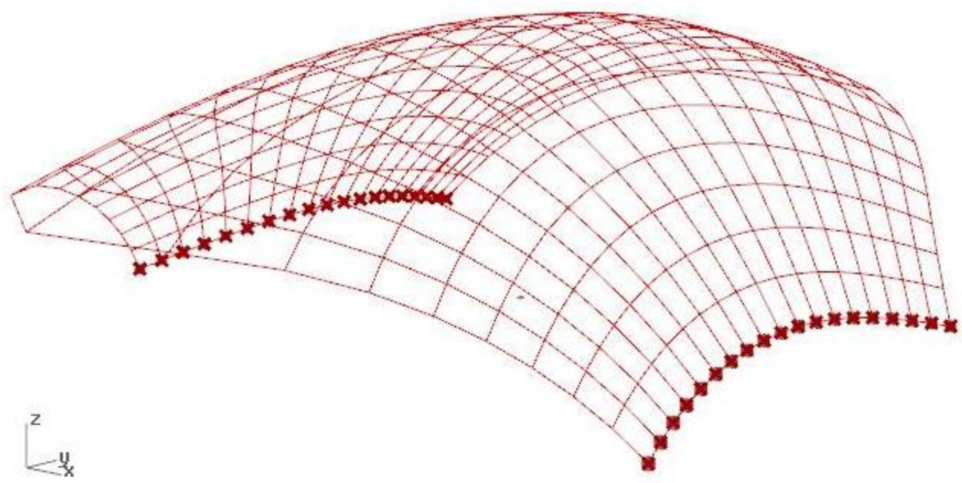
(Nodes and Curves- Structural)

&

Border Condition

&

Material and Cross Section Properties



Material:

Structural Steel; S-355

Material Properties:

Self-weight: 78.5 [kN/m^3]

Density: 7850 [kg/m^3]

Elastic modulus: 2.100e+5[N/mm^2]

Poisson ratio: 0.300

Cross Section:

Rectangular; B/H = 120^{mm}/220^{mm}

Structural Simulation

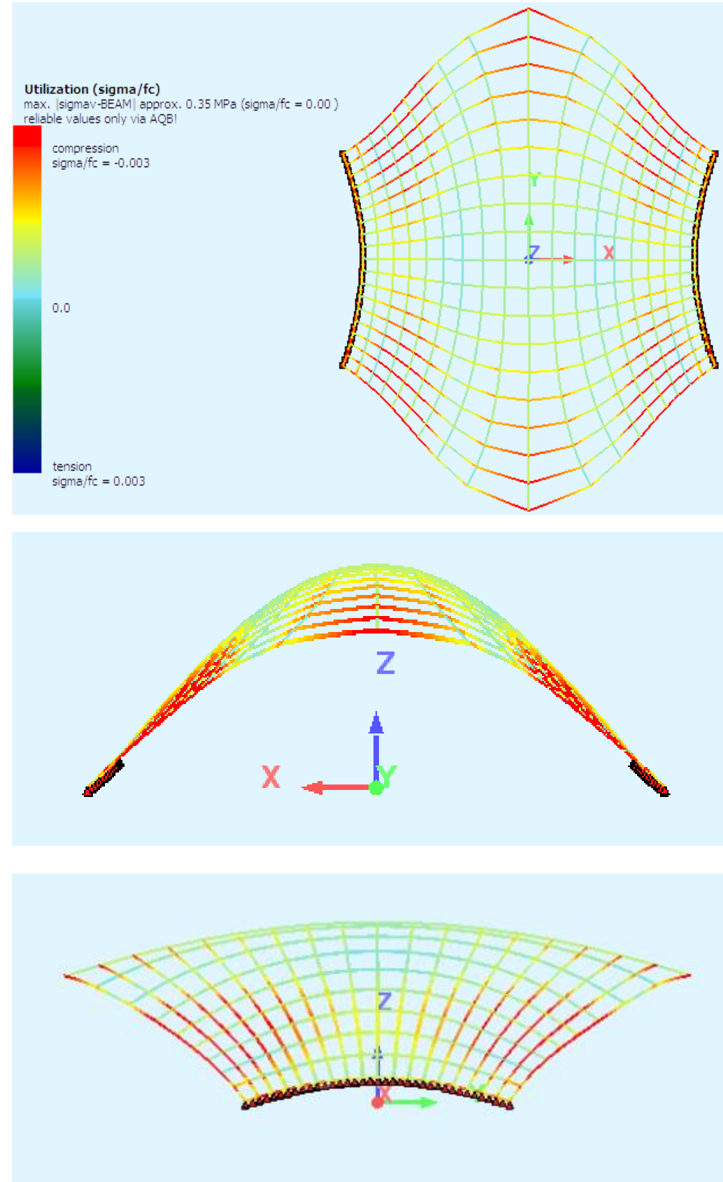
Synclastic Beam

Processing:

FEM – Sofistik

Solvers:

Load, ASE



Structural Analysis

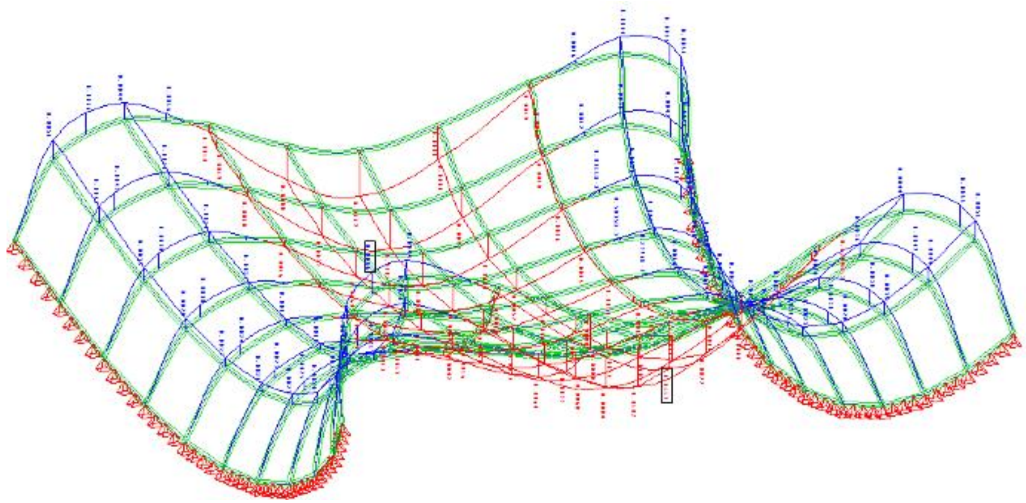
Anticlastic Beam

Nodal Displacement

Node Number	X-Coordinate(m)	Y-Coordinate(m)	Z-Coordinate(m)	Z- Displaced Node Numbers	Z- Displacement(mm)
1001	7.791	8.838	-1.271	1019	0.1401
1002	7.792	-8.838	-1.275	1020	0.1153
1003	6.019	8.501	-2.305	1021	-0.0582
1004	6.020	-8.501	-2.309	1022	-0.2466
1005	4.096	8.284	-3.063	1023	-0.3254
1006	4.096	-8.284	-3.066	1024	-0.2459
1007	2.072	8.161	-3.524	1025	-0.0570
1008	2.073	-8.161	-3.528	1026	0.1165
1009	0.000	8.122	-3.679	1027	0.1408
1010	0.000	-8.121	-3.683	1028	0.1121
1011	-2.073	8.161	-3.524	1029	0.0896
1012	-2.073	-8.161	-3.527	1030	-0.0516
1013	-4.096	8.284	-3.061	1031	-0.2043

Nodal displacement for parabolic beam structure in Z.

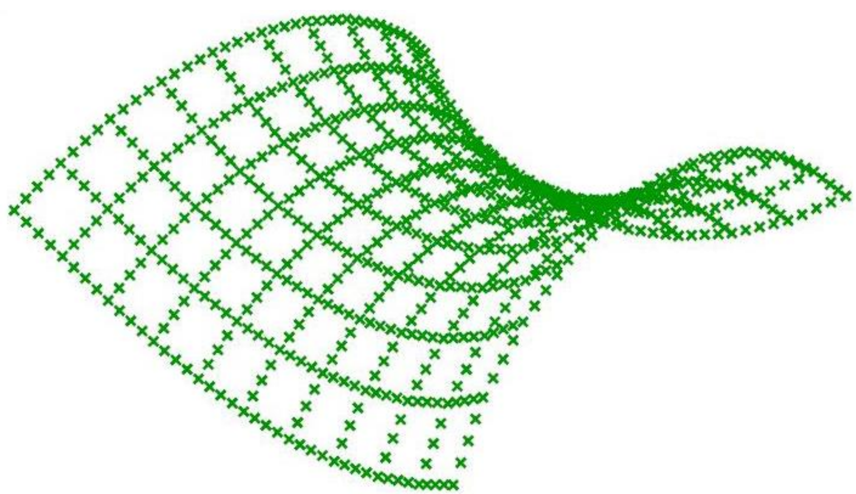
(Min = -0.376mm, Max = 0.178mm)



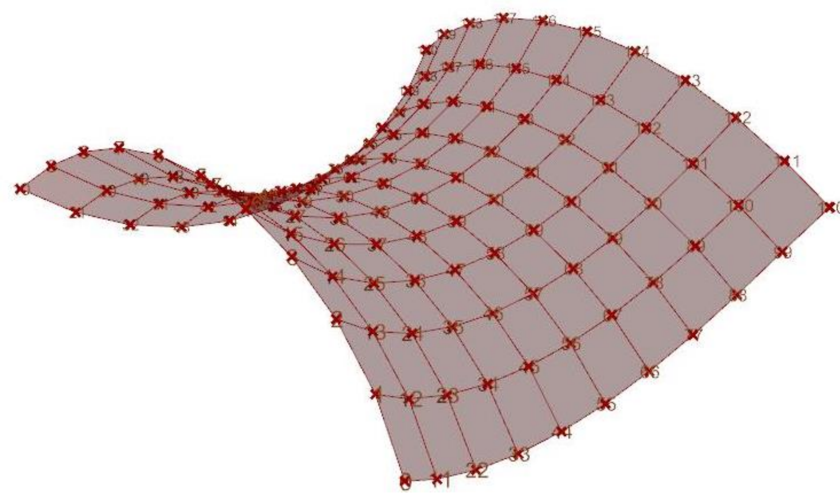
Structural Analysis

Anticlastic Beam

Data Exchange, Sofistik to Rhino



Sofistik Nodes

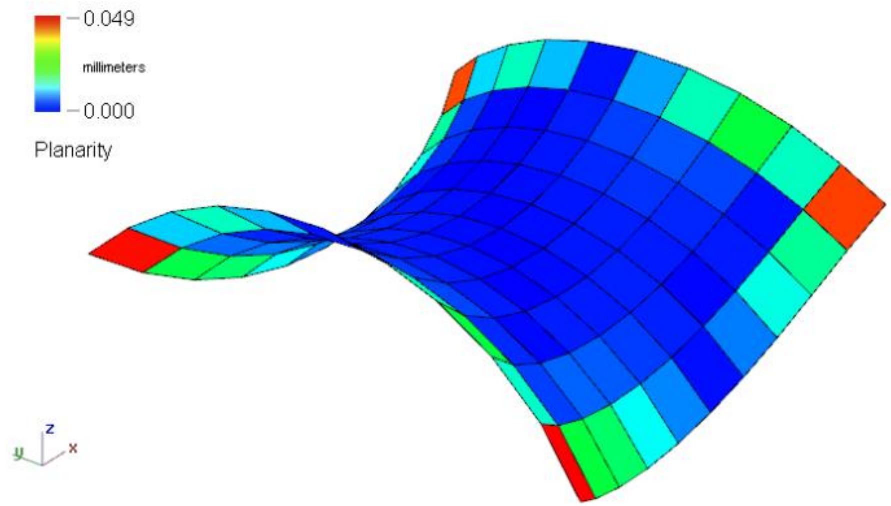


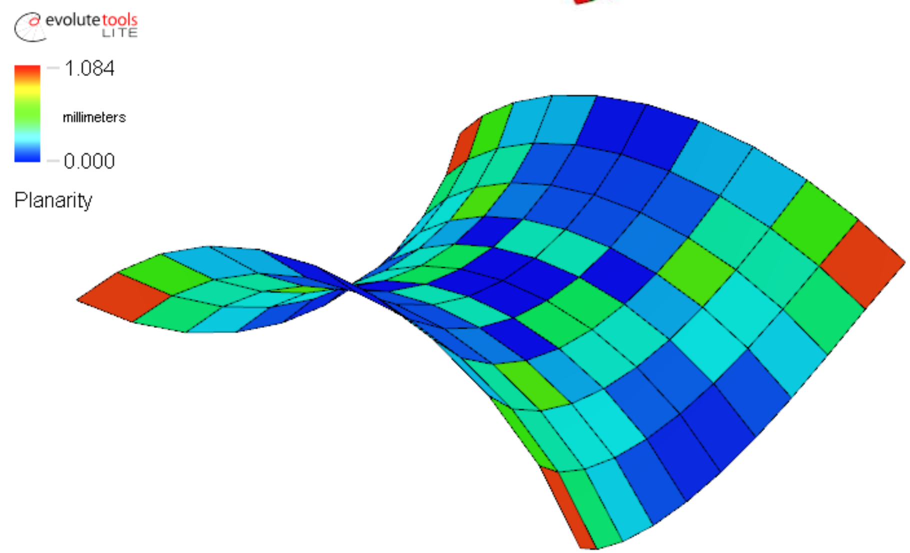
Mesh after Displacement

Structural Analysis

Anticlastic Beam

Planarity Before-After





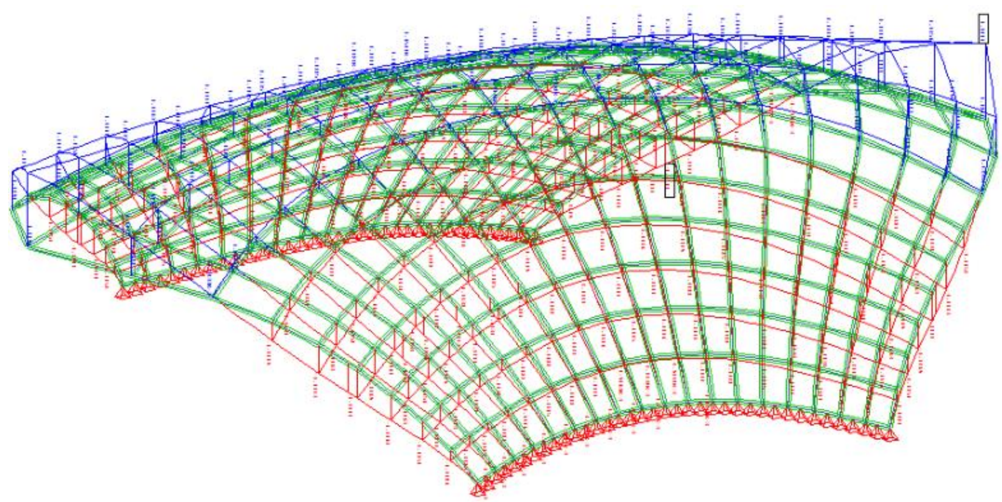
Structural Analysis

Synclastic Beam

Nodal Displacement

Node Number	X-Coordinate(m)	Y-Coordinate(m)	Z-Coordinate(m)	Z-Displaced Node Numbers	Z-Displacement (mm)
1001	13.220	7.495	0.063	1002	-0.1339
1002	12.499	8.125	1.095	1003	-0.2536
1003	11.779	8.820	2.021	1004	-0.3425
1004	11.055	9.586	2.844	1005	-0.3868
1005	10.297	10.437	3.583	1006	-0.3674
1006	9.433	11.409	4.272	1007	-0.2476
1007	8.337	12.566	4.936	1008	0.0368
1008	6.761	13.992	5.575	1009	0.5187
1009	4.335	15.692	6.043	1010	1.0067
1010	-0.031	17.448	5.970	1011	0.4957
1011	-4.355	15.679	6.042	1012	0.0106
1012	-6.772	13.985	5.572	1013	-0.2710
1013	-8.342	12.566	4.934	1014	-0.3867

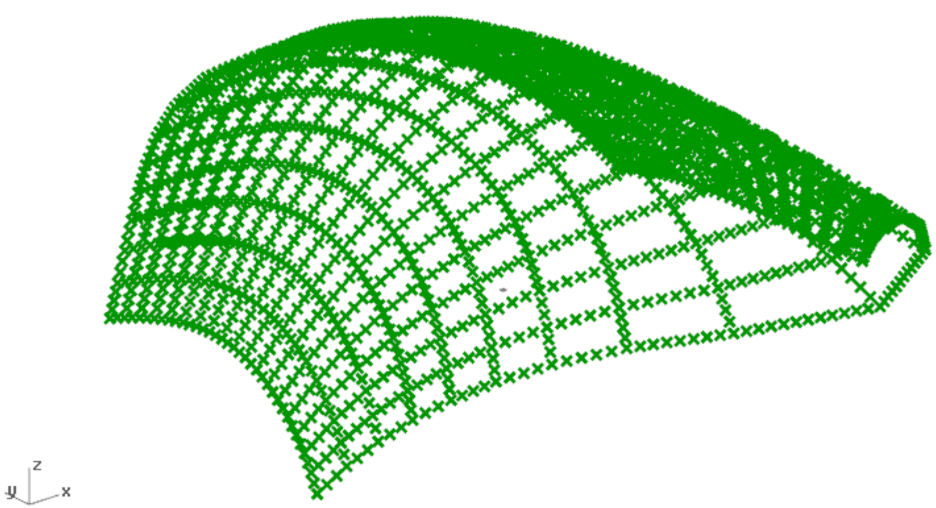
Nodal displacement for synclastic beam structure in Z. (Min = -0.405mm, Max = 1.1mm)



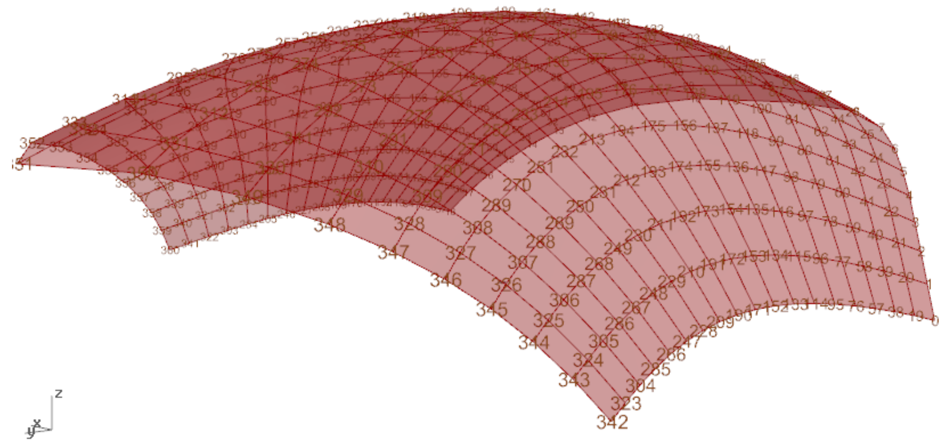
Structural Analysis

Synclastic Beam

Data Exchange, Sofistik to Rhino



Sofistik Nodes

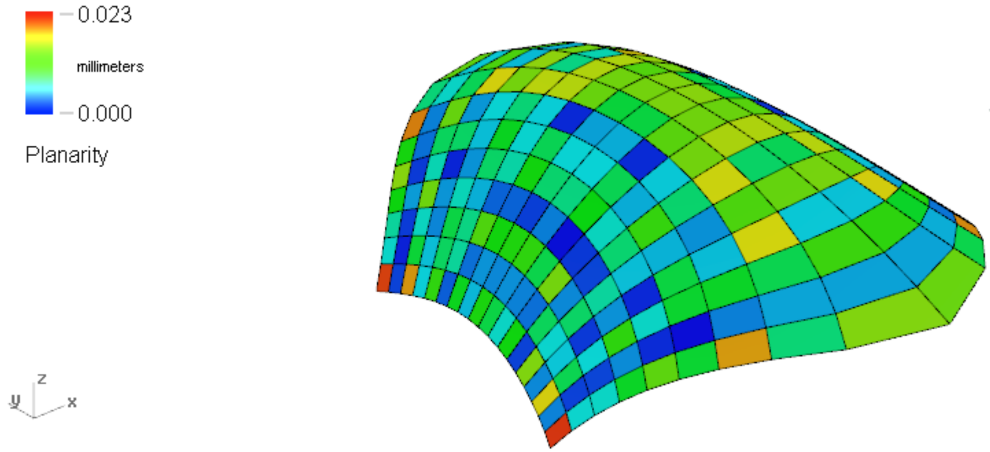


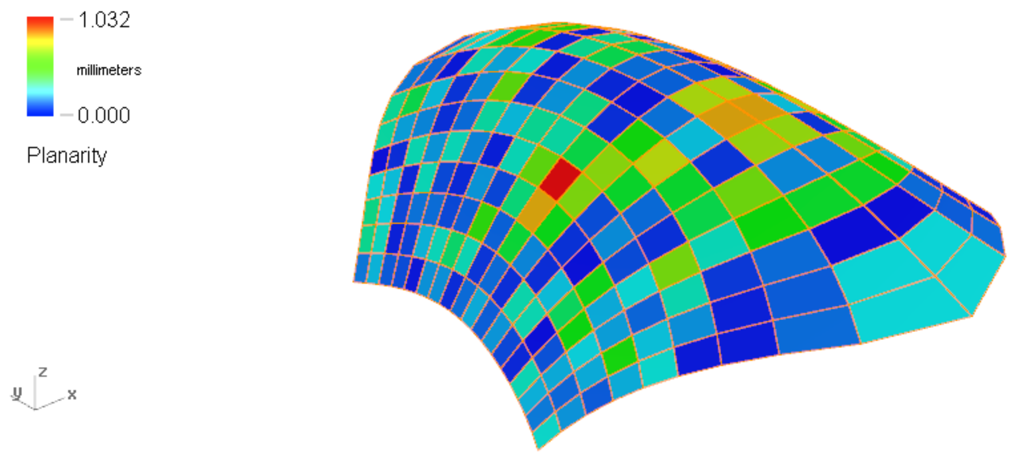
Mesh after Displacement

Structural Analysis

Synclastic Beam

Planarity Before-After

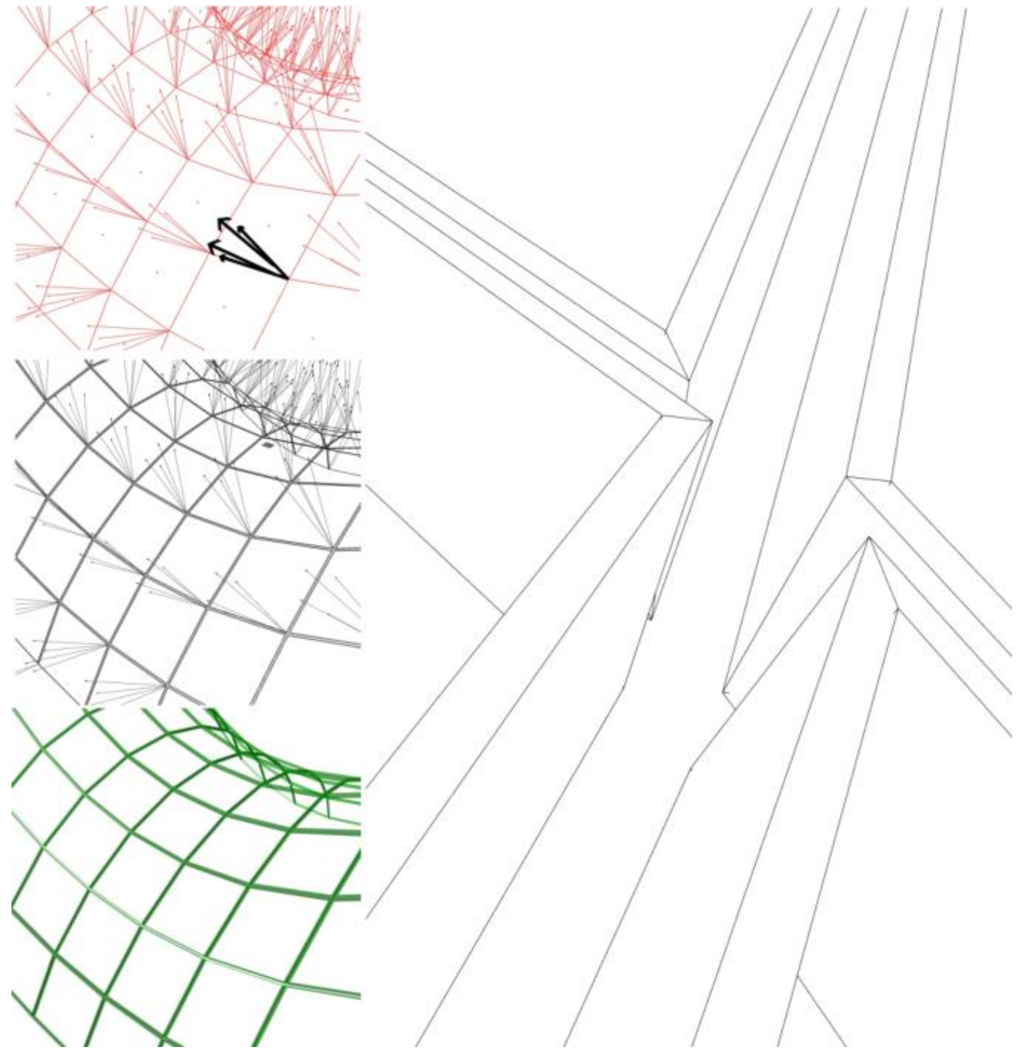




Conventional Meshes

and

Node Construction



Construction

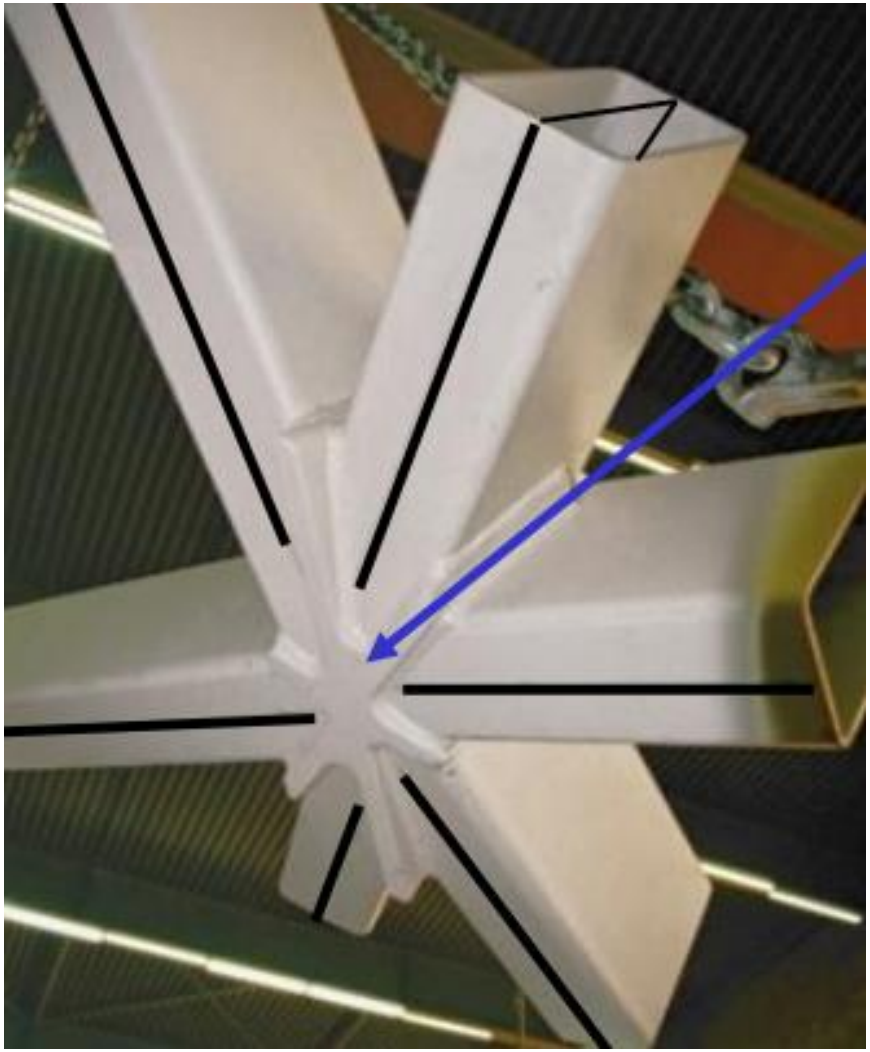
when

neighboring normal vectors are not coplanar

Conventional Meshes

and

Node Construction



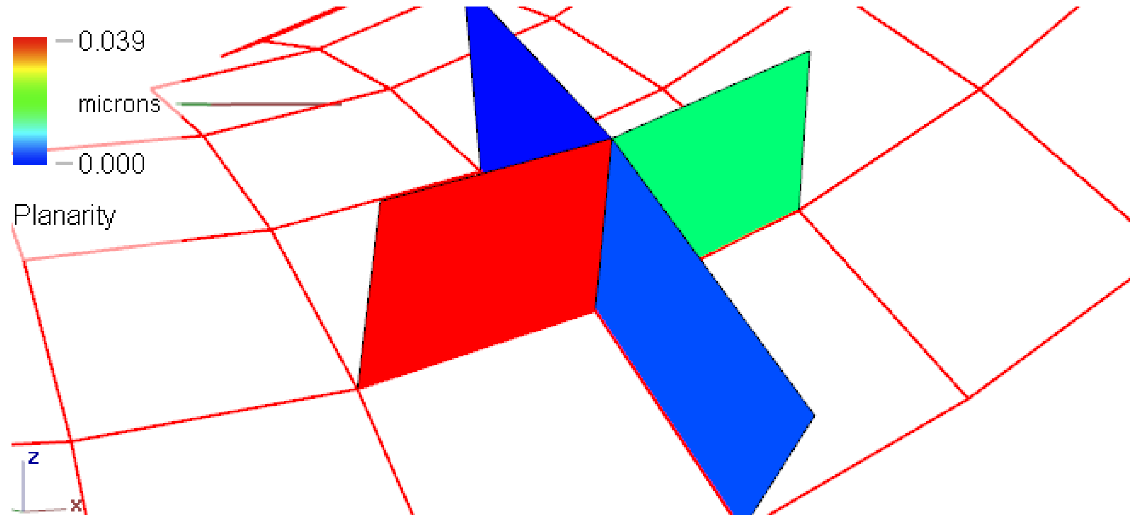
Node Construction

in Triangular Meshes

PQ Meshes

and

Torsion Free Nodes

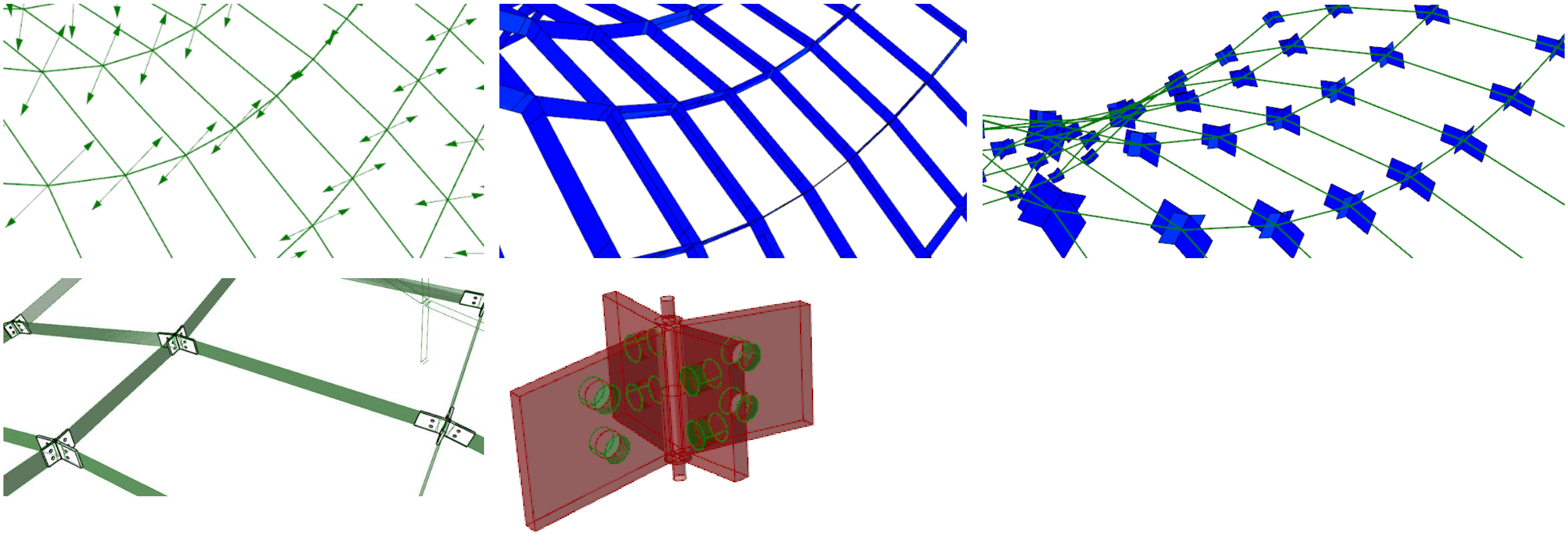


Coplanarity of neighboring normal vectors in PQ mesh

PQ Meshes

and

Torsion Free Nodes



Node Design Process

PQ Meshes

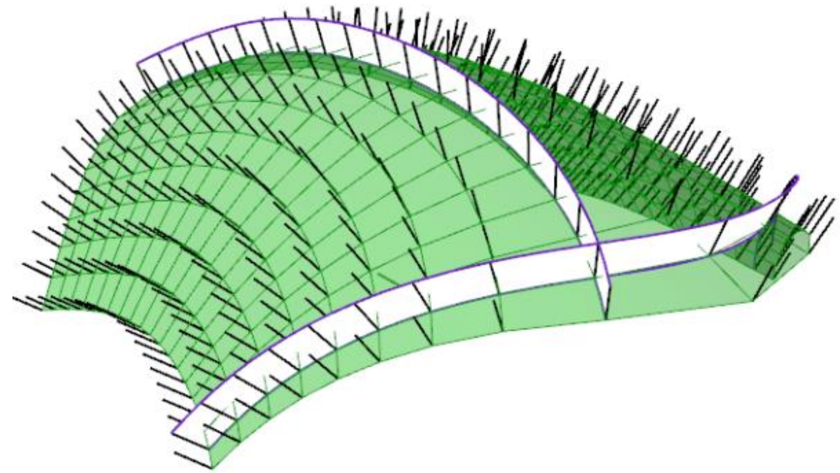
and

Torsion Free Nodes

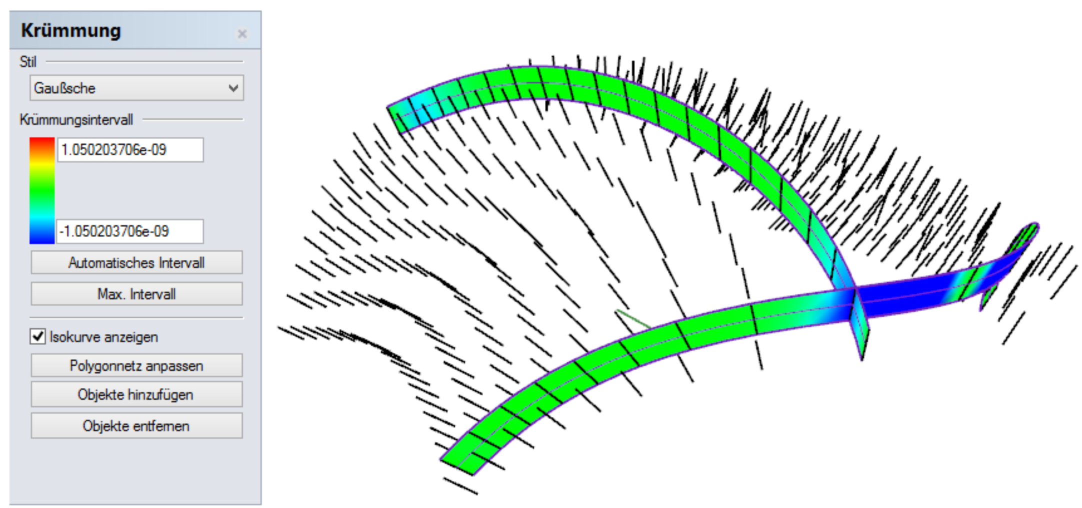
Construction Benefits
1. Alignment of Axes' Plane
2. No torsion Force in Nodes
3. Capability of Offset Meshes
4. Less Complexity in the Node Construction
5. Vertical Extruded Central Element

Further Development in Construction;

PQ Meshes and Flat Sheets of Material

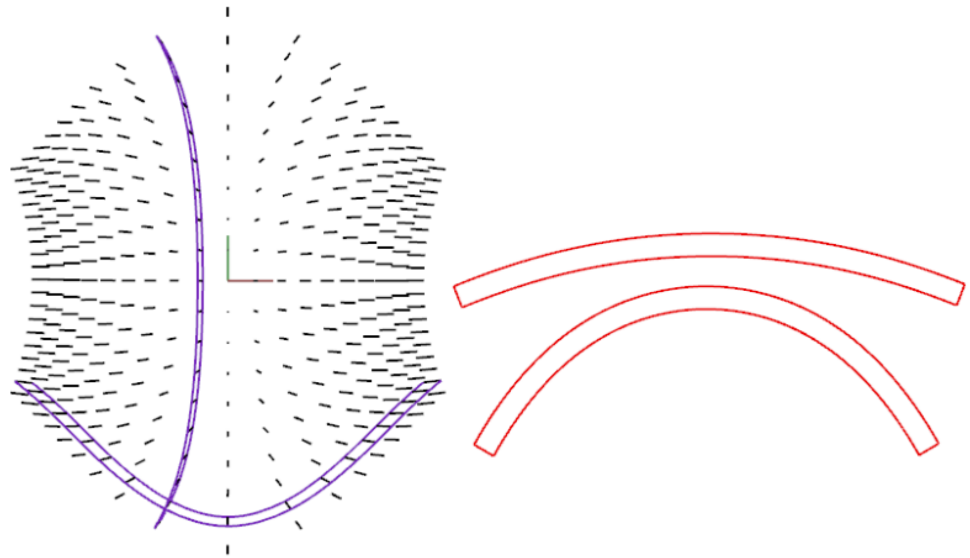


Gaussian curvature of normal stripes

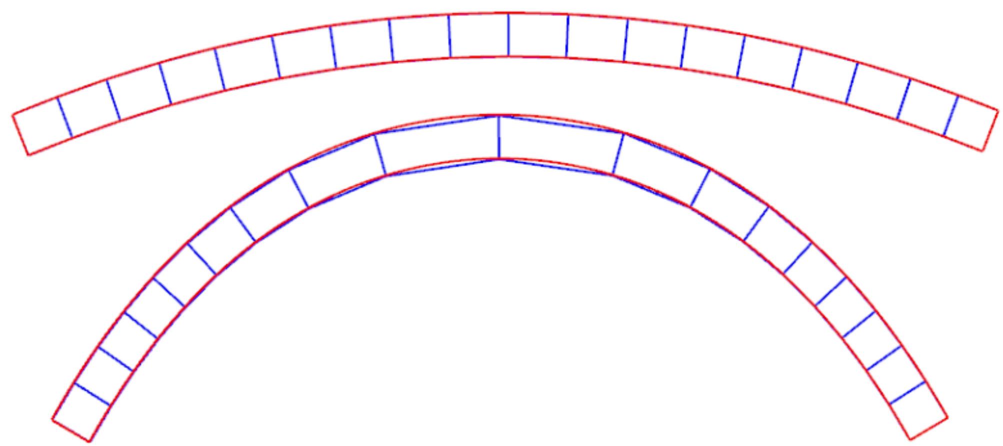


Further Development in Construction;

PQ Meshes and Flat Sheets of Material



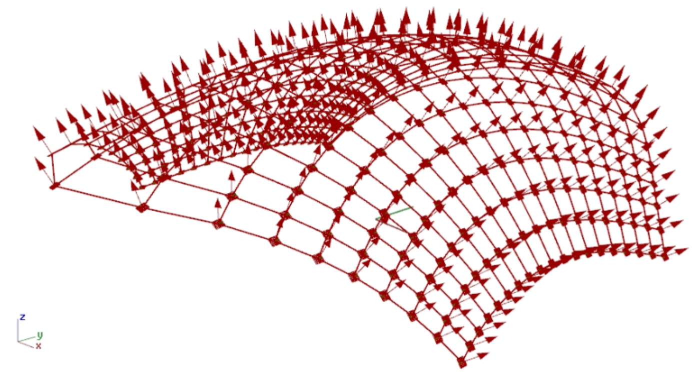
Unrolling Normal Stripes



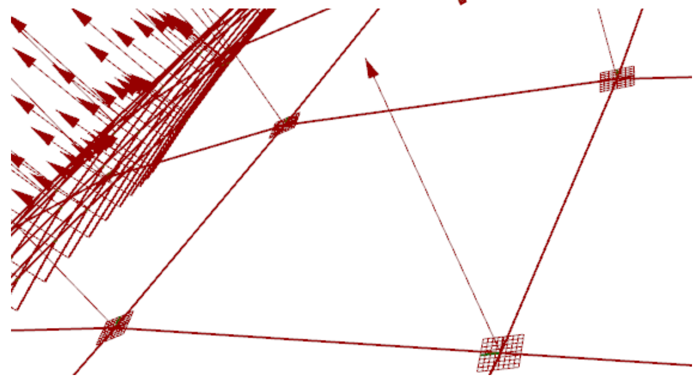
Discretized version of developable surface

Further Development in Construction;

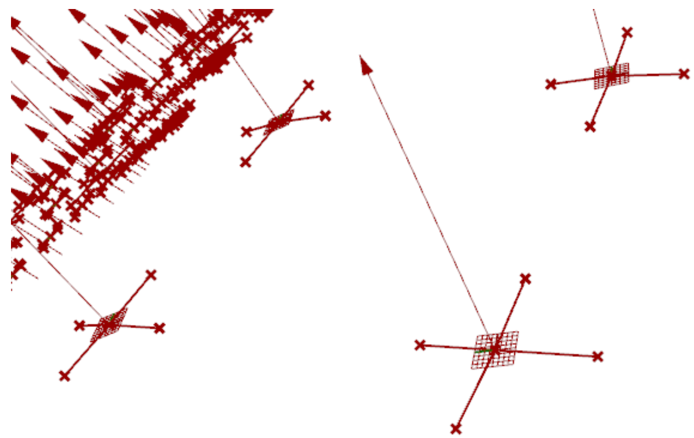
Detailing Process



Mesh, normal vectors and normal plane at each node



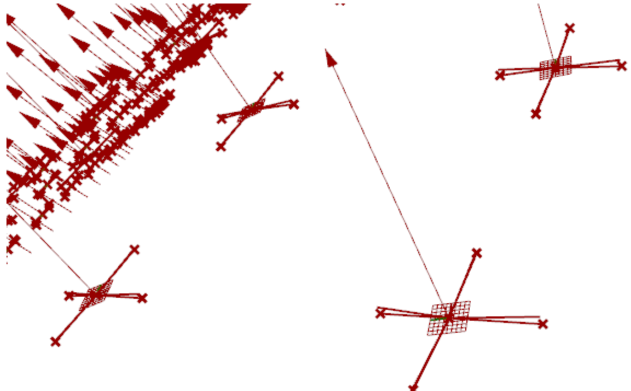
Nodes and Neighbor edges



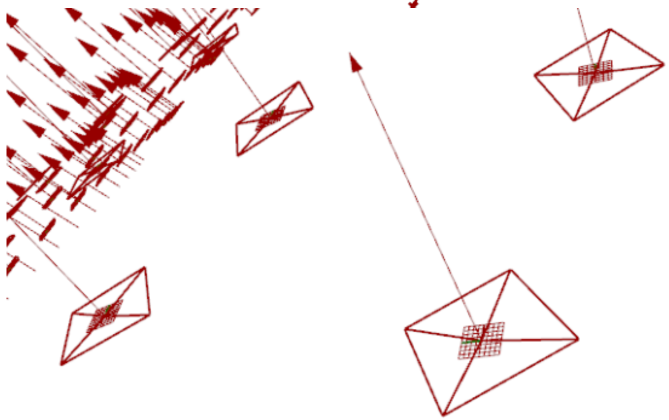
Specifying the length of connectors (evaluating edges)

Further Development in Construction;

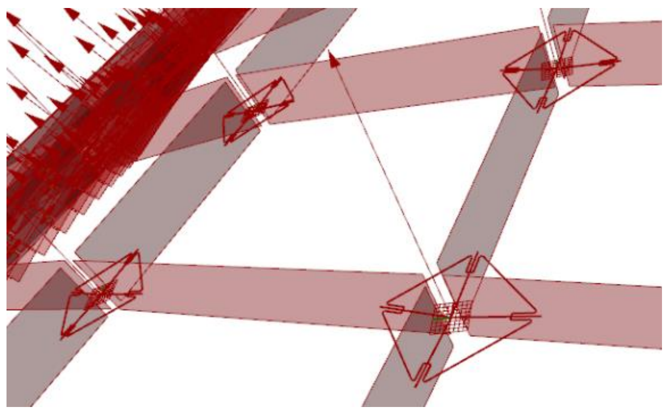
Detailing Process



Projecting the evaluated curve on normal plane



Extracting connector's boundary



Generating cuts on connectors based on beam's thickness

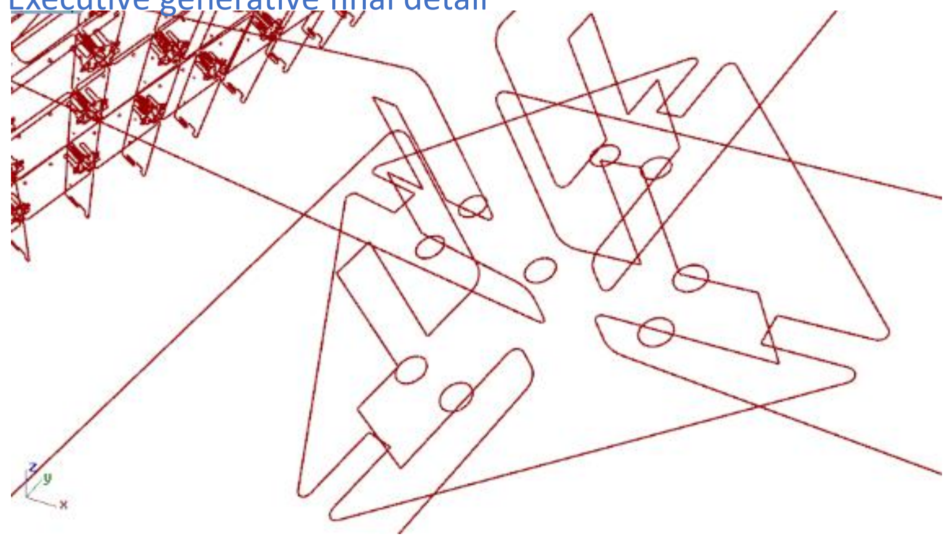
Further Development in Construction;

Detailing Process

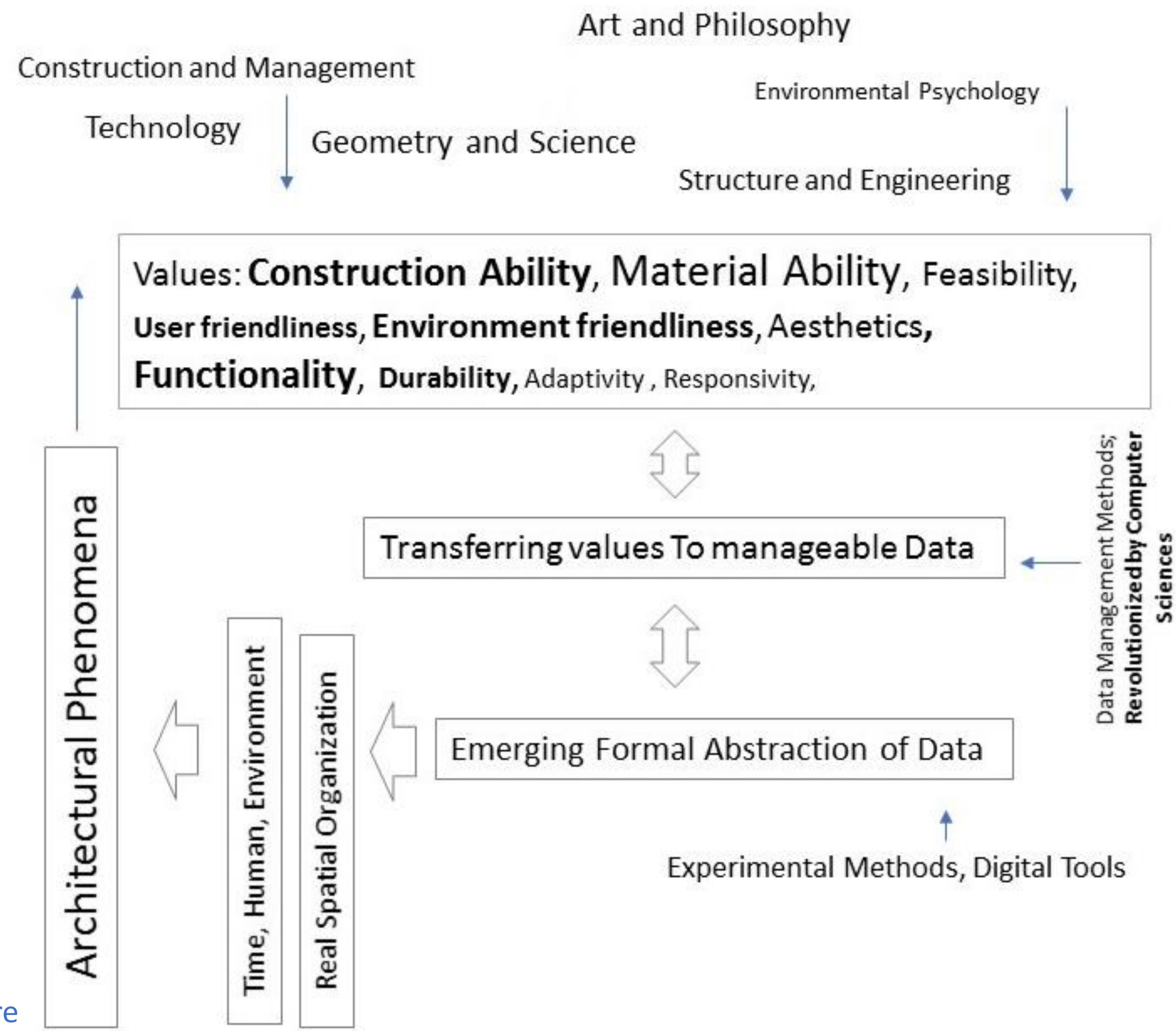
Parameters

1. Beam Thickness
2. Connector Thickness
3. Beam Height
4. Thickness Tolerance
5. Pin Height
6. Pin Leg Radius
7. Scale Factor
8. Beam's Corner Fillet Radius
9. Connector's Corner Fillet Radius
10. Position of the Connectors on their Normal
11. Pin position Radius
12. Connector's Size
13. Position of Pin on Connectors

Executive generative final detail

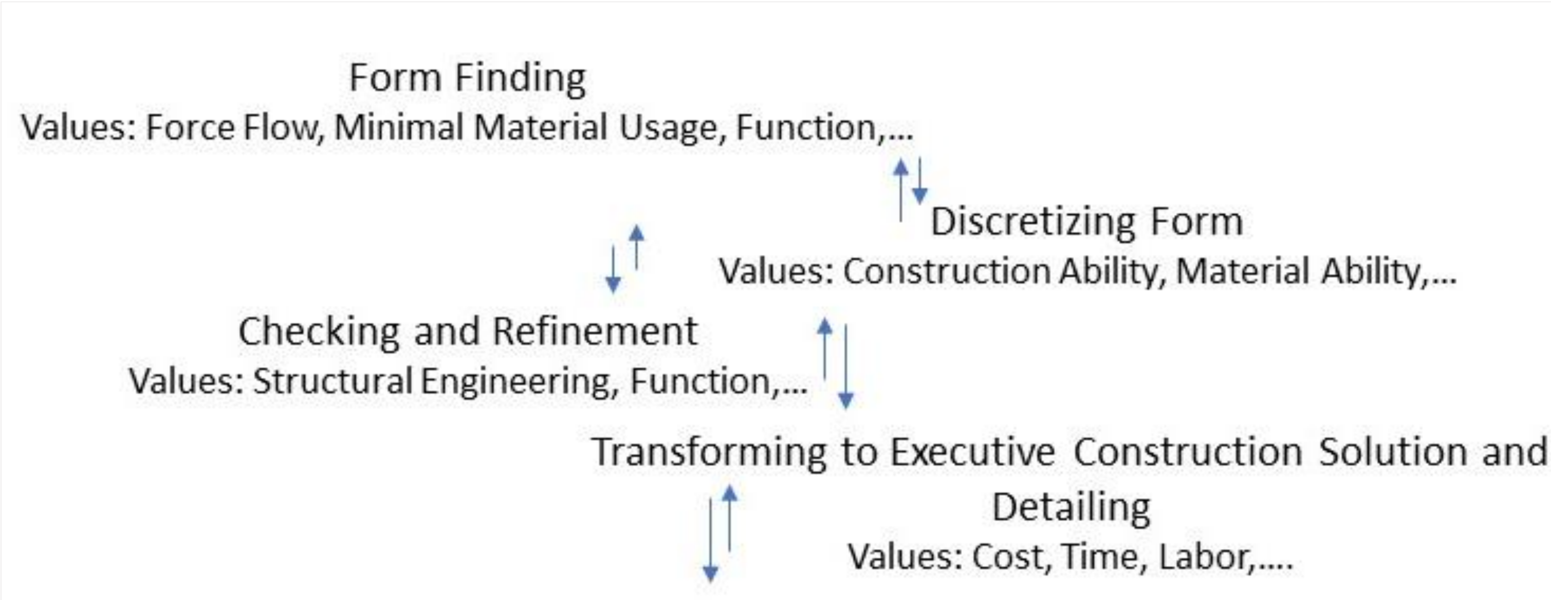


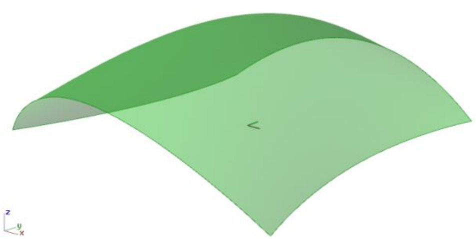
Emerging Architecture

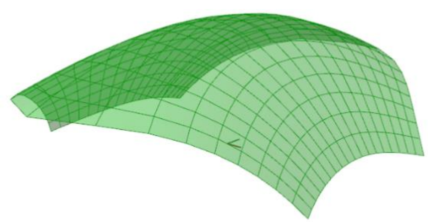


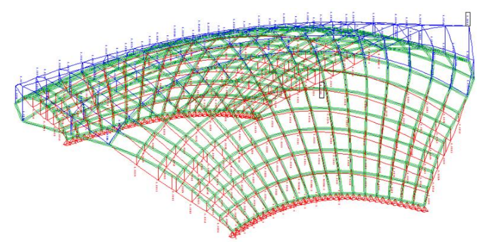
Process of Emerging Architecture

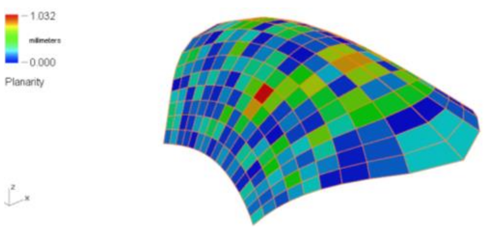
Project Process

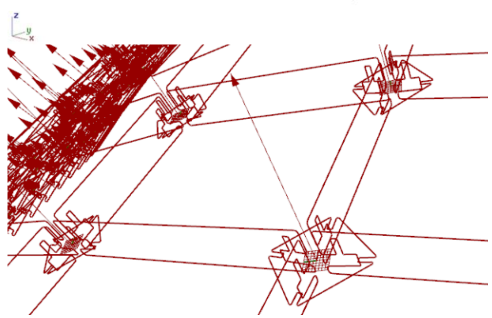












Benefits and Necessity of the Project

Benefits

Geometry

- **PQ Faces**
- **Coplanar Normal Vectors**
- **Multi-Layer Mesh**

Material

- **Flat Sheets of Material**

Construction

- **Not Complex Connectors**
- **Faster Production**
- **Low Cost Production**
- **Fast Assembling and Disassembling**
- **Easy Transportation**

Necessity

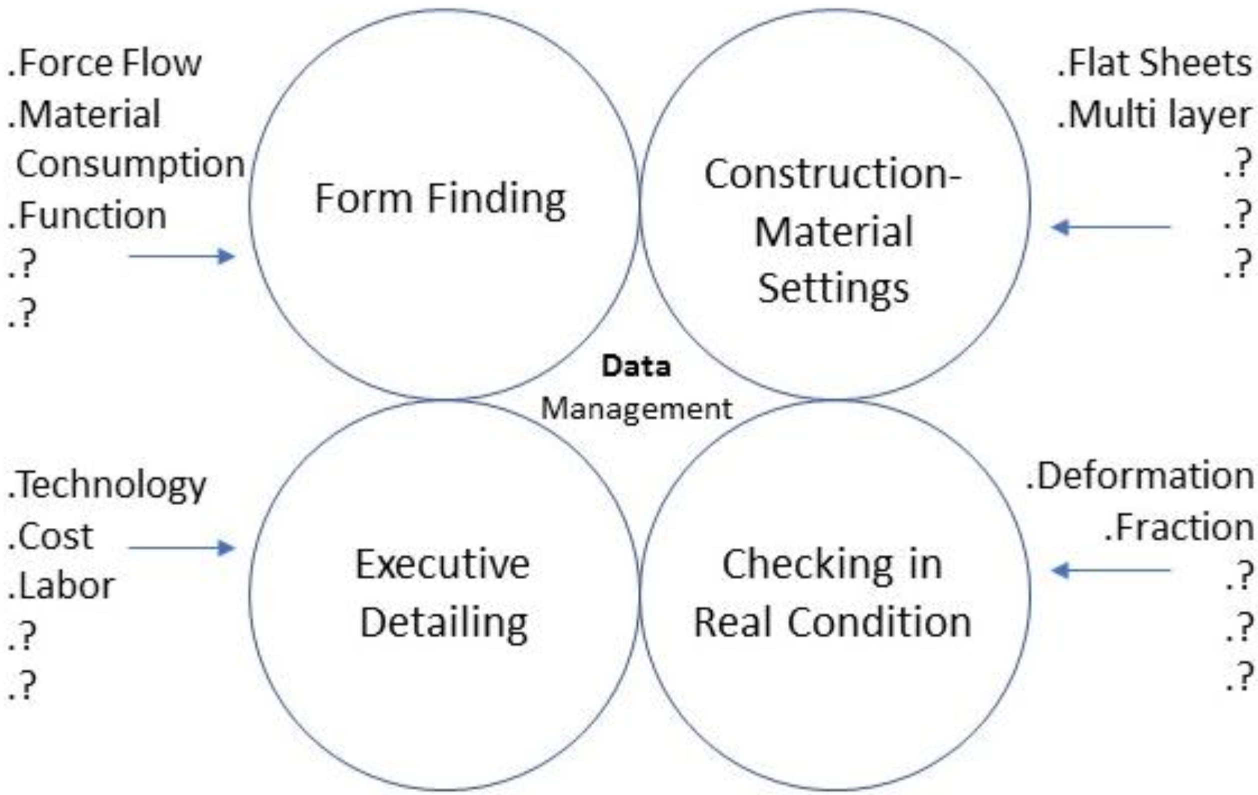
Accentuating on Process and Objectives

Implementing Values in Design-Construction Process

Showing Practical Data Transformation

Conclusion

Process and Values



Conclusion

Other Possible Values

Form Finding Values:

- Natural light penetration
- Gathering and Meeting Points Density
- Access and transition

Construction and Material Settings:

- Type of Material (Masonry, Steel, Composites, Recycling ….)
- Same Parts
- …

Checking in Real Condition:

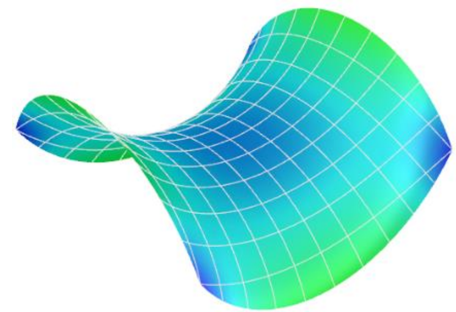
- Users' Reaction
- Recycling duration
- Environmental Affects
- …

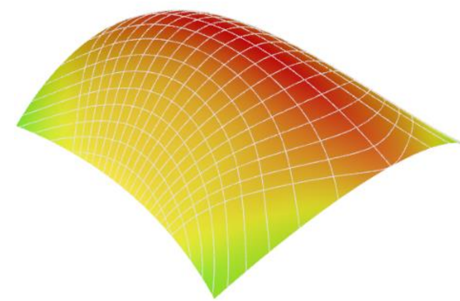
Executive Detailing:

- Transportation
- Local or International Technology
- Gray Energy
- …

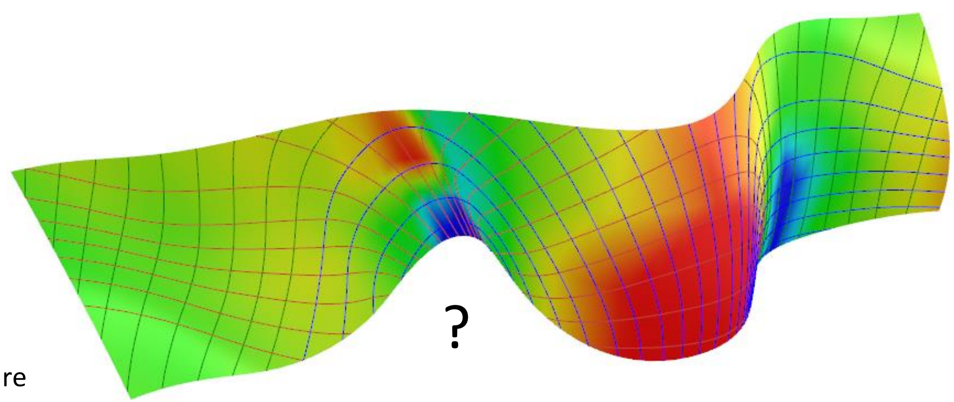
Conclusion

Further Question about PQ Mesh





Surfaces with Constant -(Blue) and +(Red) Gaussian curvature



Surface with variable - and +Gaussian curvature