The Cast Shell

Topologically Optimised Cast Glass Shell Exhibition Booth

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6 July 2020
P5

Elegance


INNOVATION
INFORMATION
INCOME
FINANCE
SELECT
EDIT
TEAM
IDEA
Product

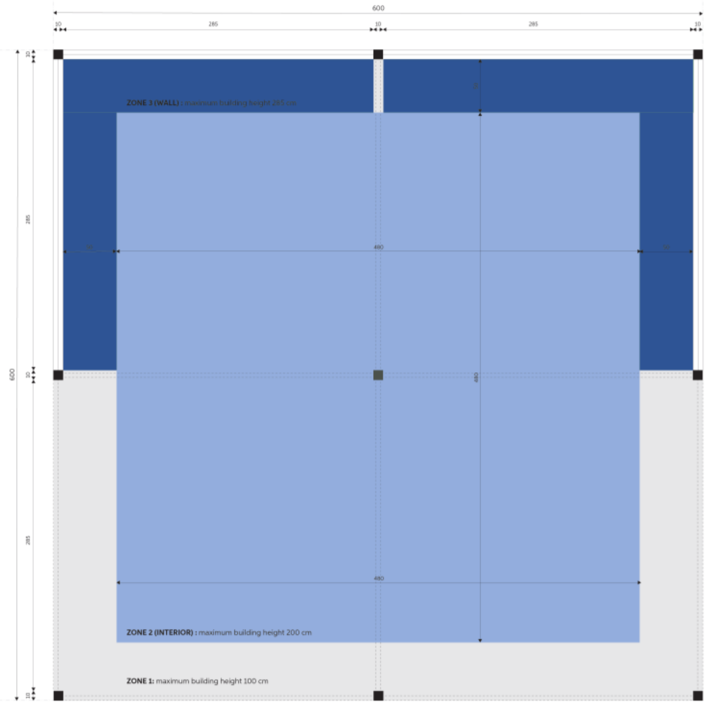

(Oikonomopoulou, 2019)

"simplicity is
complexity resolved"
- Constantin Brancusi

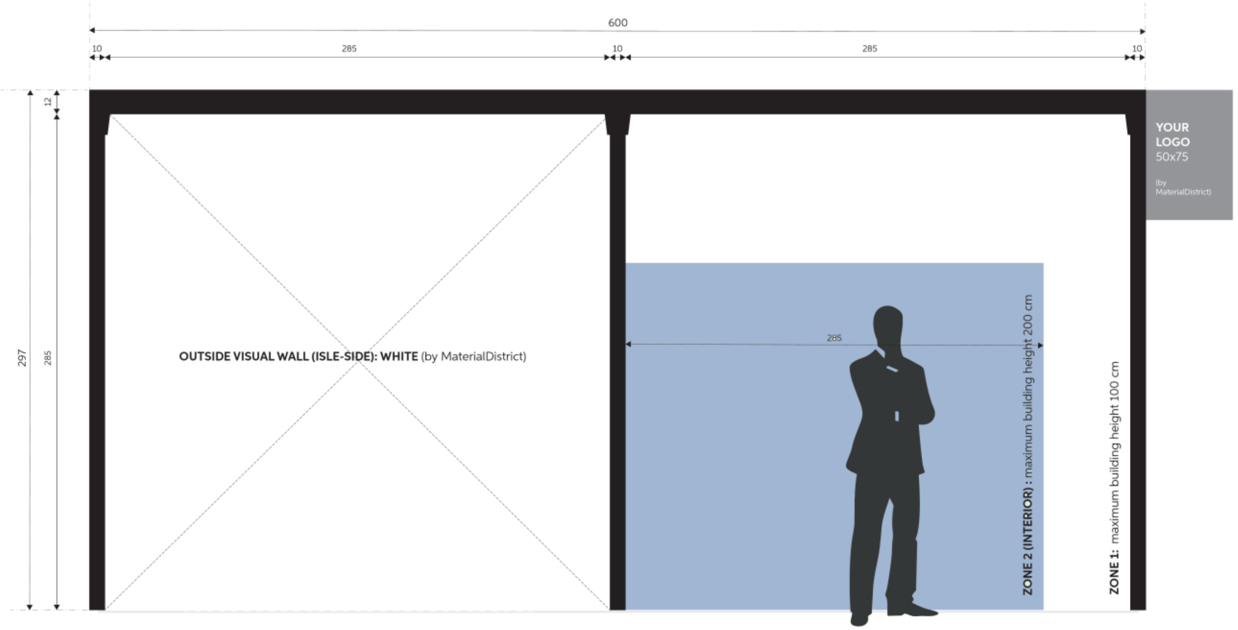
Yatzer, 2017

MaterialDistrict., 2020

Design criteria



Top View (overview)



Side Views (left & right)

MaterialDistrict, 2020

MaterialDistrict., 2020

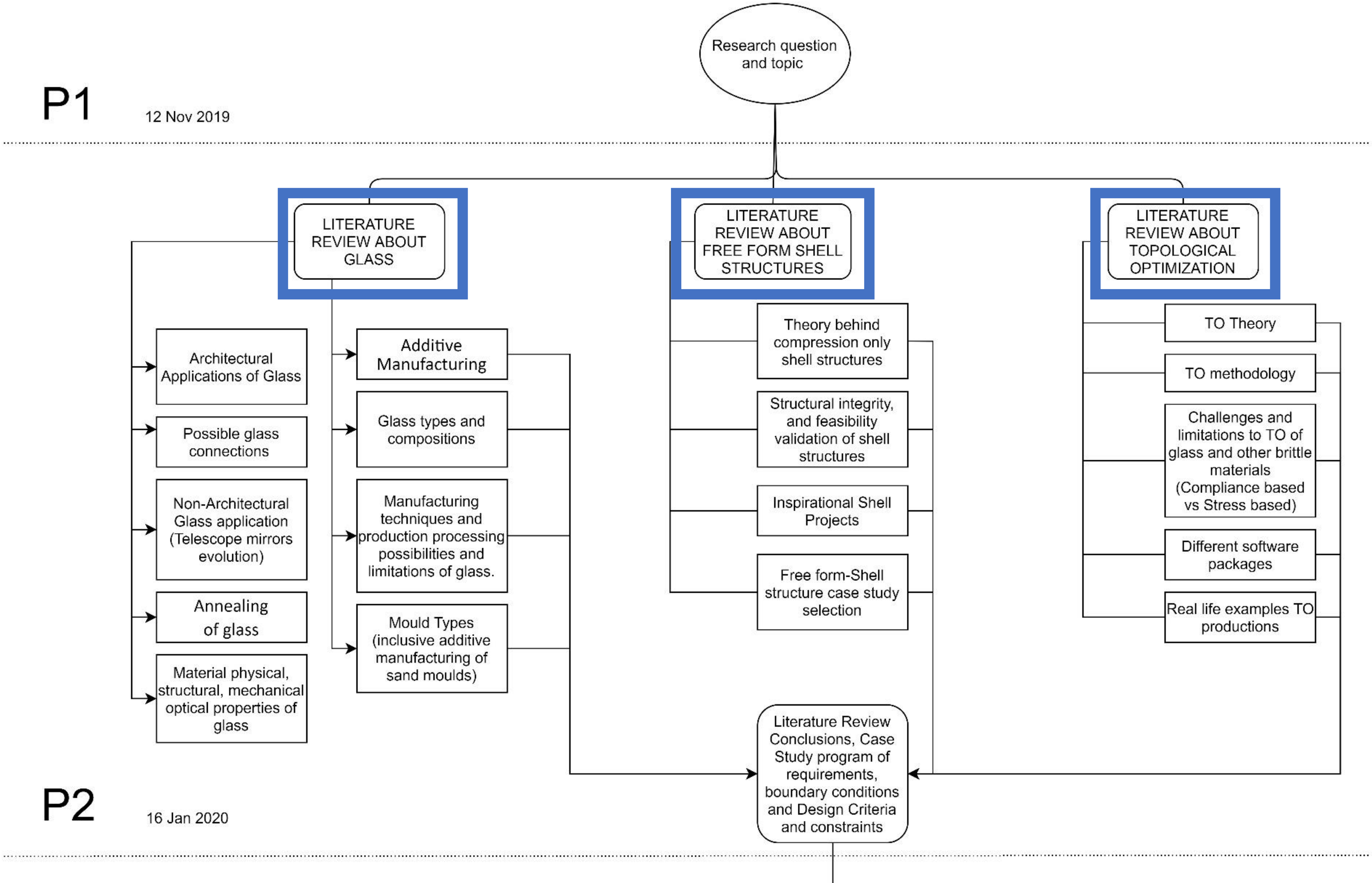
Research Question:

What is the potential of using topologically optimized cast glass in building a shell structure?

Glass

Topology Optimization (TO)

Shell



Research question and topic
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LITERATURE REVIEW ABOUT TOPOLOGICAL OPTIMIZATION
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Glass types and compositions
Manufacturing techniques and production processing possibilities and limitations of glass.
Mould Types (inclusive additive manufacturing of sand moulds)
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TO methodology
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Real life examples TO productions
Literature Review Conclusions, Case Study program of requirements, boundary conditions and Design Criteria and constraints
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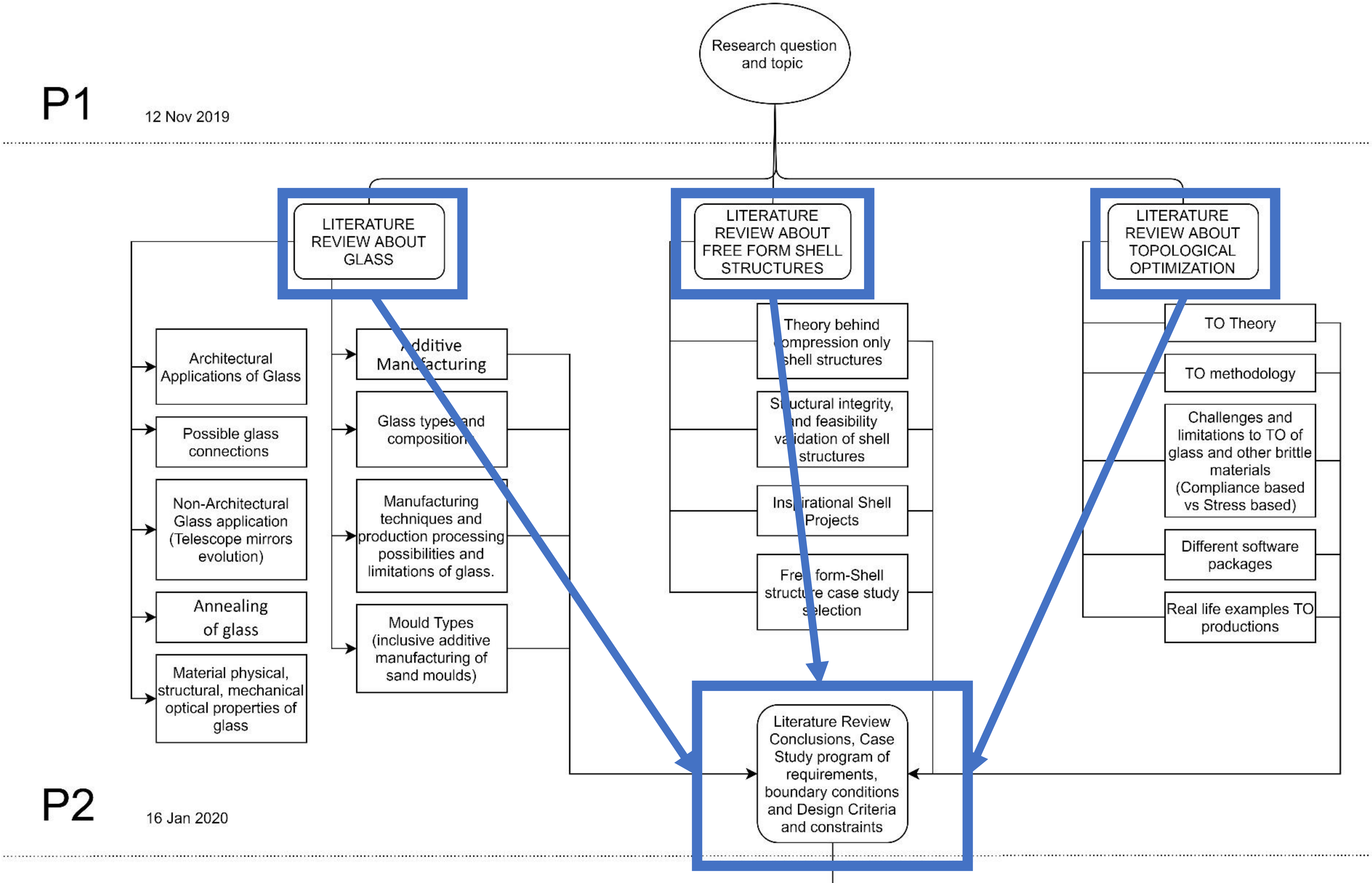
16 Jan 2020



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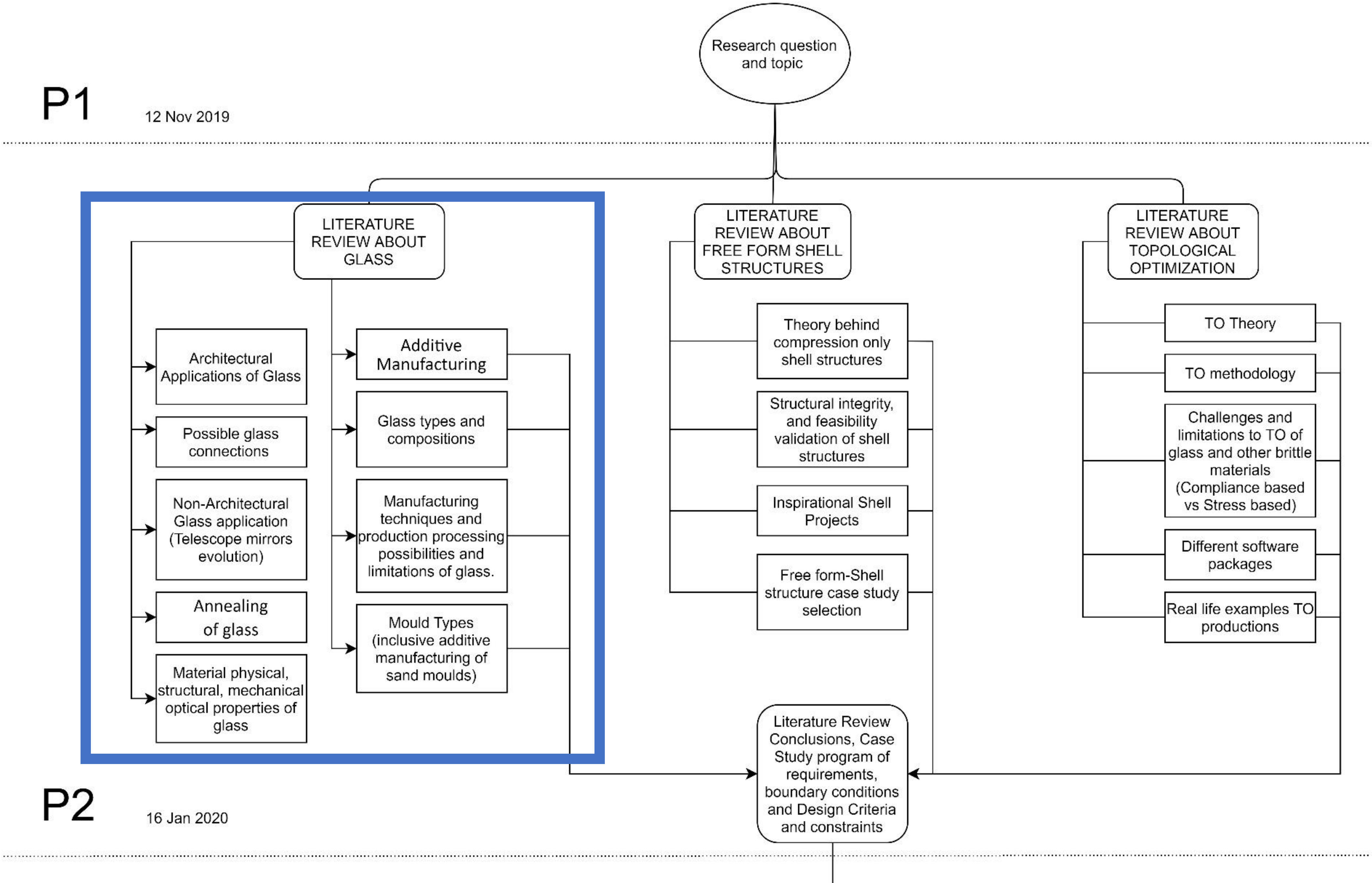

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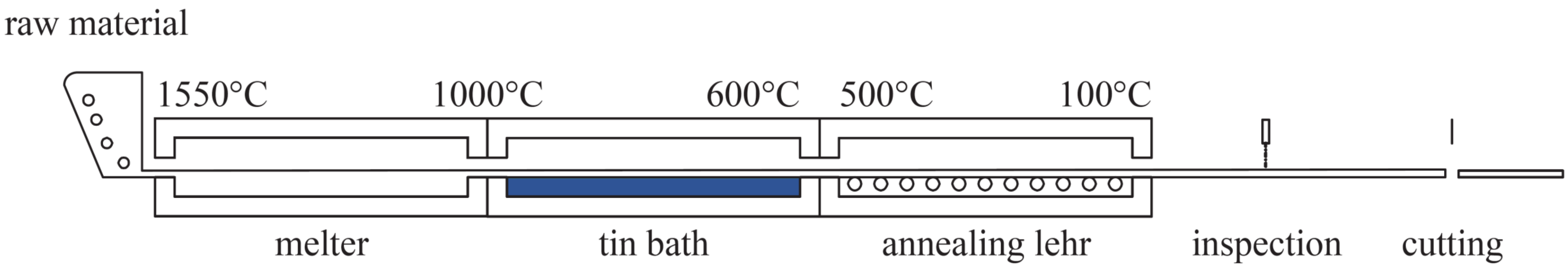
Glass



Schematic illustration of float glass production by means of a tin bath (Oikonomopoulou, 2019)

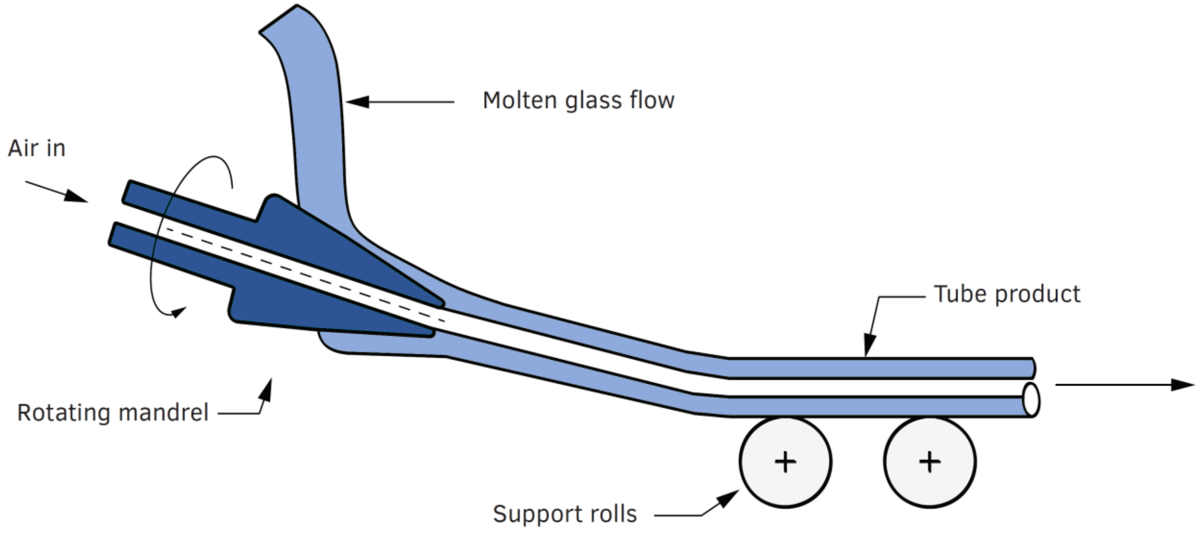
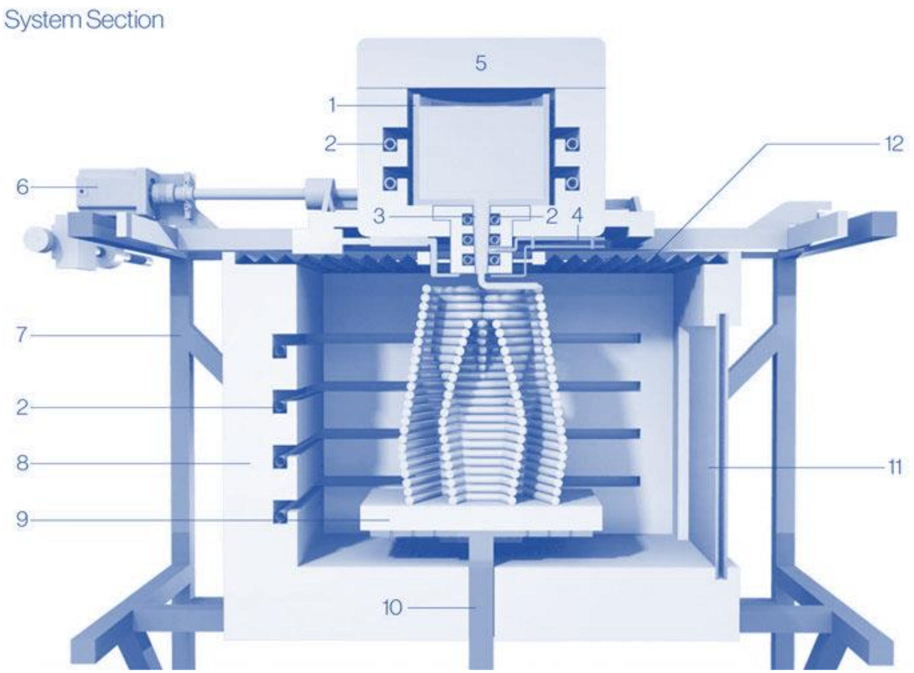


FIG. 2.5 Principle of the Danner process.

Principle of the Dannner process of extruded glass (Oikonomopoulou, 2019)

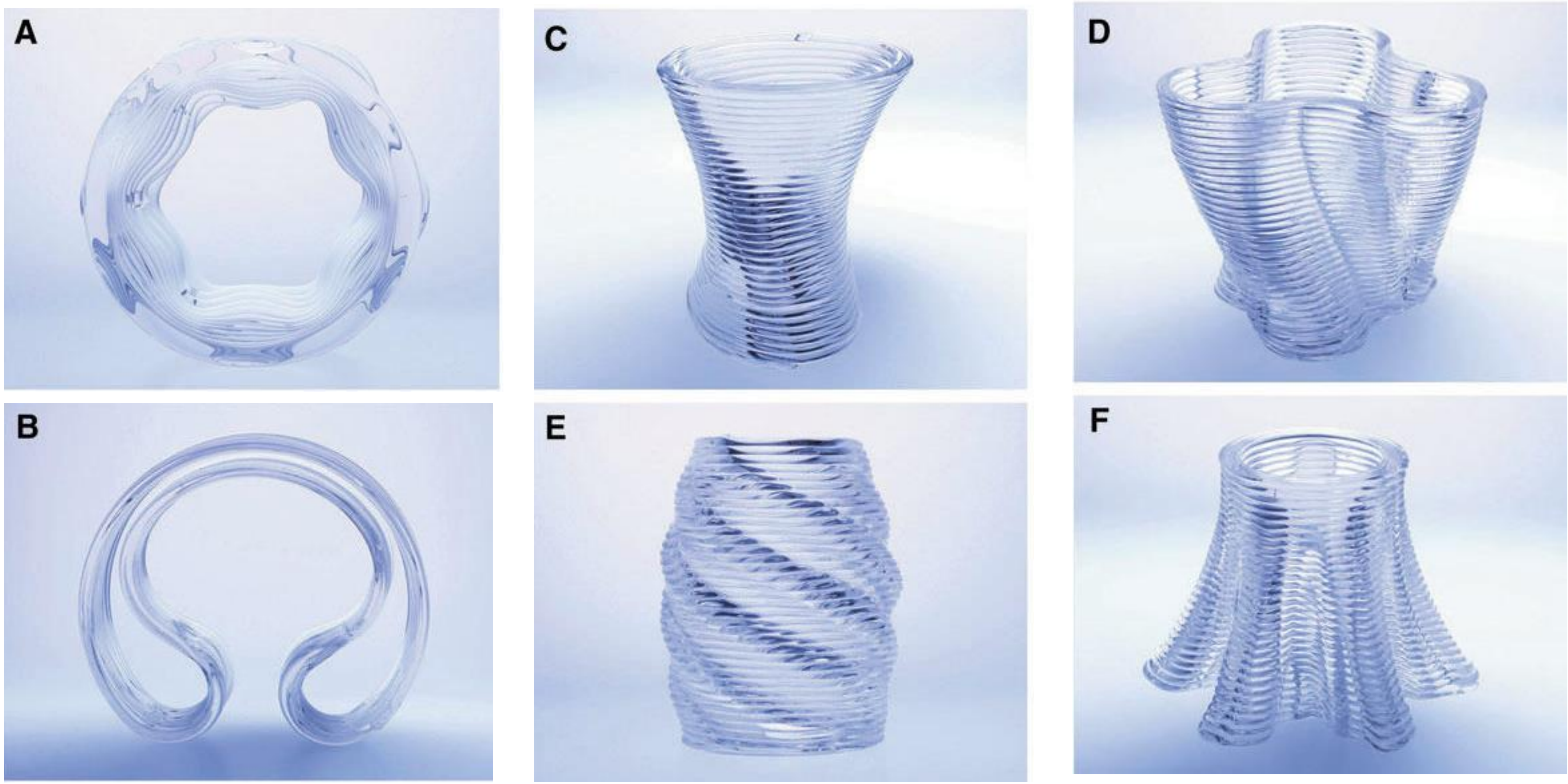


A cross sectional render of 3D printed glass. (Klein et al., 2015)

Apple store glass box in Zorlu, Istanbul, Turkey by Foster + Partners and Nous Studio (Baldwin, 2018)

Tubular extruded glass column tree structure in Aechen, Germany for (Knaack, 1998)

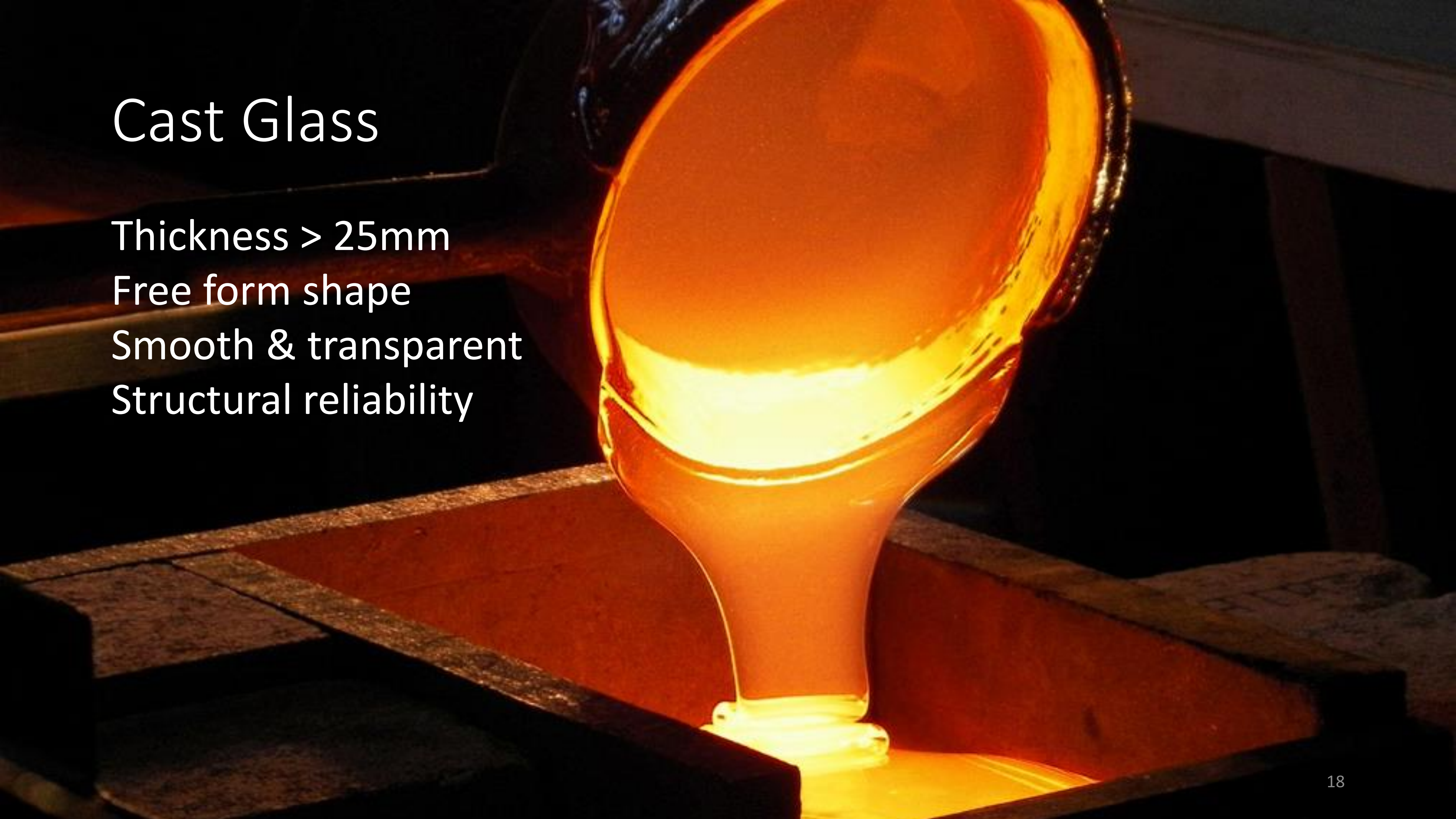
The Glass Swing at Delft University (Snijder et al., 2019)



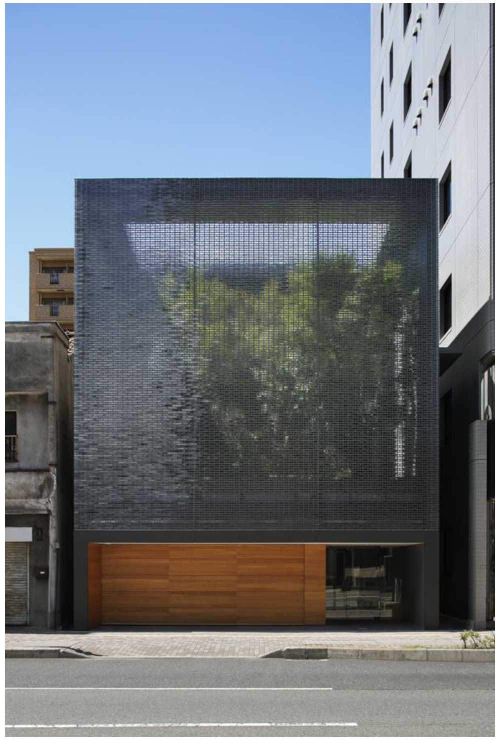
Object printed using the platform in figure19 (Klein et al., 2015)

Cast Glass

Thickness > 25mm
Free form shape
Smooth & transparent
Structural reliability



Christal House ABT TU Delft (Stevens, 2019)

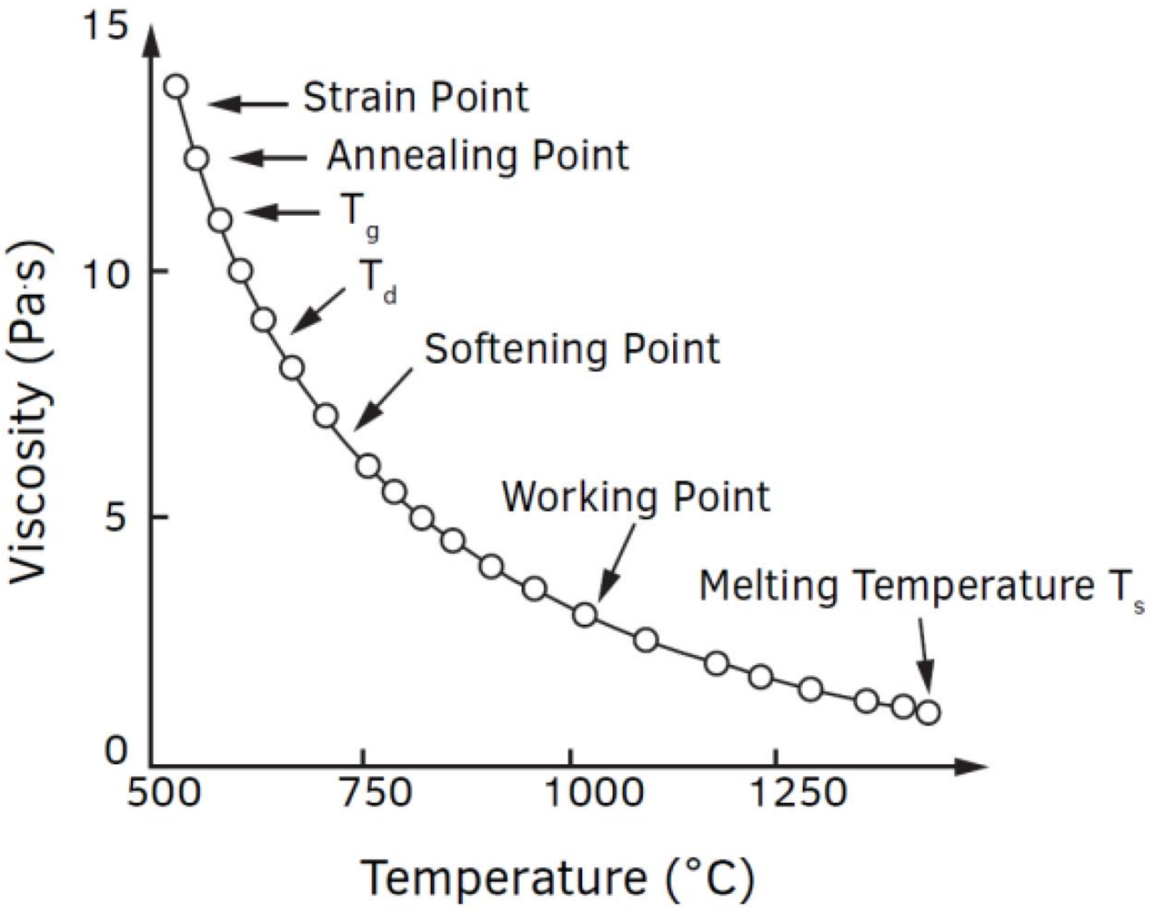


Glass Optical House (Hiroshi Nakamura & NAP, 2017)

Glass Crown Fountain at night in Chicago (Minner, 2011; Ermengem, 2019)

Atocha Memorial in Madrid, Spain with SCHOTT Borosilicate Glass (SCHOTT, 2007)

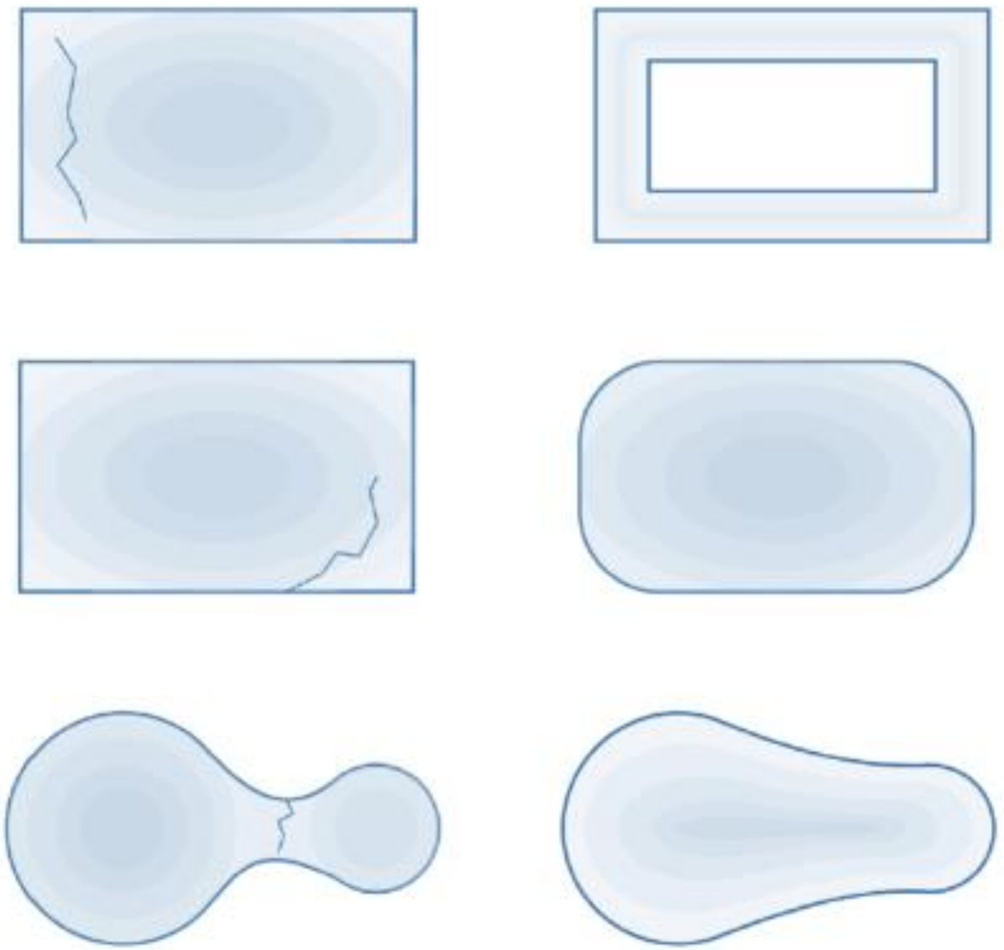
Annealing



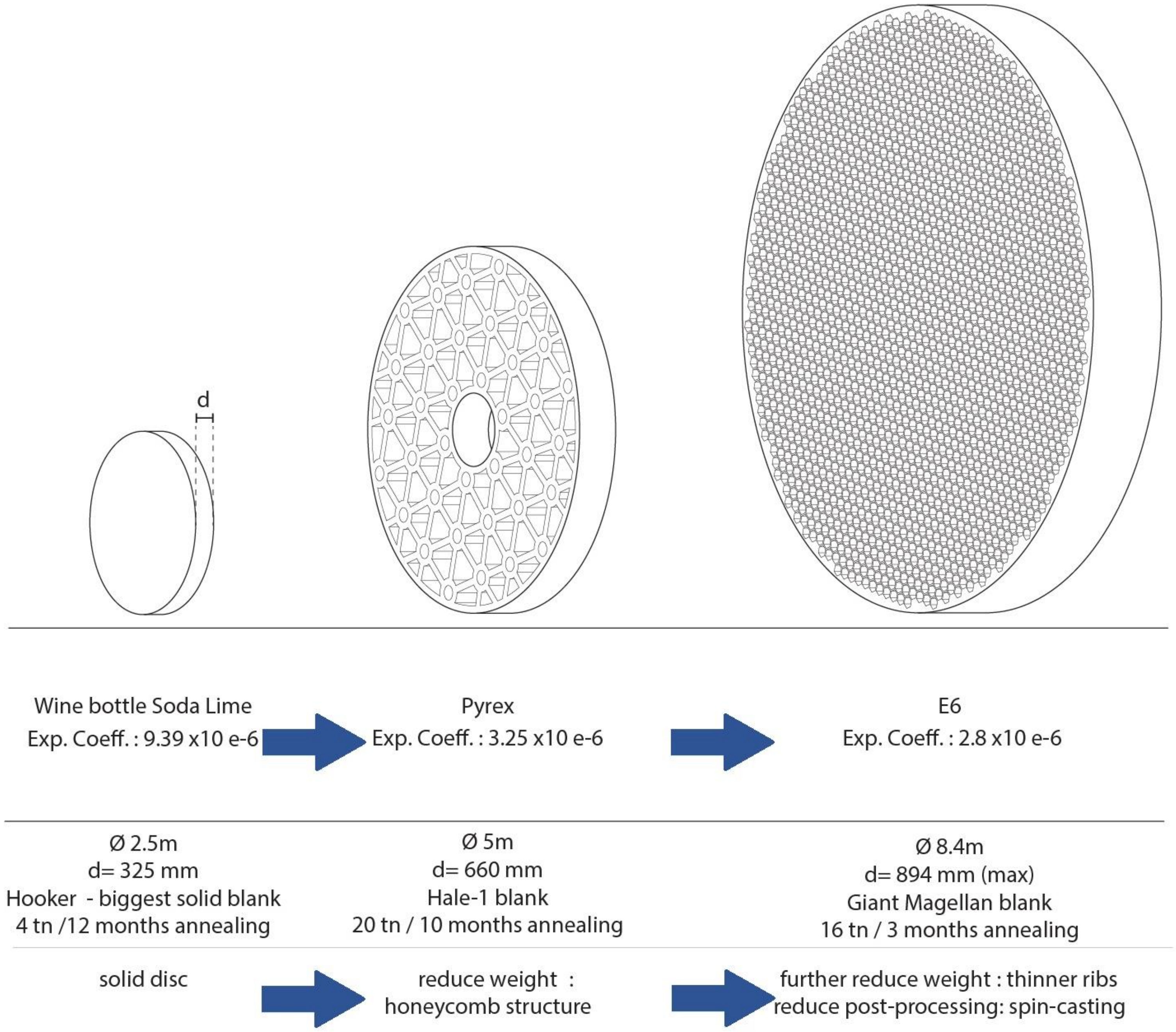
As function: the relationship between viscosity and temperature of soda lime glass (Oikonomopoulou, 2019)

Design Criteria

- Curved shapes (no sharp edges).
- Even distribution of material (mass and volume)
- Thickness range of shell & structural dissected elements (5-10cm)
- Max annealing time (less 3 months)

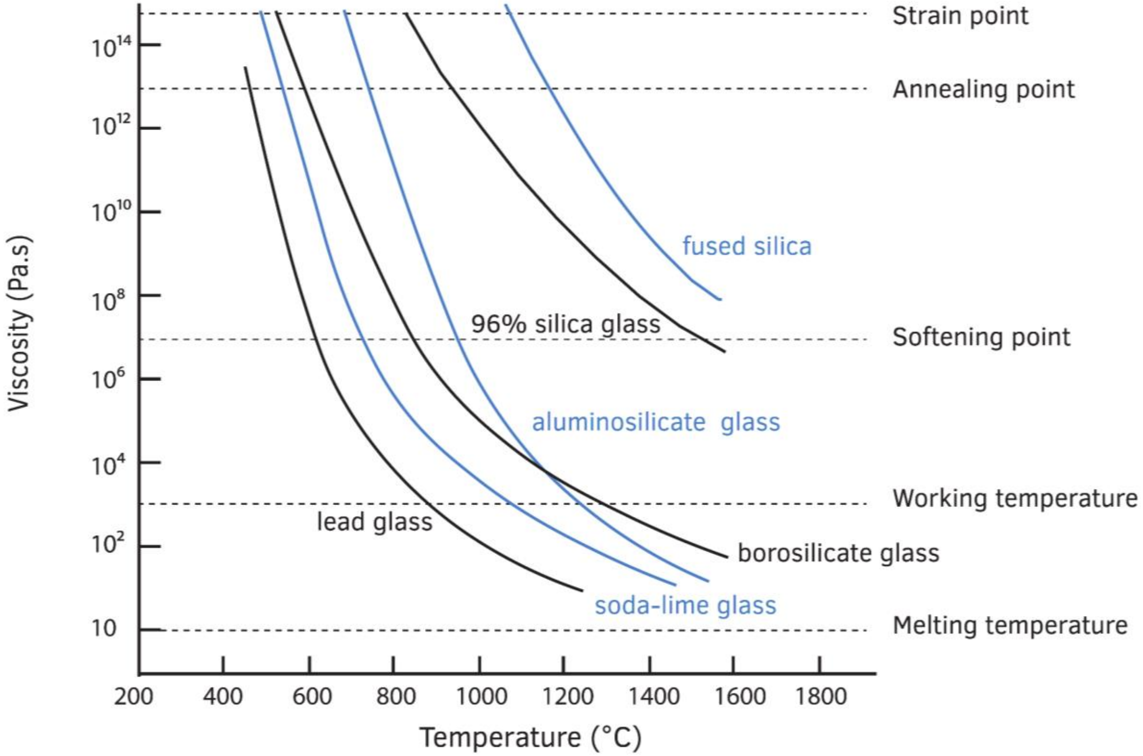


Design principles for a strong glass, and faster homogeneous annealing time using smart design. From top and bottom: reduced weight or thickness, rounded forms with especially no sharp edges, and an even distribution of mass (Damen, 2019)



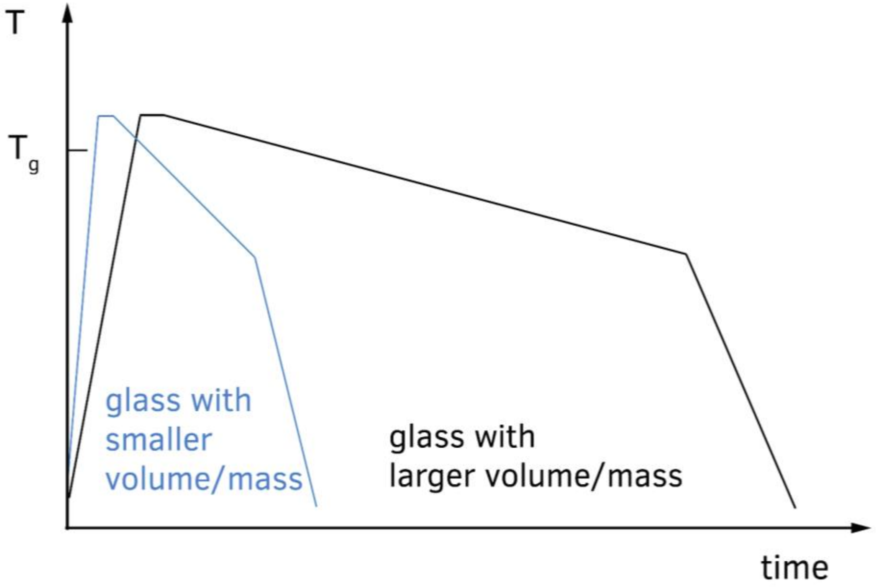
Cast glass evolution in increased size and a reduced annealing time. (Zirker, 2005; as presented in Oikonomopoulou, 2019)

Type of glass



Approximate viscosity vs temperature curvatures for different types of glass (Shand, Armistead 1958; as presented by Oikonomopoulou, 2019)

Volume/ Mass



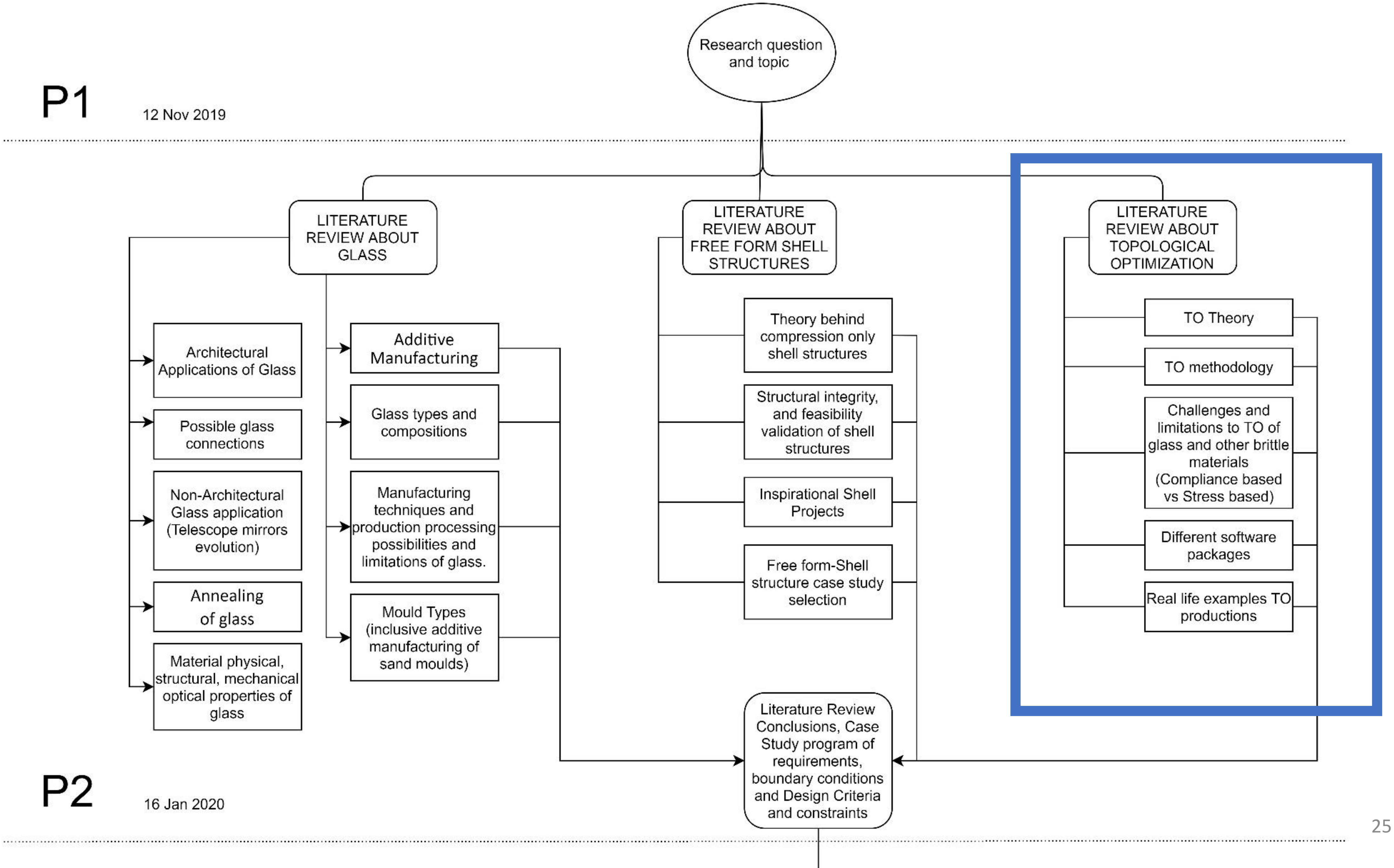
A scheme showing how annealing time can be reduced by decreasing the volume (Schott AG, 2004; as presented by Oikonomopoulou, 2019)

Borosilicate glass

Glass type	Mean melting Point at 10 Pa.s*	Softening Point	Annealing Point	Strain Point	Density	Coefficient of Expansion 0°C - 300°C	Young's Modulus
	[°C]	[°C]	[°C]	[°C]	Kg/m^3	10^{-6}/°C	GPa
Soda-lime (window glass)	1350-1400	730	548	505	2460	8.5	69
Borosilicate	1450-1550	780	525	480	2230	3.4	63
Lead silicate	1200-1300	626	435	395	2850	9.1	62
Aluminosilicate	1500-1600	915	715	670	2530	4.2	87
Fused-silica	>>2000	1667	1140	1070	2200	0.55	69
96% silica	>>2000	1500	910	820	2180	0.8	67

** These values are only given as a guideline of the differences between the various glass types. In practice, for each glass type there are numerous of different recipes resulting into different properties.*

Approximate properties of different types of glass (Oikonomopoulou, 2019)



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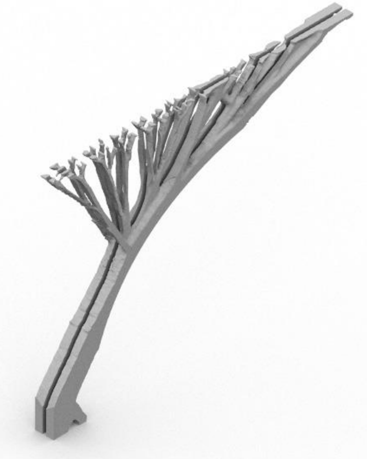
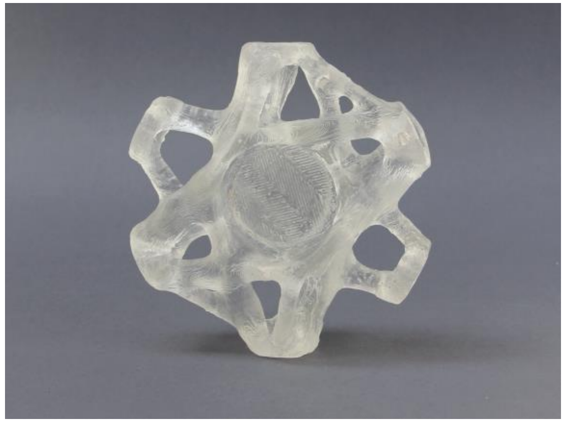
Topology Optimization

ETH Zurich slab TO using ABAQUS (Jipa et al., 2016)

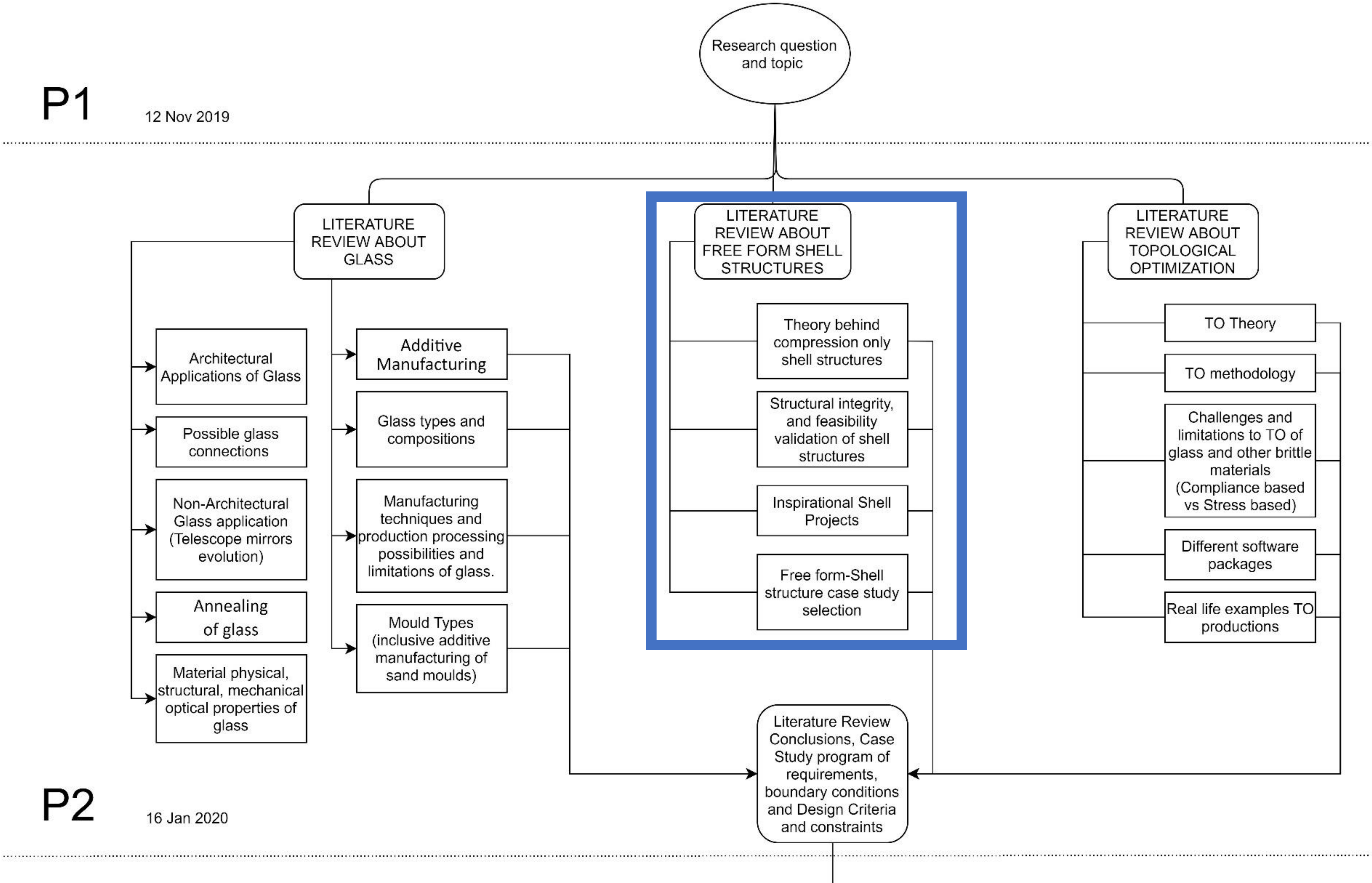
Light Rider: The 3D printed TO motorcycle (Grolms, 2016)



TO process of the split geometry by Bhatia (2019)



Casted TO node for heavy structure (Damen, 2019)



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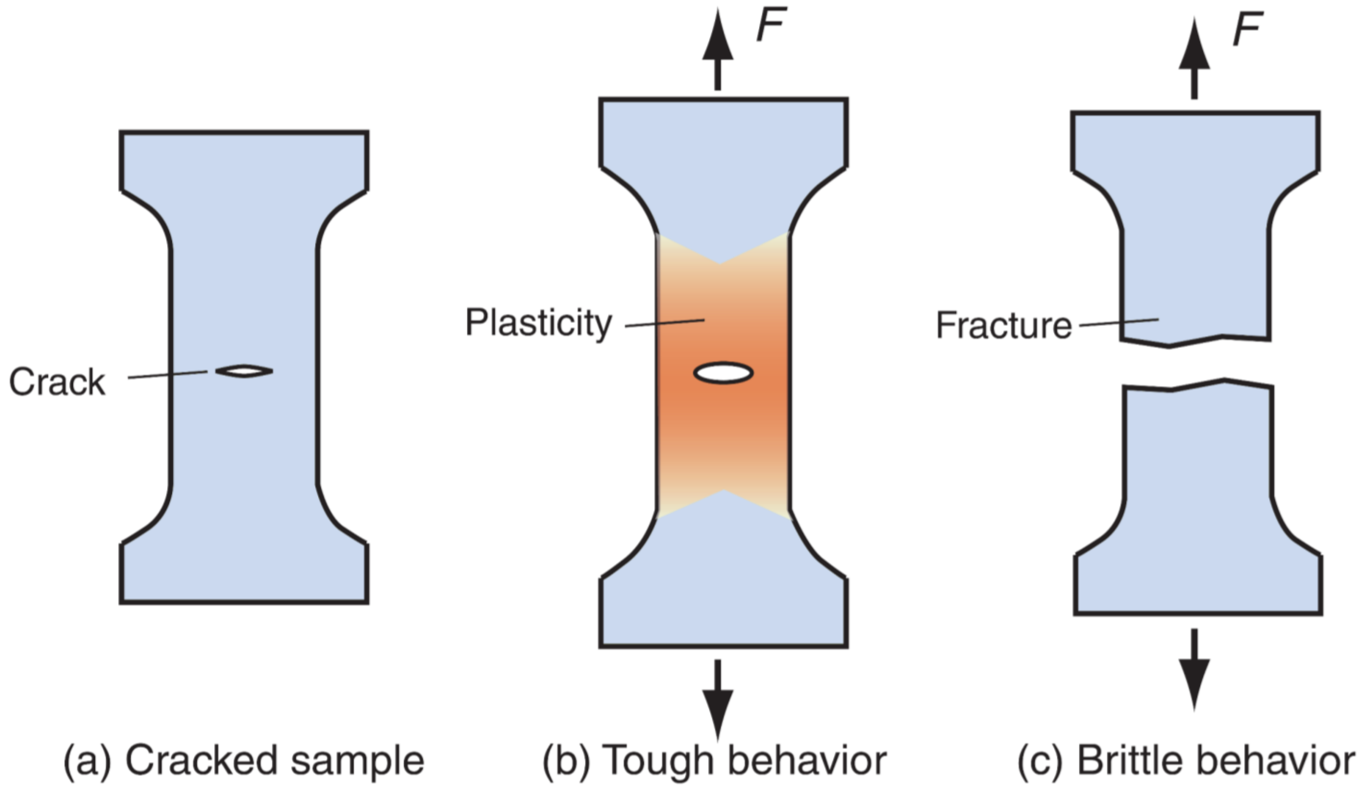
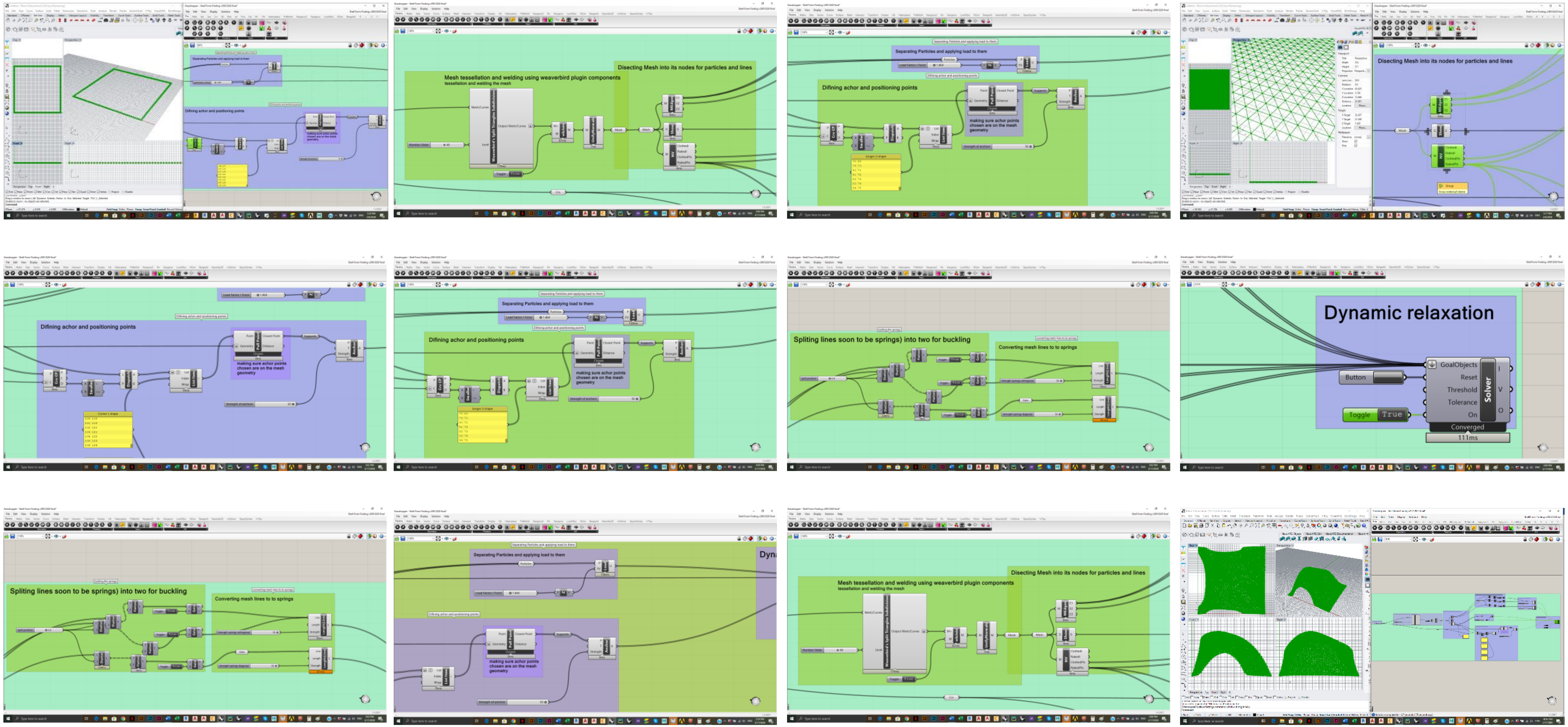
Shells

Gaudi's Hanging Chain Models(Dragicevic, 2015)

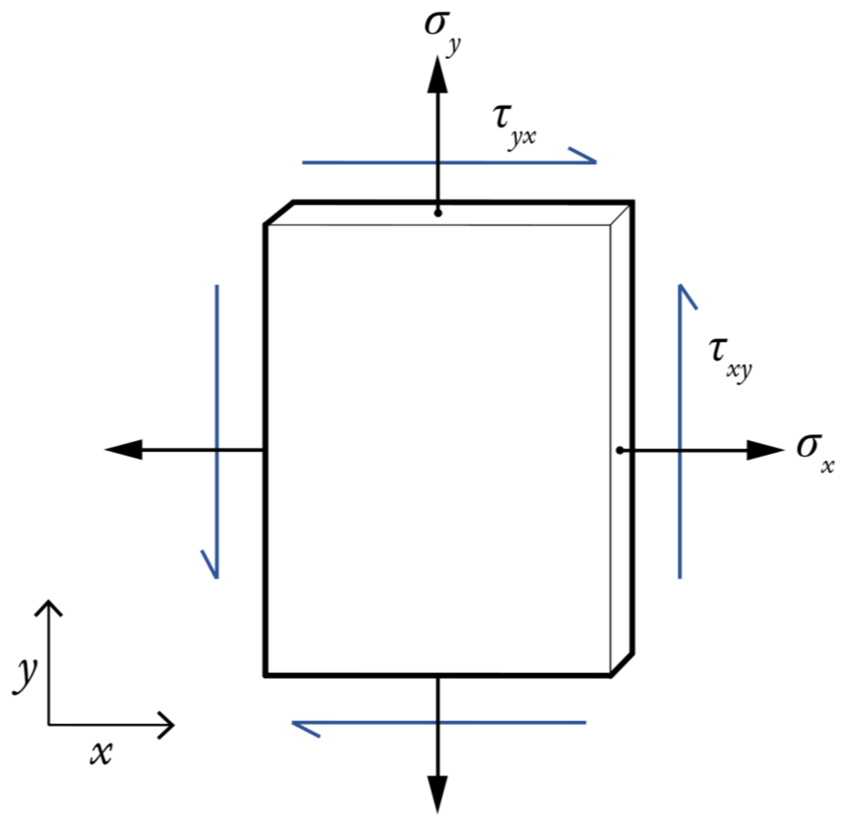
Gaudí’s Hanging Chain Models(Dragicevic, 2015)



Tough and Brittle behaviour. in the crack in the material is shown. In b the material is tough, and its plasticity prevents the crack from immediately propagating when loaded. c depicts a brittle material like glass where a crack propagates at a stress lower than its yield strength (Ashby et al., 2019, fig 8.1 p. 205)



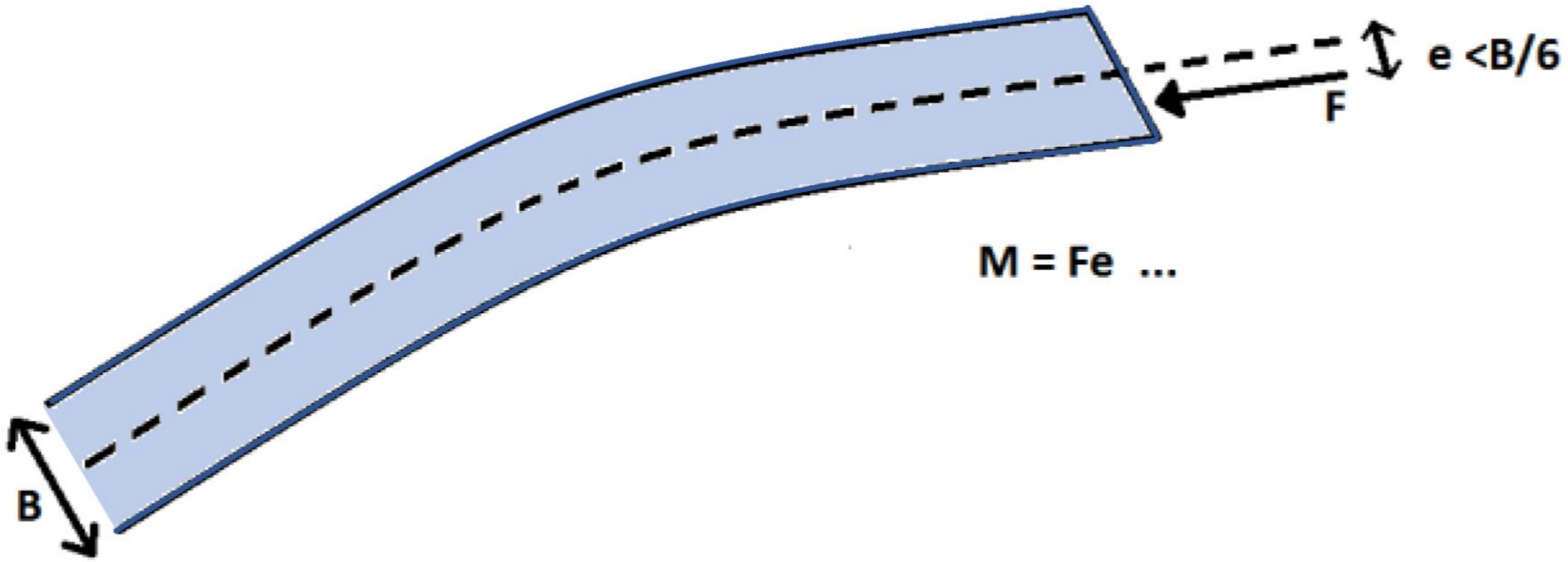
Dynamic relaxation using spring-particle grasshopper method for form finding. The procedure and algorithm script are explained in appendix C



Plane Stress (Goodno & Gere, 2018)

Design criteria

Max deflection should not exceed 1/6th the thickness of the shell so as to avoid eccentricity, moment, tensile stresses, loss of shell behaviour and thus fracture of glass. This is why TO will be compliance based and **deflection driven**

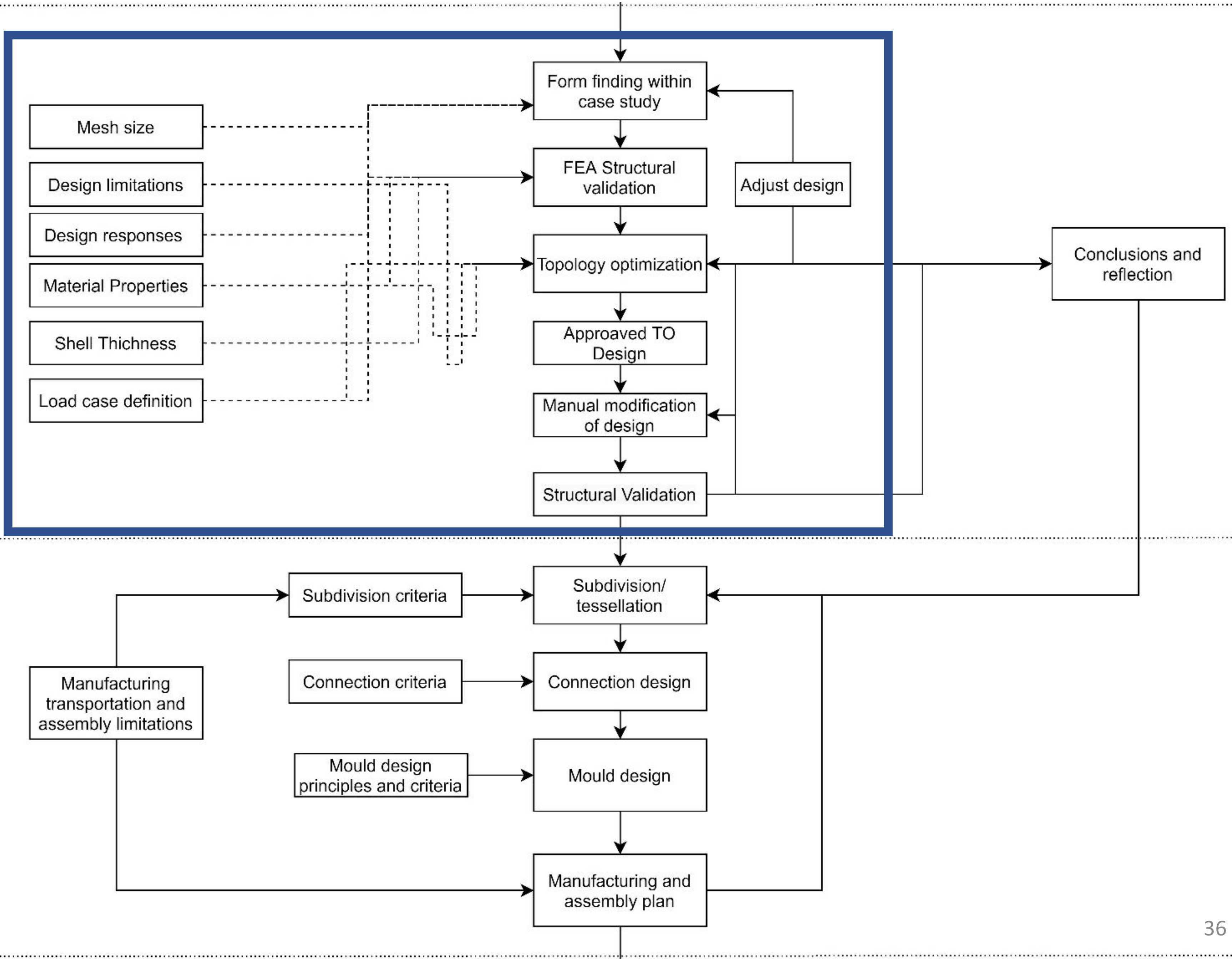


Normal Force Eccentricity Limit in Section view of a shell (Source: Author)

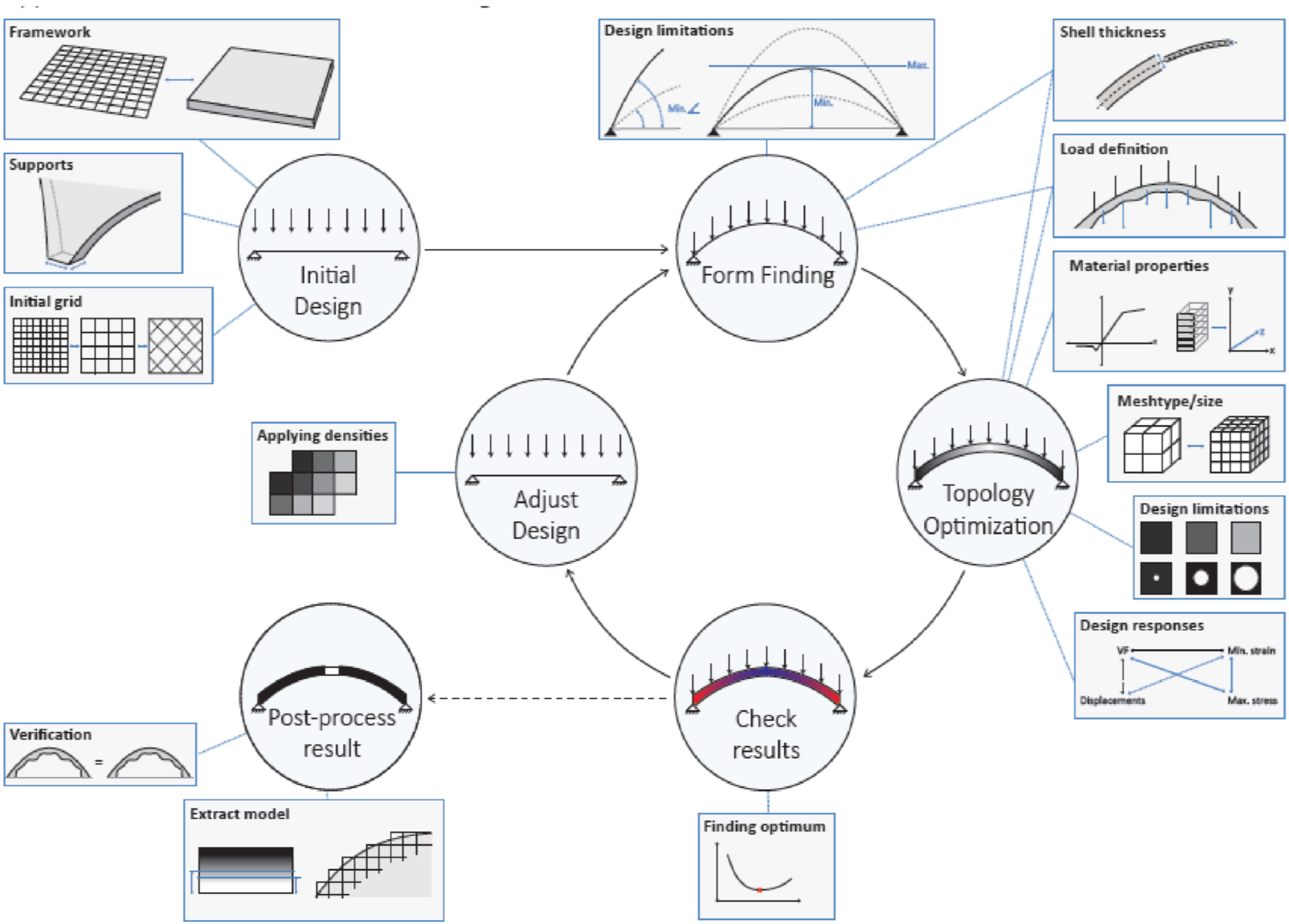
16 Jan 2020

P3 26 March

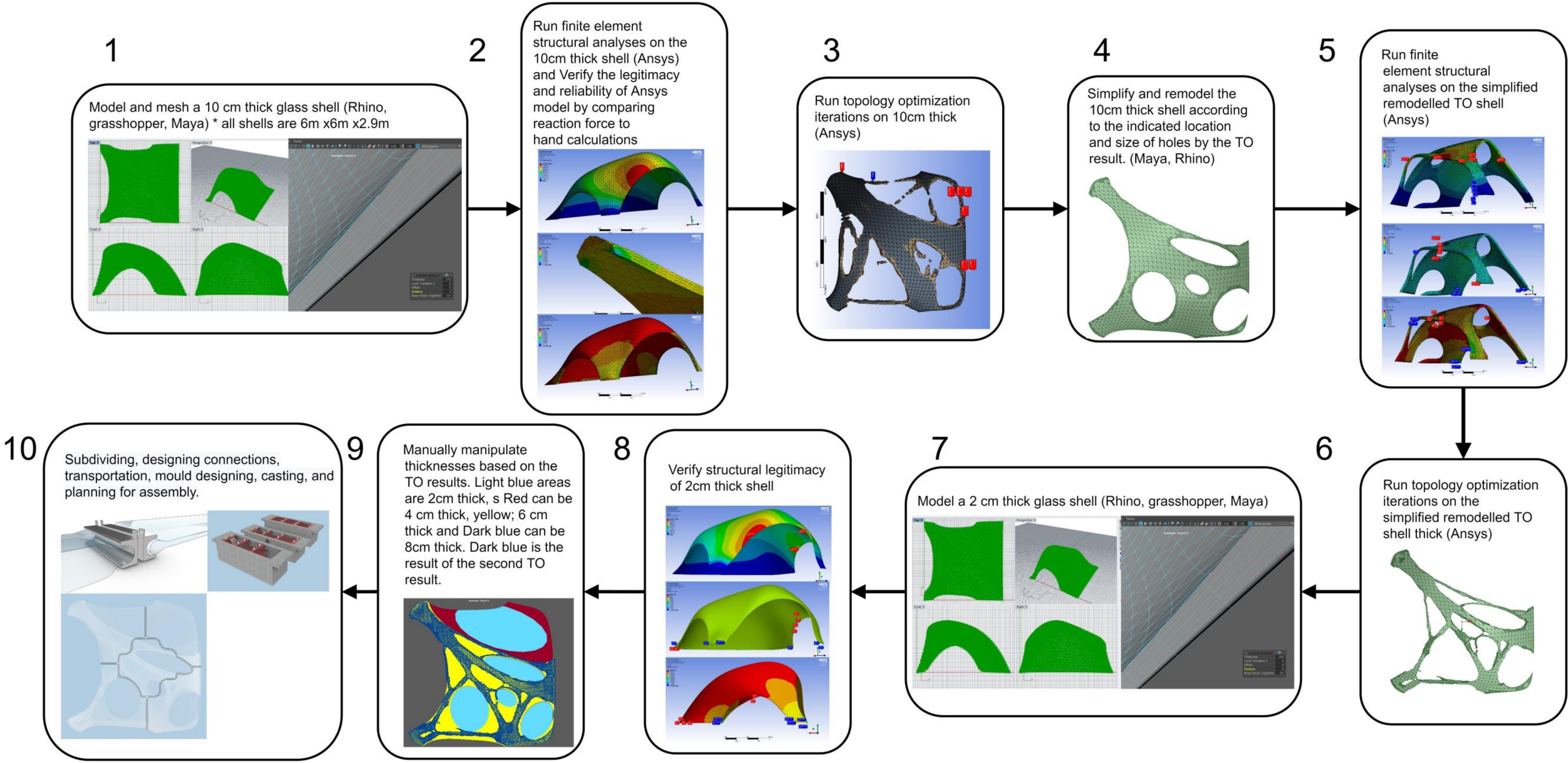
P4 21 May



Design evolution



Overview of the process from form finding to Topology Optimization (Bartels & Houben, 2016)


1
Model and mesh a 10 cm thick glass shell (Rhino, grasshopper, Maya) * all shells are 6m x6m x2.9m
2
Run finite element structural analyses on the 10cm thick shell (Ansys) and Verify the legitimacy and reliability of Ansys model by comparing reaction force to hand calculations
3
Run topology optimization iterations on 10cm thick (Ansys)
4
Simplify and remodel the 10cm thick shell according to the indicated location and size of holes by the TO result. (Maya, Rhino)
5
Run finite element structural analyses on the simplified remodelled TO shell (Ansys)
6
Run topology optimization iterations on the simplified remodelled TO shell thick (Ansys)
7
Model a 2 cm thick glass shell (Rhino, grasshopper, Maya)
8
Verify structural legitimacy of 2cm thick shell
9
Manually manipulate thicknesses based on the TO results. Light blue areas are 2cm thick, s Red can be 4 cm thick, yellow; 6 cm thick and Dark blue can be 8cm thick. Dark blue is the result of the second TO result.
10
Subdividing, designing connections, transportation, mould designing, casting, and planning for assembly.

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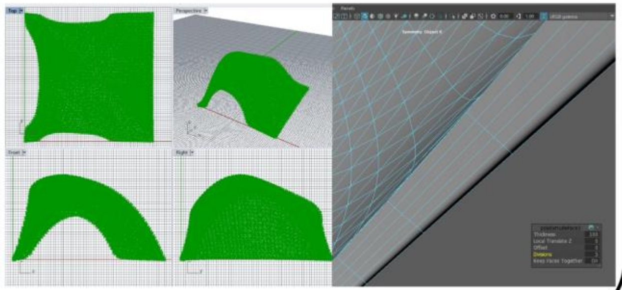

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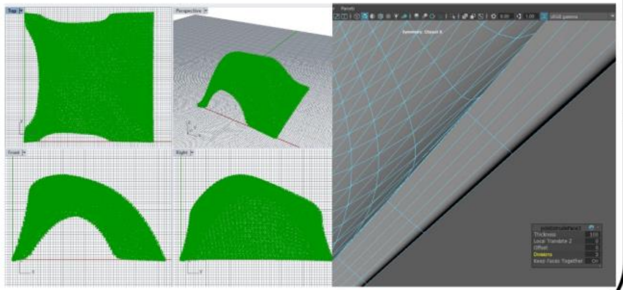

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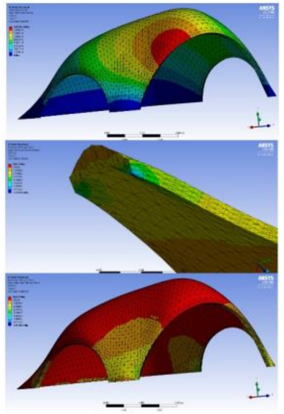

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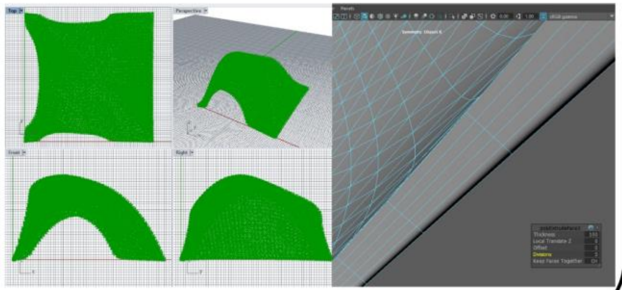

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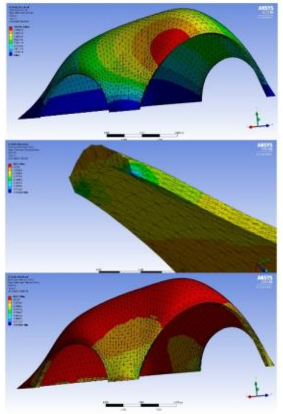

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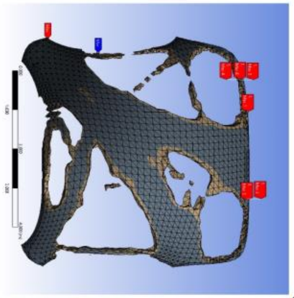
Run topology optimization iterations on 10cm thick (Ansys)



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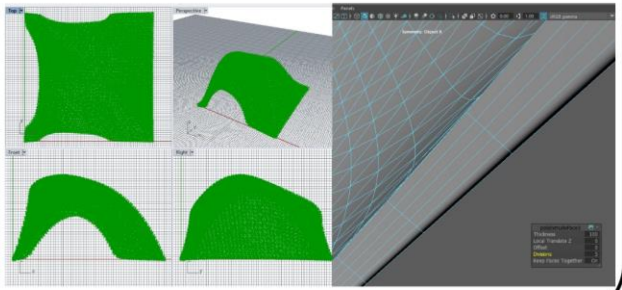

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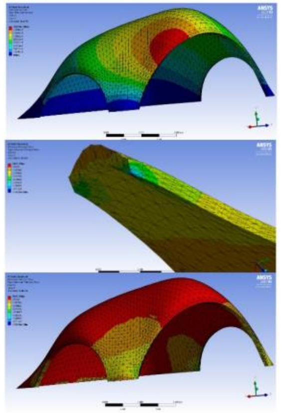

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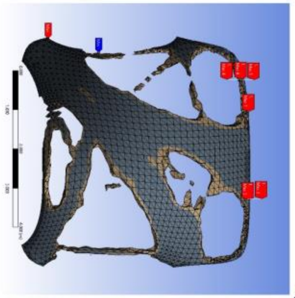

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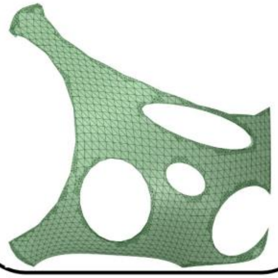
Simplify and remodel the 10cm thick shell according to the indicated location and size of holes by the TO result. (Maya, Rhino)



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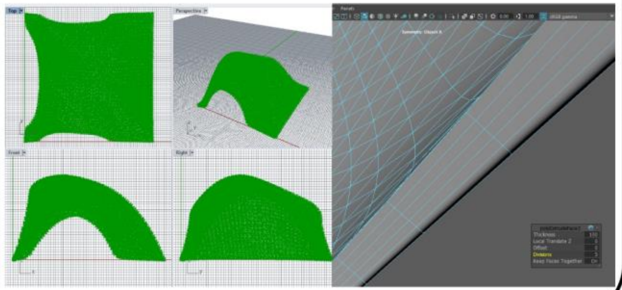

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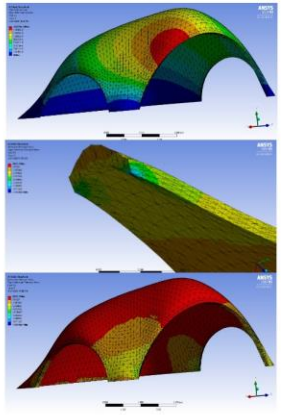

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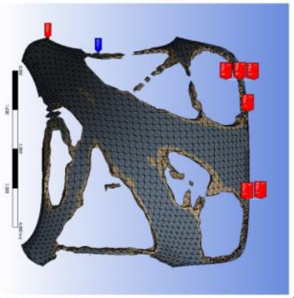

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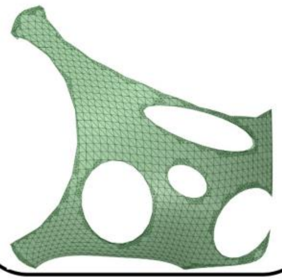
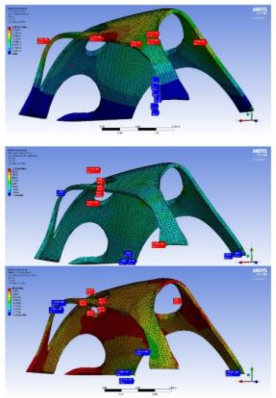
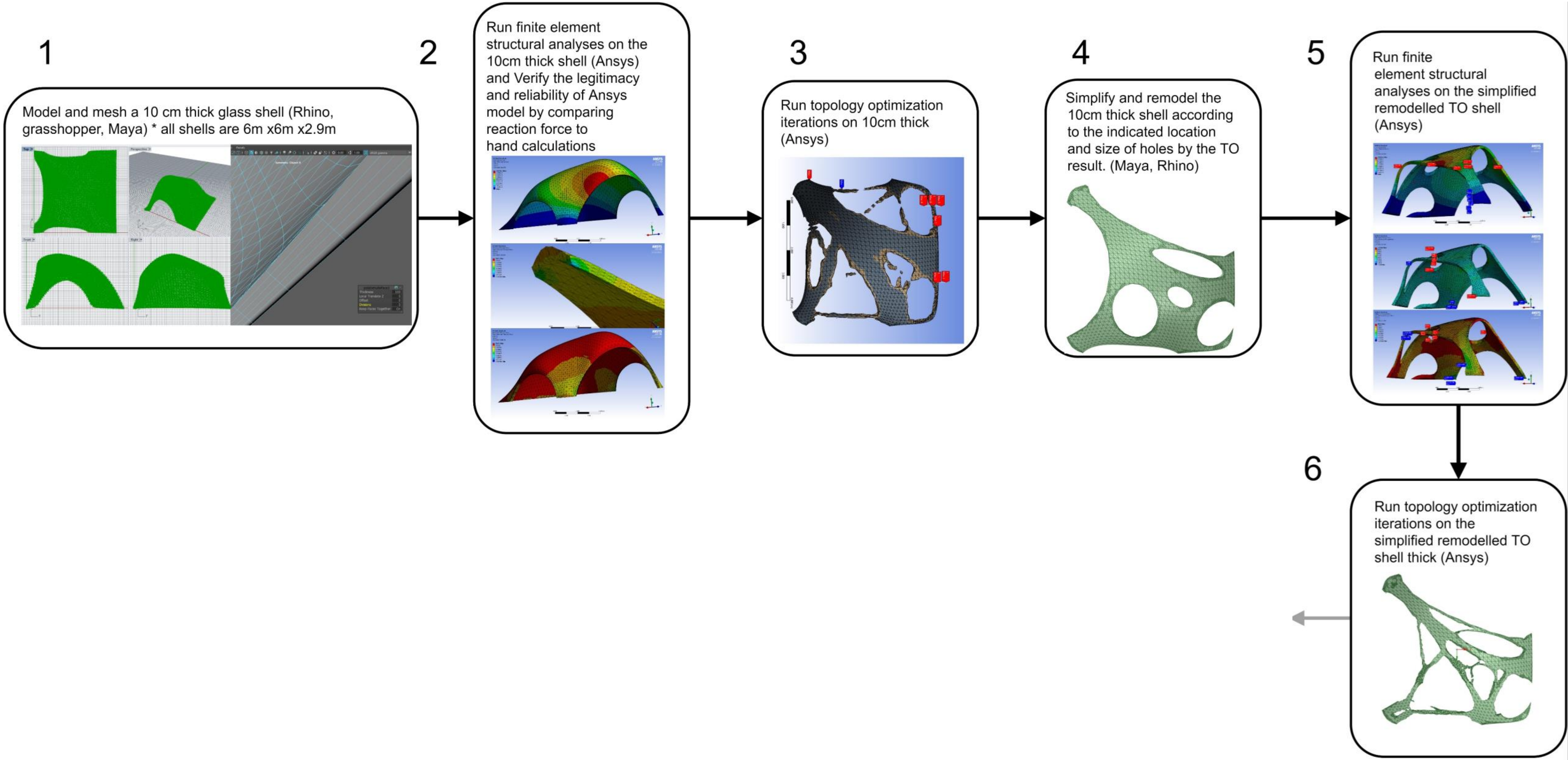


5

Run finite element structural analyses on the simplified remodelled TO shell (Ansys)

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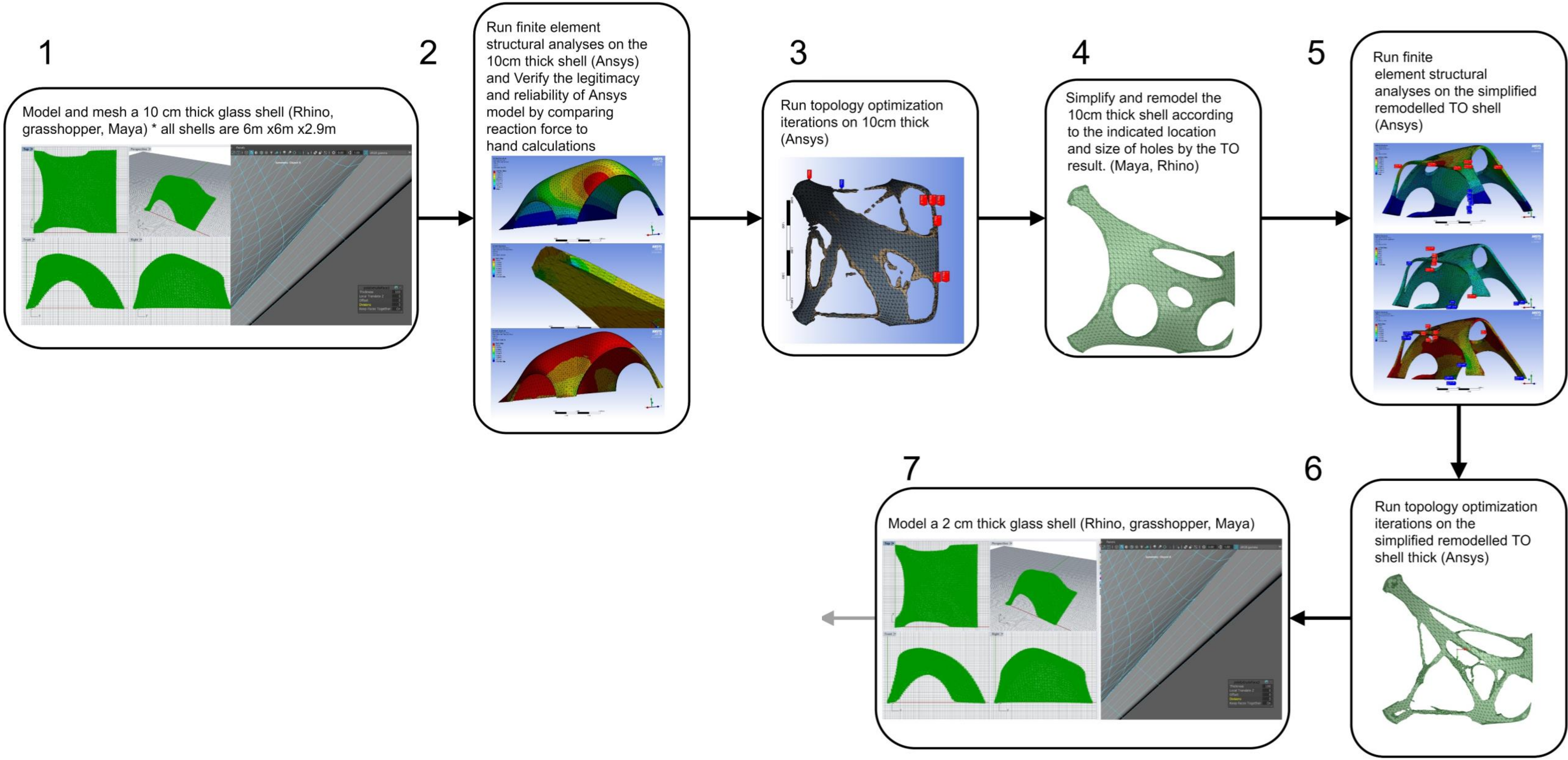
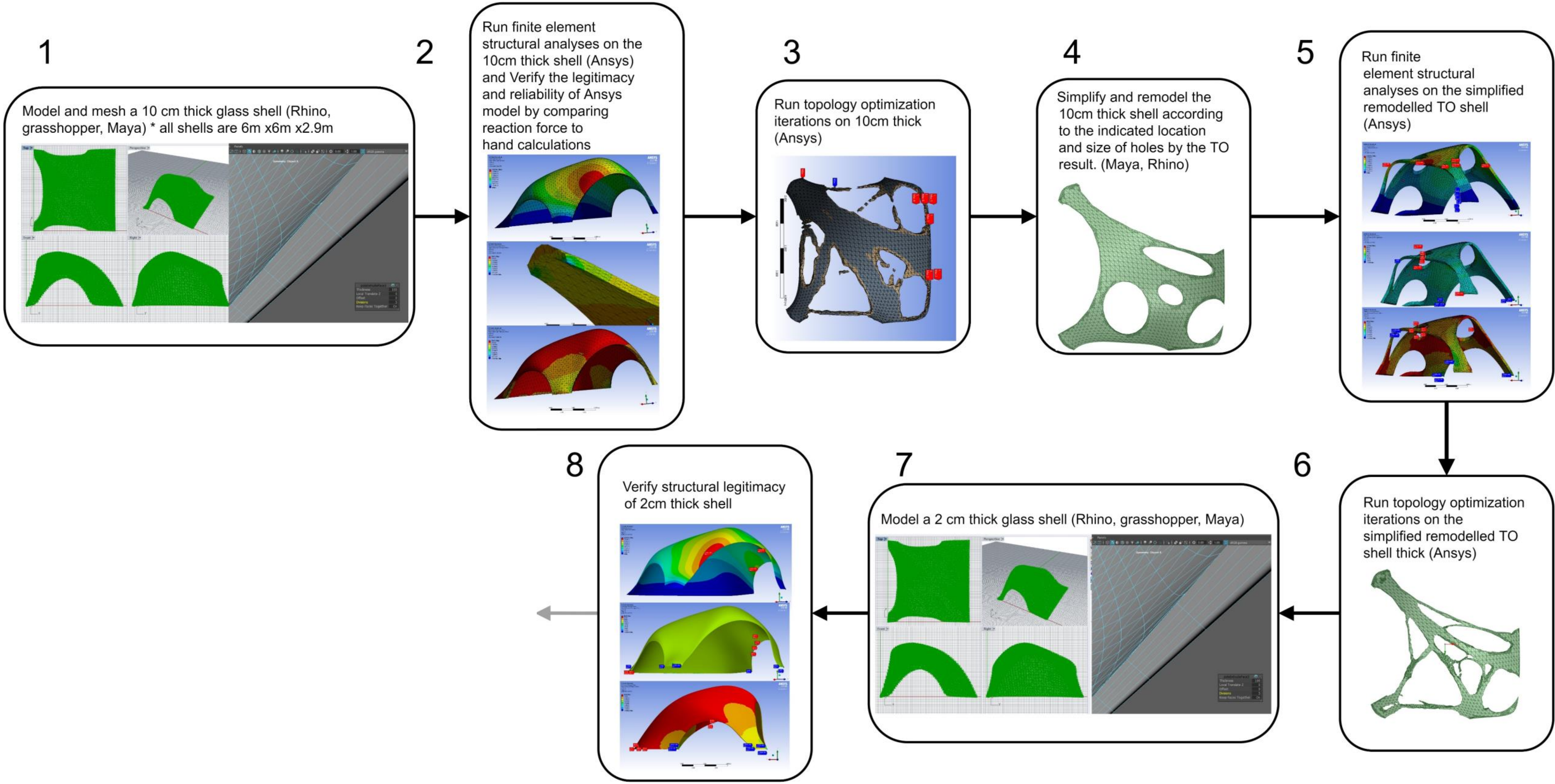

1
Model and mesh a 10 cm thick glass shell (Rhino, grasshopper, Maya) * all shells are 6m x6m x2.9m
2
Run finite element structural analyses on the 10cm thick shell (Ansys) and Verify the legitimacy and reliability of Ansys model by comparing reaction force to hand calculations
3
Run topology optimization iterations on 10cm thick (Ansys)
4
Simplify and remodel the 10cm thick shell according to the indicated location and size of holes by the TO result. (Maya, Rhino)
5
Run finite element structural analyses on the simplified remodelled TO shell (Ansys)
6
Run topology optimization iterations on the simplified remodelled TO shell thick (Ansys)
7
Model a 2 cm thick glass shell (Rhino, grasshopper, Maya)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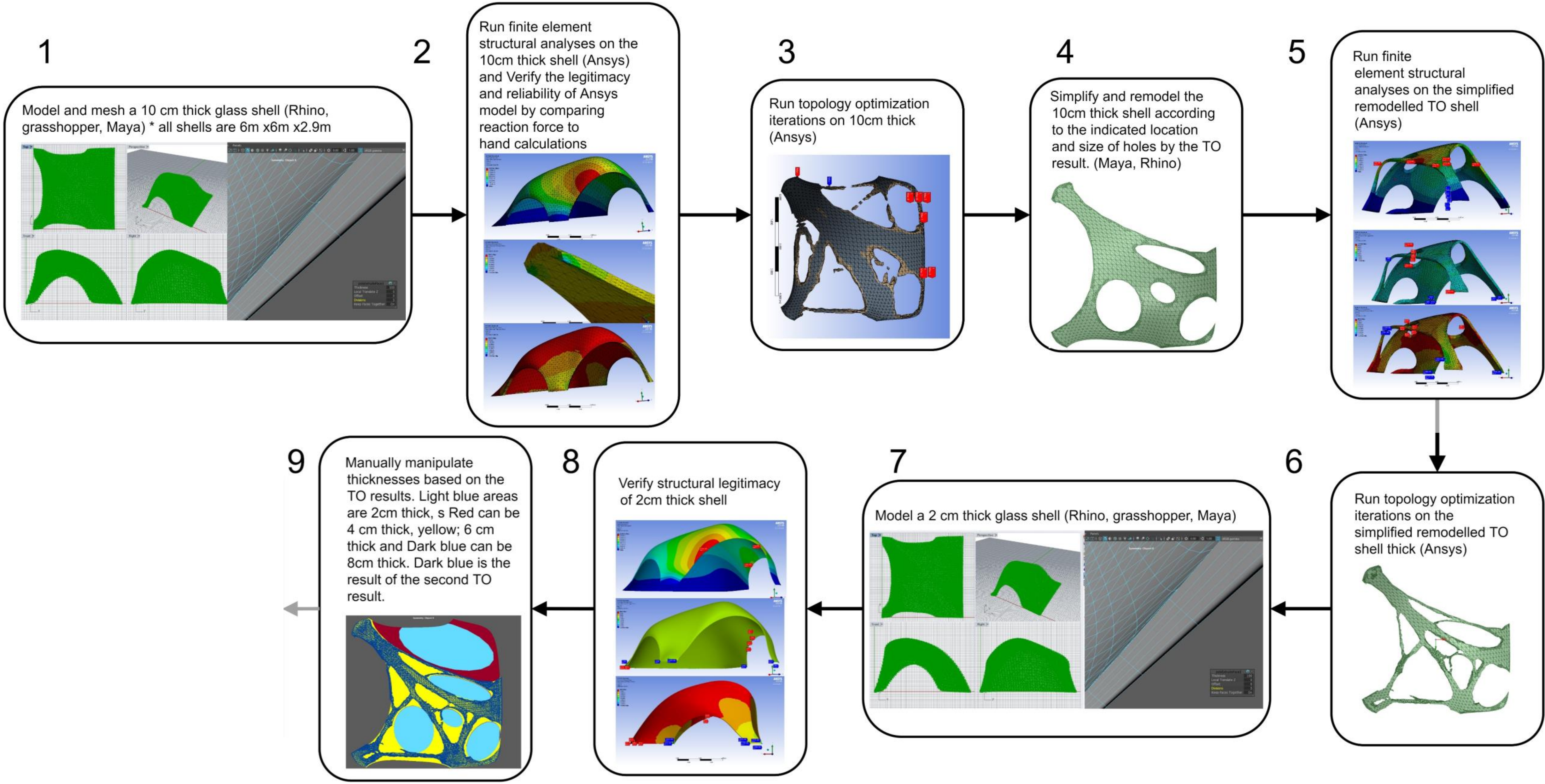
7
Model a 2 cm thick glass shell (Rhino, grasshopper, Maya)
8
Verify structural legitimacy of 2cm thick shell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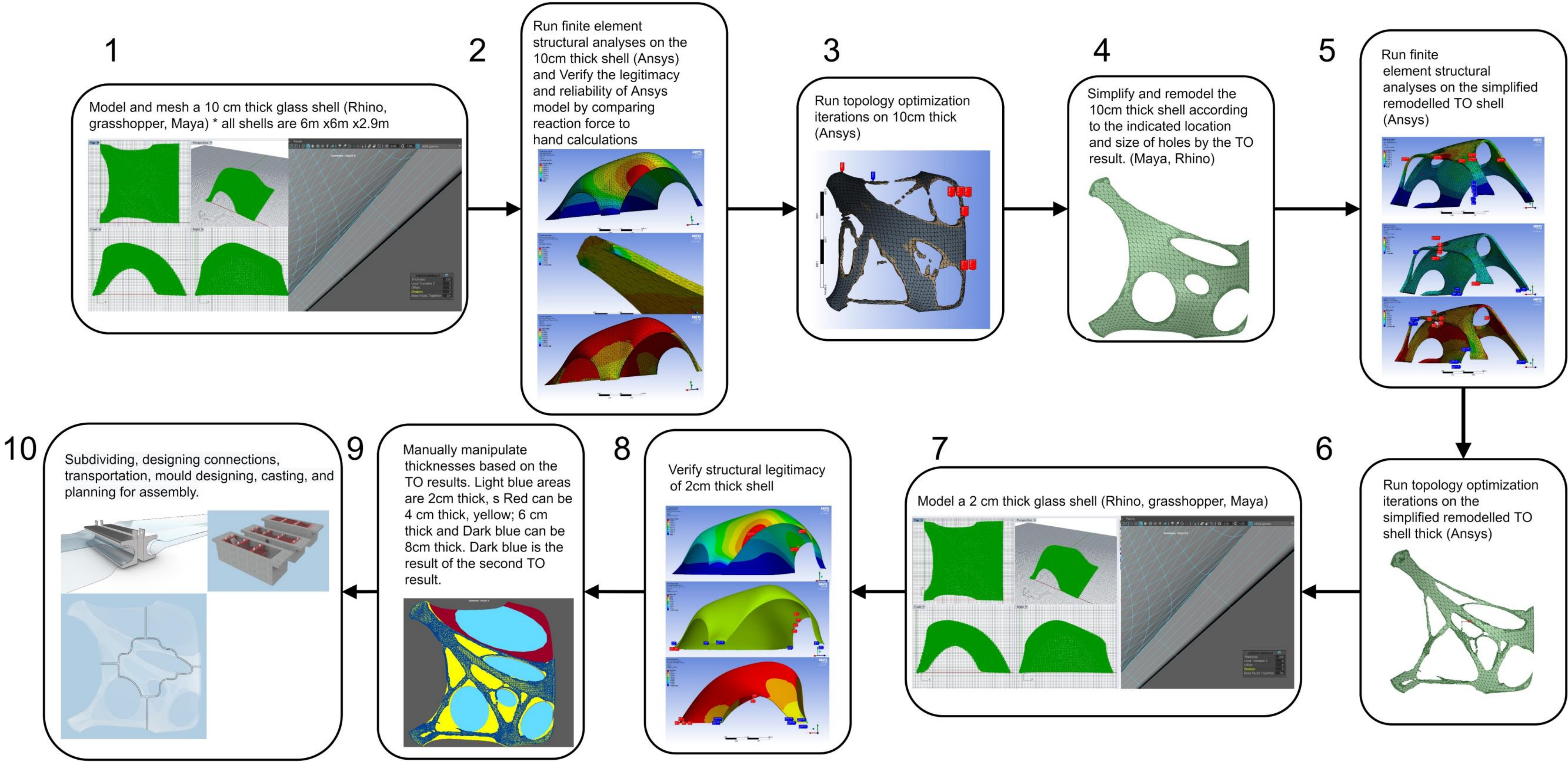
Model a 2 cm thick glass shell (Rhino, grasshopper, Maya)
8
Verify structural legitimacy of 2cm thick shell
9
Manually manipulate thicknesses based on the TO results. Light blue areas are 2cm thick, s Red can be 4 cm thick, yellow; 6 cm thick and Dark blue can be 8cm thick. Dark blue is the result of the second TO result.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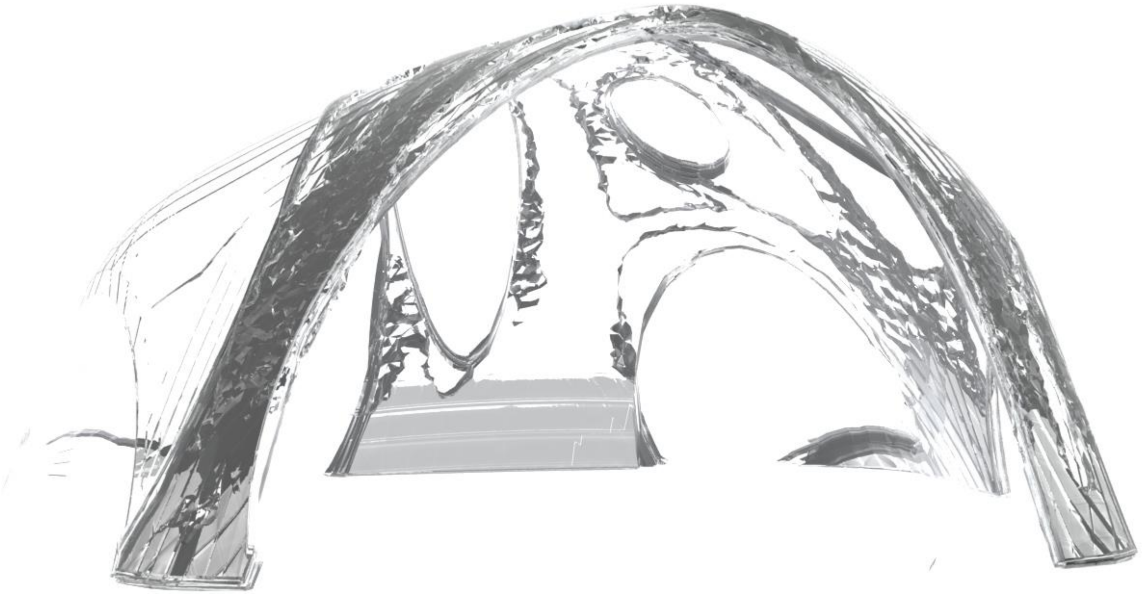
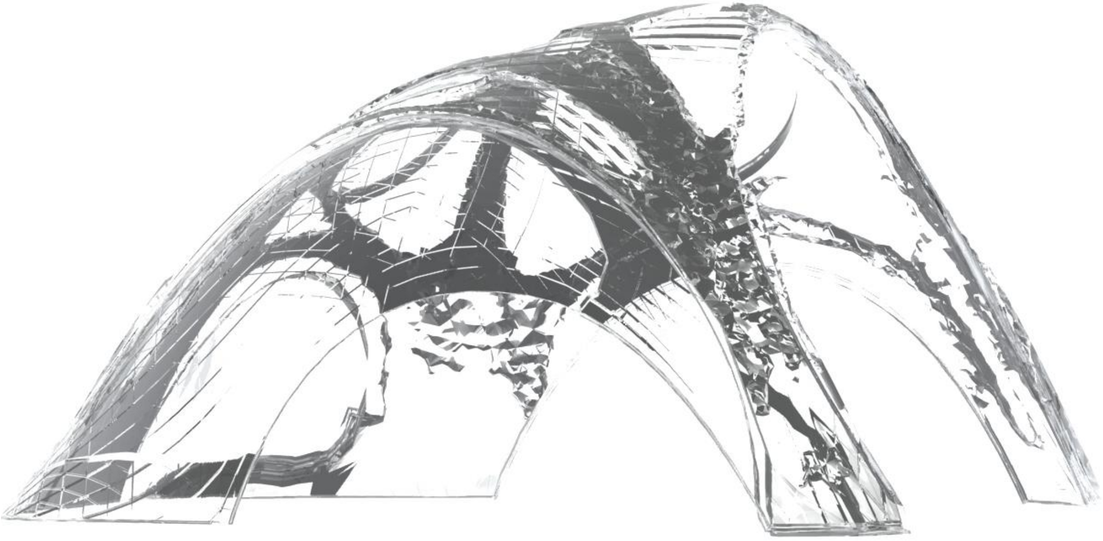
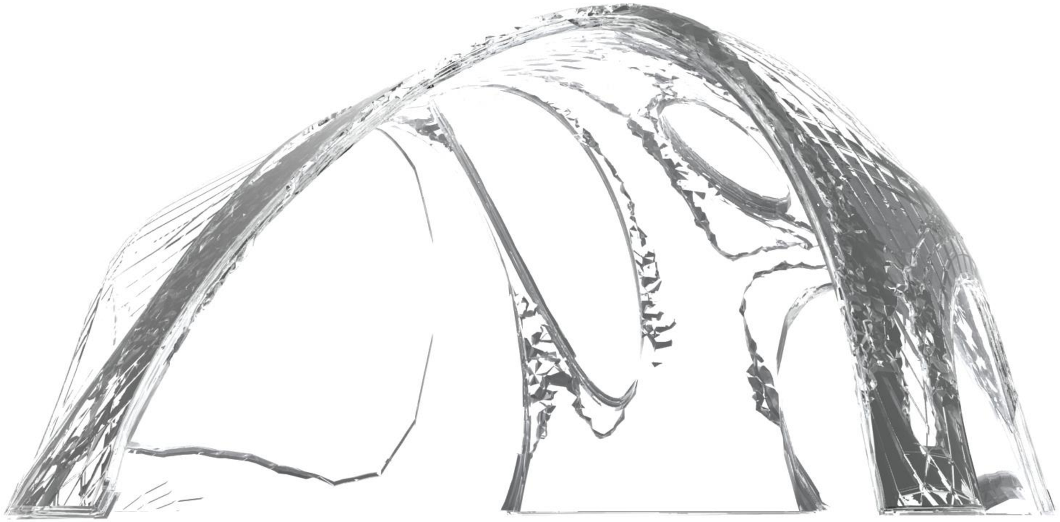
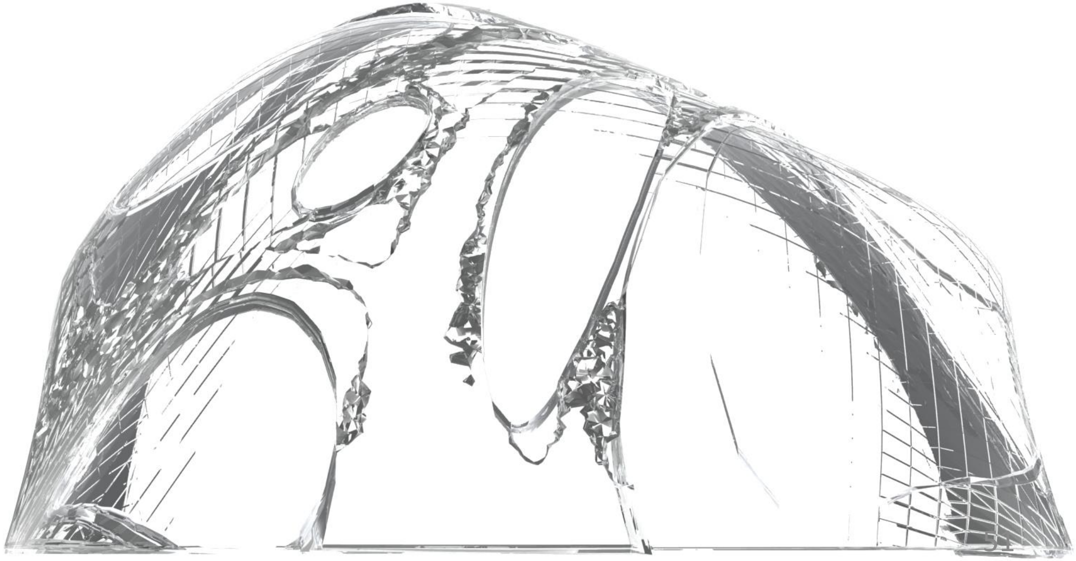
10
Subdividing, designing connections, transportation, mould designing, casting, and planning for assembly.

Structural Validation

Table 9 FEA results from Ansys regarding the 3 different analyzed shells. Please look Appendix C for all FEA results

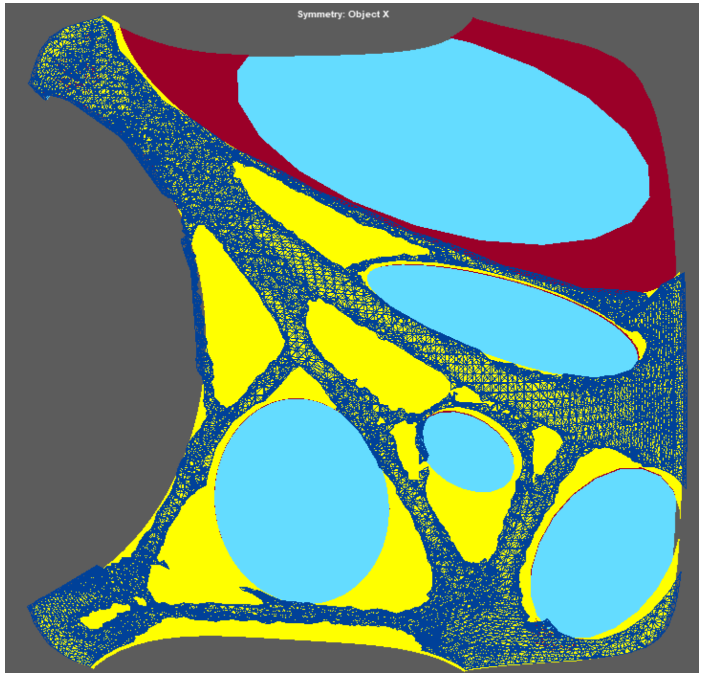
	Permitted limit by Material properties or shell dimensions	Ansys Shell analyses results before TO 10cm thick	Ansys Shell analyses results After TO 10cm thick	Ansys Shell analyses results before/without TO 2cm thick
Maximum Principle stress (tensile stress) [MPa]	26.5	0.050007	0.11716	0.086317
Minimum Principle stress (compressive stress) [MPa]	265 – 1000 ***	0.0026977	0.0085319	0.020139
Deformation m	(1/6) * thickness for the 10 cm thick shells it is 16.67mm, and for the 2cm it is 3.33mm	0.0163 mm	0.0277 mm	0.0222 mm

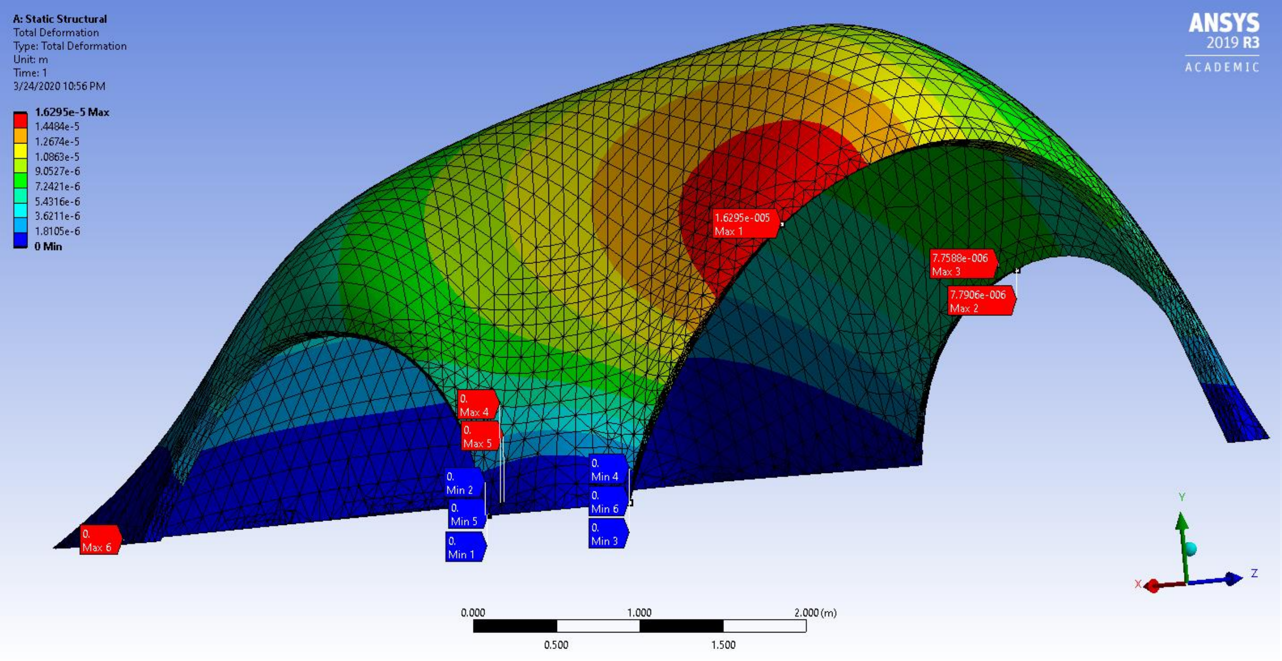





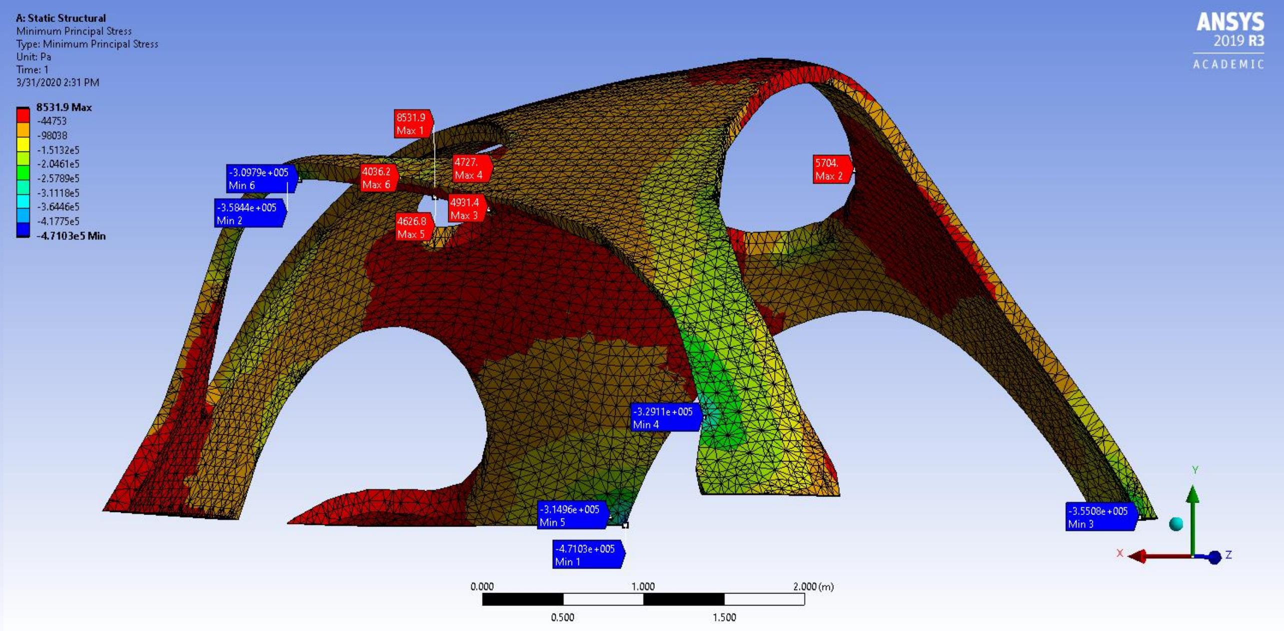
Mass reduction

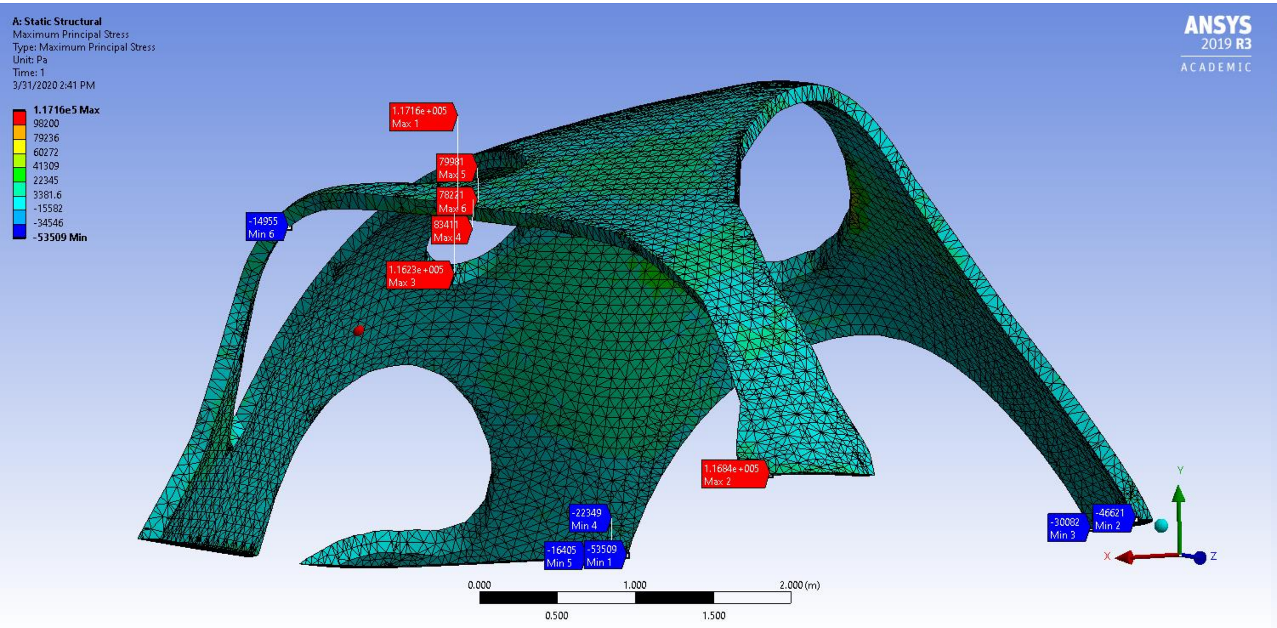
Shell version	Mass [Tonnes]	Mass reduction percentage
Original 10 cm solid shell	8.729	0%
8 cm shell with wholes at TO indicated areas	3.175	64%
4 cm shell with cut away material at TO indicated areas	1.906	78%
Solid 2 cm shell	1.598	82%
The manually adjusted shell with varying thickness from 8,6,4, to 2cm	4.138	53%
The manually adjusted shell with varying thickness from 8,6,4, to 2cm including additional ribs for extra reinforcement at connections	4.998	43%

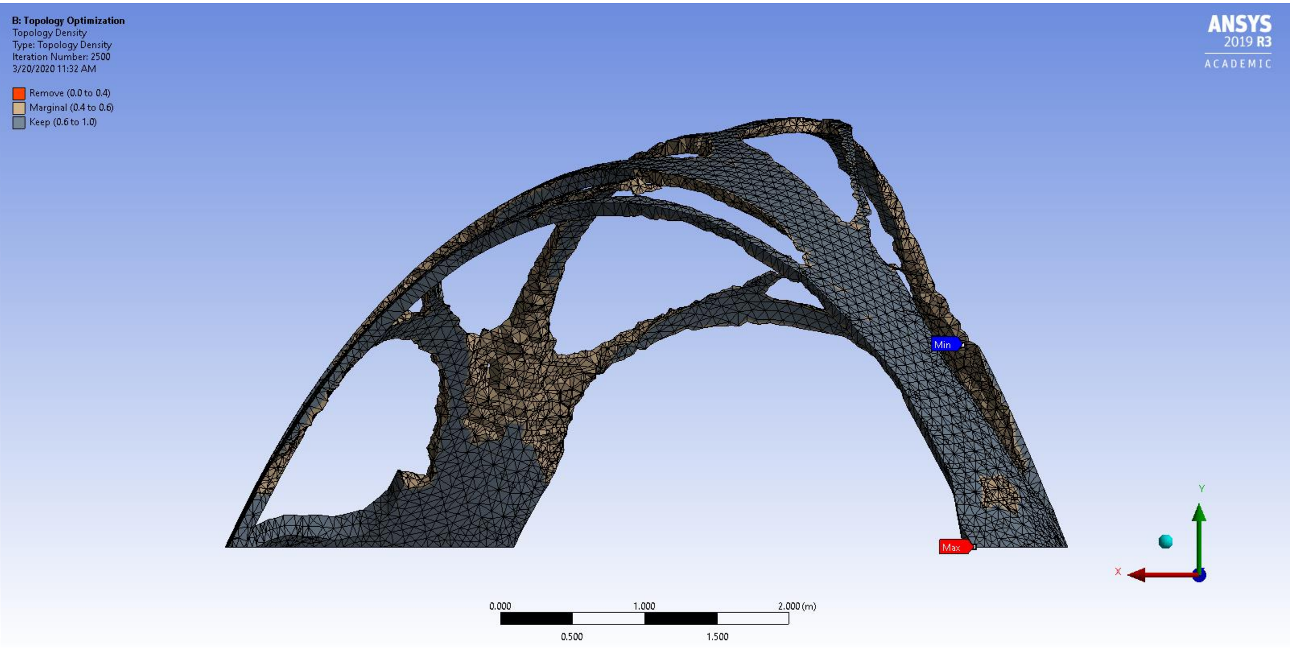
43% mass reduction

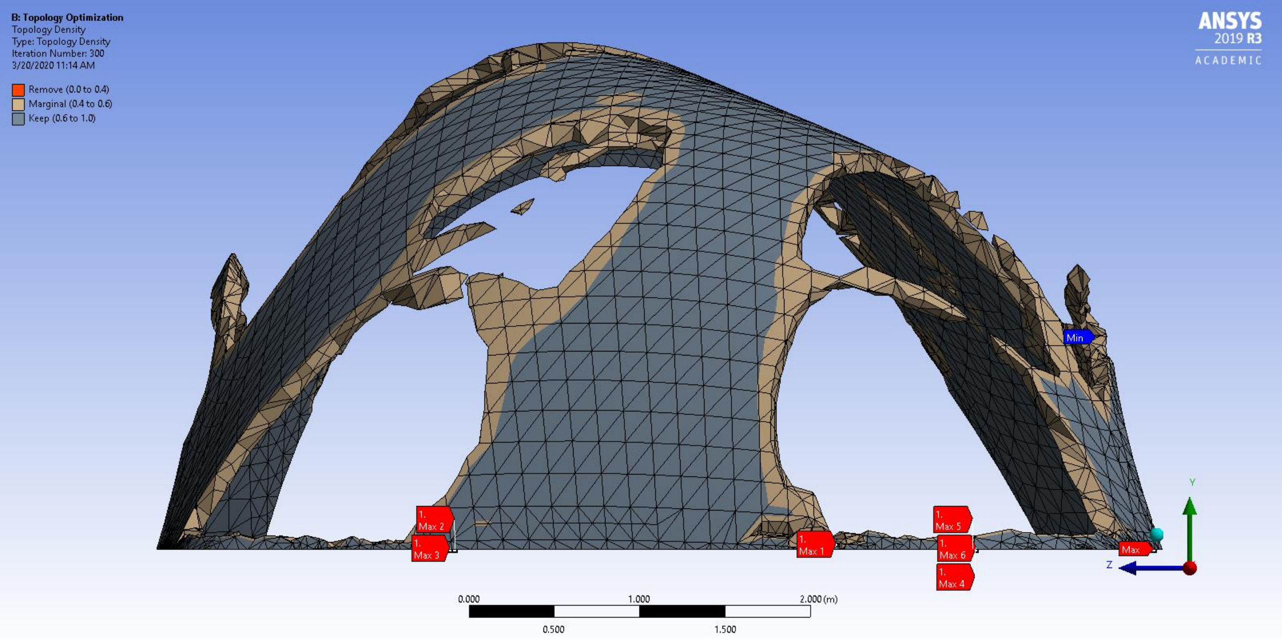


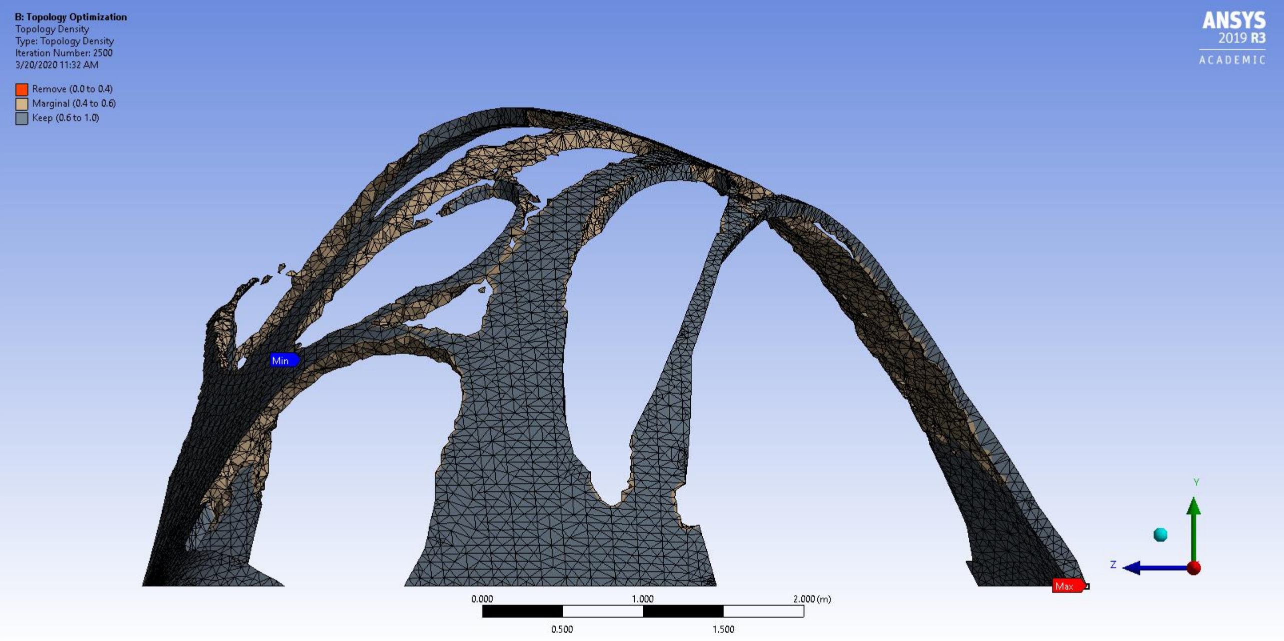

A: Static Structural
Total Deformation
Type: Total Deformation
Unit: m
Time: 1
3/24/2020 10:56 PM
1.6295e-5 Max
1.4484e-5
1.2674e-5
1.0863e-5
9.0527e-6
7.2421e-6
5.4316e-6
3.6211e-6
1.8105e-6
0 Min
ANSYS
2019 R3
ACADEMIC
0.000
1.000
2.000 (m)
0.500
1.500

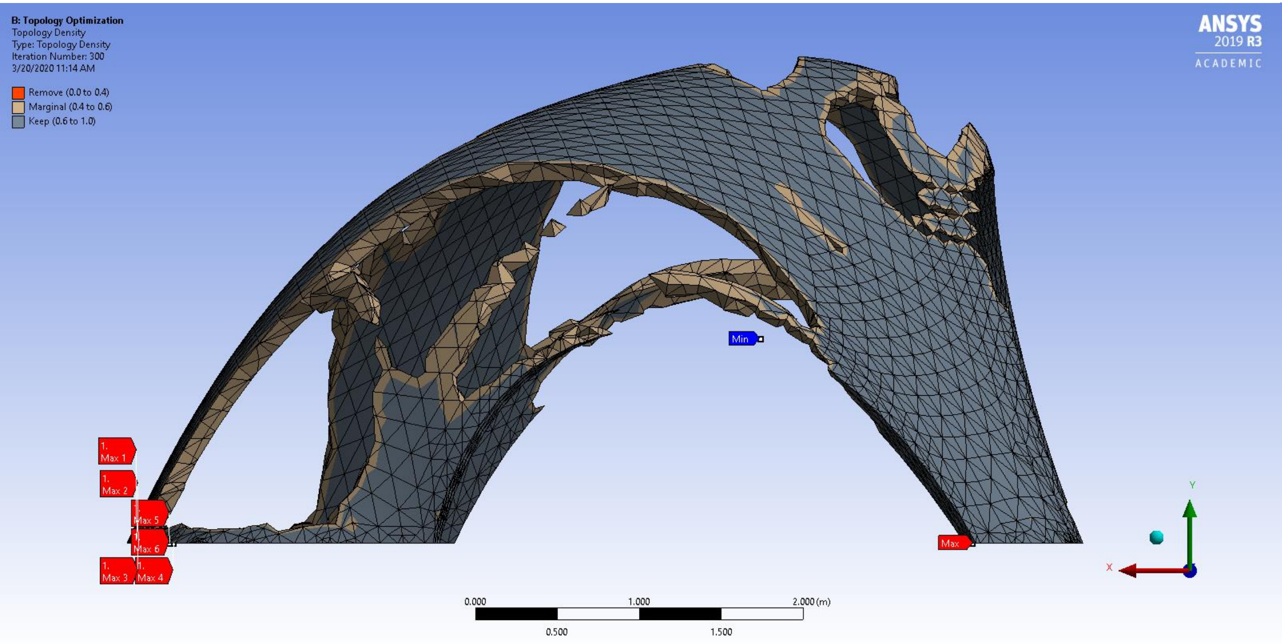

A: Static Structural
Minimum Principal Stress
Type: Minimum Principal Stress
Unit: Pa
Time: 1
3/31/2020 2:31 PM
8531.9 Max
-44753
-98038
-1.5132e5
-2.0461e5
-2.5789e5
-3.1118e5
-3.6446e5
-4.1775e5
-4.7103e5 Min
ANSYS
2019 R3
ACADEMIC
0.000
1.000
2.000 (m)
0.500
1.500

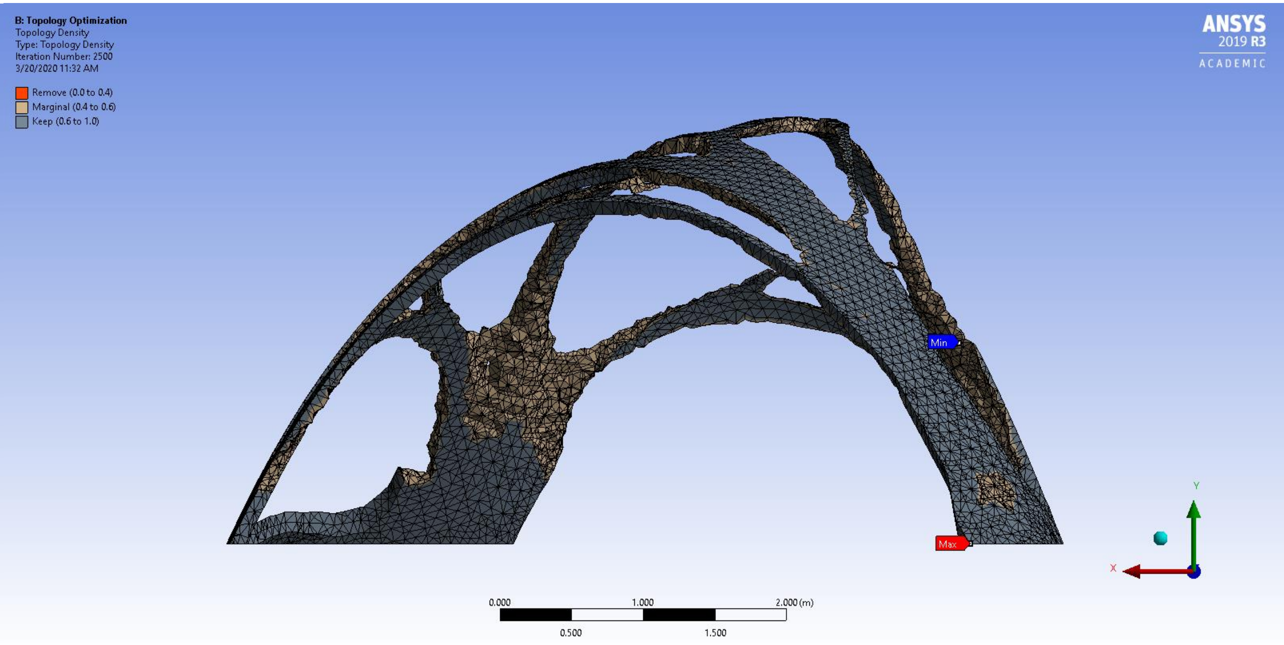

A: Static Structural
Maximum Principal Stress
Type: Maximum Principal Stress
Unit: Pa
Time: 1
3/31/2020 2:41 PM
1.1716e5 Max
98200
79236
60272
41309
22345
3381.6
-15582
-34546
-53509 Min
ANSYS
2019 R3
ACADEMIC
0.000
1.000
2.000 (m)
0.500
1.500


B: Topology Optimization
Topology Density
Type: Topology Density
Iteration Number: 2500
3/20/2020 11:32 AM
Remove (0.0 to 0.4)
Marginal (0.4 to 0.6)
Keep (0.6 to 1.0)
ANSYS
2019 R3
ACADEMIC
Min
Max
0.000
1.000
2.000 (m)
0.500
1.500


B: Topology Optimization
Topology Density
Type: Topology Density
Iteration Number: 300
3/20/2020 11:14 AM
Remove (0.0 to 0.4)
Marginal (0.4 to 0.6)
Keep (0.6 to 1.0)
ANSYS
2019 R3
ACADEMIC
0.000
1.000
2.000 (m)
0.500
1.500


B: Topology Optimization
Topology Density
Type: Topology Density
Iteration Number: 2500
3/20/2020 11:32 AM
Remove (0.0 to 0.4)
Marginal (0.4 to 0.6)
Keep (0.6 to 1.0)
ANSYS
2019 R3
ACADEMIC
0.000
1.000
2.000 (m)
0.500
1.500

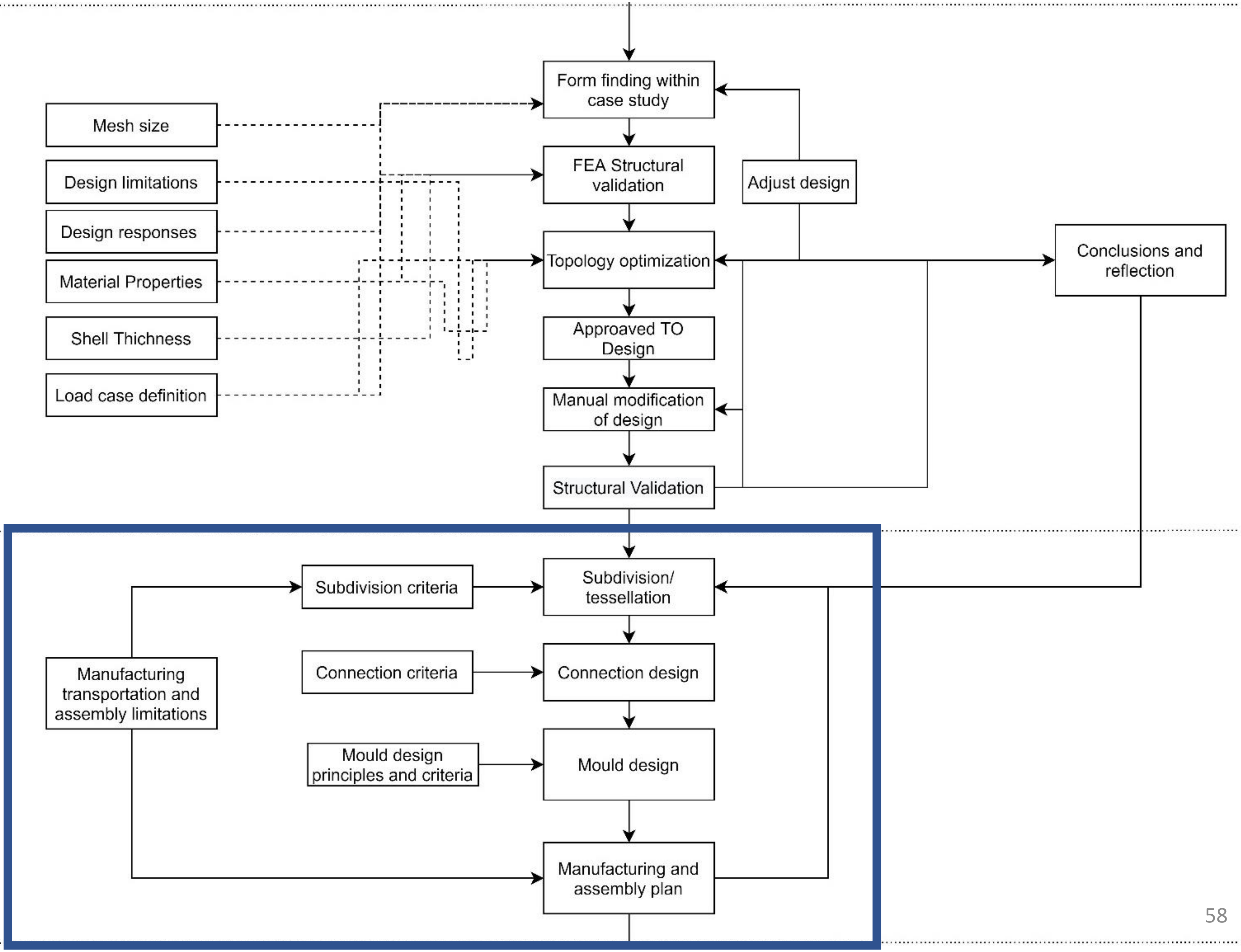

B: Topology Optimization
Topology Density
Type: Topology Density
Iteration Number: 300
3/20/2020 11:14 AM
Remove (0.0 to 0.4)
Marginal (0.4 to 0.6)
Keep (0.6 to 1.0)
ANSYS
2019 R3
ACADEMIC
0.000
1.000
2.000 (m)
0.500
1.500


B: Topology Optimization
Topology Density
Type: Topology Density
Iteration Number: 2500
3/20/2020 11:32 AM
Remove (0.0 to 0.4)
Marginal (0.4 to 0.6)
Keep (0.6 to 1.0)
ANSYS
2019 R3
ACADEMIC
0.000
1.000
2.000 (m)
0.500
1.500

Drucker–Prager Criterion

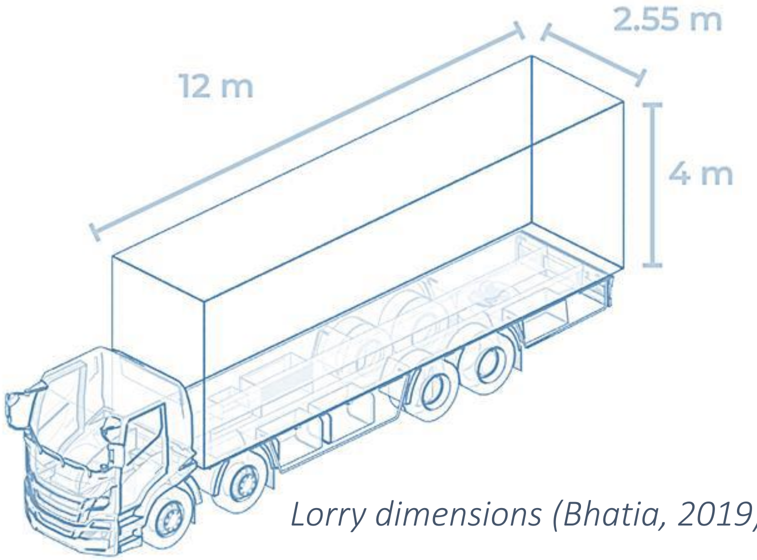
New TO algorithm for brittle material

16 Jan 2020



P3 26 March

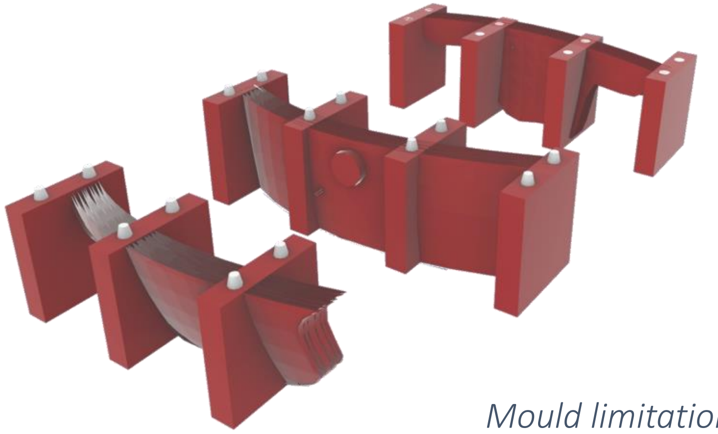
P4 21 May



Lorry dimensions (Bhatia, 2019)

Subdivision / Tessellation

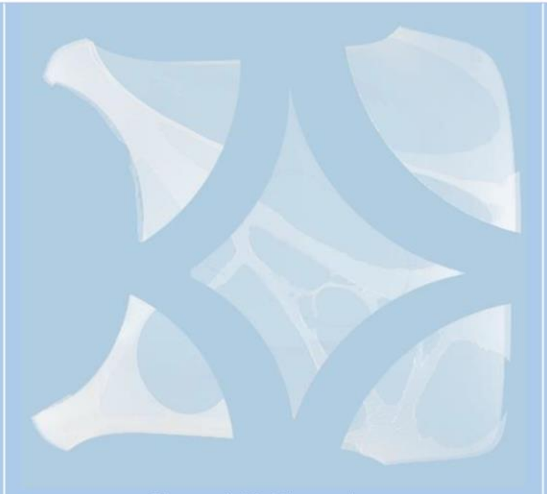
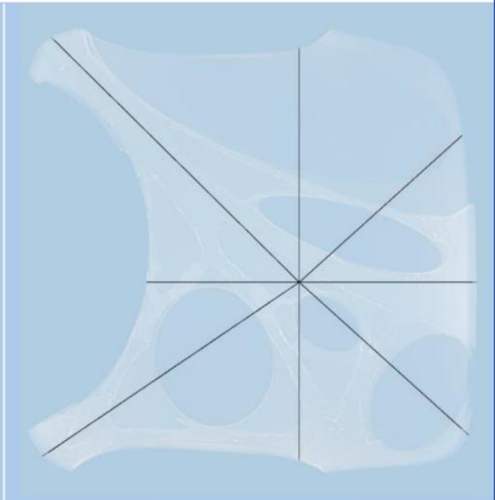
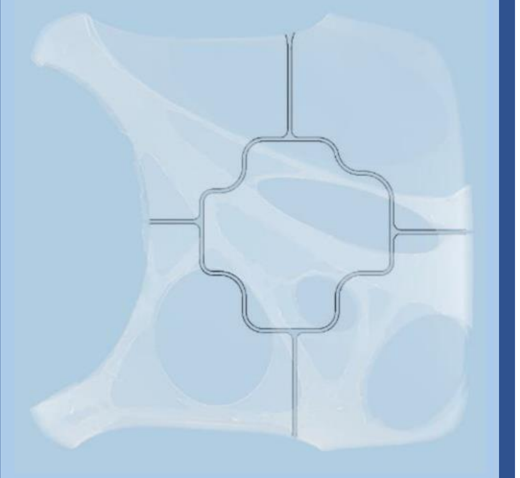
Spider crane. Limit 3T x 3.4m. See figure 102. (Uniccranes, 2020)

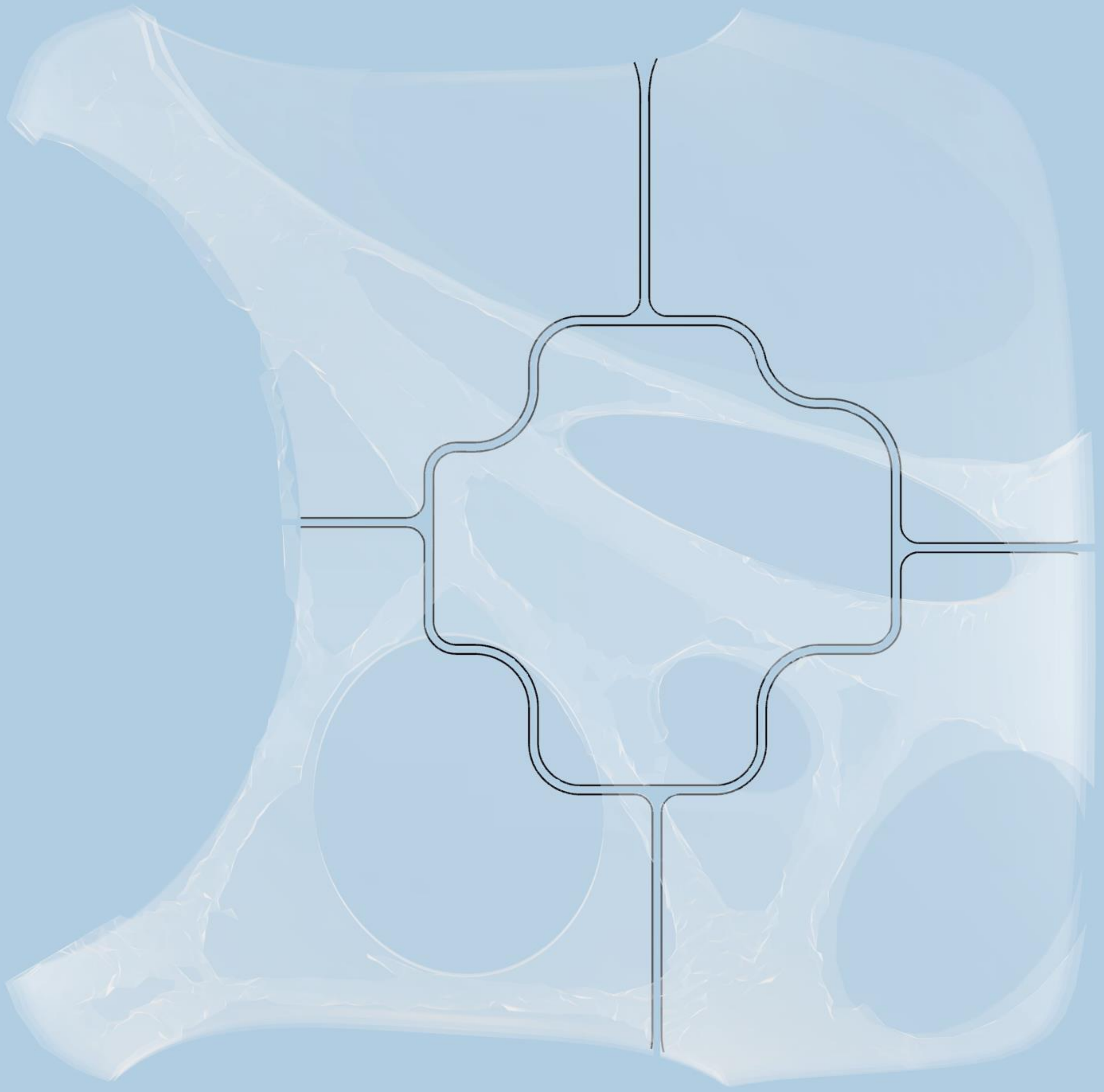


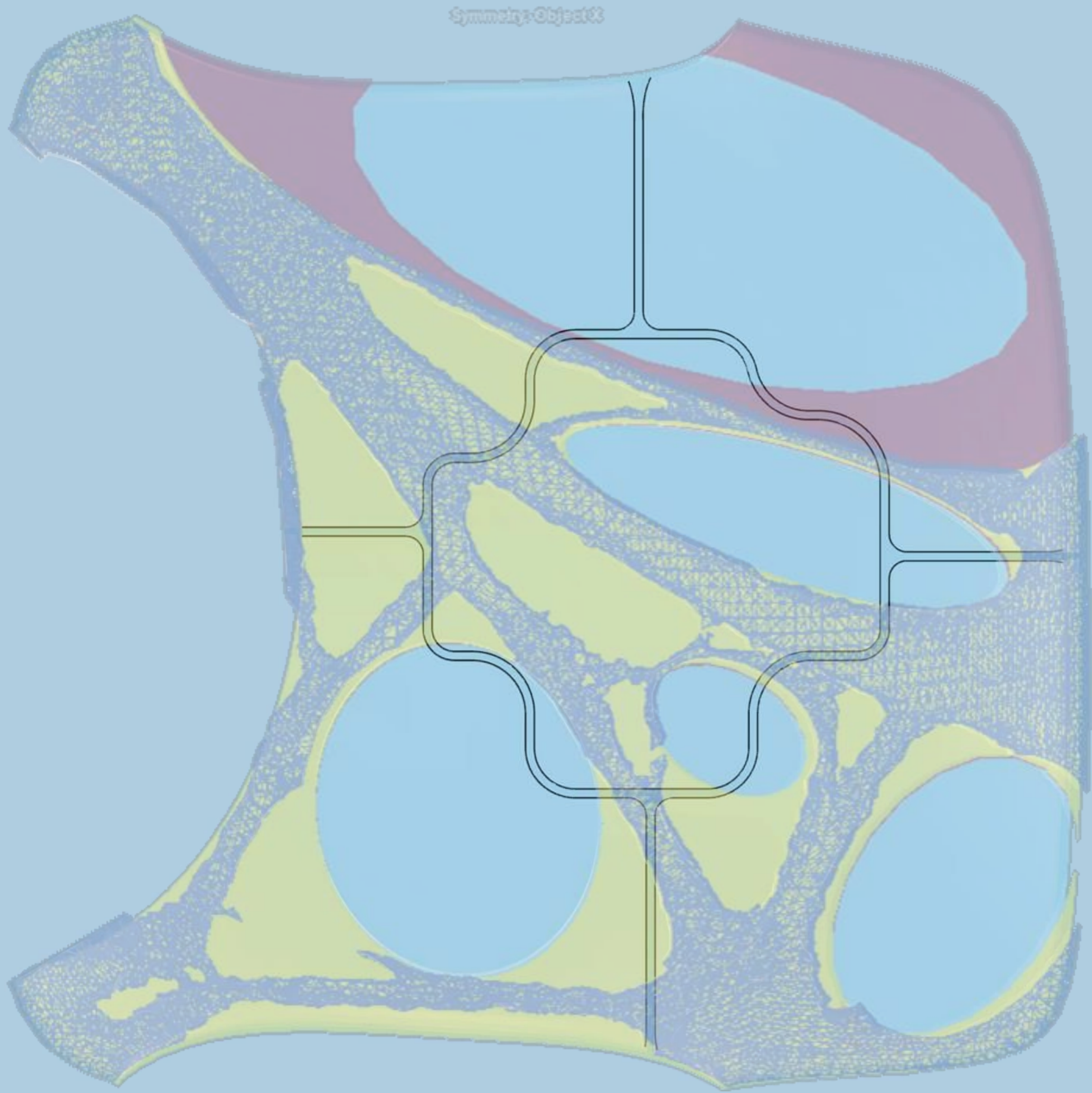
Mould limitations

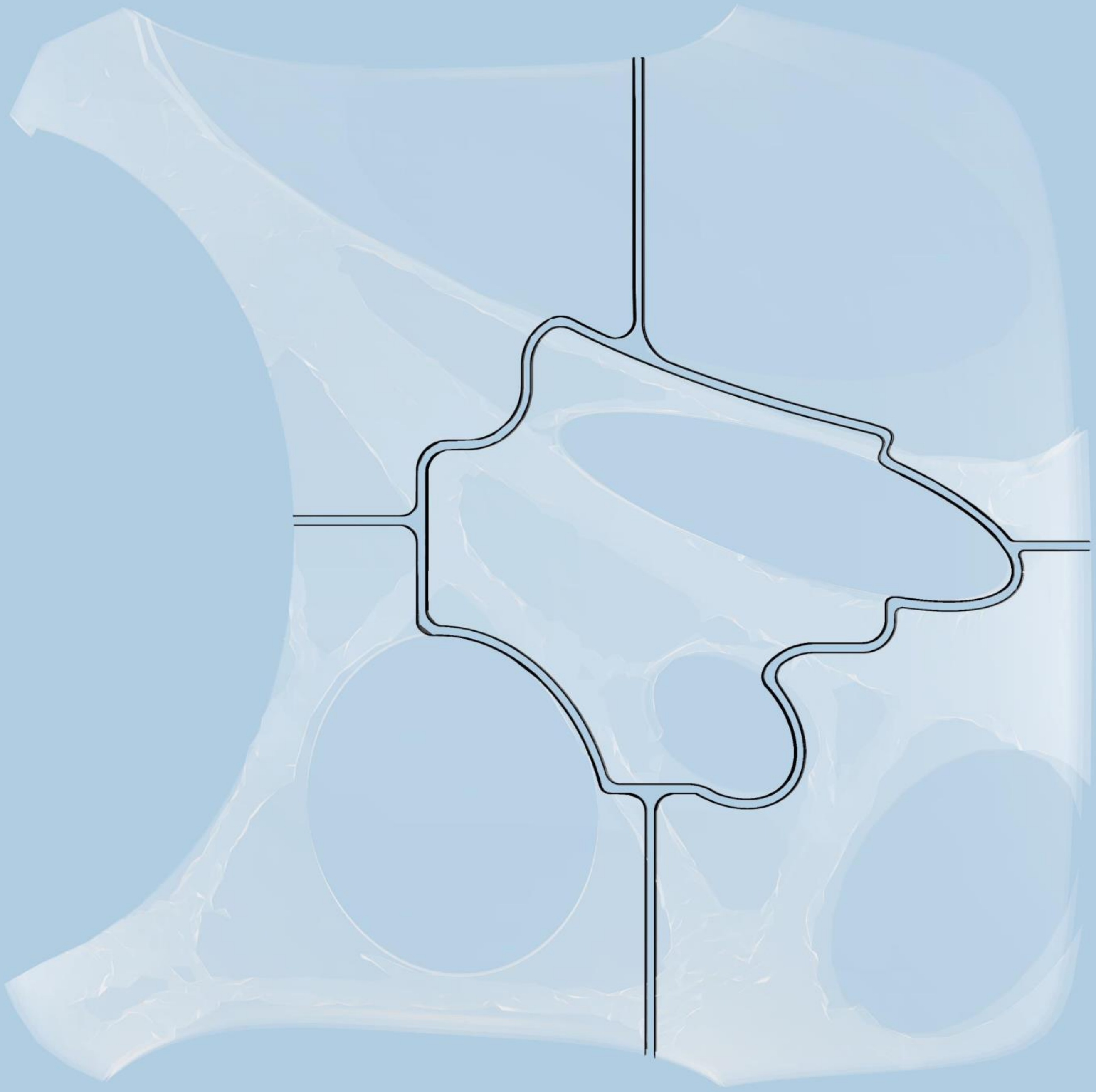
Subdivision Criteria → Compared & assessed different subdivision patterns based on criteria → Chosen the one that passed all criteria

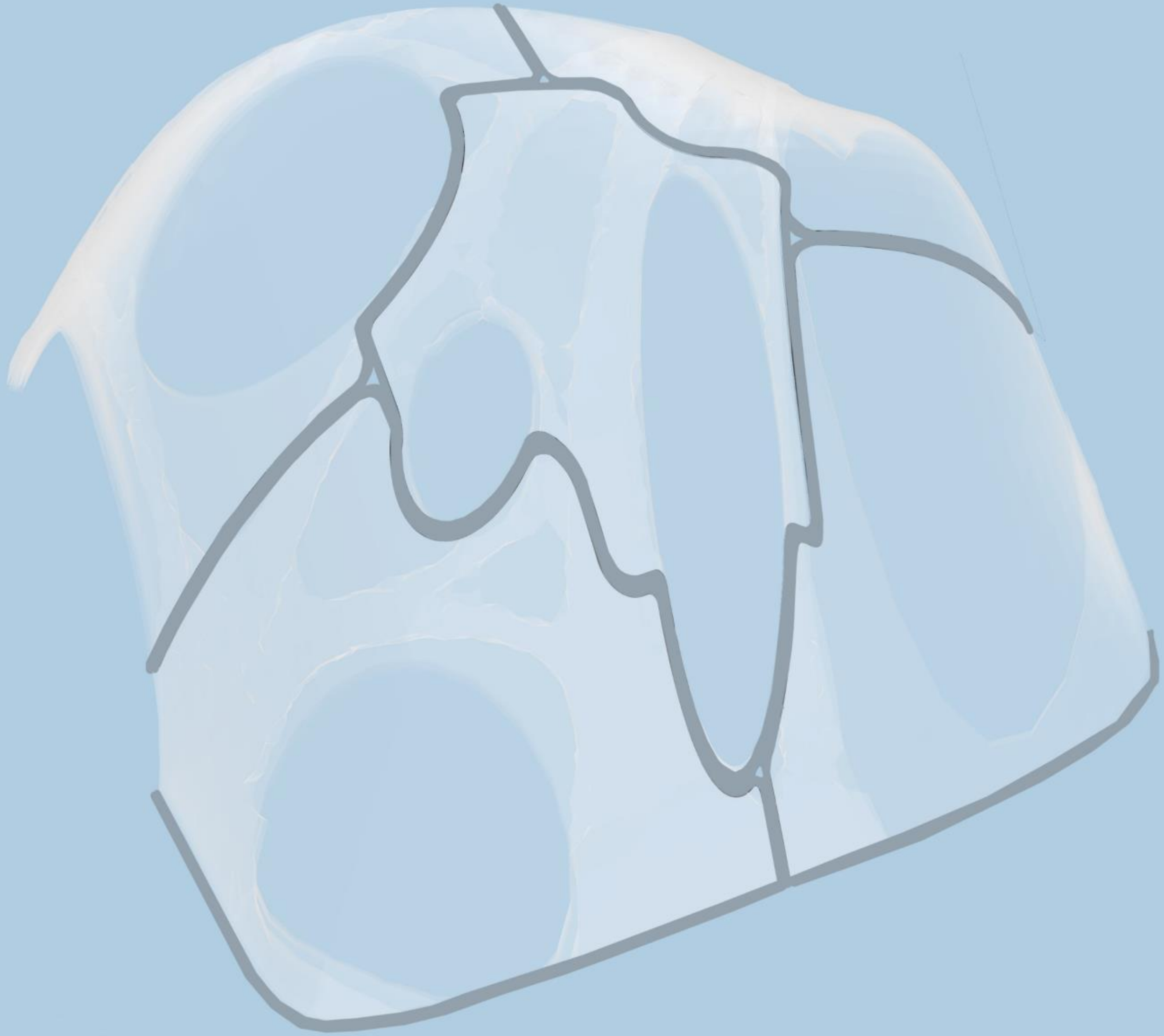
Table 12 Subdivision pattern options

Options / Criteria	 *Figure 110 Dimond cut.*	 *Figure 111 round keystone cut.*	 *Figure 112 Pie cut*	 *Figure 113 curvy cut with keystone*
Avoid sharp corners.	X	X	X	No sharp corners.
No scaffolding needed	X			No scaffolding needed
Max 6 pieces			X	5 pieces
Fits in trucks. (12 x 4 x 2.5 m)	X			Fits in 2 trucks with some adjustment in orientation
Can be lifted by spider crane (3T x 3.4m)	X		X	Can be lifted by spider crane
All elements have a comparable annealing cycle.		X		All elements have a comparable annealing cycle.
Can be manufactured within mould design limitations & criteria				Can be manufactured within mould size (4 x 2 x 1 m) and mould design criteria
Tessellation does not interfere with force flow lines.			X	Tessellation does not interfere with force flow lines.

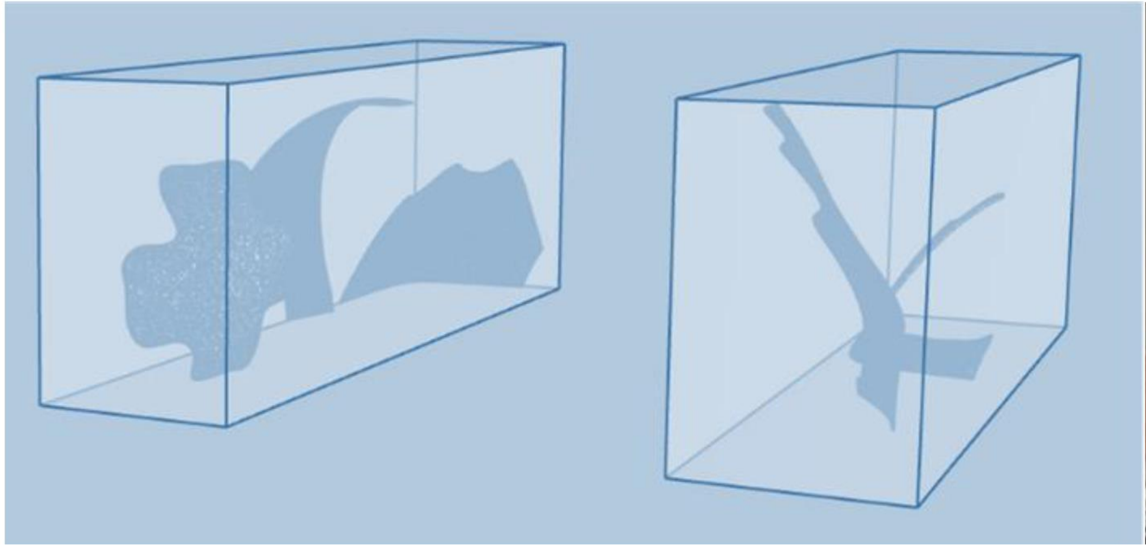



Symmetry: Object X





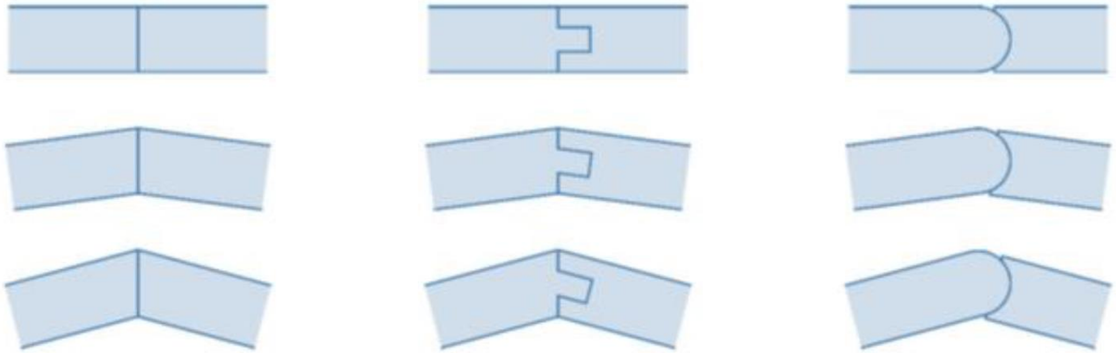
Fits in two trucks



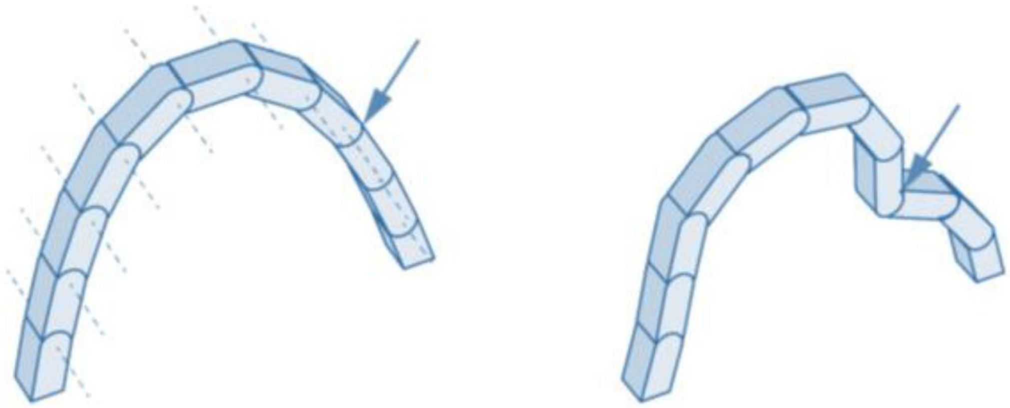
The shell elements can fit in two trucks with dimension 12 x 4 x 2.5m with adjusted orientation

CNC milled formwork of Styrofoam to support shape negative shape of shell elements in wooden boxes transported in trucks

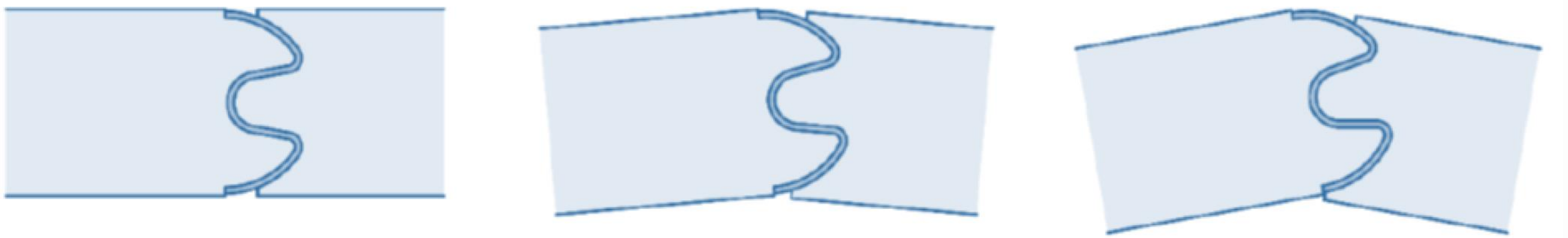
Connecting the components



“Voussoirs connection a) planar interfaces, b) tongue and groove and c) convex-concave interface” (Van der Weijst, 2019))



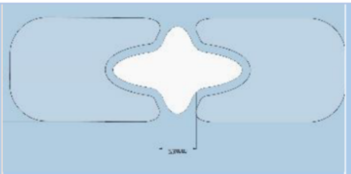
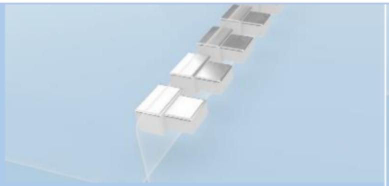
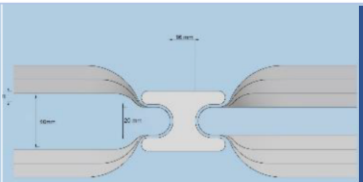
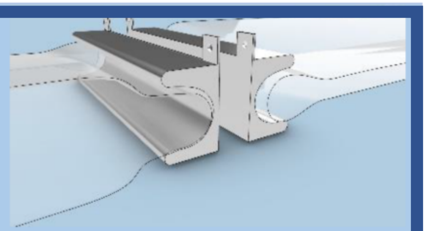
Convex concave collapse mechanism (Van der Weijst, 2019)

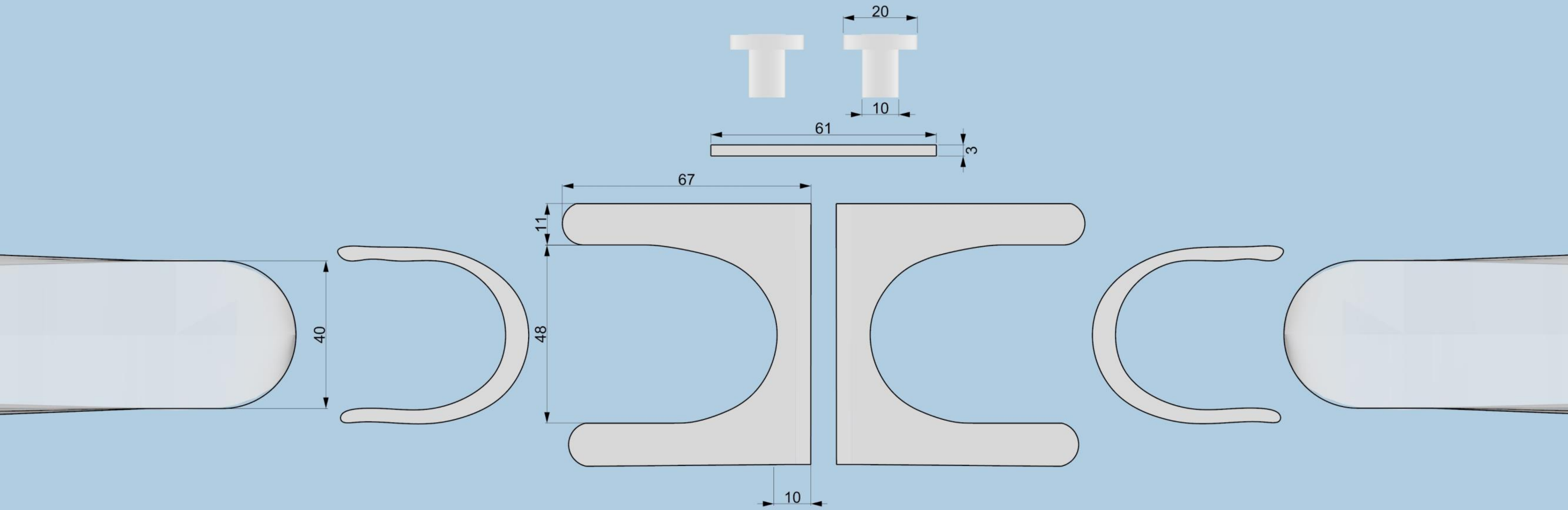


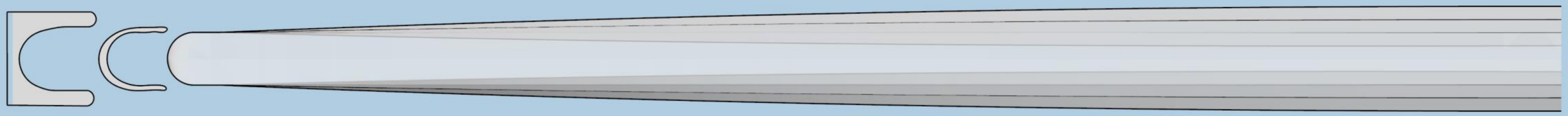
hybrid version of the concave convex and tong in groove interlocking system (van der Weijst, 2019)

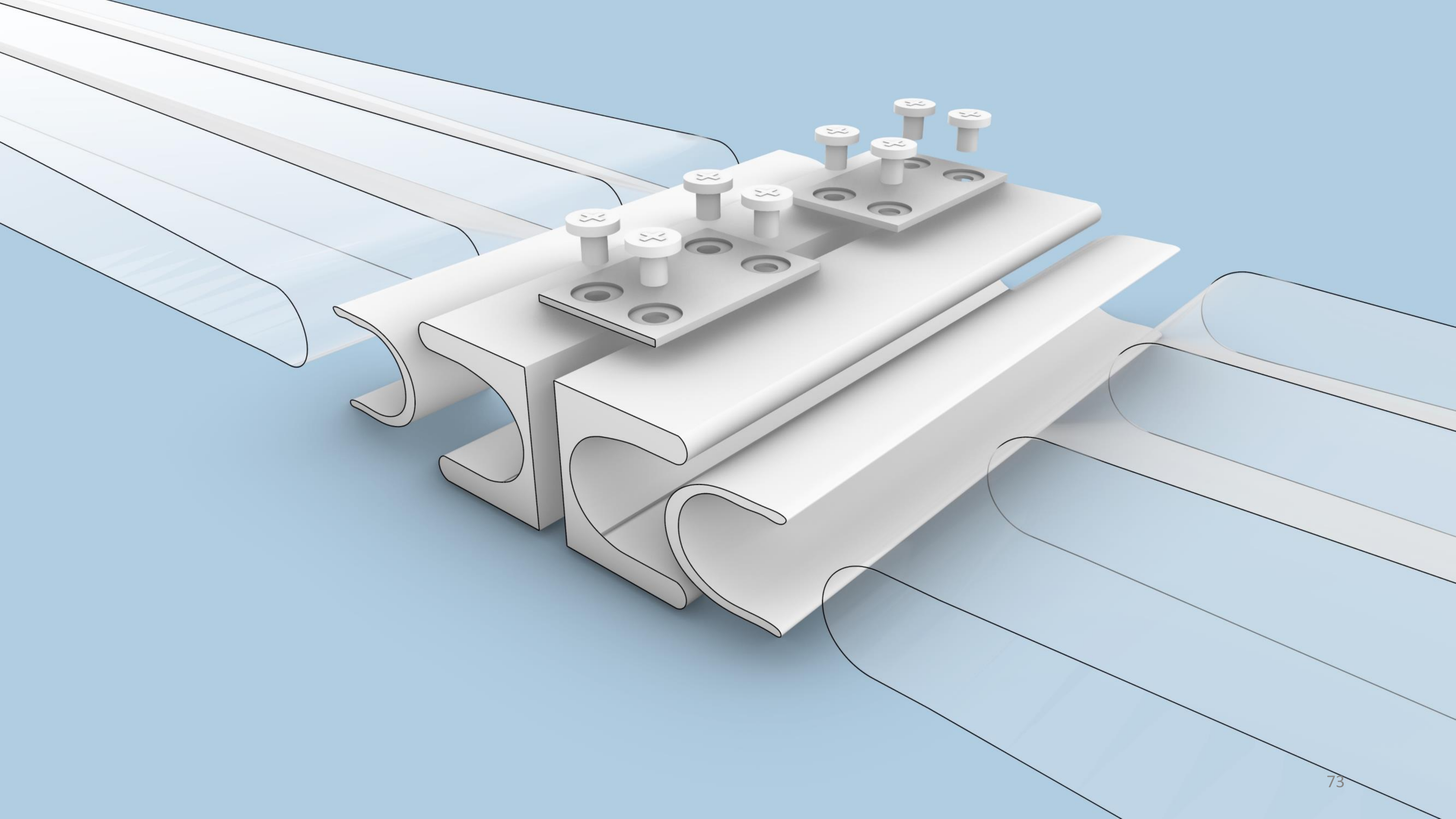
Criteria for connections → Compared & assessed different connections → Chosen the one that passed all criteria

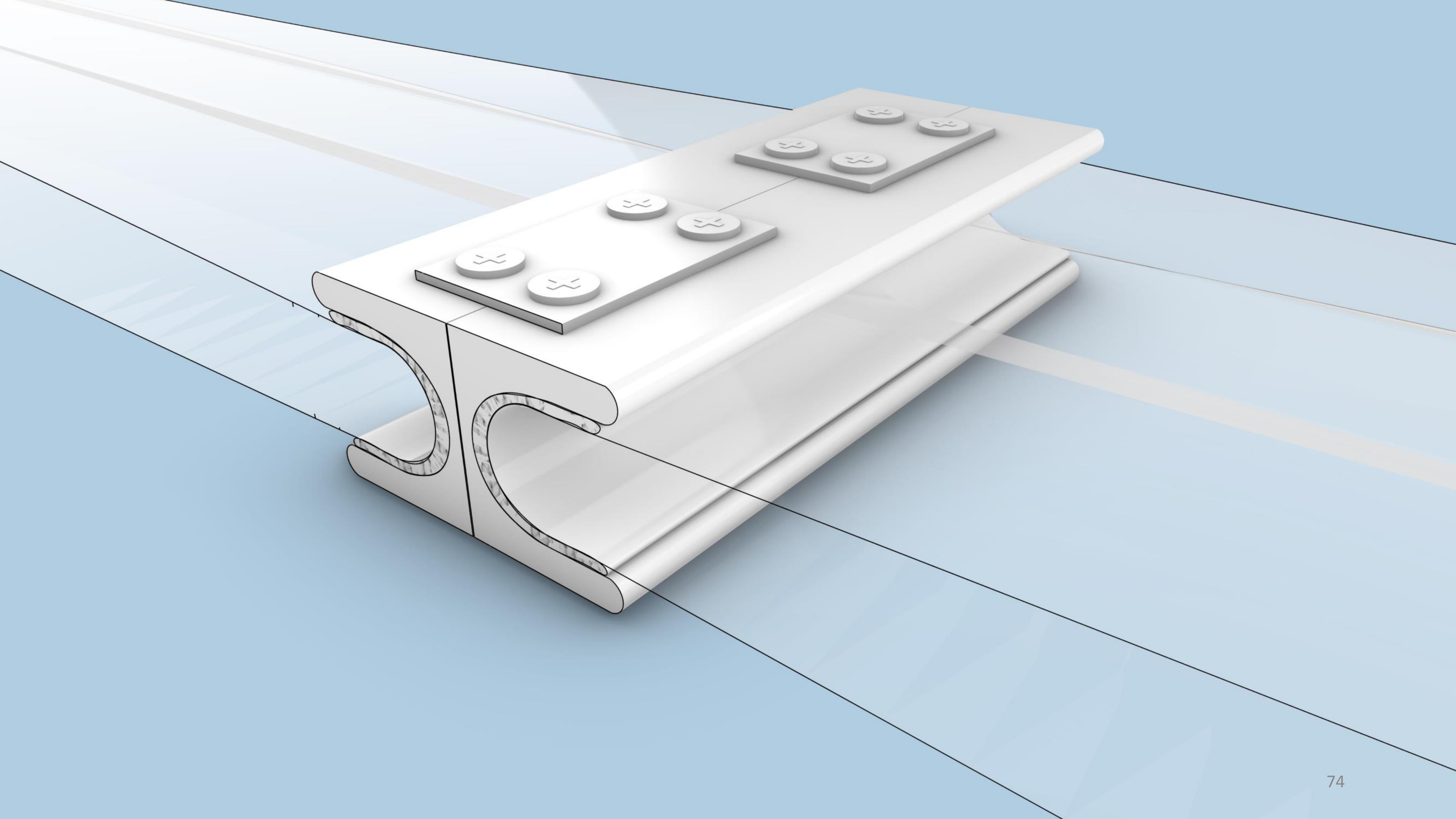
Table 14 Connection options assessed based on criteria

Connection design option / Criteria	 *Figure 129 Option 1*	 *Figure 130 Option 2*	 *Figure 131 Option 3*	 *Figure 132 Option 4*	 *Figure 133 option 5*
Easy assembly	X	X		X	Yes, since it is split
Easy manufacturing					Yes
High tolerance for variation in 3D orientation (curvature friendly)		X			Yes
Accommodating for the varying glass thicknesses around the edges of the tessellation	X				Yes, 8 and 6 thickness will gradually narrow to 4 cm. 2 cm edges will increase to 4 cm
No Sharp glass edges					Yes
Gradual change in glass thickness and even distribution of glass mass.	X			X	YES, since the groove opening is the mid-way thickness, gradual increase from 2 to 4cm and gradual decrease from 8 to 4 is possible
Load transfer preserves shell behaviour		X	X		Yes, since it is a continuous line with contact along the normal axis of shell
Connection can prevent out of plane forces.					Yes, since the tong entering the groove is greater than the curvature's diameter.
Demountable					Yes
Additional remarks	X				In comparison to option 4 the difference between 8 and 4 is more doable.


20
10
61
3
67
11
40
48
10





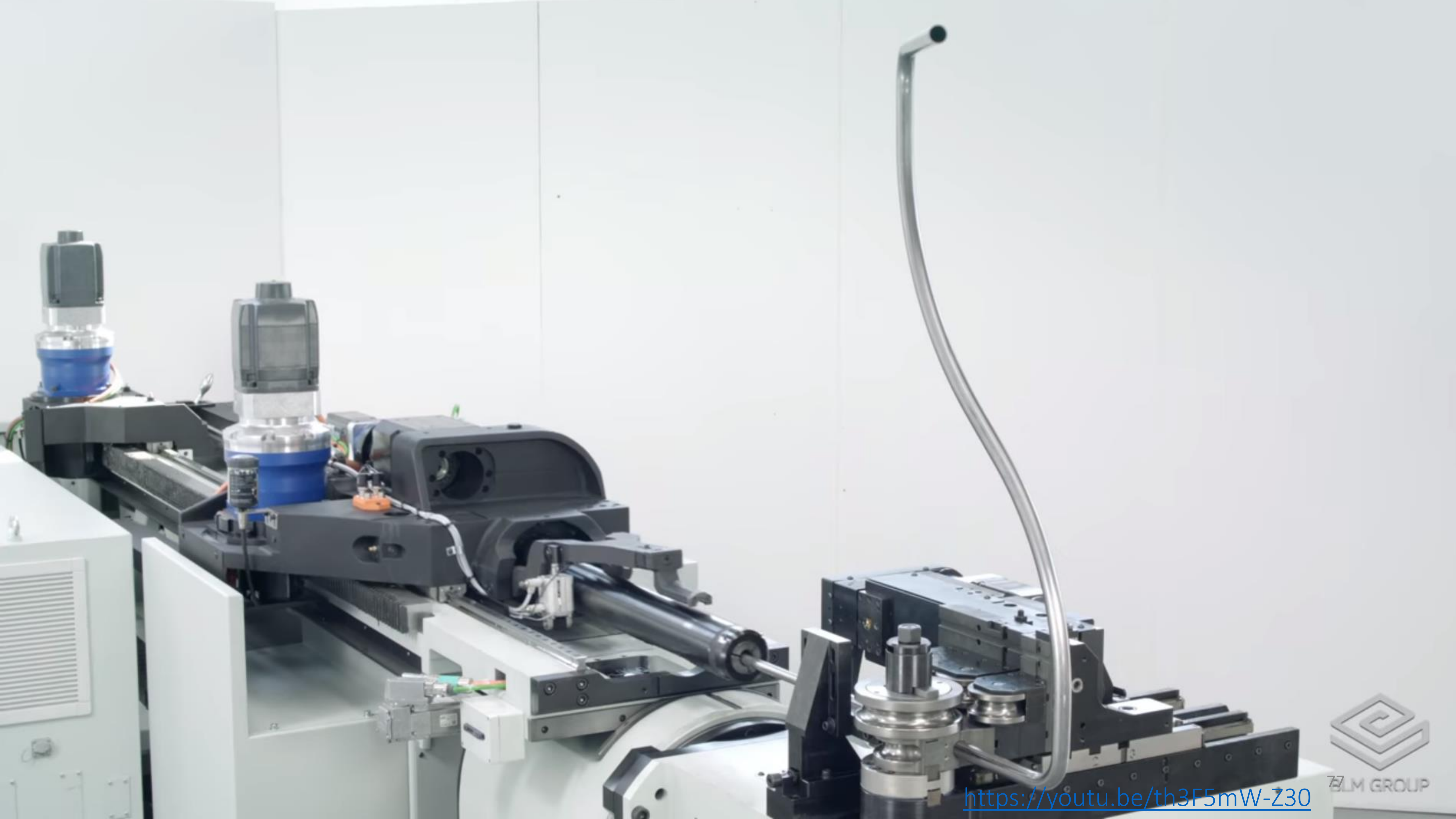


Material Criteria → Compared interlayer materials → Chosen the one that passed all criteria

Table 15 summery comparison between interlayer options (Dimas, 2020)

		POLYMERS			ELASTOMERS			METALS			HYBRIDS	
		PU	PVC	VIVAK®	NEOPRENE	SILICONE	TEFLON	COPPER	ALUMINIUM	LEAD	METAL FOAM SANDWICH	LAMINATED PU	SOFT CORE ALUMINIUM
PRIMARY	COMPRESSIVE STRENGTH ≥ 20MPa	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
PRIMARY	CREEP RESISTANT	UNKNOWN	NO	UNKNOWN	UNKNOWN	NO	MAYBE	YES	YES	YES	YES	MAYBE	YES
PRIMARY	SLIGHTLY LESS STIFF THAN GLASS	NO (MUCH LESS)	NO (MUCH LESS)	YES	NO (MUCH LESS)	NO (MUCH LESS)	MAYBE	NO (MORE)	YES	YES	YES	MAYBE	YES
PRIMARY	ABILITY TO BE SHAPED IN FINAL GEOMETRY & THICKNESS	YES INJECTION MOLDING	YES INJECTION MOLDING	YES VACUUM FORMING	NO N/A	YES INJECTION MOLDING	MAYBE/ NO MILLING	YES PRESS FORMING	YES PRESS FORMING	YES PRESS FORMING	MAYBE/ NO *COMBINATION*	MAYBE *COMBINATION*	MAYBE *COMBINATION*
PRIMARY	CIRCULARITY	YES	YES	YES	YES	NO	MAYBE	YES	YES	NO	MAYBE/ NO	MAYBE/ NO	MAYBE/ NO
SECONDARY	OPTICAL QUALITY	TRANSPARENT/ TRANSLUCENT	TRANSPARENT/ TRANSLUCENT	TRANSPARENT/ TRANSLUCENT	OPAQUE WHITE	TRANSLUCENT	TRANSLUCENT	REFLECTIVE RED-BROWN	REFLECTIVE SILVER	OPAQUE ASH GRAY	REFLECTIVE	TRANSLUCENT/ OPAQUE	REFLECTIVE
SECONDARY	THERMAL EXPANSION COEFFICIENT* GLASS: 4-10 MSTRAIN/ ° C	90-92	45-180	120-130	110-240	250-300	120-180	15-23	18-26	18-30	UNKNOWN	UNKNOWN	UNKNOWN
SECONDARY	DURABILITY: WATER, FIRE & UV	YES	YES	YES	YES	WATERTIGHT FOR APPROX. 20 YEARS YES YES	YES	YES *DISCOLORATION FROM WATER*	YES	YES	MAYBE *CONSIDER THE EDGES*	YES	YES

The values for the thermal expansion coefficient have been retrieved from CES EduPack 2019

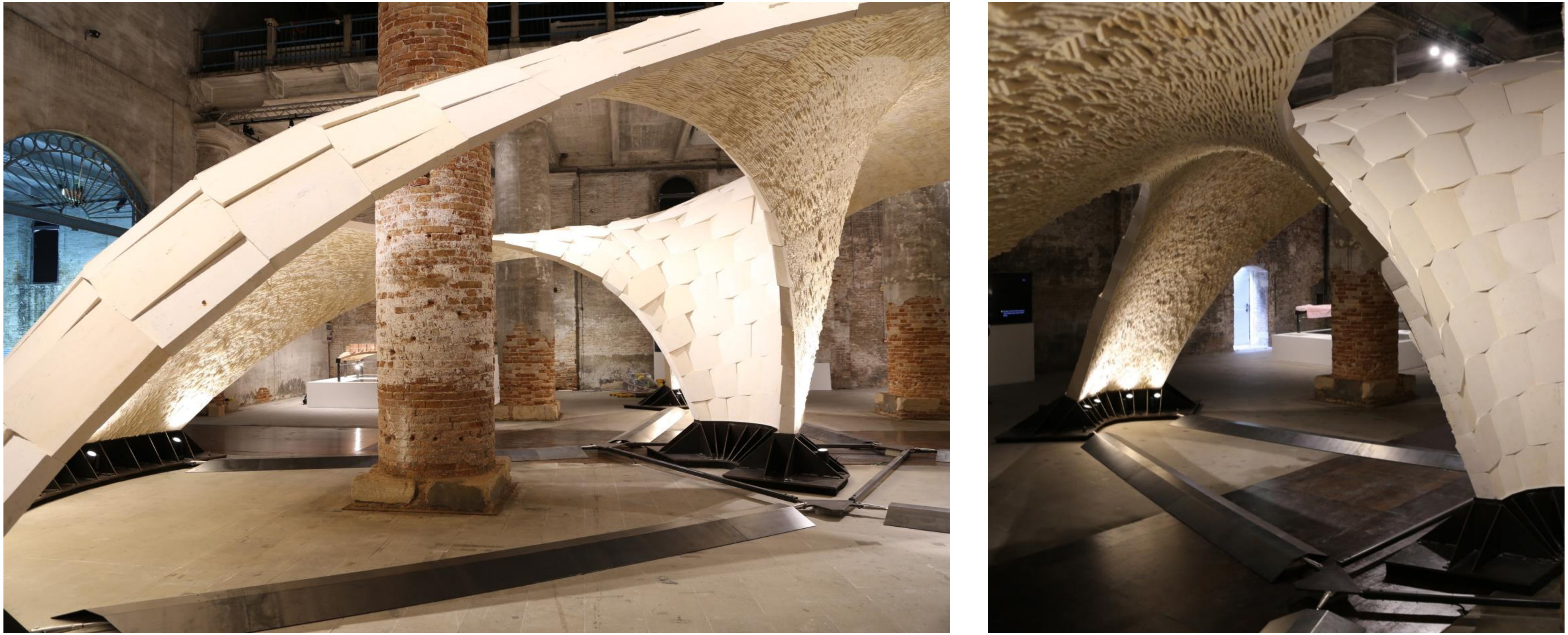


https://youtu.be/th3F5mW-Z30

https://youtu.be/th3F5mW-Z30

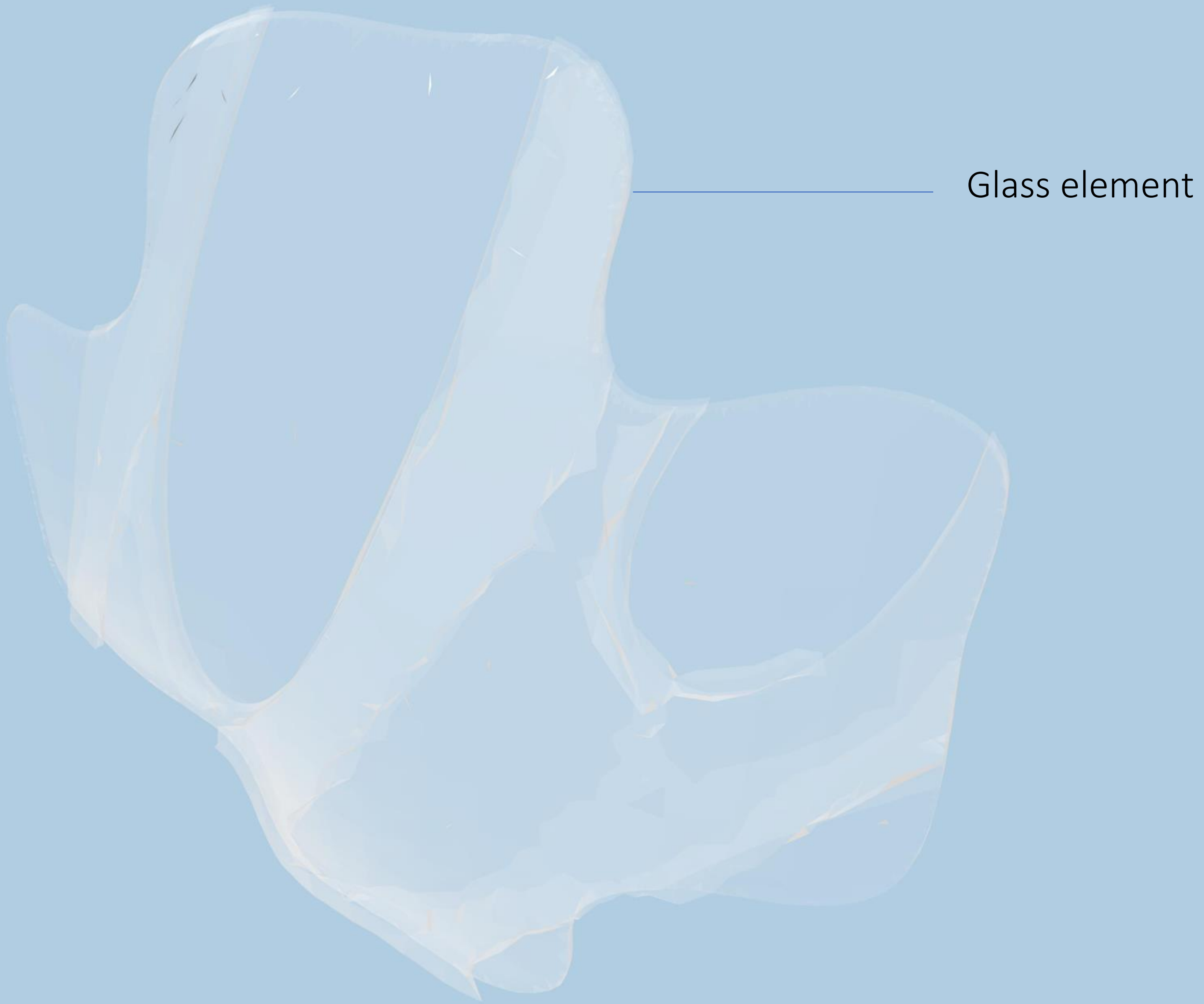
Foundation of the shell

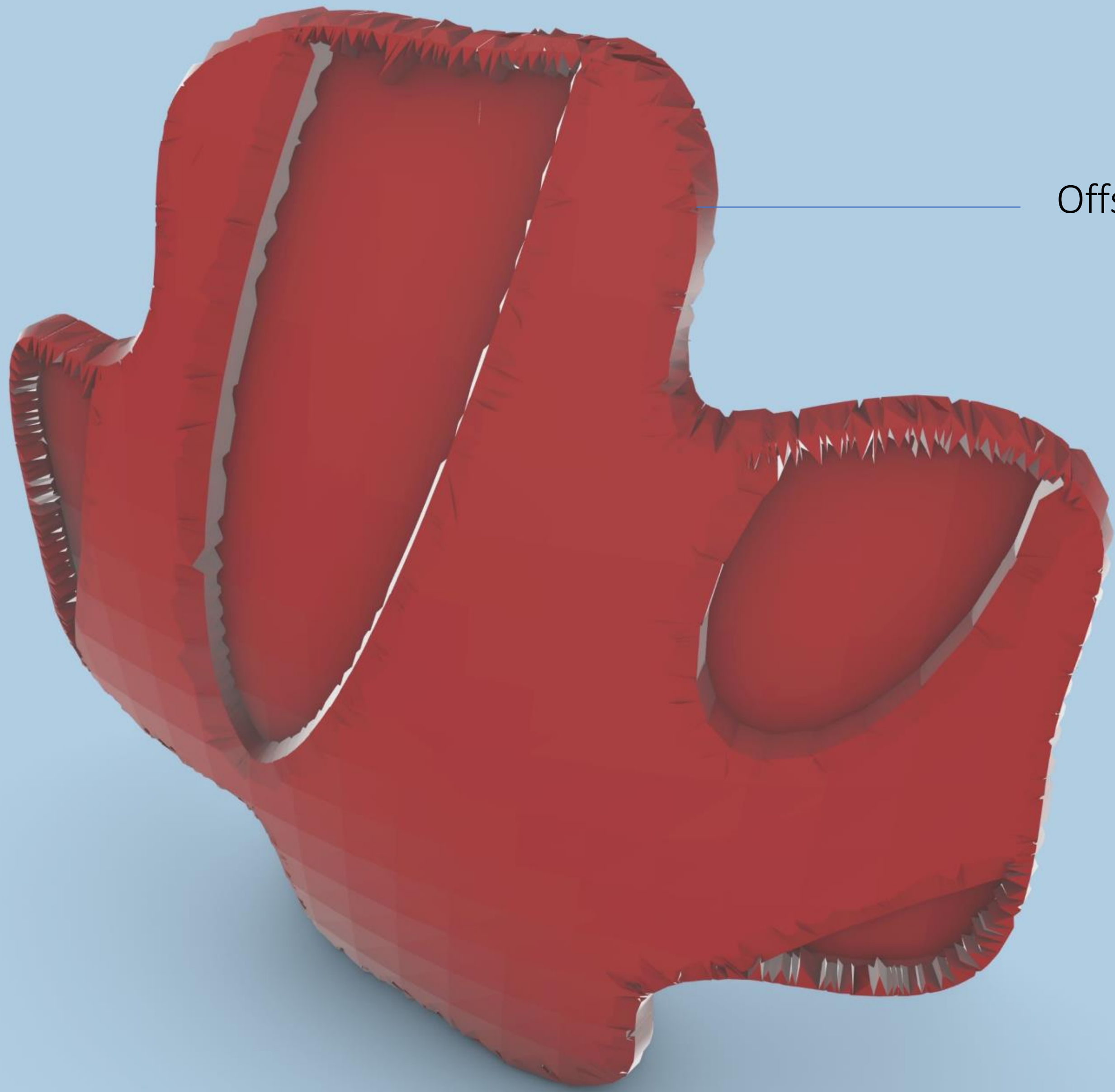
Foundation

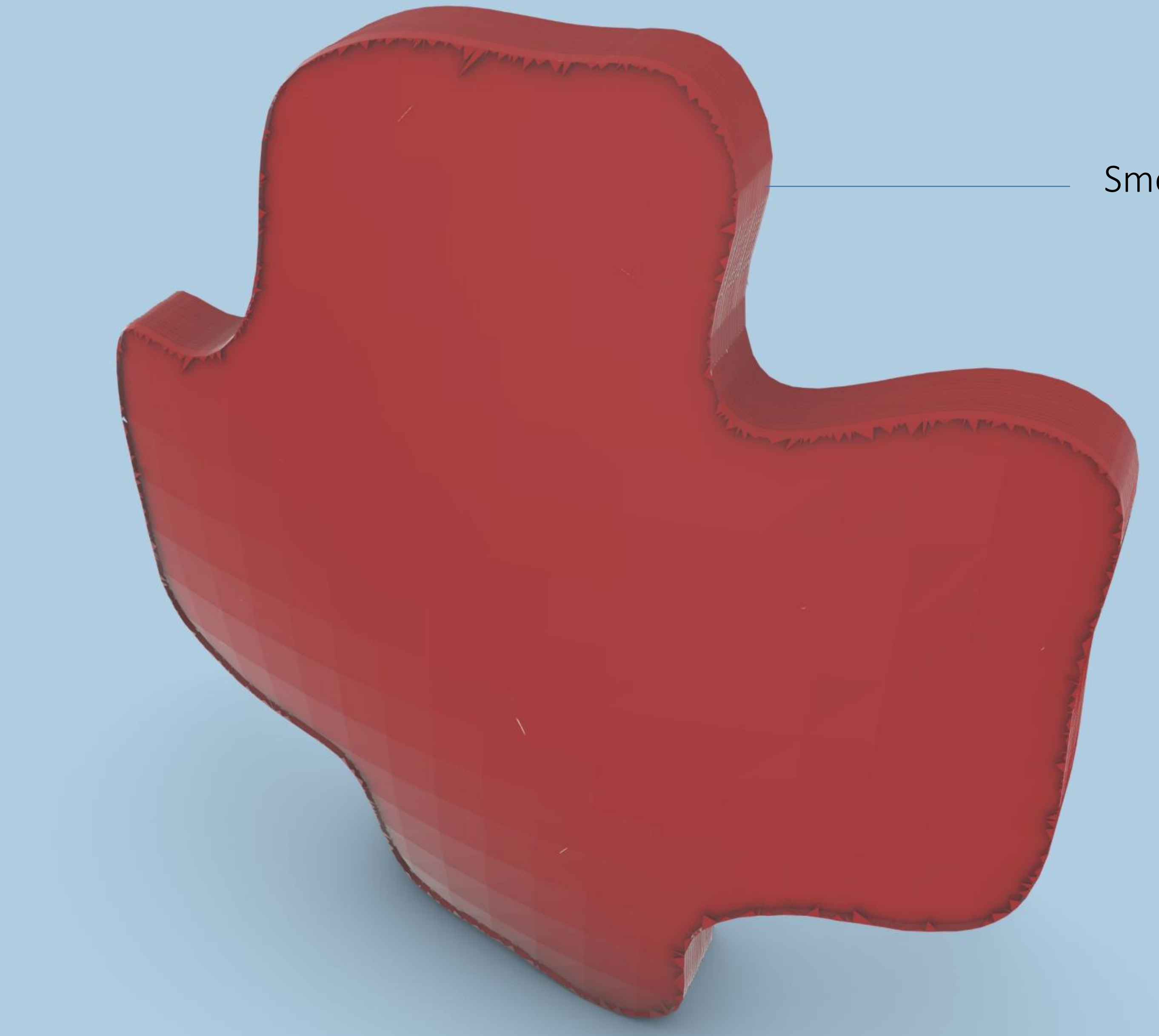


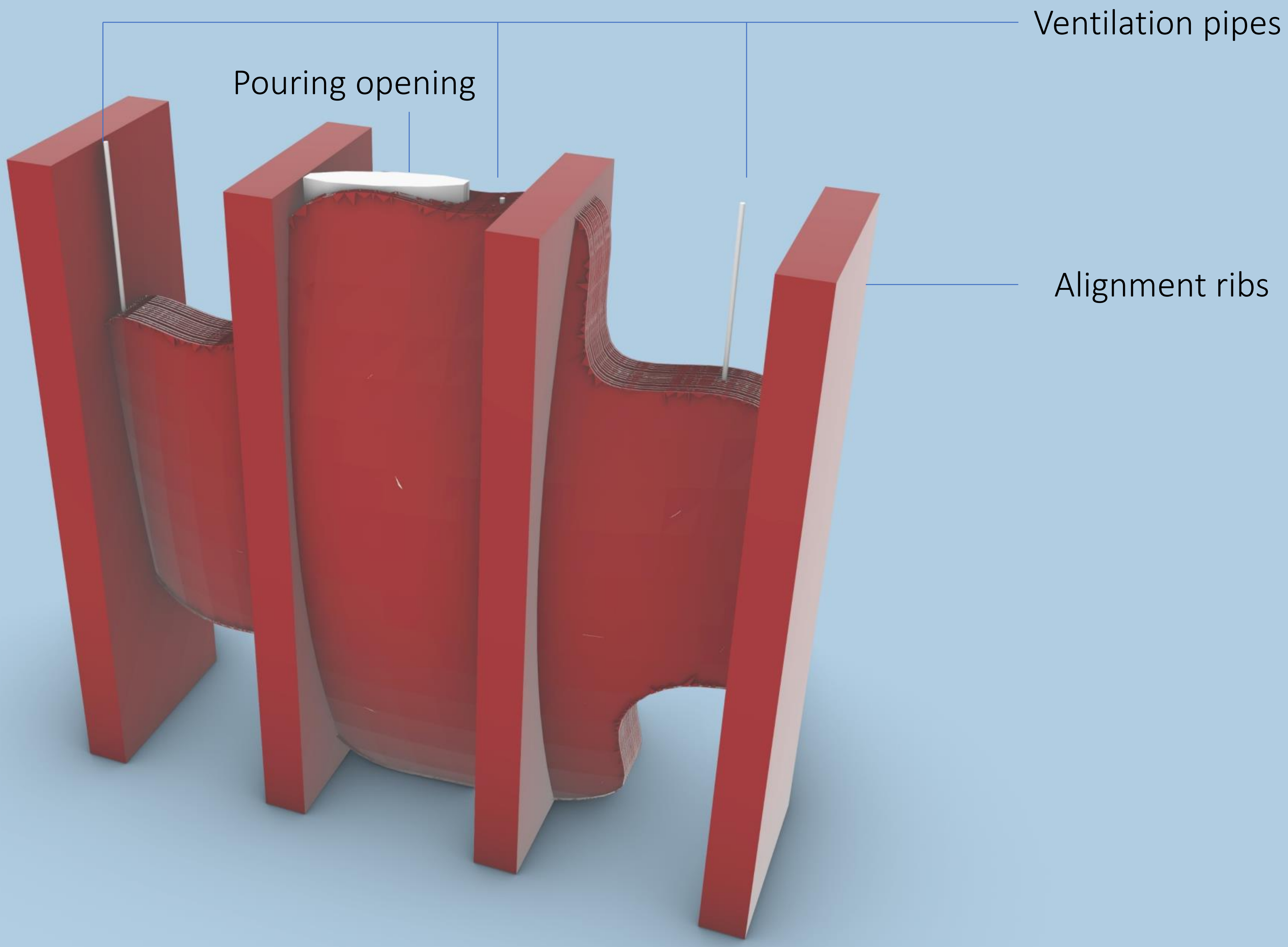
The Armadillo Vault, showing a fixed support and tension-based foundation creating a compression ring effect. (Frearson, 2017)

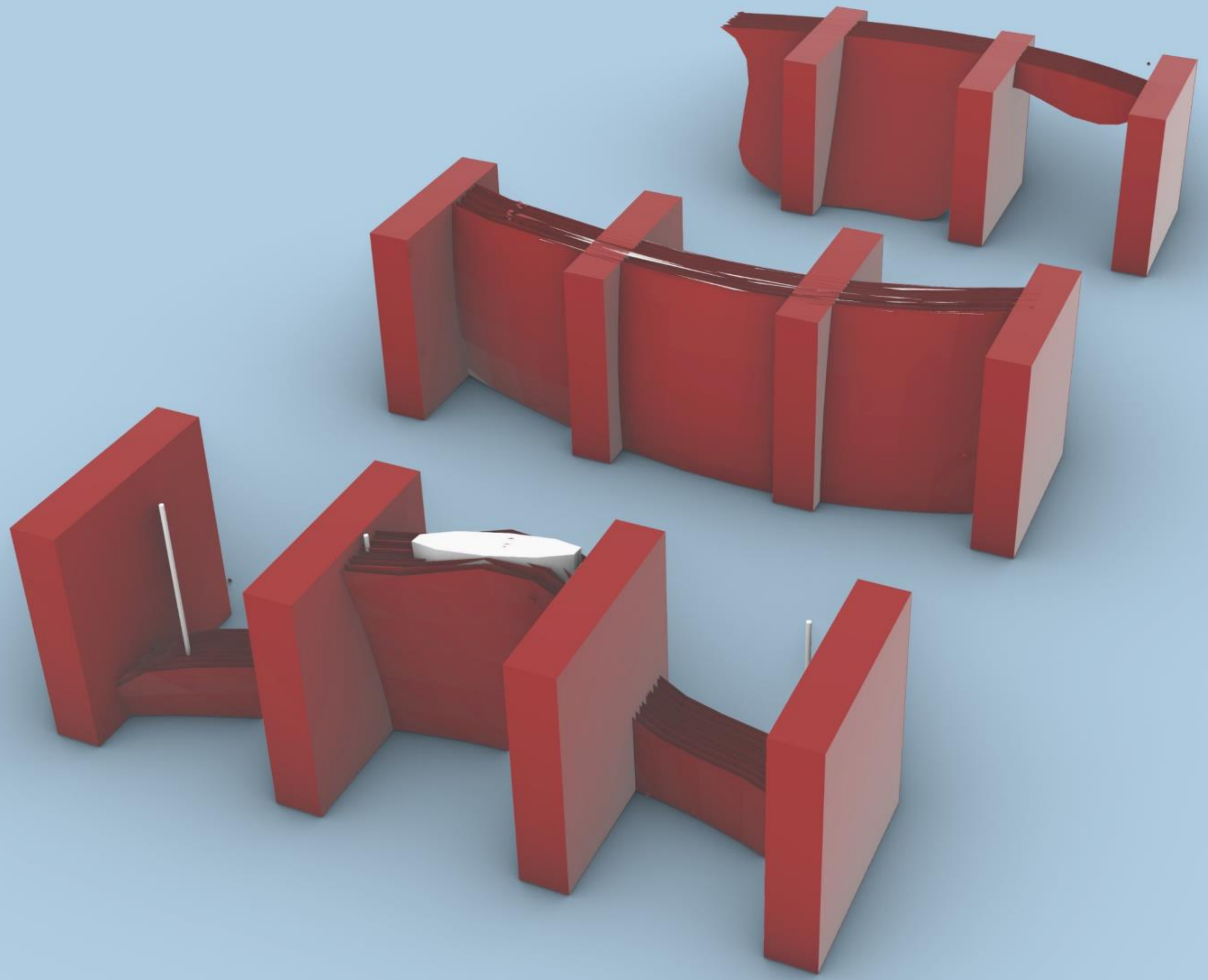
Cast glass production

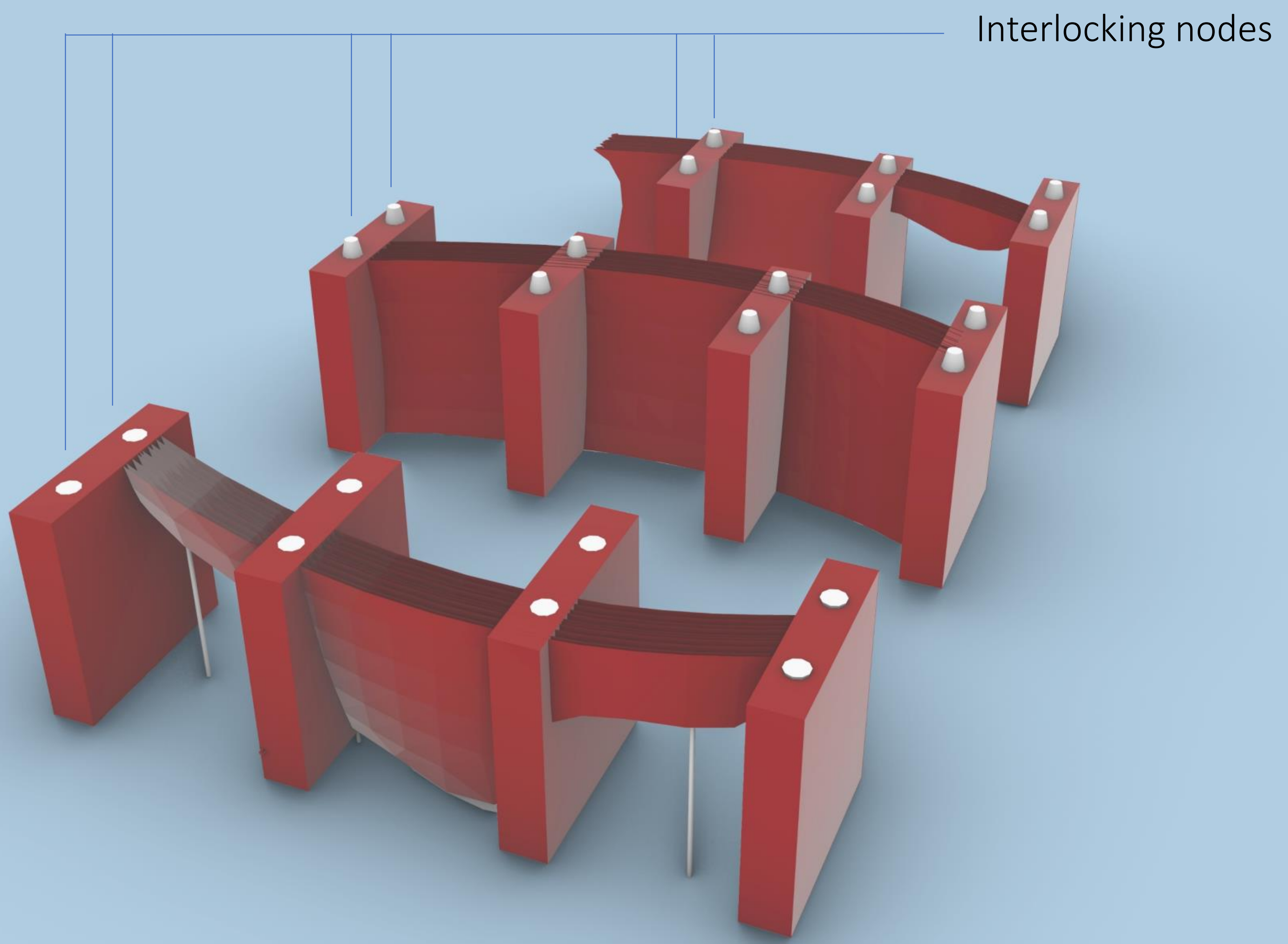

Glass element


Offset > 50mm


Smoothed surface

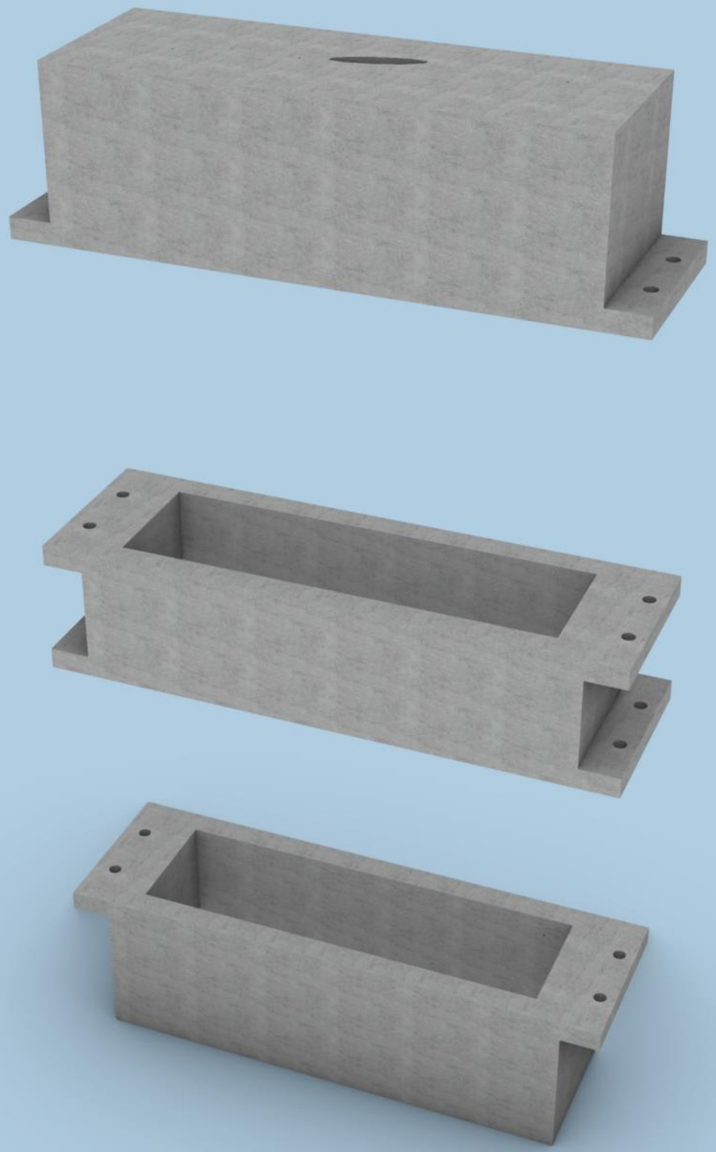

Ventilation pipes
Pouring opening
Alignment ribs

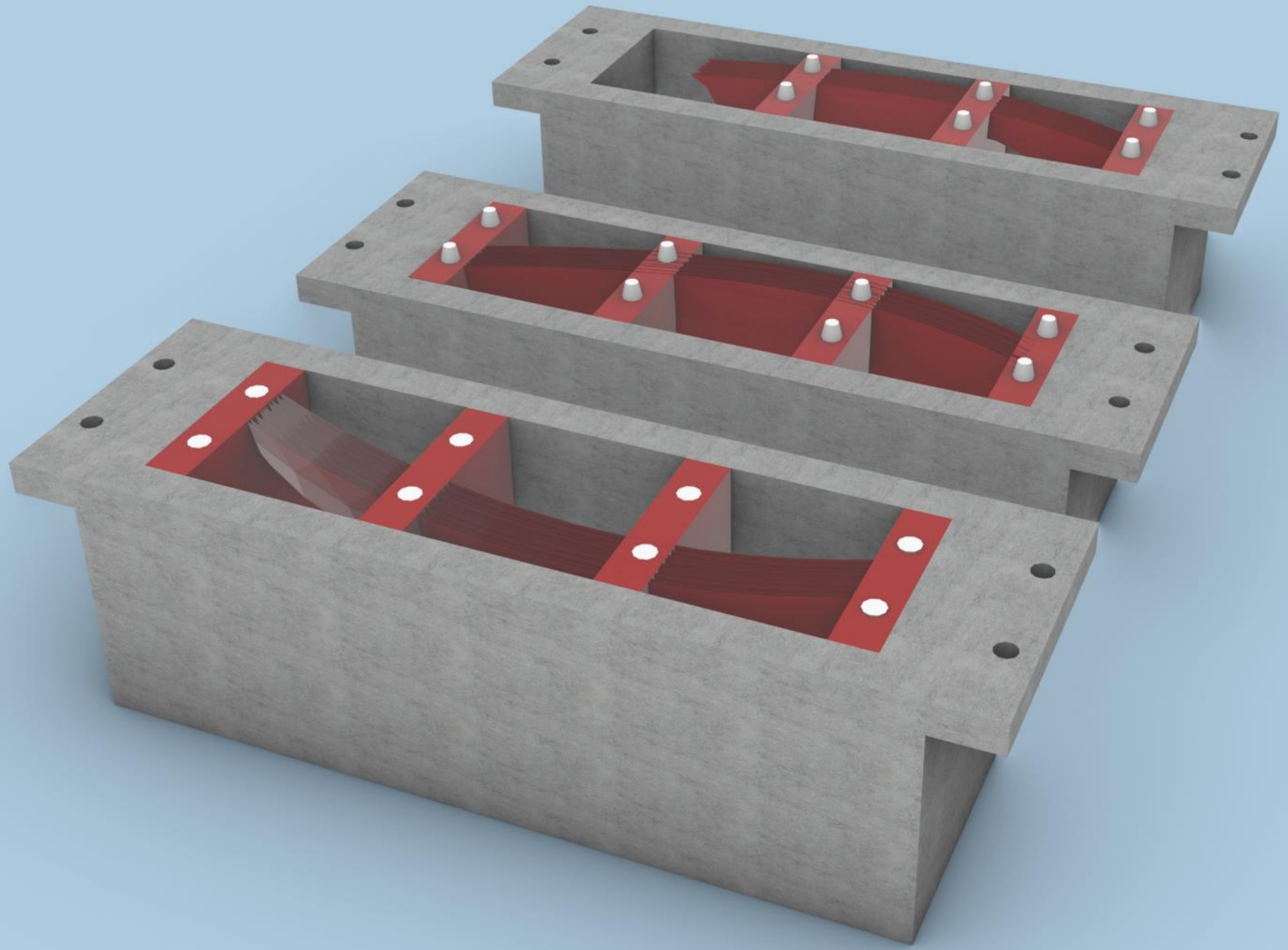


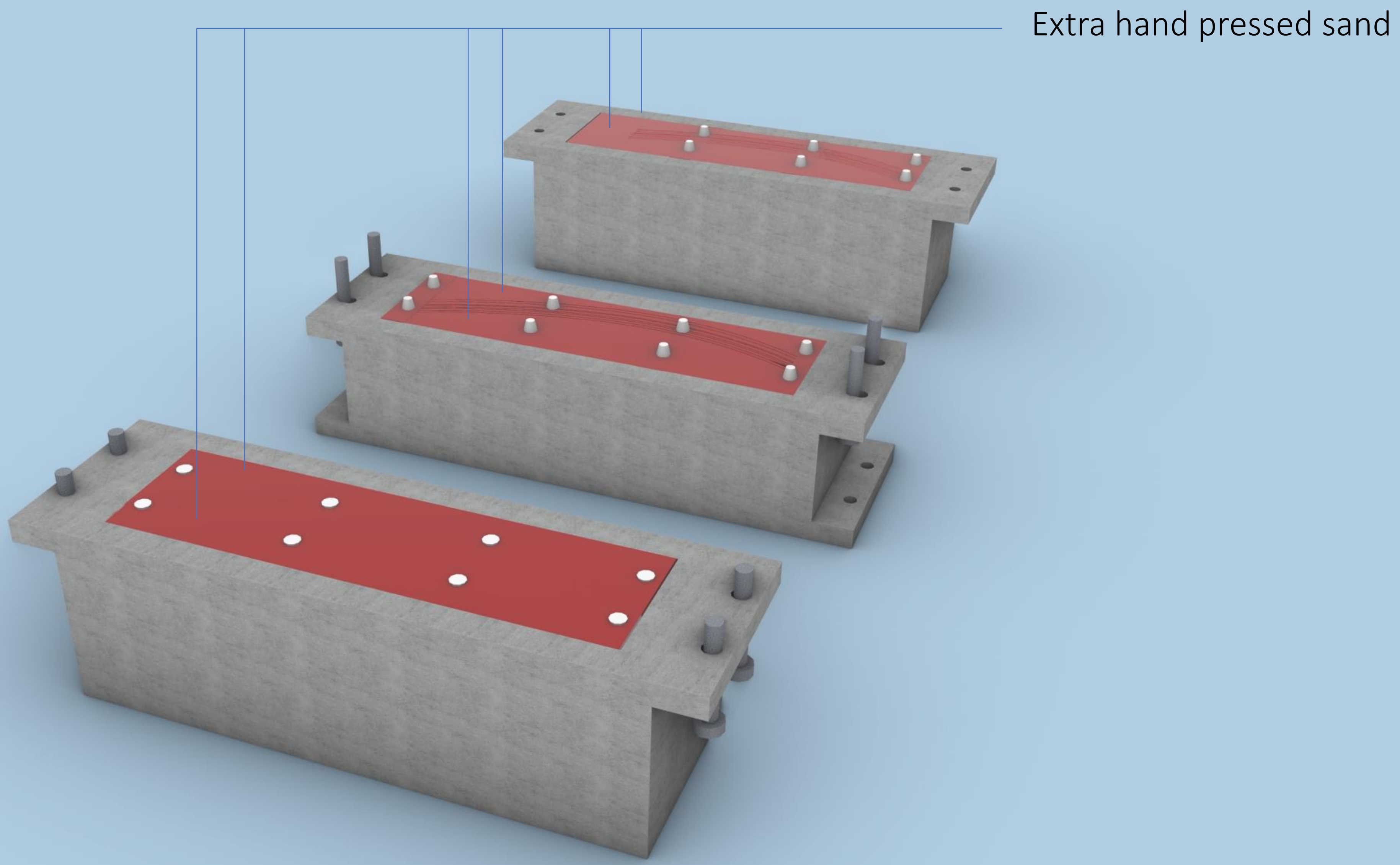


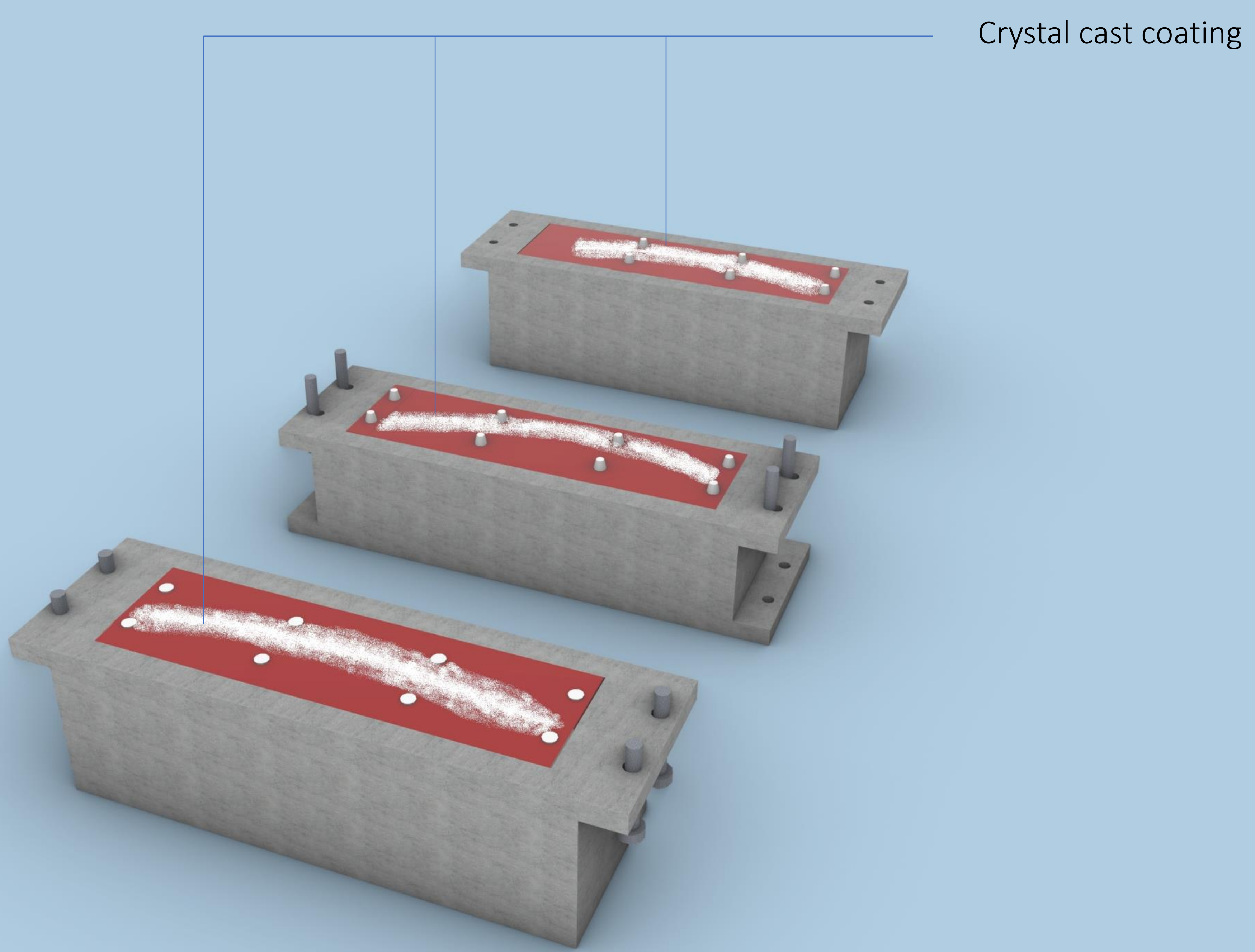
Interlocking nodes

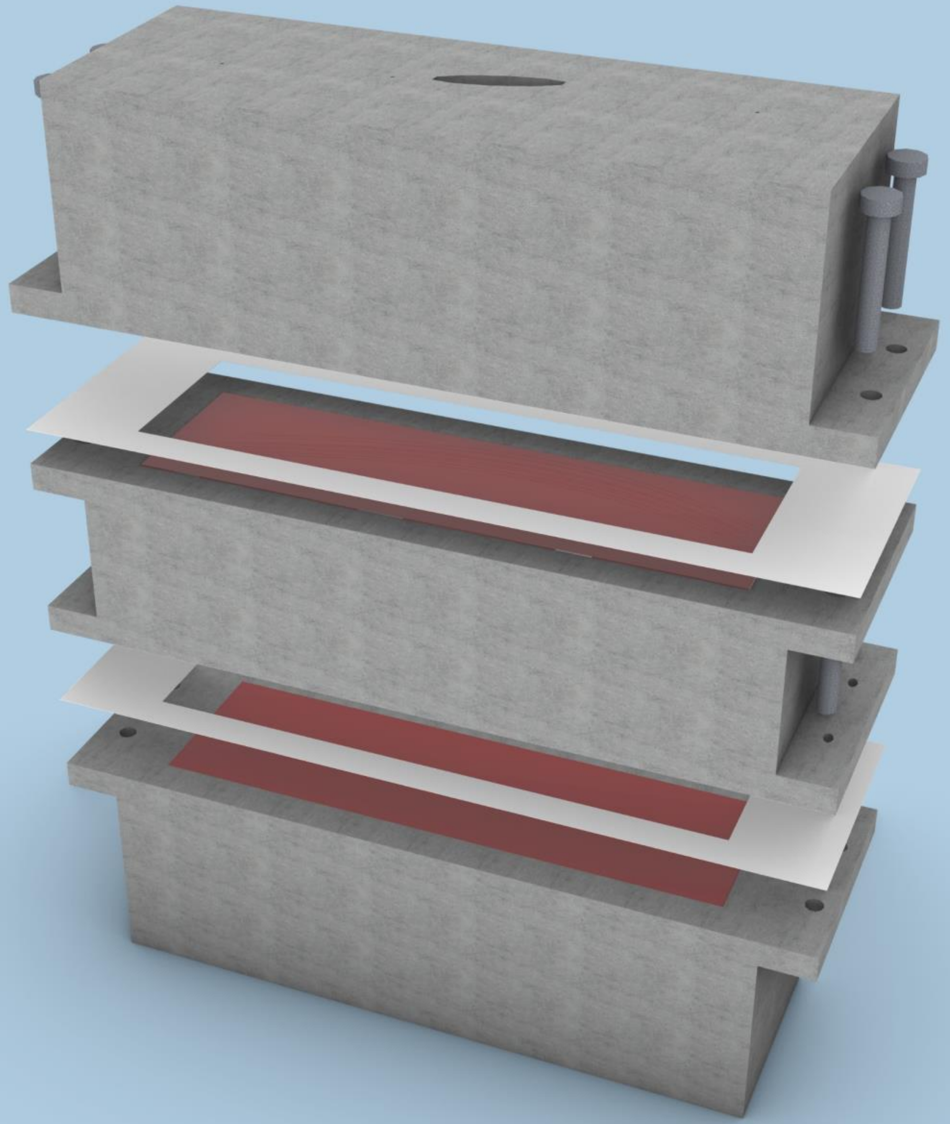
VX4000 (VoxelJet, 2018b)

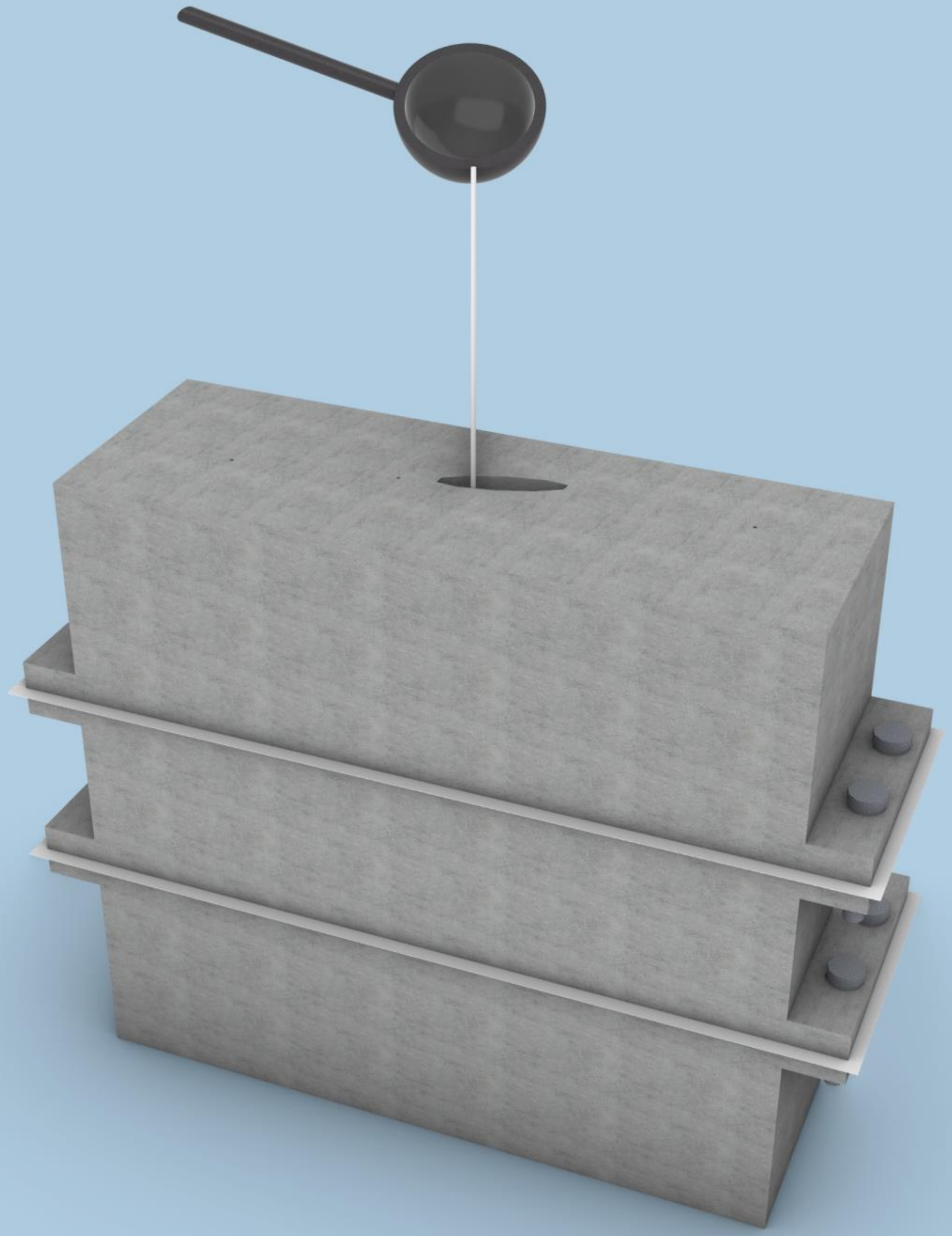


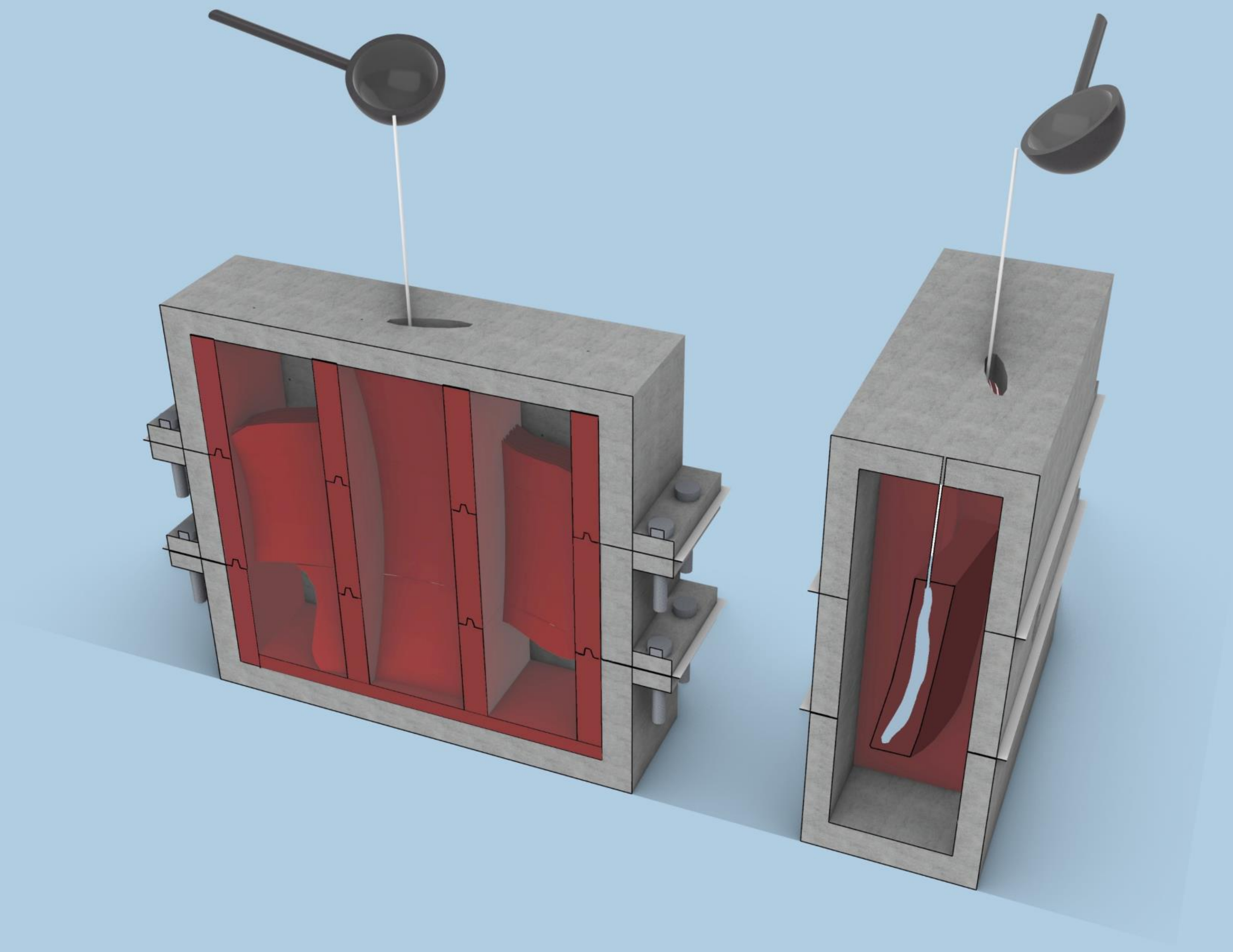


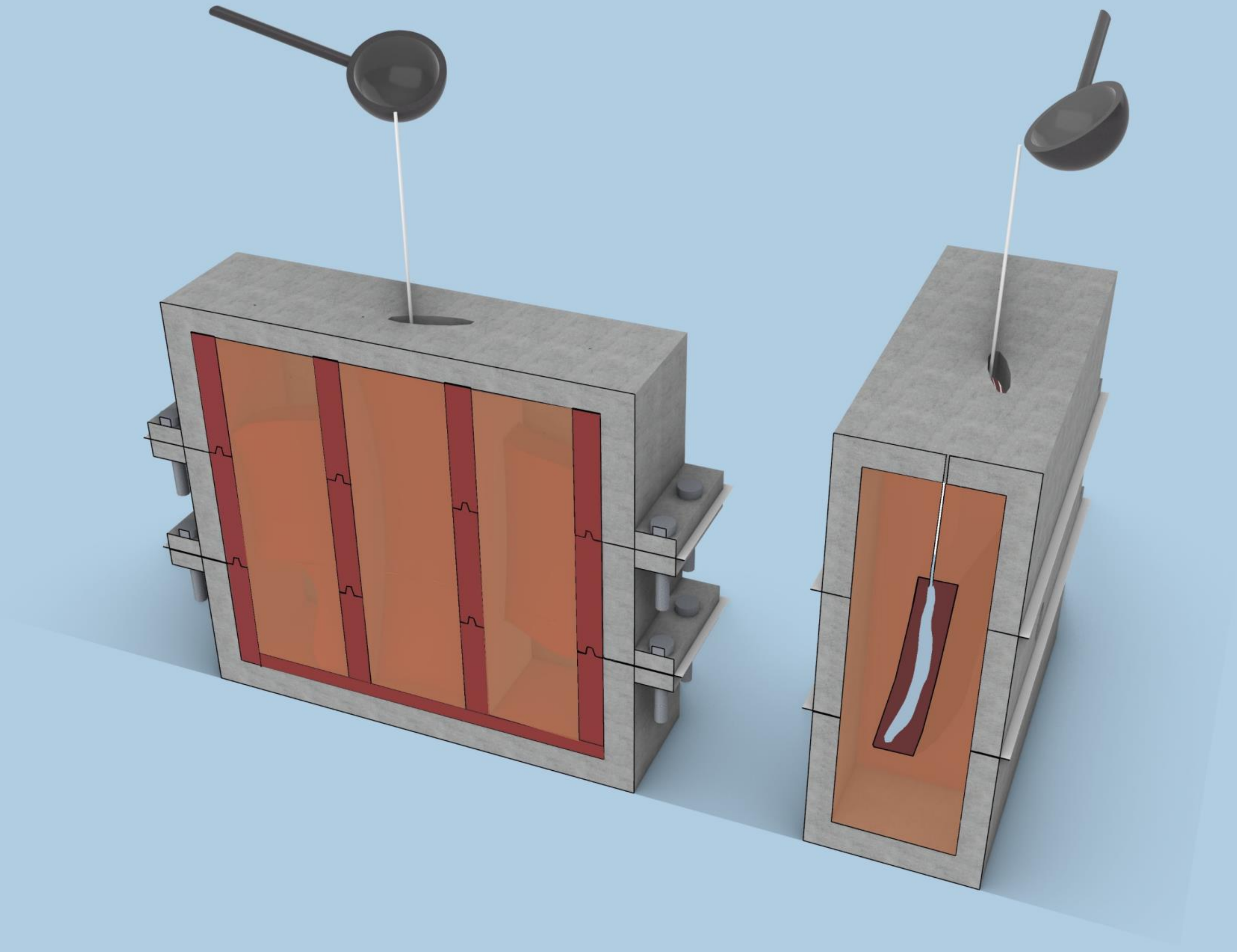

Extra hand pressed sand


Crystal cast coating

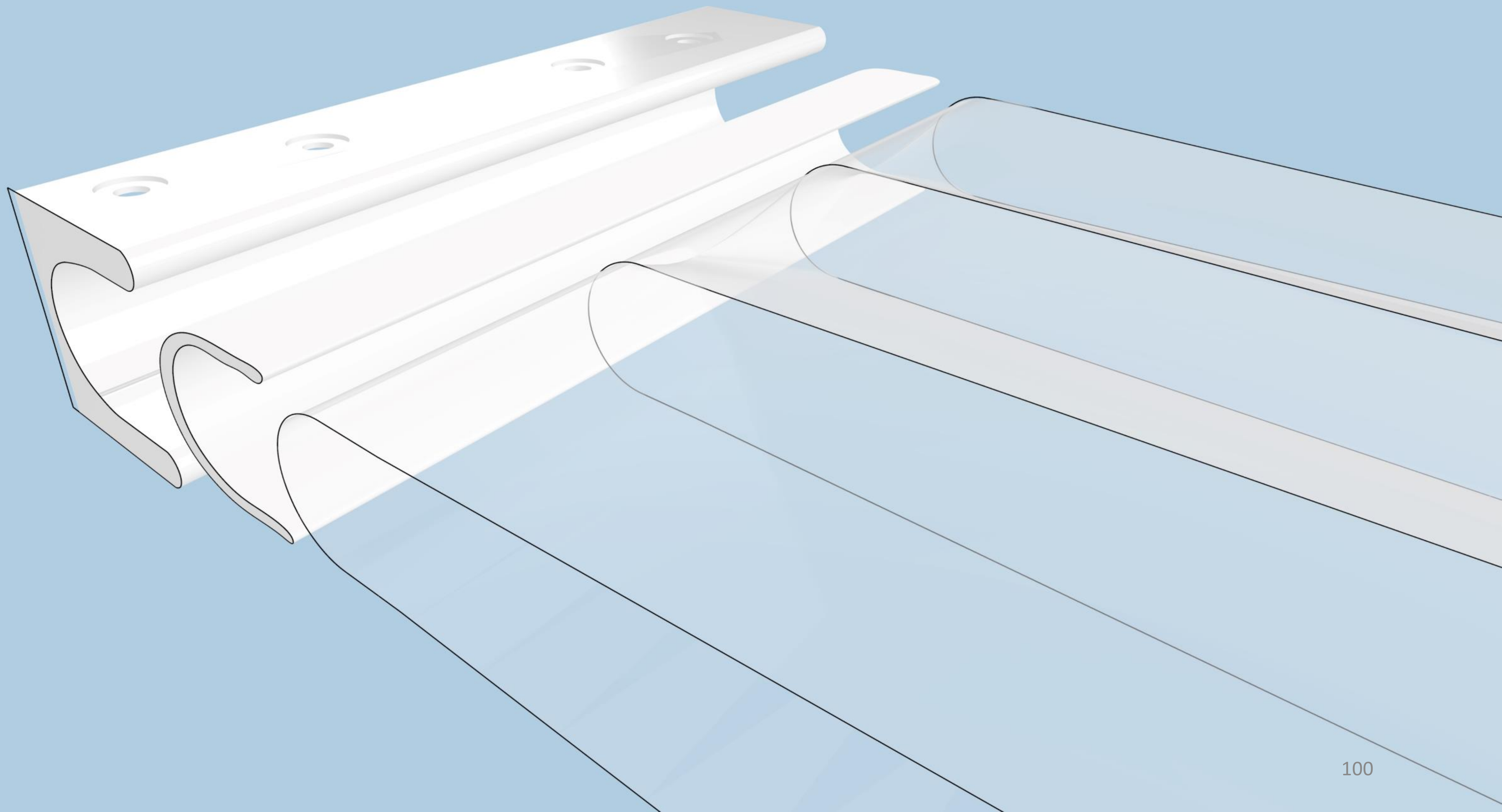


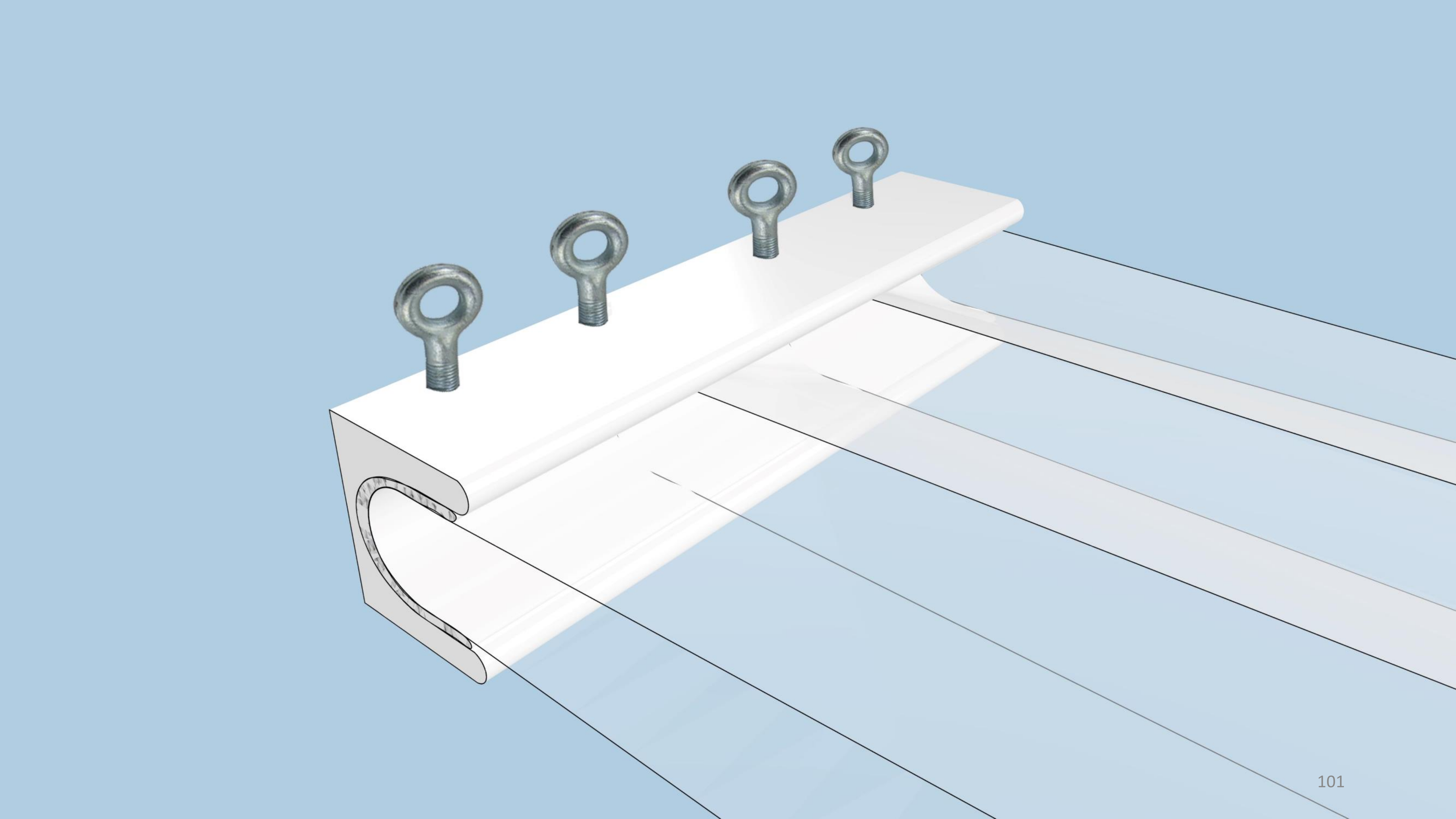


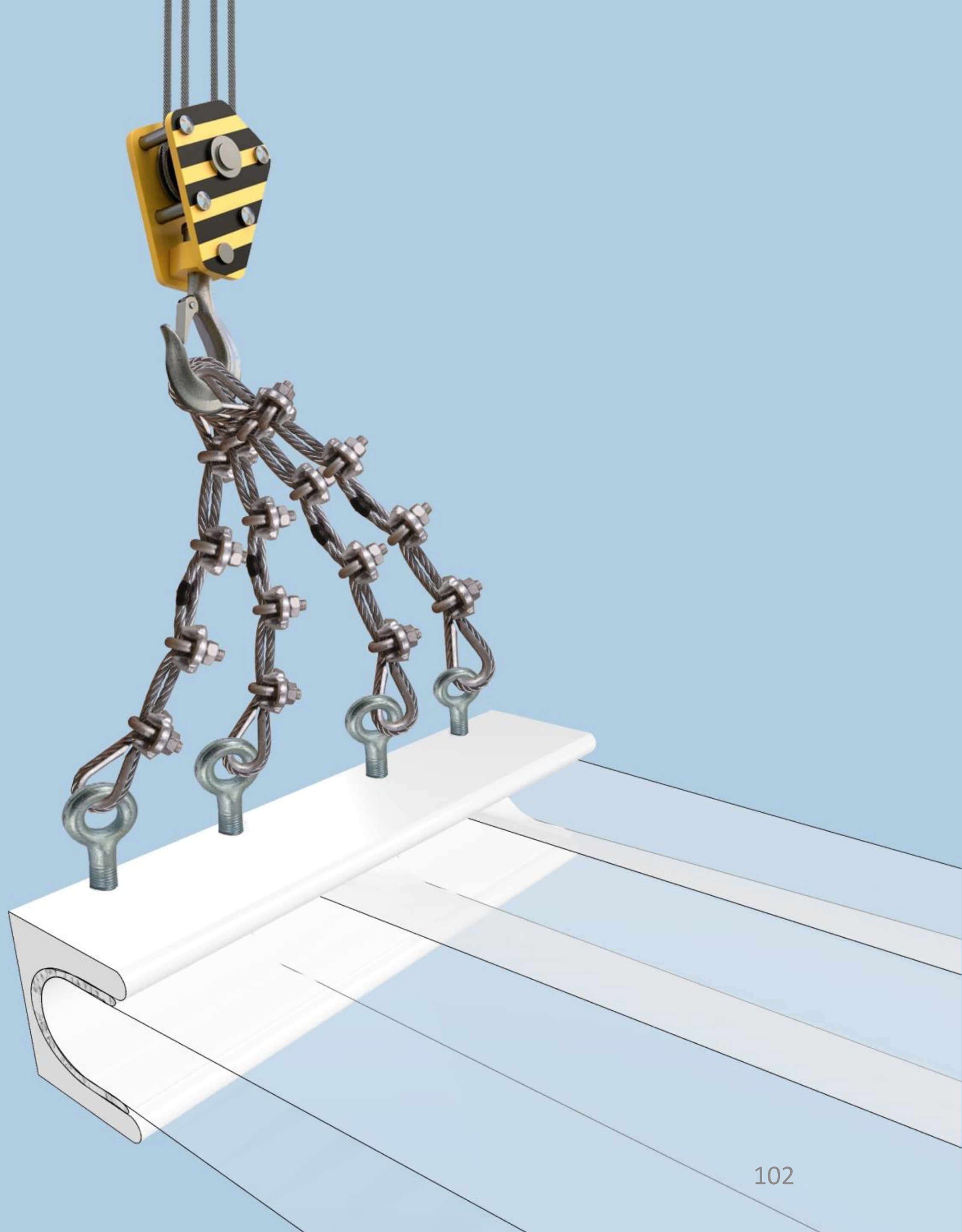


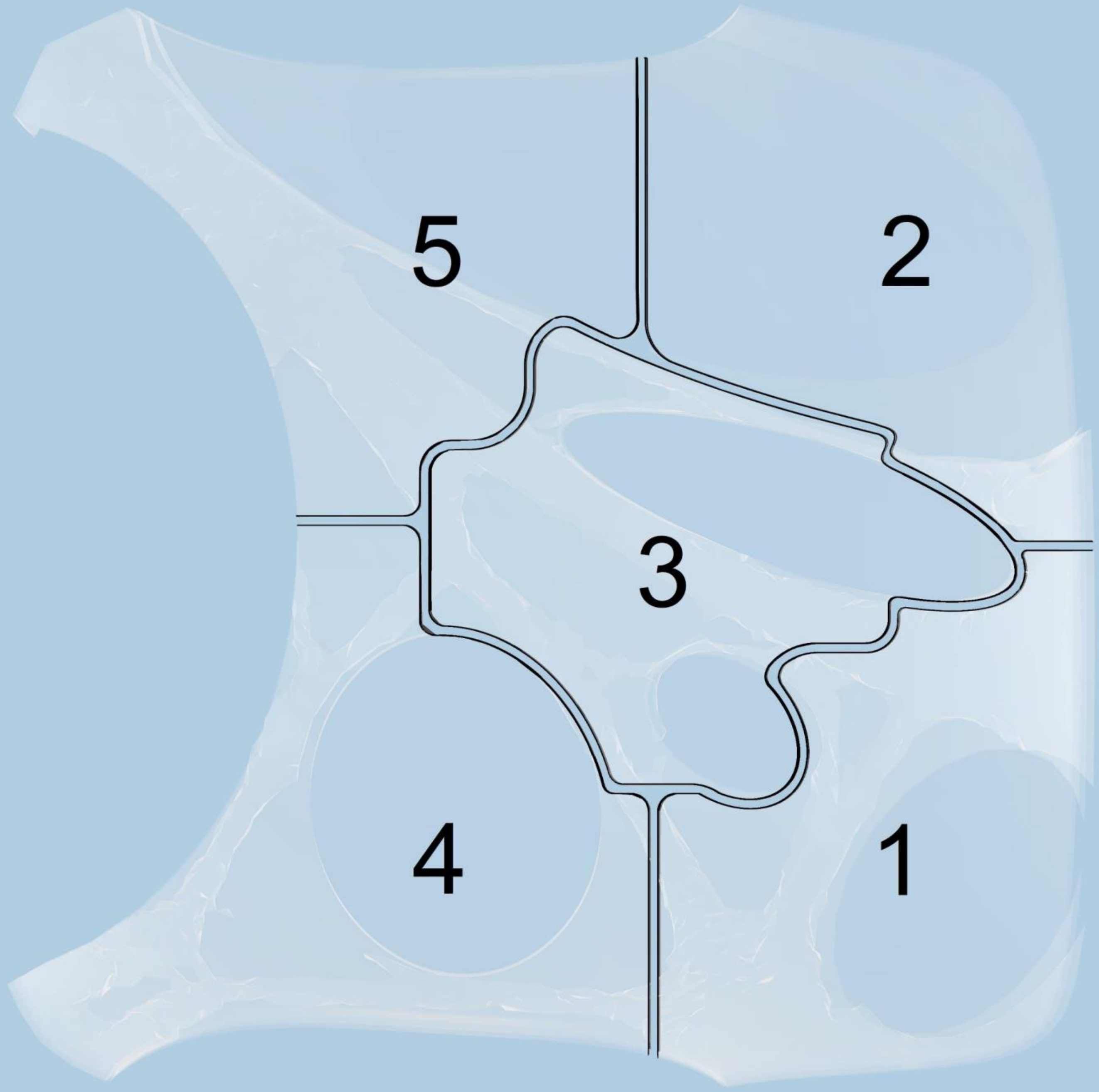


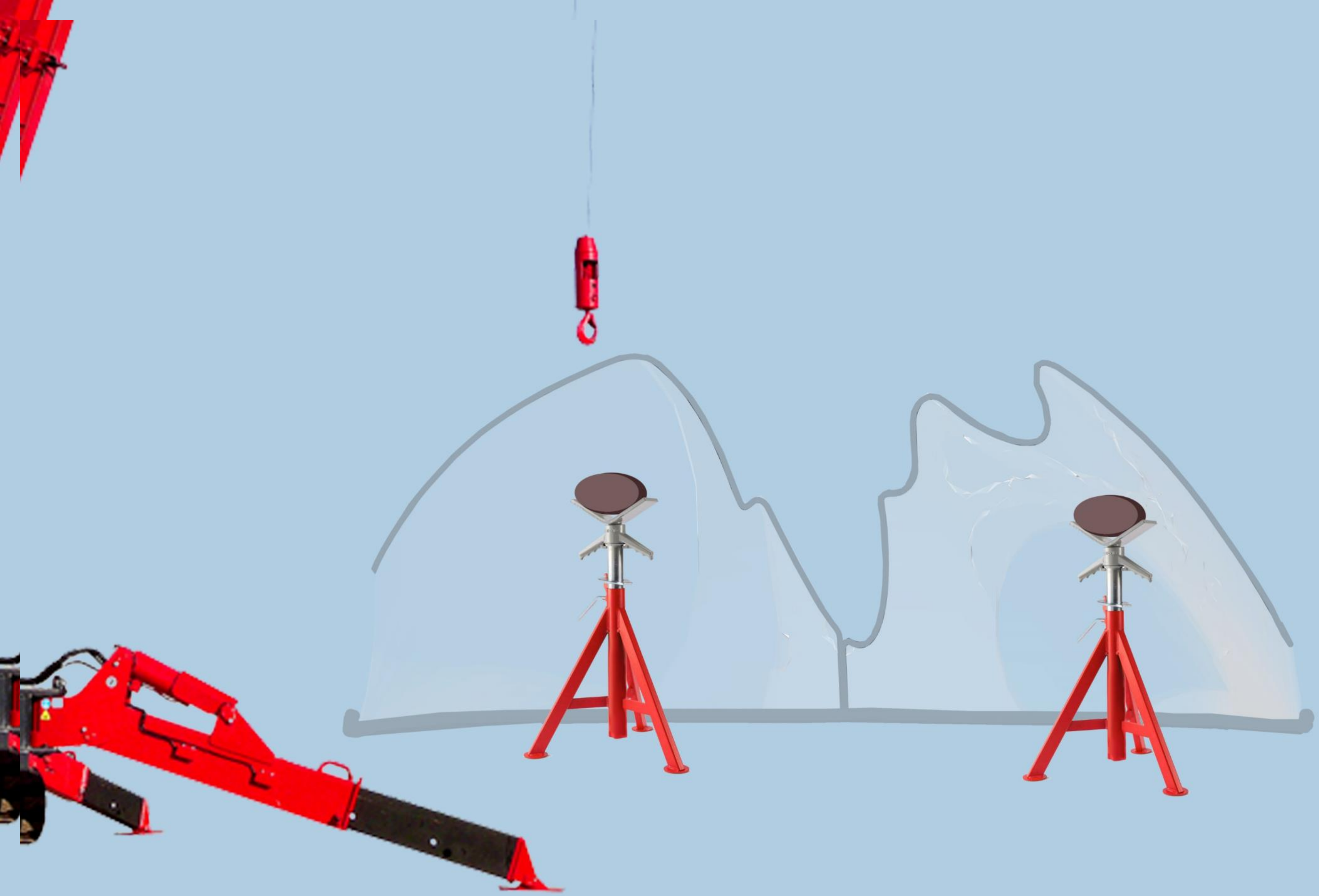
Assembly

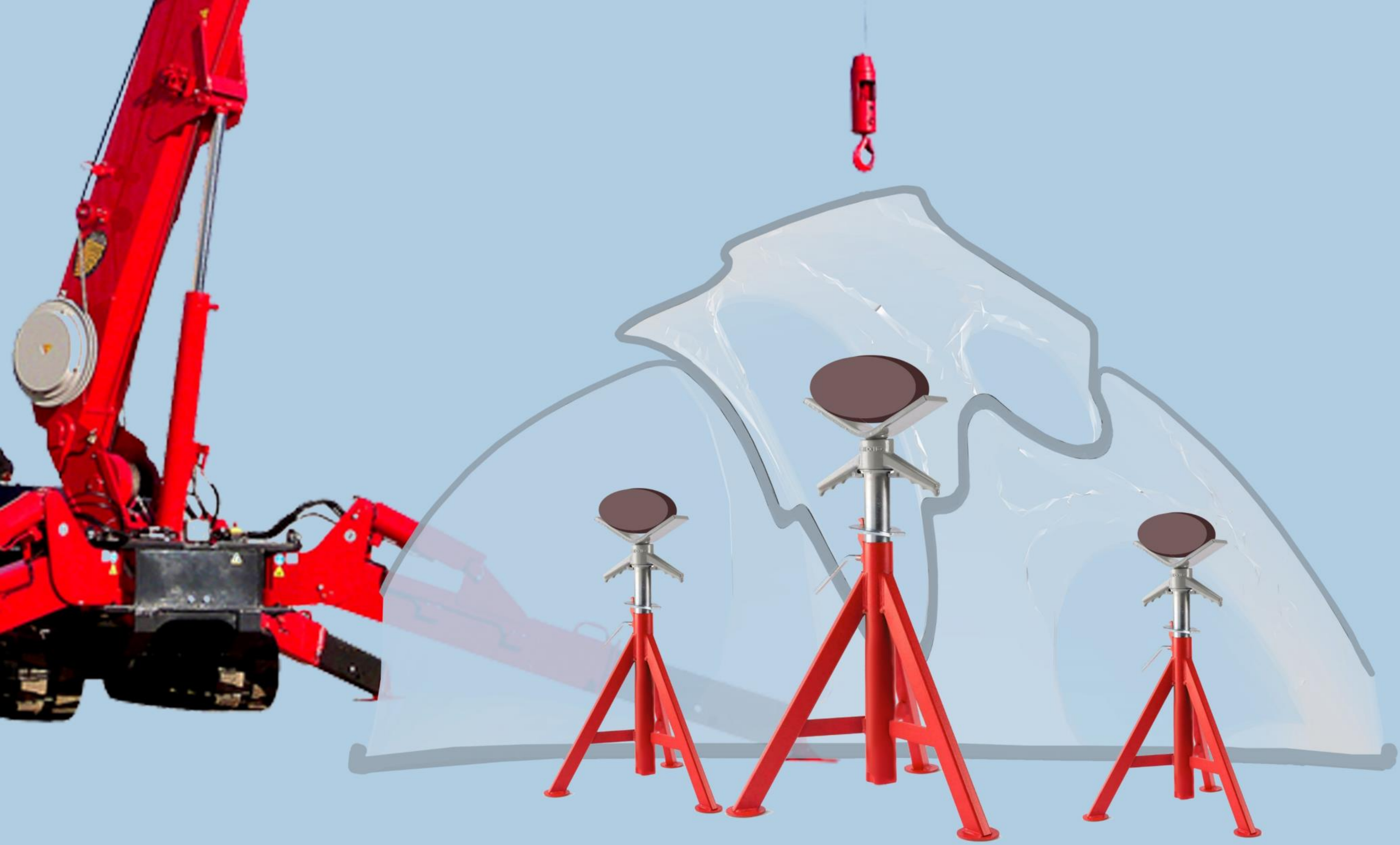


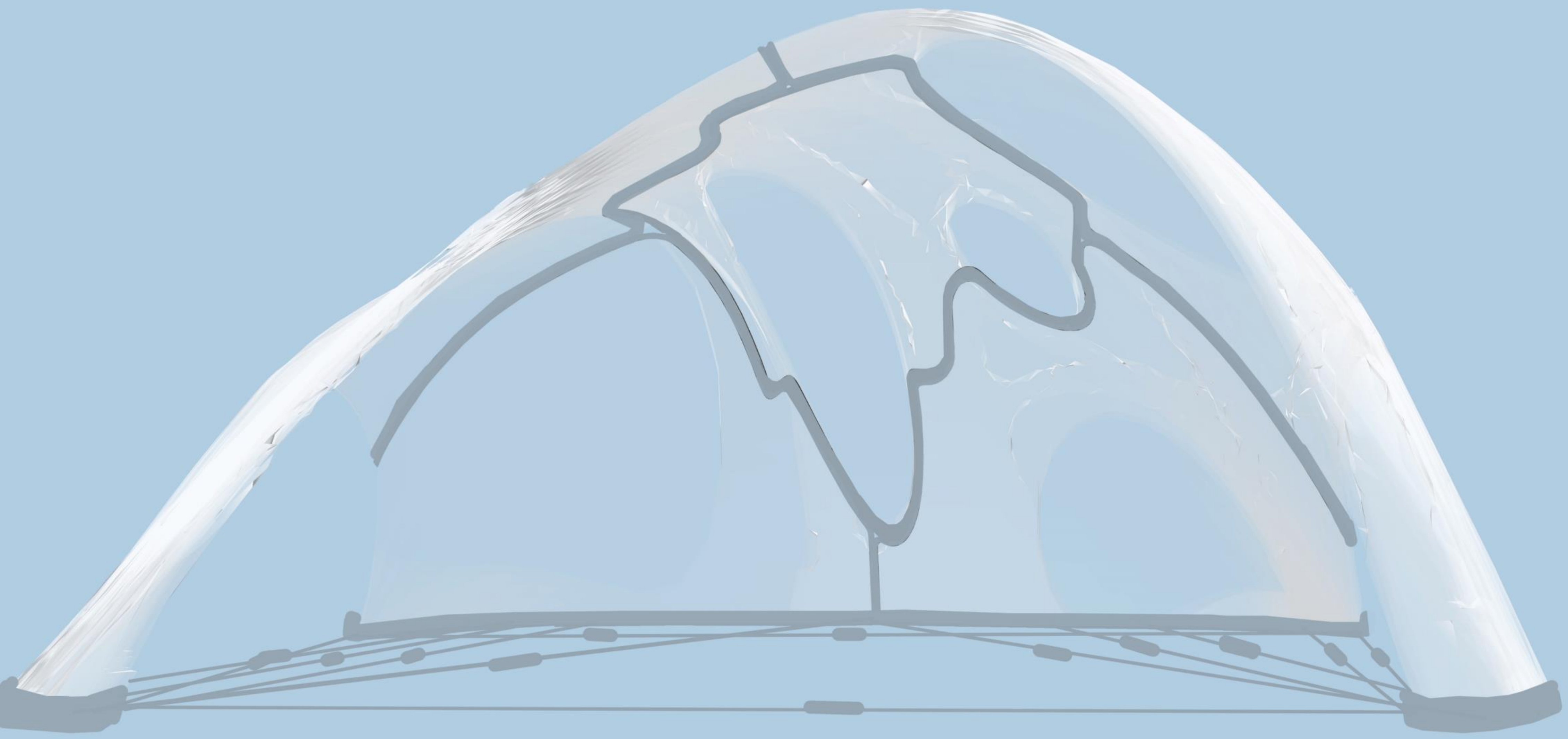


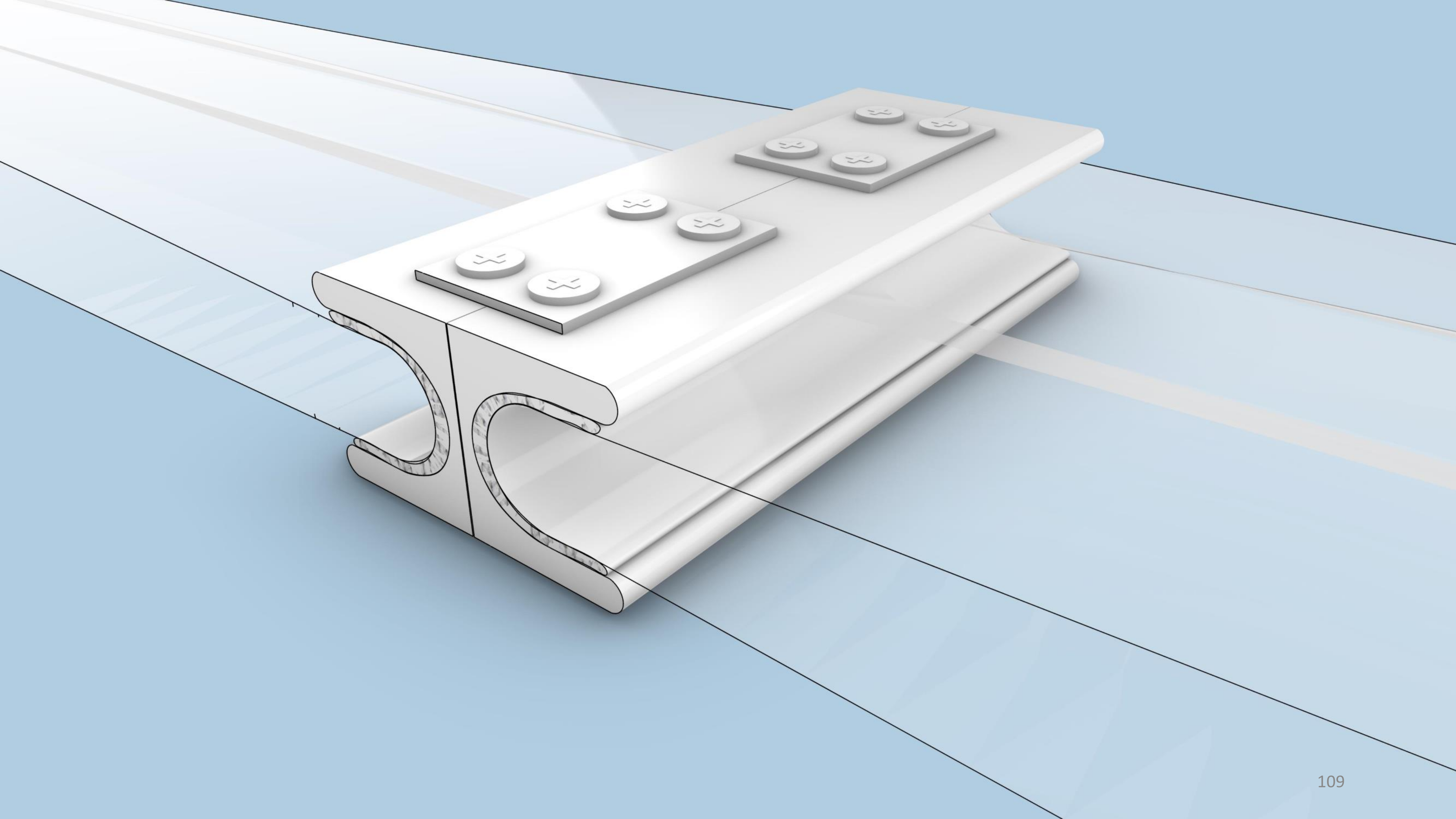



5
2
3
4
1









Conclusion


NEVER MISS A
GREAT MATERIALS
STORY AGAIN
MATERIAL DISTRICT
ALL YOU NEED
TO KNOW IN
YOUR POCKET.
MATERIAL DISTRICT
ROTTERDAM
MATERIAL EXHIBITION

"simplicity is complexity resolved"
- Constantin Brancusi

Yatzer, 2017

Does it stop here?

Braaksma & Roos, n.d.

Doyle, 2018

Andres, 2016

Thank you!

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