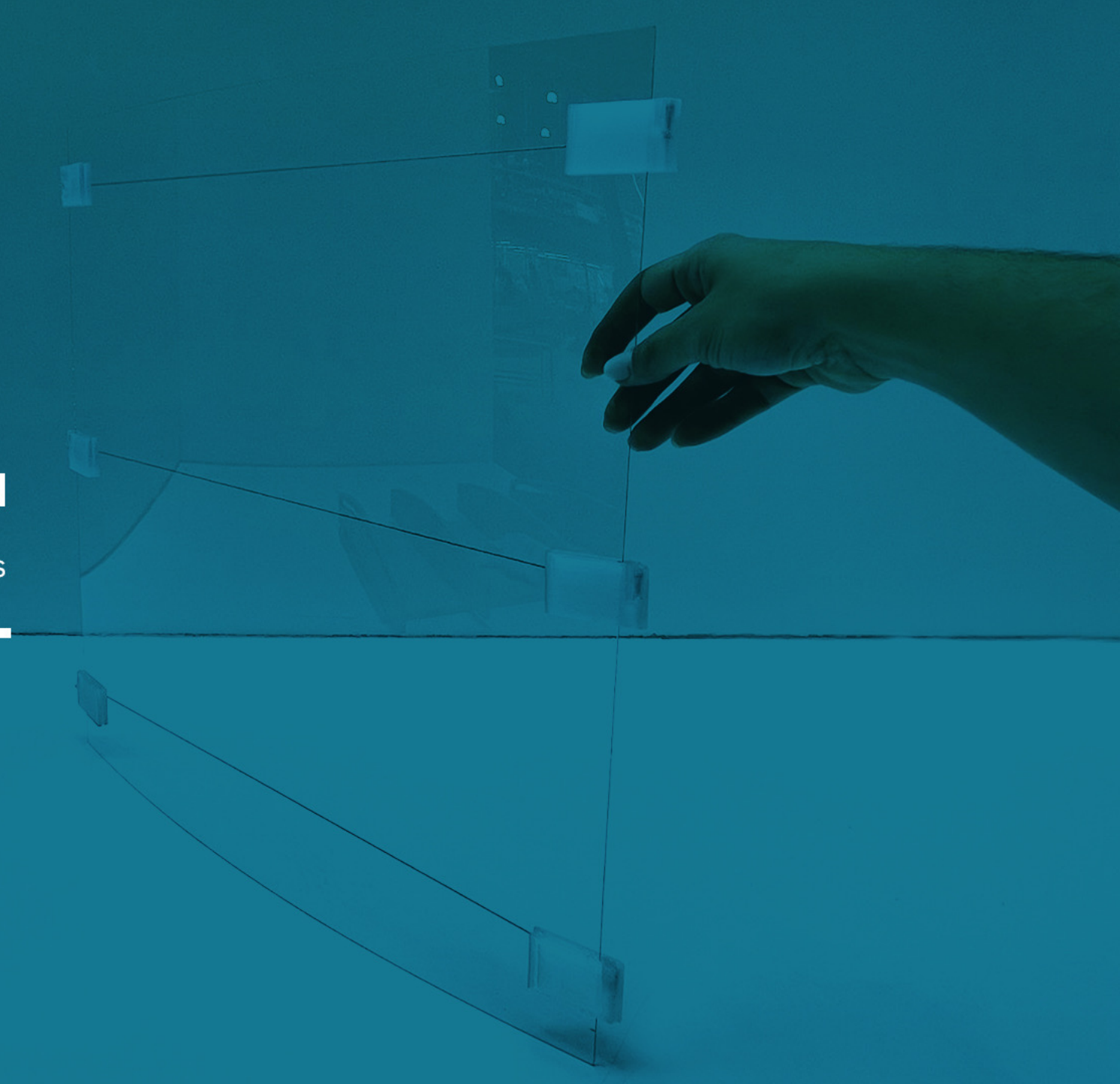
THIN GLASS INSTALLATION

integrated design for glass projects

Marialena Toliopoulou

P5 PRESENTATION



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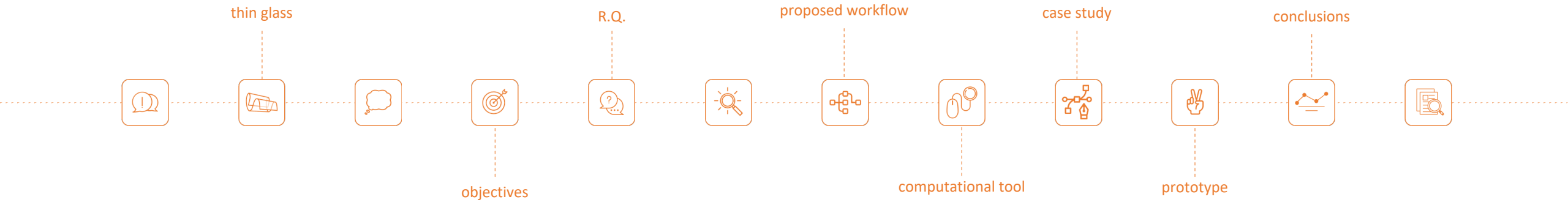
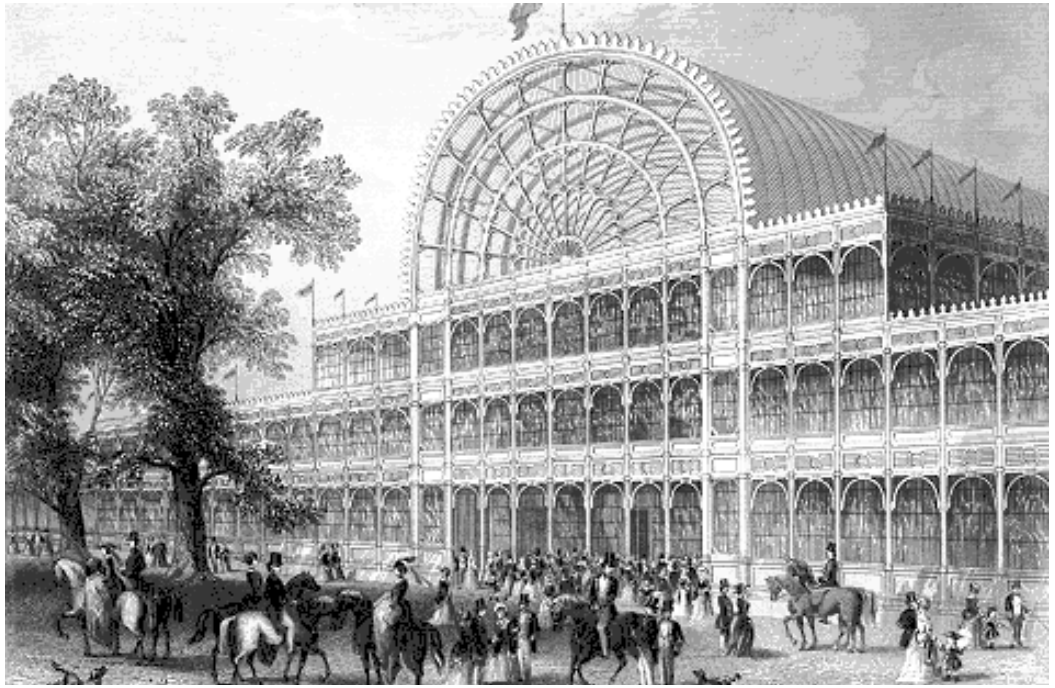
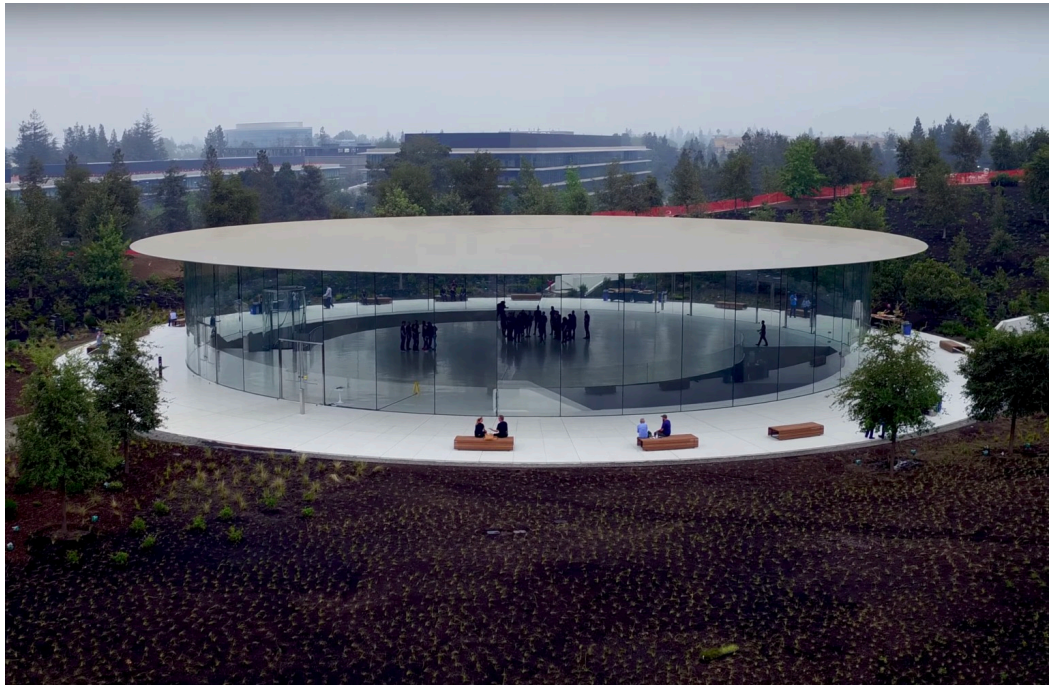

thin glass
R.Q.
proposed workflow
case study
conclusions
objectives
computational tool
prototype

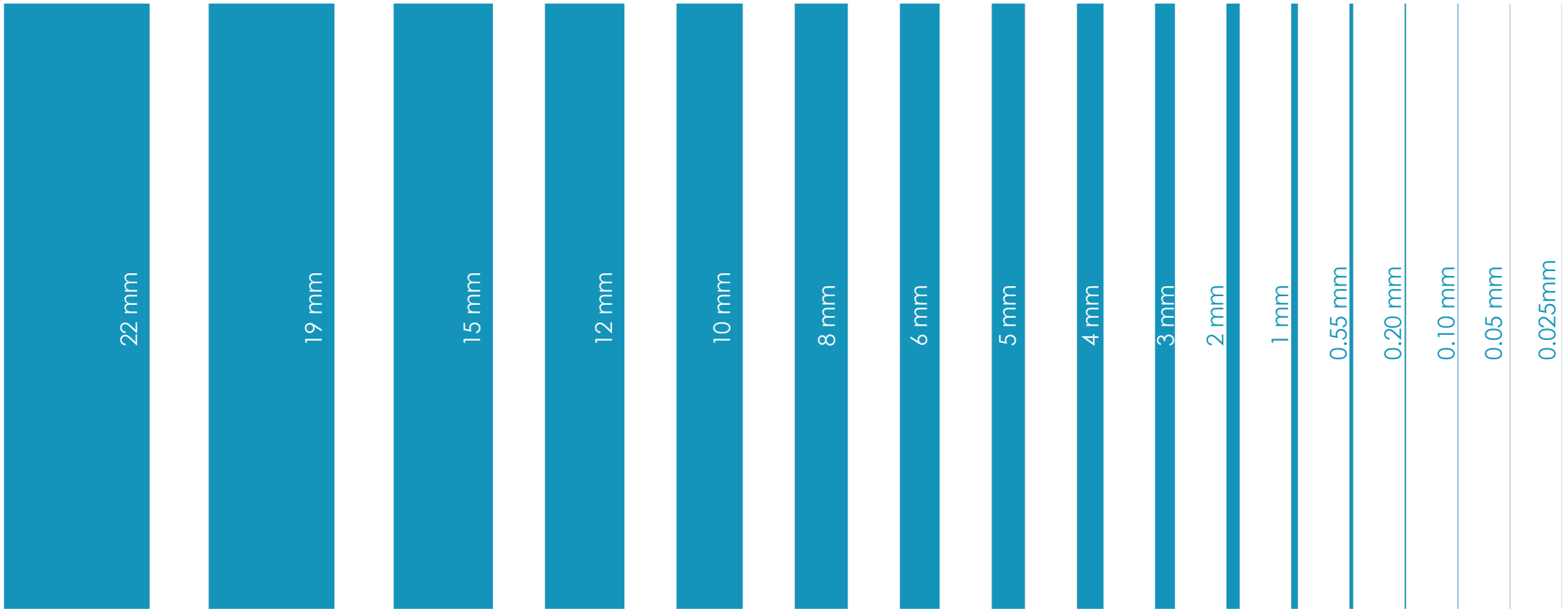
PROBLEM STATEMENT





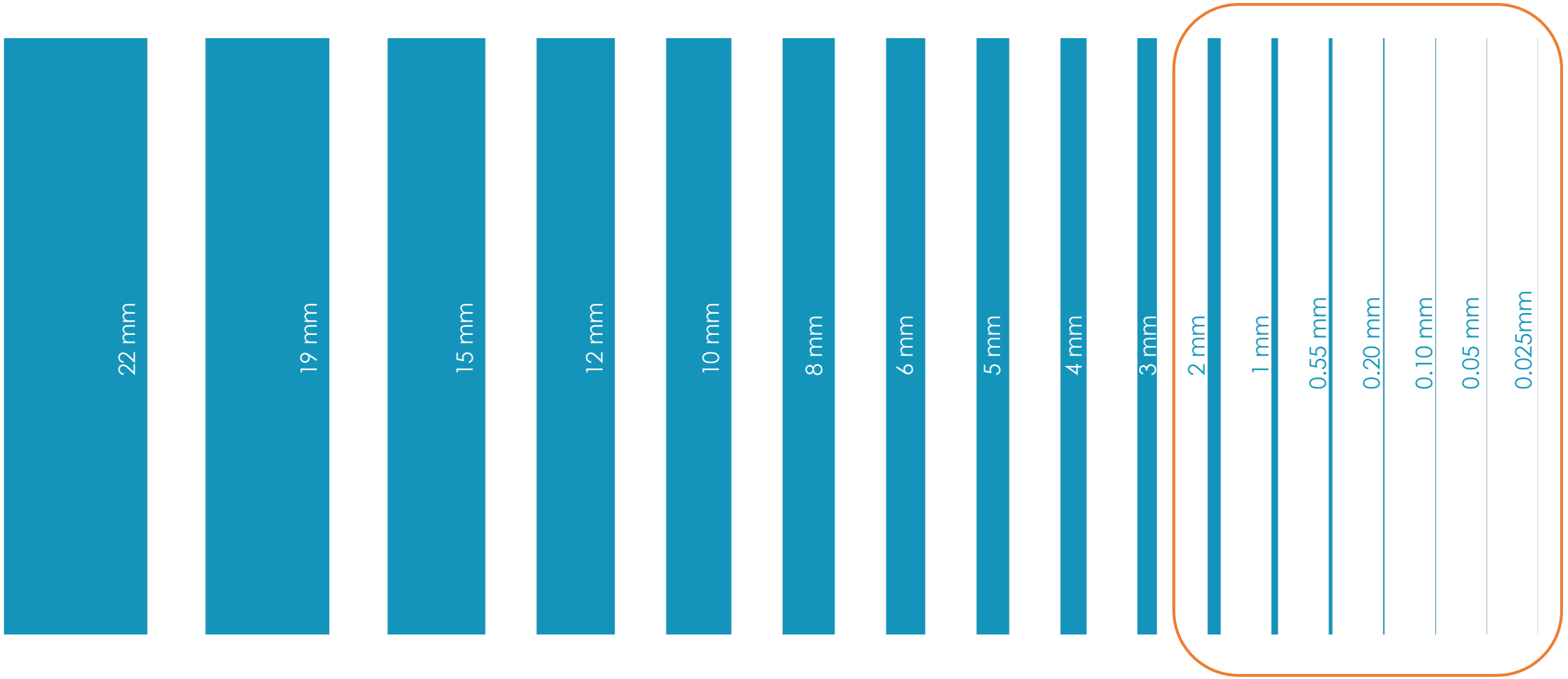
PROBLEM STATEMENT

GLASS



scaled comparison of the different glass thicknesses

THIN GLASS



scaled comparison of the different glass thicknesses

THIN GLASS

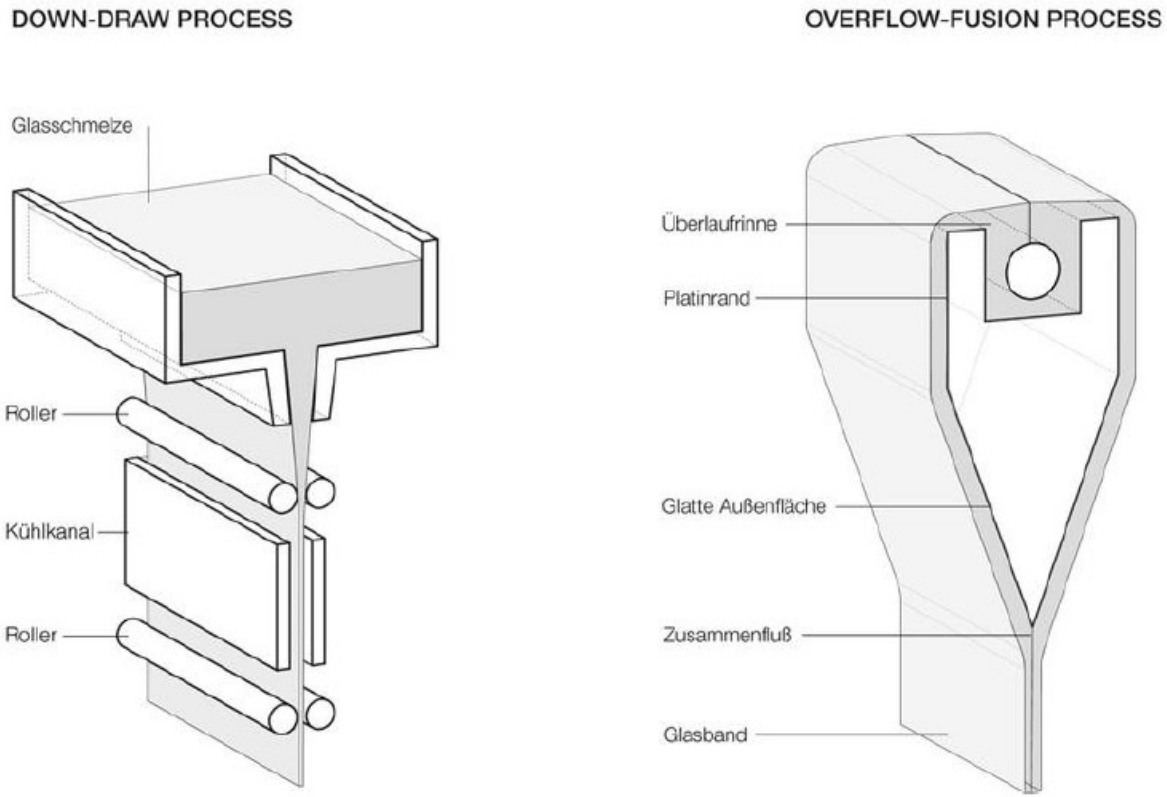
Type	Material	Formula	Composition
	Silica sand	SiO_2	60-75 %
	Lime	Na_2O	5-12 %
	Soda	CaO	12-18 %
	Magnesia	MgO	0-6 %
Alkaline Earth ASG	Alumina	AL_2O_3	15-25 %
	Alkaline earth		~15 %
Alkali ASG	Alumina	AL_2O_3	10-25 %
	Alkali		> 10 %

Typical compositions of Alkaline Earth ASG and Alkali ASG, without specification on the used metals. (Wikipedia, 2022)

	Material	Formula	Composition
Soda – Lime – Silica Glass	Silica sand	SiO_2	60-75 %
	Lime	Na_2O	5-12 %
	Soda	CaO	12-18 %
	Magnesia	MgO	0-6 %
	Alumina	AL_2O_3	0-3 %

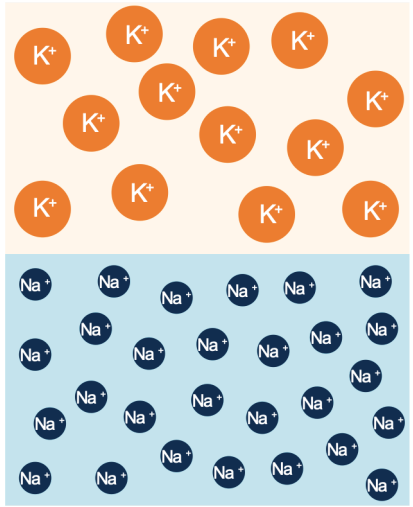
Typical composition of a soda-lime-silica glass (O' Regan, 2014)

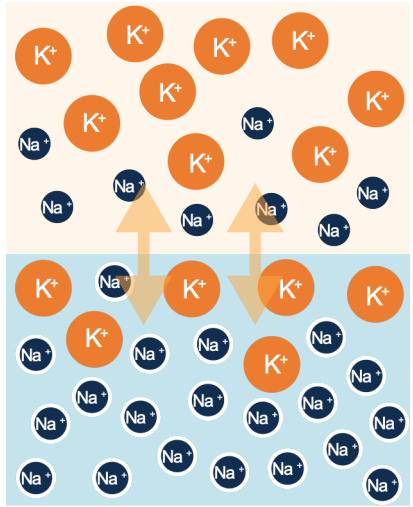
THIN GLASS

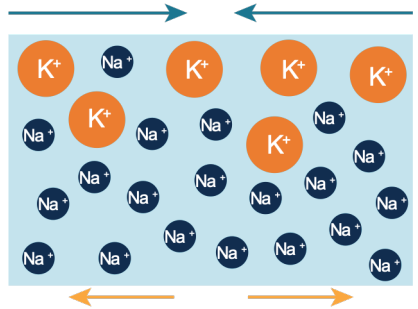


(Albus & Robanus, 2014)

THIN GLASS



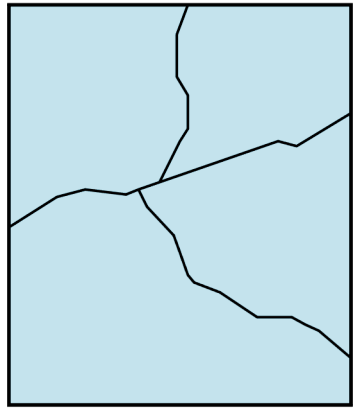




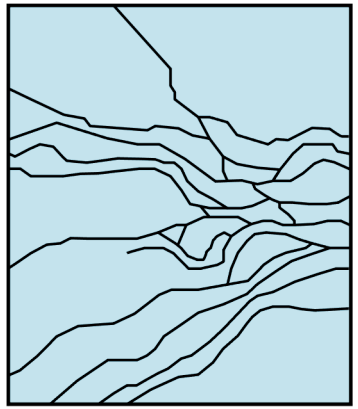
chemical tempering / ion exchange process diagrams

THIN GLASS

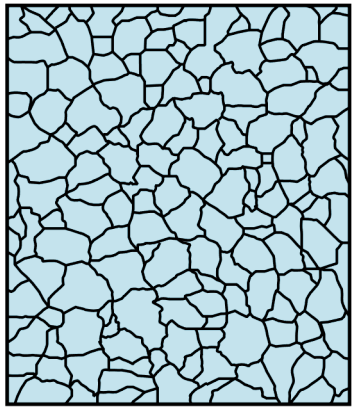
annealed glass



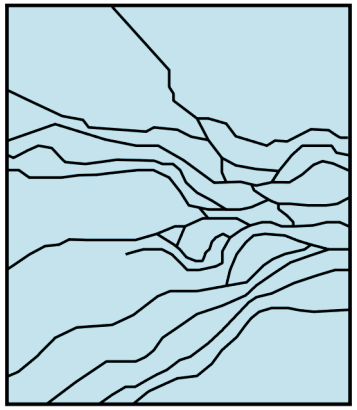
heat-strengthened



fully strengthened



chemically strengthened



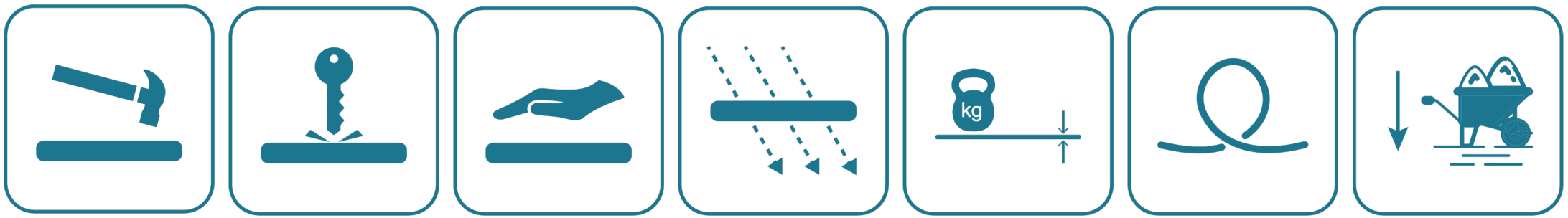
breaking pattern of the different strengthening processes

THIN GLASS

	Characteristic strength EN166612	Unit
Annealed	45	MPa
Heat strengthened	70	MPa
Fully tempered	120	MPa
Chemically tempered	150	MPa

Thin glass products	Design strength	Unit
Xensation glass	±260	MPa
Gorilla glass	200	MPa
Falcon glass	±200	MPa
Leoflex glass	260	MPa

THIN GLASS



high impact resistance

great scratch resistance

outstanding surface quality

high transparency

thin and strong

extreme flexibility

less raw material

advantages of thin glass products when compared to regular float glass

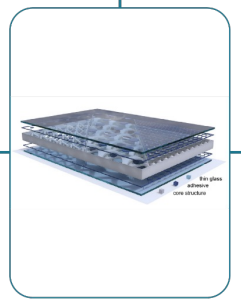
THIN GLASS

foldable smartphones utilize thin glass products for their screens

HYPOTHESIS

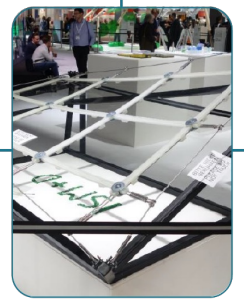
EXISTING RESEARCH

COMPOSITE PANELS



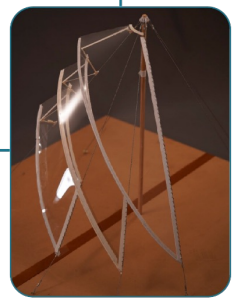
(Pfarr et al., 2022)

TENSILE STRUCTURES



(Peters et al.,2019).

FRAMED PANES



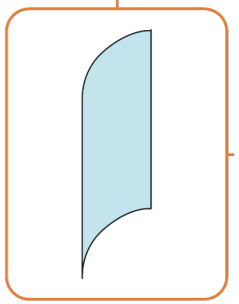
(Stoddard, 2019)

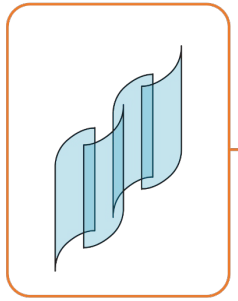
(Pennetier, 2017)

SCULPTURES

FLEXIBILITY

CURVED PANELS





HYPOTHESIS

OBJECTIVES

explore the limitations of thin glass and take advantage of its flexibility

define a computational method that will set boundaries and inform the design process

provide an **insight** on the use of thin glass **in construction**

RESEARCH QUESTION

How can a design of a thin glass installation be informed by the use of computational methods?

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How can a design of a thin glass installation be informed by the use of computational methods?

THIN GLASS

What are the limitations of thin glass in construction?

What is the optimal way to bend thin glass and achieve its maximum capabilities?

GENERAL GLASS DESIGN

What types of connections are used in (structural) glass design?

Which of the existing connections could be utilized for thin glass?

COMPUTATIONAL TOOLS

What kind of tools can be utilized to optimize the design of thin glass structures?

What data should be used and how, so as to provide limitations within the design process?

LITERATURE RESEARCH

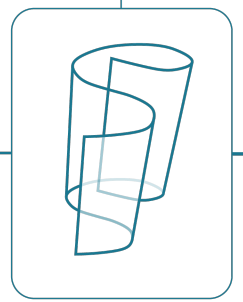
LITERATURE RESEARCH

CASE STUDIES

thin glass pavilion. source: EOC Engineers.

thin glass sculpture by Sophie Pennetier (2017)

MATERIAL



DOs

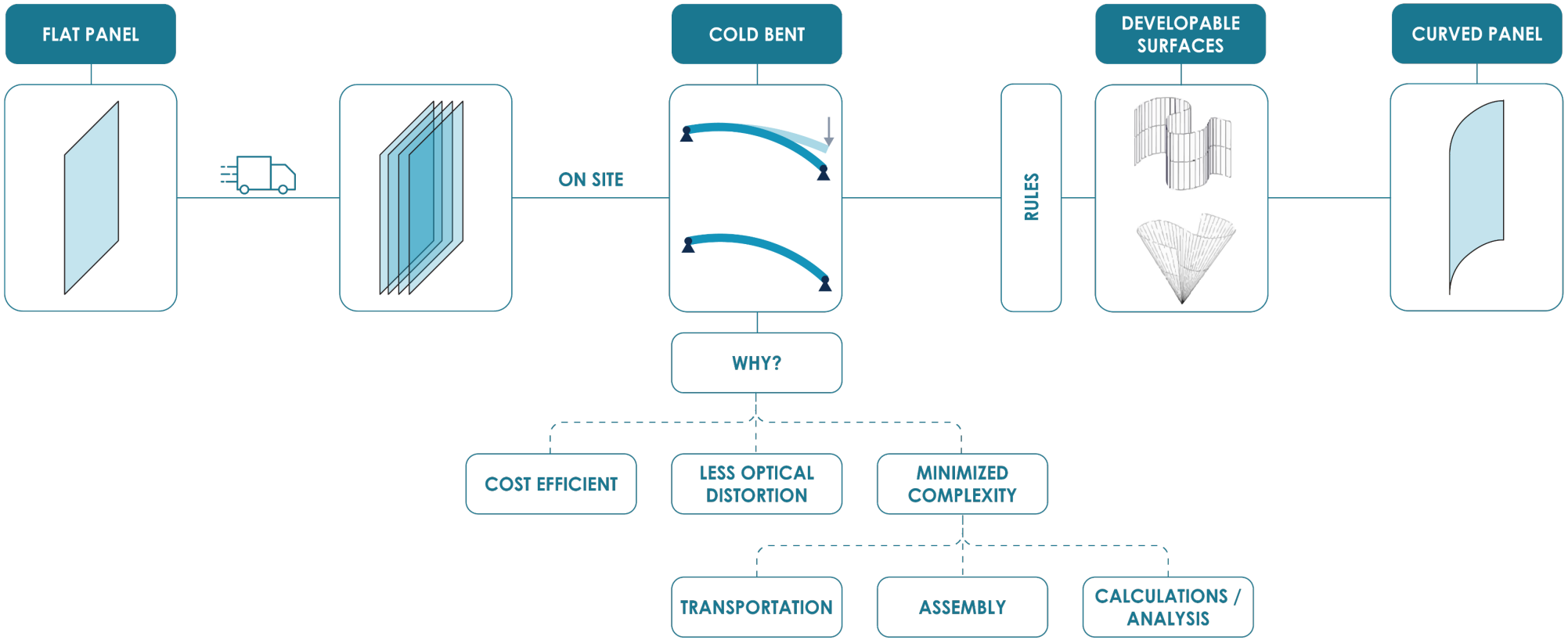
DON'Ts

GUIDELINES

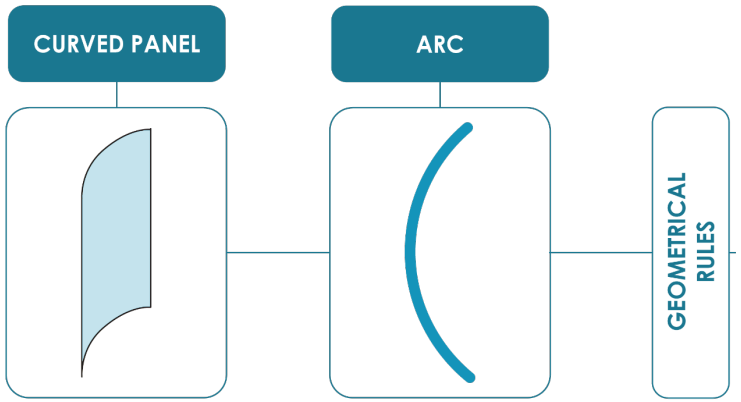
LIMITATIONS

PROPOSED WORKFLOW

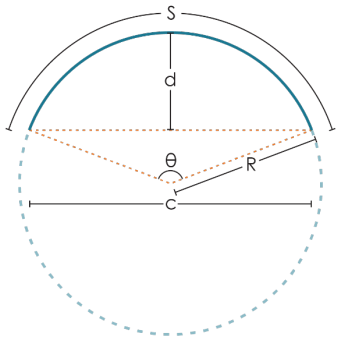
LIMITATIONS



PROPOSED WORKFLOW

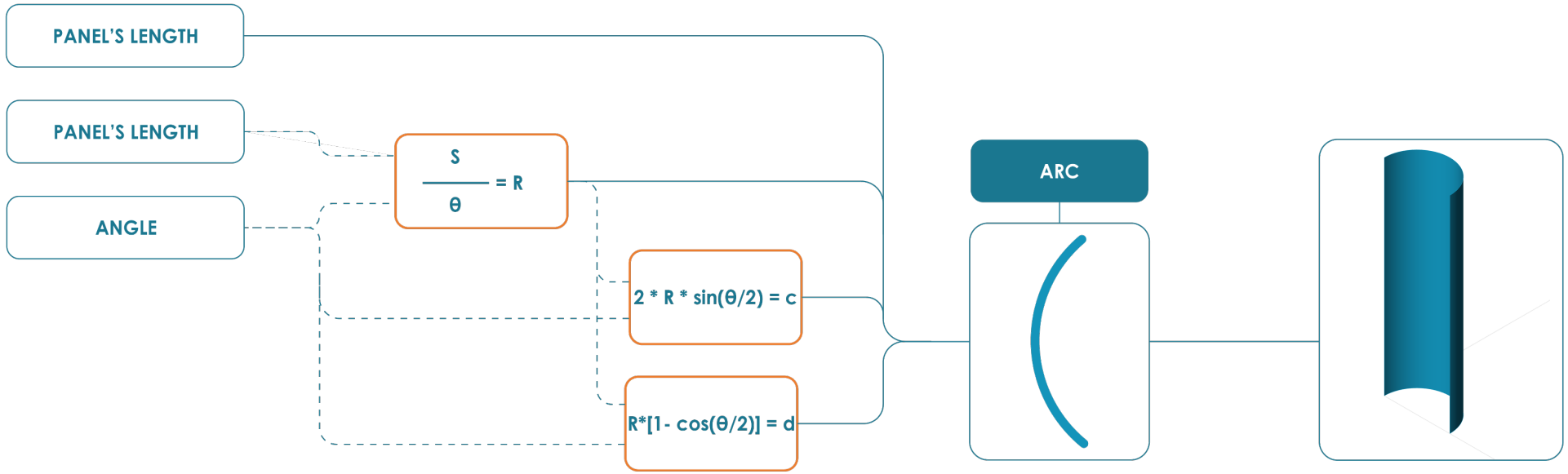


GEOMETRICAL RULES



- ARC LENGTH (S) — $S = \frac{\theta}{360} \cdot 2\pi R$
- DEPTH (d) — $d = R\left(1 - cos\frac{\theta}{2}\right)$
- CHORD LENGTH (c) — $c = 2 \cdot R \cdot sin\frac{\theta}{2}$
- RADIUS (R)
- ARC ANGLE (θ)

PROPOSED WORKFLOW



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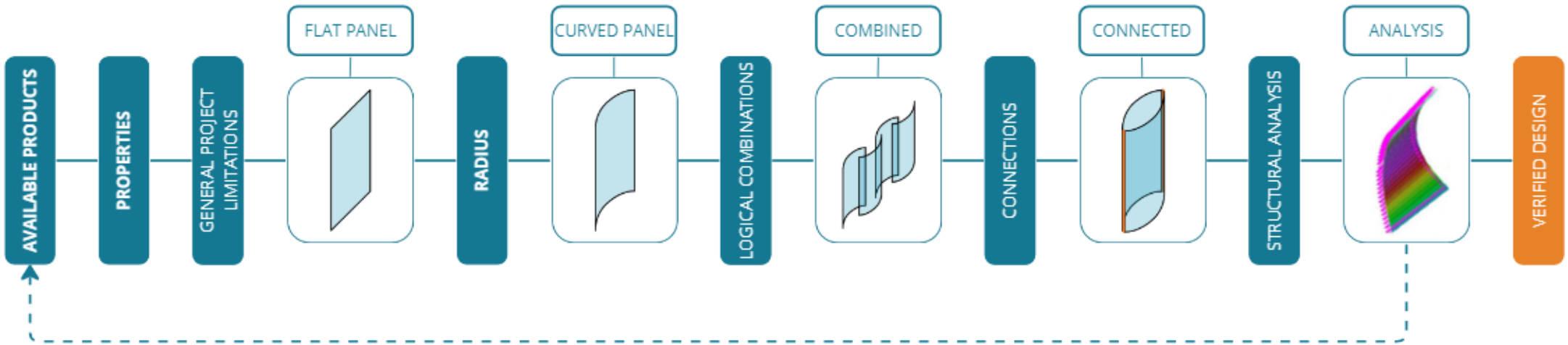

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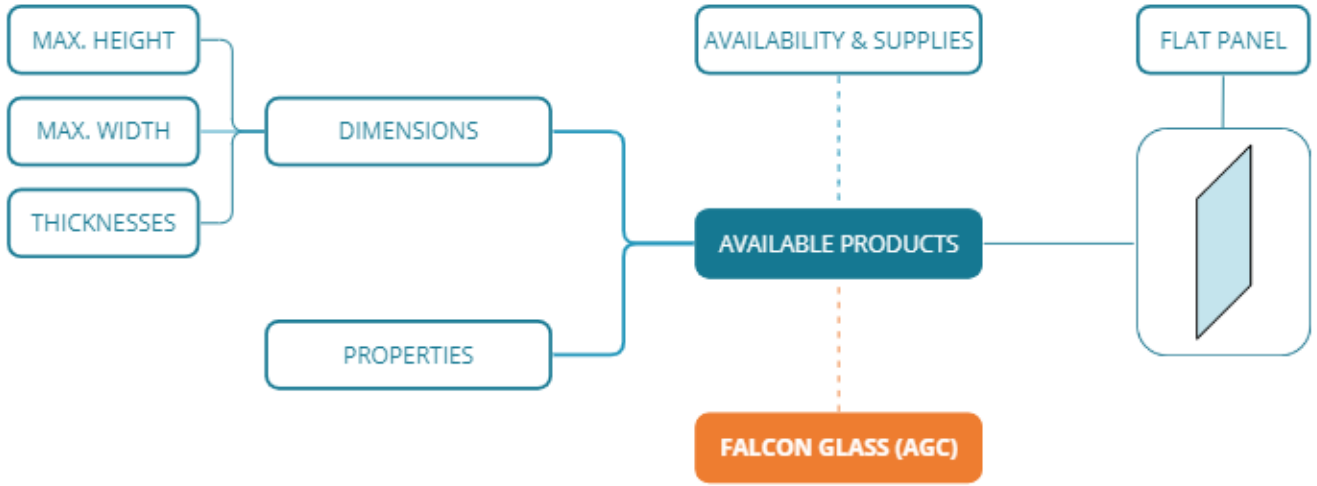
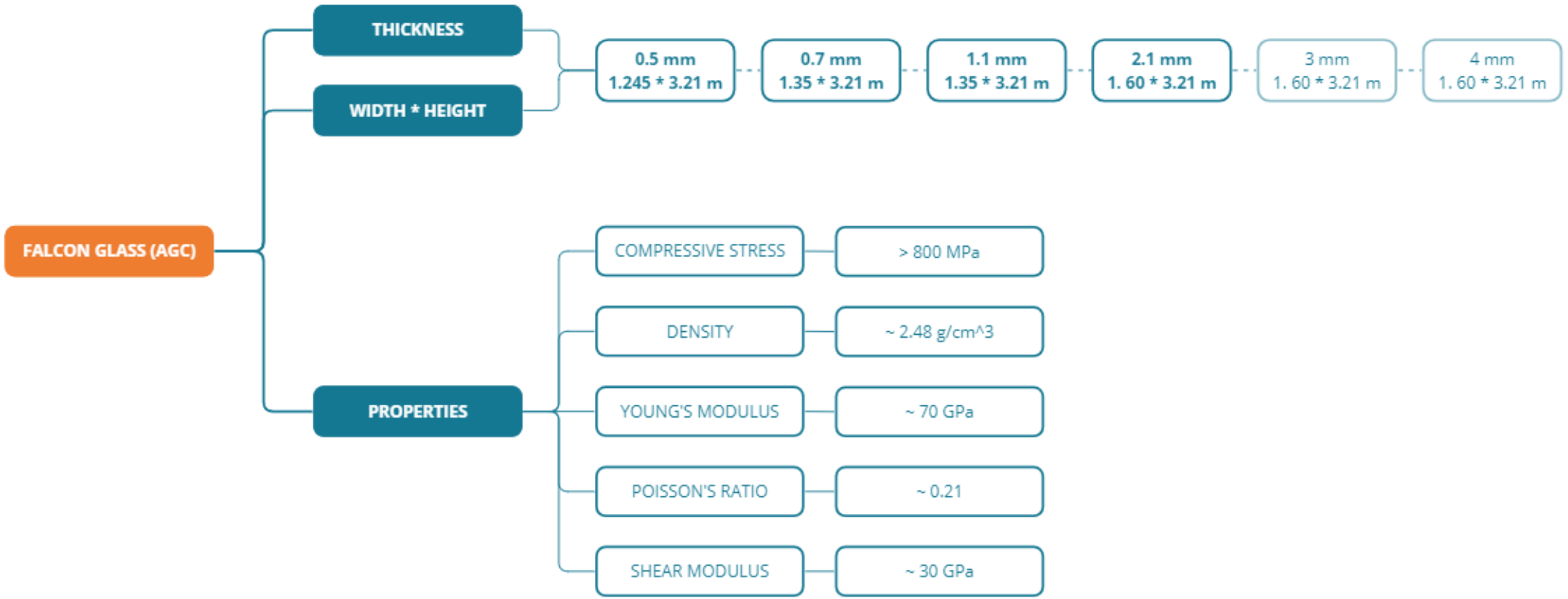


PROPOSED WORKFLOW

PRODUCT SPECS



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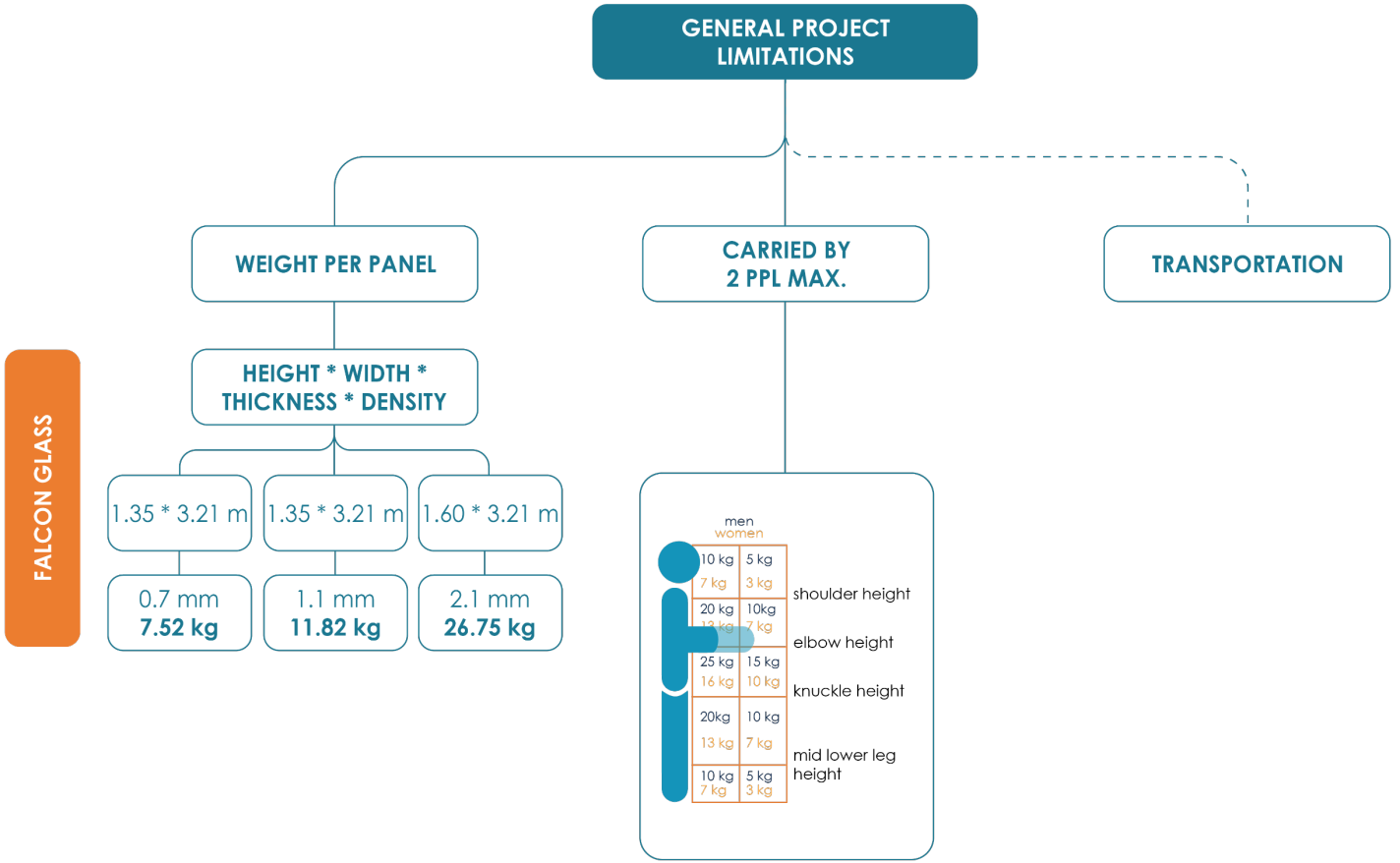

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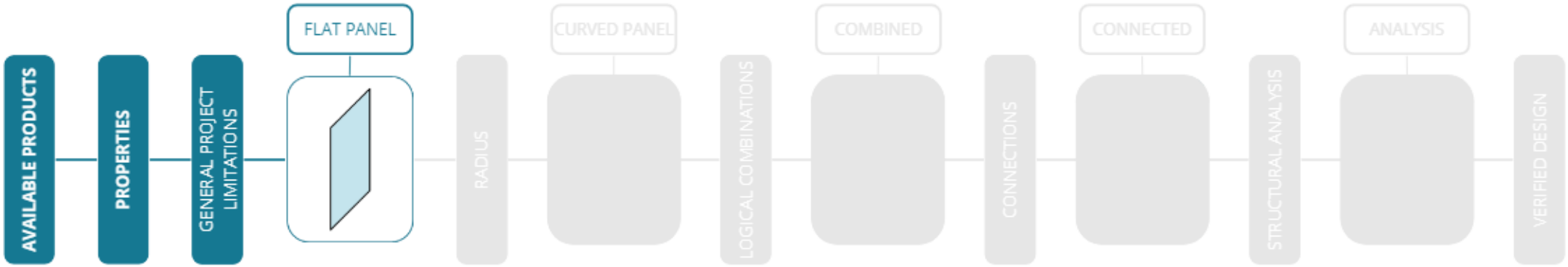
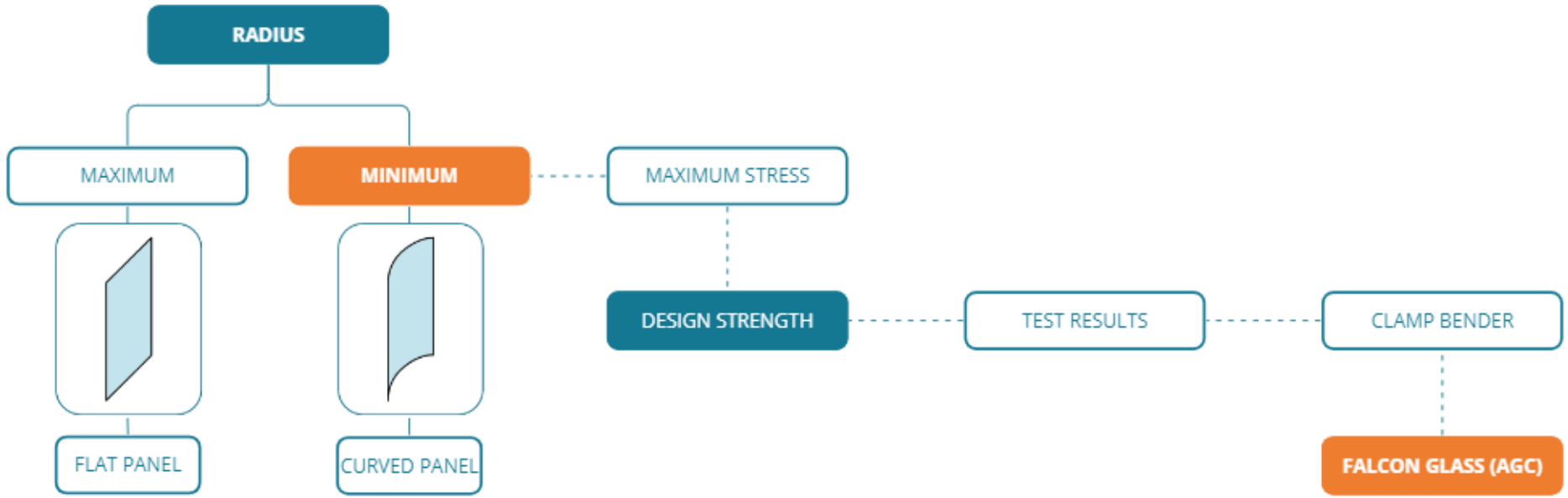


PROPOSED WORKFLOW

BENDING

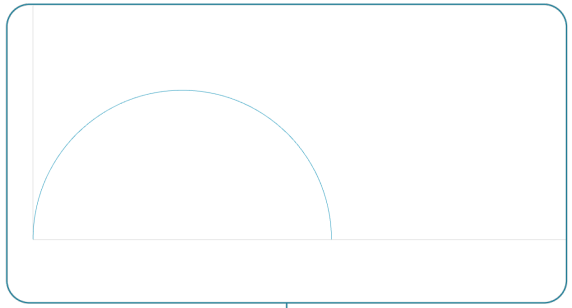


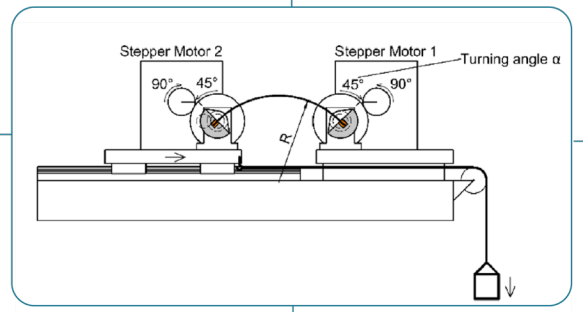
PROPOSED WORKFLOW

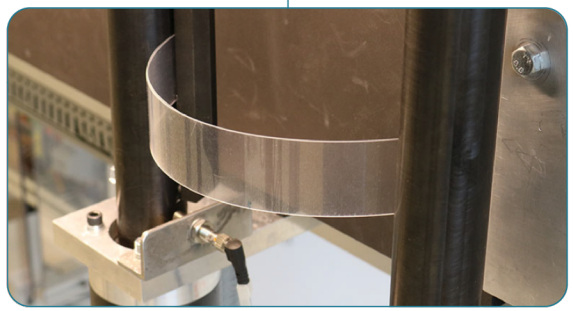
FALCON GLASS

AGC | TU DRESDEN | TU DARMSTAND |

CLAMP BENDER







- **SPEED** — 2 MPa/sec
- **STRESS** — $\sigma = \frac{Mh_g}{2I}$
- **BENDING MOMENT** — $M = \frac{EI}{R} = \frac{2EI\alpha}{L_e}$
- **ROTATIONAL ANGLE INCREASE** — $\dot{\alpha} = \frac{\dot{\sigma} L_e}{Eh_g}$
- **DISTANCE BETWEEN MOTORS** — $d = L_e \frac{\sin\alpha}{\alpha} + 2\cos\alpha x_1 + 2\sin\alpha\left(y_1 + \frac{h_g}{2}\right)$

PROPOSED WORKFLOW

MATERIAL TESTING

FALCON GLASS

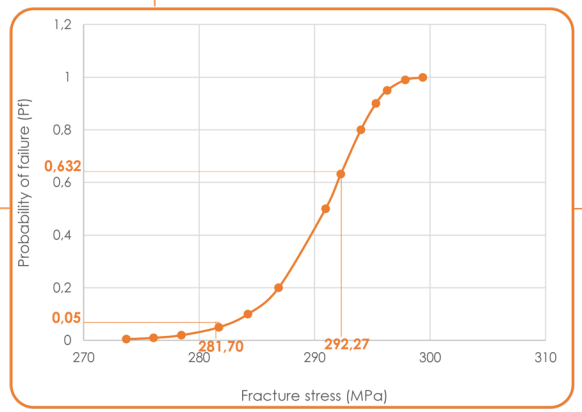
CLAMP BENDER

TEST RESULTS

n (number of specimens)	SPECIMEN	THICKNESS (h_0)	RADIUS (R)	STRESS (σ)
1	L12405A_01	0,520	74,31	245,038
2	L12405A_09	0,516	63,75	283,294
3	L12405A_28	0,516	63,75	283,294
4	L12405A_31	0,521	64,1	284,614
5	L12405A_26	0,527	64,7	285,22
6	L12405A_29	0,521	63,87	285,228
7	L12405A_08	0,519	63,18	287,235
8	L12405A_19	0,520	63,29	287,565
9	L12405A_07	0,514	62,5	287,98
10	L12405A_02	0,518	62,72	288,783
11	L12405A_11	0,521	63,06	289,169
12	L12405A_23	0,524	63,29	289,915
13	L12405A_14	0,515	61,95	290,819
14	L12405A_10	0,515	61,95	290,96
15	L12405A_06	0,521	62,61	290,968
16	L12405A_17	0,512	61,51	291,335
17	L12405A_25	0,526	63,06	291,667
18	L12405A_12	0,517	62,06	291,714
19	L12405A_21	0,513	61,51	291,762
20	L12405A_24	0,523	62,72	291,853
21	L12405A_04	0,519	62,06	292,56
22	L12405A_22	0,515	61,51	293,184
23	L12405A_30	0,522	62,28	293,212
24	L12405A_13	0,512	60,98	293,867
25	L12405A_18	0,521	61,84	294,591
26	L12405A_15	0,514	60,98	295,158
27	L12405A_03	0,516	61,08	295,391
28	L12405A_27	0,526	62,17	295,842
29	L12405A_16	0,513	60,66	295,994
30	L12405A_20	0,523	61,84	296,147
31	L12405A_05	0,517	60,98	296,737
32	L12405A_32	0,524		

WEIBULL DISTRIBUTION

LASER CUT EDGE (L12405A)



EN 1288

CHARACTERISTIC VALUE

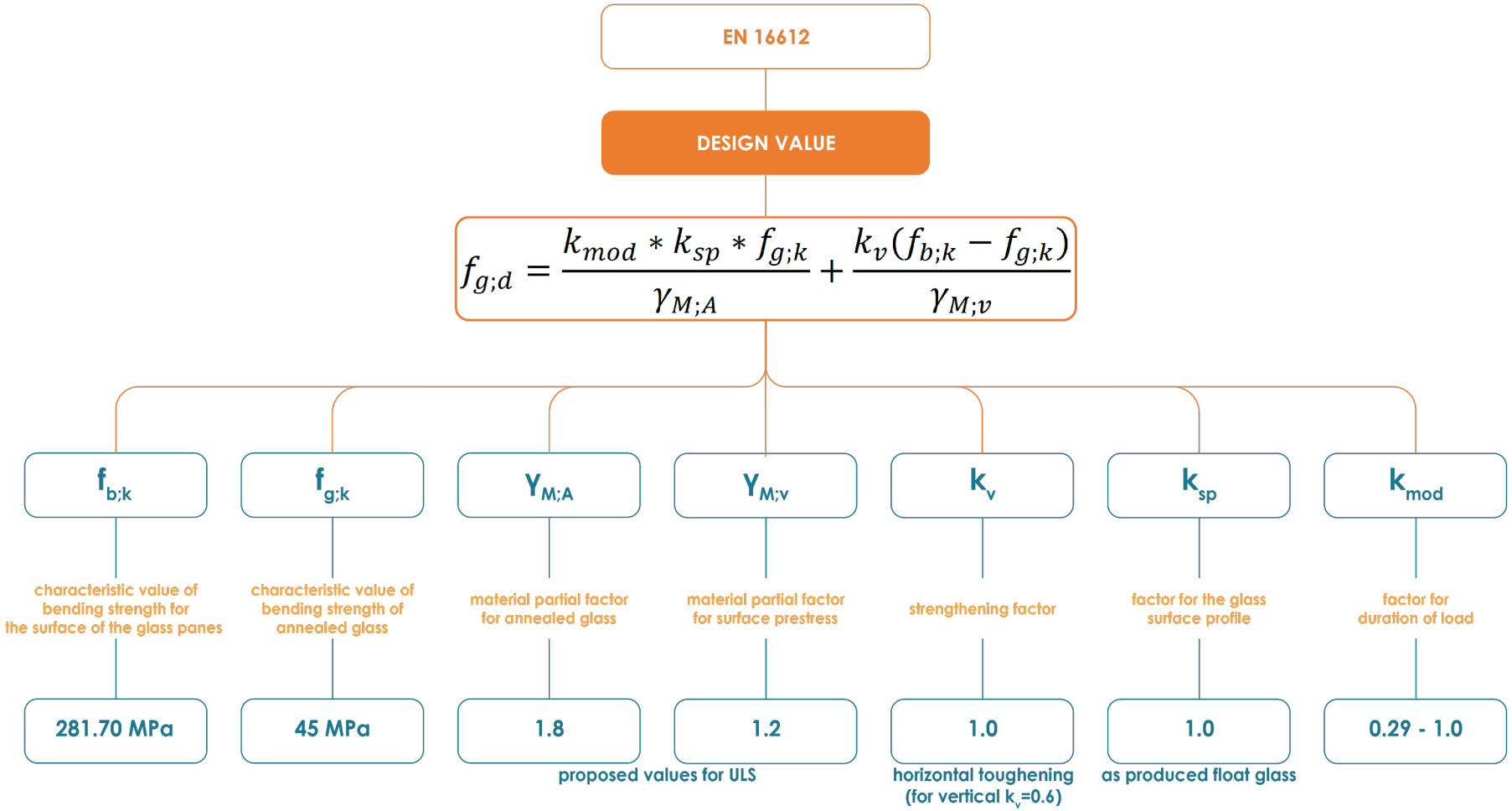
5% PROBABILITY OF FAILURE

281.70 MPa

EN 16612

DESIGN VALUE

PROPOSED WORKFLOW



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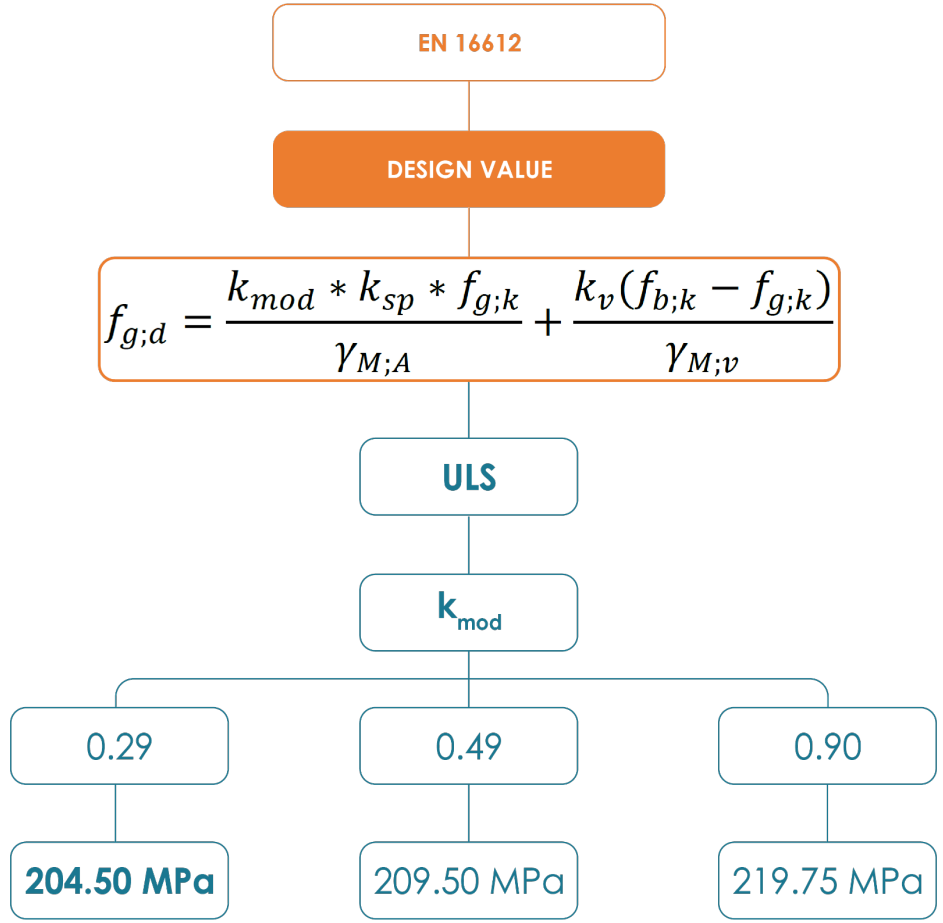

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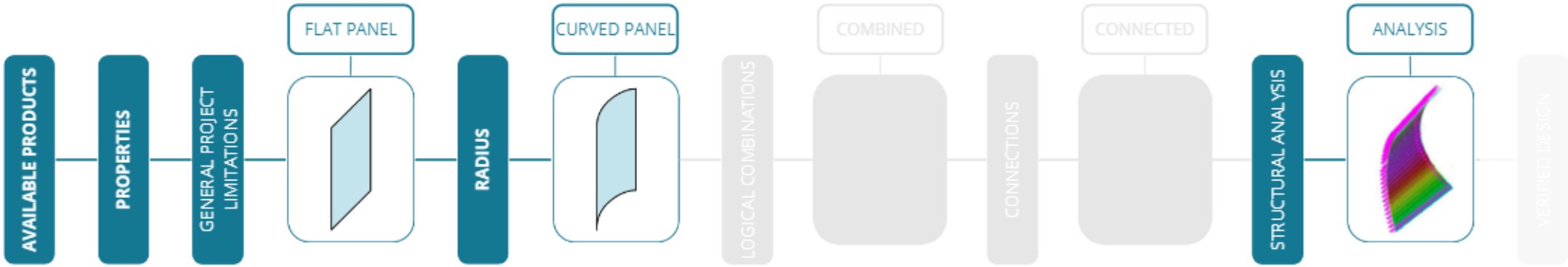

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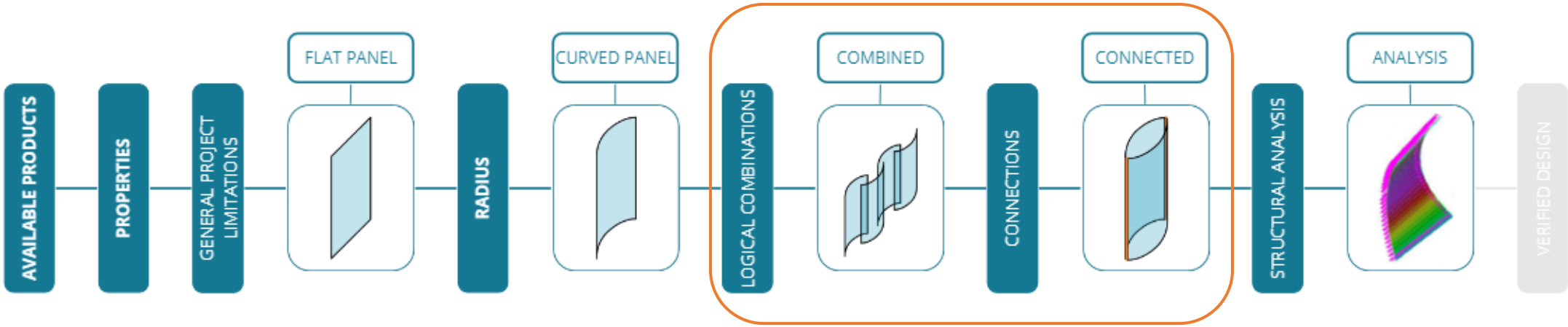

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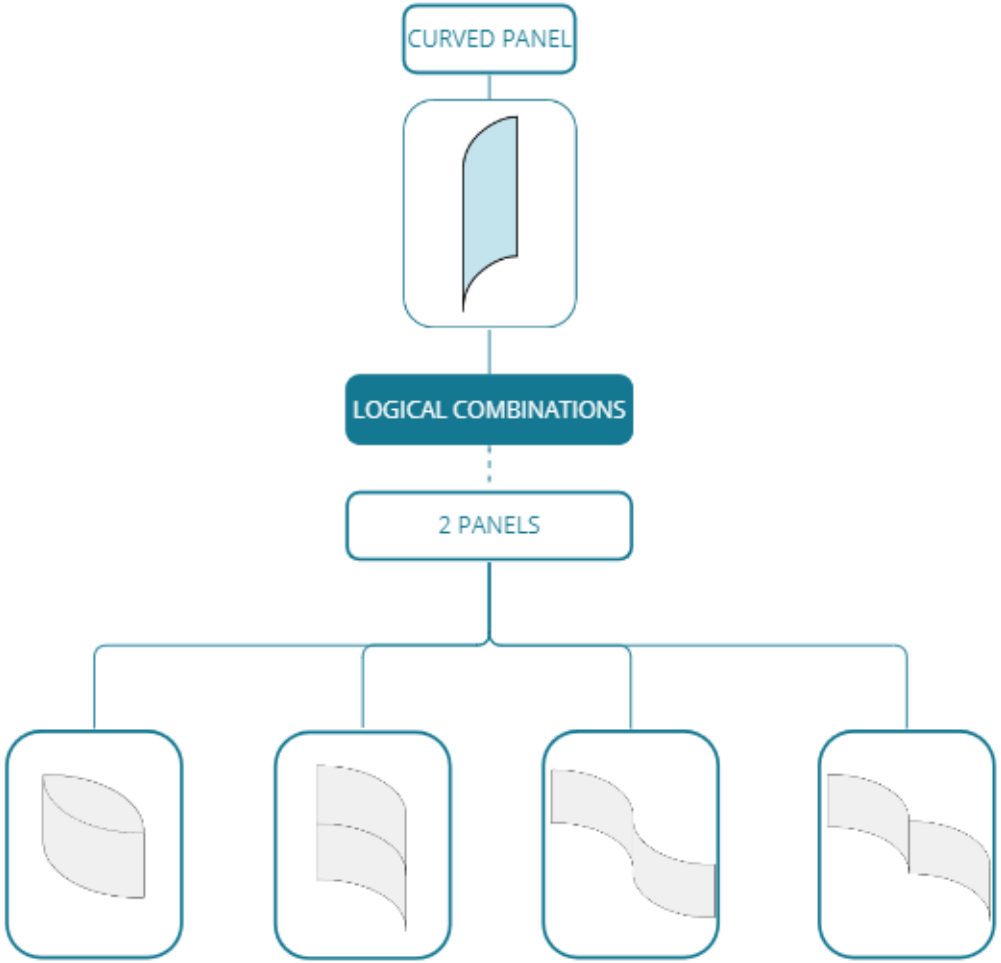
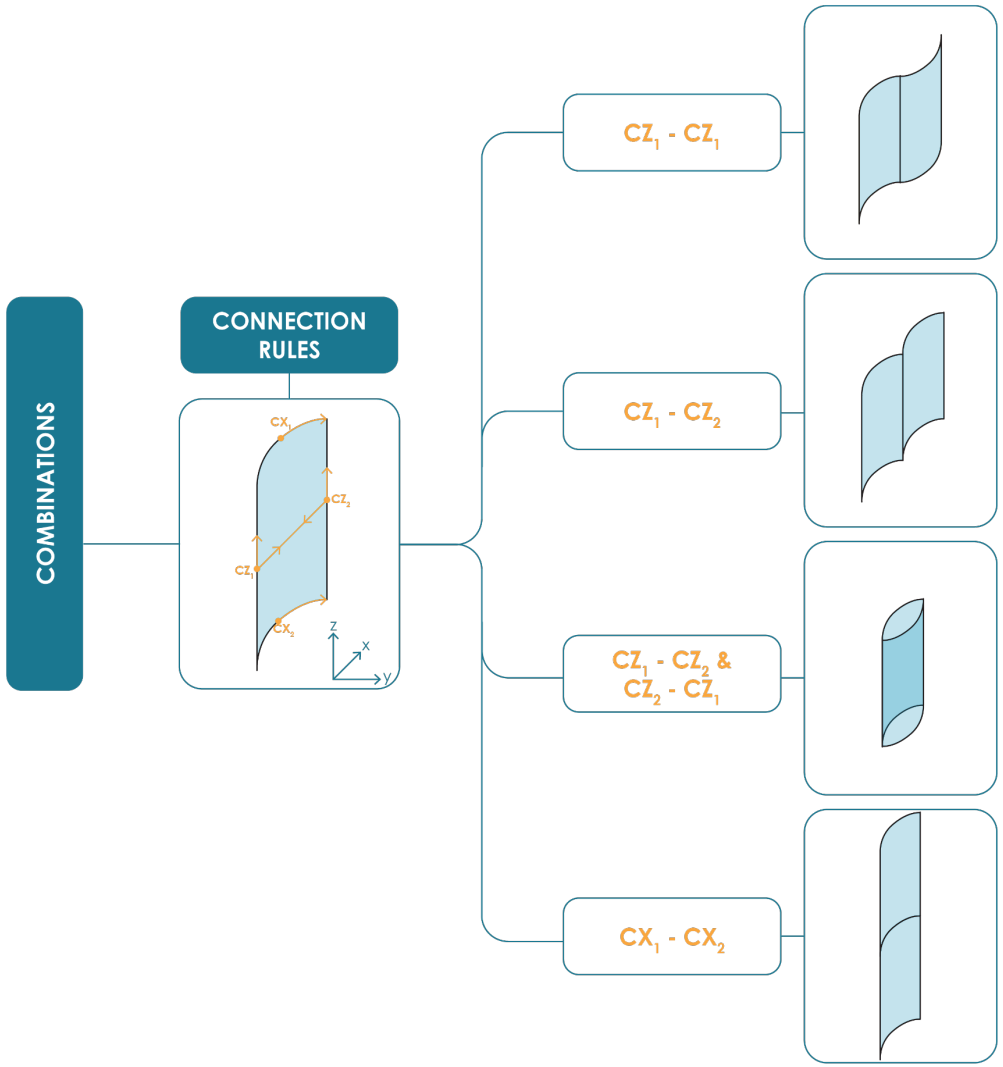


PROPOSED WORKFLOW

DESIGN COMBINATIONS



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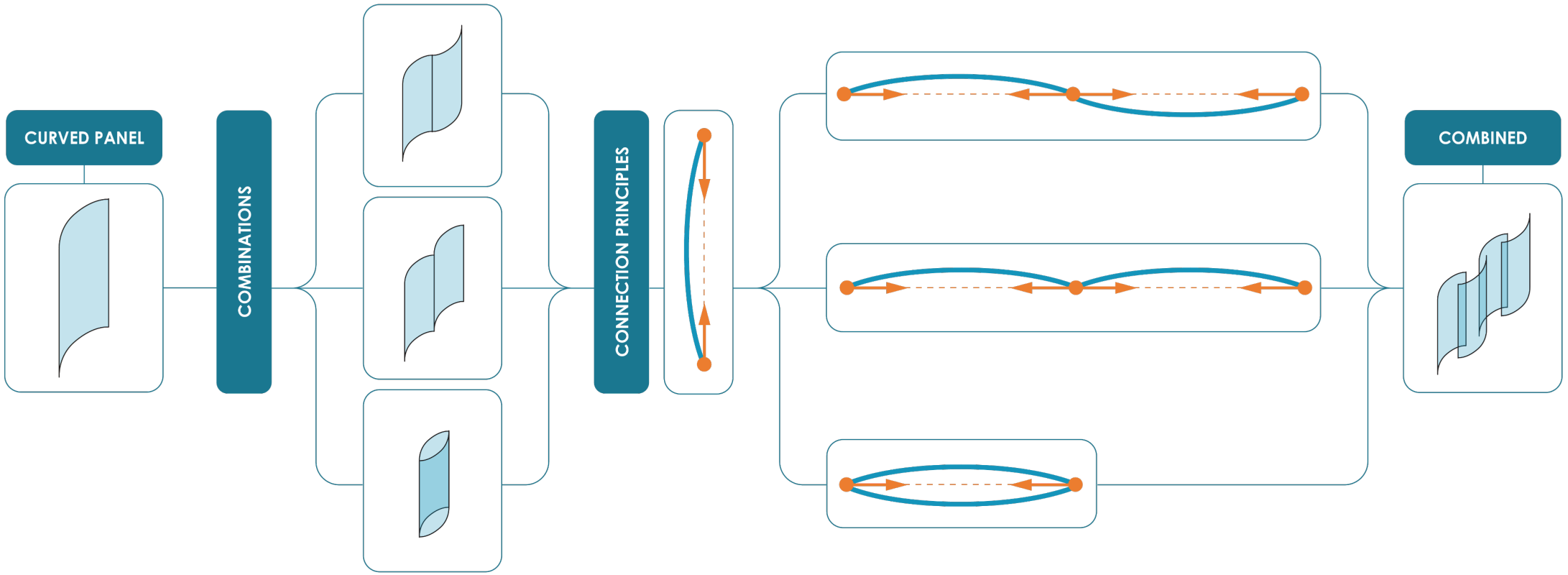

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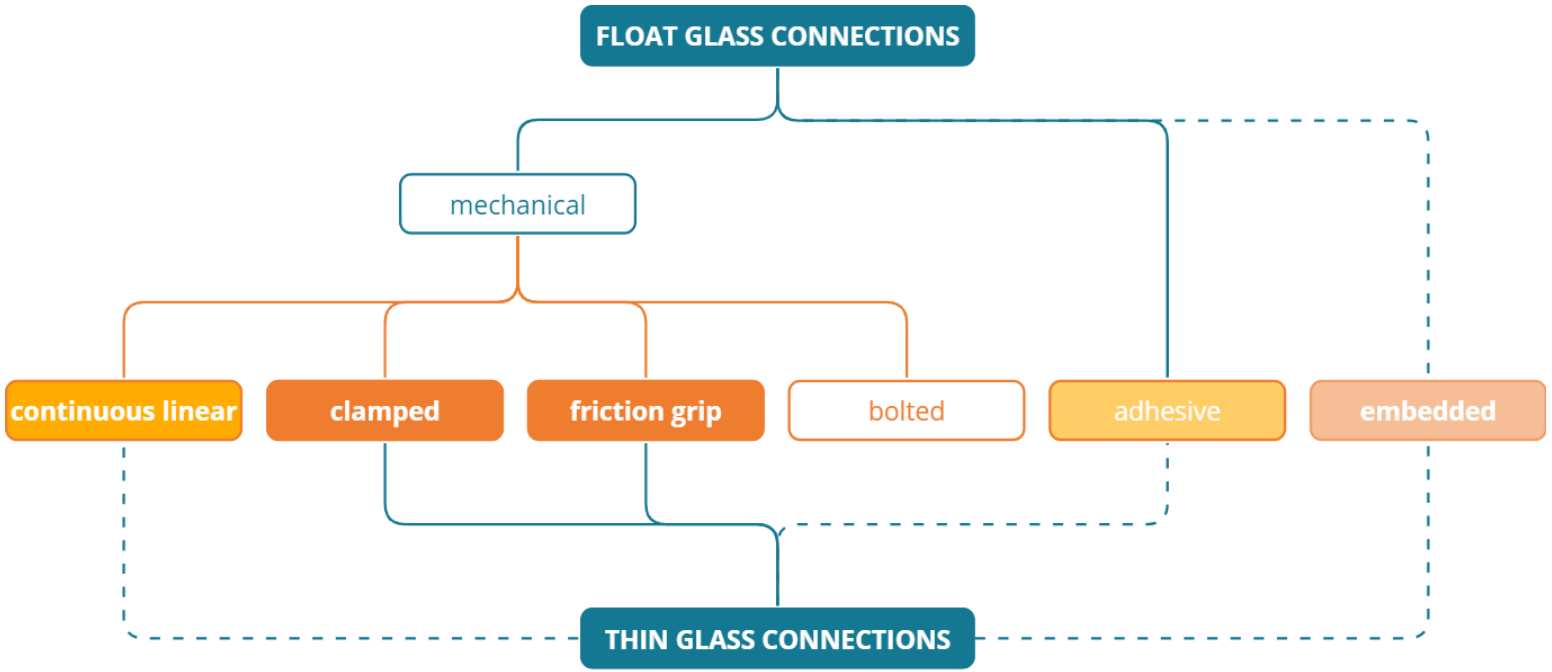
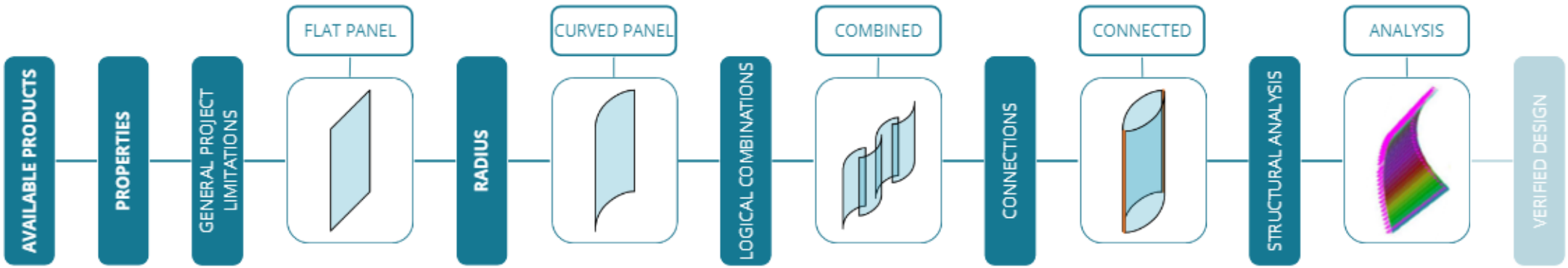
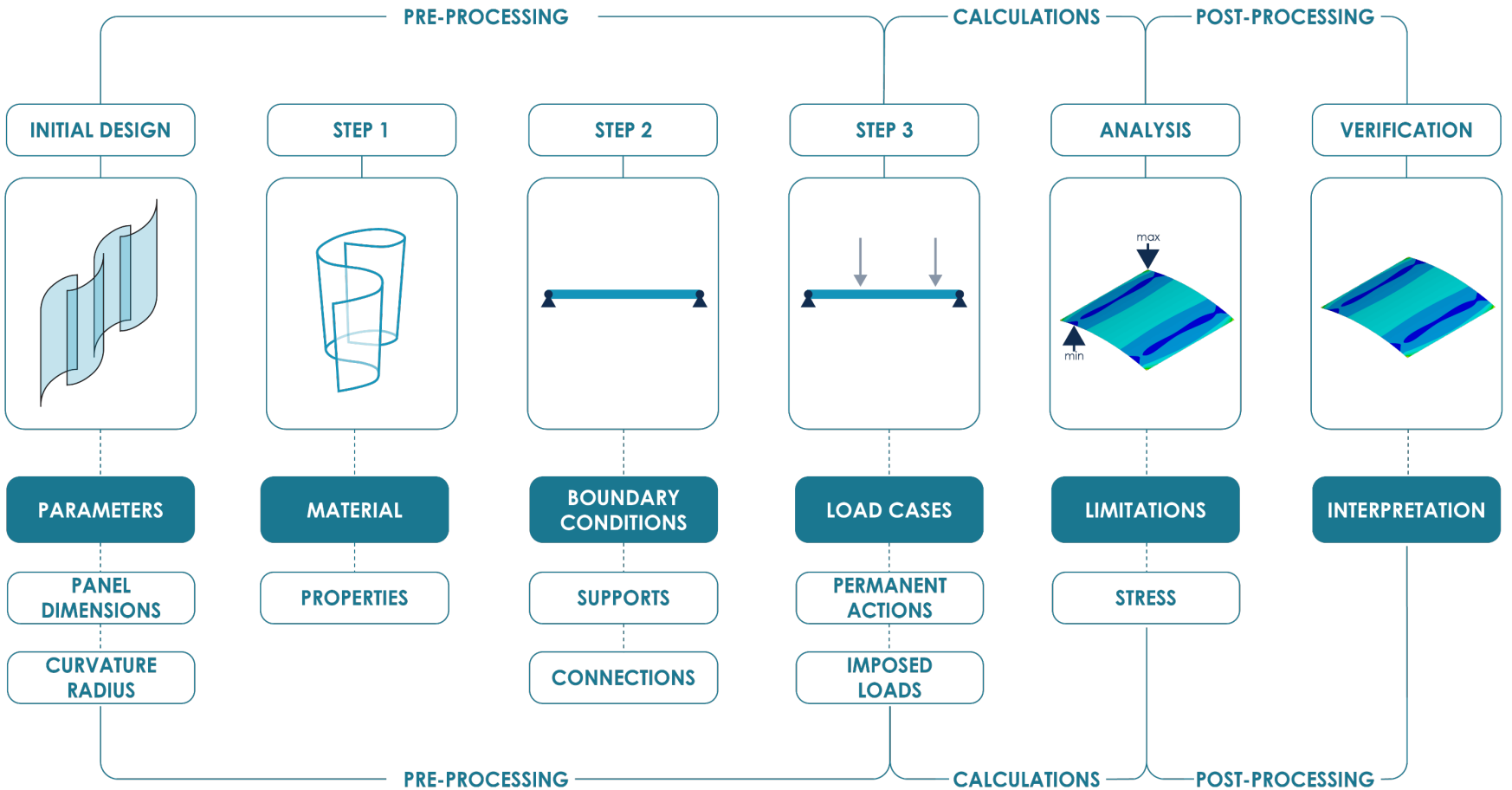


PROPOSED WORKFLOW



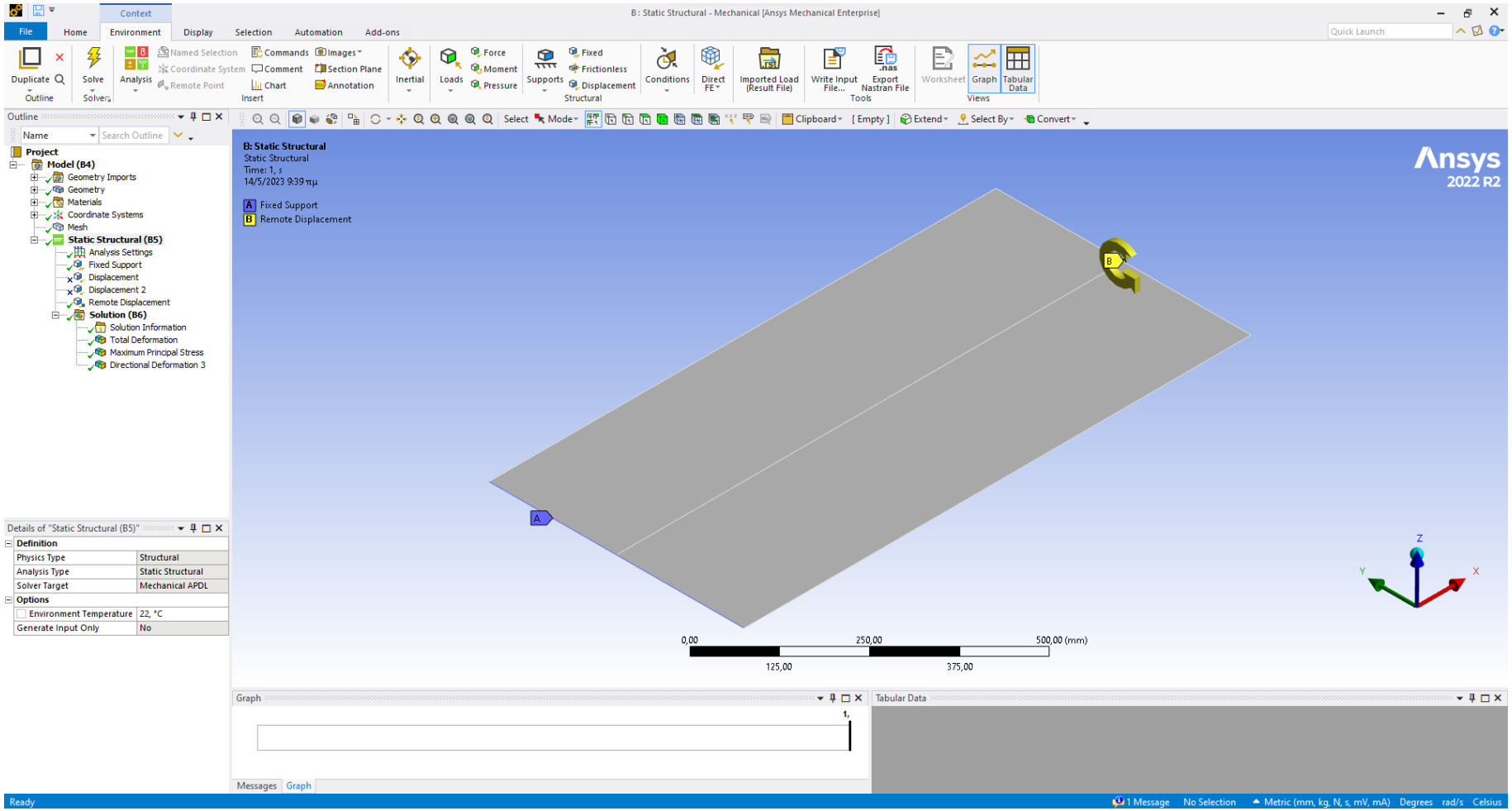
PROPOSED WORKFLOW

FINITE ELEMENT METHOD



PROPOSED WORKFLOW

ANSYS Workbench (2022 R2)



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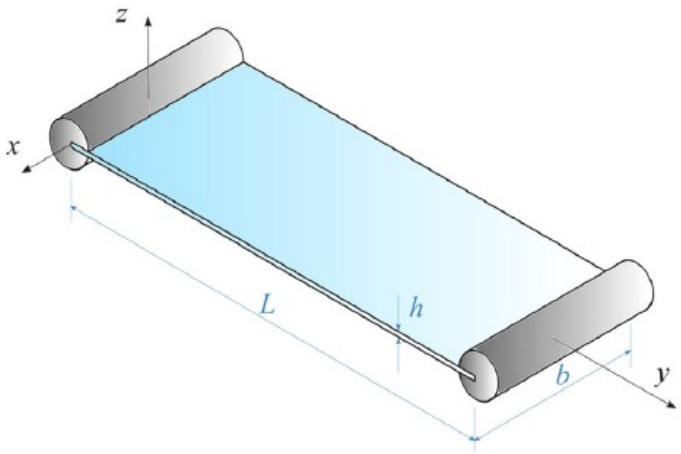
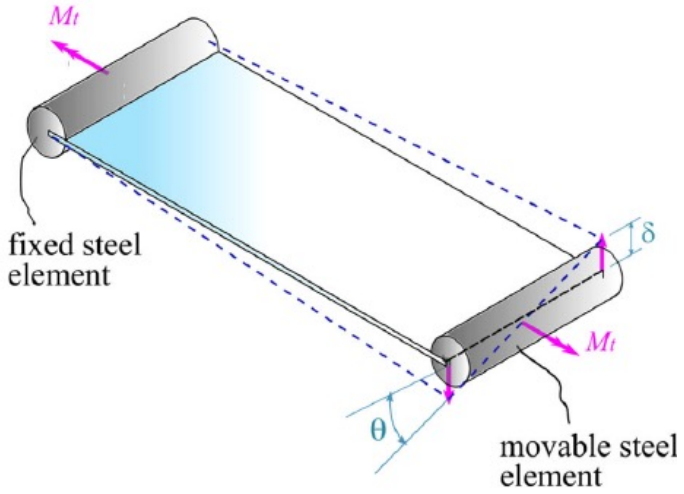
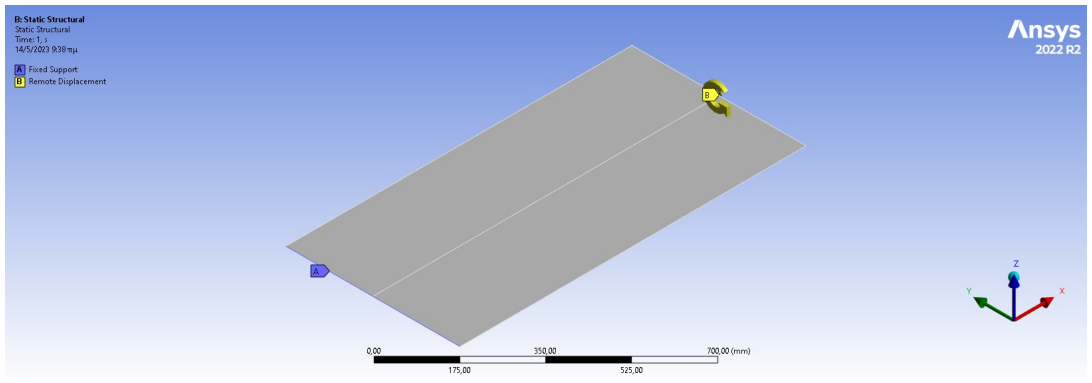
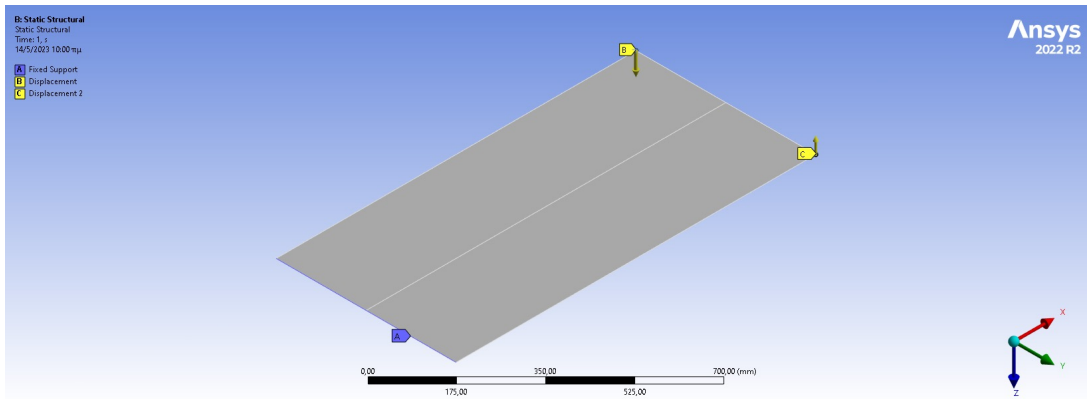




Galuppi and Riva (2022)





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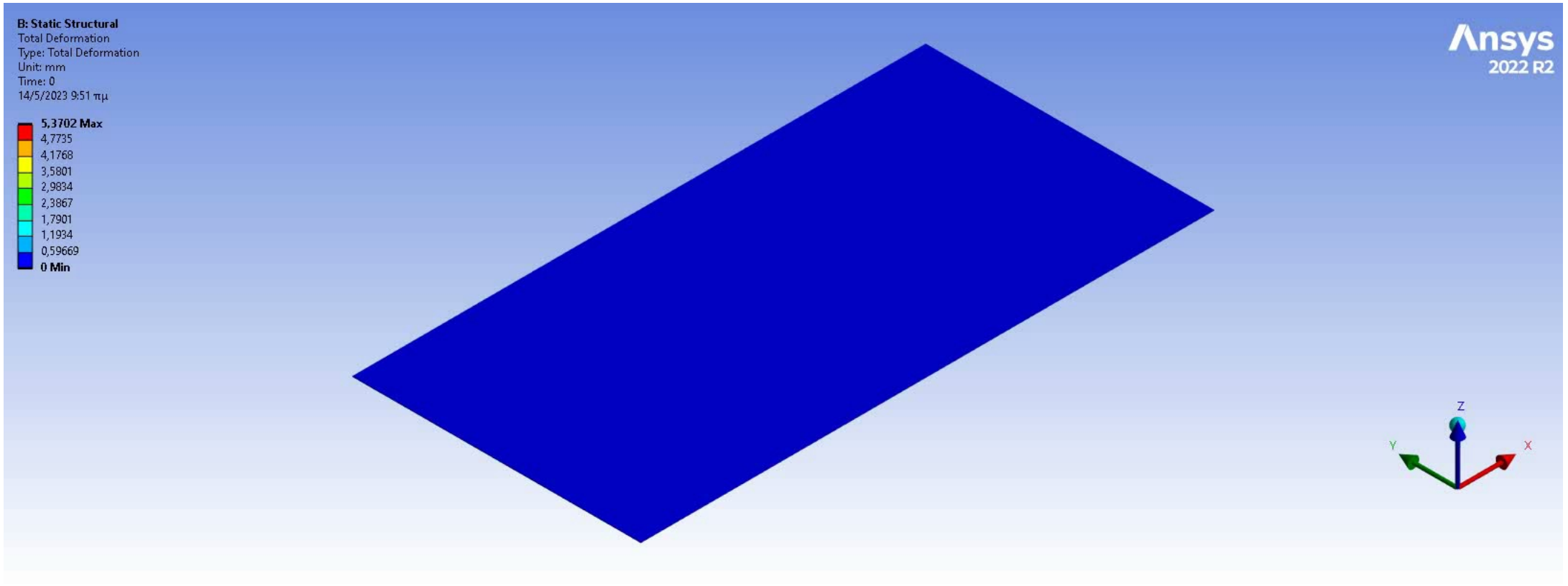

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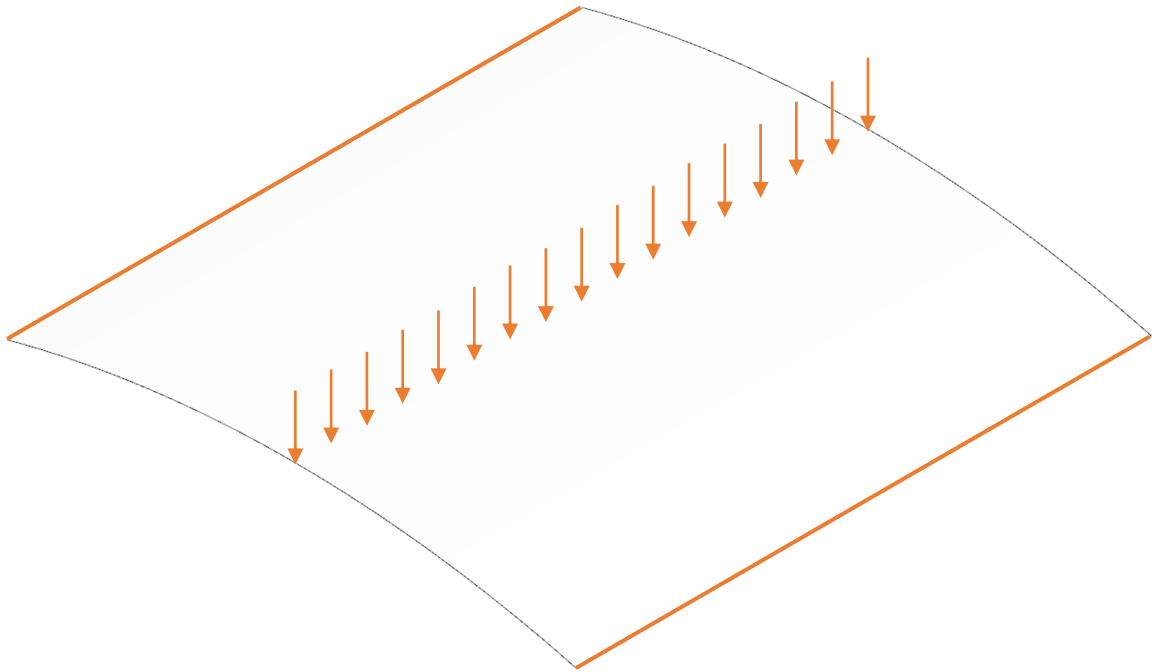

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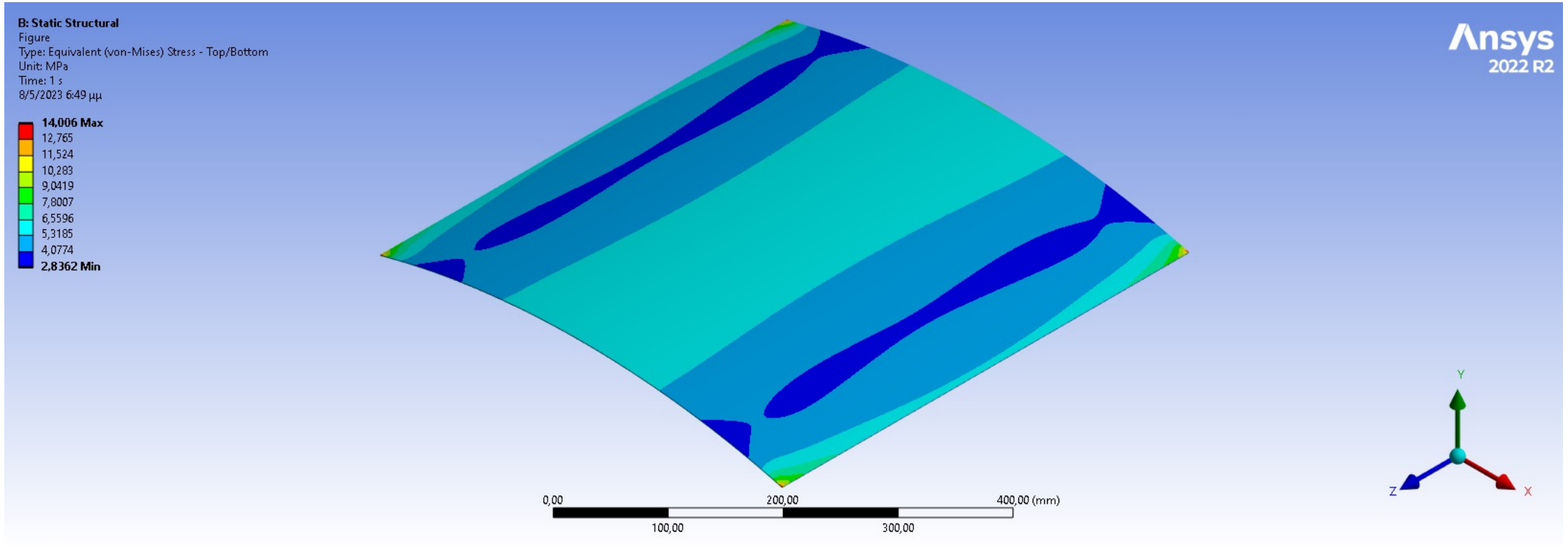

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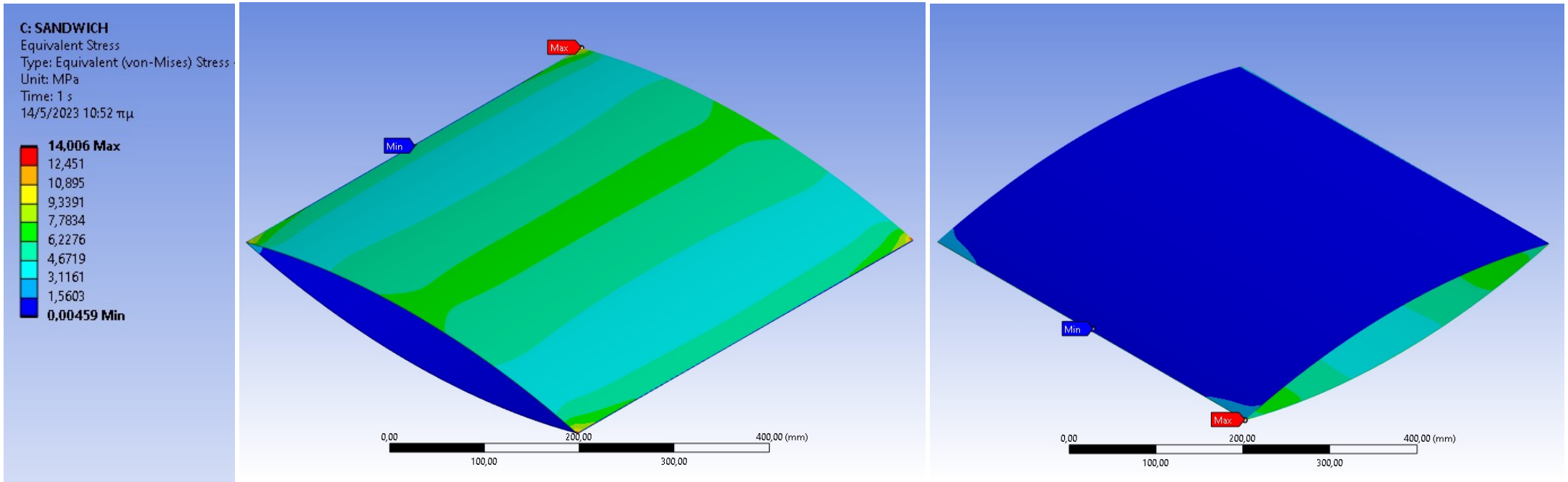

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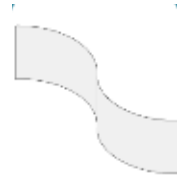

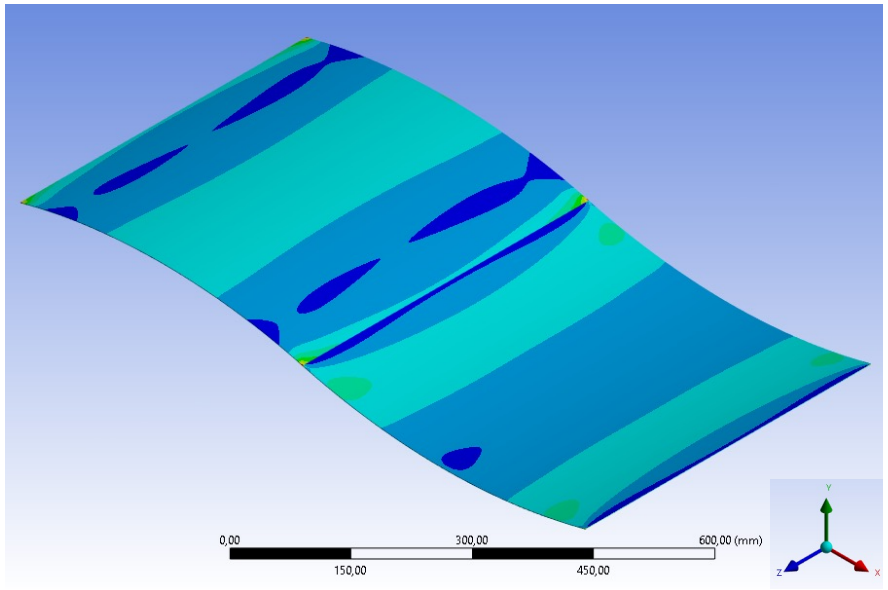

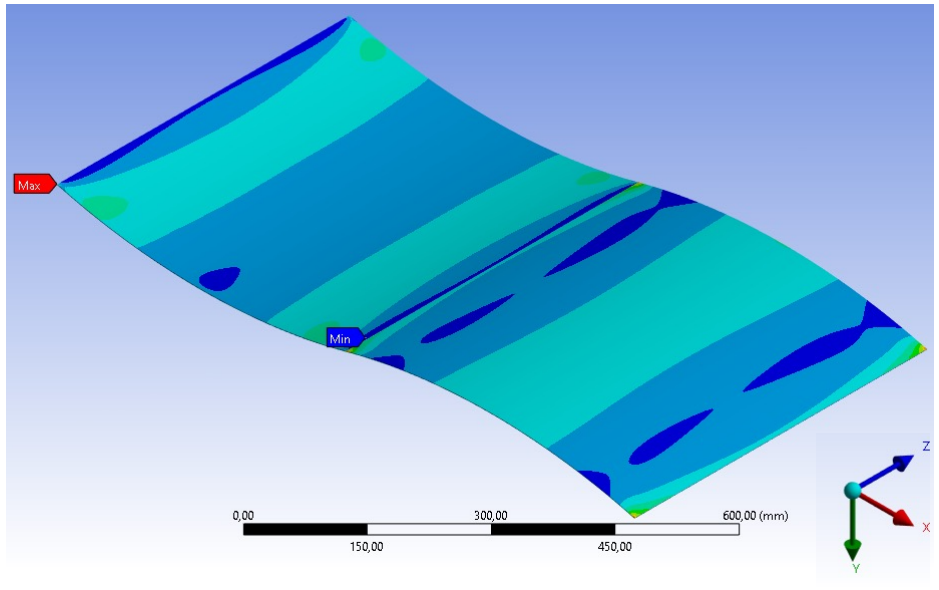

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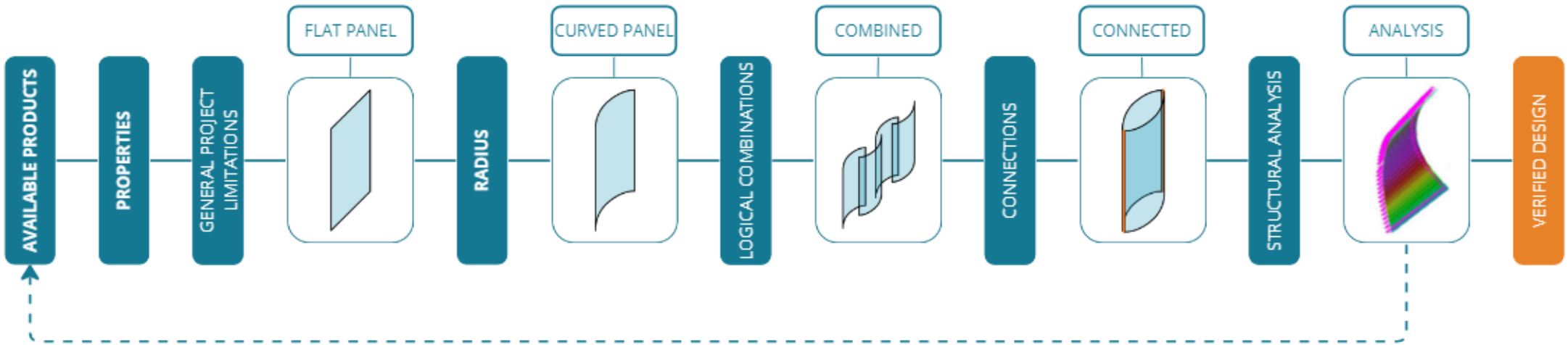

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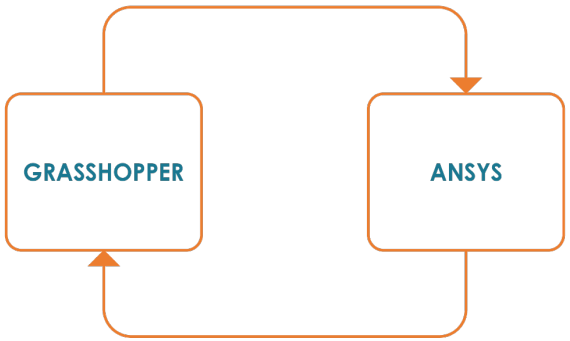

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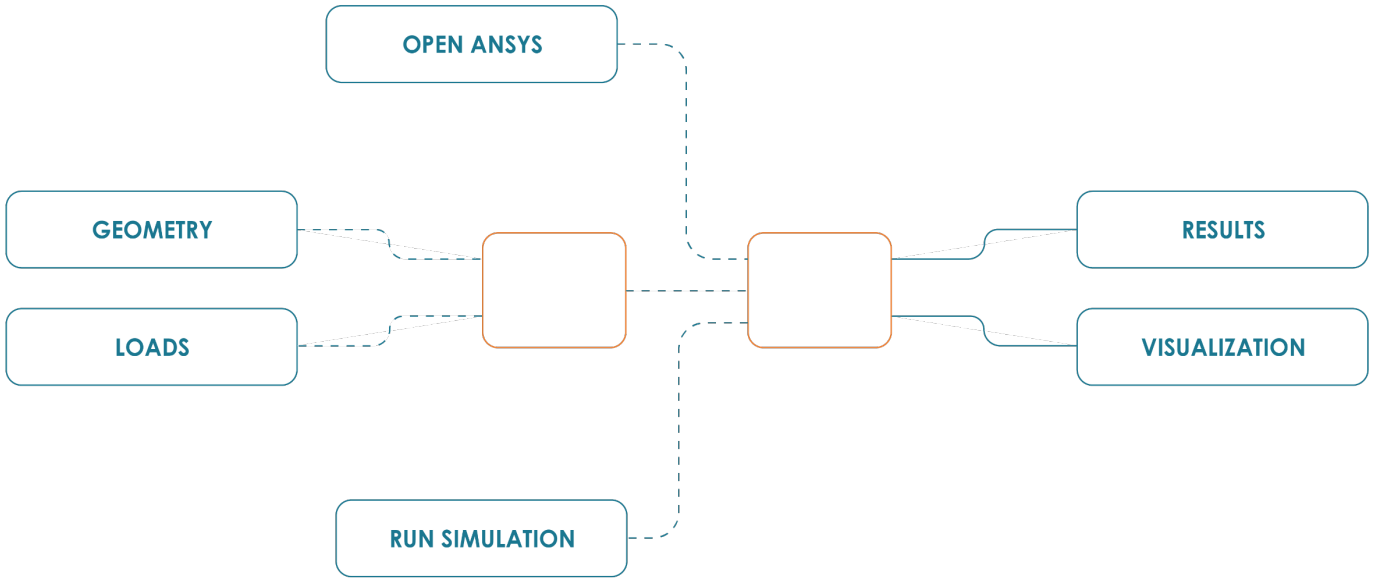
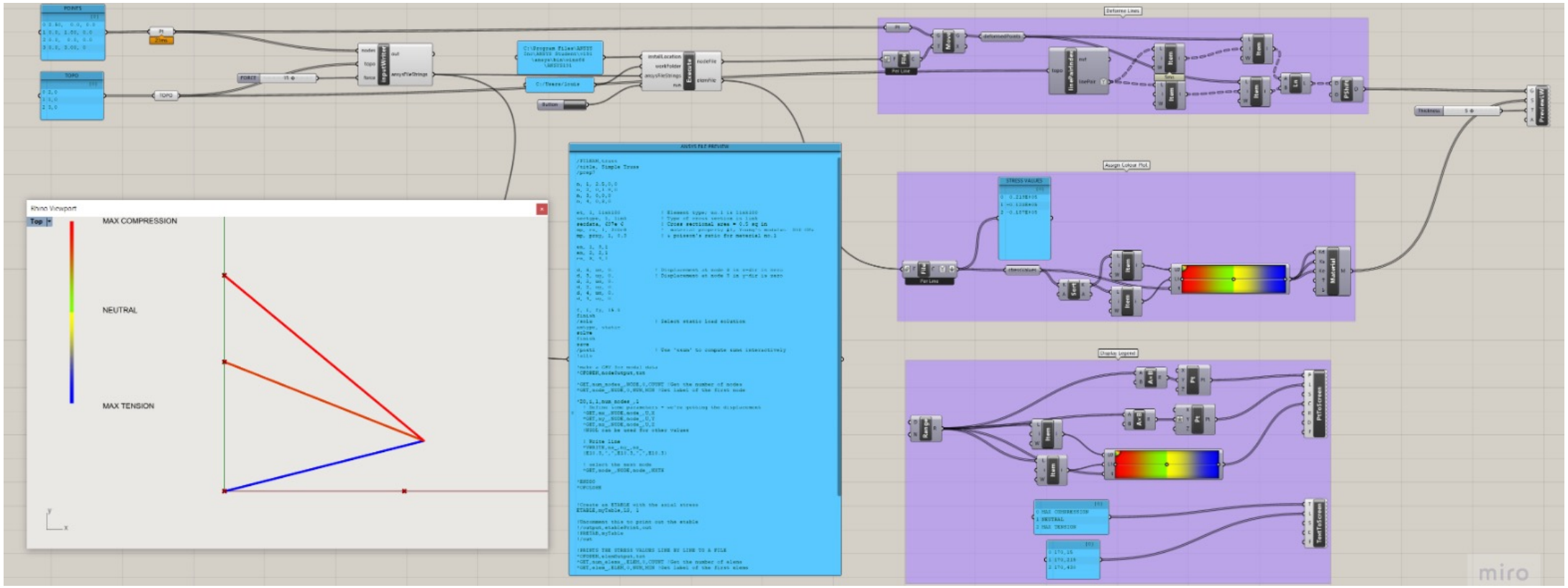


PROPOSED WORKFLOW

DESIGN TO ANALYSIS



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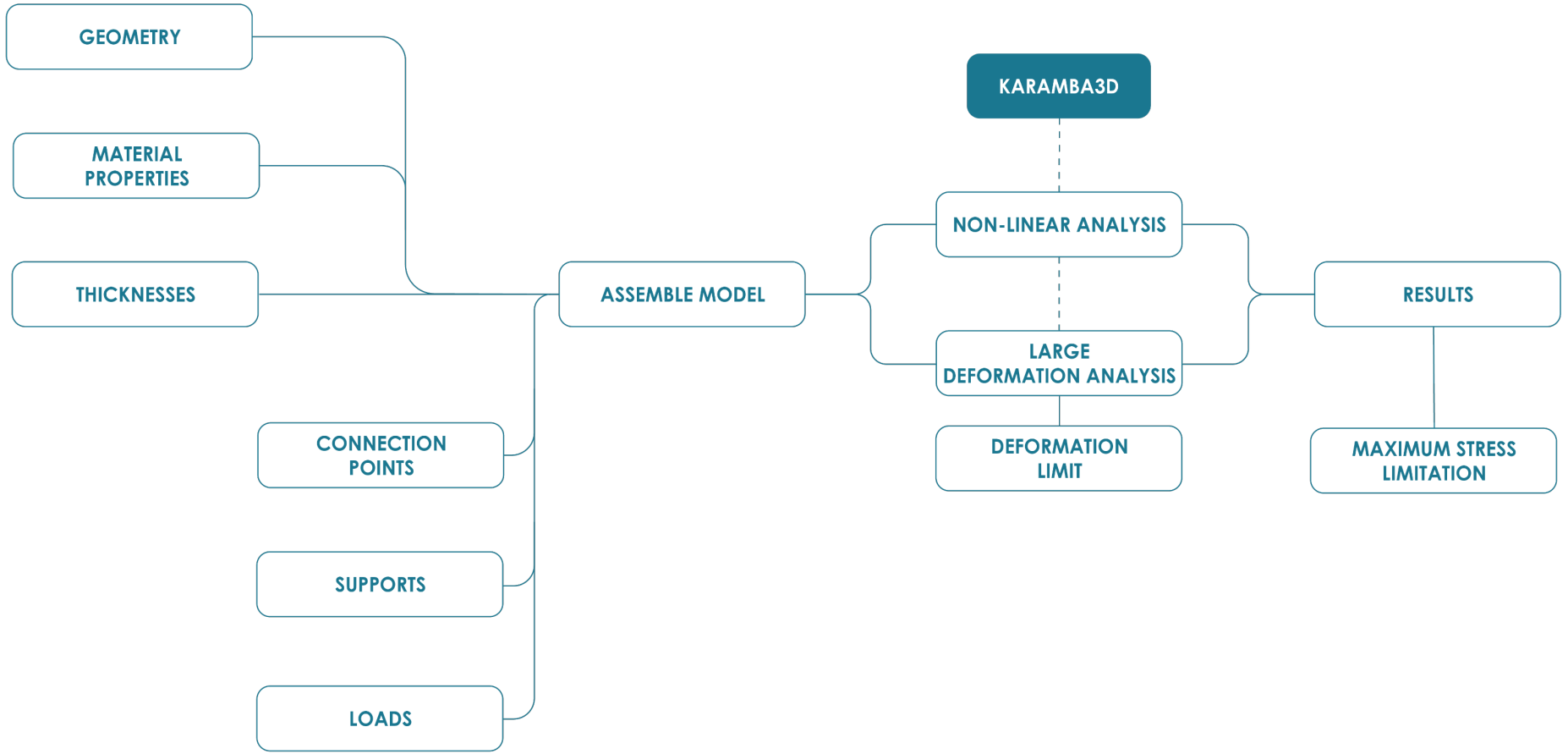
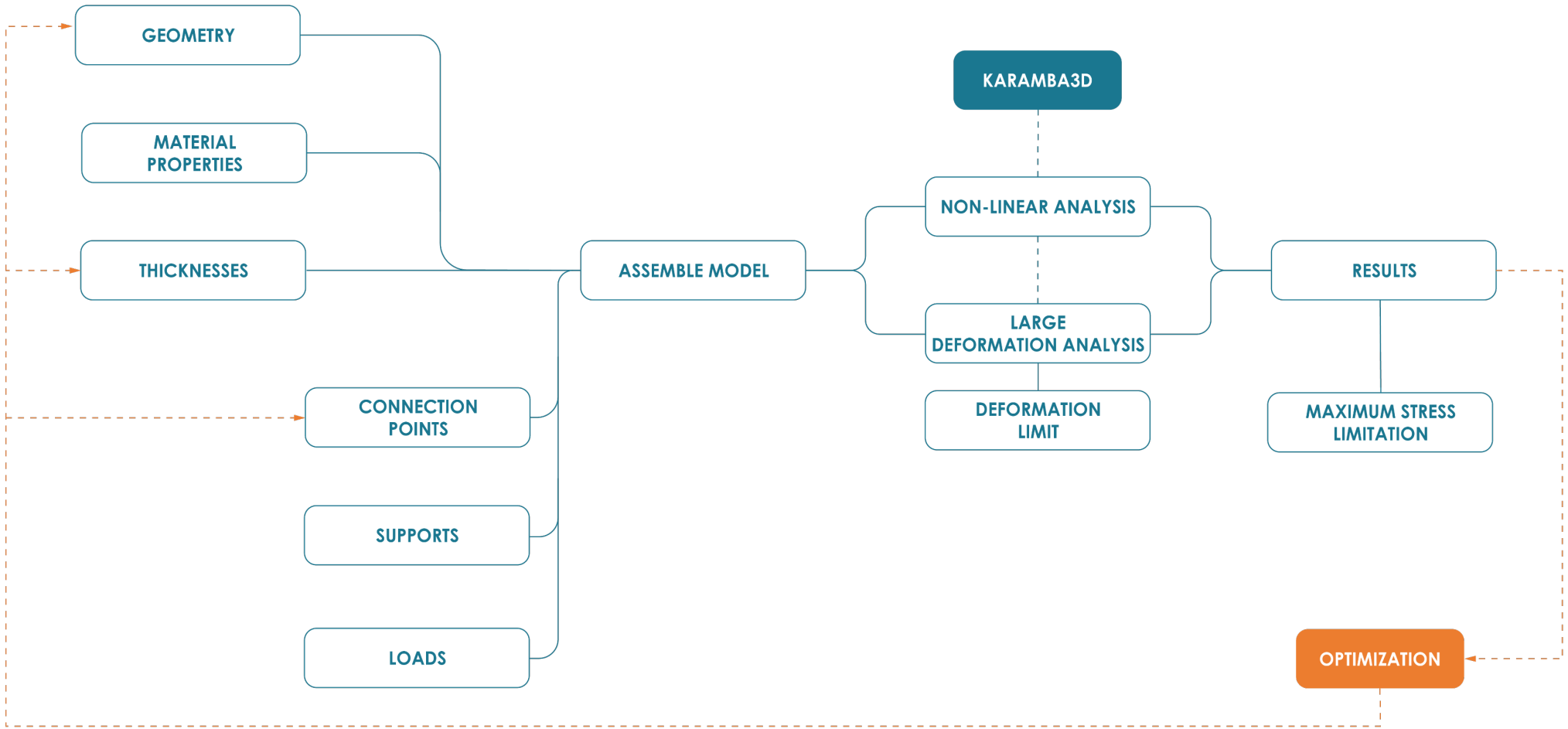
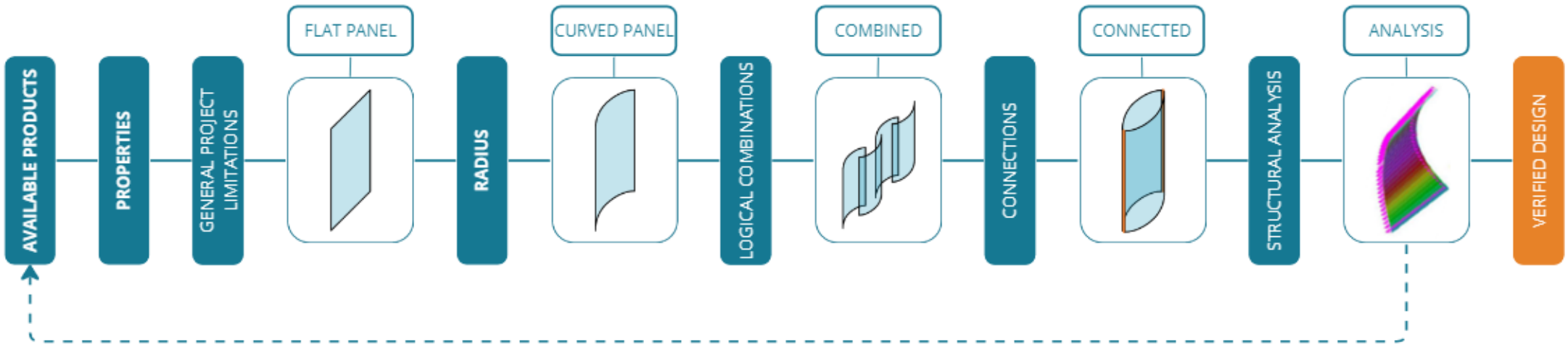


PROPOSED WORKFLOW

DESIGN TO ANALYSIS



PROPOSED WORKFLOW



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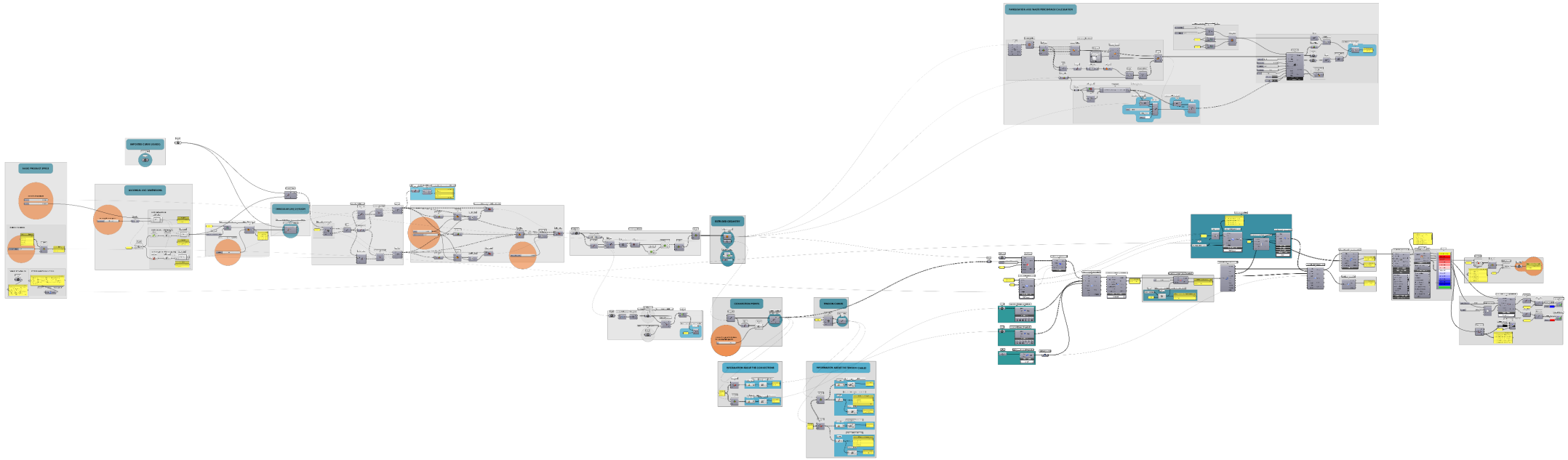

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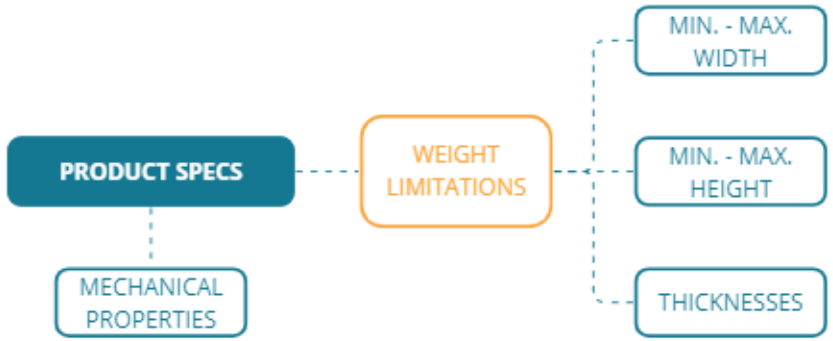

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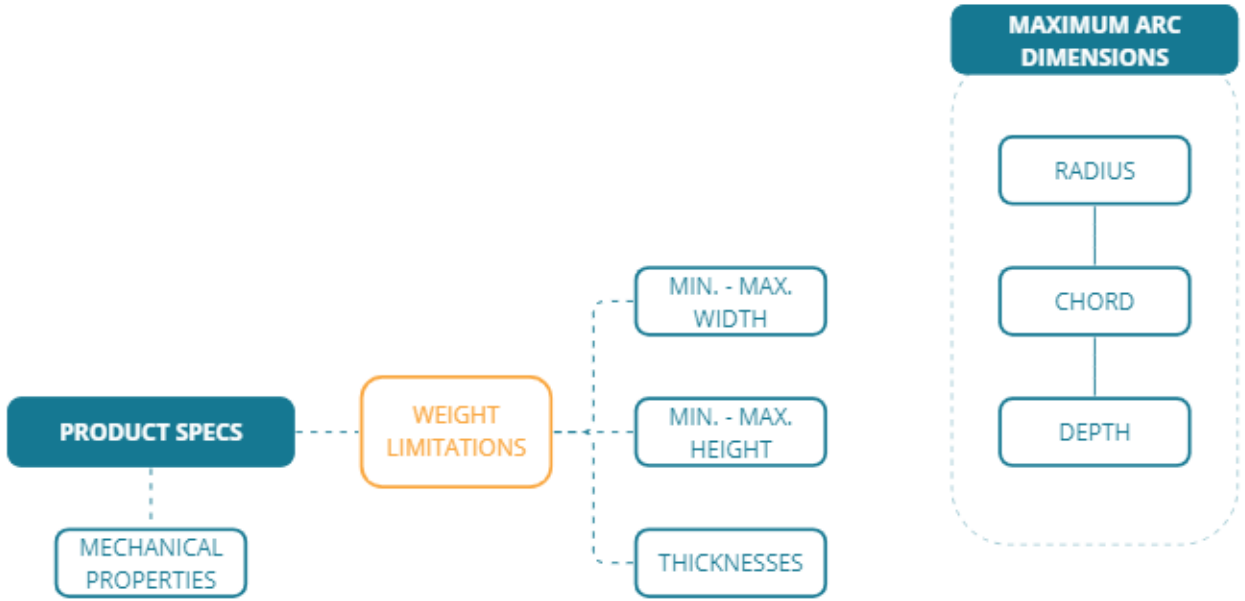

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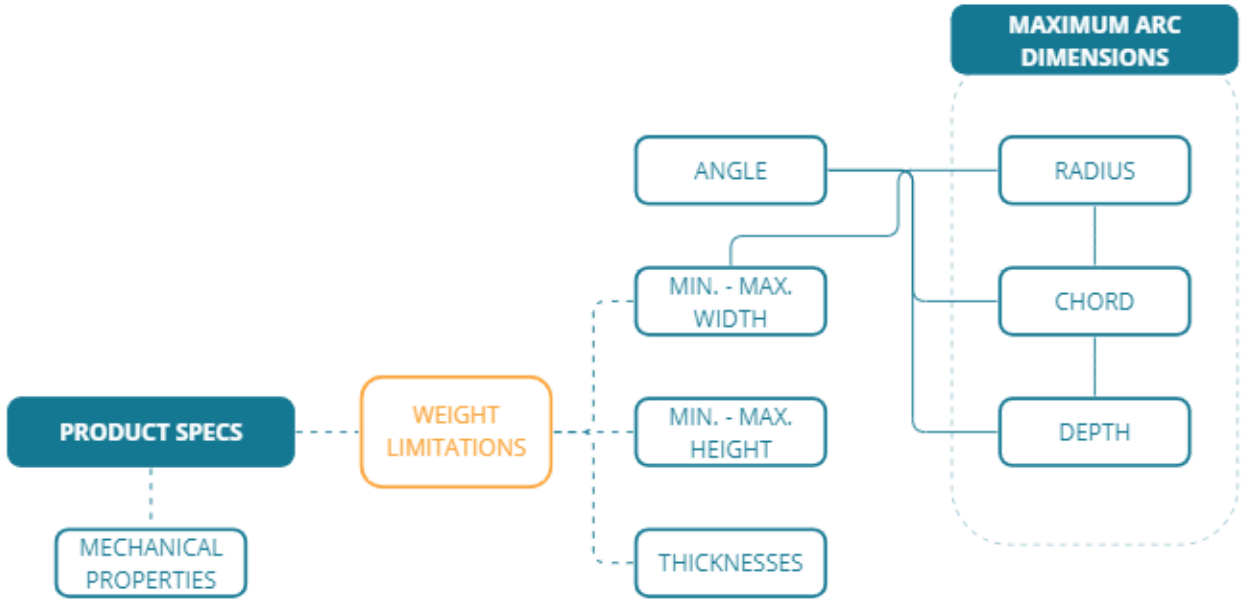

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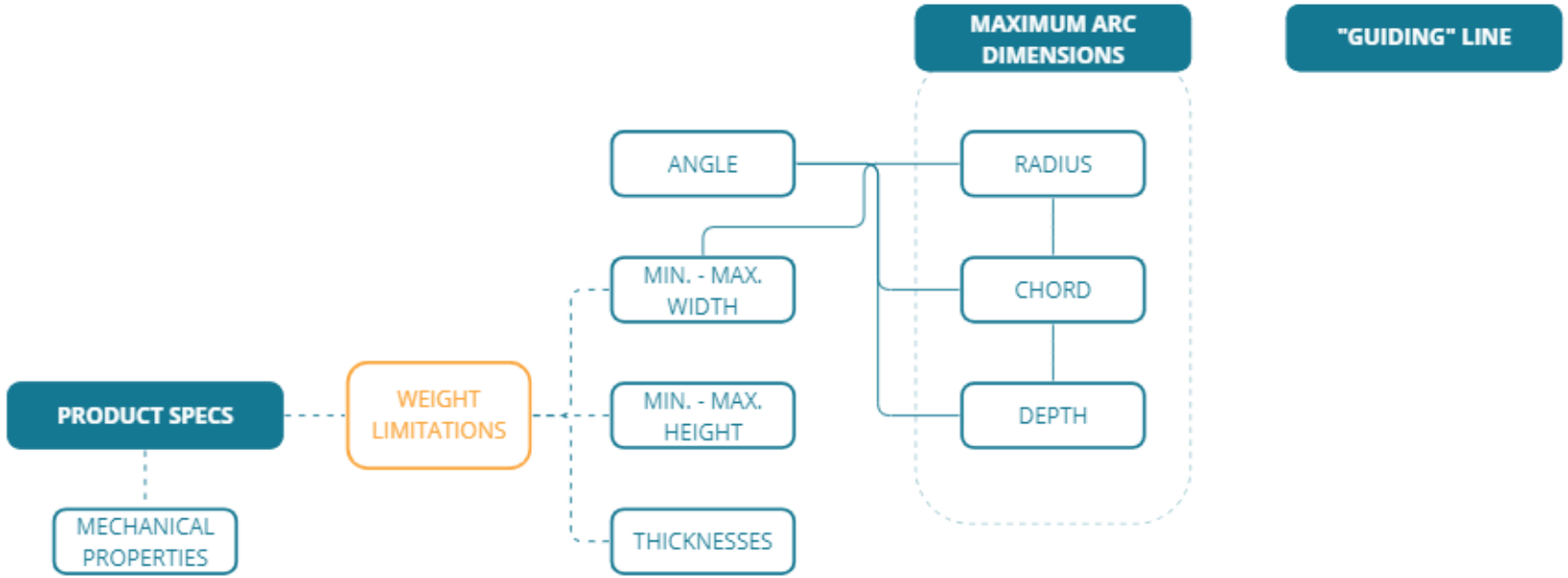

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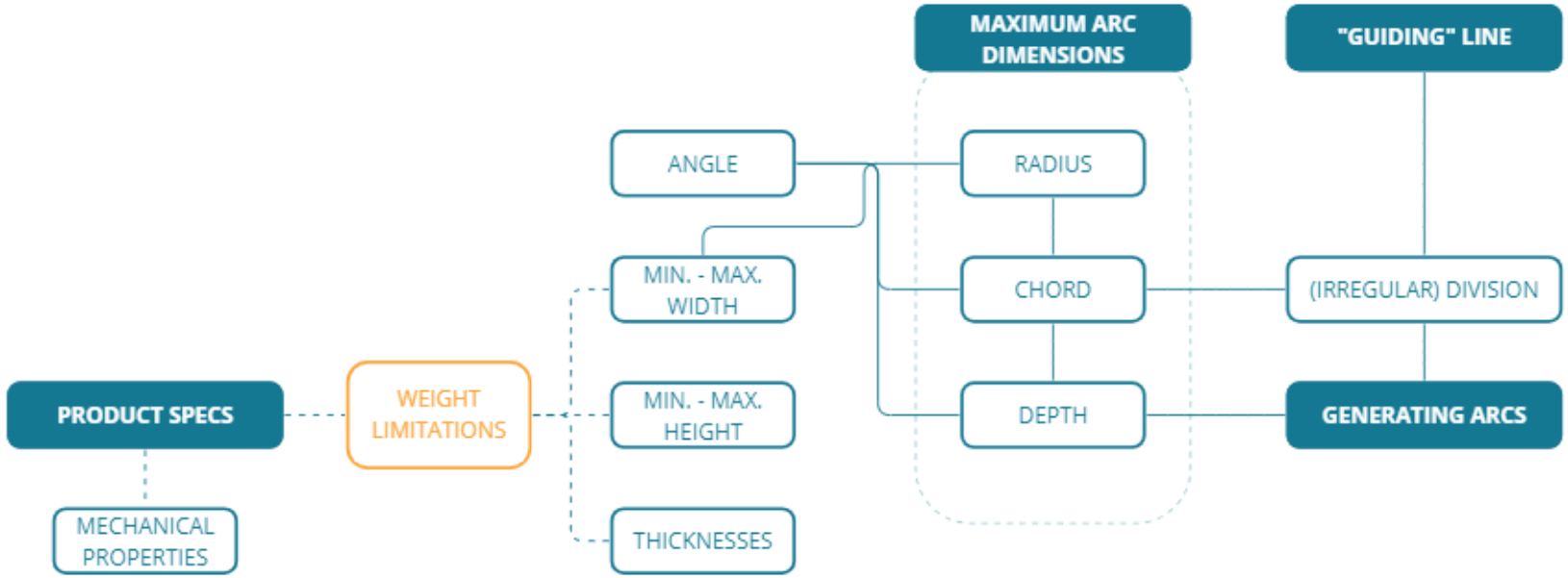

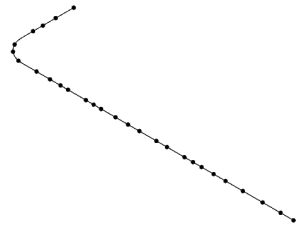

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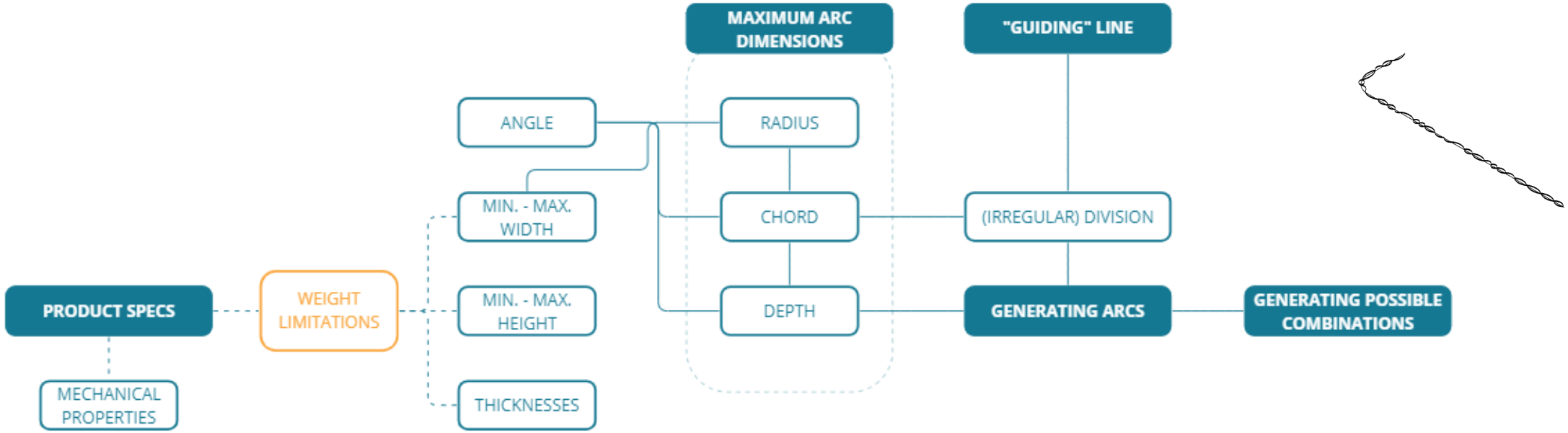

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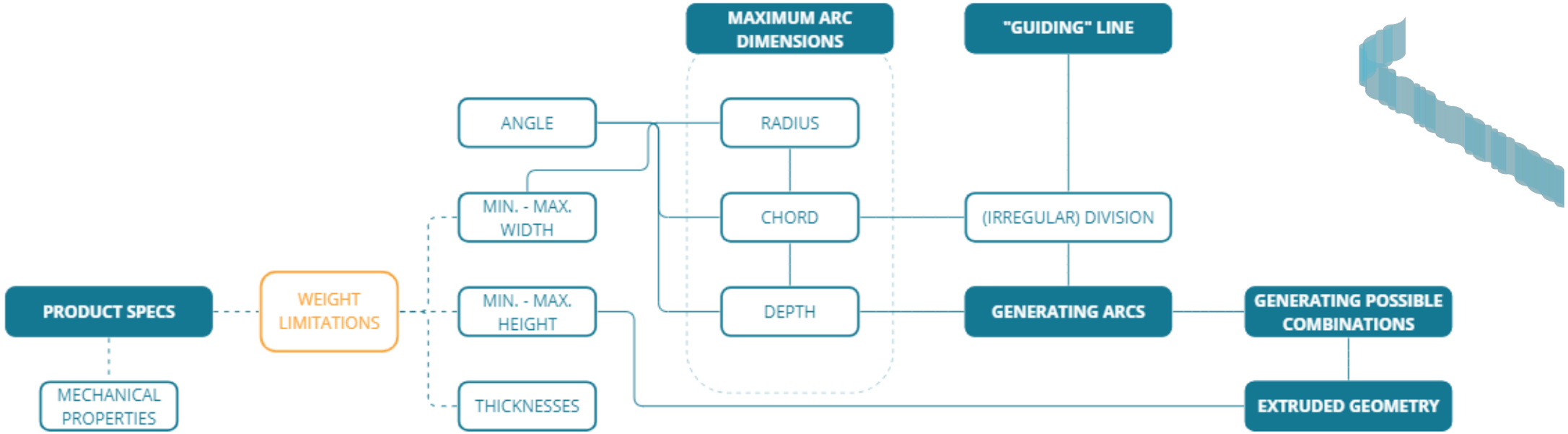

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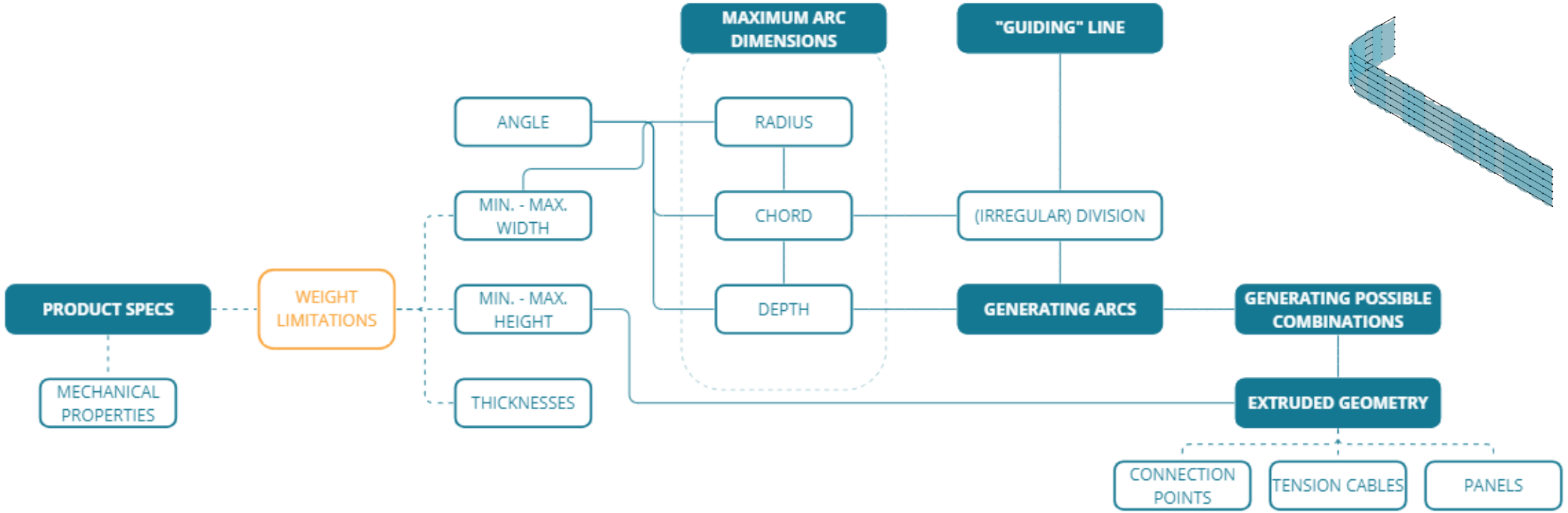

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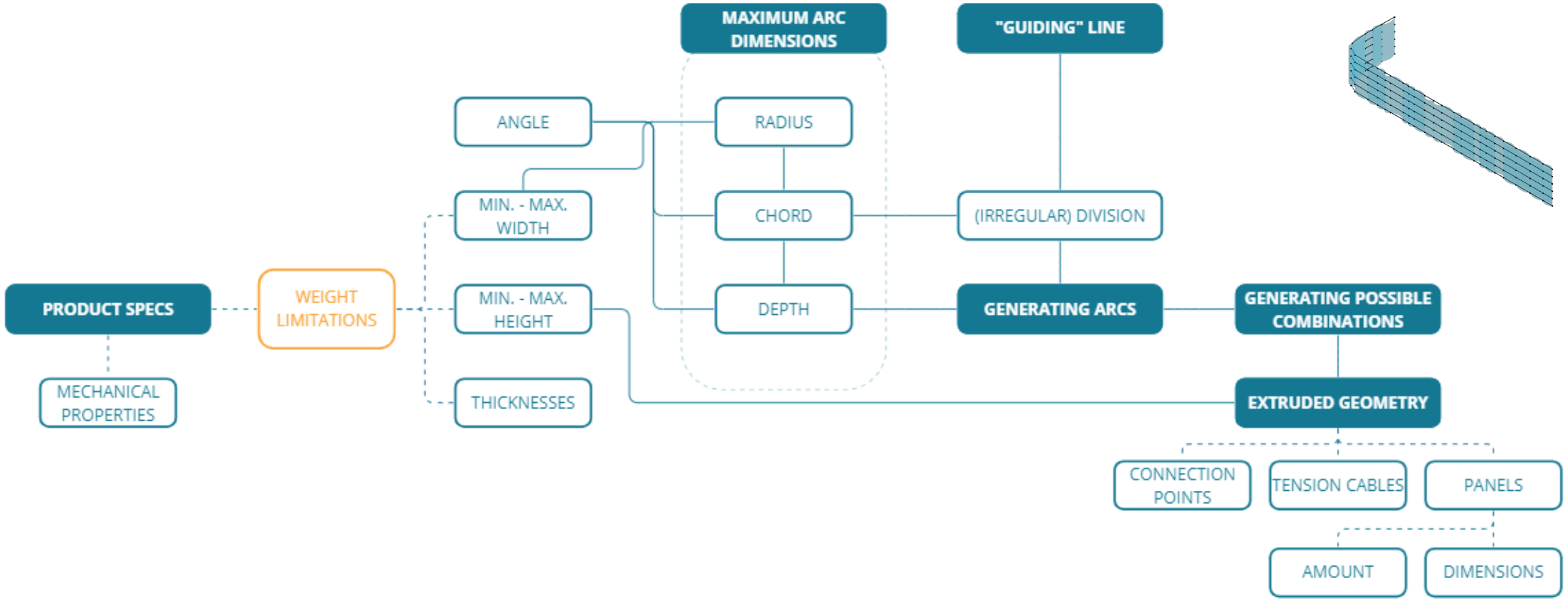

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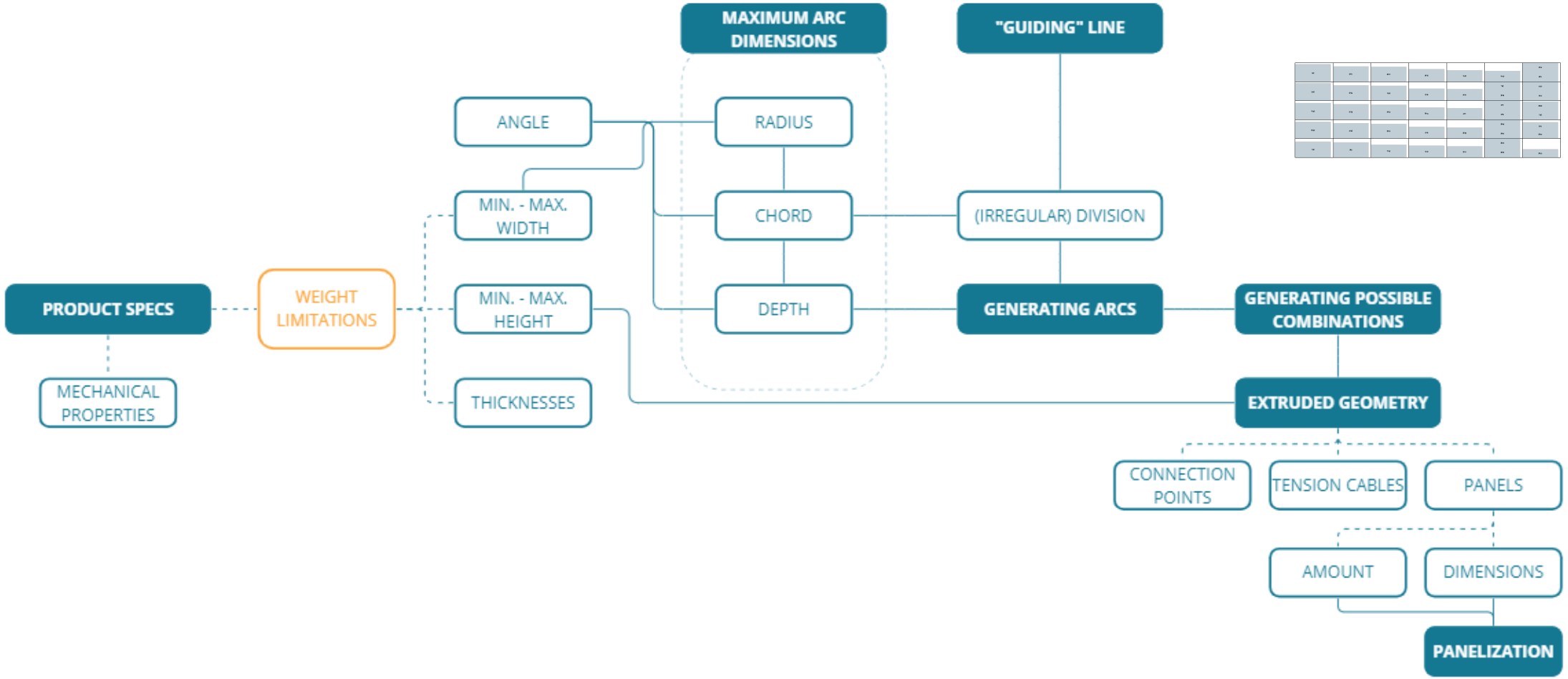

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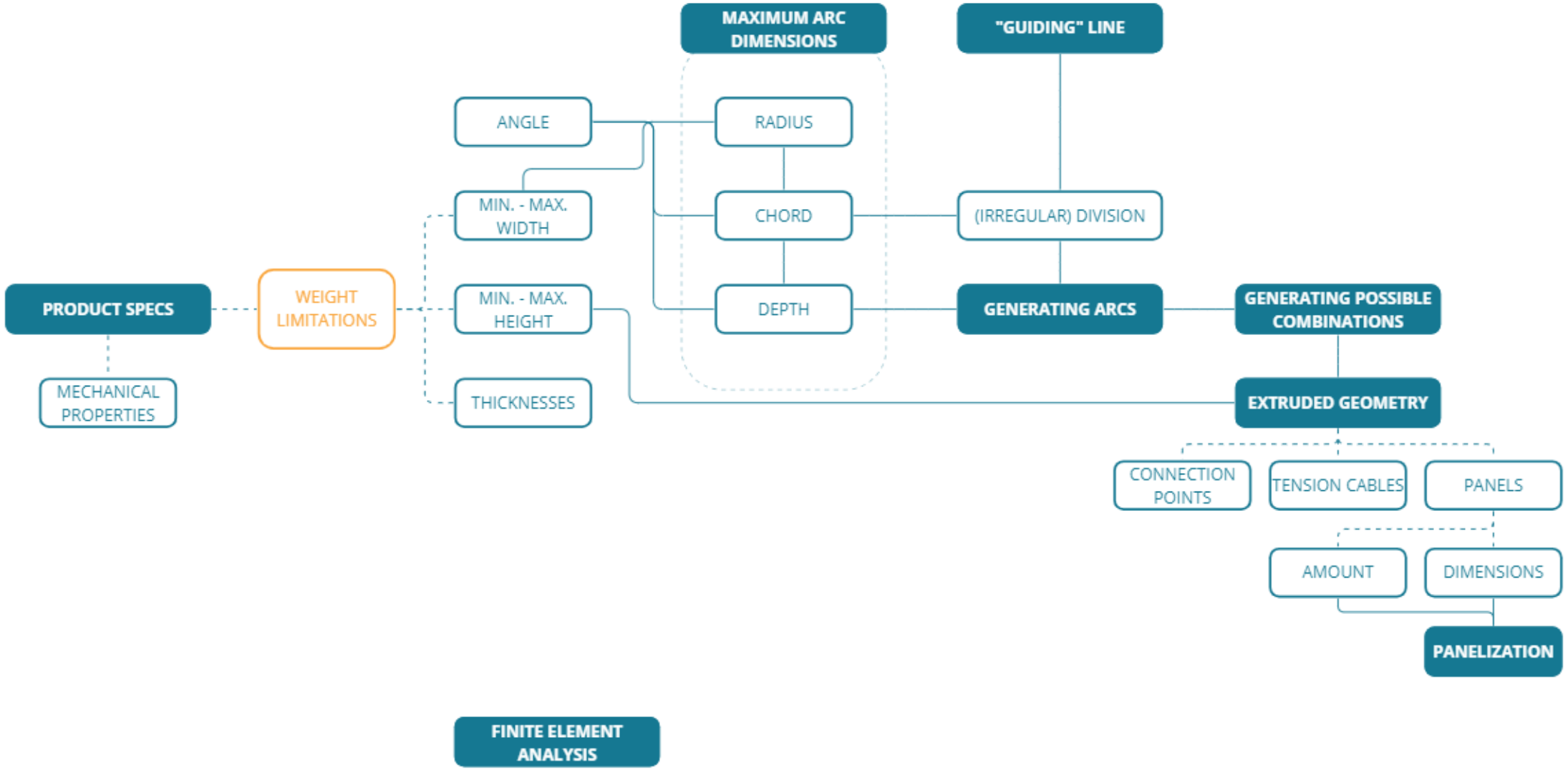

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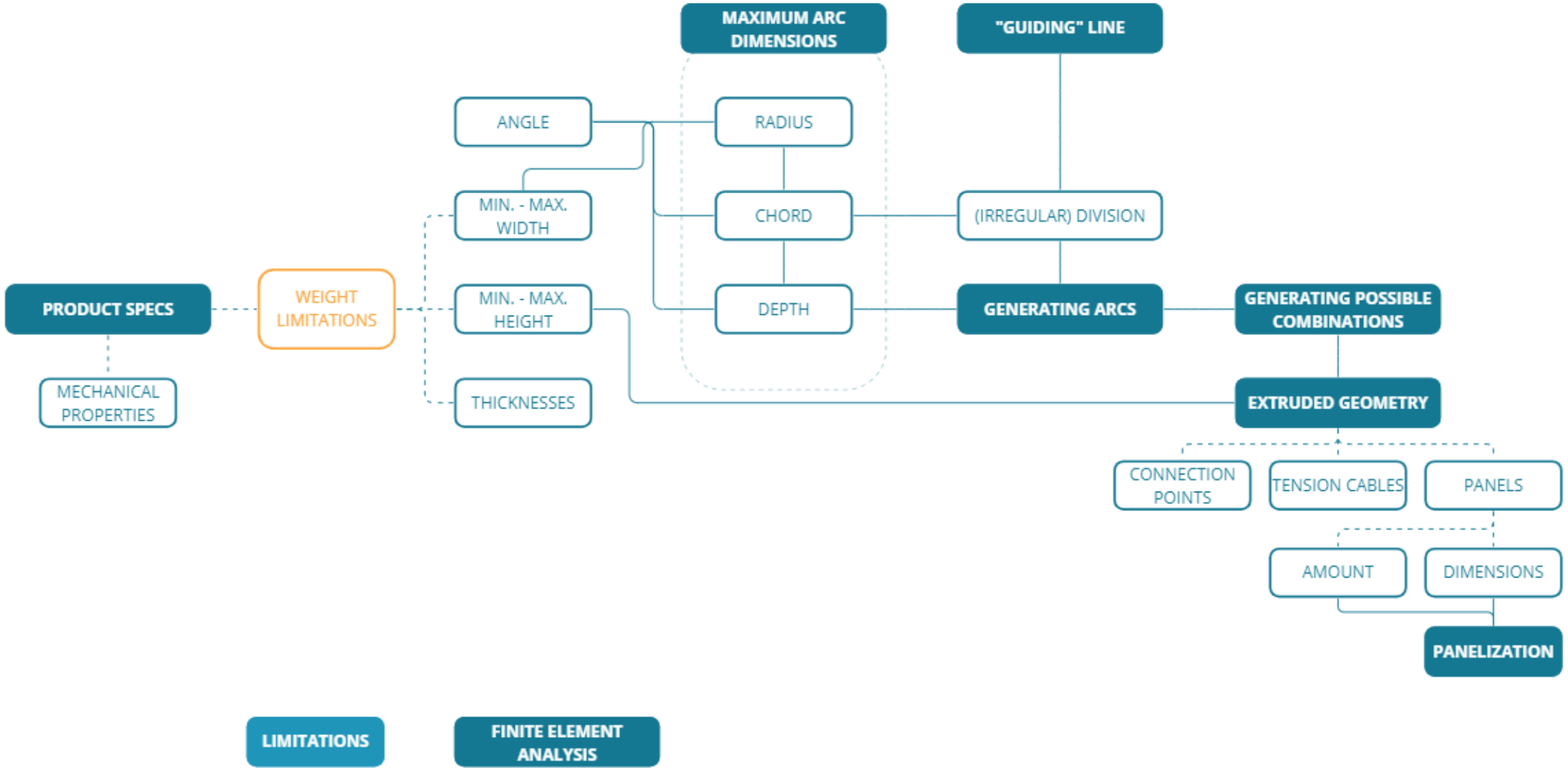

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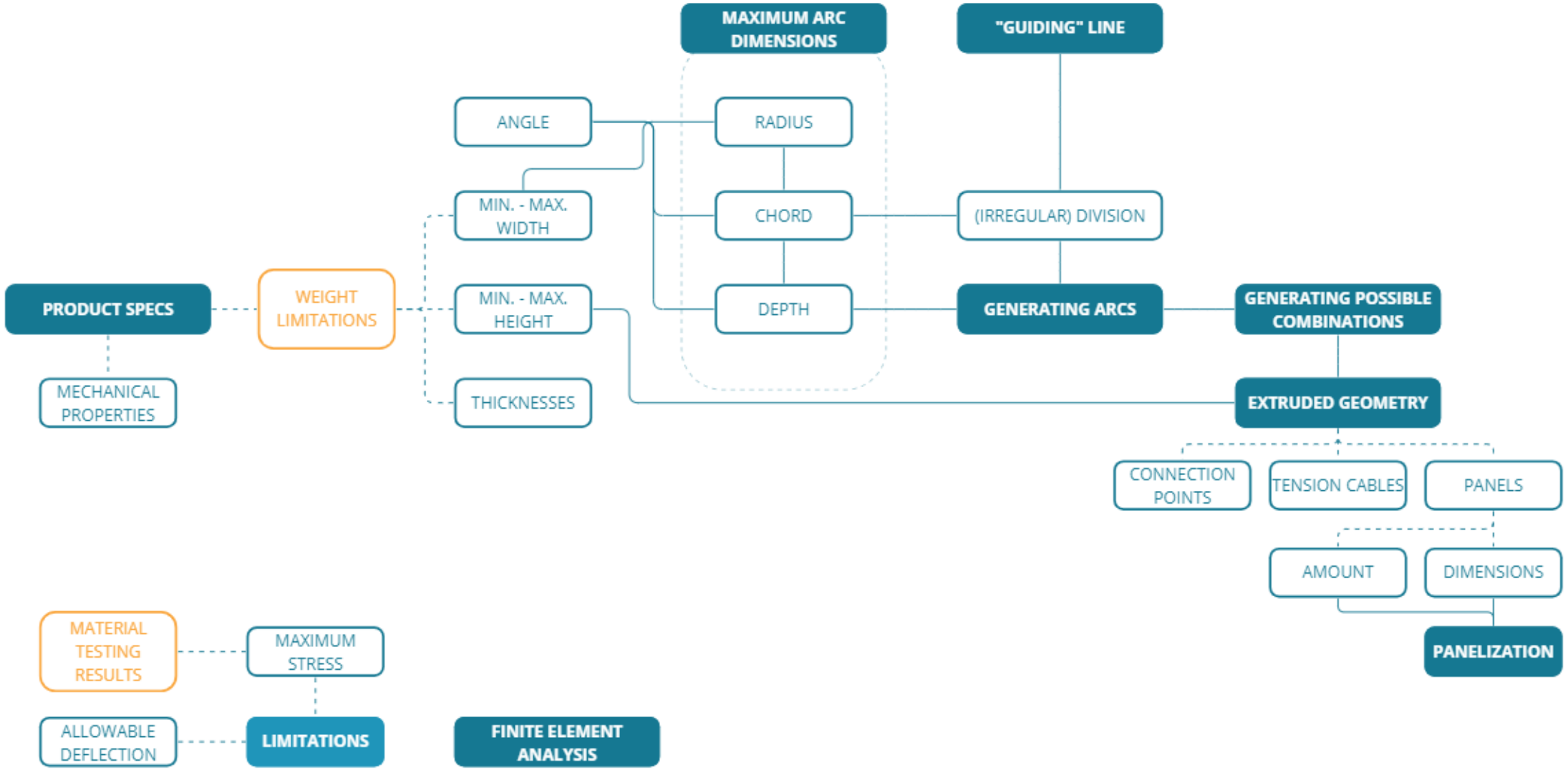

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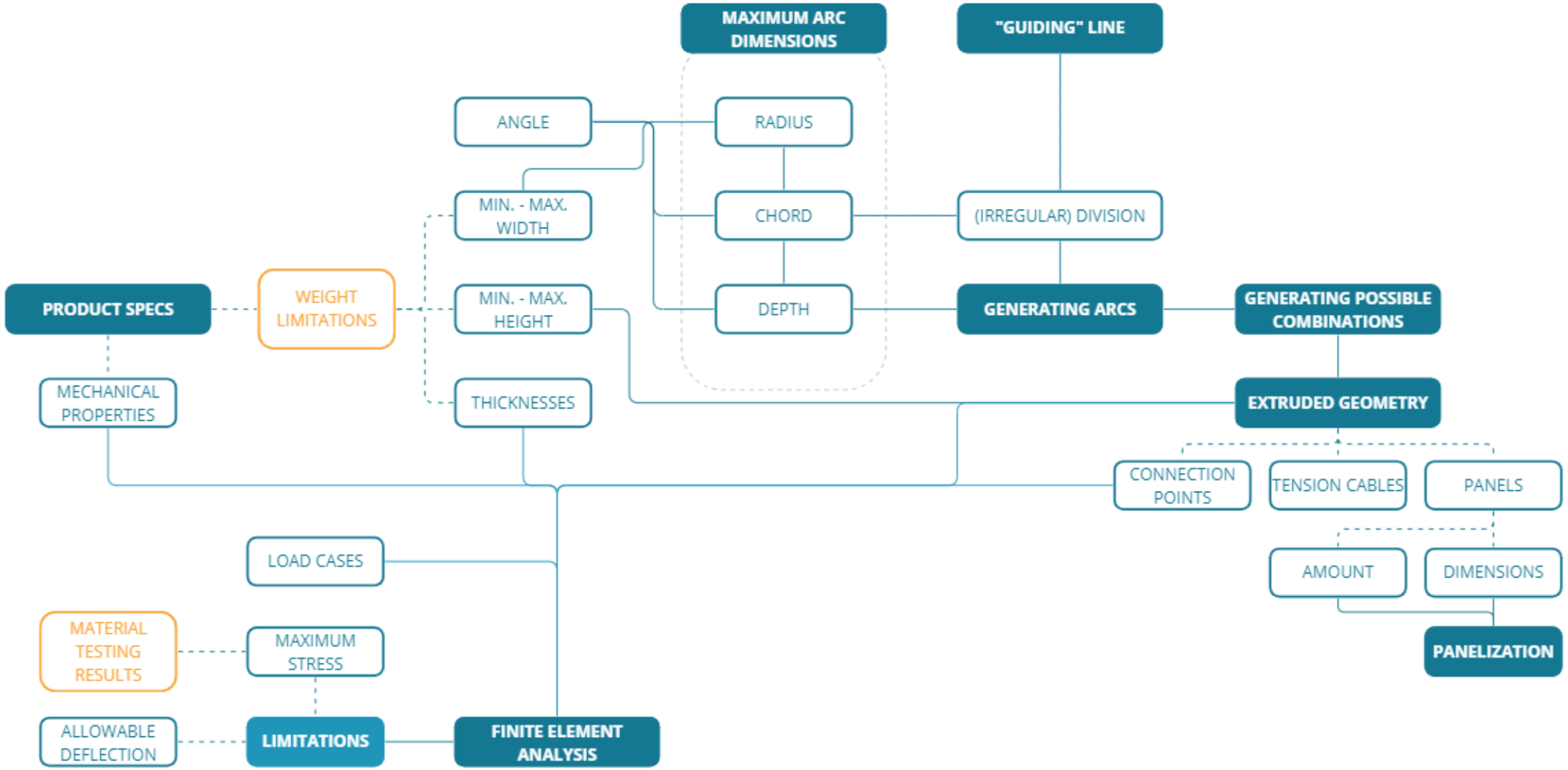

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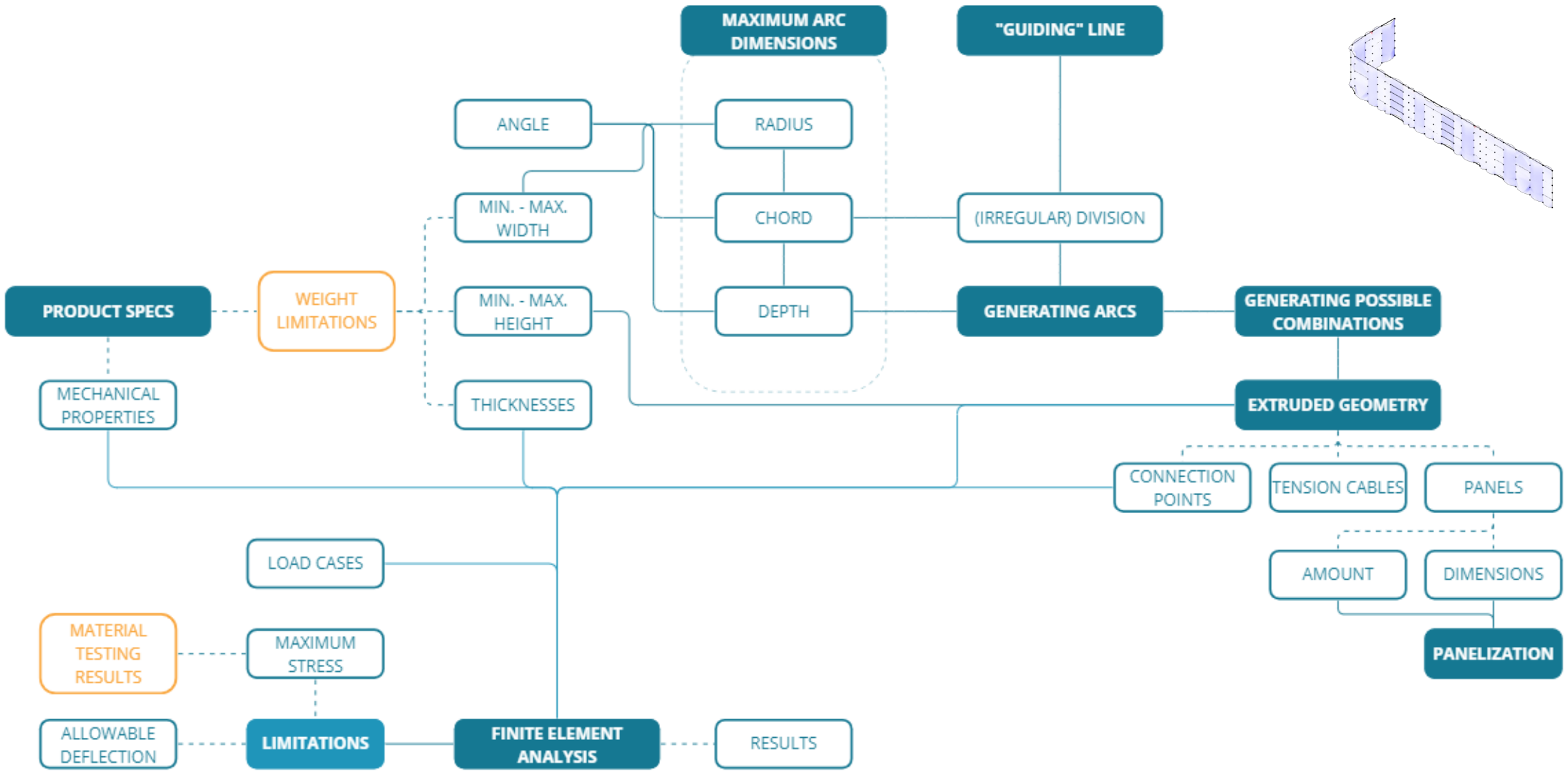

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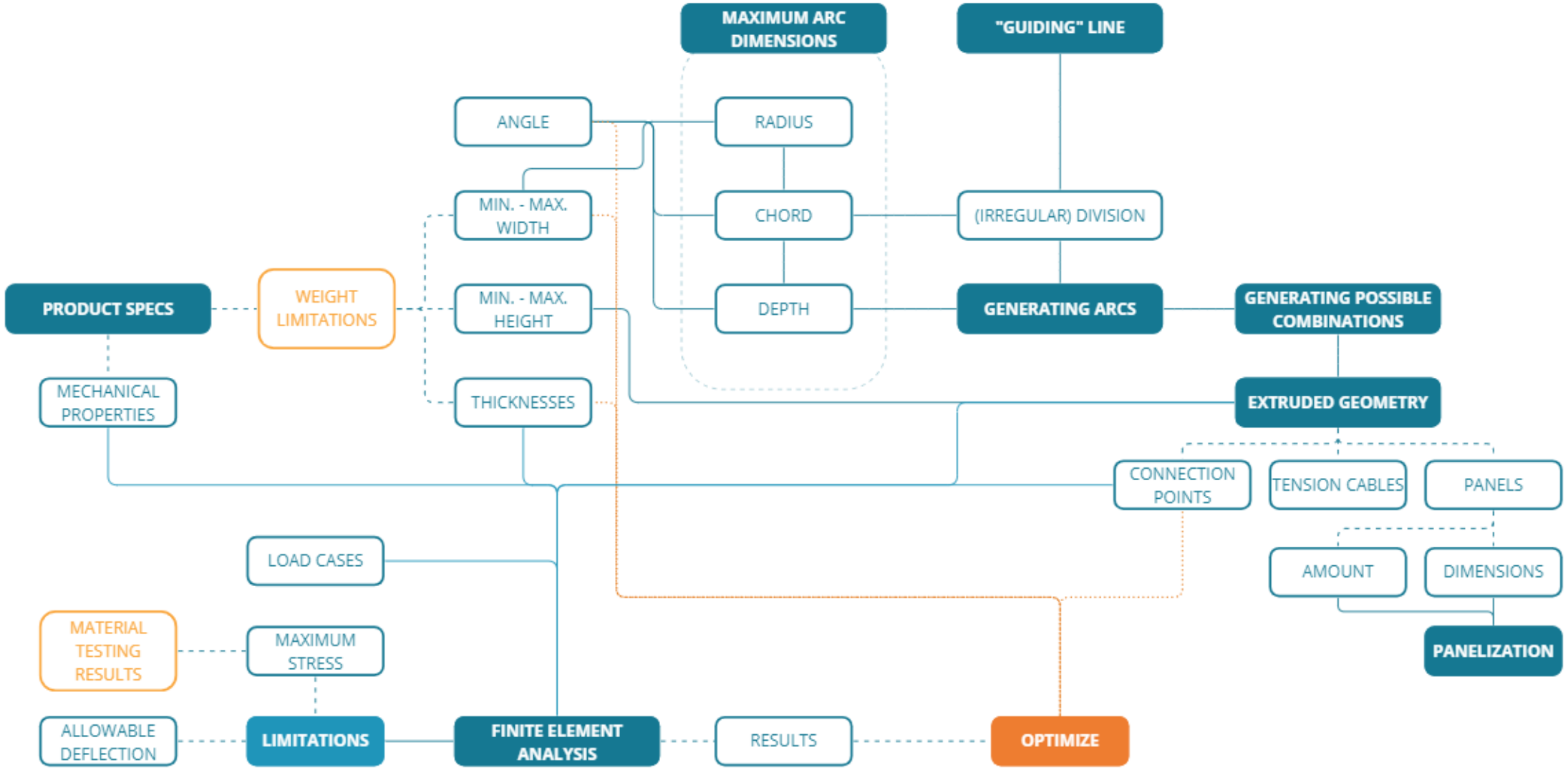

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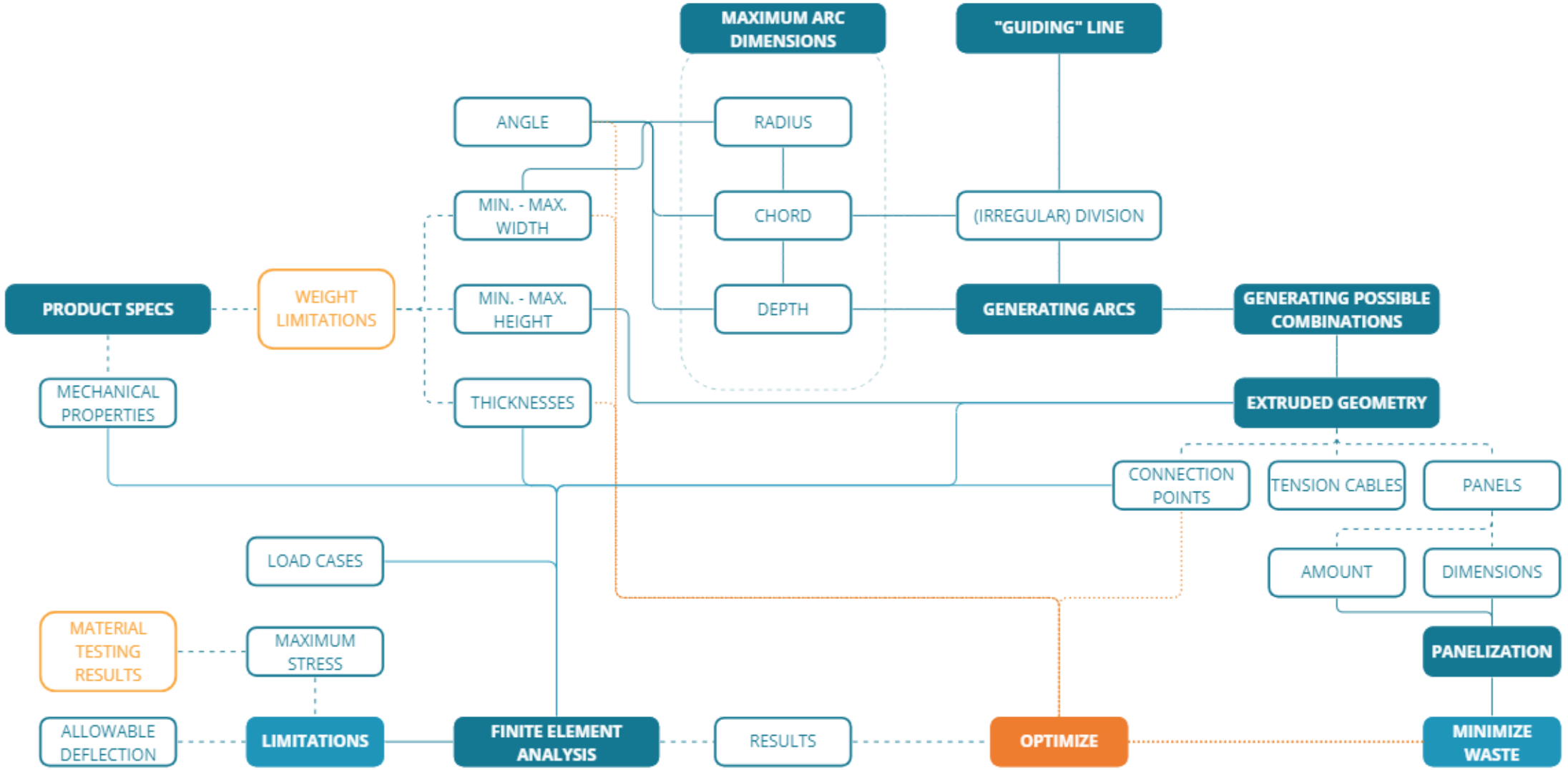

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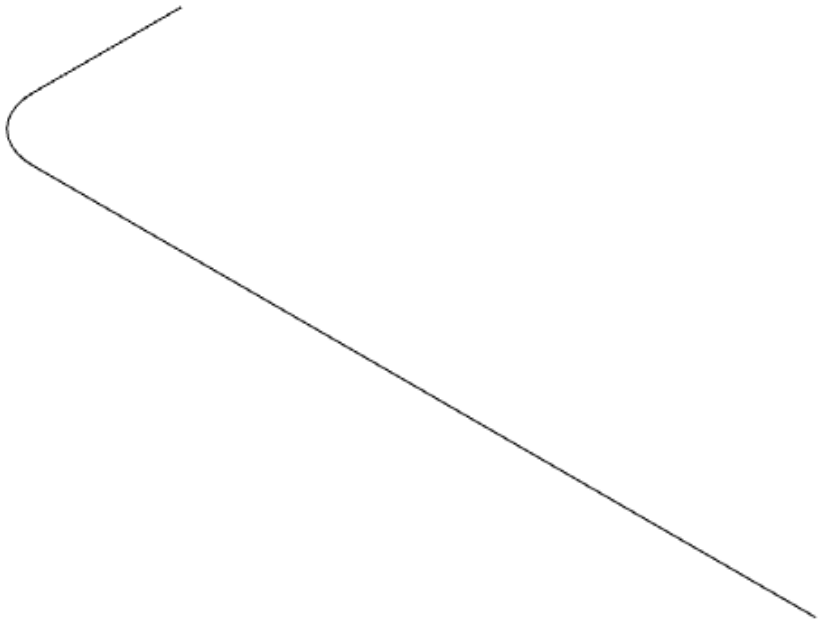

CASE STUDY

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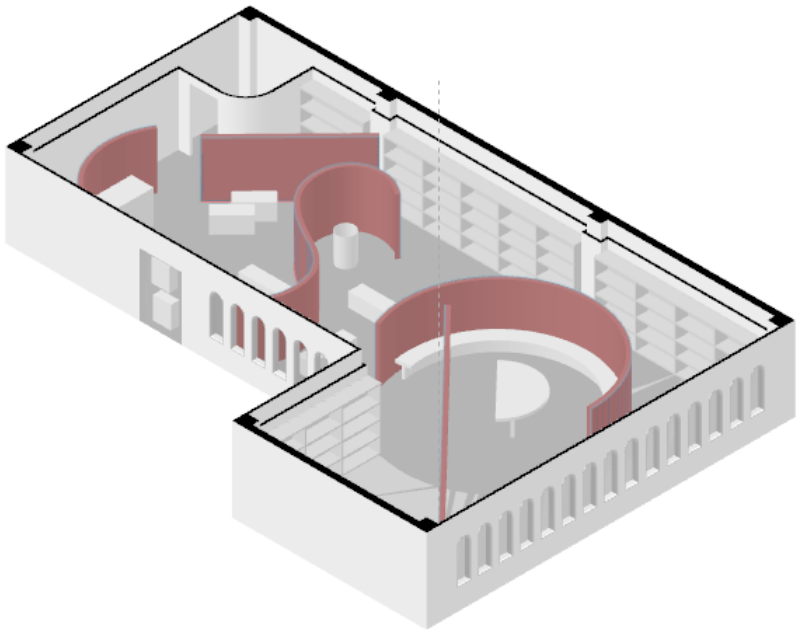
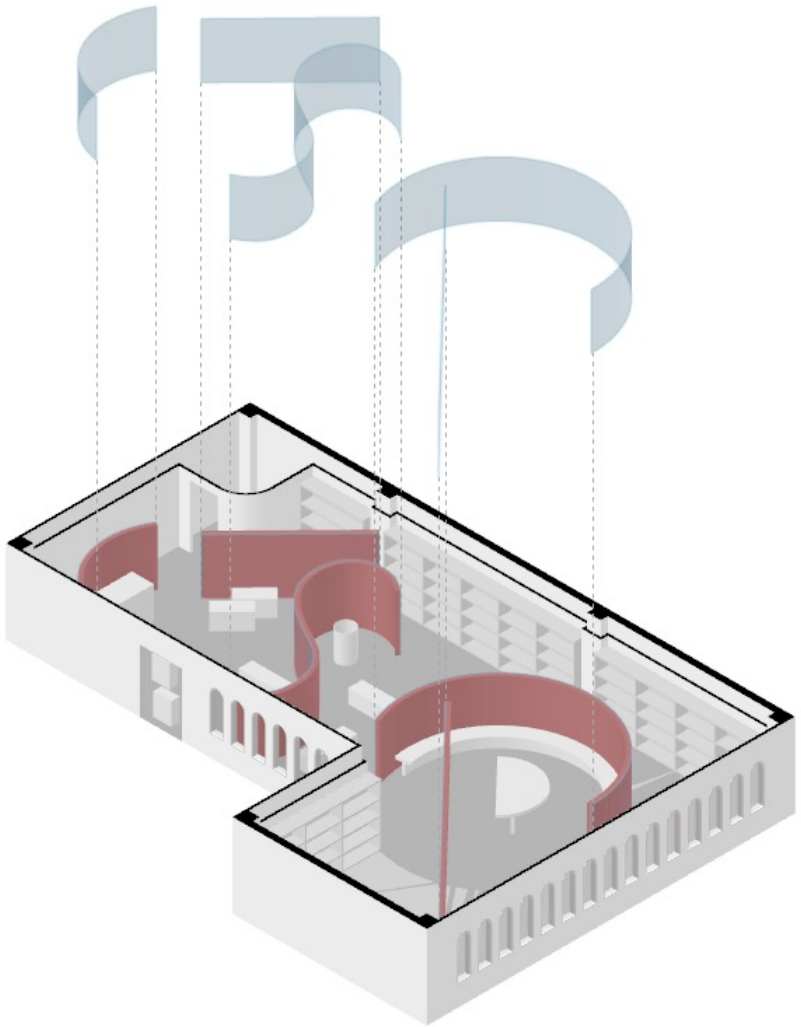
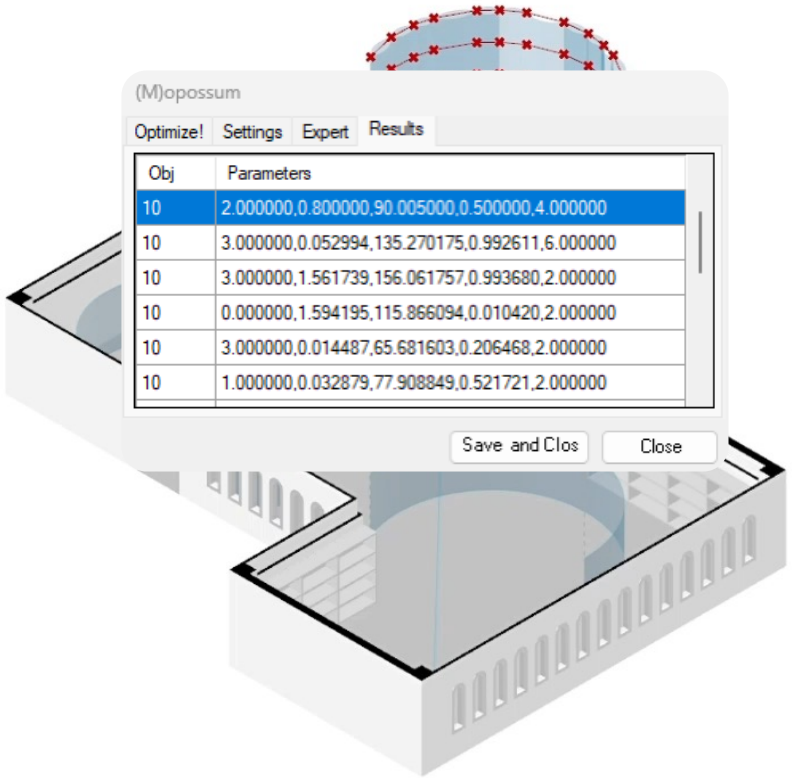


https://www.archdaily.com/931013/the-terramater-store-renesa-architecture-design-interiors-studio

CASE STUDY

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Expert
Results
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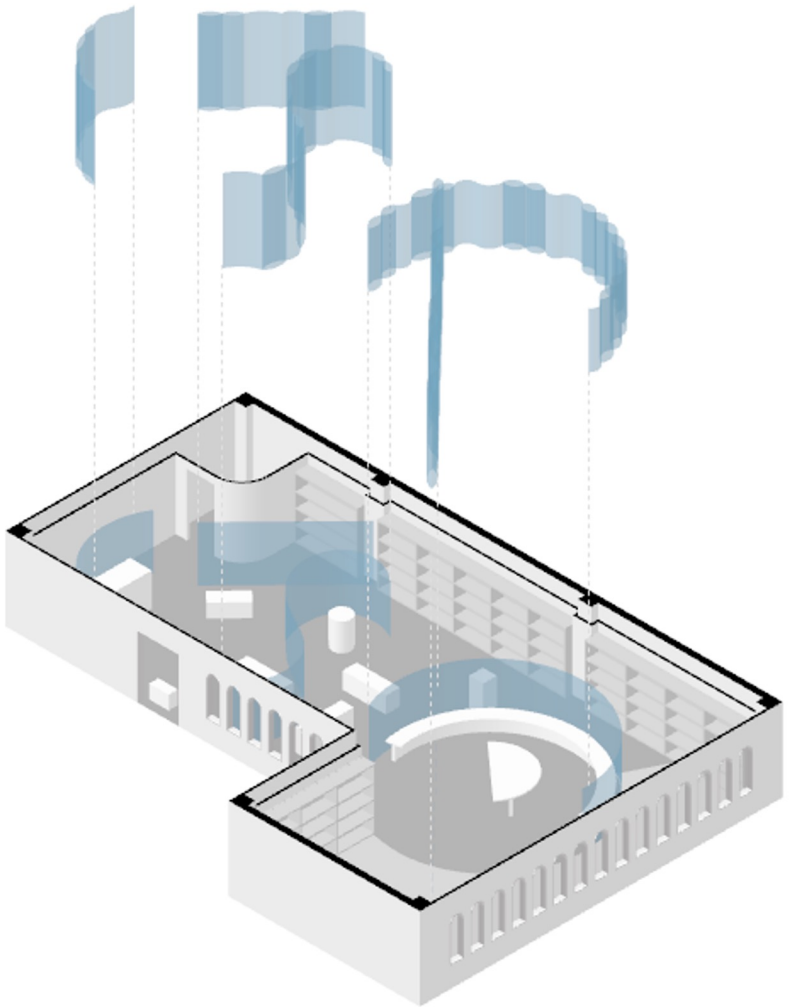
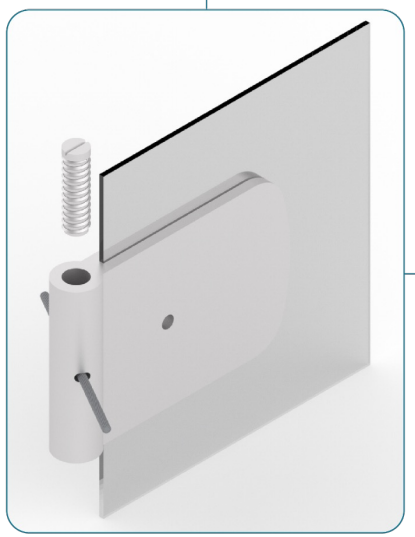
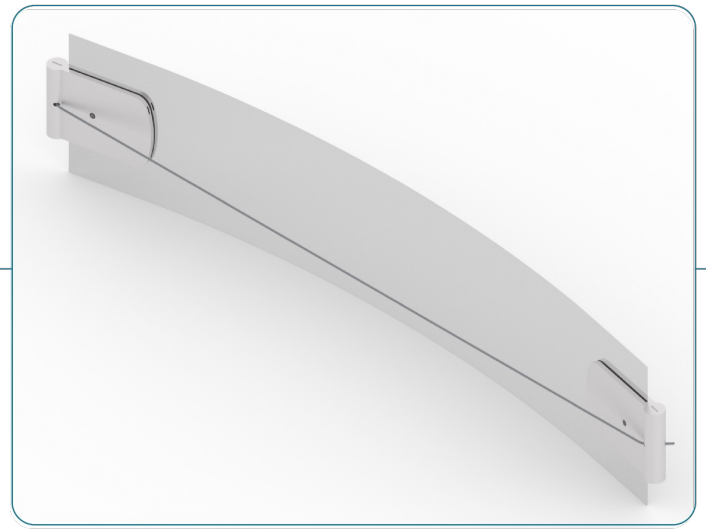
CASE STUDY

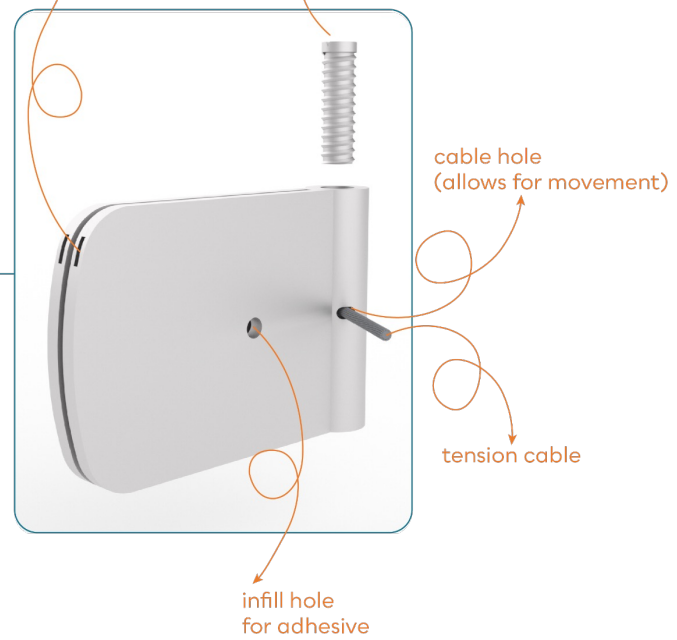
OPTIMIZATION



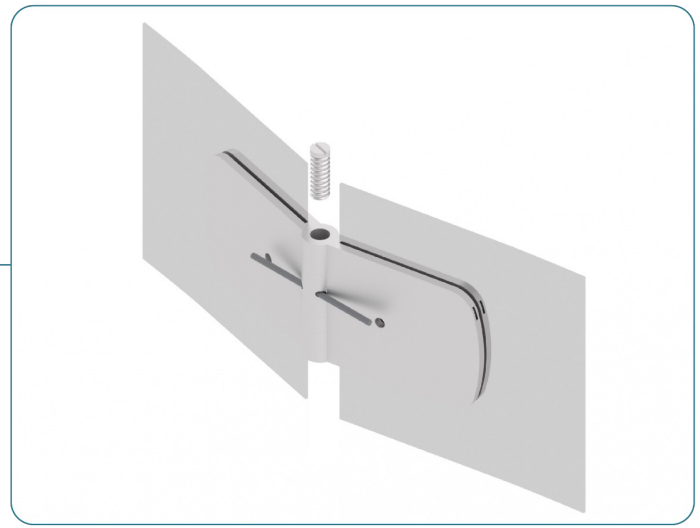
CONNECTION PRINCIPLES

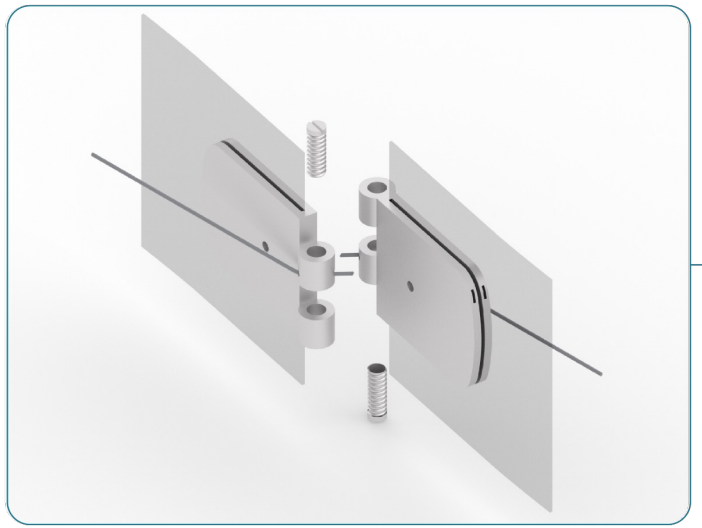






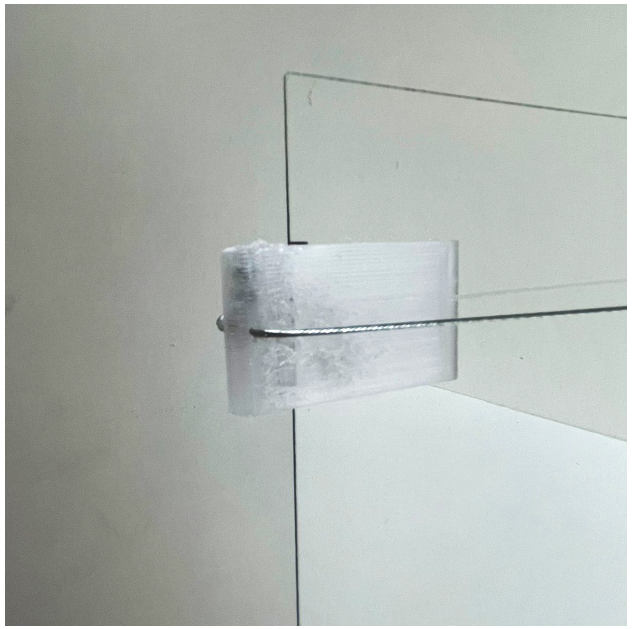
EQUAL TENSION NEEDED





DIFFERENT TENSION PER PANEL

PROTOTYPE

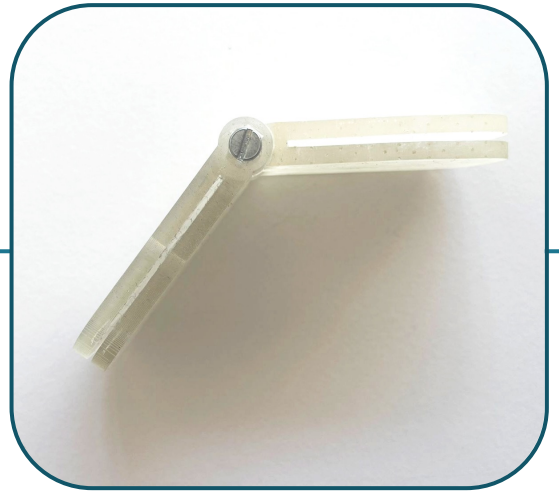


PROTOTYPE

3D PRINTED CONNECTIONS

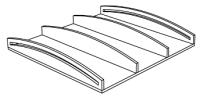
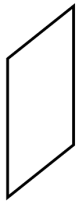
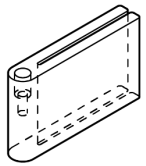
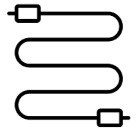
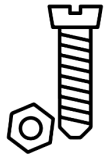
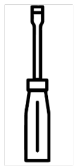
TRANSPARENT PETG

TRANSPARENT RESIN



PROTOTYPE

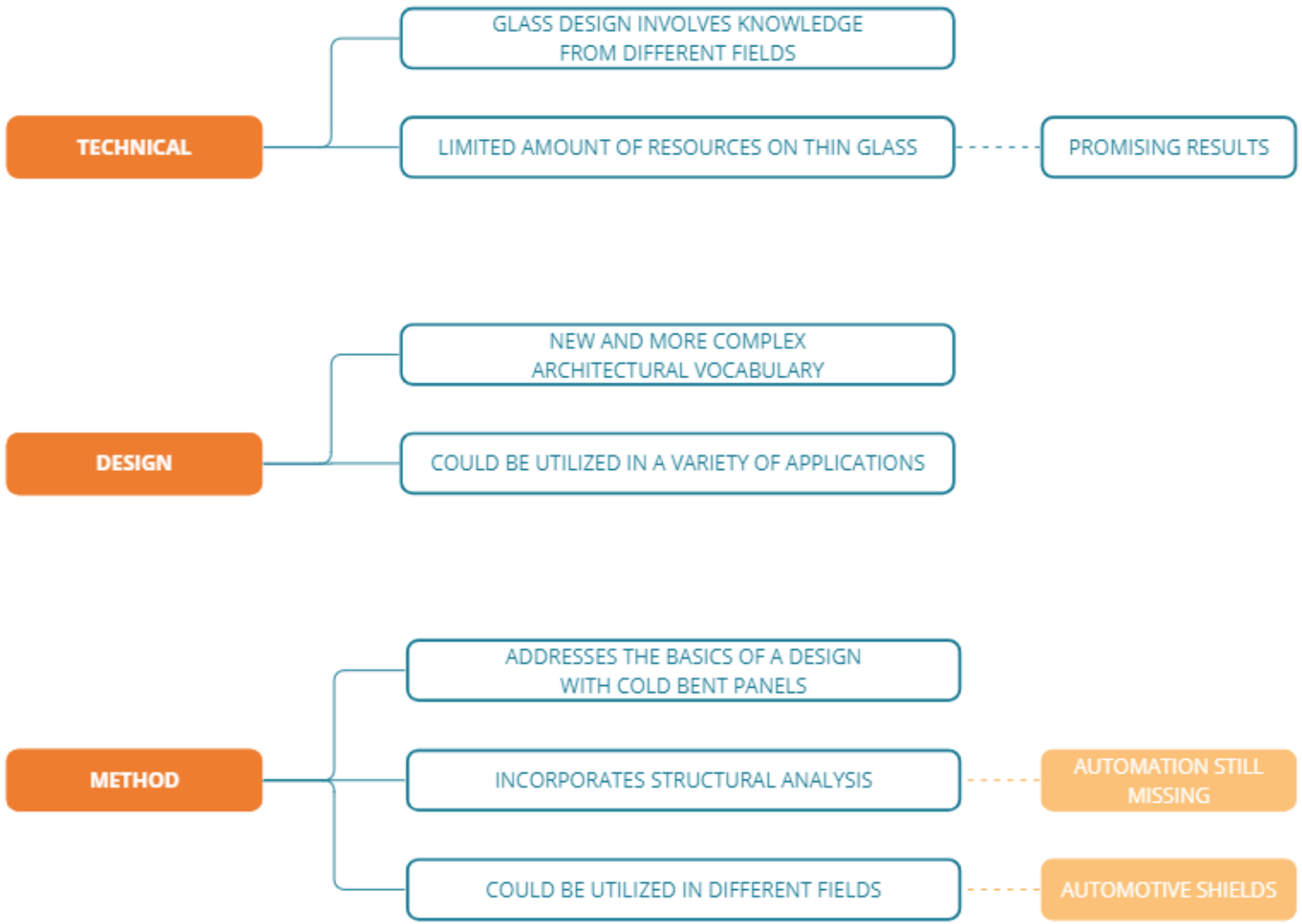
EQUIPMENT CATALOGUE

MOULD	FALCON GLASS PANEL	3D PRINTED CONNECTIONS	CLAMPS	WIRE	BOLTS	SCREWDRIVER	PLIERS	WIRE CUTTER
								
x1	x1	x6	x6	x3	x6	x1	x1	x1

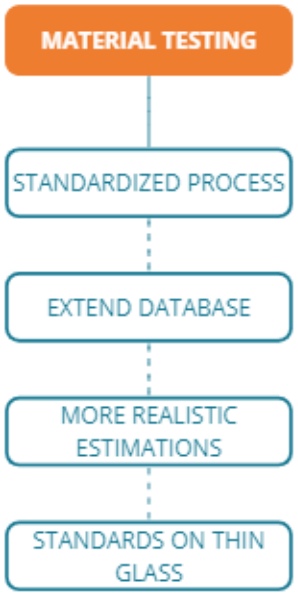
PROTOTYPE

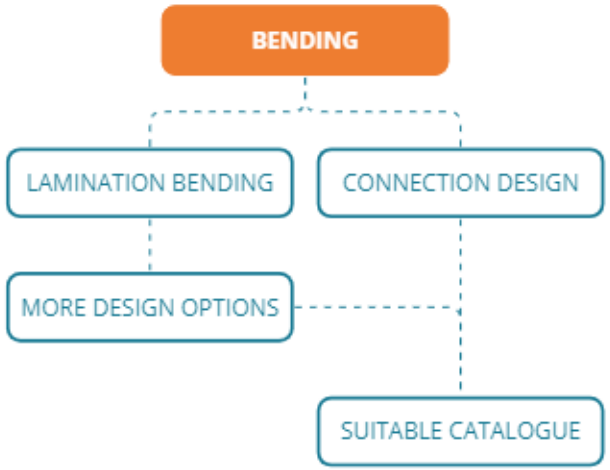
ASSEMBLY PROCESS

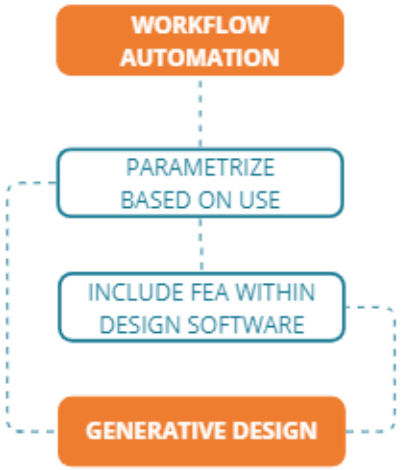
CONCLUSIONS



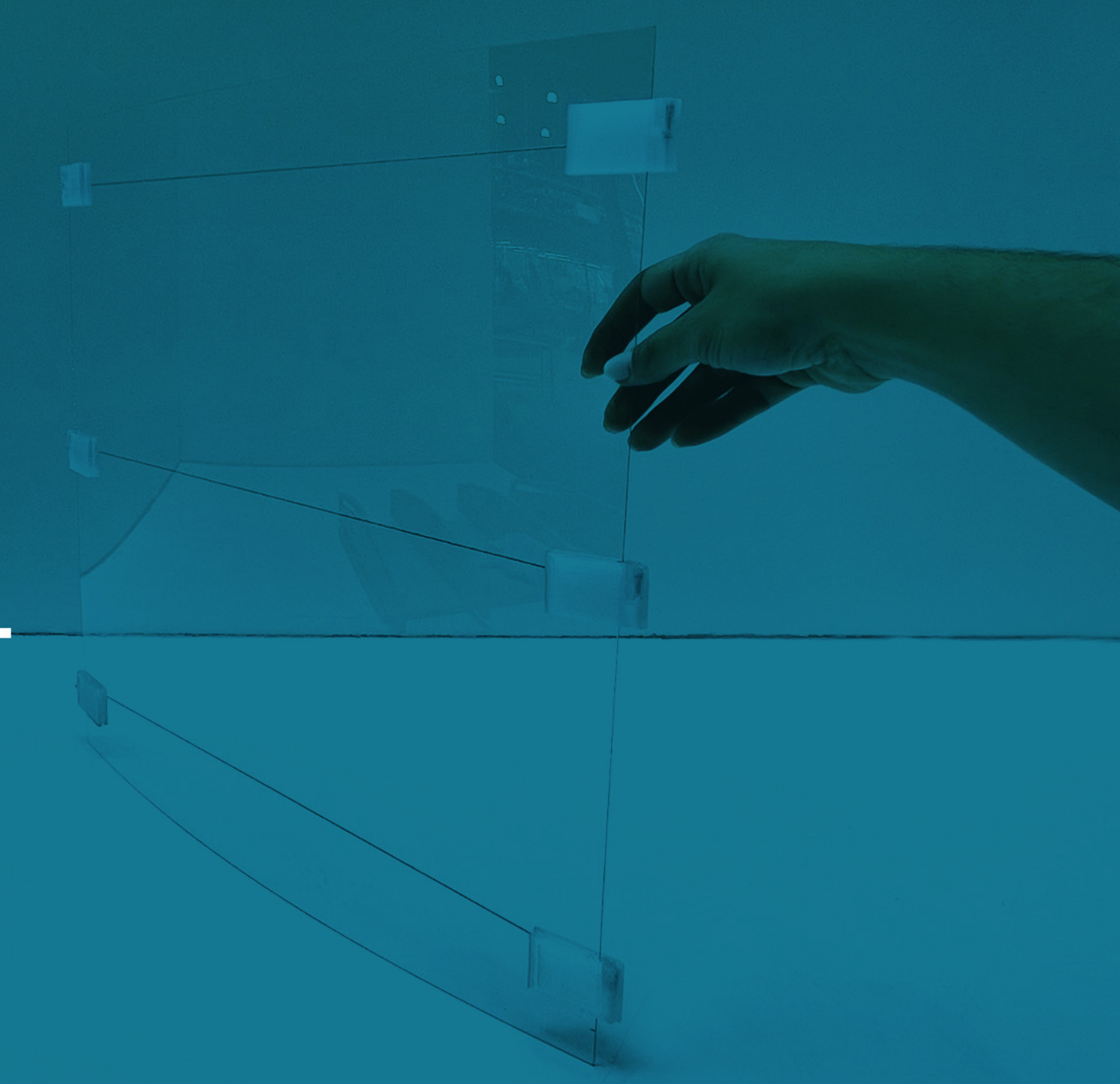
FURTHER RESEARCH







THANK YOU



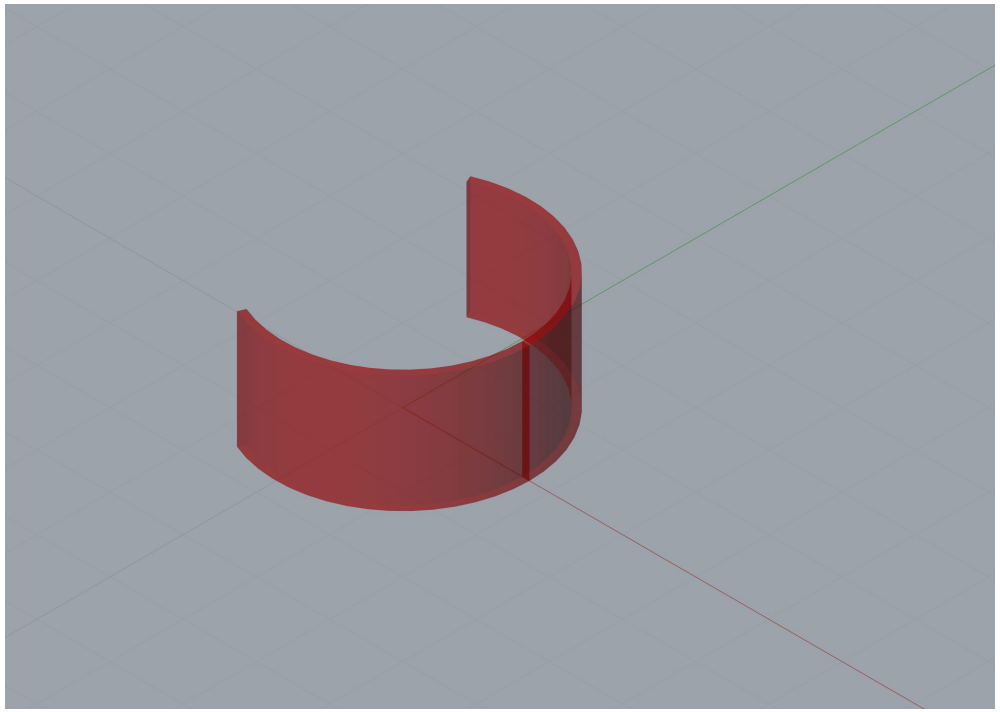
SPECIAL THANKS

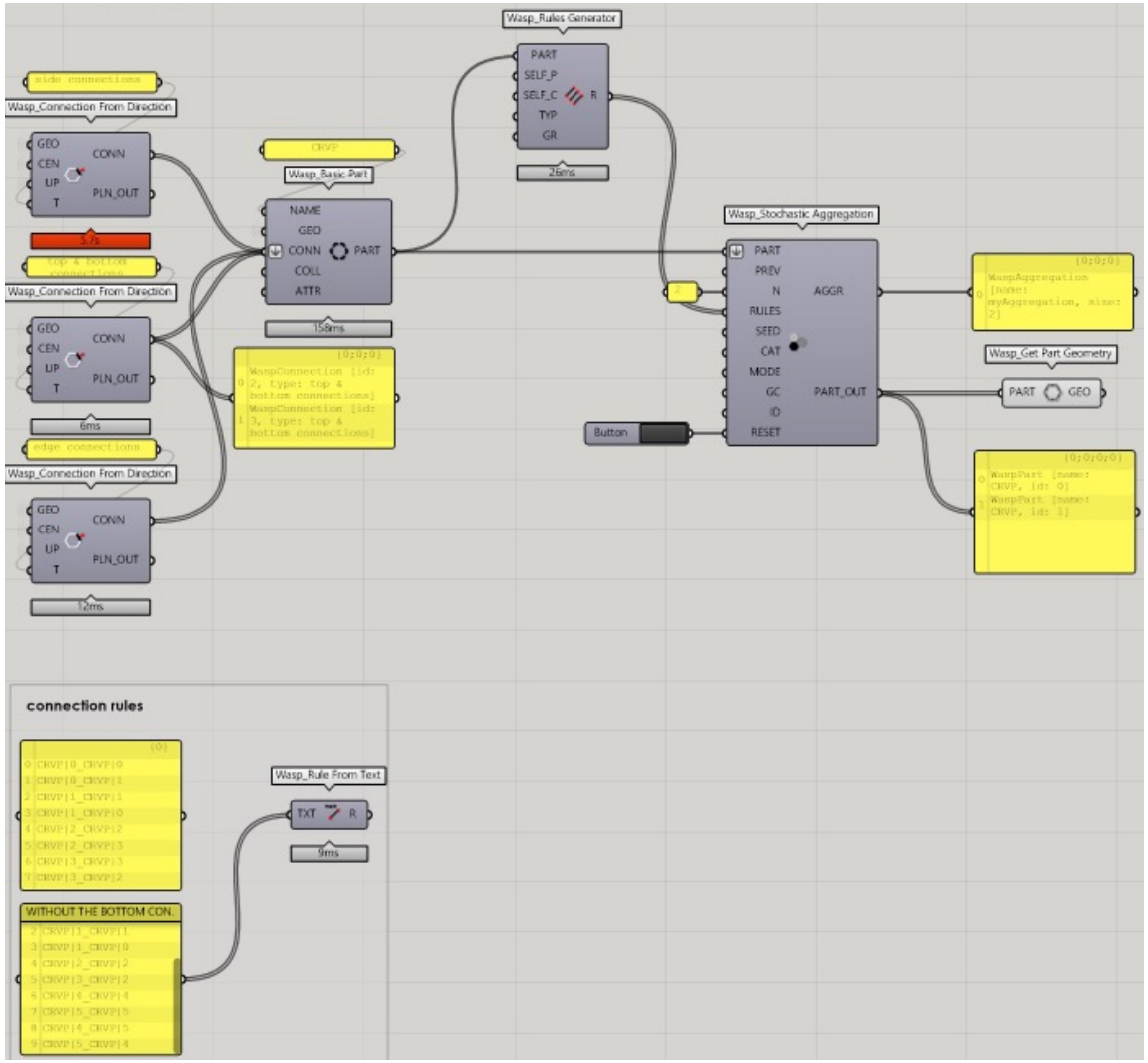
ANNEX

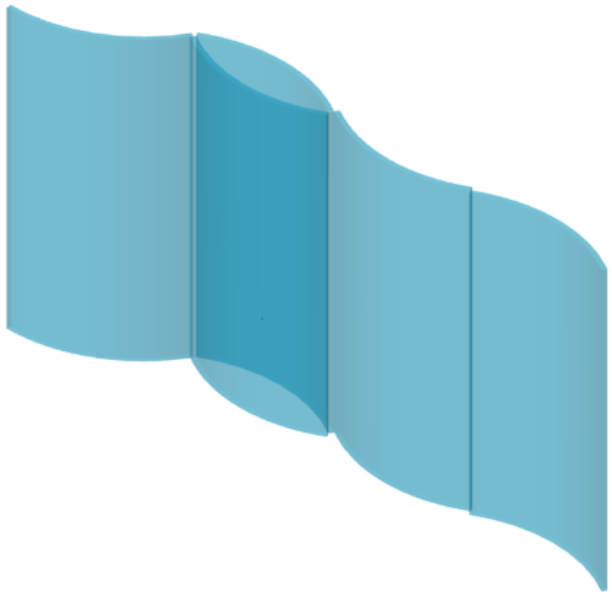
					
					
CONTINUOUS	●	●	●	●	●
CLAMPED	●	●	●		●
FRICTION GRIP	●	●	●		
HYBRID	●	●	●	●	●

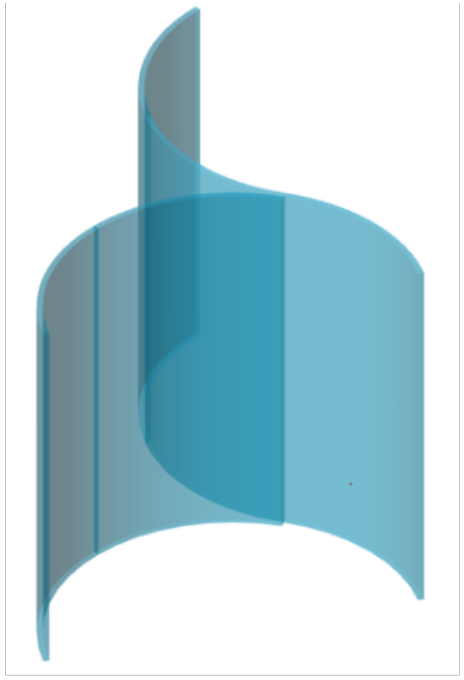
ANNEX

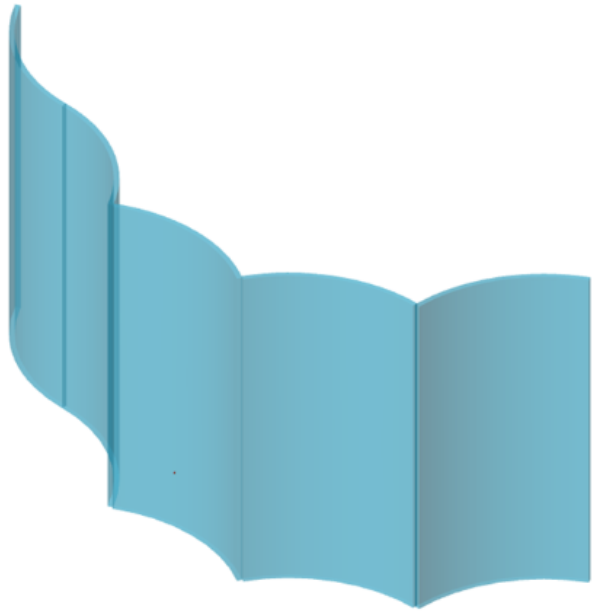
WASP DEFINITION



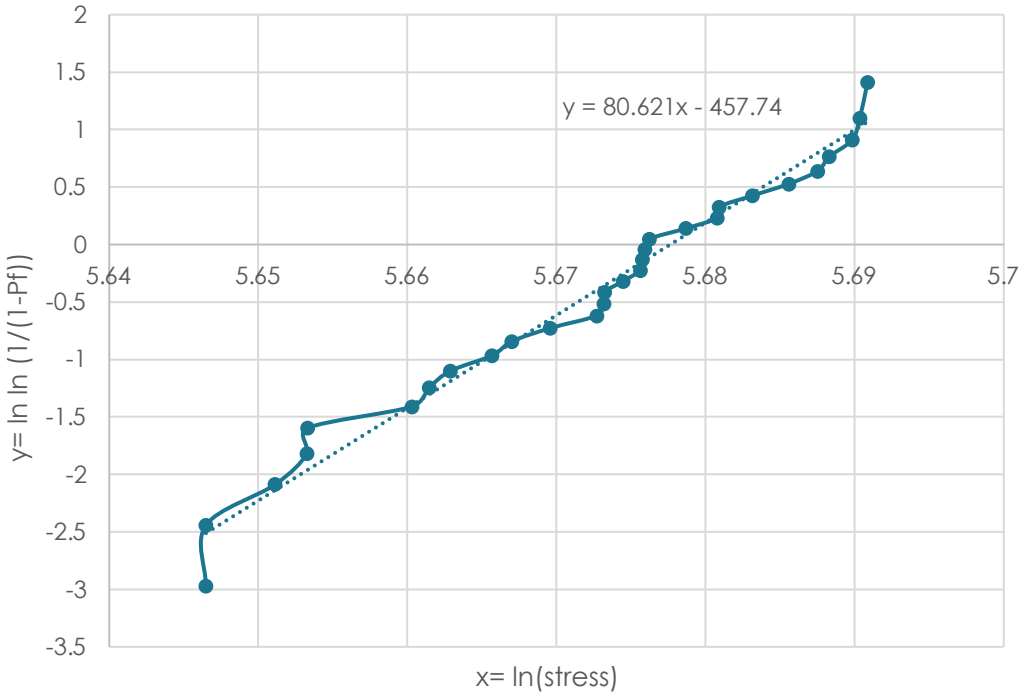


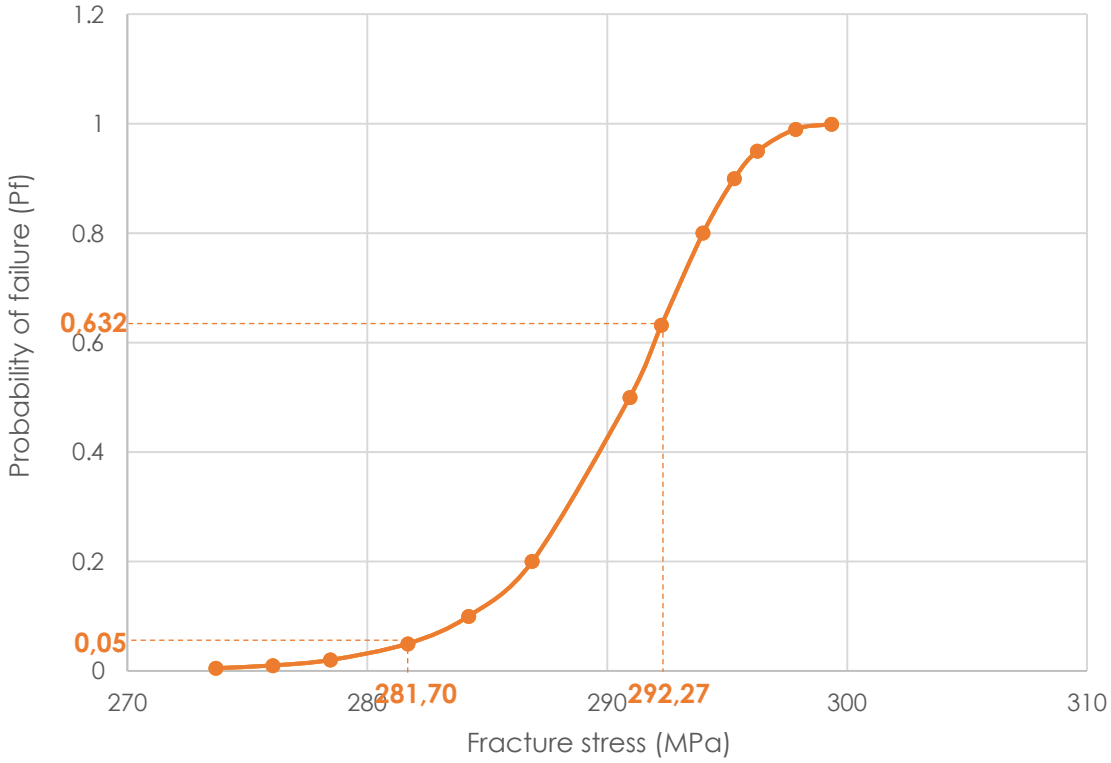




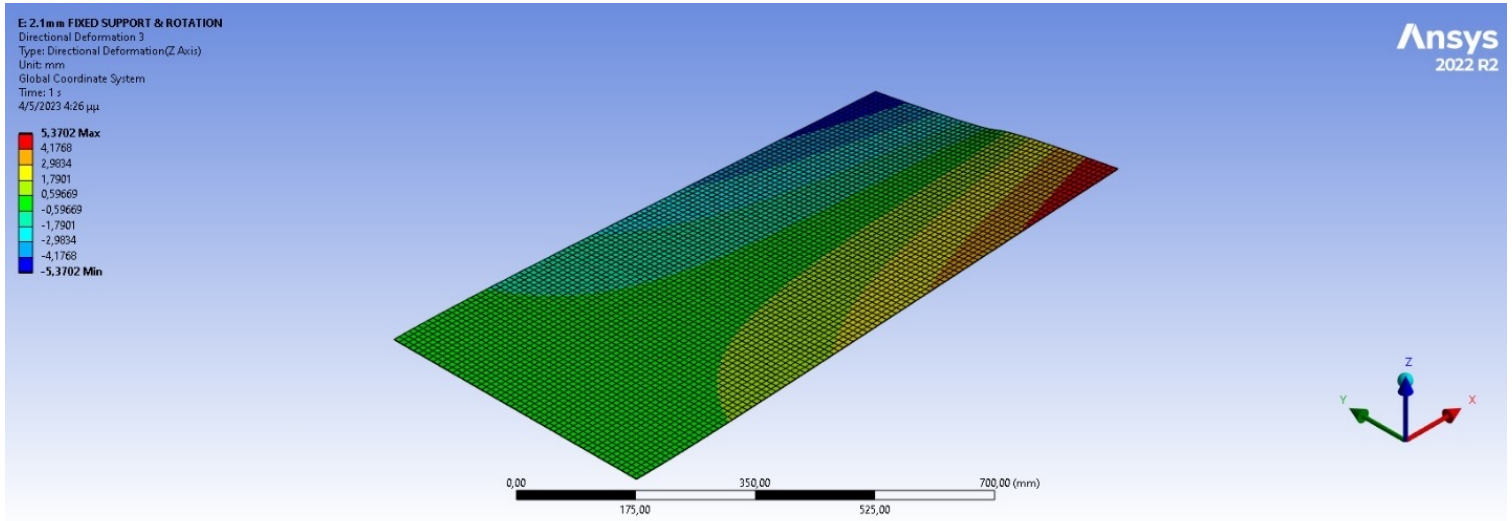


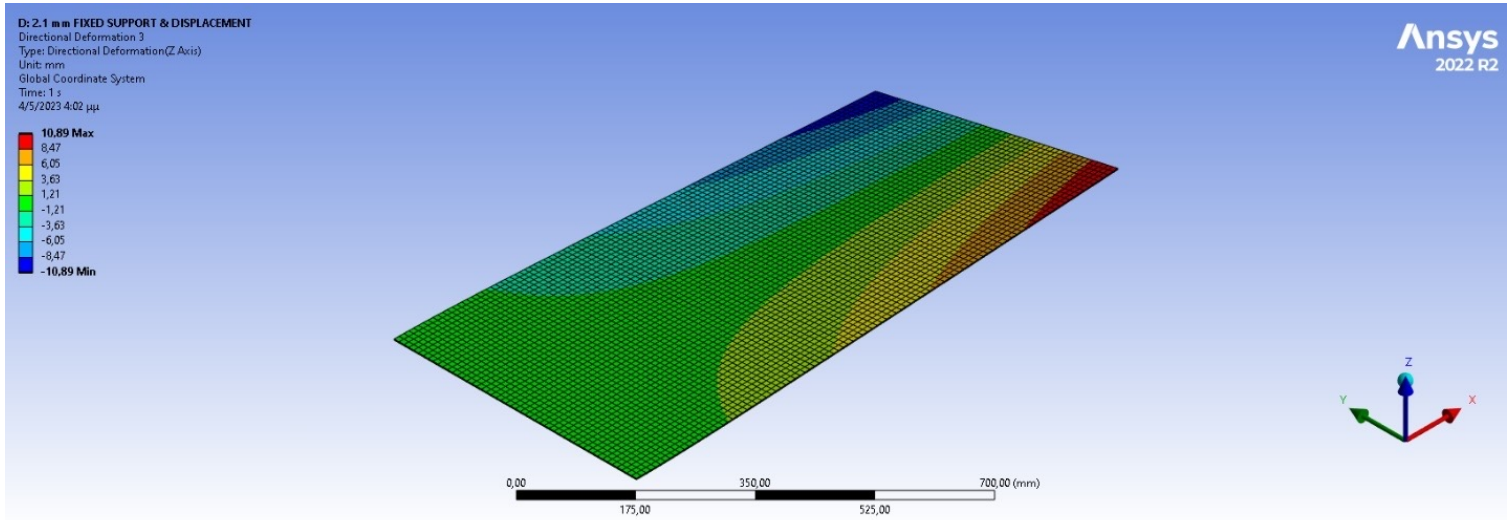
WEIBULL DISTRIBUTION



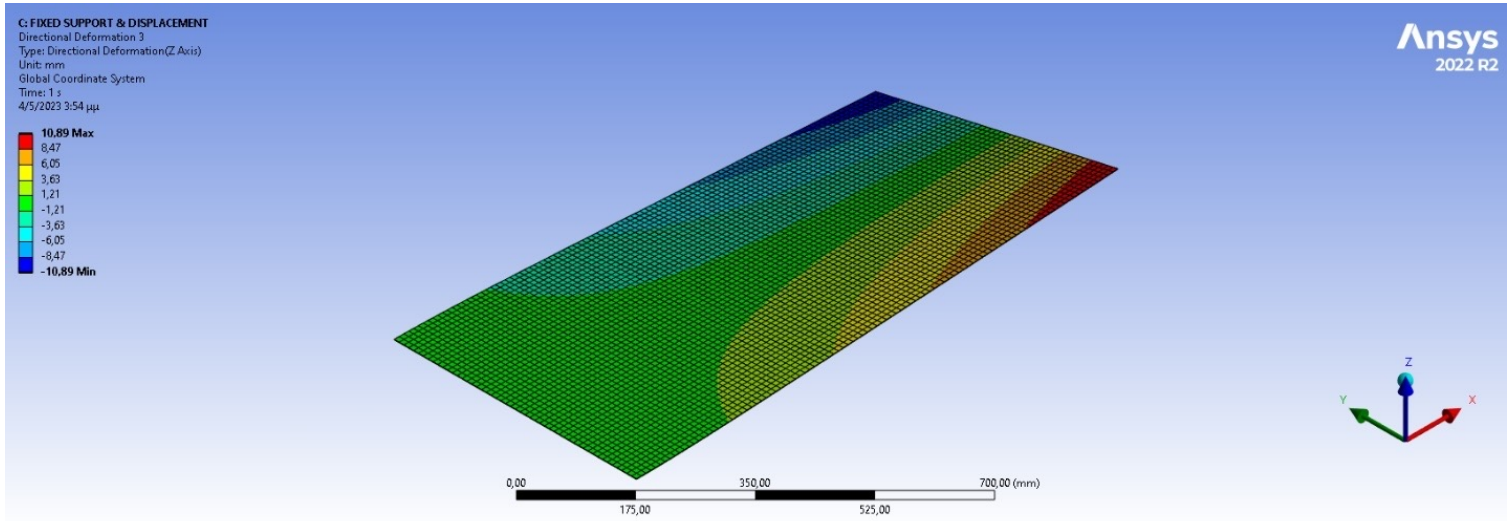


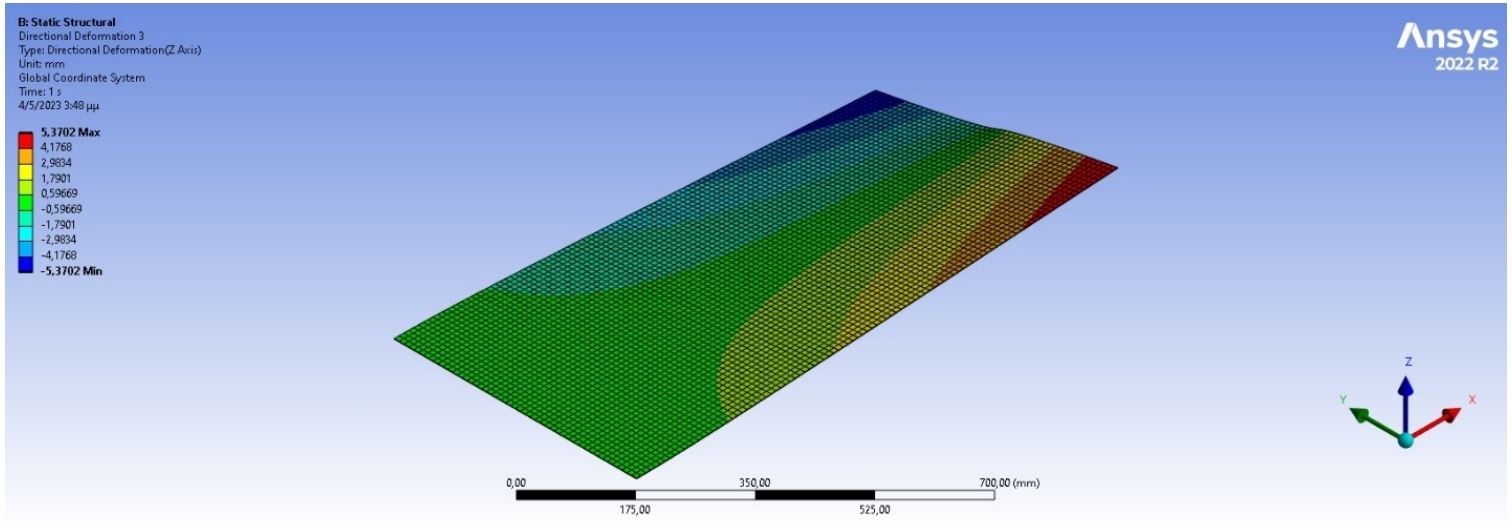
ANNEX


E: 2.1mm FIXED SUPPORT & ROTATION
Directional Deformation 3
Type: Directional Deformation(Z Axis)
Unit: mm
Global Coordinate System
Time: 1 s
4/5/2023 4:26 µµ
5,3702 Max
4,1768
2,9834
1,7901
0,59669
-0,59669
-1,7901
-2,9834
-4,1768
-5,3702 Min
Ansys
2022 R2
0,00
350,00
700,00 (mm)
175,00
525,00
Z
Y
X


D: 2.1 mm FIXED SUPPORT & DISPLACEMENT
Directional Deformation 3
Type: Directional Deformation(Z Axis)
Unit: mm
Global Coordinate System
Time: 1 s
4/5/2023 4:02 µµ
10,89 Max
8,47
6,05
3,63
1,21
-1,21
-3,63
-6,05
-8,47
-10,89 Min
Ansys
2022 R2
0,00
350,00
700,00 (mm)
175,00
525,00
Z
Y
X

ANNEX


C: FIXED SUPPORT & DISPLACEMENT
Directional Deformation 3
Type: Directional Deformation(Z Axis)
Unit: mm
Global Coordinate System
Time: 1 s
4/5/2023 3:54 μμ
10,89 Max
8,47
6,05
3,63
1,21
-1,21
-3,63
-6,05
-8,47
-10,89 Min
Ansys
2022 R2
0,00
350,00
700,00 (mm)
175,00
525,00
Z
Y
X


B: Static Structural
Directional Deformation 3
Type: Directional Deformation(Z Axis)
Unit: mm
Global Coordinate System
Time: 1 s
4/5/2023 3:48 μμ
5,3702 Max
4,1768
2,9834
1,7901
0,59669
-0,59669
-1,7901
-2,9834
-4,1768
-5,3702 Min
Ansys
2022 R2
0,00
350,00
700,00 (mm)
175,00
525,00
Z
Y
X

		Action	Value	Units	Load duration	k_{mod}
Variable (short-term)		Live load	1.0 – 2.0	kN/m^2	30 min	0.69
		Wind gusts	0.58 – 0.68		5 sec (or less)	1.0
		Wind	0.51		10 min equivalent	0.74
		Seismic				
Permanent		Self weight		kN/m^2	Permanent (50 years)	0.29
		Dead loads	0.0 – 1.0	kN/m^2		
		Dead load (point)		kN		
NLD Partial factor	γ_G	permanent actions	1.35			
	γ_Q	variable actions	1.5			

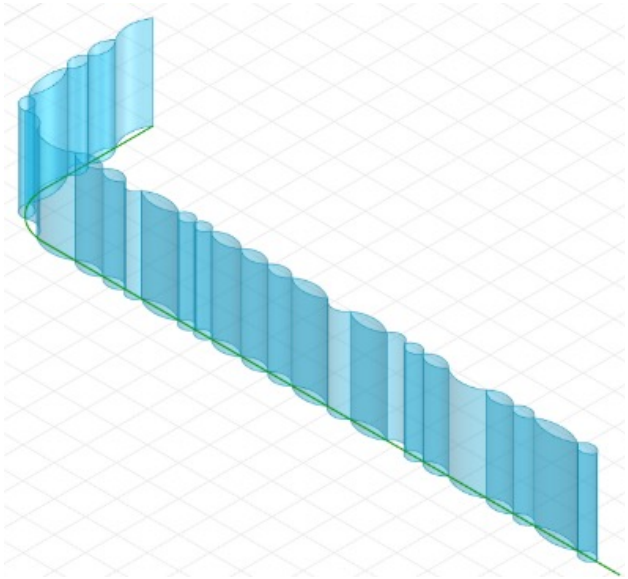
[1] The wind velocity in the Netherlands is categorized in 3 different areas, that also include the sub-categories of coastal, non-urbanized and urbanized. The values refer to the wind area II, that Delft belongs to, for an urbanized neighbourhood and for a structure of a maximum height of 10 meters.
[2] According to the Dutch Annex for Eurocode 1, the basic wind speed in wind area II would be 26 m/s.

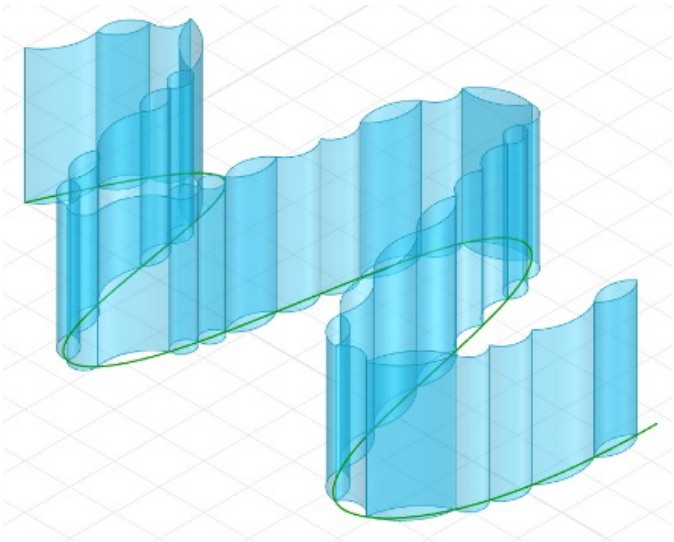
LOAD CASES

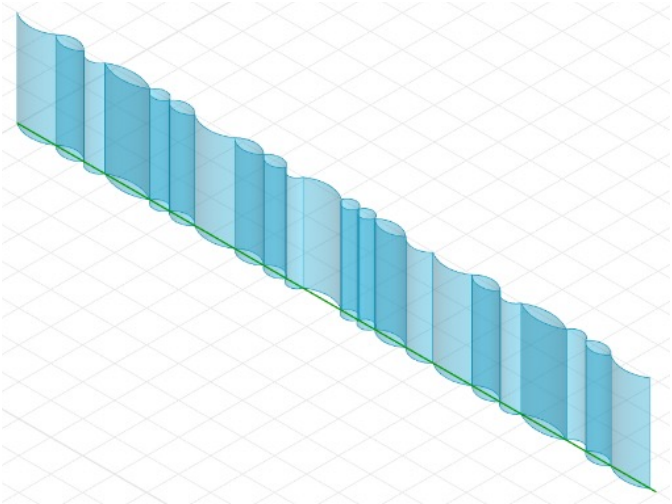
	Exterior structure	Interior structure
ULS FQP	$1.35 * F_{weight} + 1.5 * F_{wind}$	$\gamma_G * F_{weight} + \gamma_Q * F_{live}$
	$1.35 * F_{weight} + 1.5 * (F_{wind} + F_{live})$	
ULS IF	$1.35 * F_{weight} + 1.5 * (F_{wind} + F_{live})$	$1.35 * F_{weight} + 1.5 * F_{live}$
SLS FQP	$1.0 * F_{weight} + 1.0 * F_{live} + 0.5 * F_{wind} + 0.5 * F_t 1.0 * F_{weight} + 1.0 * F_{live} + 0.5 * F_{wind} + 0.5 * F_t \ 1.0 * F_{weight} + 1.0 * F_{live}$	
SLS IF	$1.0 * F_{weight} + 1.0 * F_{live} + 0.5 * F_{gusts} + 0.5 * F_t$	$1.0 * F_{weight} + 1.0 * F_{live}$

[11] *F_t defines the load due to temperature change. According to Eurocode 1, this can be calculated as: $F_t = A*E*\Delta T$, where A is the cross-sectional area of the element, E the Young's modulus and ΔT the temperature difference, which is normally 28 degrees.*

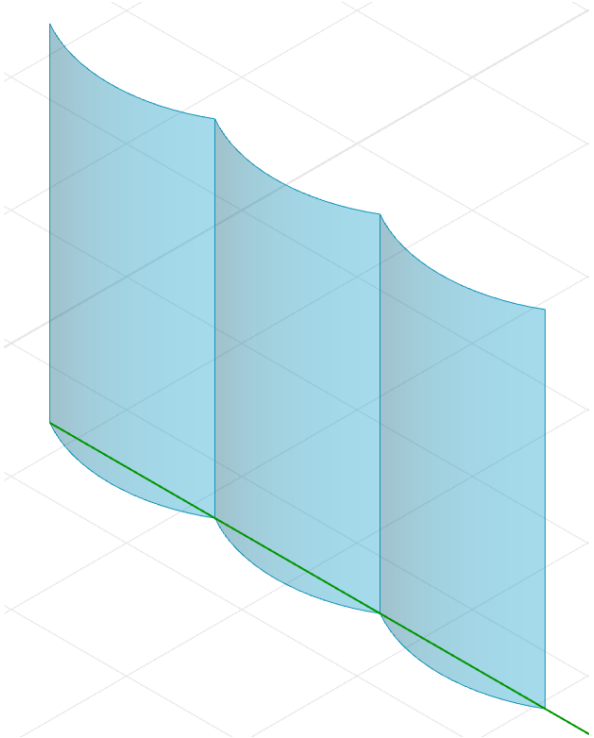
CASE STUDY

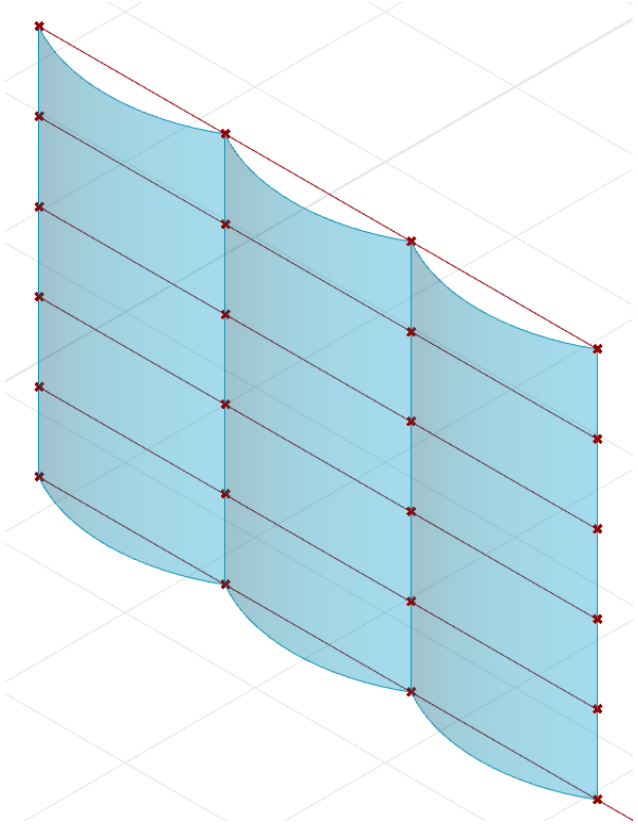


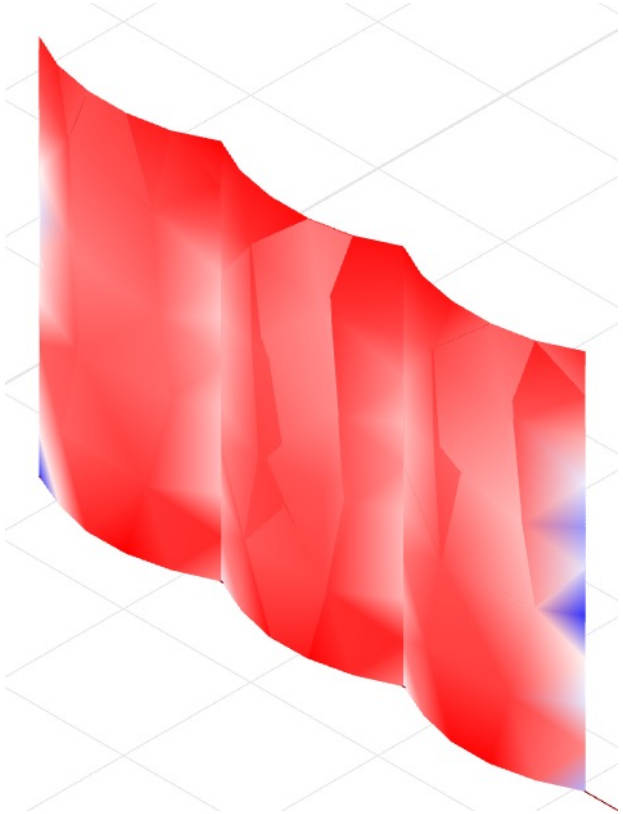


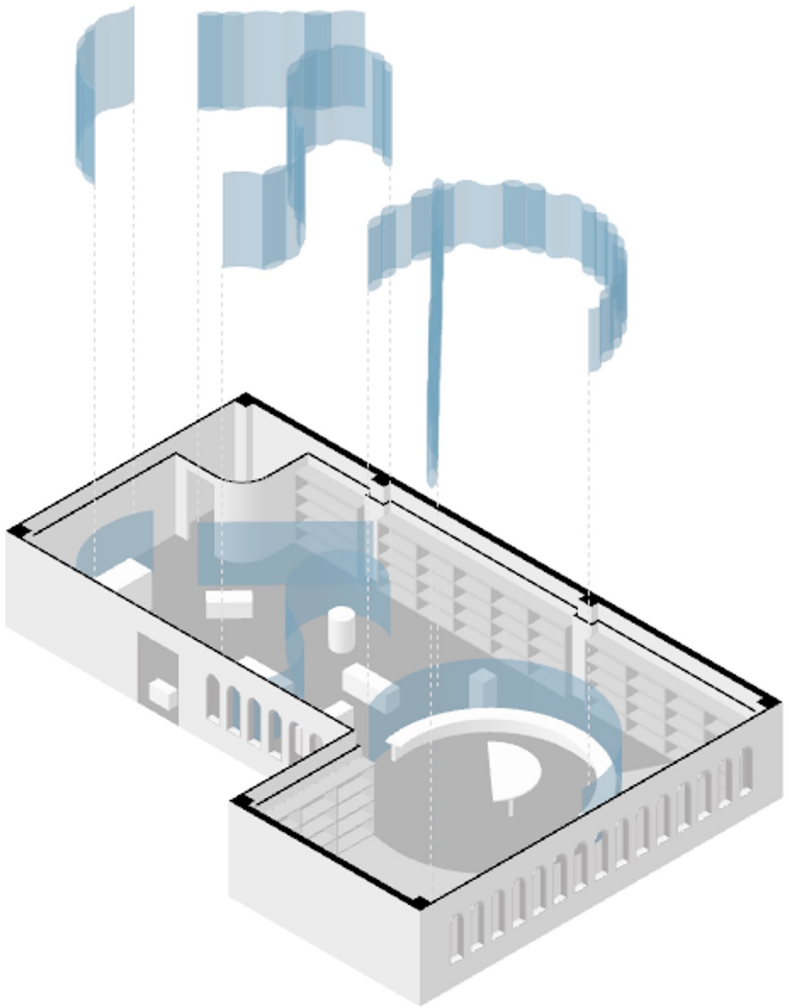


CASE STUDY



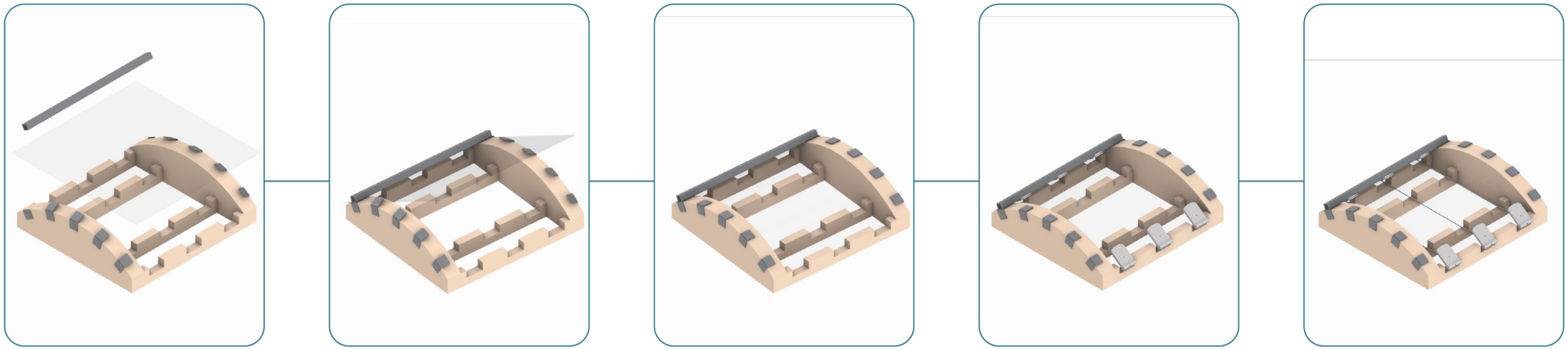




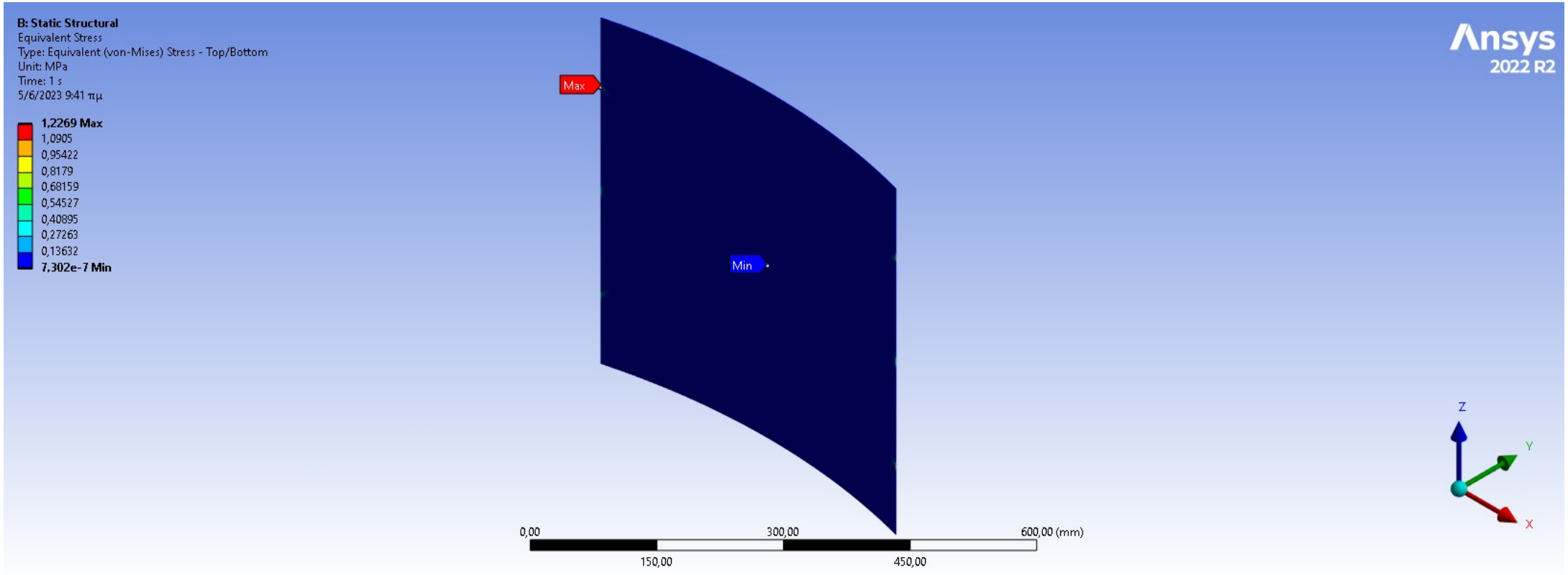


PROTOTYPE

ASSEMBLY PROCESS



PROTOTYPE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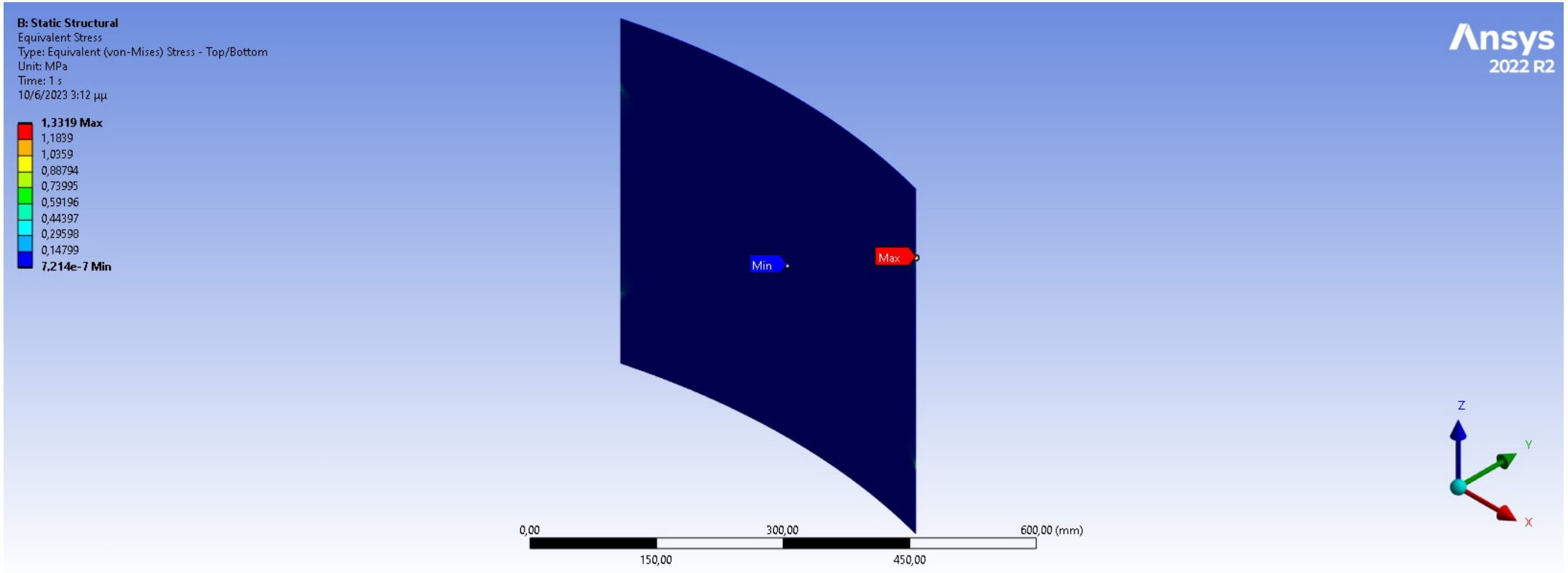
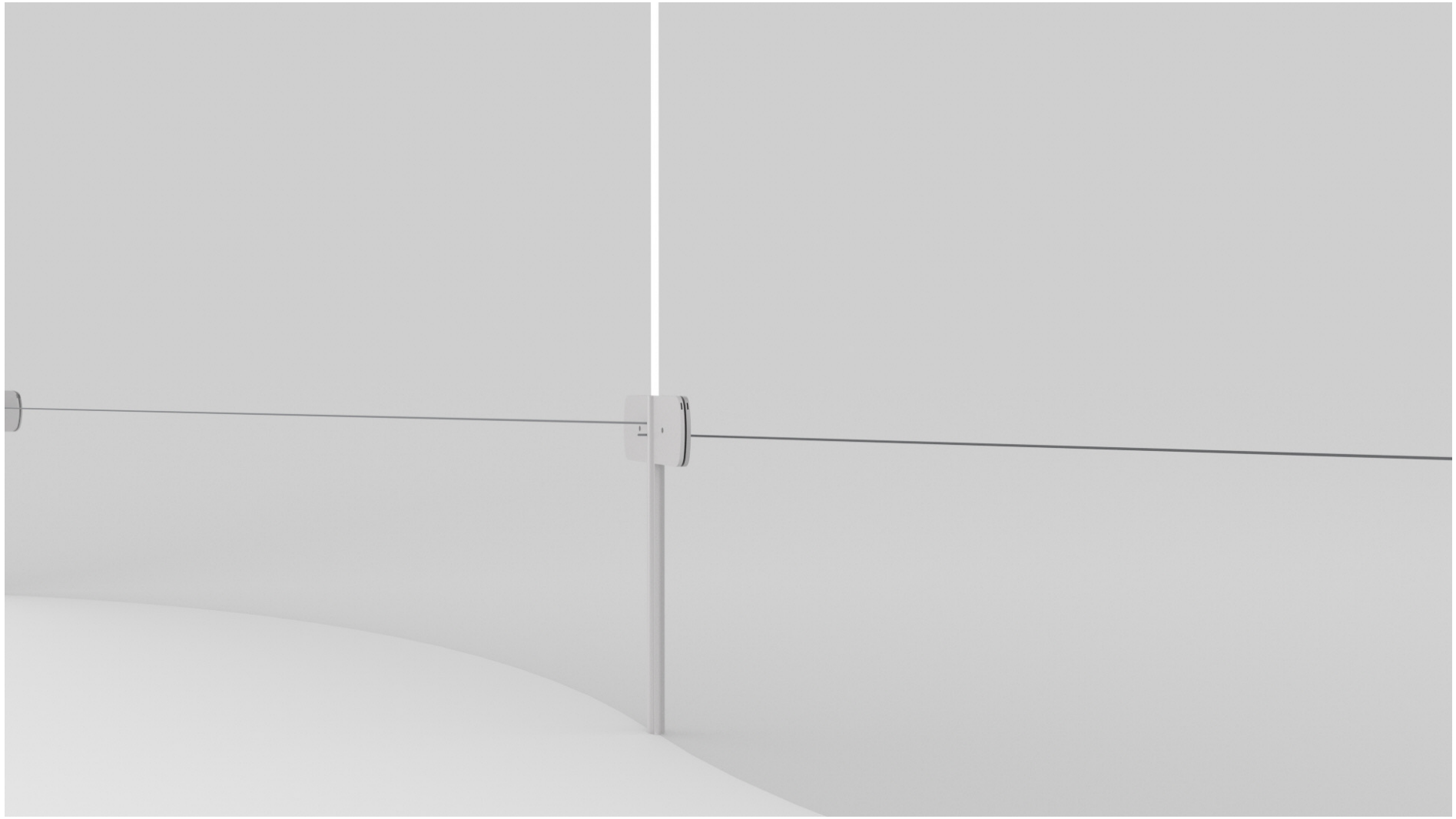
Equivalent Stress
Type: Equivalent (von-Mises) Stress - Top/Bottom
Unit: MPa
Time: 1 s
5/6/2023 9:41 πμ
1,2269 Max
1,0905
0,95422
0,8179
0,68159
0,54527
0,40895
0,27263
0,13632
7,302e-7 Min
Max
Min
Ansys
2022 R2
0,00
300,00
600,00 (mm)
150,00
450,00
Z
Y
X


B: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress - Top/Bottom
Unit: MPa
Time: 1 s
10/6/2023 3:12 µµ
1,3319 Max
1,1839
1,0359
0,88794
0,73995
0,59196
0,44397
0,29598
0,14799
7,214e-7 Min
Min
Max
0,00
300,00
600,00 (mm)
150,00
450,00
Ansys
2022 R2
Z
Y
X



ANNEX

IMAGE SOURCES

Crystal Palace
https://www.archdaily.com/397949/ad-classic-the-crystal-palace-joseph-paxton/51d4964db3fc4b9e0f0001cf-ad-classic-the-crystal-palace-joseph-paxton-image

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Samsung Galaxy Z Flip
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GIF IMAGES

https://metropolismag.com/projects/so-il-hong-kong-museum/?utm_source=Main+List&utm_campaign=51bb767abb-EMAIL_CAMPAIGN_2019_01_02&utm_medium=email&utm_term=0_ceb057ffe6-51bb767abb-290183553&mc_cid=51bb767abb&mc_eid=06d089f0a1

https://www.dezeen.com/2015/08/03/pattersons-associates-len-lye-museum-new-zealand-folded-mirrored-facade/?utm_medium=email&utm_campaign=Daily+Dezeen+Digest&utm_content=Daily+Dezeen+Digest+CID_1bbc9d67588576f65b99efe808167f27&utm_source=Dezeen+Mail

https://www.archdaily.com/963909/shinhan-ex-pace-atelier-ki-jun-kim-plus-studio-in-loco