Design of a Reusable Float Glass System

Extending the Life Cycle of Primary Glass Structures

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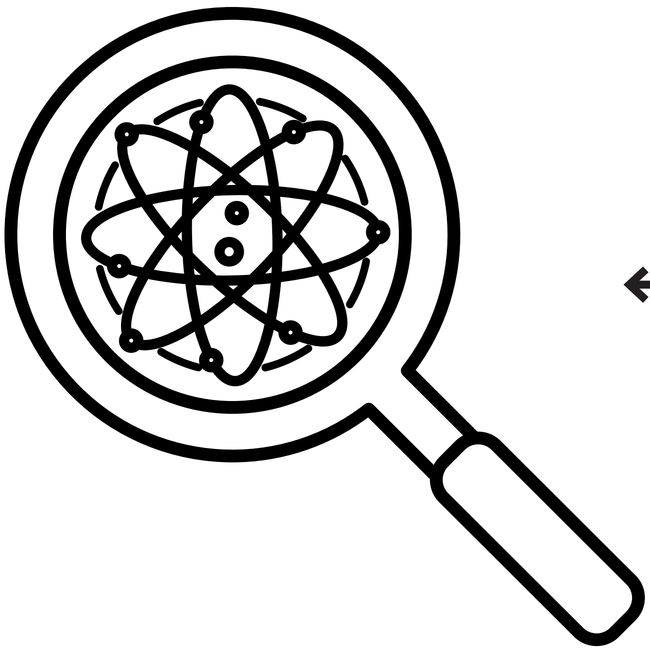


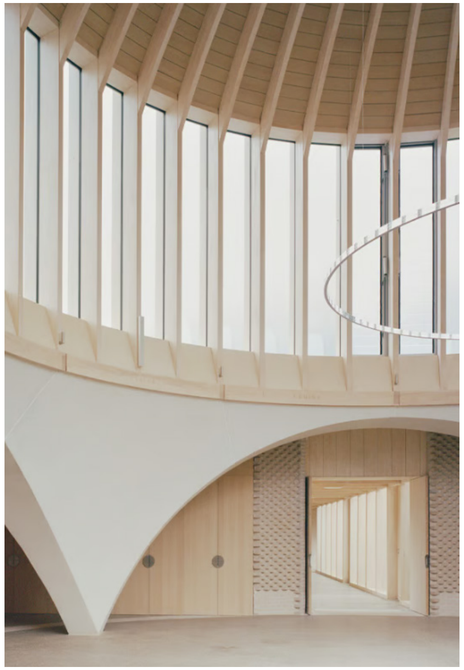
Sciences

Creative subjects

The Portalen pavilion - Deployable Gridshell by Summum Engineering

3D printed concrete pedestrian bridge - Summum Engineering

Glass pavilion structure at Apple's headquarters- Eckersley O'Callaghan



New Temple Complex - Structural design by Eckersley O'Callaghan

A structure is not just a technical necessity that holds an object up - it is an essential part of the design itself. Without structure, there is no shape, no space; in fact, there is no built object at all.

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Context

2500 BC
Jewellery and vessels

From Cole, S. E. (2014)

Roman times
Untransparent Cast glass window panes

From 'An experiment in the manufacture of Roman window glass', originally published in Glass News No. 9 (January 2001), and later in ARA Bulletin No. 13 (August 2002)

Middle Ages
Crown-glass

From Giese et al., 2024.

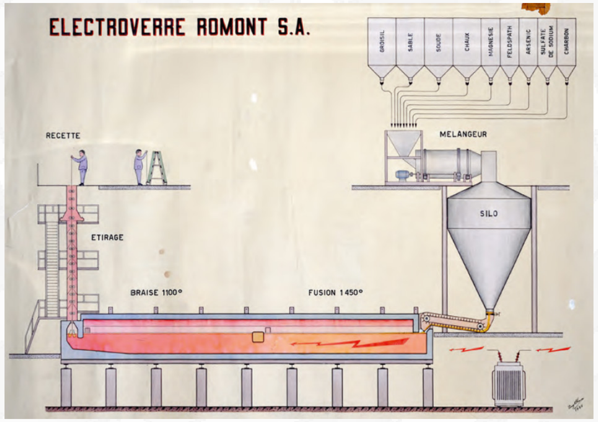
Late 17th Century
Plate glass

From Giese et al., 2024.

Industrial Revolution
Cilinder glass

From Giese et al., 2024.

Beginning 20th Century
Fourcault process



From Giese et al., 2024.

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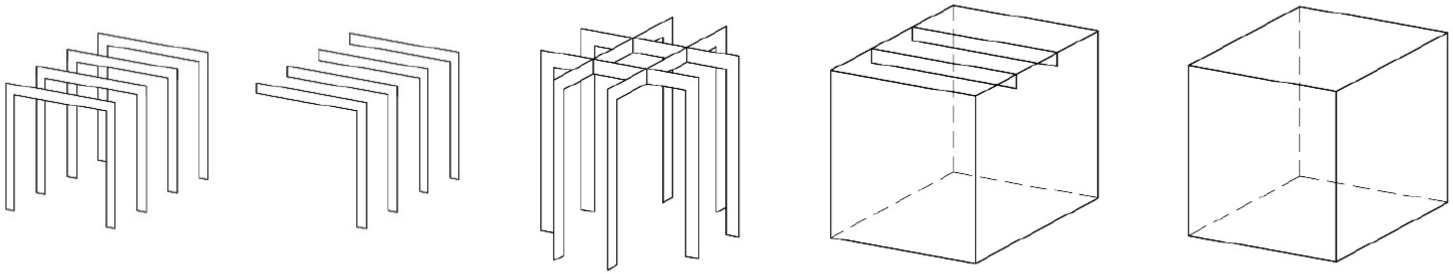
Context

20th century

Post-treatment techniques



Frames | Grills | Beam wall systems | Plate wall systems

From Jóźwik, 2022

Context

Building entrances

From Rammig, 2022

Social gathering places

From Jóźwik, 2022

Context

Exhibition spaces

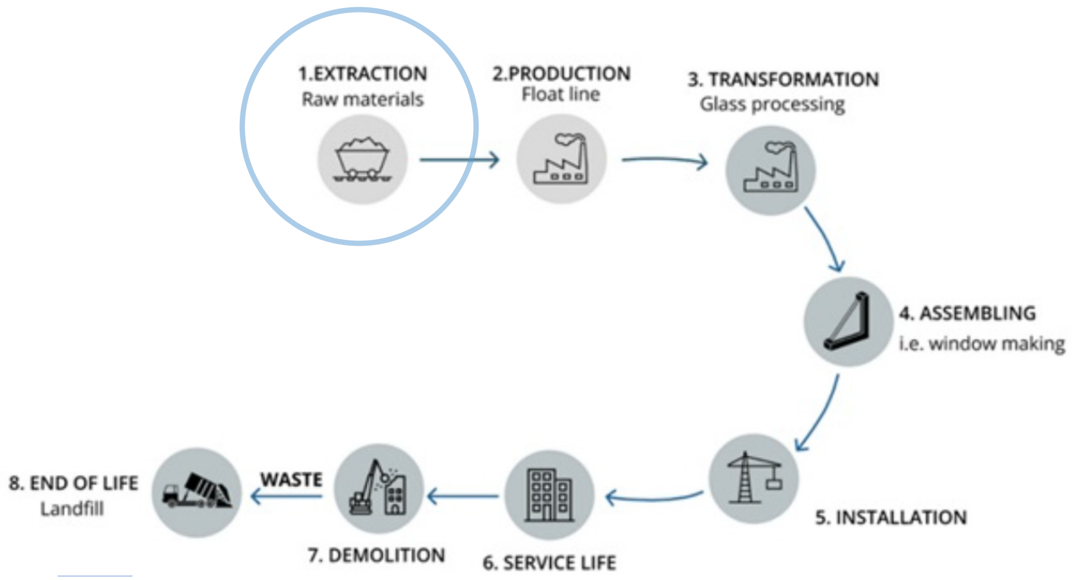
(TW-Architects, 2001). Photo by Franziska Safrane, Larry Williams, and Bele Marx.

Restauration projects

From (Barou et al., 2018)

The construction sector is responsible for approximately 40% of global greenhouse gas (GHG) emissions (Alexandrou et al., 2022).

Problem Statement



From Rota et al., 2023

Depletion of natural resources

Habitat destruction

Generate CO2 emissions

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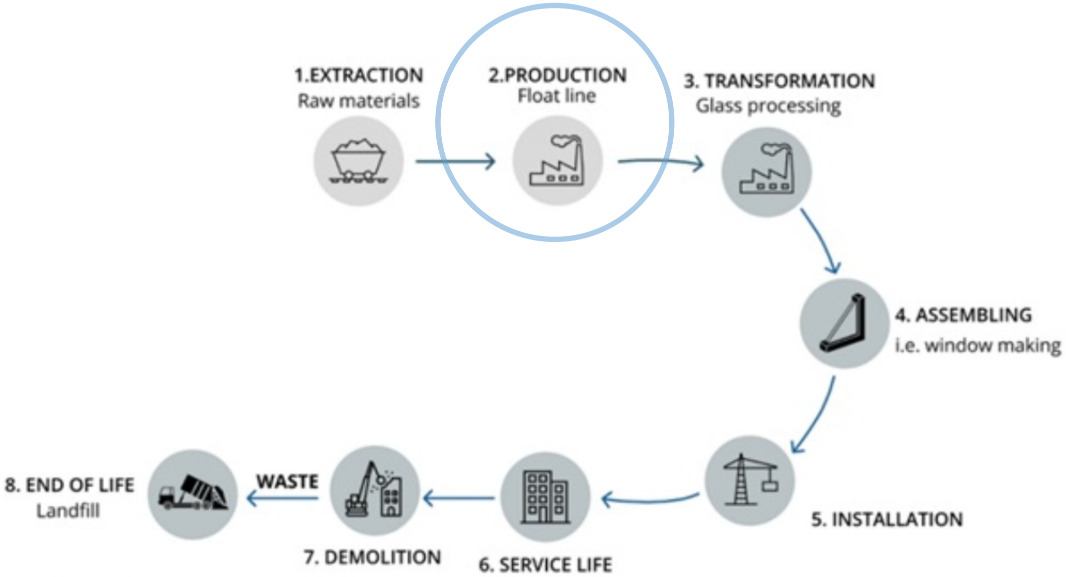
Problem Statement

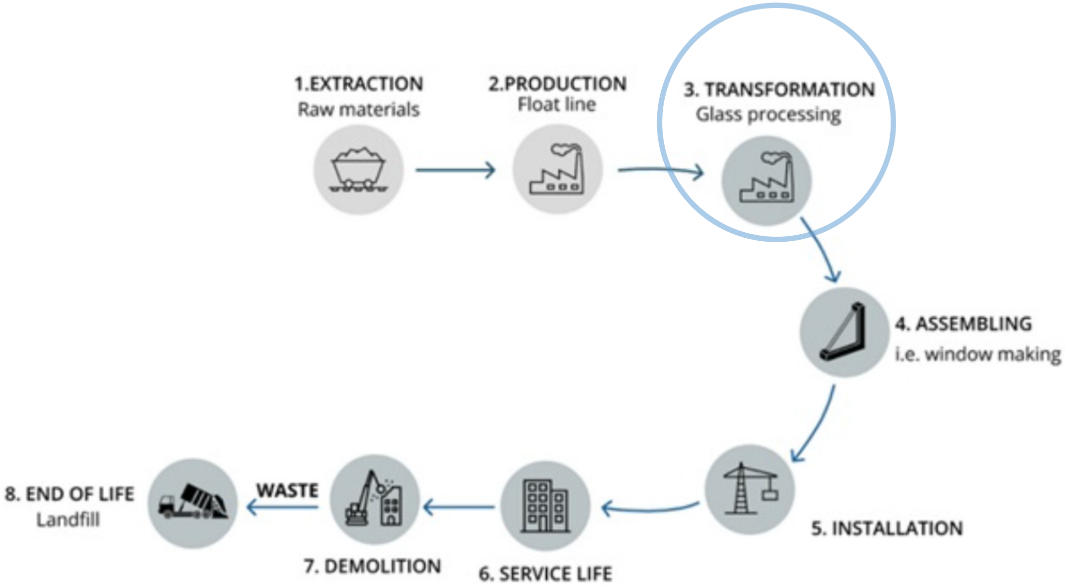


From Rota et al., 2023

Energy intensive melting process

Often relies on fossil fuels

Problem Statement

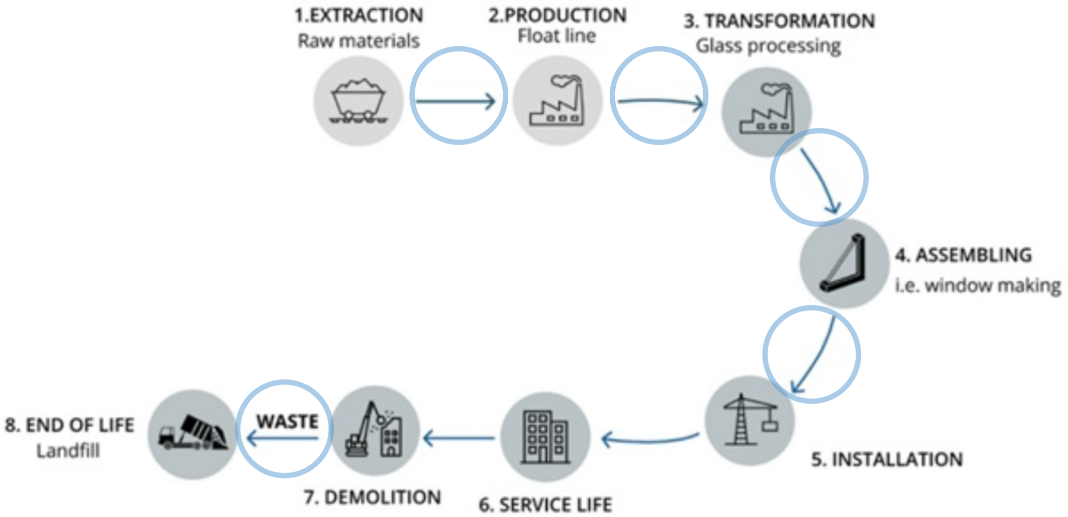


From Rota et al., 2023

Energy intensive

Generate CO2 emissions

Problem Statement



From Rota et al., 2023

CO2 emissions during transportation

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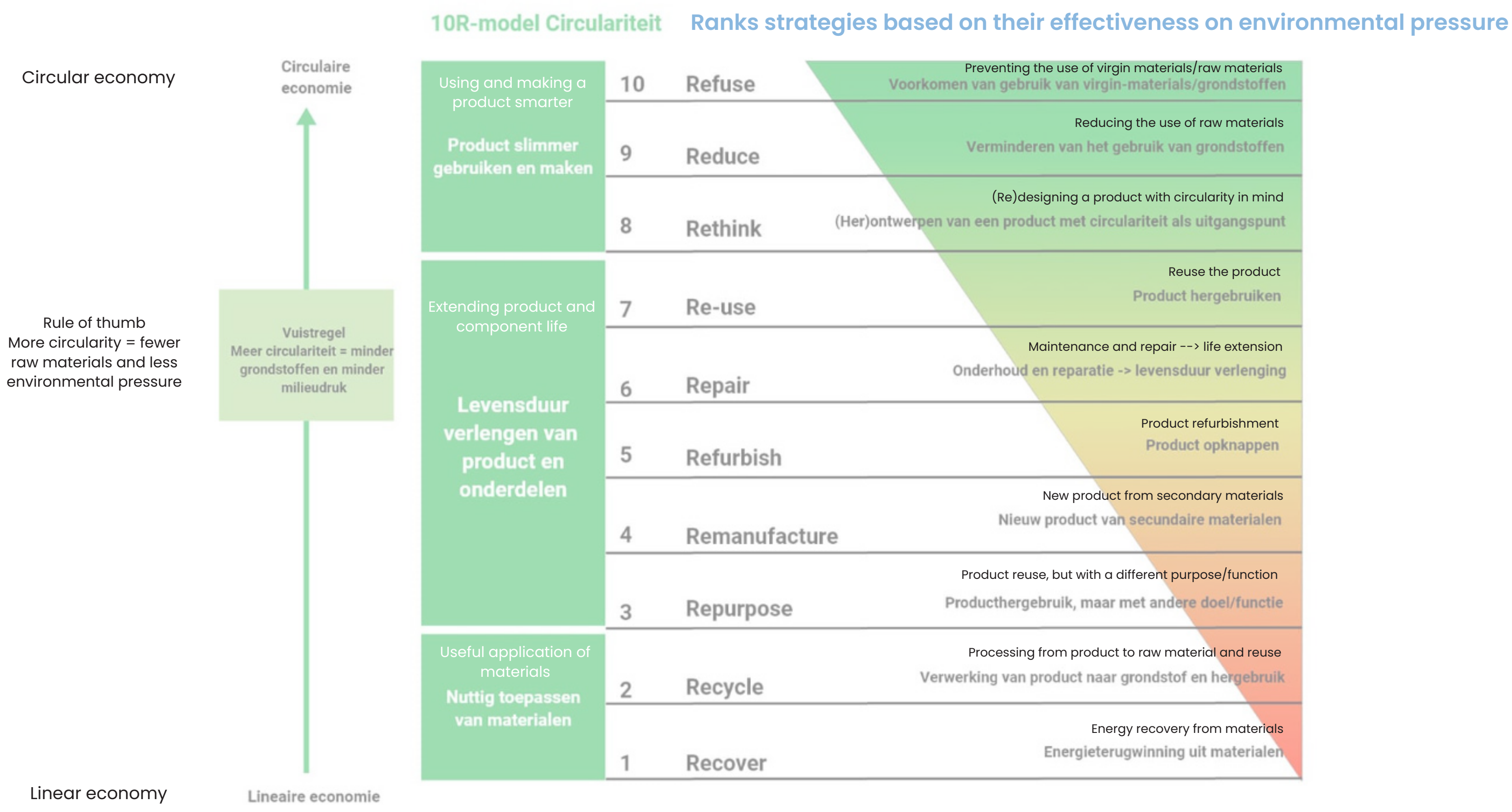
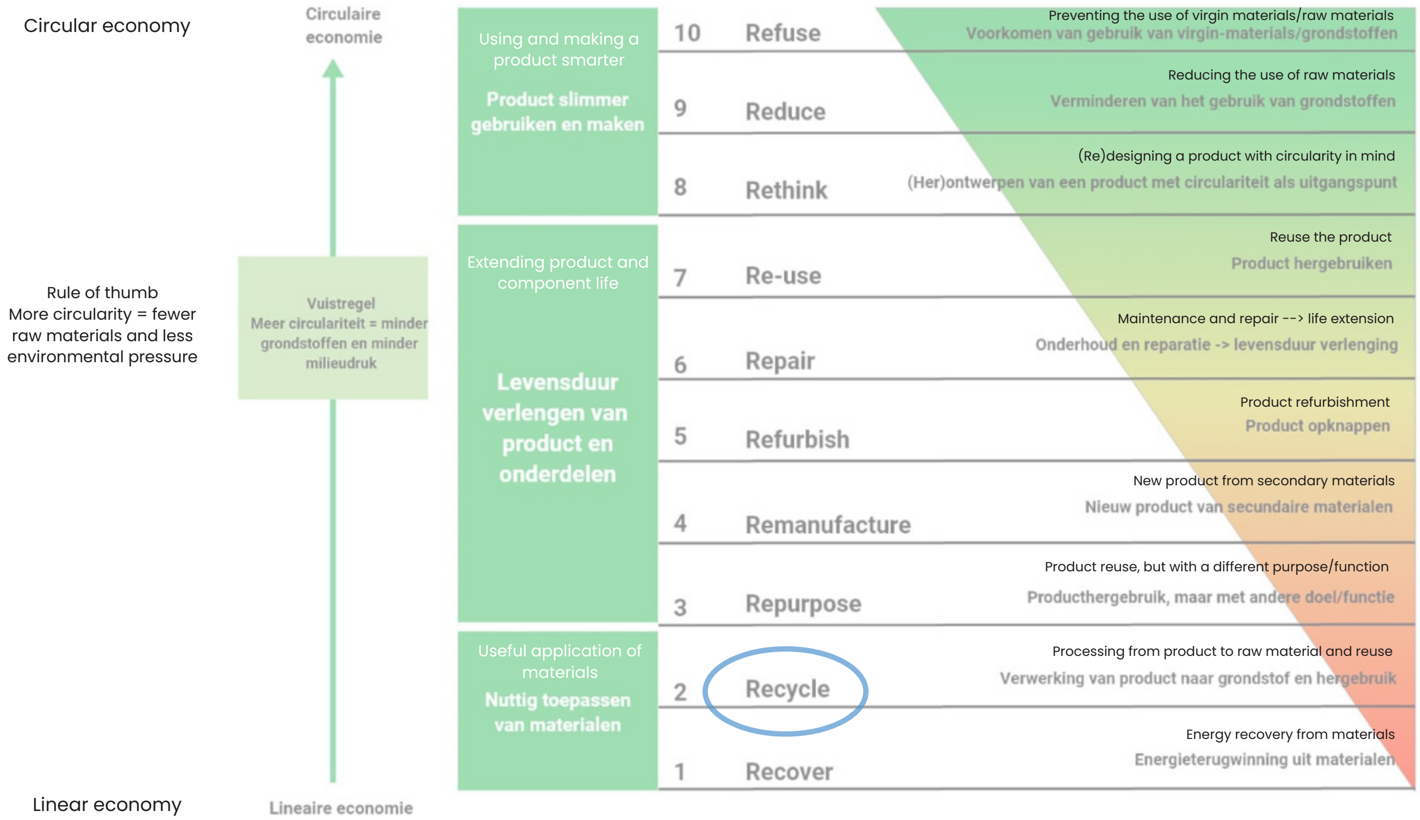
Minimizing environmental impact of the construction industry



Framework for a circular building practice (translated from Platform CB'23, 2019)

Minimizing environmental impact of the construction industry



Framework for a circular building practice (translated from Platform CB'23, 2019)

7,5% recycled back into new float glass

Recycling involves remelting

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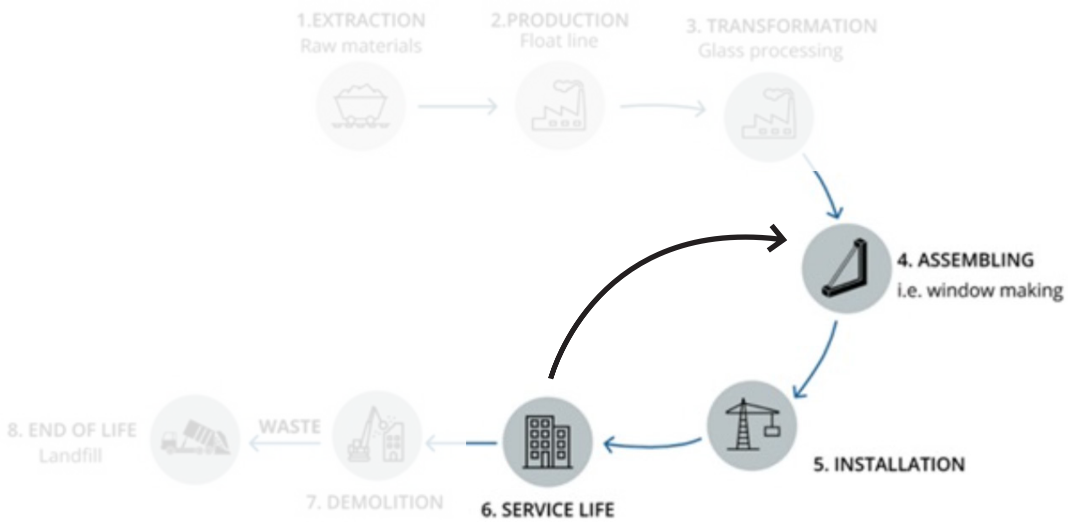
Research objective

Designing a float glass system that can be reused



Adapted from Rota et al., 2023

Purpose

The design outcome presents an **initial, potentially applicable solution** that **helps extend the functional lifespan of structural glass**, thereby contributing to waste reduction, resource conservation, and the avoidance of unnecessary energy use.

It **introduces a new paradigm** in structural float glass design by exploring how a structure can be made reusable, to **encourage designers and researchers** to **move beyond traditional recycling methods** and actively explore other circular strategies.

A final design solution that appeals to people by its architectural expression and innovative nature, **serving in this context more as an artwork** for the broader public that **encourages reflection on radically new possibilities for the future of construction**.

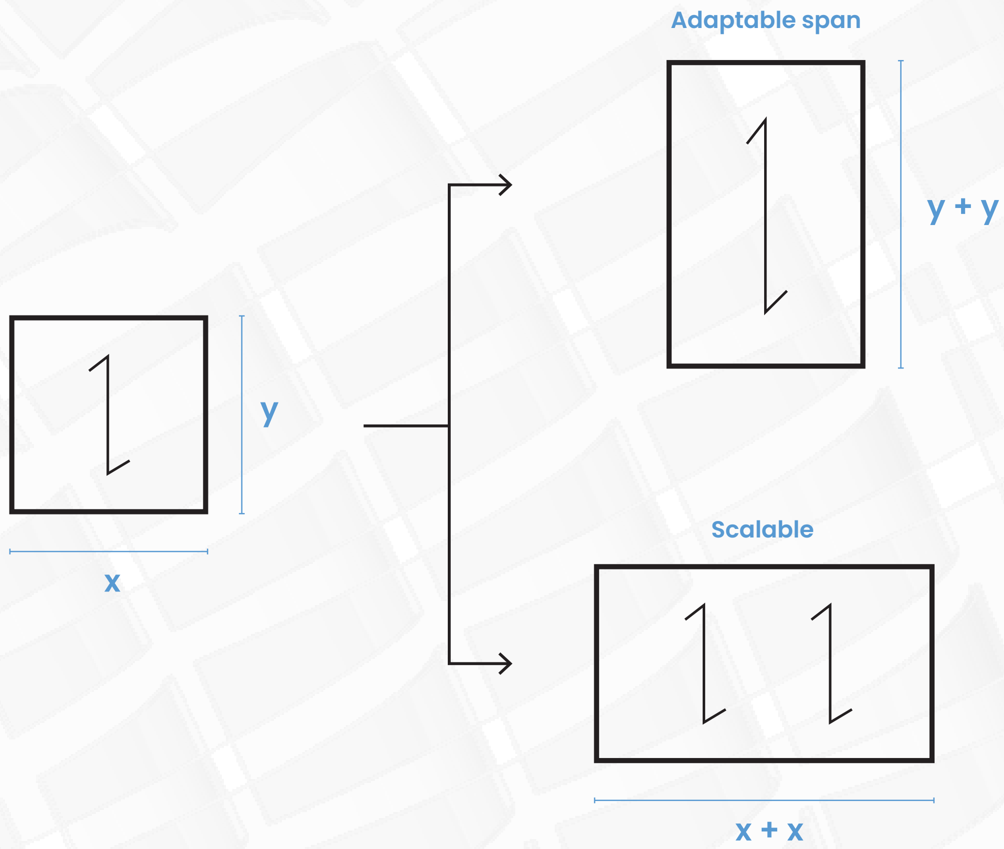
Research question

“Which **structural elements** and **connections** enable the design of a **structurally feasible** and **spatially adaptable** float glass system that can be **manually assembled and disassembled** by a small team for reconfiguration at different locations, ensuring its reusability?”

Design requirements

1. The system should be scalable by expansion in the x-direction, while maintaining an open floor plan.

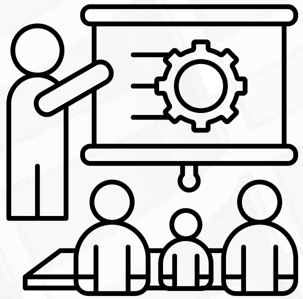
2. The system should be extendable in the y-direction to accommodate different spans, while maintaining an open floor plan.



Design requirements

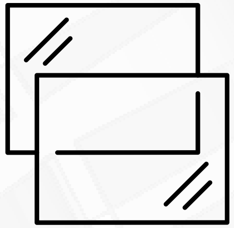
3. The system should be designed to be as lightweight as possible to support manual assembly and disassembly

4. The system should be designed to allow manual assembly and disassembly without the need for complex building instructions.

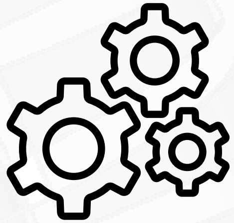


Design requirements

5. The proposed system is a response to existing all-glass structures, in which transparency is a key design principle. The new system will therefore be developed in such a way that it does not compromise the transparent quality of all-glass structures.



6. The system must consist of a minimal number of standardized building components to simplify the manufacturing and construction process, and to optimize the reuse potential of the structural components.



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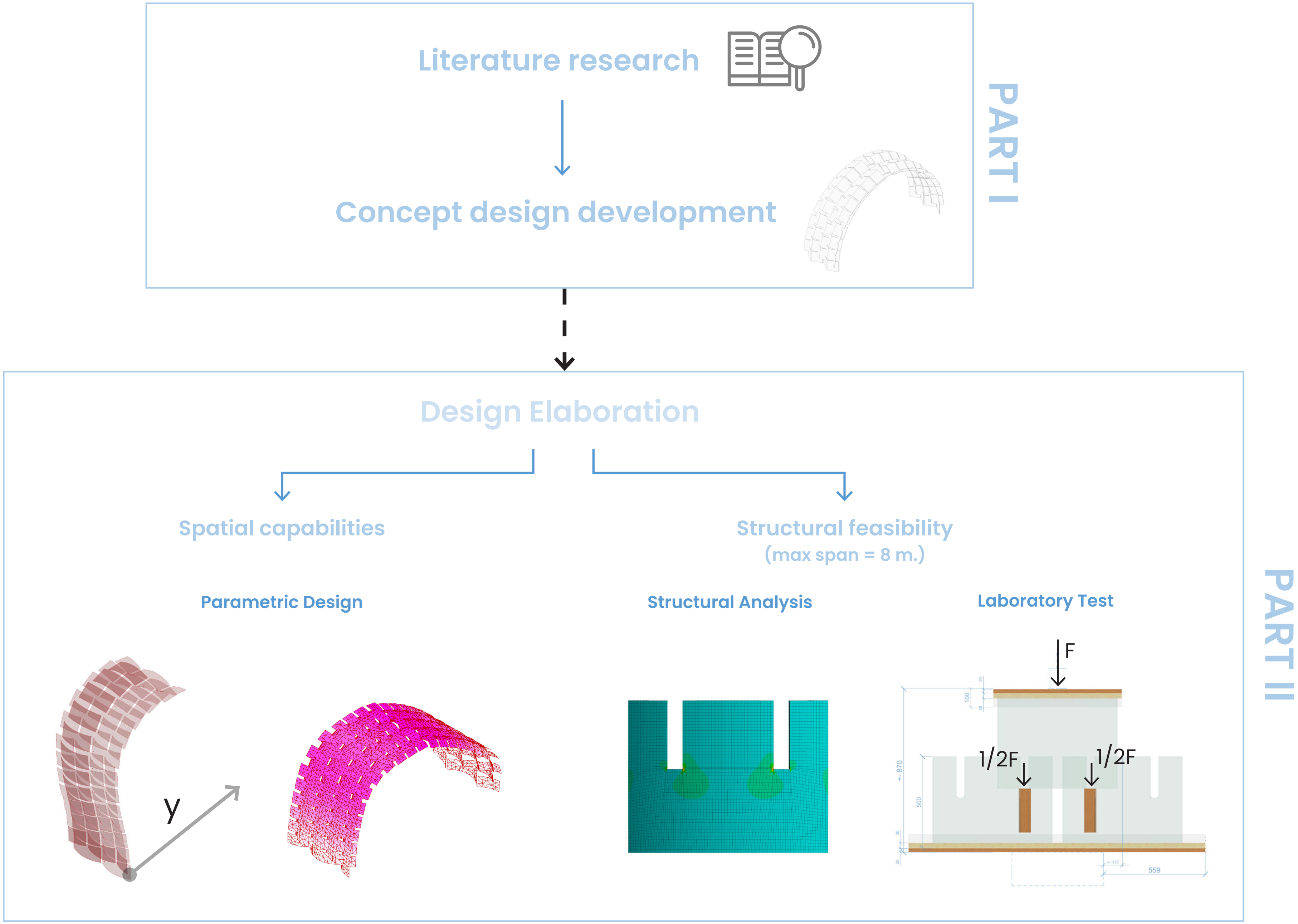

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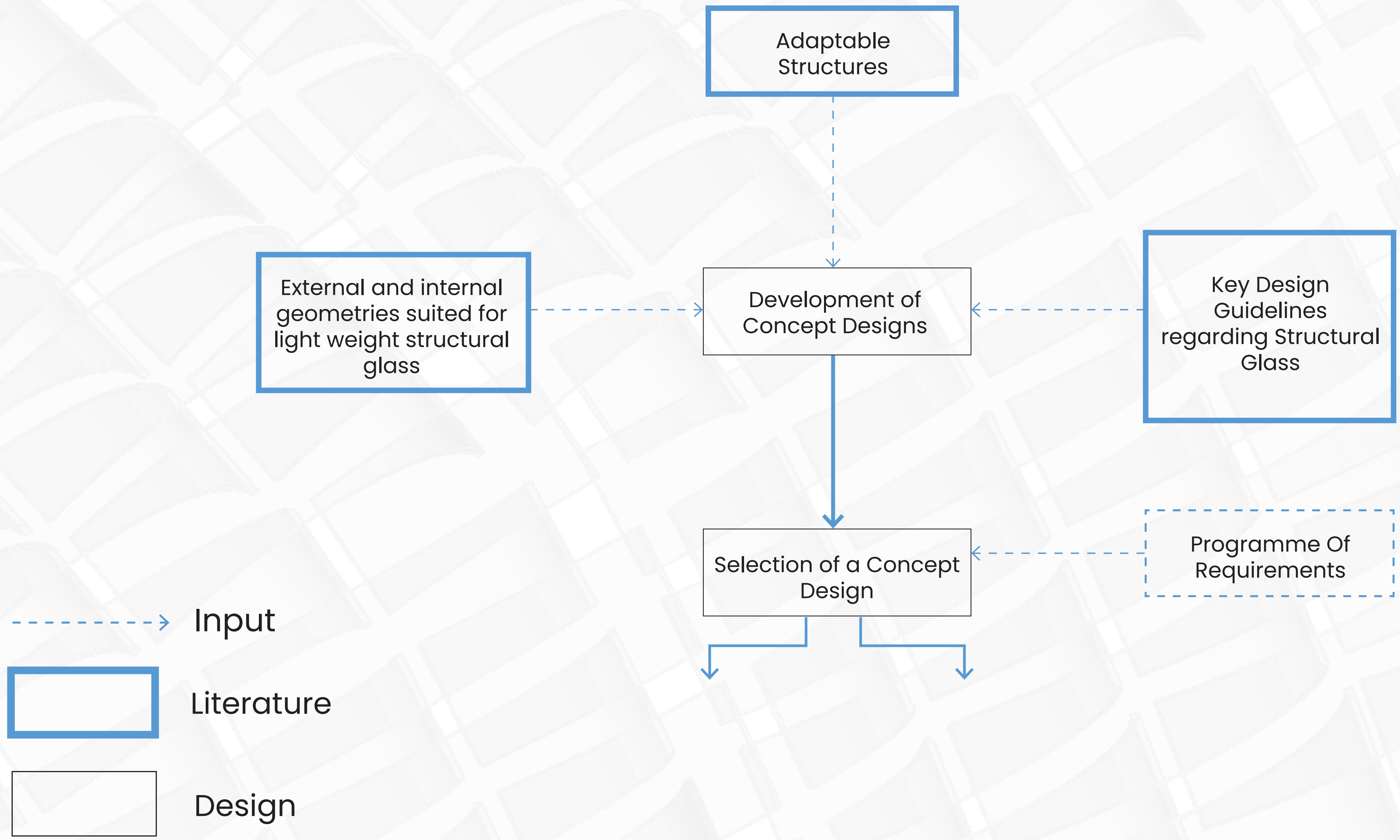
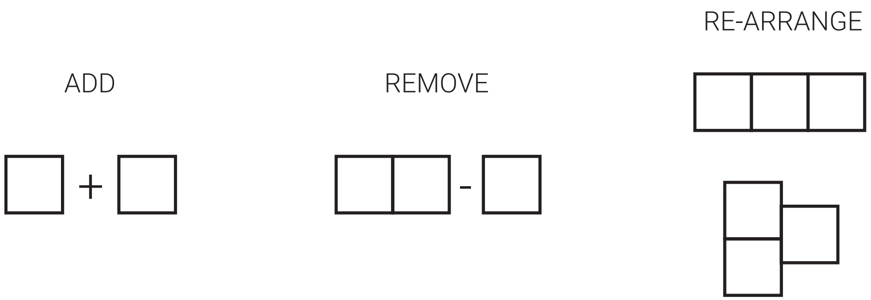
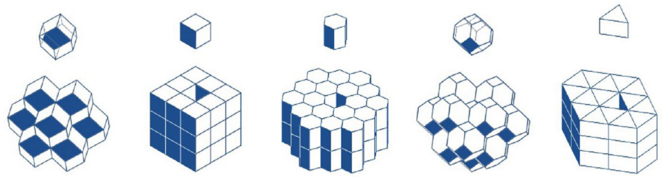
PART I: Concept Development



Adaptable Structures

MODULAR STRUCTURES

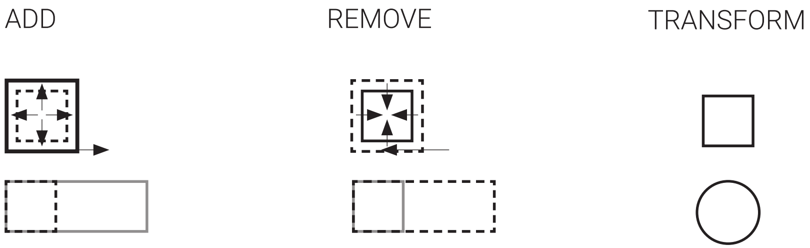


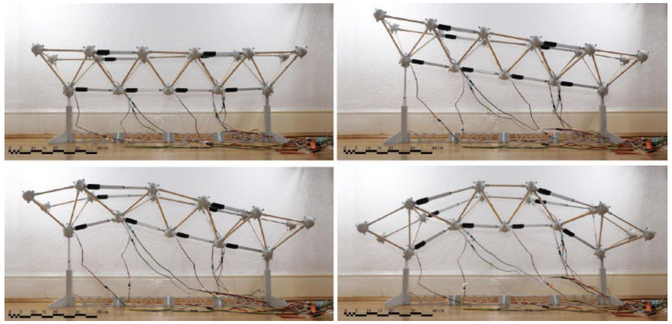


From Mitsimponas & Symeonidou, 2024

Adaptable Structures

TRANSFORMABLE STRUCTURES

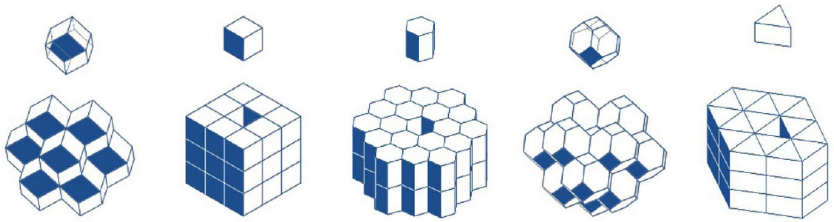




From Hussein et al., 2021

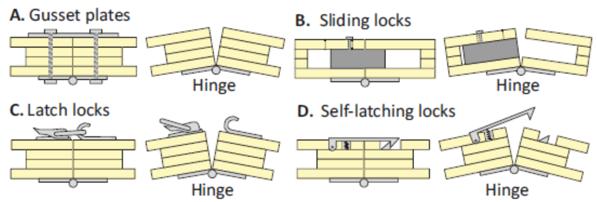
Chosen approach

Modular approach

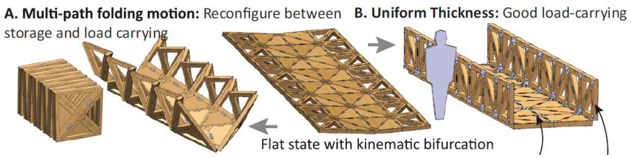


From Mitsimponas & Symeonidou, 2024

Transformable approach

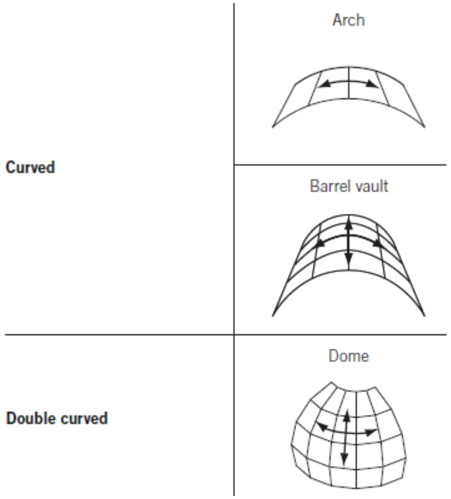


From Zhu & Filipov, 2024



From Zhu & Filipov, 2024

Light Weight Glass Structures

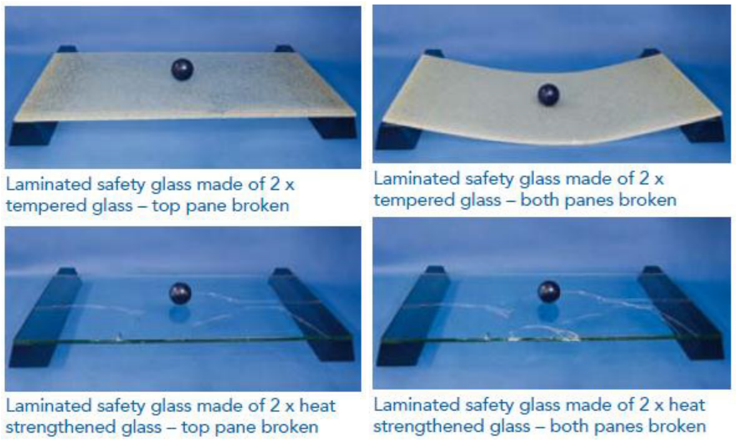


From Wurm, 2007

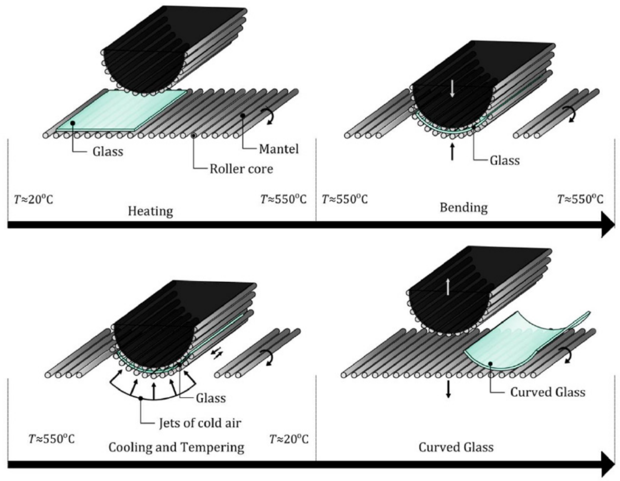
From Wurm, 2007

Key Design Guidelines

safety - strength - shape possibilities - standard dimensions



From Van Dooren, 2014



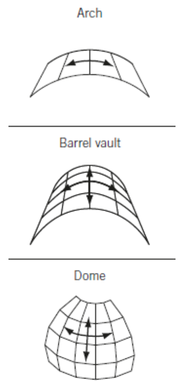
From Datsiou, 2017

Development of concept designs

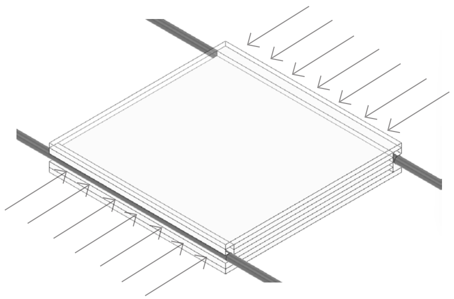
Modularity

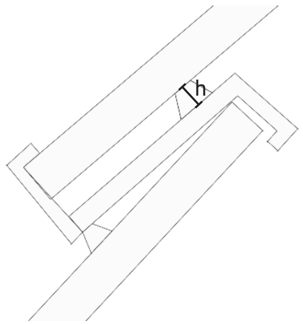
From Mitsimponas & Symeonidou, 2024

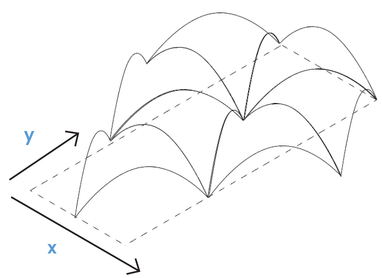
External geometry that stimulates compressional force transfer



From Wurm, 2007







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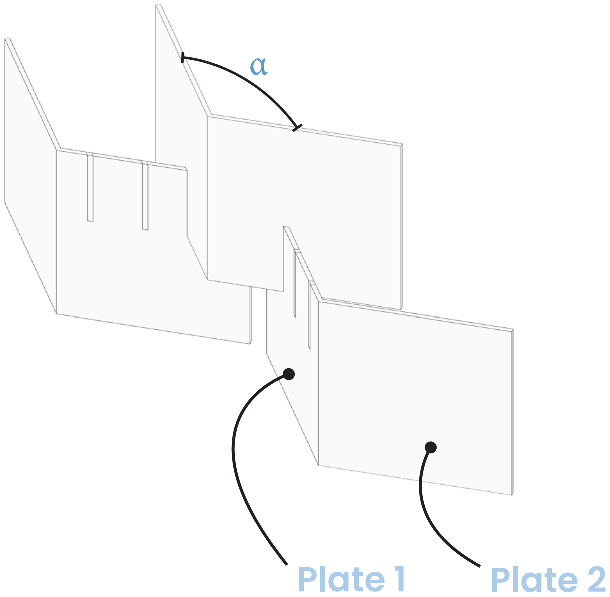
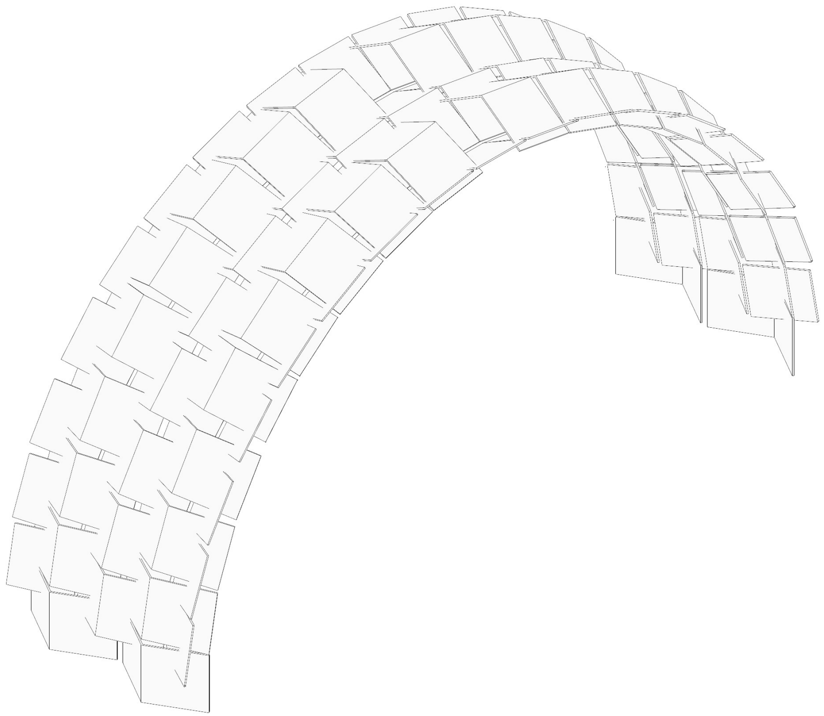
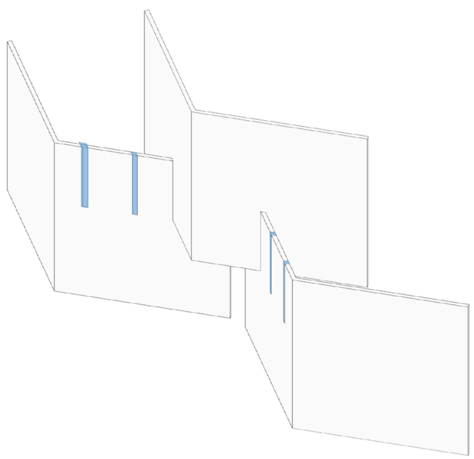
Chosen design concept



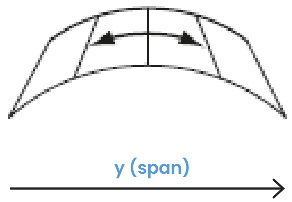


Fulfillment of design requirements

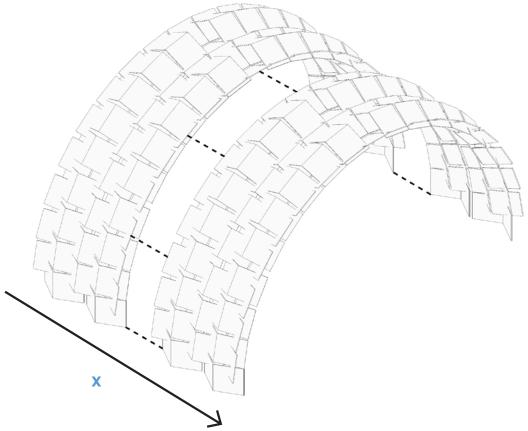
Adaptable span by adding multiple slots along the length of the module, allowing for interlocking in different angles



Creation of external geometry that supports force transfer in compression

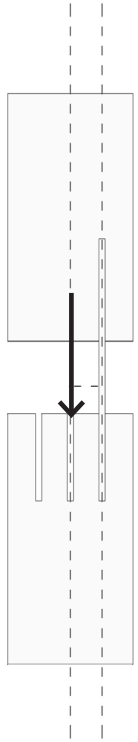


Adaption in x-direction by linking module rows

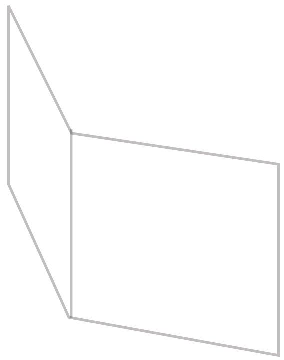


Fulfillment of design requirements

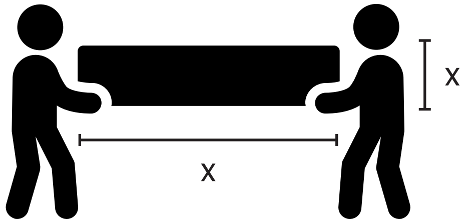
Intuitive and repetitive assembly method
- easy assembly and disassembly



1 standardized element: ease of production, assembly, optimal reuse of structural components at new sites

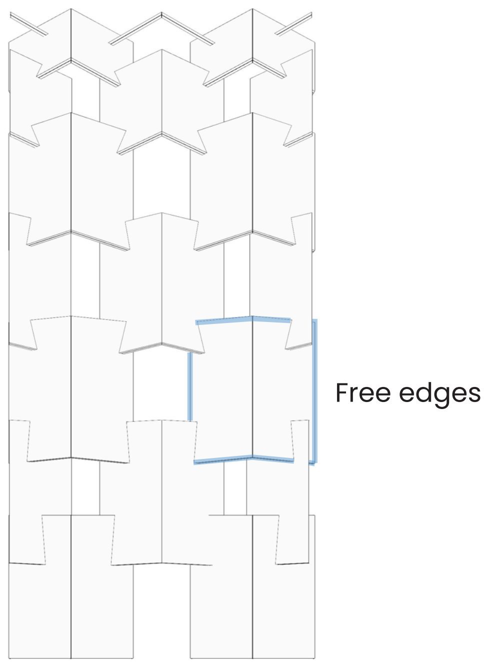


Can be carried by people without the use of a crane



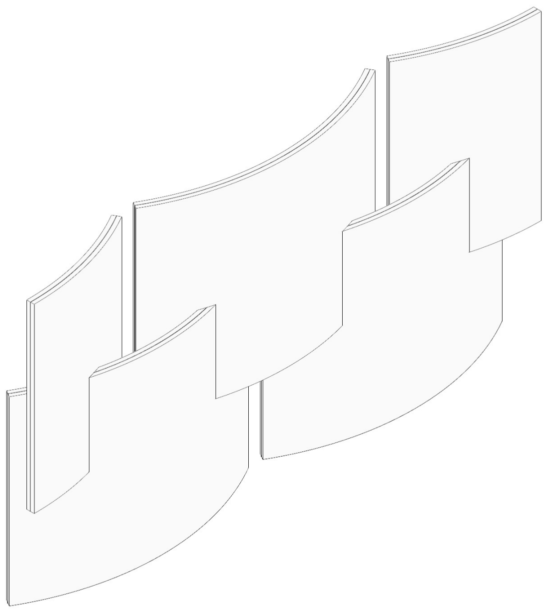
Fulfillment of design requirements

Position of slots keeps module edges clear, enhancing transparency

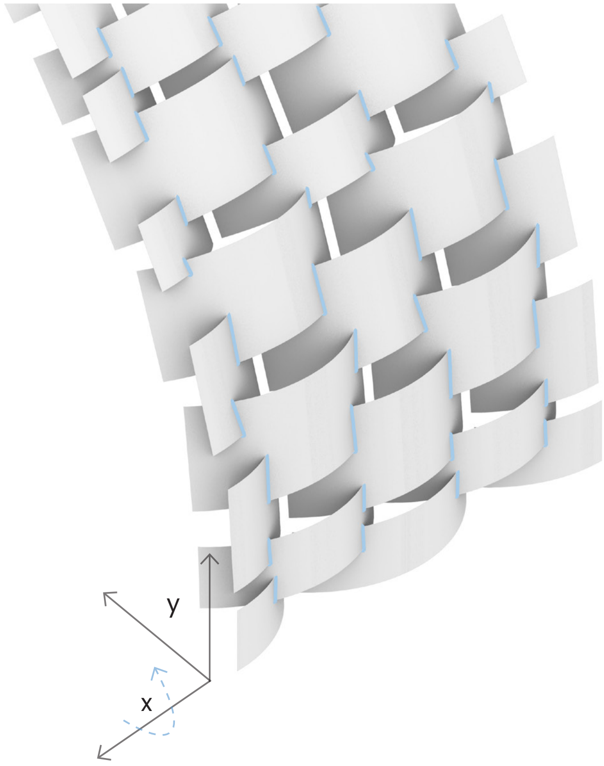


Improvement of the concept

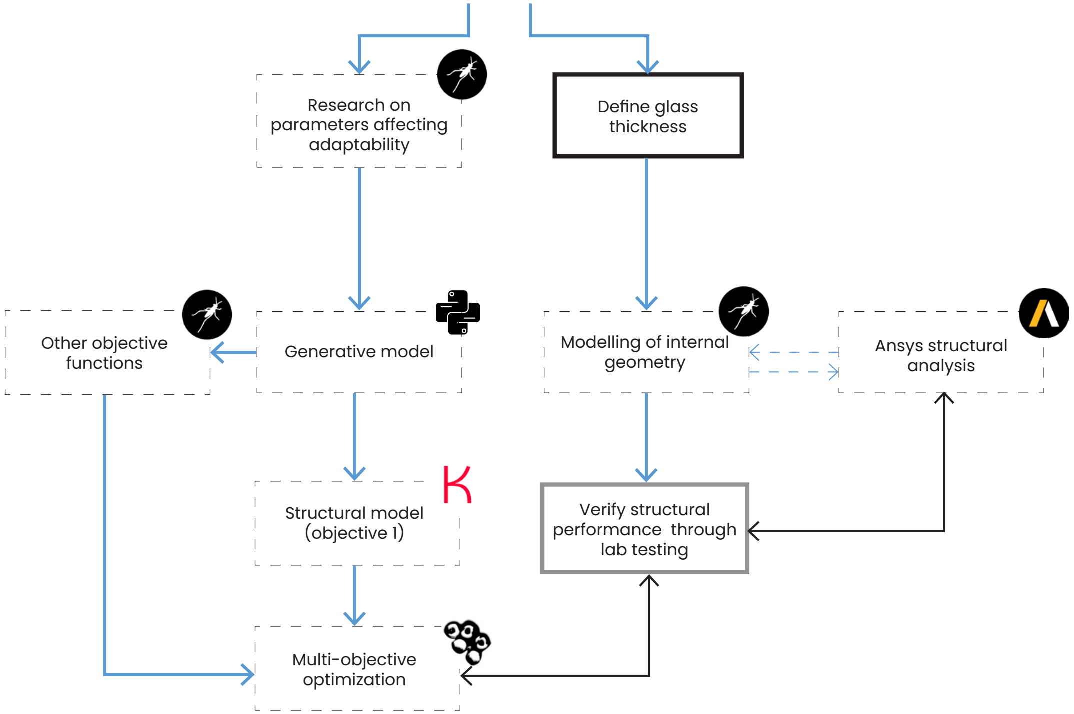
Elimination of structurally weak shear connection: one curved glass plate



Hinged connection



PART II: Design Elaboration



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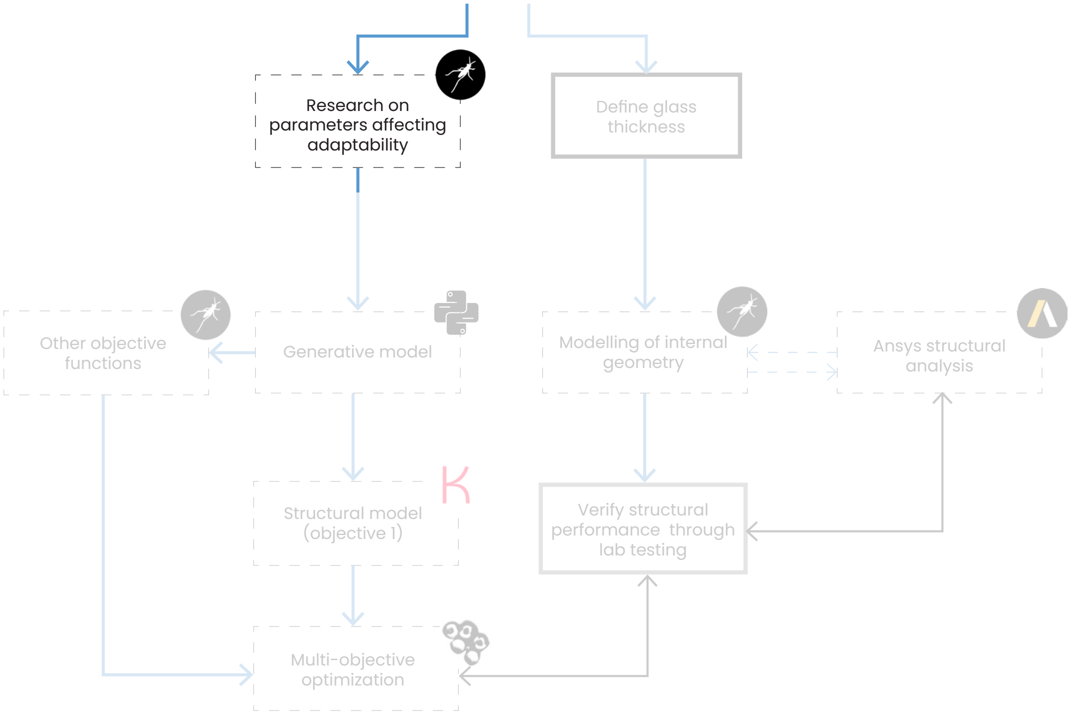

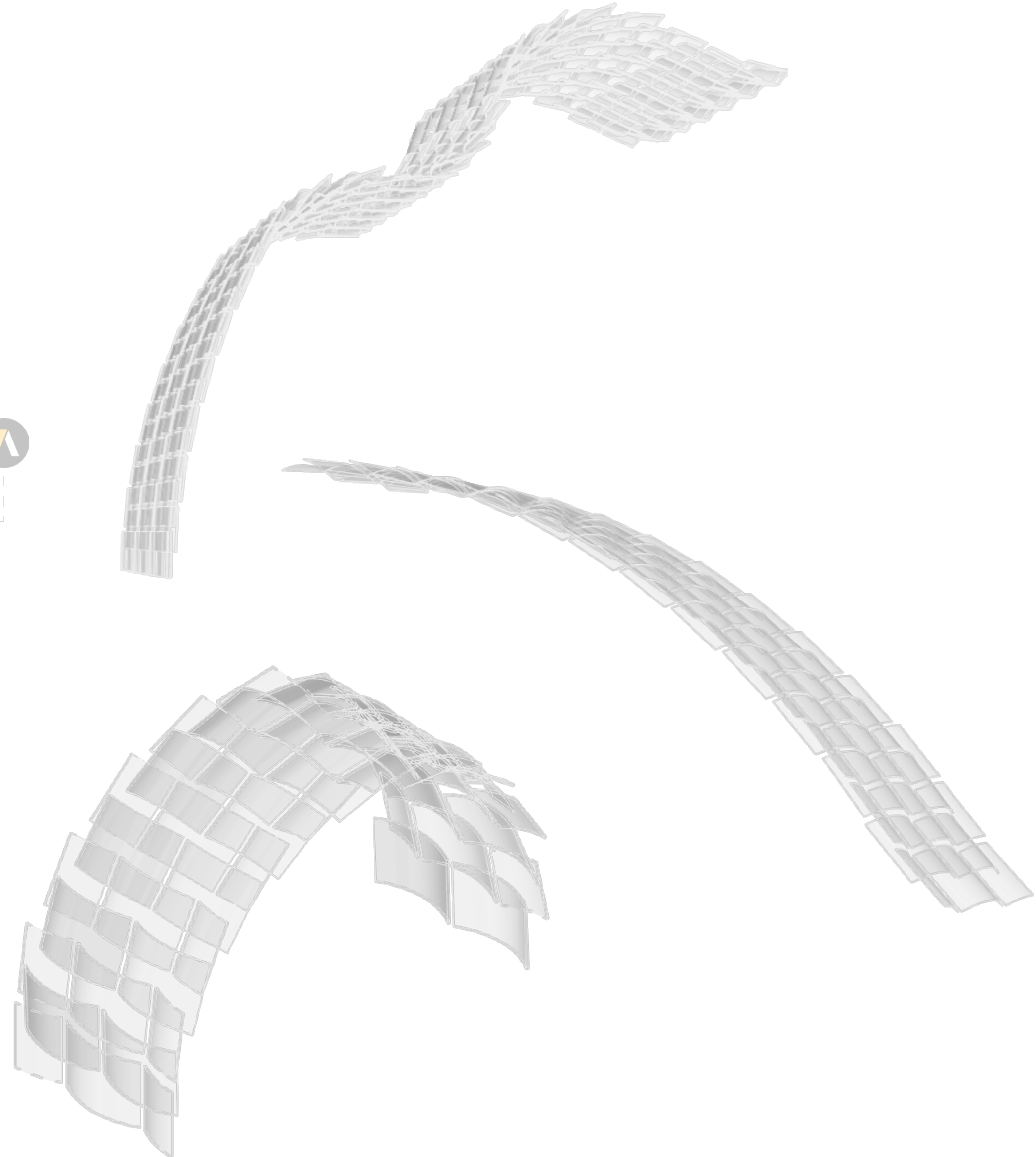

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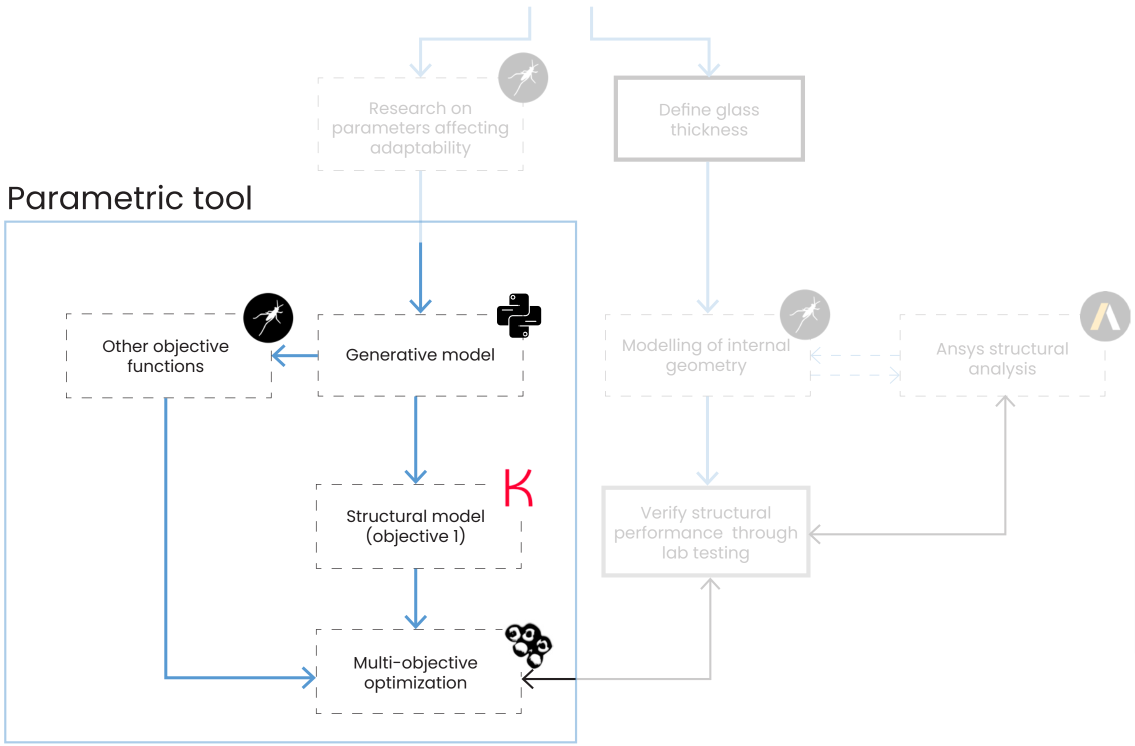

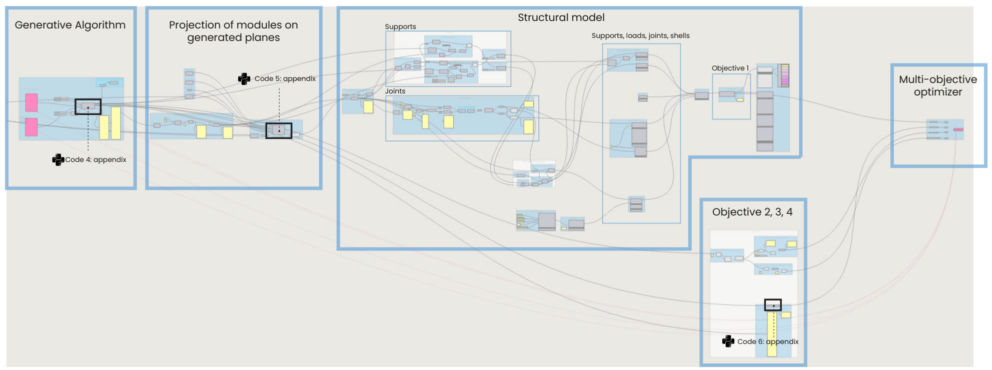

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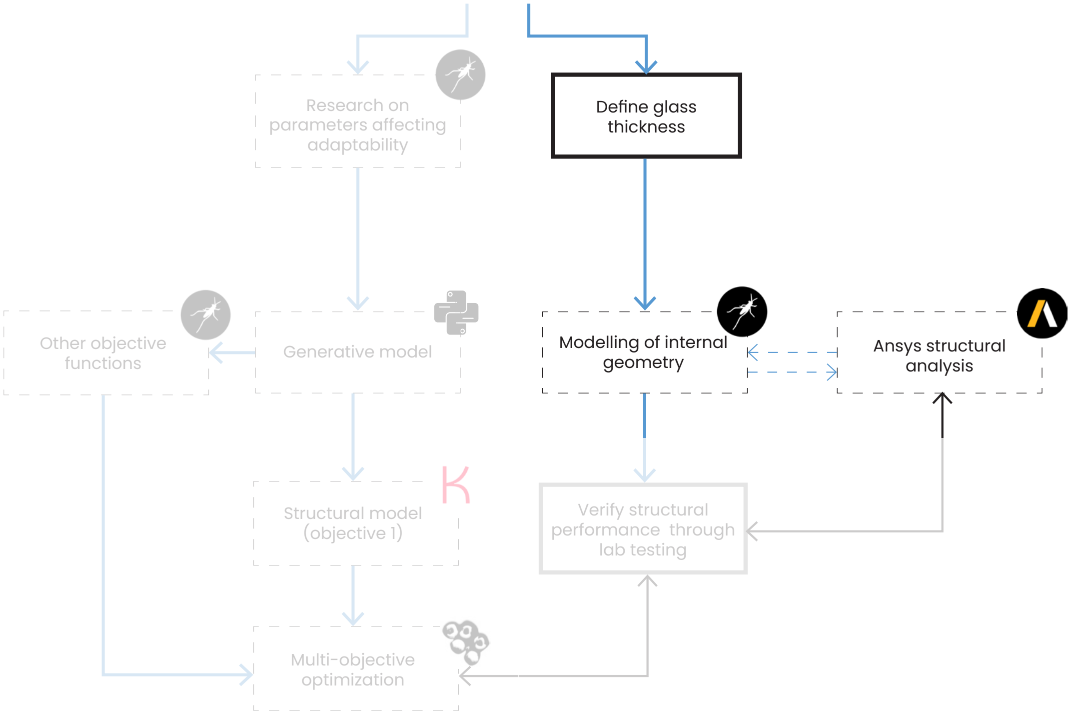

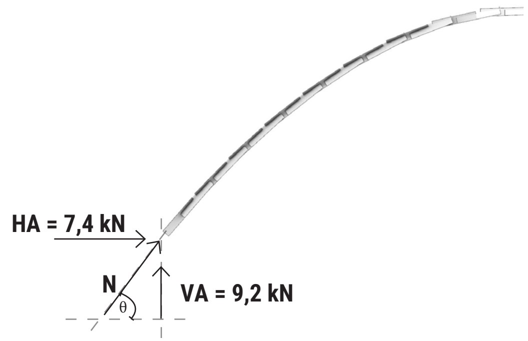

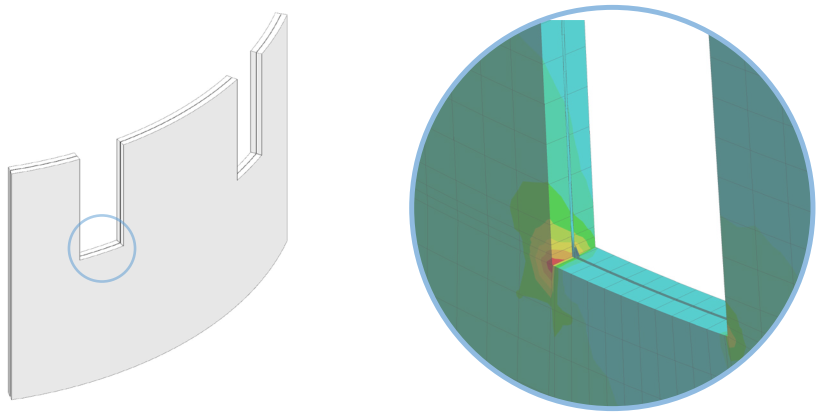

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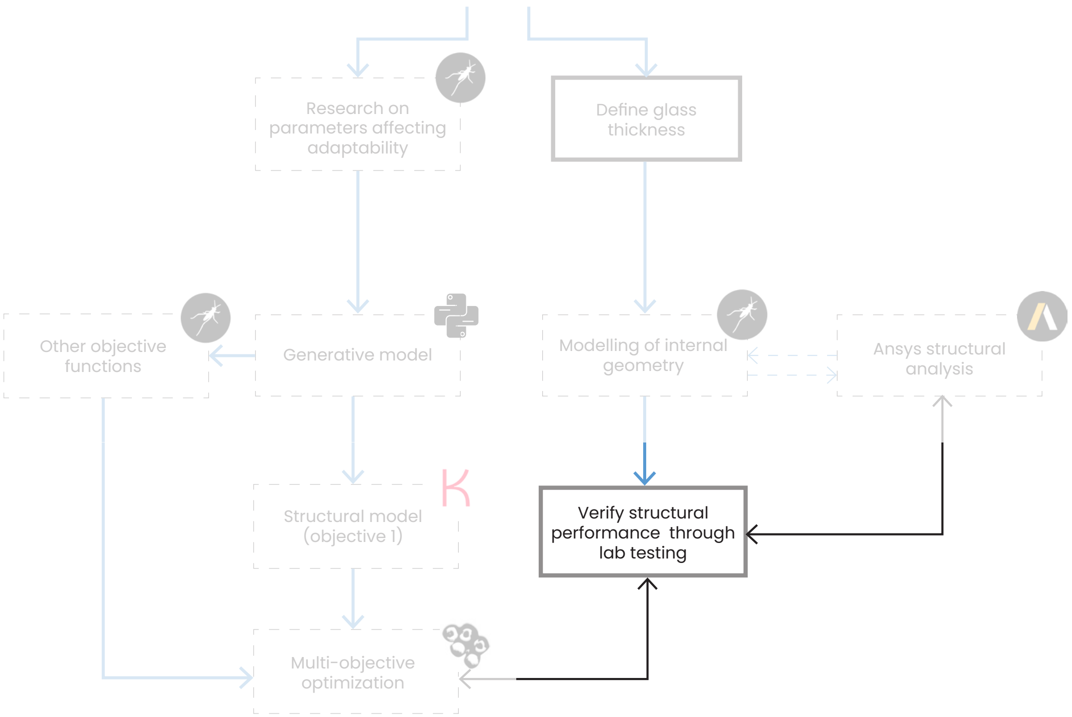
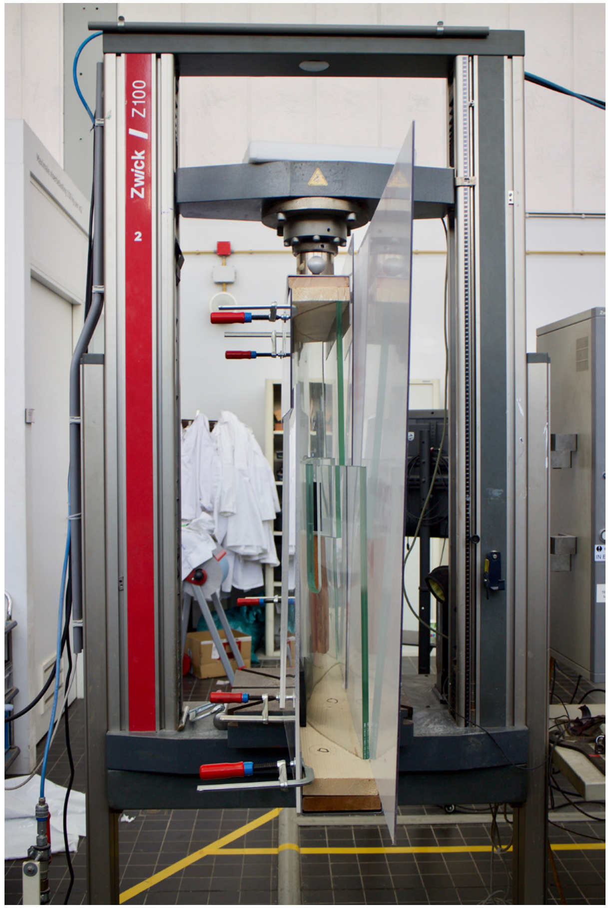
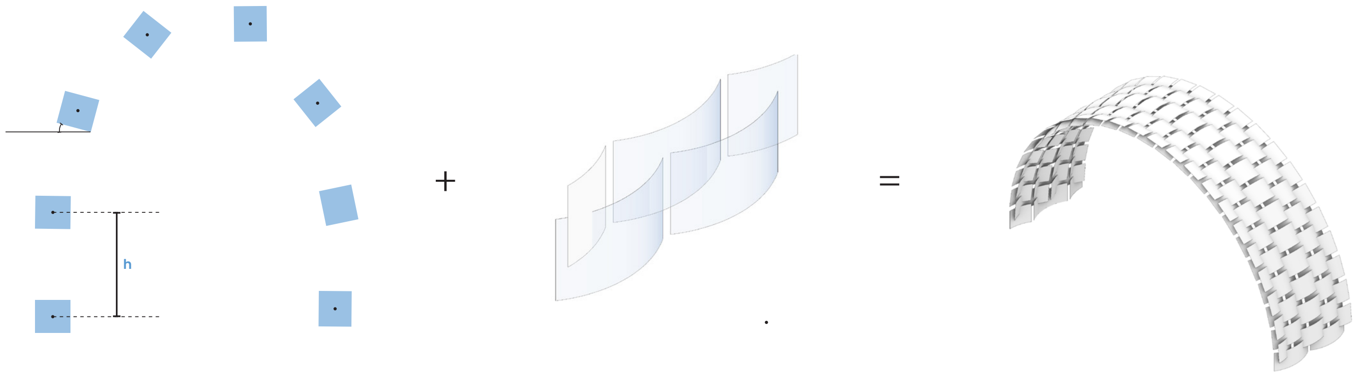




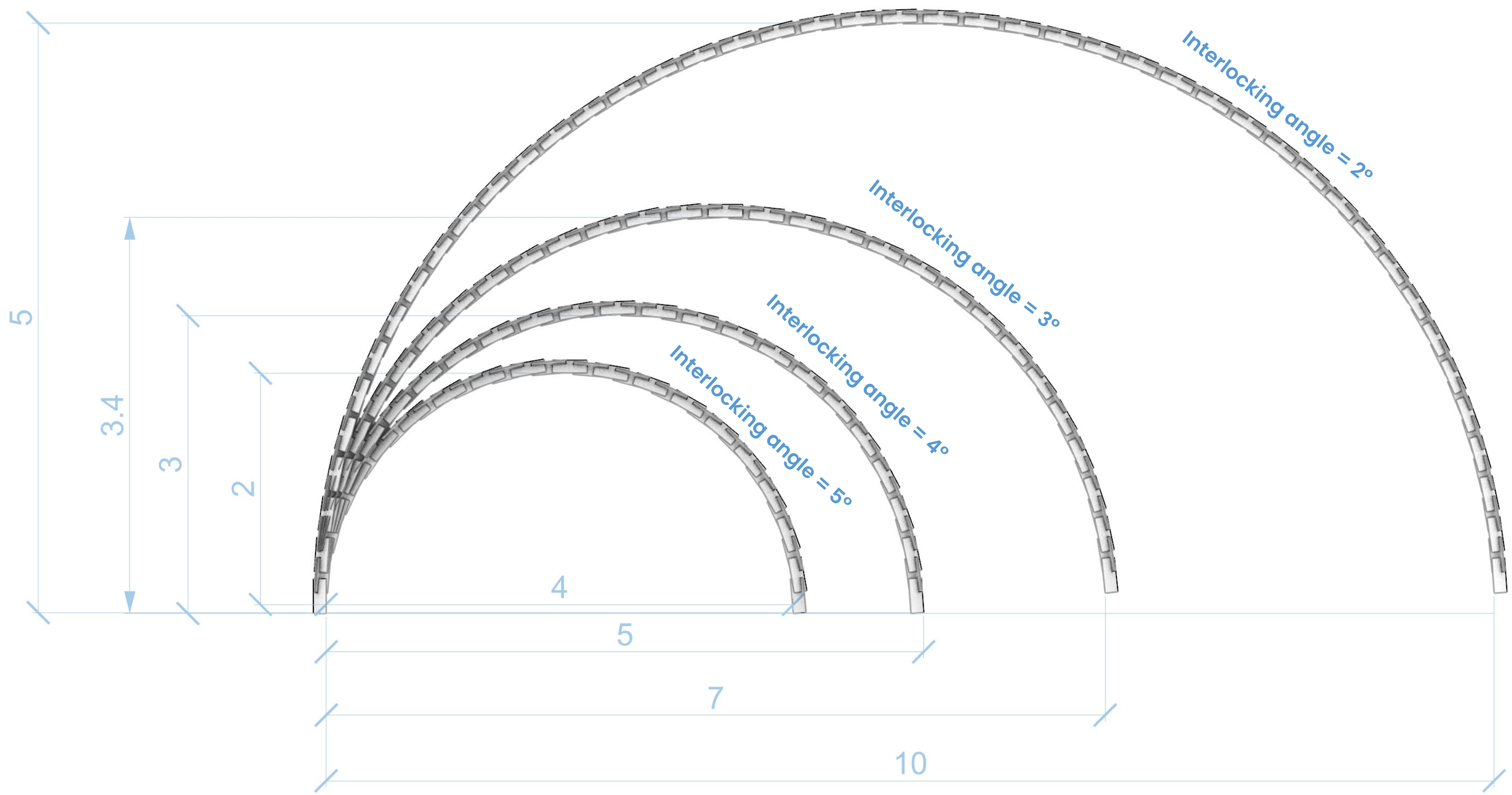
Parameters affecting adaptability




```
#Import libraries
import Rhino.Geometry as rg
import math

#Define base plane as world YZ p
base_plane = rg.Plane.WorldYZ

current_plane = base_plane
planes = []

#Read angle (in degrees) from th
a = angle_step

for i in range(n):
    #Add current_plane to the li
    planes.append(current_plane)

    #Copy current_plane for rota
    rotated_plane = current_plan

    #Rotate copied plane around
    rg.Plane.Rotate(rotated_plan

    #Clone rotated plane to appl
    moved_plane = rotated_plane.

    #Create vector on local y-ax
    move_vector = rotated_plane.

    #Move cloned plane along the
    moved_plane.Origin += move_v

    #Use this relocated plane as
    current_plane = moved_plane
```

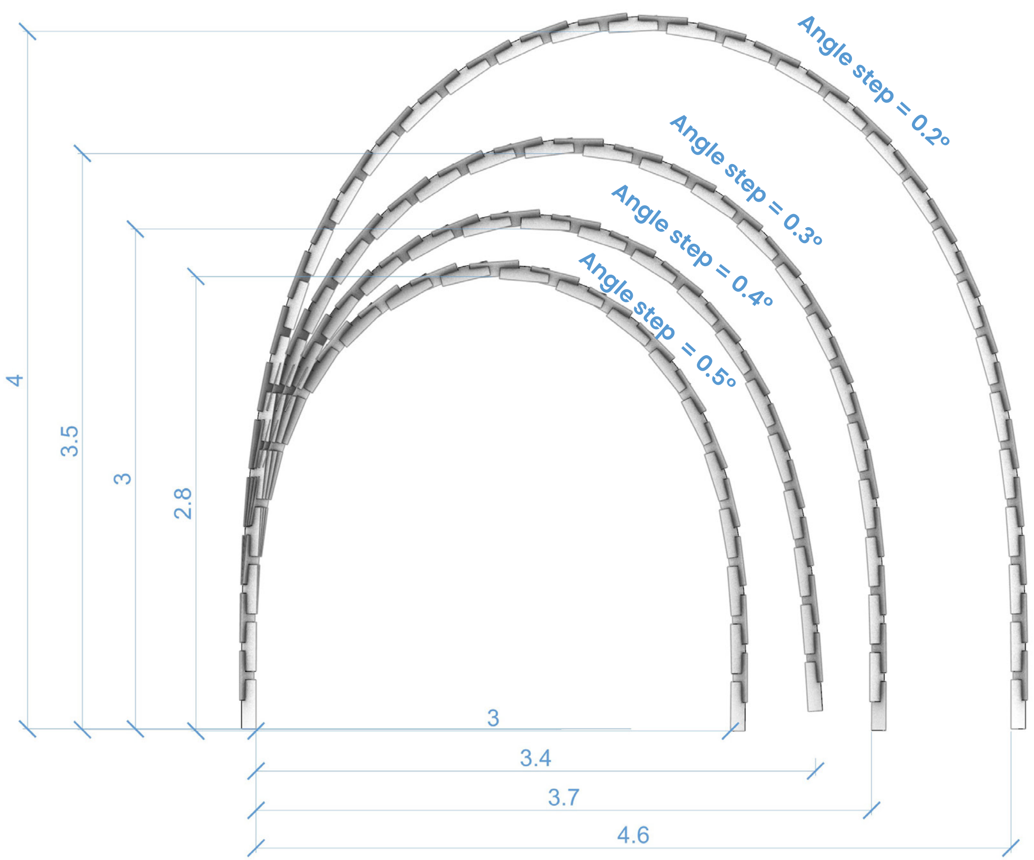
Parameter 1: interlocking angle

Consistent interlocking angle



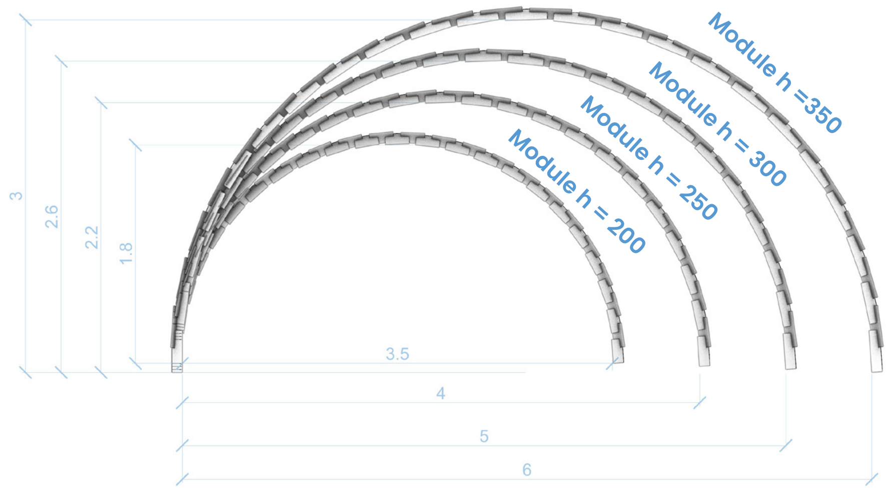
Parameter 1: interlocking angle

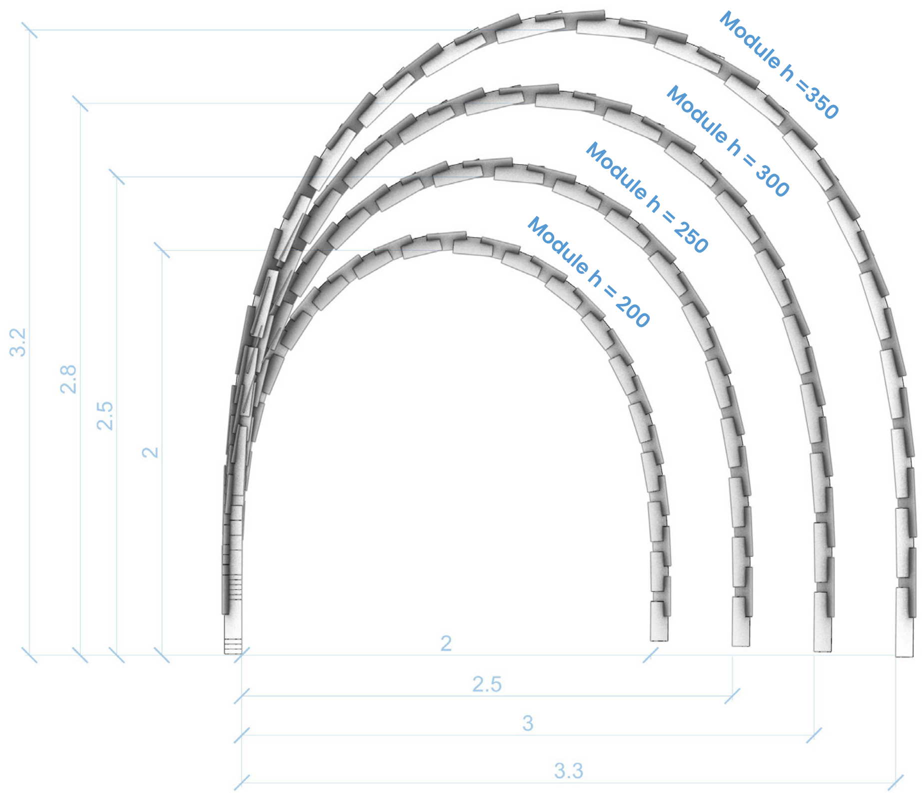
Different interlocking angles



Parameter 2: module height

5 cm height difference





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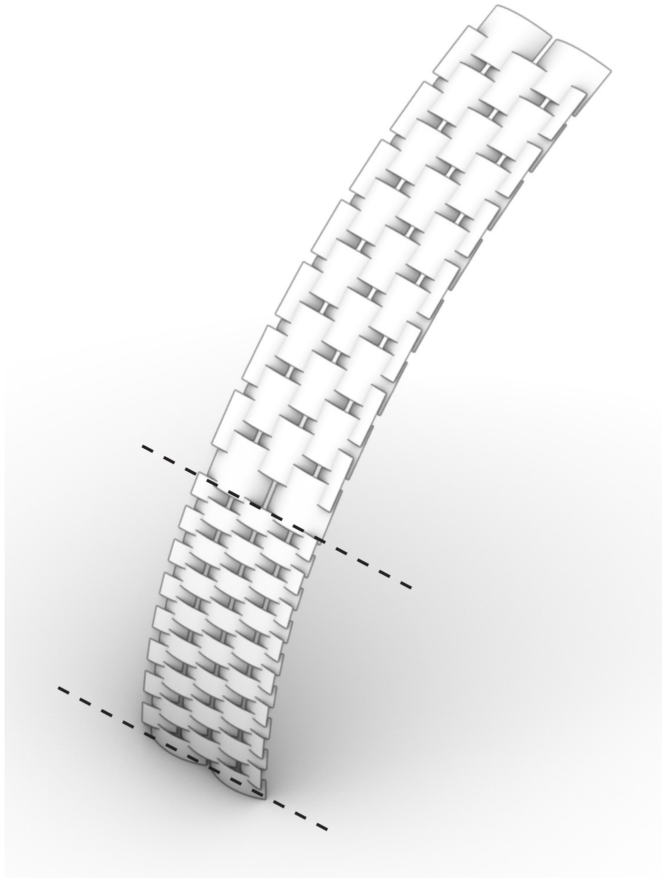
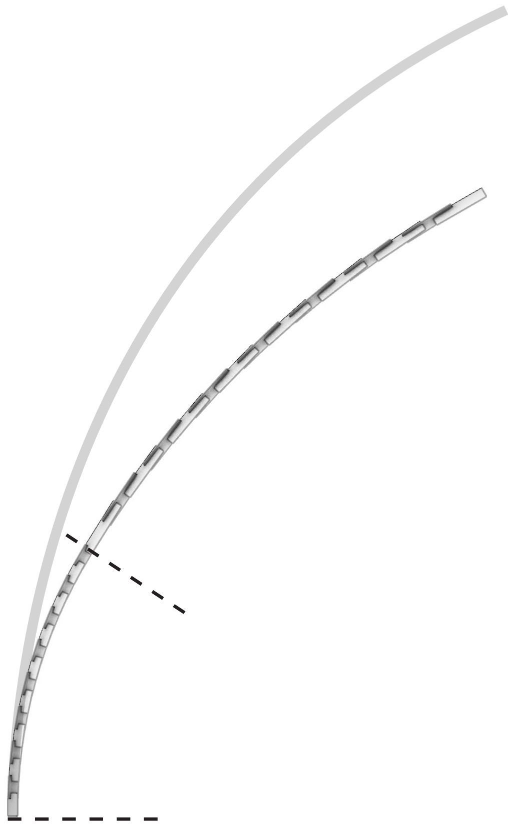
Parameter 2: module height

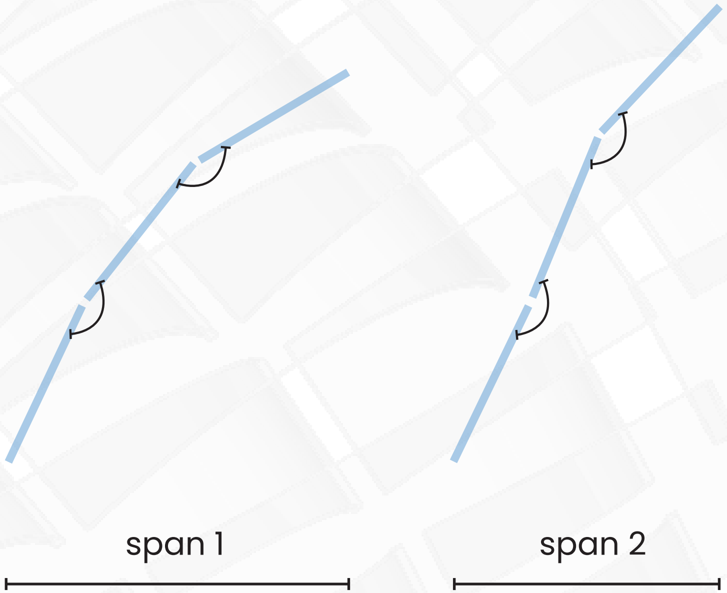




```
import Grasshopper

#Ensure there are at least 2
if n < 2:
    n = 2

#Ensure the number of cluste
if num_clusters < 1:
    num_clusters = 1

#Calculate the maximum numbe
cluster_size = int(math.ceil

#Set the starting plane to t
base_plane = rg.Plane.WorldY
current_plane = base_plane

#List to store all clusters
all_planes = []

for cluster_index in range(n
    #Create a new list for th
    current_cluster = []

    for i in range(cluster_s
        #Compute the "absolu
        global_index = cluste
        #Stop if we've alrea
        if global_index >= n
            break
```

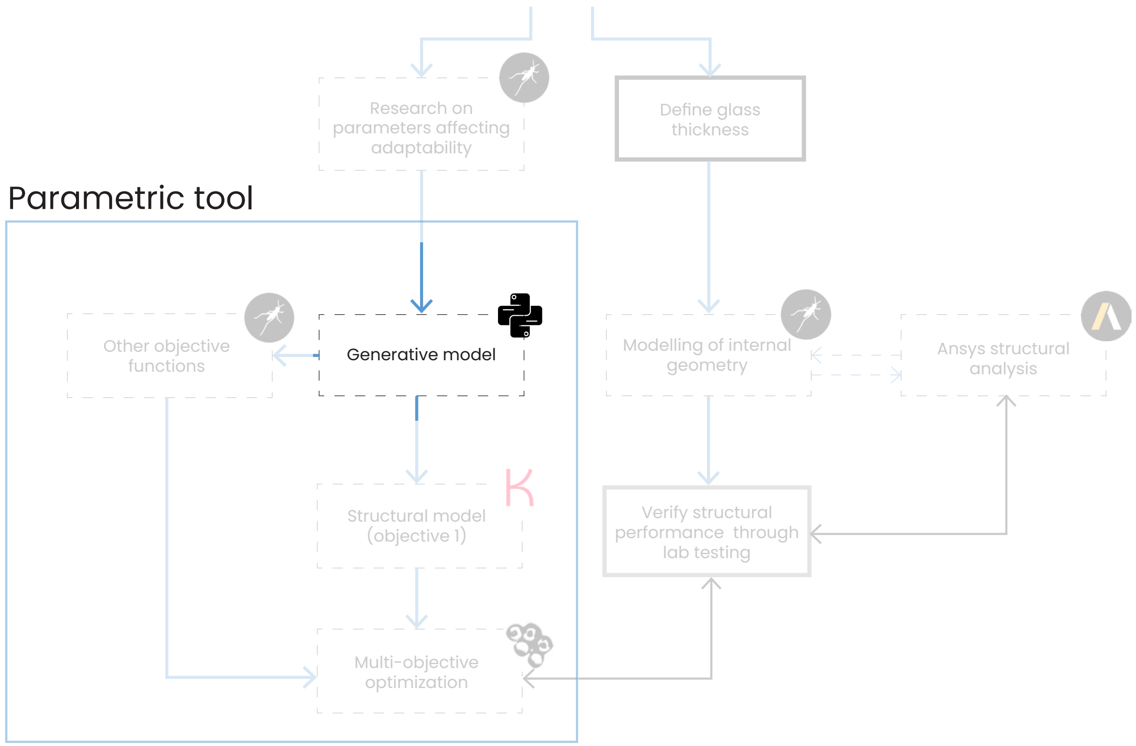
Conclusion

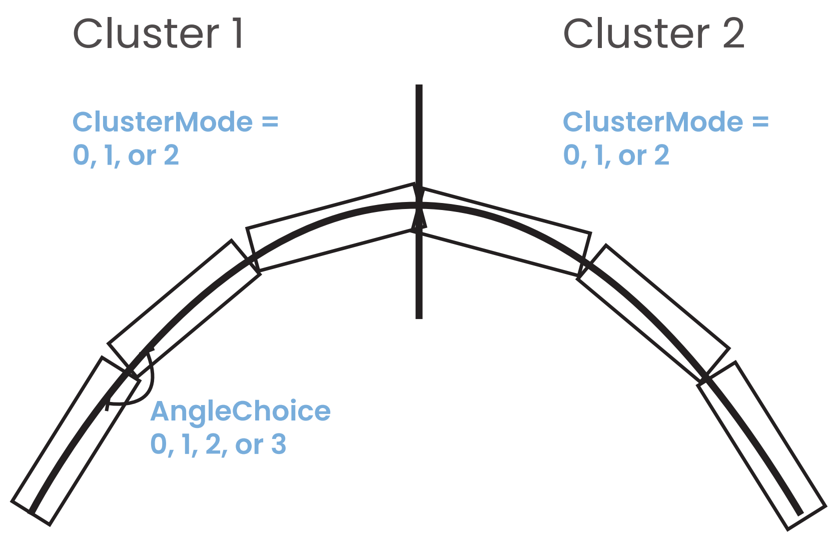
Interlocking angle



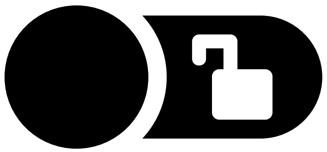
Module height order

Generative model

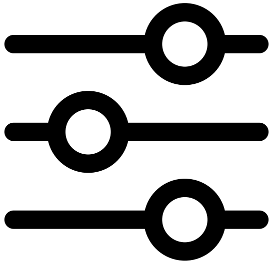




Fixed parameters

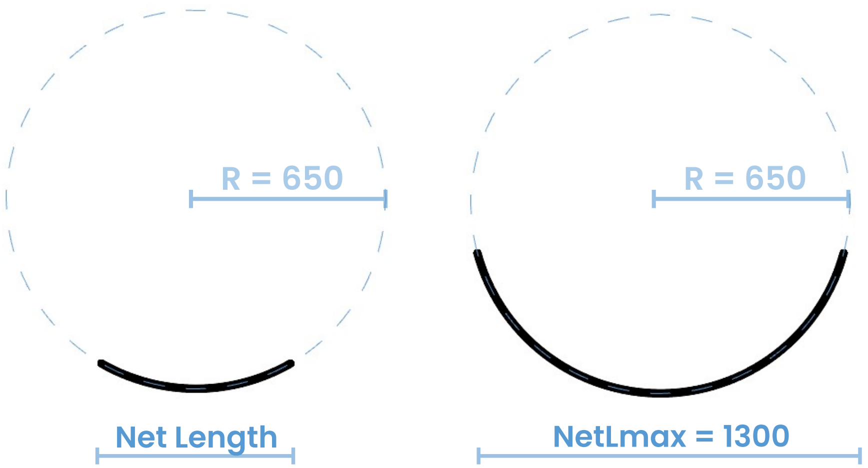


Variable parameters



Fixed parameters

Small bending radius to maximize the amount of interlocking angles while minimizing the net length

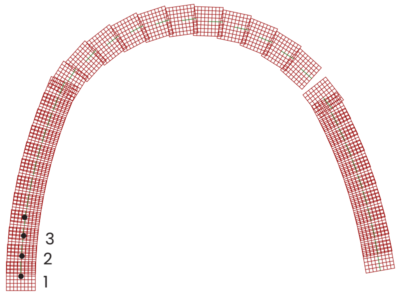


First module height = 0.5 m
to carry a long module

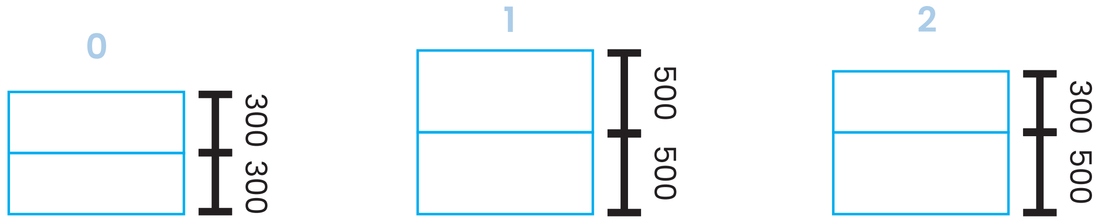
Second module height = 30 cm: contrast with 0.5, allowing enough span variation

Variable parameters

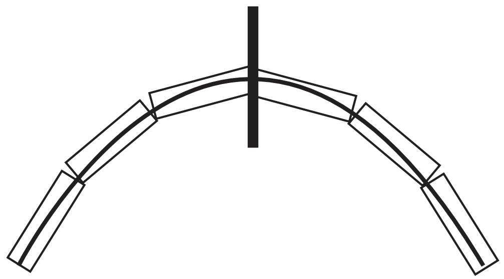
Amount of stacked modules



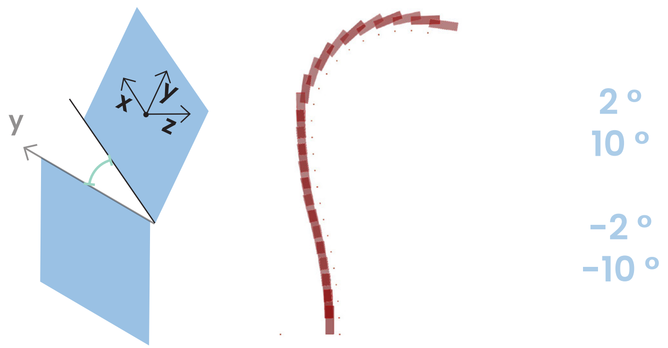
Clustermodes



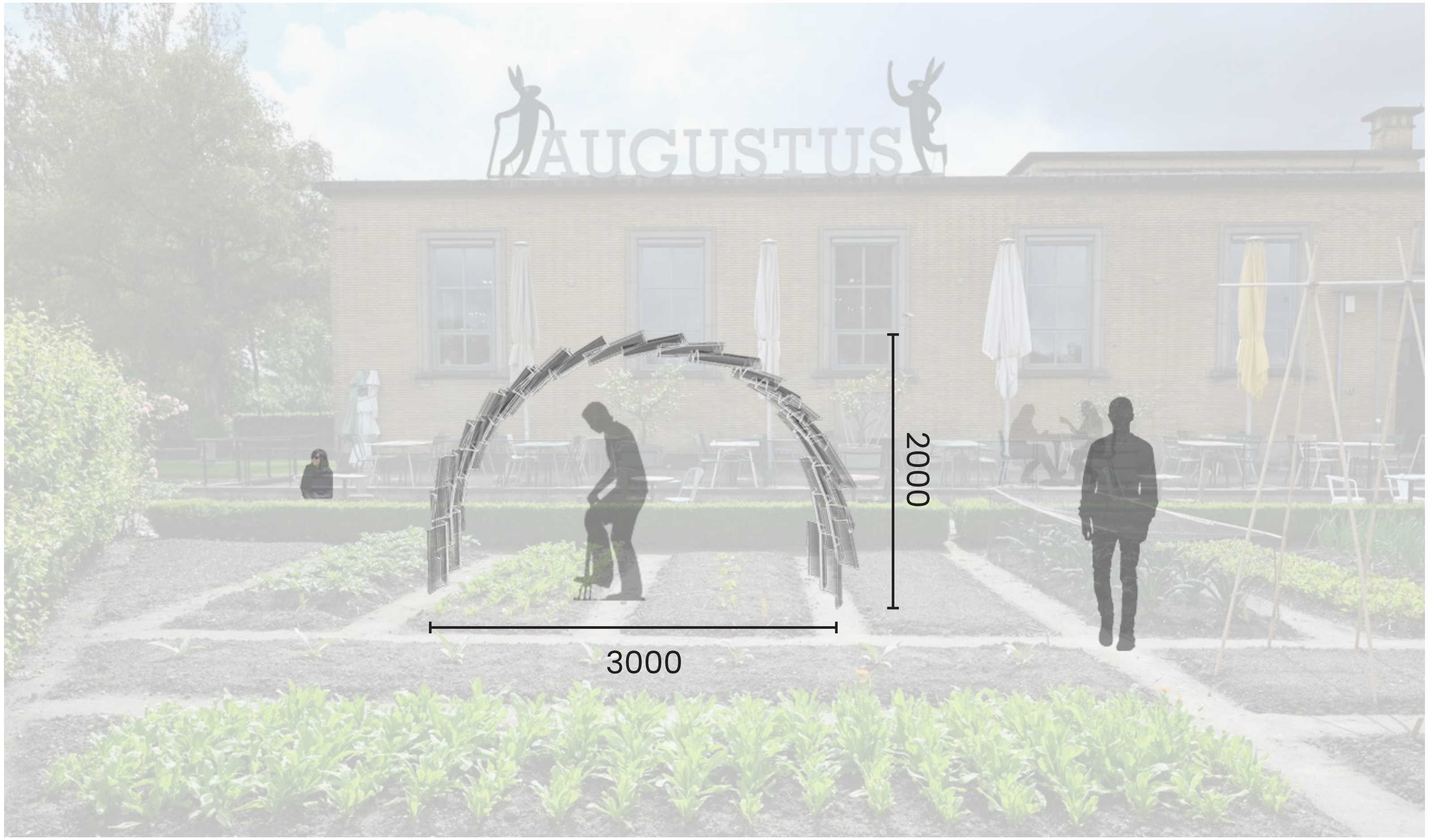
Amount of clusters



Angle between modules (AngleChoice)



```python

#Add angles with angle choice 0 if amount of
L = len(pattern)
if len(angles) < L:
    angles += [0] * (L - len(angles))
else:
    angles = angles[:L]

#Loop through each plane in the structure
for idx, H in enumerate(pattern):
    #add world YZ plane to the data tree
    planes_tree.Add(current, path)

    #Retrieve angle index
    angle_idx = angles[idx]
    #Link angle map value to correct angle in
    angle_deg = angle_map[angle_idx]
    rad       = rad_map[angle_idx]

    #Determine shift on Y axis depending on m
    H_prev = pattern[idx-1] if idx > 0 else N
    H_next = pattern[idx+1] if idx < len(patt

    if idx in prev_starts:
        # eerst checken of H_next geen None i
        if H_next is not None and H_next <= H
            move_dist = H - (0.5 * H_next) +
        else:
            move_dist = H - (0.5 * H) + 25

    elif H_next is None:
        move_dist = (0.5 * H) + 25

    elif H_next < H:
        move_dist = H - (0.5 * H_next) + 25

    elif H_next > H:
        move_dist = H - (0.5 * H) + 25

    elif H_prev is not None and H_prev <= H:
        move_dist = H - (0.5 * H) + 25
```



Background image: by Van Wendel de Joode, R. (n.d.). Vegetable garden at Villa Augustus (Dordrecht)

Order of module heights

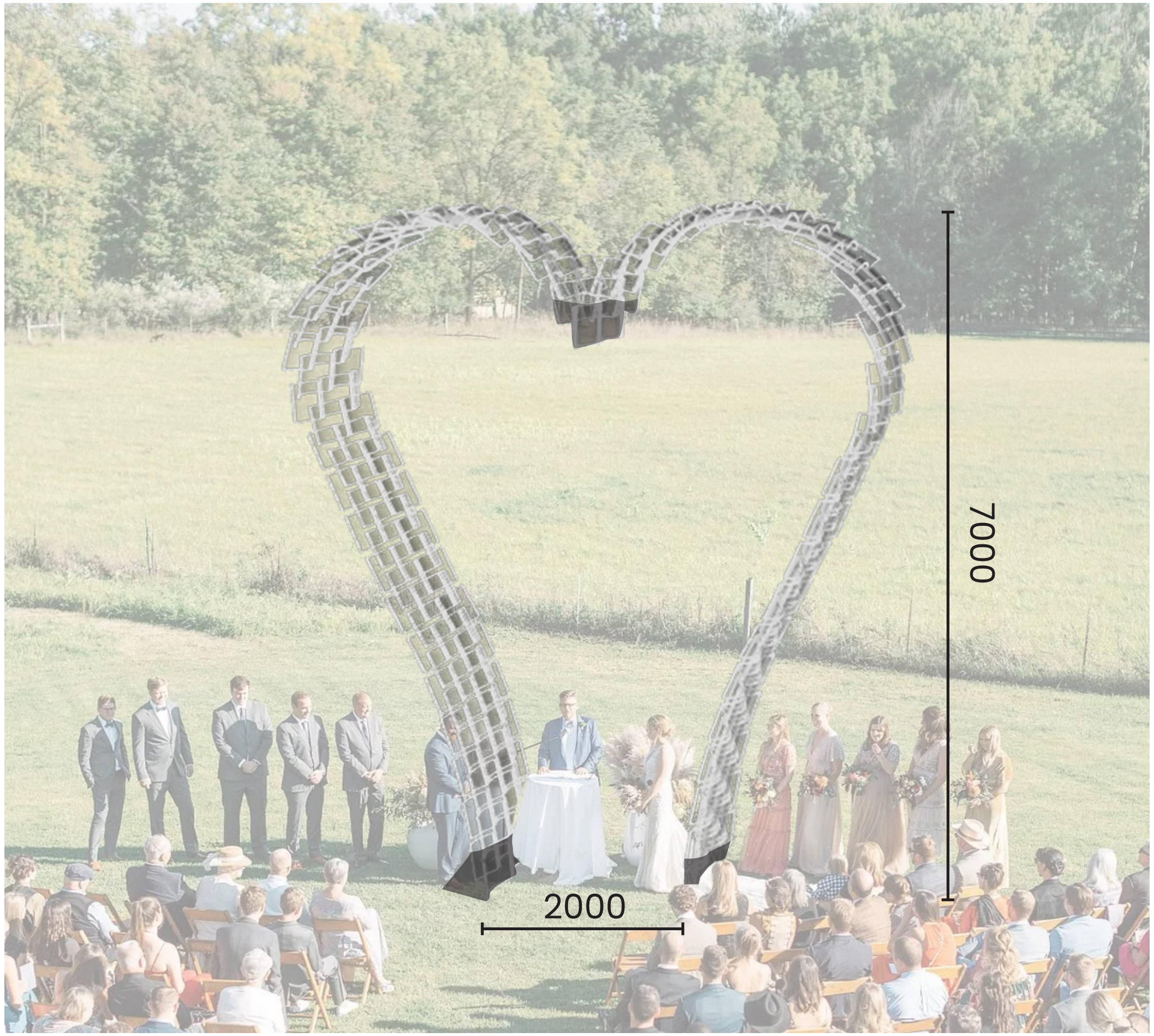
0	300
1	500
2	300
3	300
4	300
5	500
6	500
7	300
8	500
9	500
10	500
11	500
12	500
13	500
14	500
15	500
16	300
17	300
18	500
19	500
20	300
21	300
22	300
23	500

Order of interlocking angles

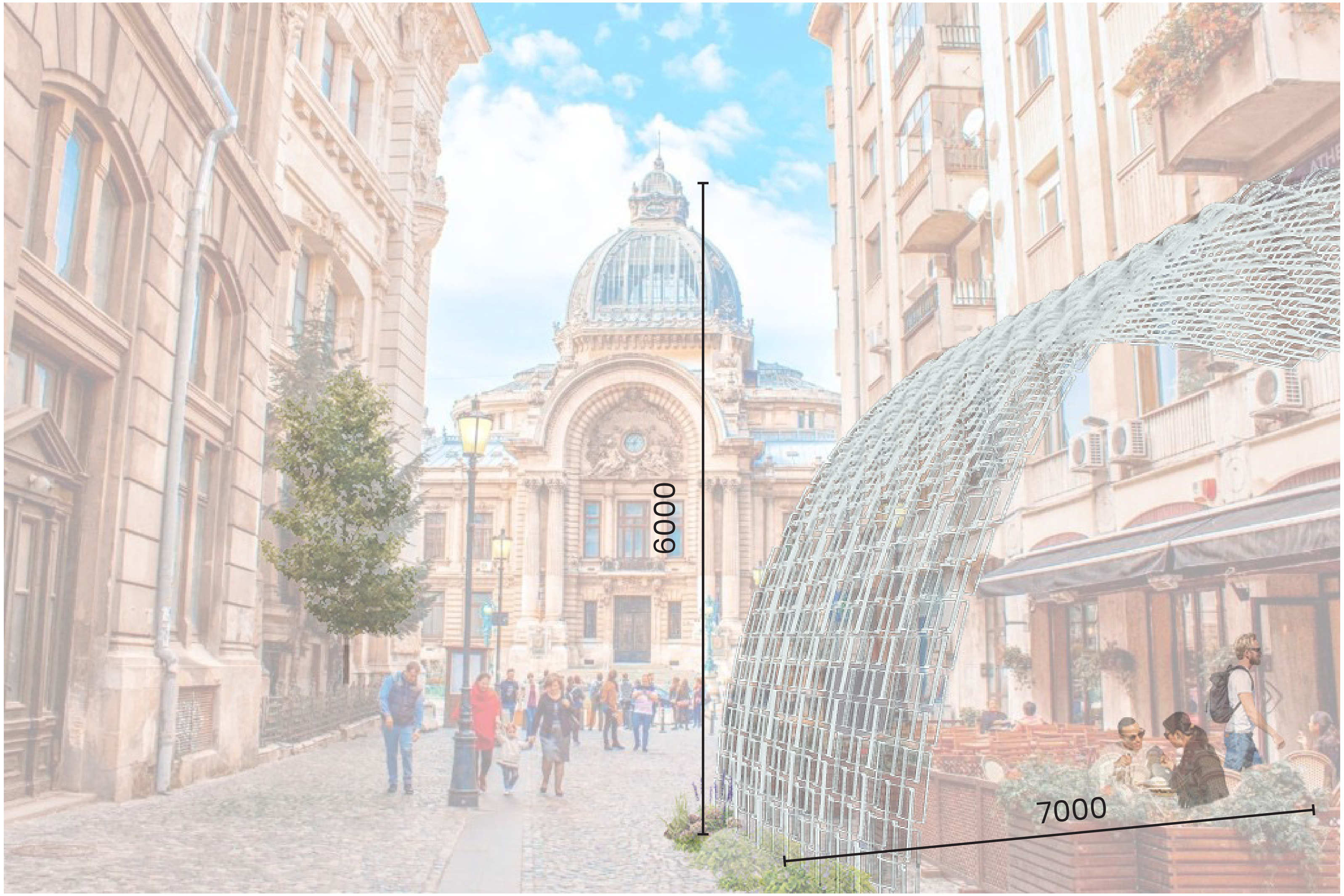
0	2
1	2
2	2
3	2
4	2
5	10
6	10
7	10
8	10
9	10
10	10
11	10
12	10
13	10
14	10
15	10
16	10
17	10
18	10
19	-2
20	-2
21	-2
22	-2
23	-2

Background image: by De Meester, L. (2021). World Press Photo exhibition in the Koepelgevangenis, Breda

Background image: by Koolbergen, K. (2023). The Darwin Flower Garden

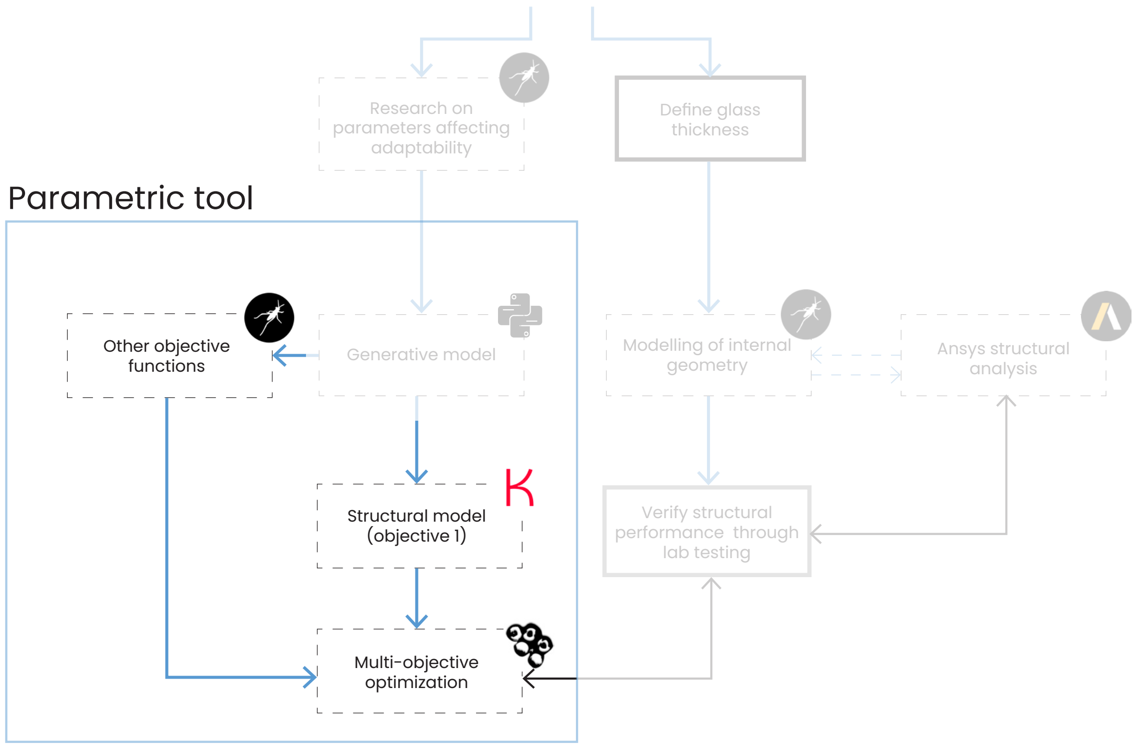


Background image: by Lobach, A. (n.d.)

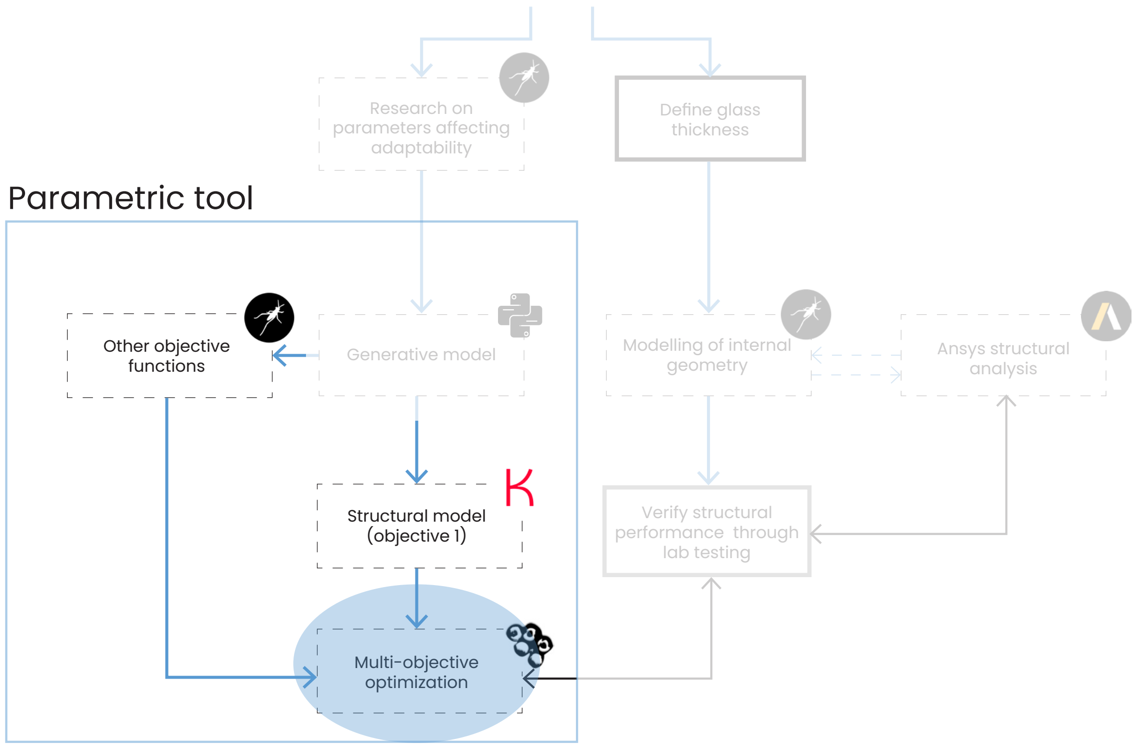


Background image: by Sibai, R. (2014). Bucharest, Romania

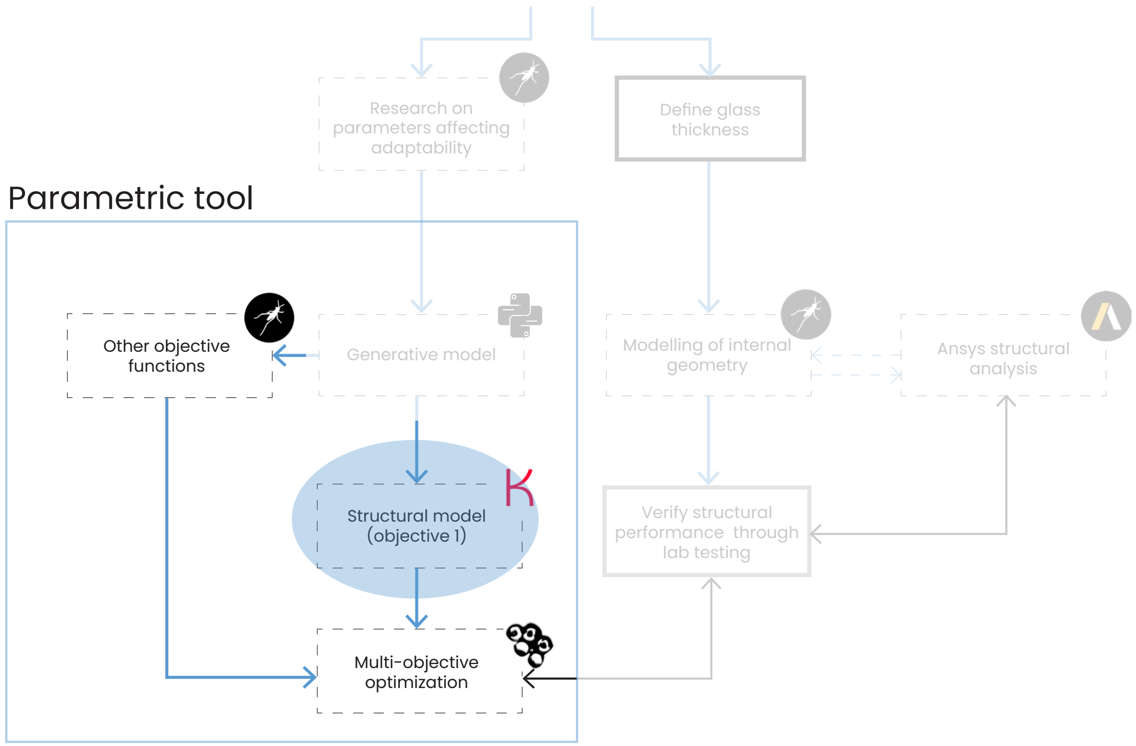
Multi-objective optimization



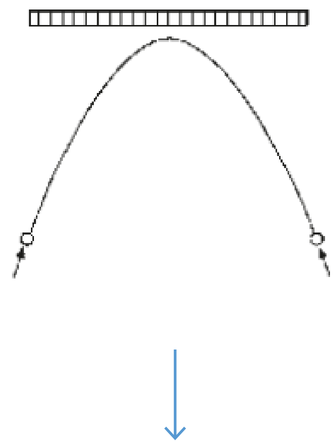
Multi-objective optimization



Multi-objective optimization

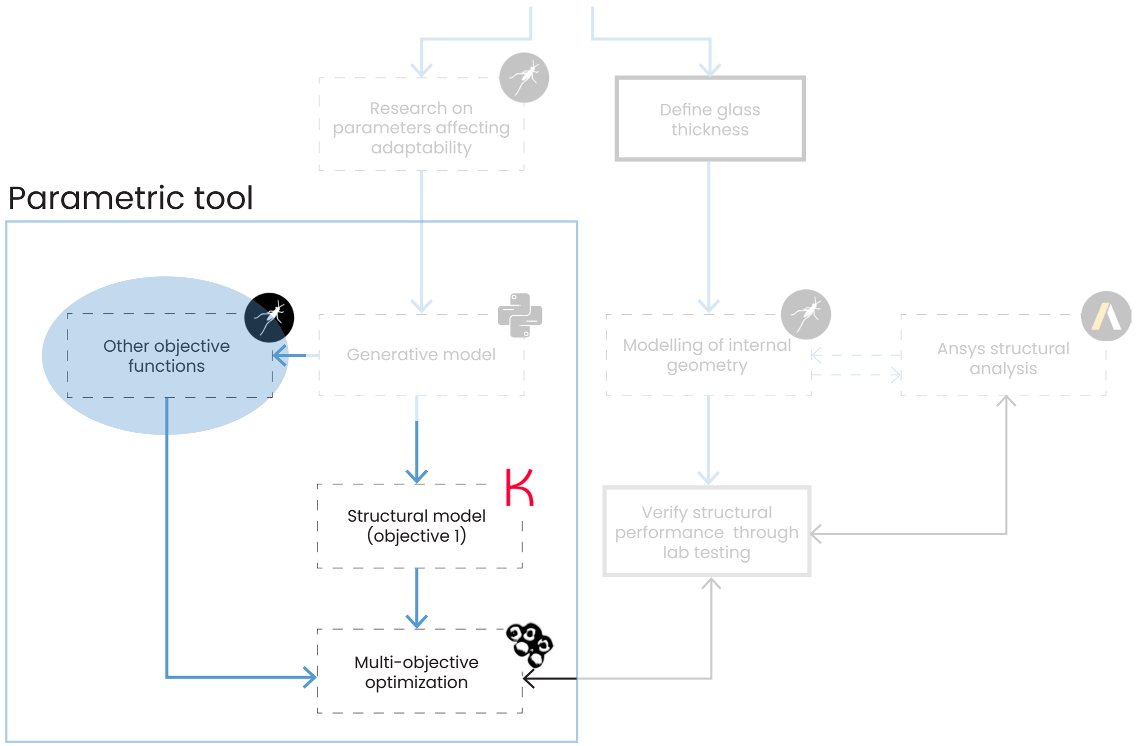


Objective 1.
Minimize global structural displacement resulting from self-weight, as the structure is primarily subjected to its own weight.



Minimize material use

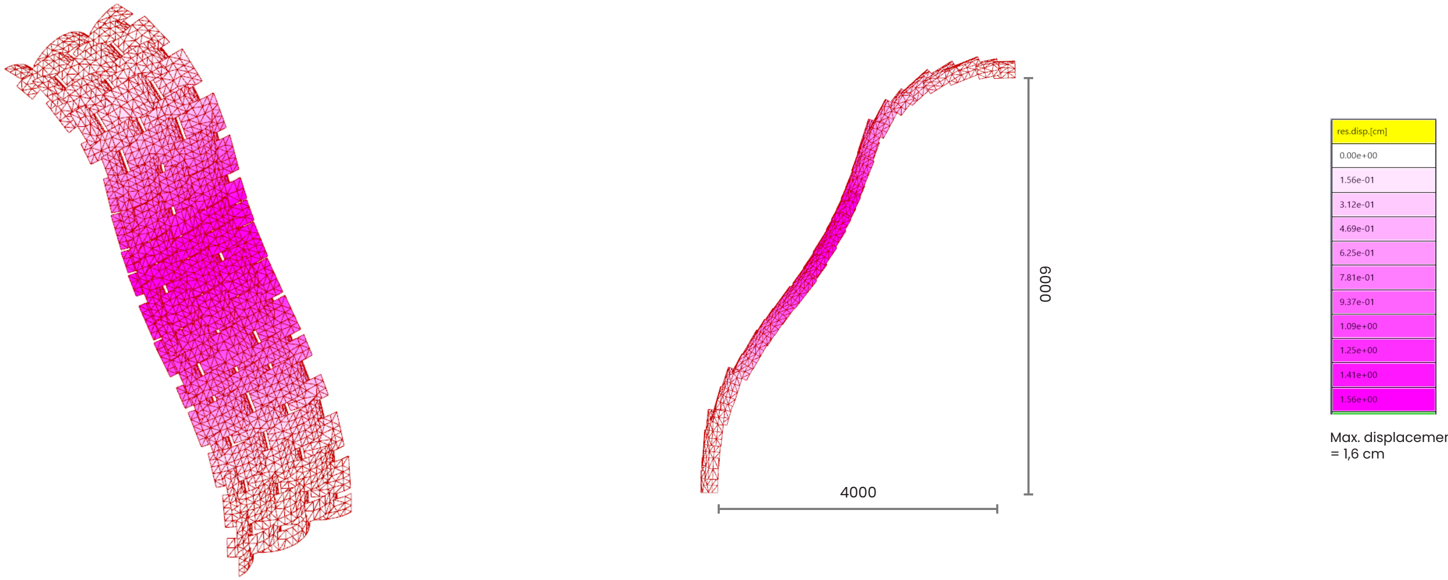
Multi-objective optimization



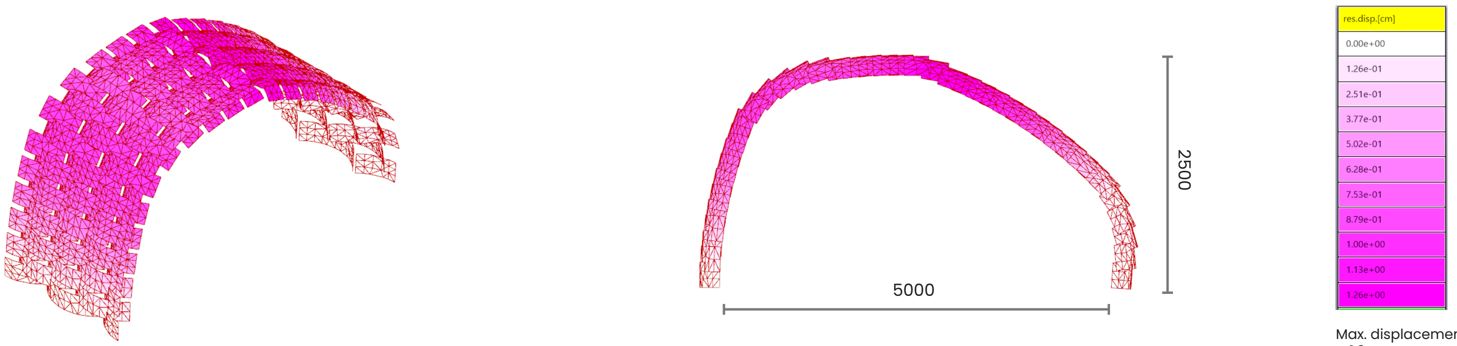
Objective 2.
Minimize alternation between module height

Minimize complex building instructions

Minimal global structural displacement



Max. displacement
= 1,6 cm



Max. displacement
= 1,3 cm

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Minimal alternation between module heights

$$\text{Total difference} = \sum_{i=0}^{n-1} |h_i - h_{i+1}|$$

list of order of module heights

0	300
1	500
2	300
3	300
4	300
5	500
6	500
7	300
8	500
9	500
10	500

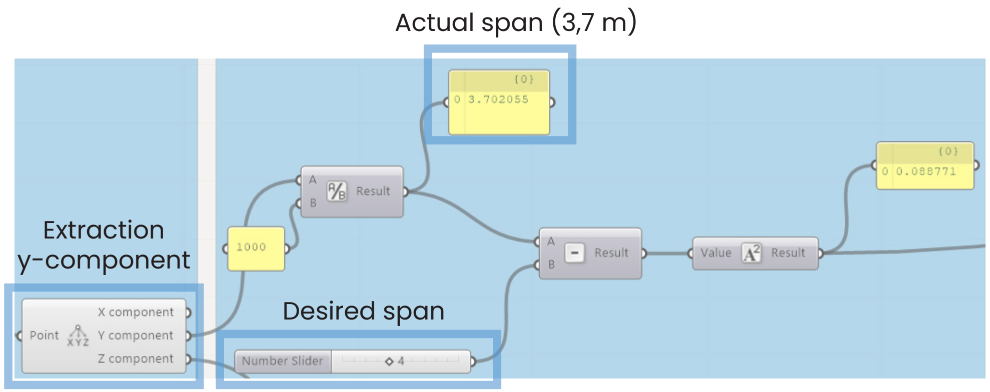
diff. = 200

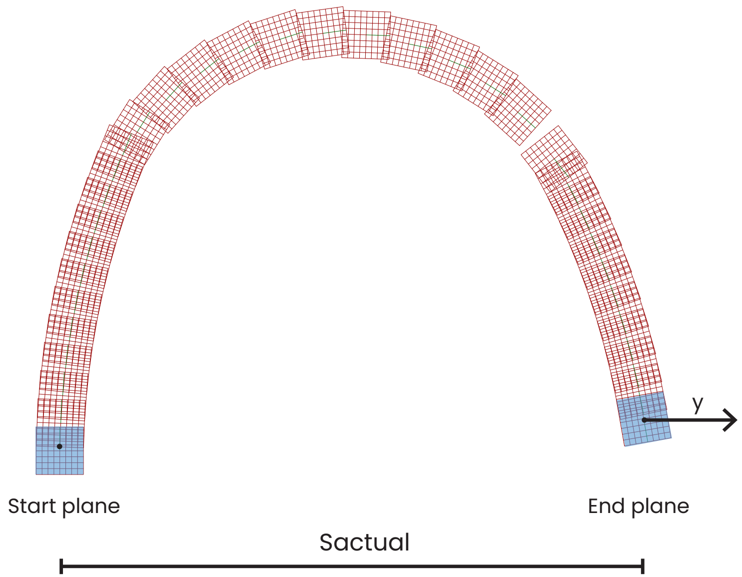
diff. = 200

diff. = 0

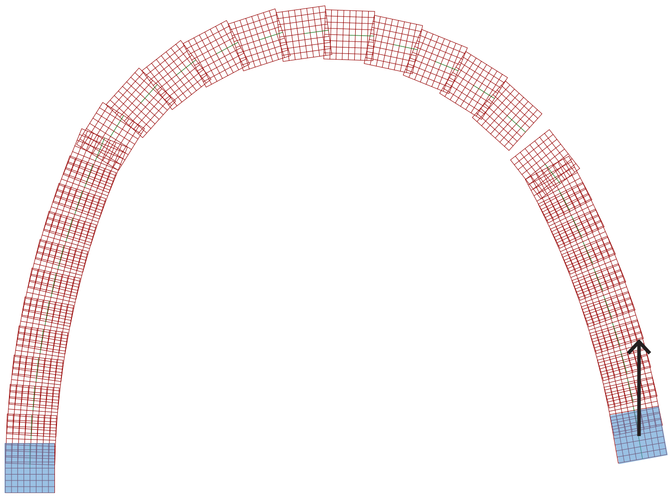
Minimal deviation from desired span

$$\mathcal{L} = (S_{\text{actual}} - S_{\text{desired}})^2$$





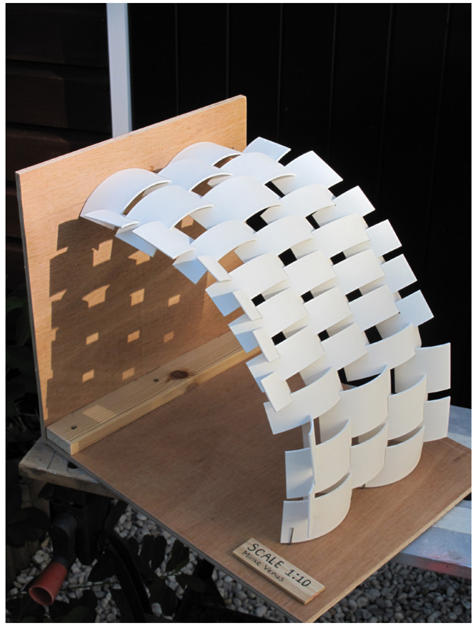
Deviation final module to ground level



Start plane (z = 0)

Z-value of end plane

Shapes that fit uneven ground levels as well as vertical elements



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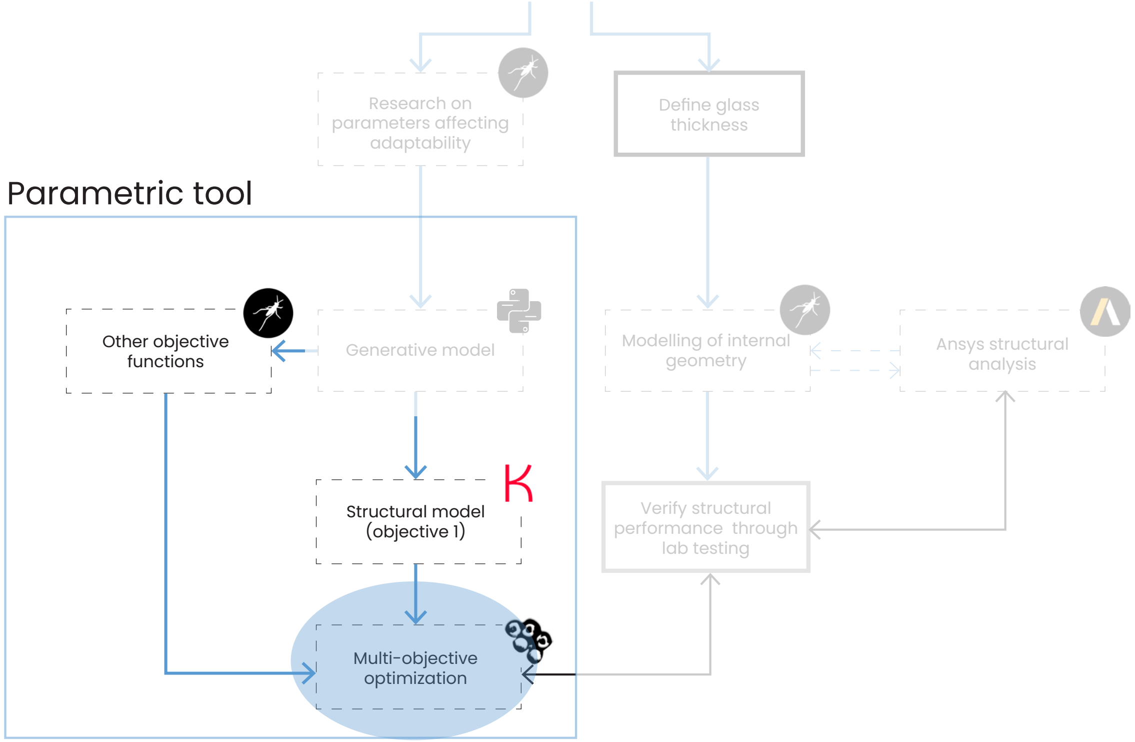
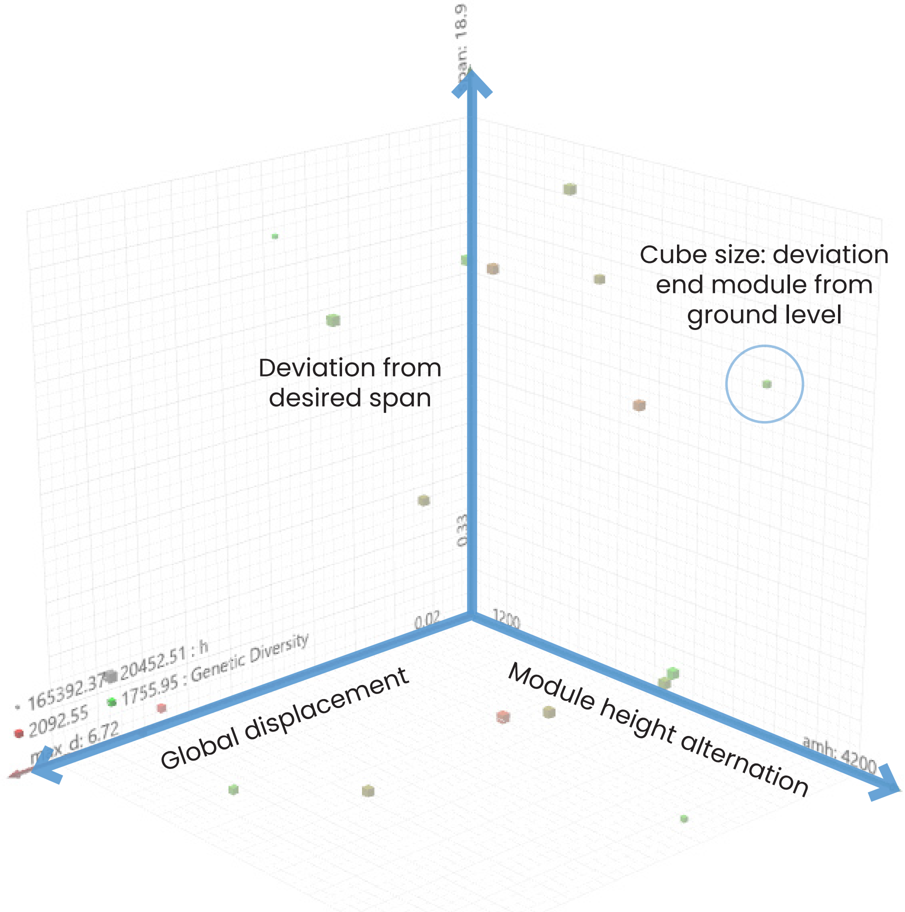
Optimization process



Design solutions in a threedimensional space



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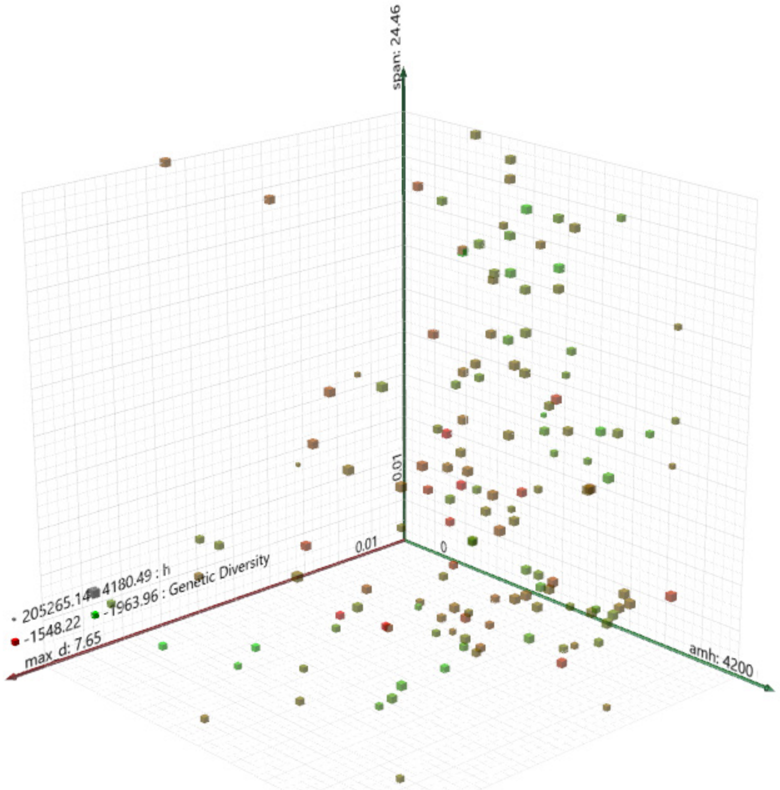
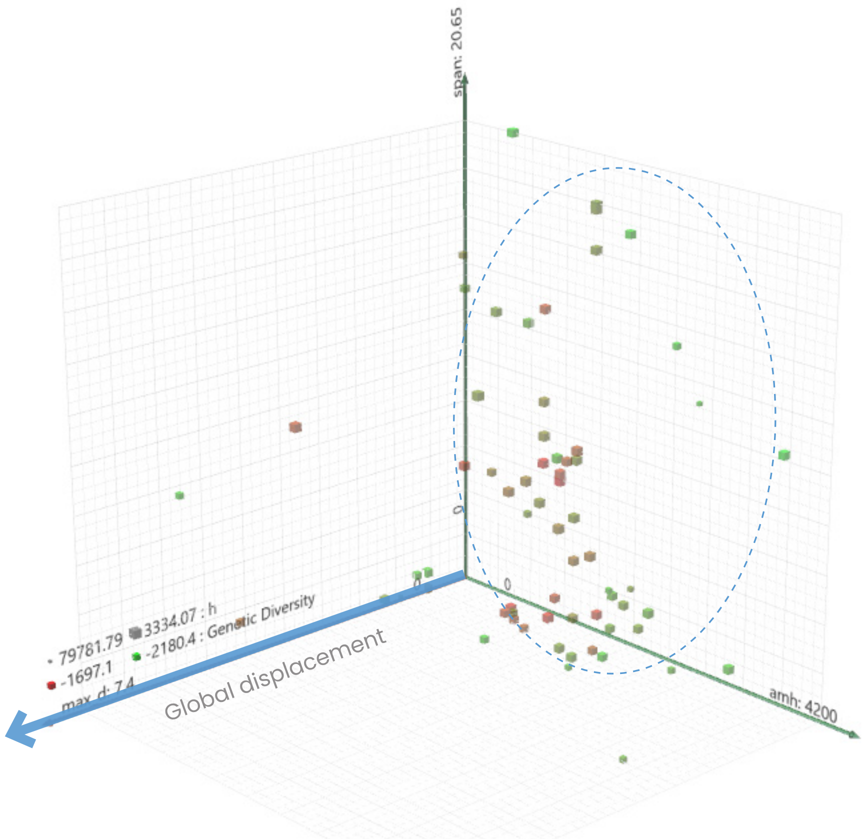
Optimization process

Randomly scattered



Closer to 0, along displacement axis



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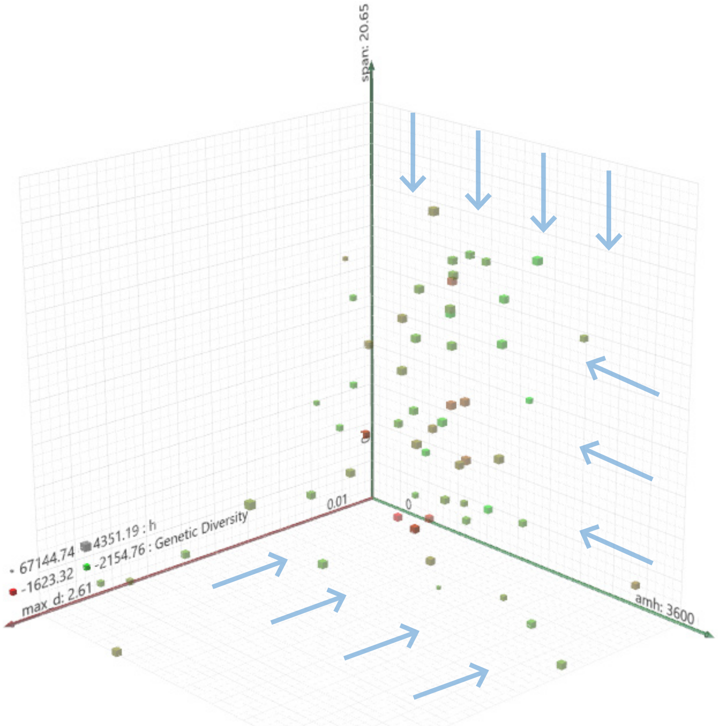
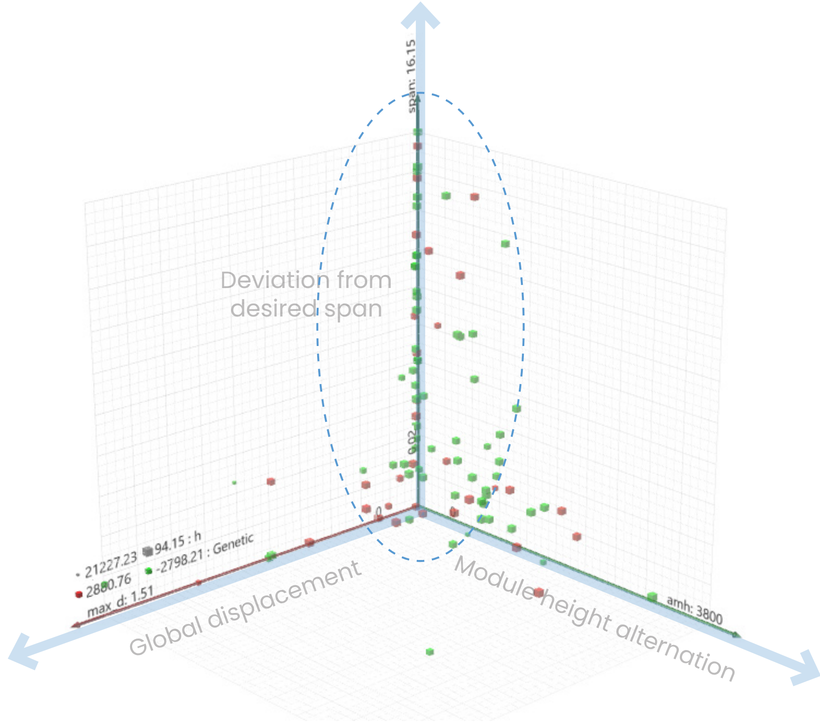
Optimization process

More concentrated near the origin on all three objective axes



Most solutions gathered on the span axes, with global displacement and module height alternation near to 0.



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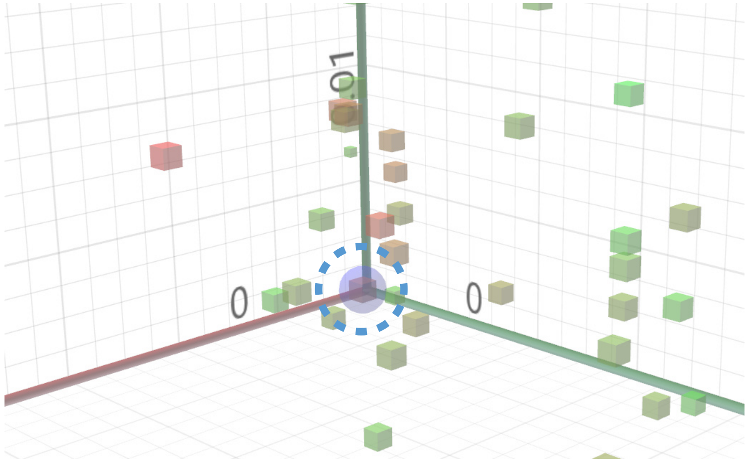
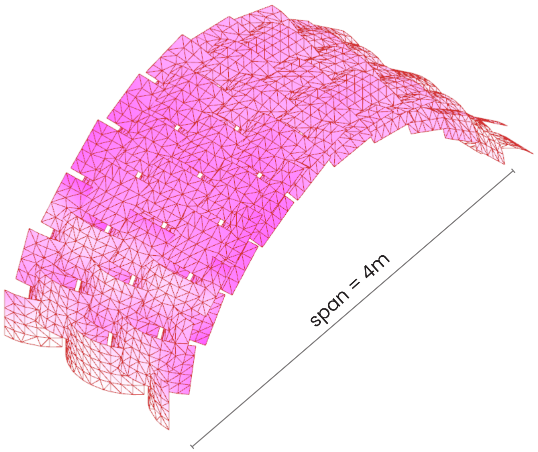
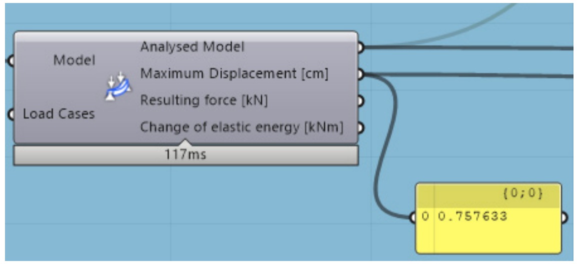
Optimization results





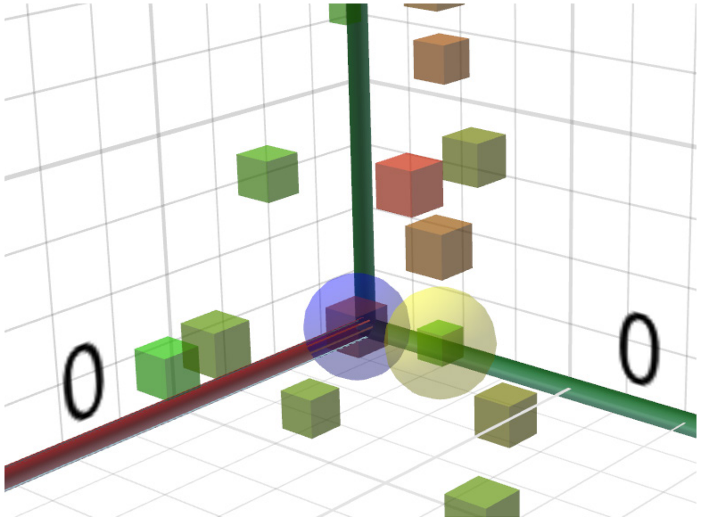
Global displacement = 0.8 cm



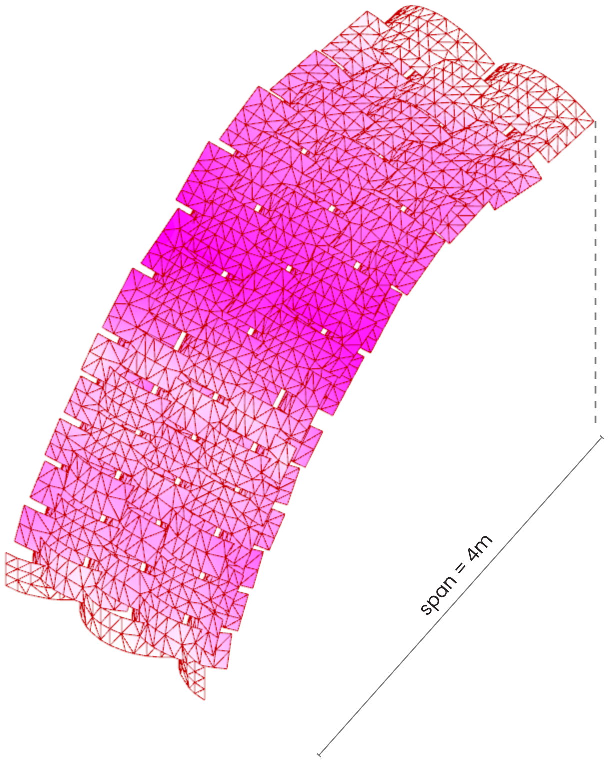
Module height alternation = 0

0	500
1	500
2	500
3	500
4	500
5	500
6	500
7	500
8	500
9	500
10	500
11	500
12	500
13	500
14	500
15	500
16	500
17	500
18	500
19	500
20	500

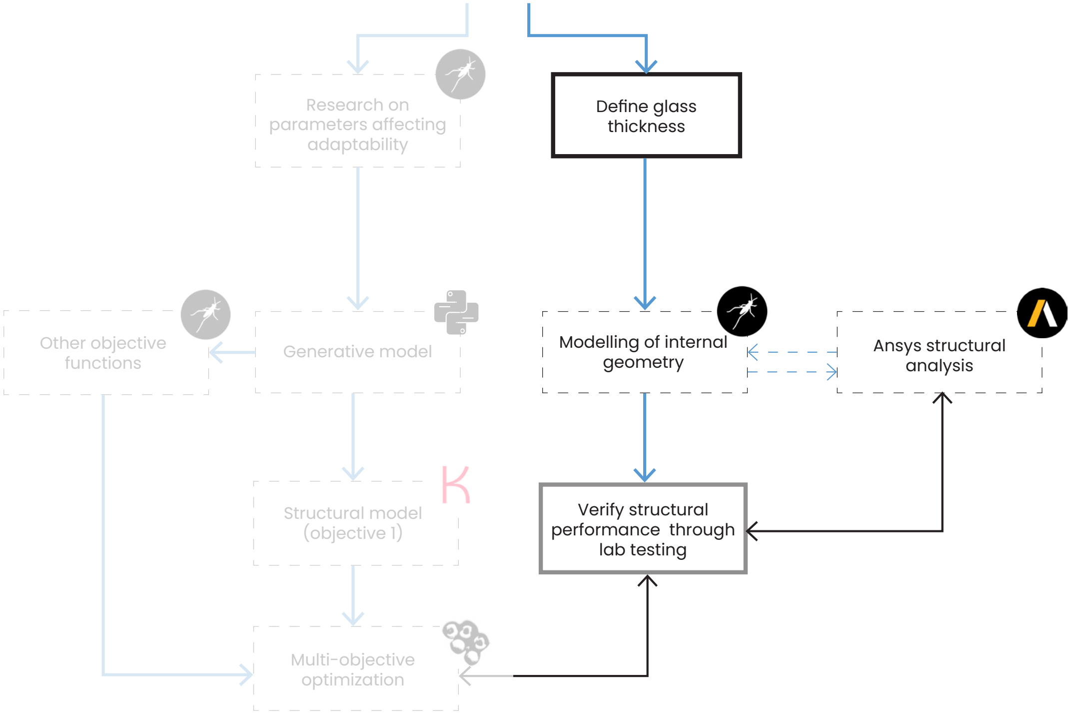
Optimization results



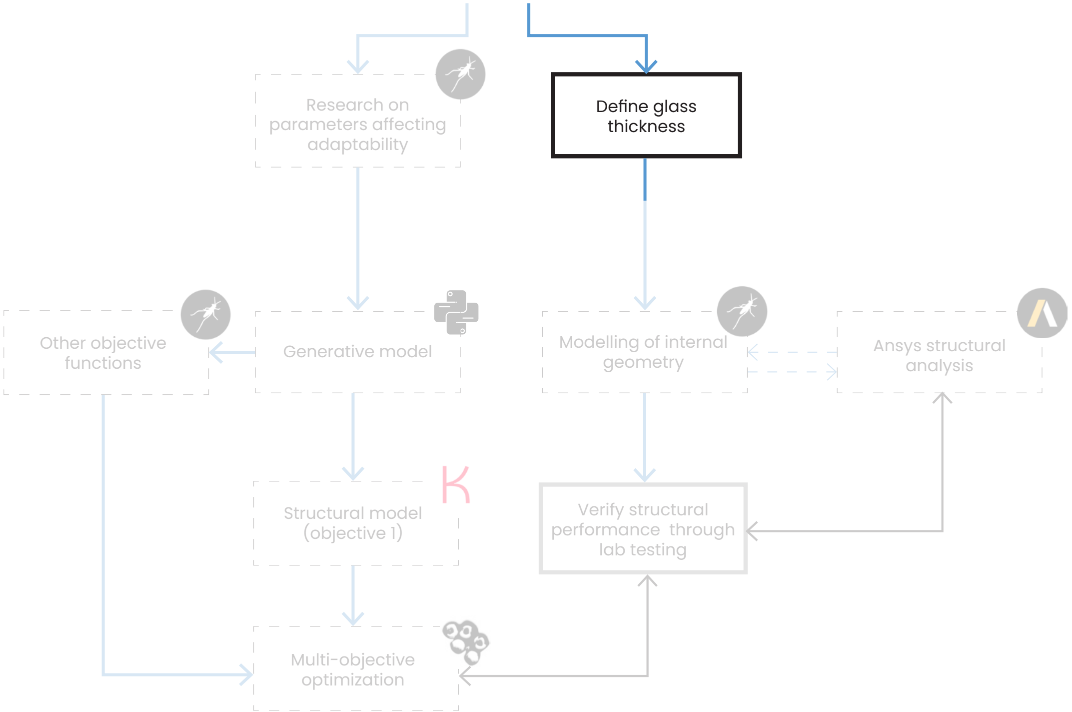
Equal span and technical performance, suitable for other spatial requirements.

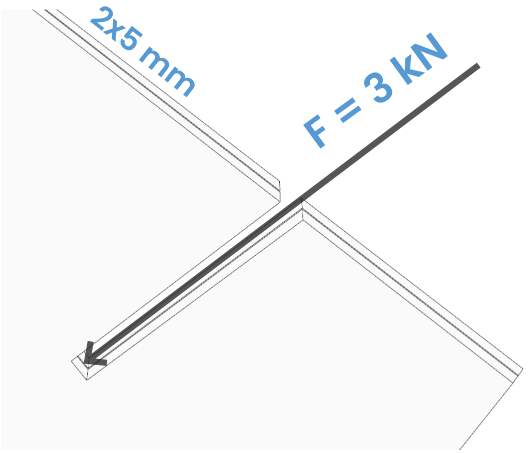


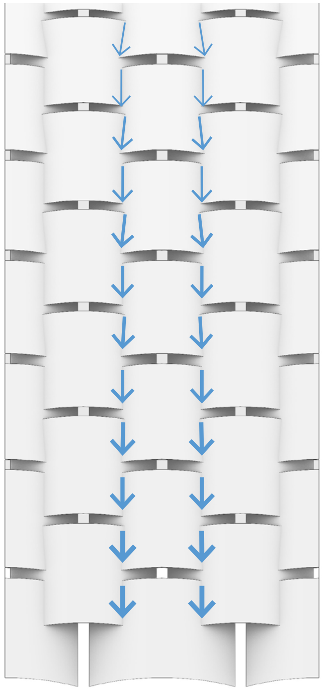
Structural Analysis and Verification



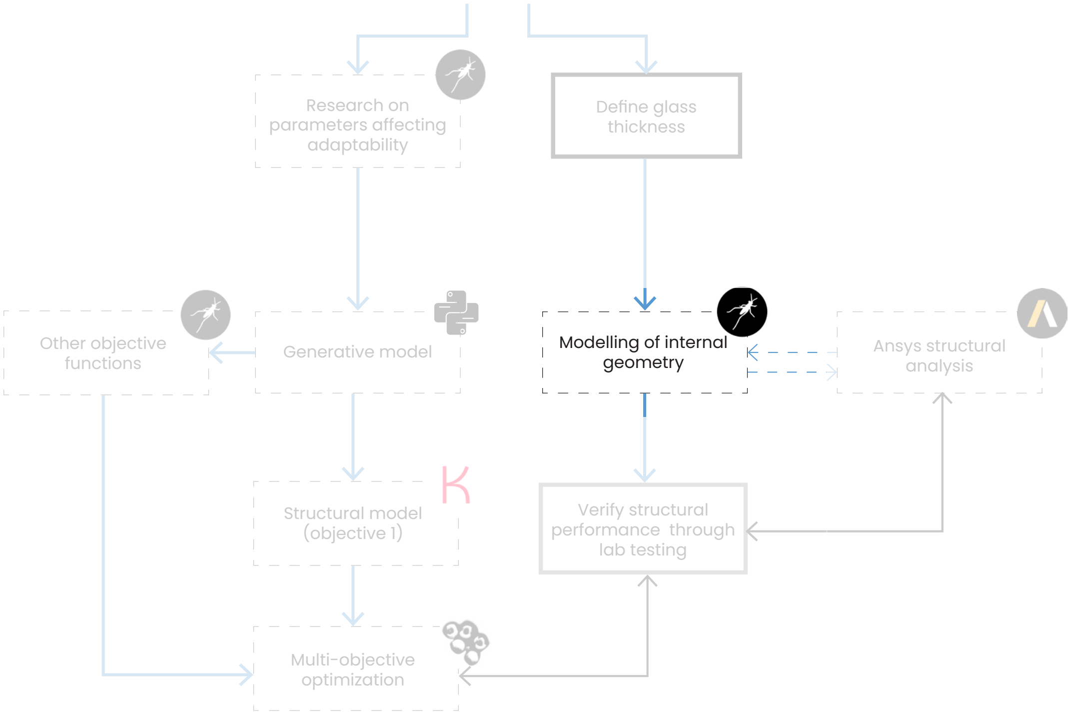
Preliminary hand calculations

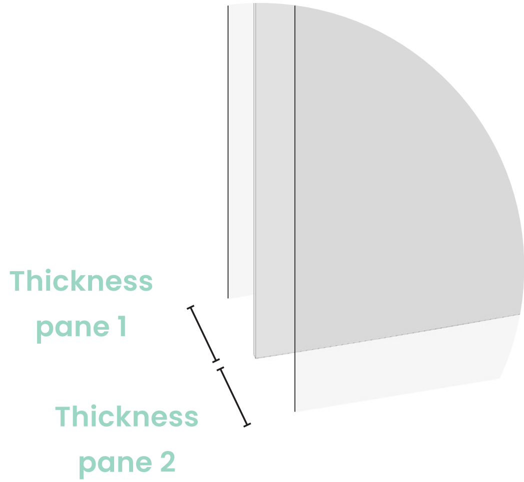


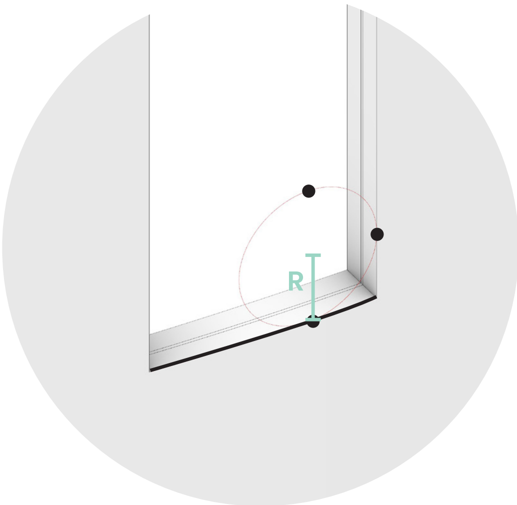




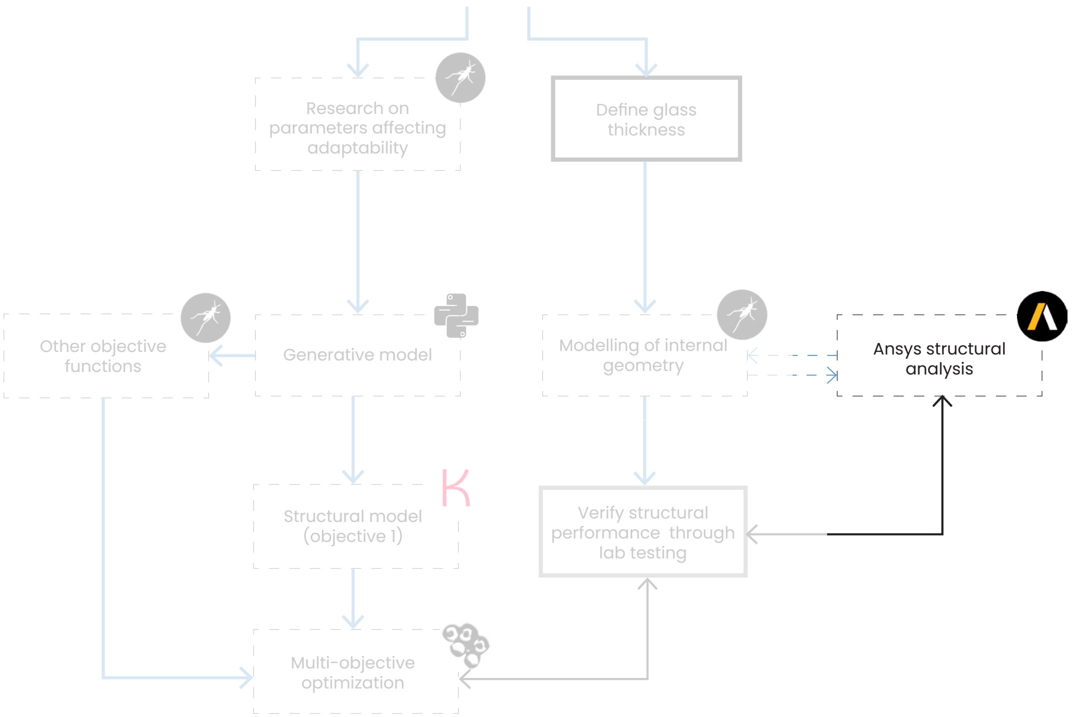
Parametric model internal geometry



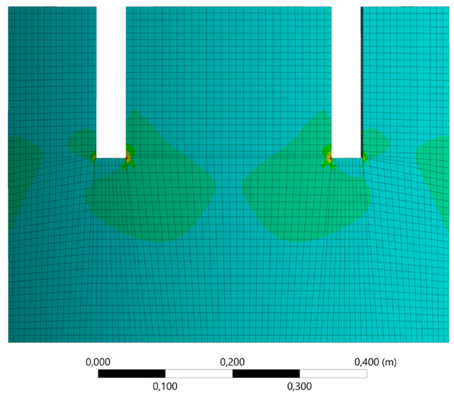




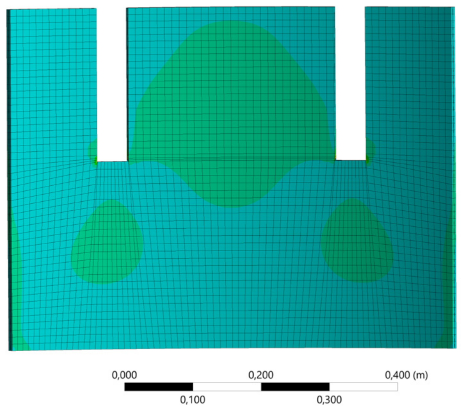
Analysis results 2x5 mm



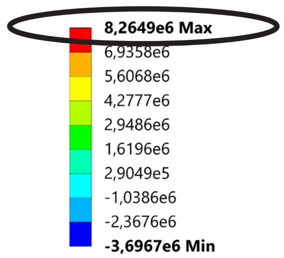
Front view



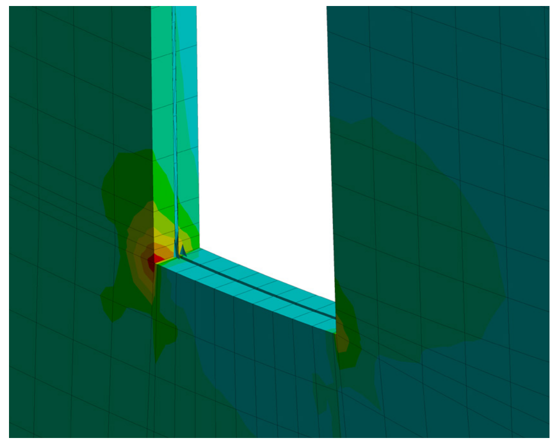
Back view



A: Static Structural
Maximum Principal Stress
Type: Maximum Principal Stress
Unit: Pa
Time: 1 s
02/05/2025 10:21:51



Slot view



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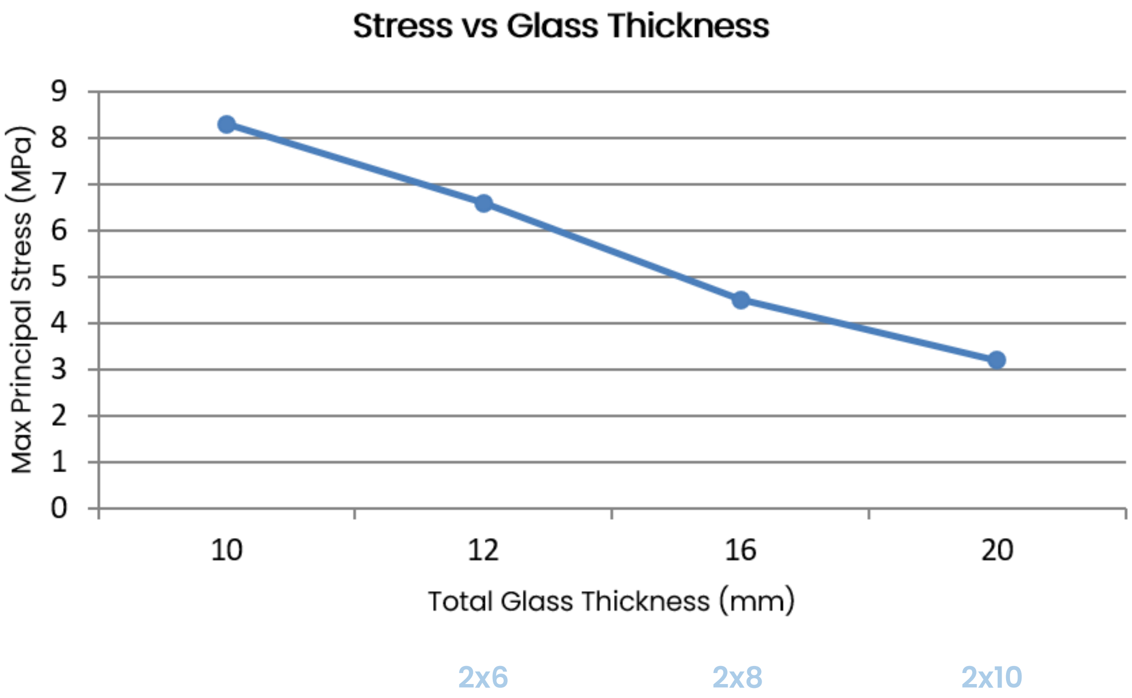
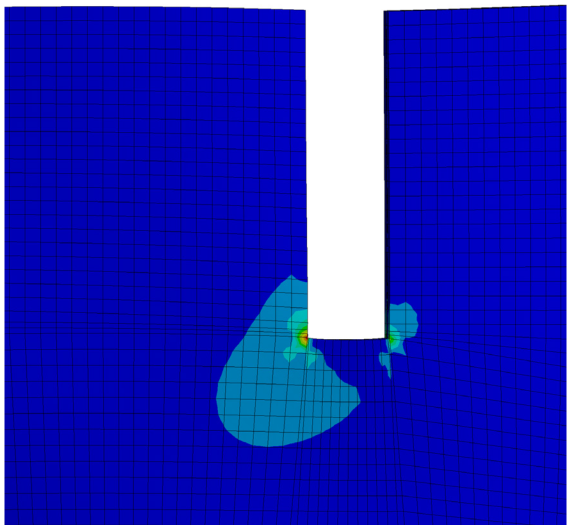
Other results

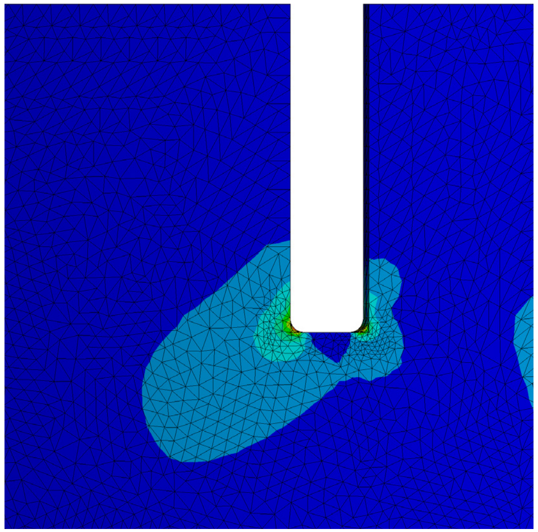


Slot corner radius

Without slot corner radius

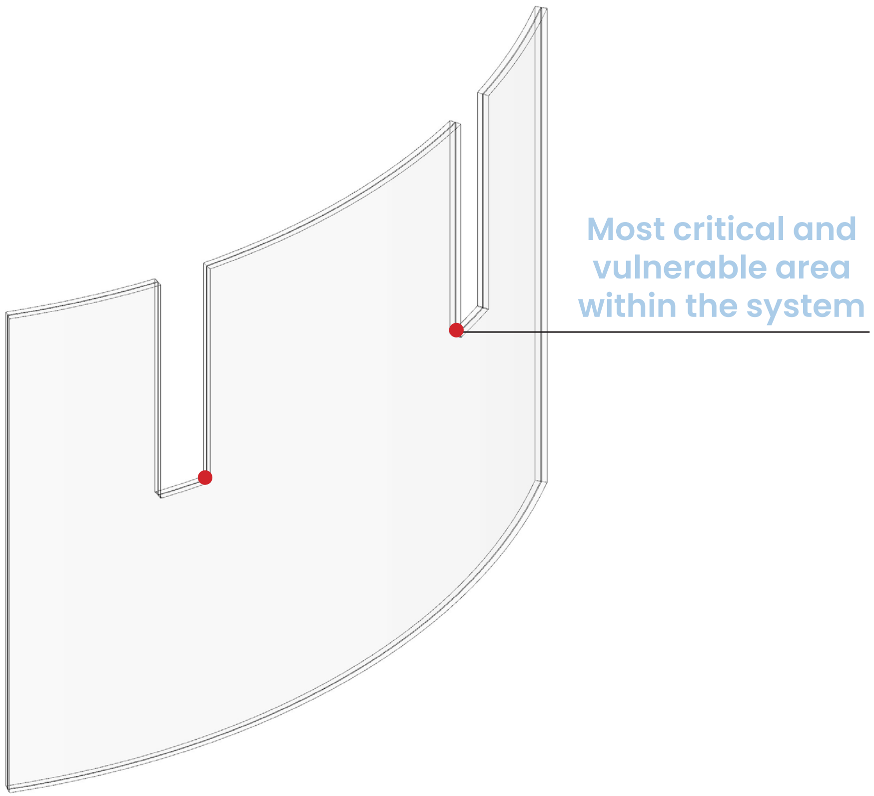


Slot corner radius of 10 mm

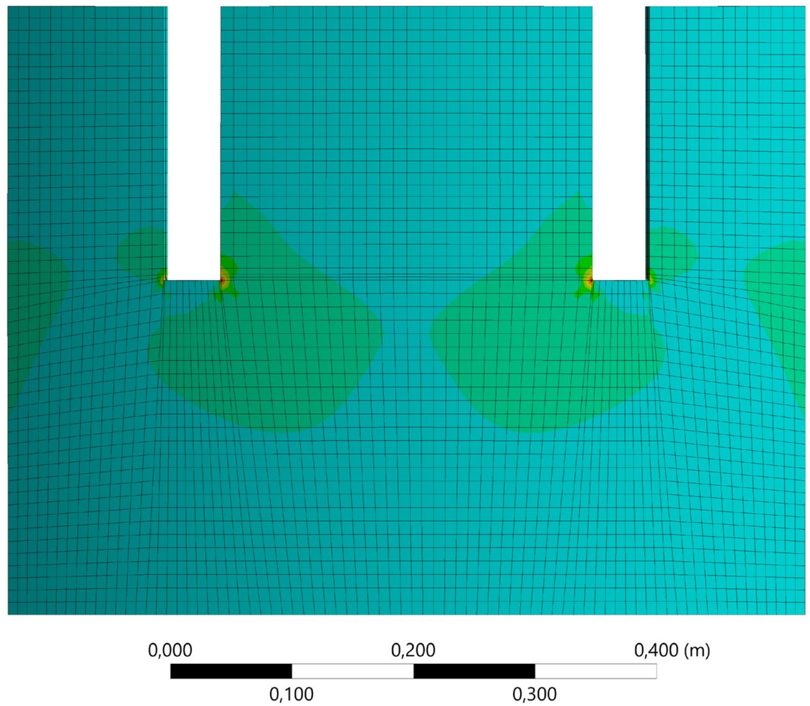


peak stress decreased from
6.5 MPa to 4.7 MPa for 2x6 mm

Conclusion



2x5 mm should satisfy



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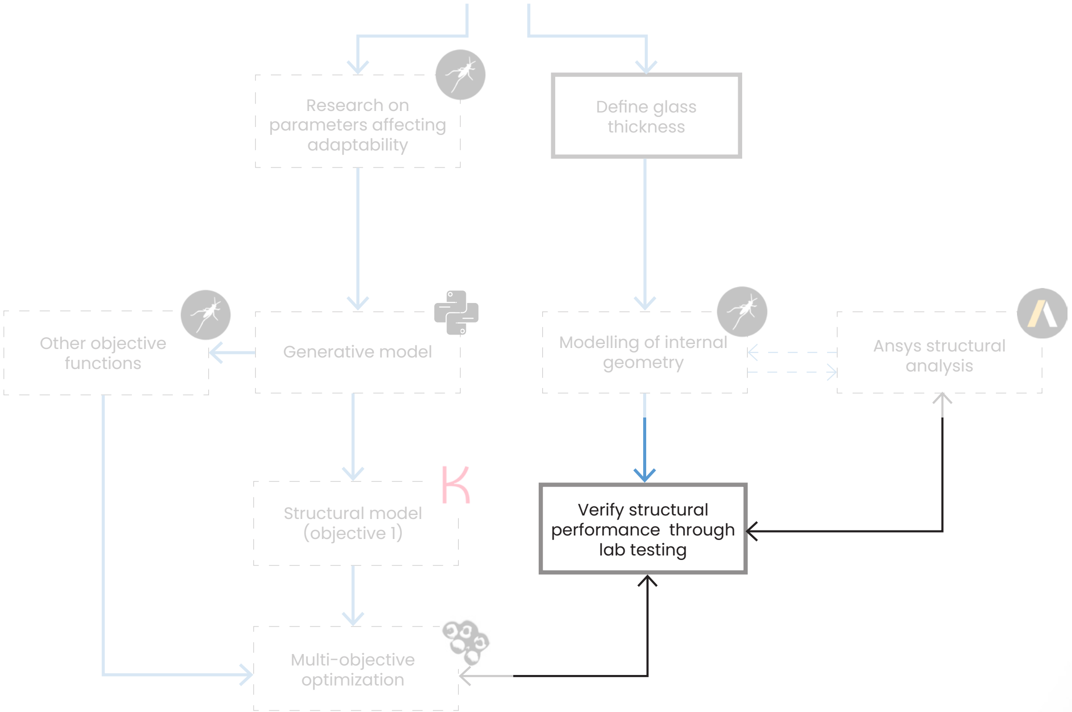
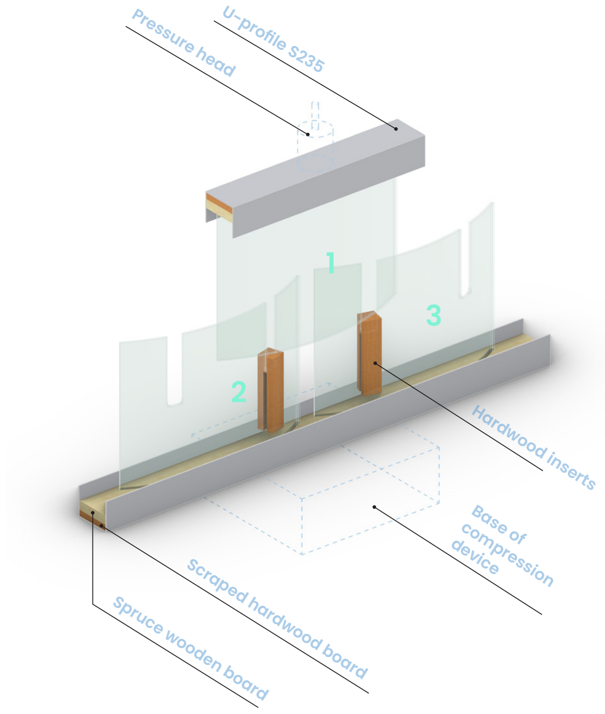
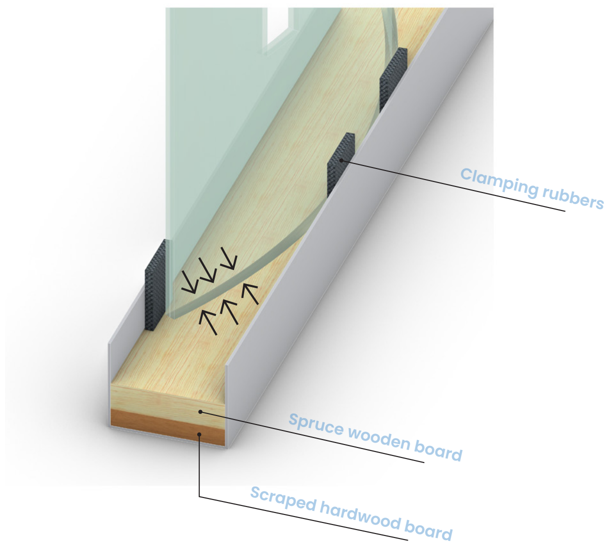
Laboratory test







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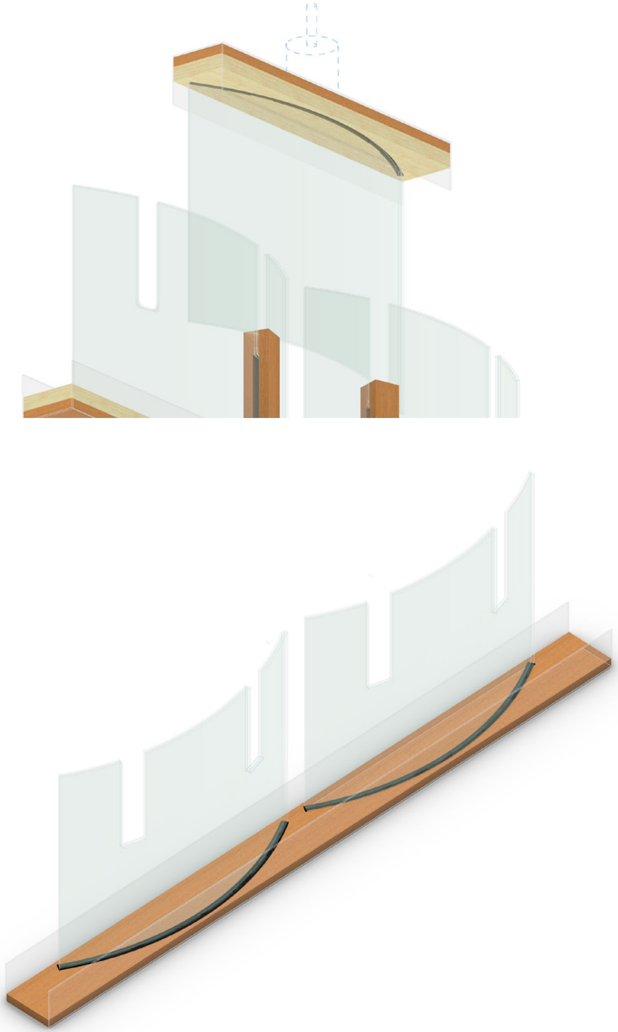
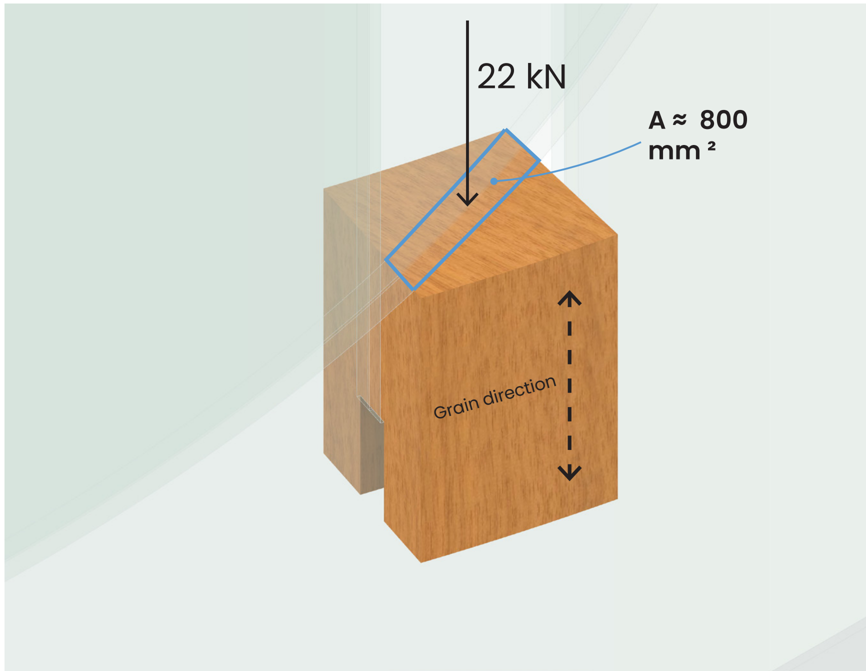
Laboratory test

Hardwood as intermediate material between steel profiles and glass

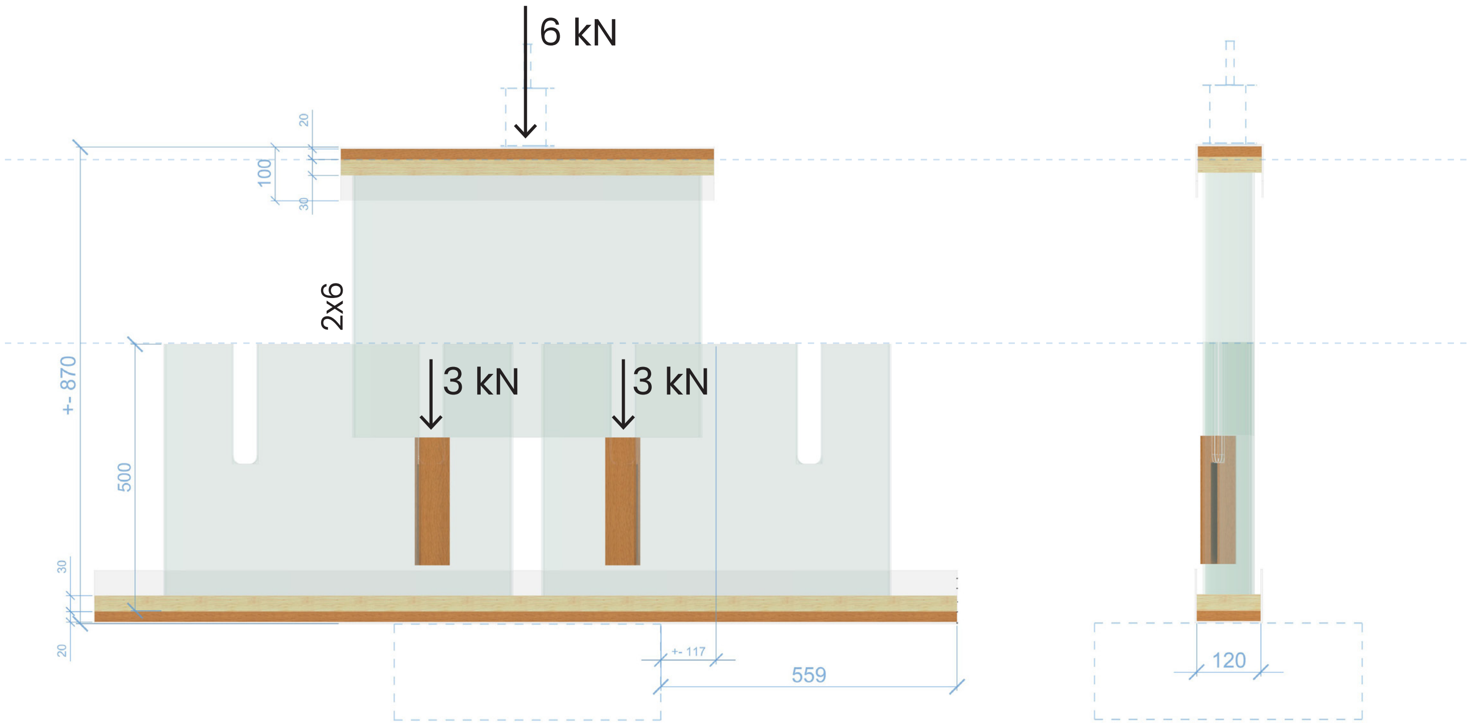


Hardwood in the slots

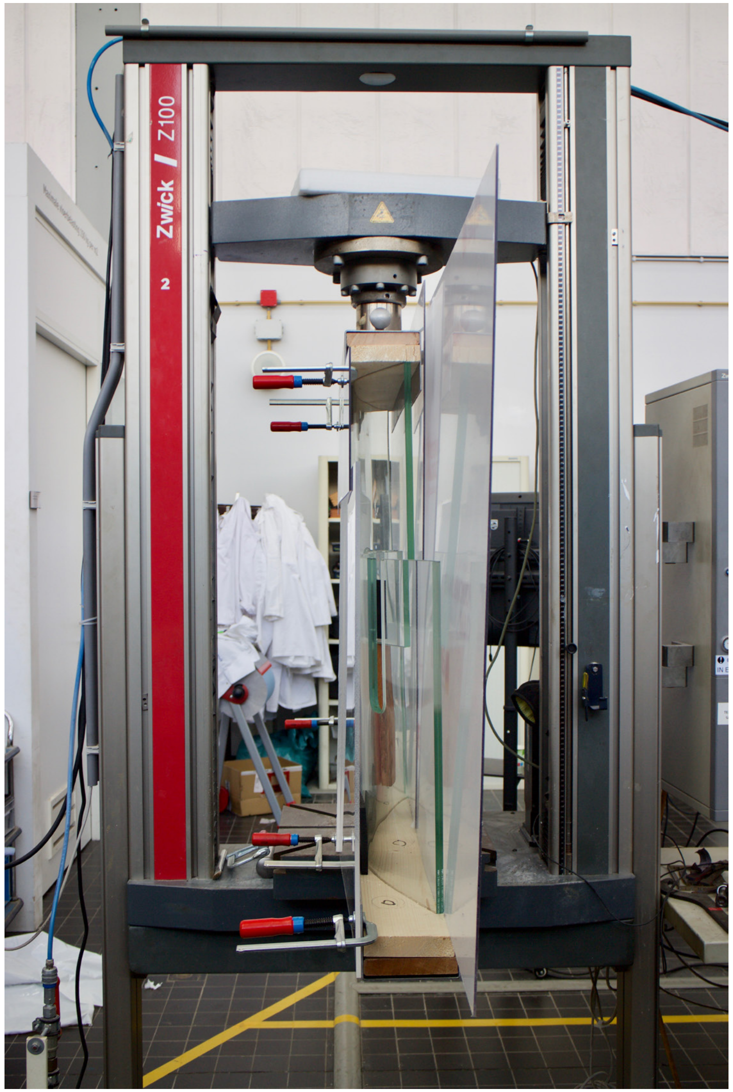


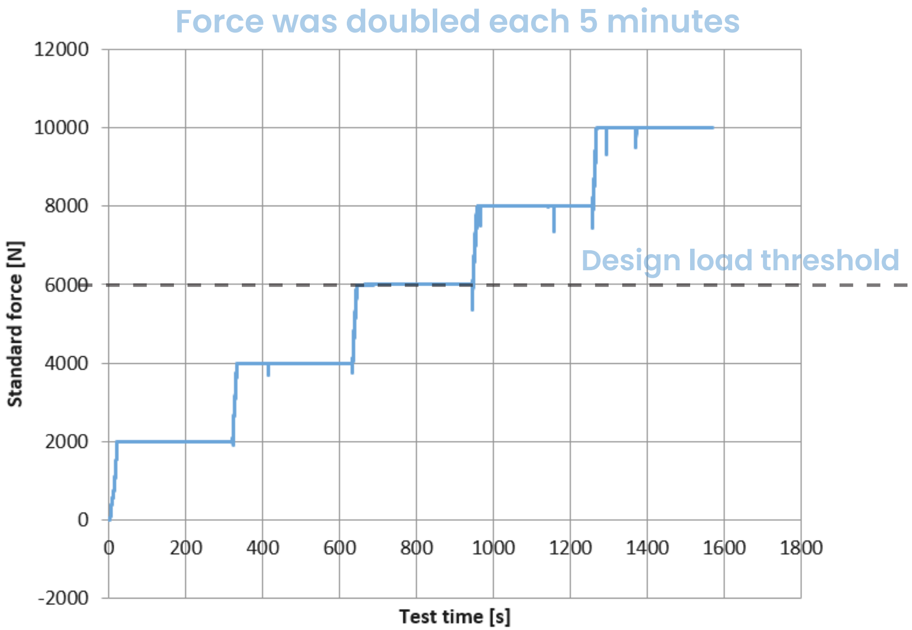
$$
\begin{aligned}
F &= \sigma \times A \\
&= 28.4\,\mathrm{MPa} \times 800\,\mathrm{mm}^2 \\
&= 22\,720\,\mathrm{N} \\
&= 22.7\,\mathrm{kN}
\end{aligned}
$$

Laboratory test



Laboratory test





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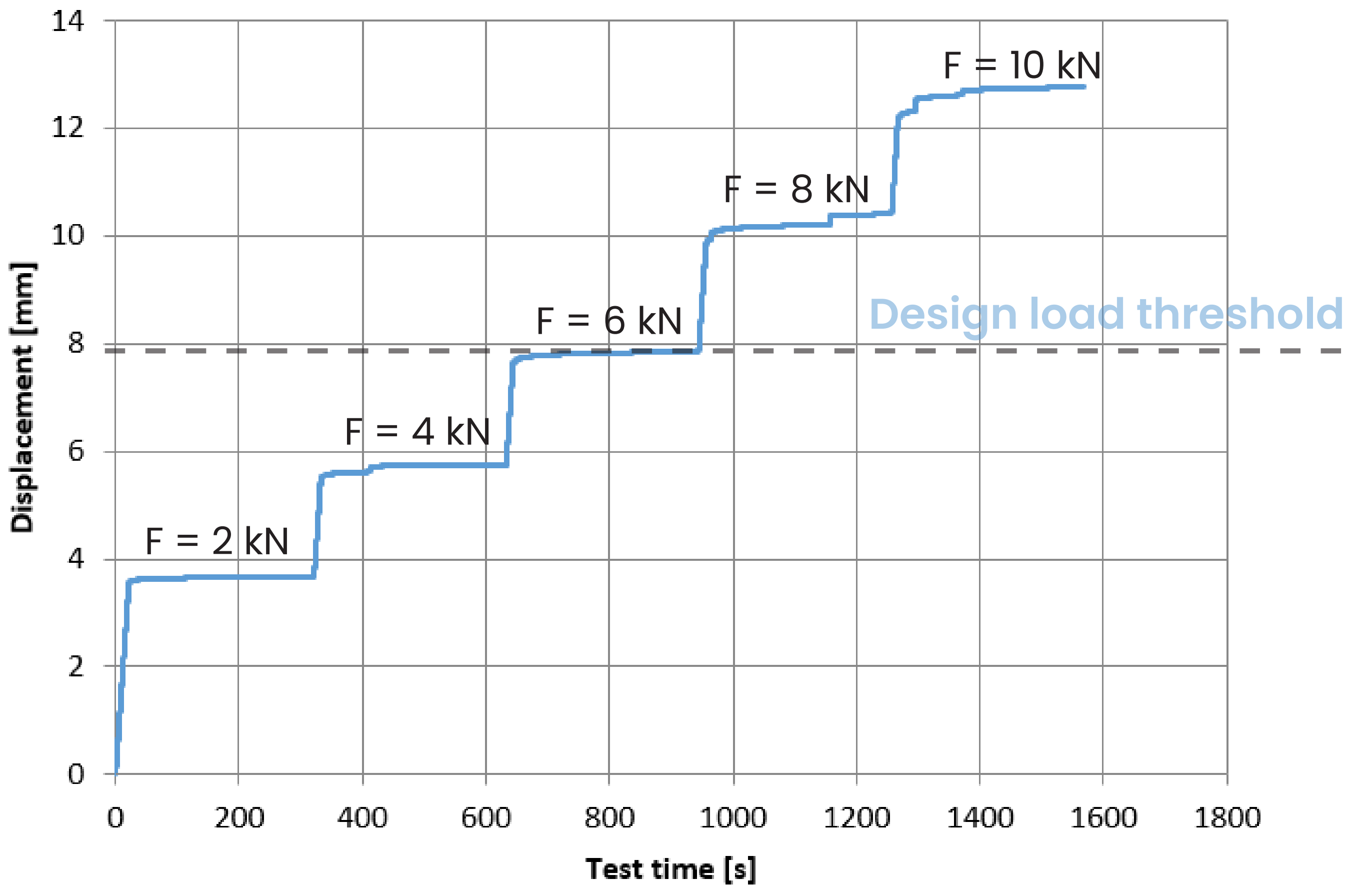
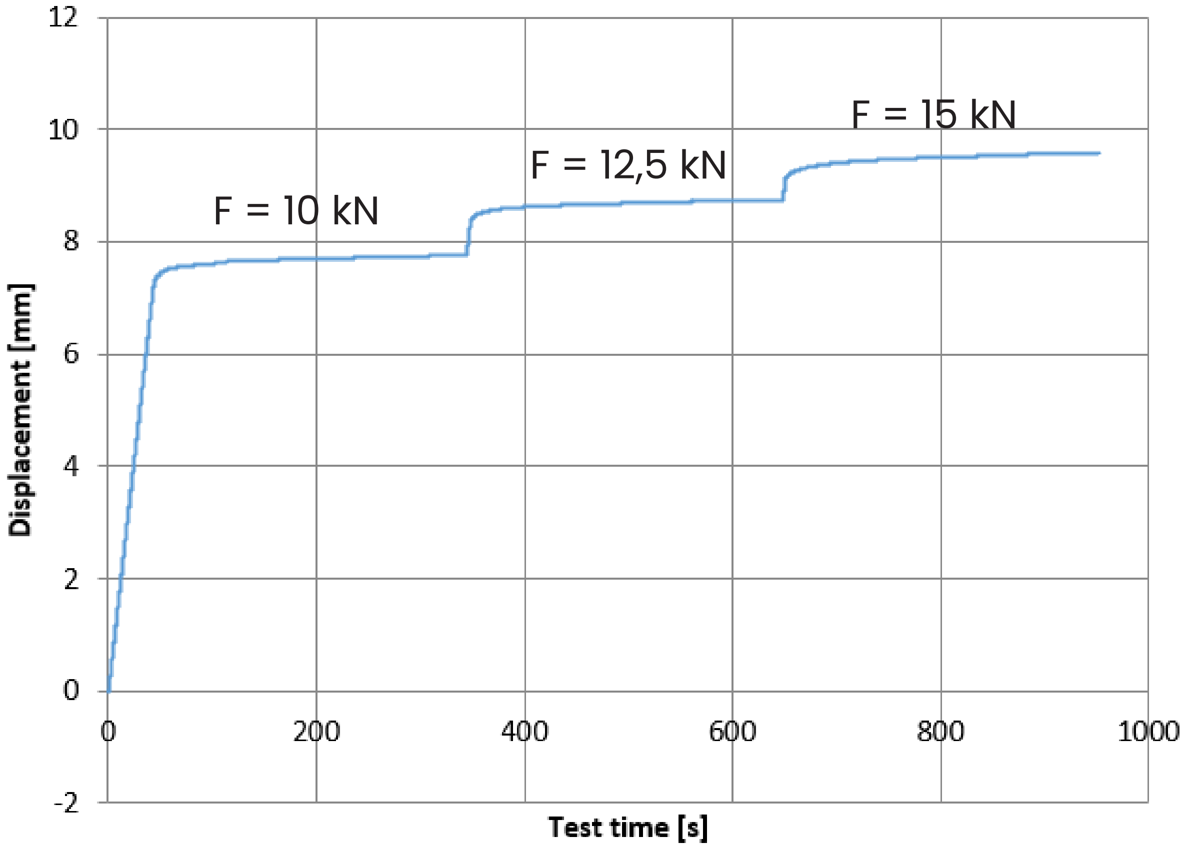
Laboratory test



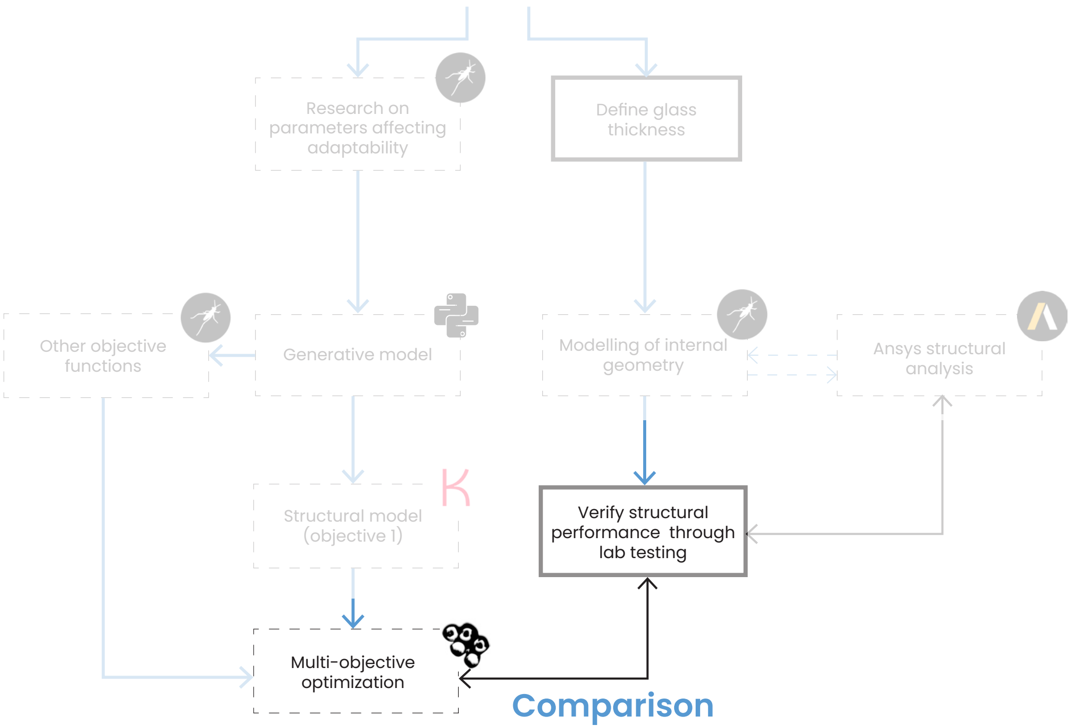
Laboratory test

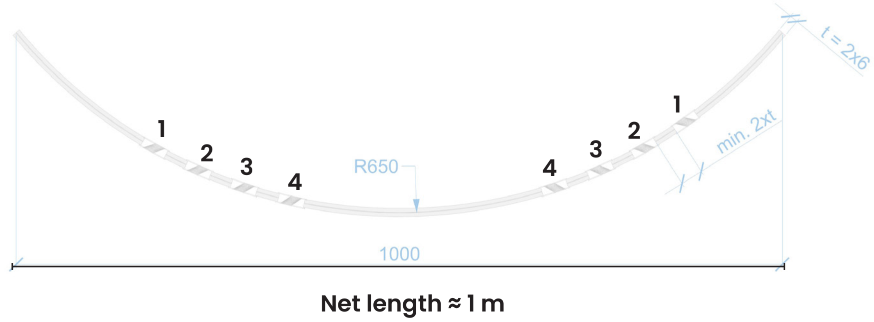
Restarted test at 10 kN, increase of 2,5 kN each 5 minutes

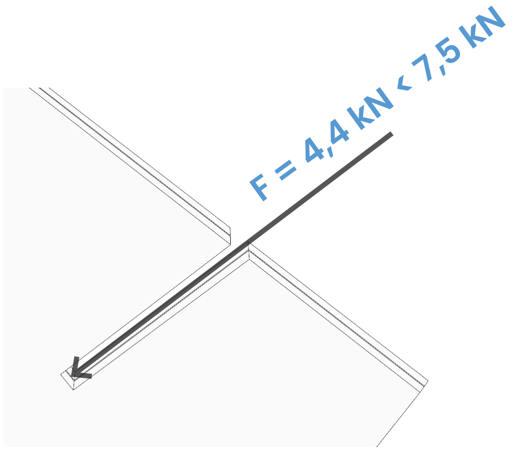


The modules could handle at least 2,5 times the design load (7,5 kN per slot.)

Conclusion







Modules made from fully toughened laminated glass, 2×6 mm thick, 1 meter long, and up to 0.5 meters in height, show strong potential for use in compression-based structures spanning up to 8 meters

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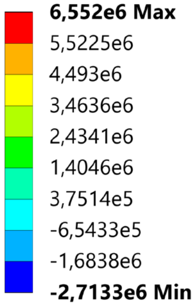
Conclusion

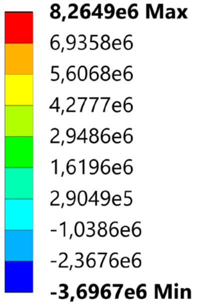
Expected that 2x5 mm thick modules are feasible

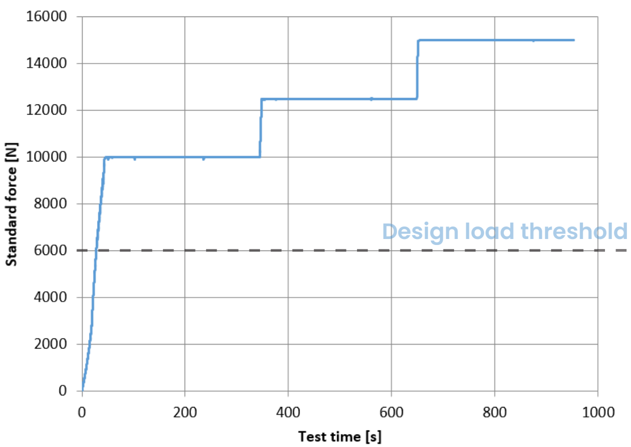
2x6: 6,6 MPa



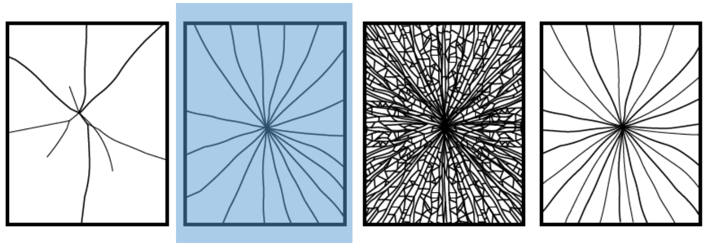
1,7 MPa increase

2x5: 8,3 MPa





Recommended to use heat-strengthened glass



From Rammig, 2022

Should be verified in a next test

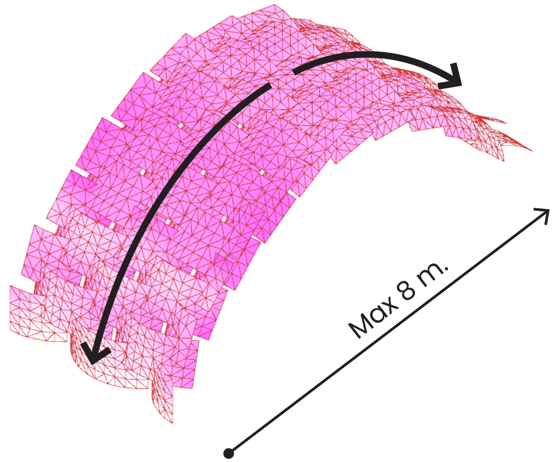
Final conclusion

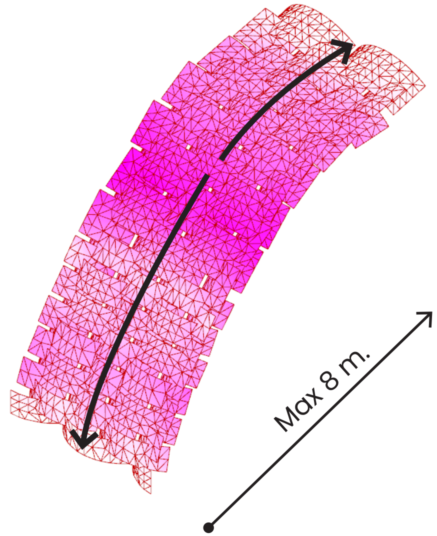
"Which **structural elements** and **connections** enable the design of a **structurally feasible** and **spatially adaptable** float glass system that can be **manually assembled and disassembled** by a small team for reconfiguration at different locations, ensuring its reusability?"

Final design

Structurally feasible modular float glass system, proven to span up to 8 meters in a compression-oriented global shape.

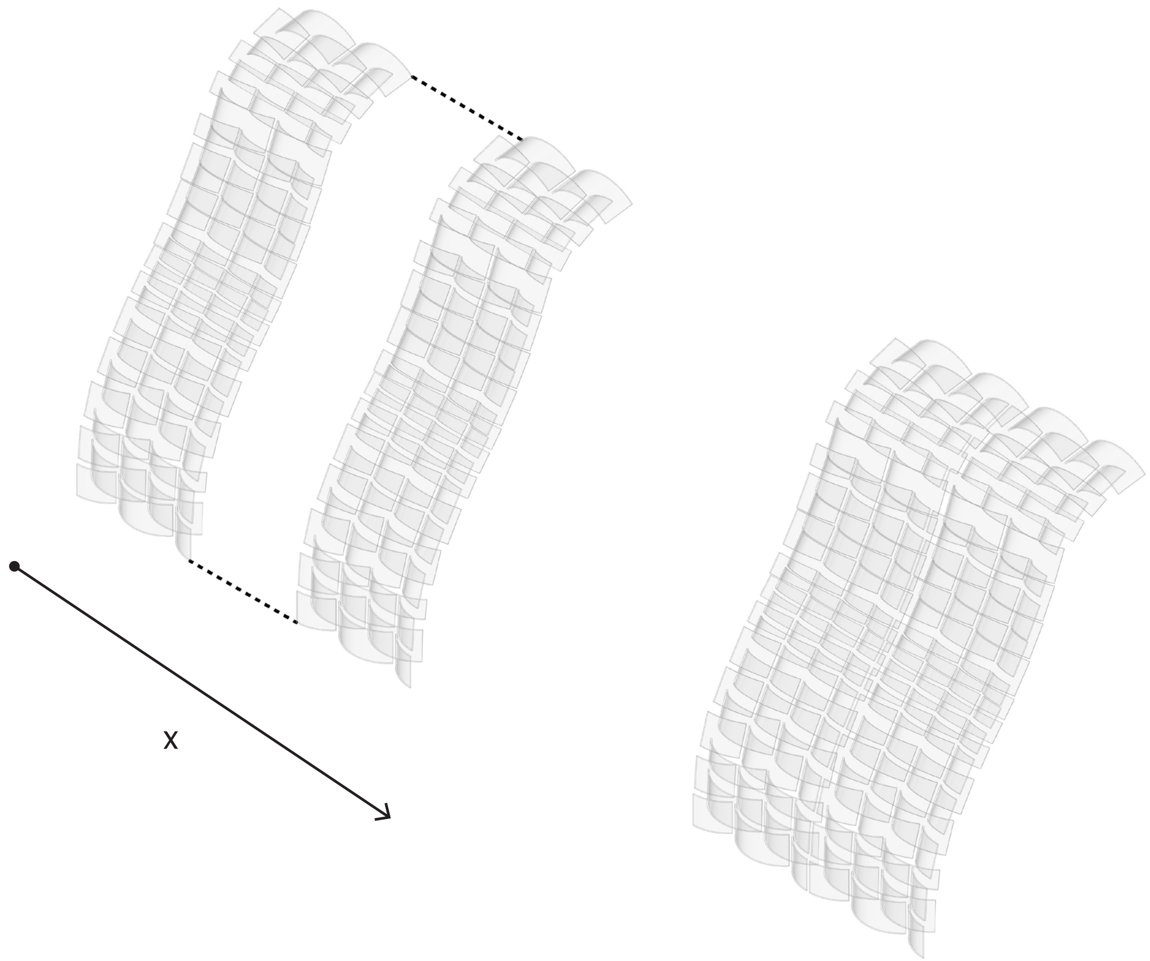
The shape and consequently the span (y-direction) can be adapted by means of the interlocking angle and the module height alternation.





Final design

The system is scalable in the x-direction by linking multiple rows of module units.



Final design

The modules are made of curved glass with integrated slots at the top, enabling straightforward assembly and disassembly, as the modules only need to be slid together or apart.

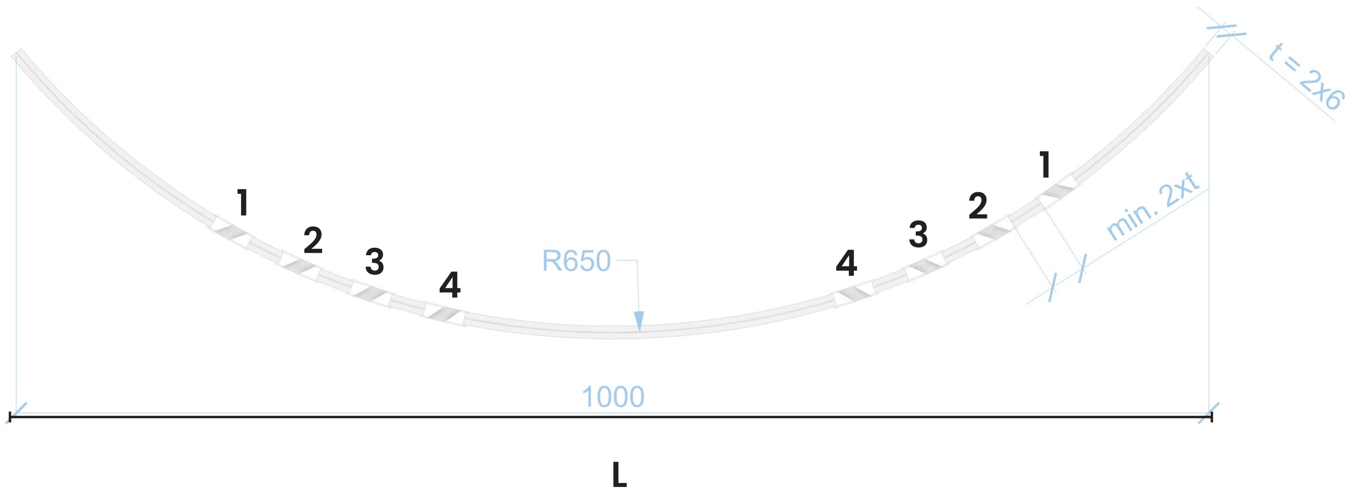
Final design

The system uses two standardized modules with integrated connections, simplifying production, assembly, and reuse at new sites.

A 500 mm high module allows manual handling with the 1-meter length, while a 300 mm height creates contrast to encourage varied span outcomes.

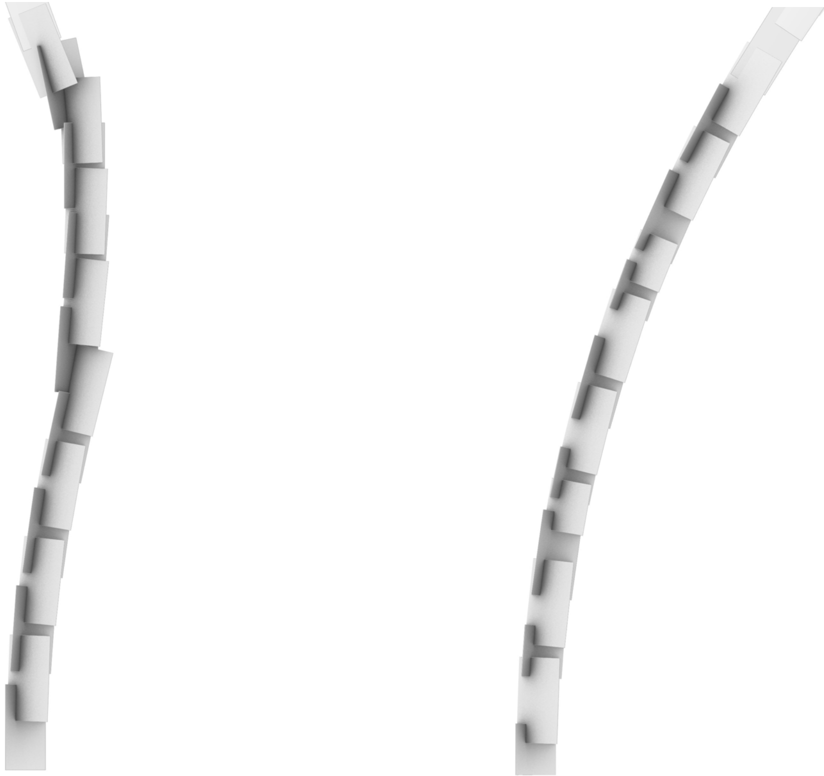
Final design

Four slots are combined into a one meter long module with a 650 mm bending radius, maximizing the amount of integrated interlocking angles while minimizing length and weight for easier manual handling.



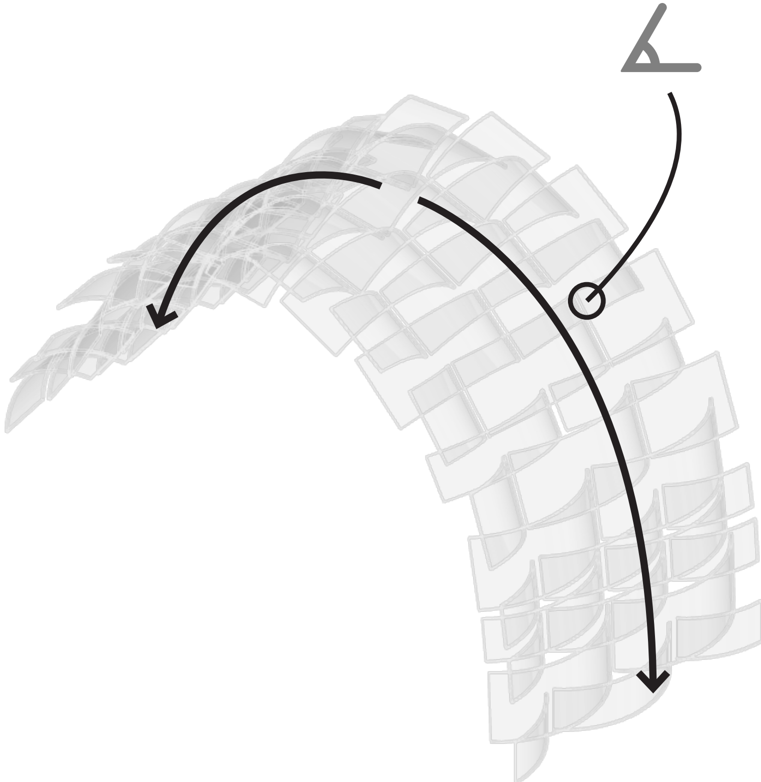
Final design

The combination of two negative angles (-2° and -10°) and two positive angles (2° and 10°) enables the formation of both convex and concave shapes, giving precise control over the global geometry and, consequently, the span.



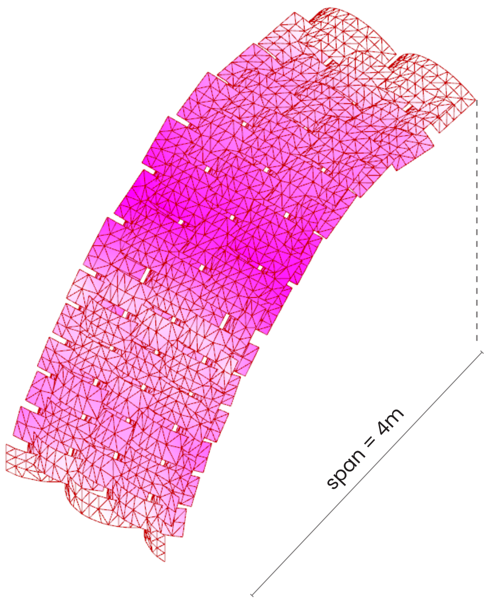
Final design

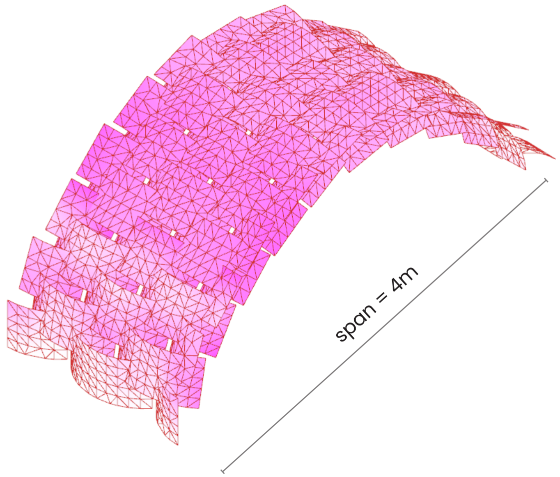
The integration of these angles supports the parametric tool in generating different curved external geometries that primarily transfer forces through compression, promoting lightweight construction.



Final design

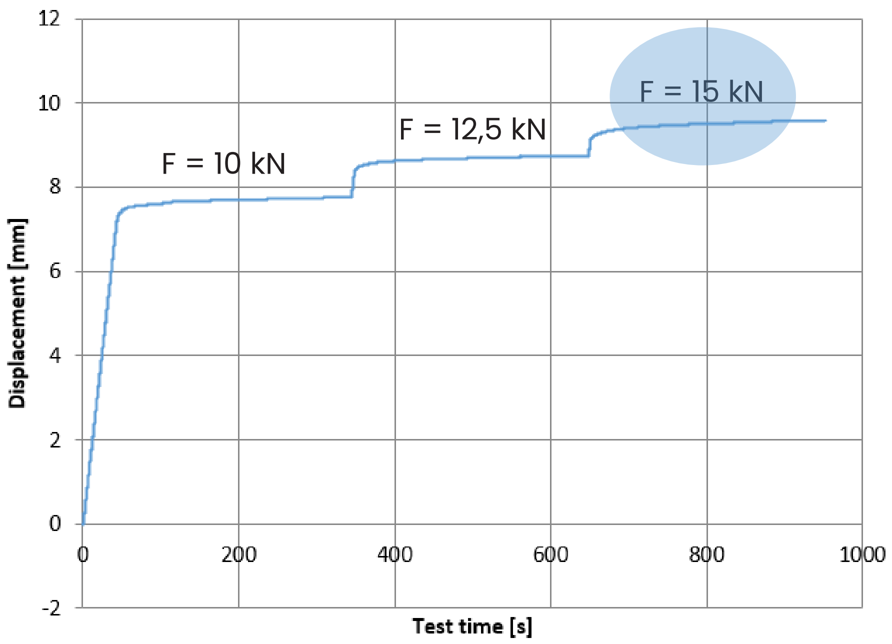
The parametric tool enables the generation of different shapes that fit a specificied span, simultaneously stimulating ease of assembly and light weight construction.





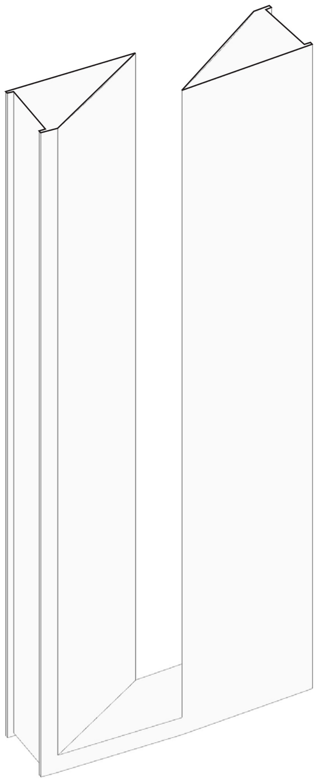
Final design

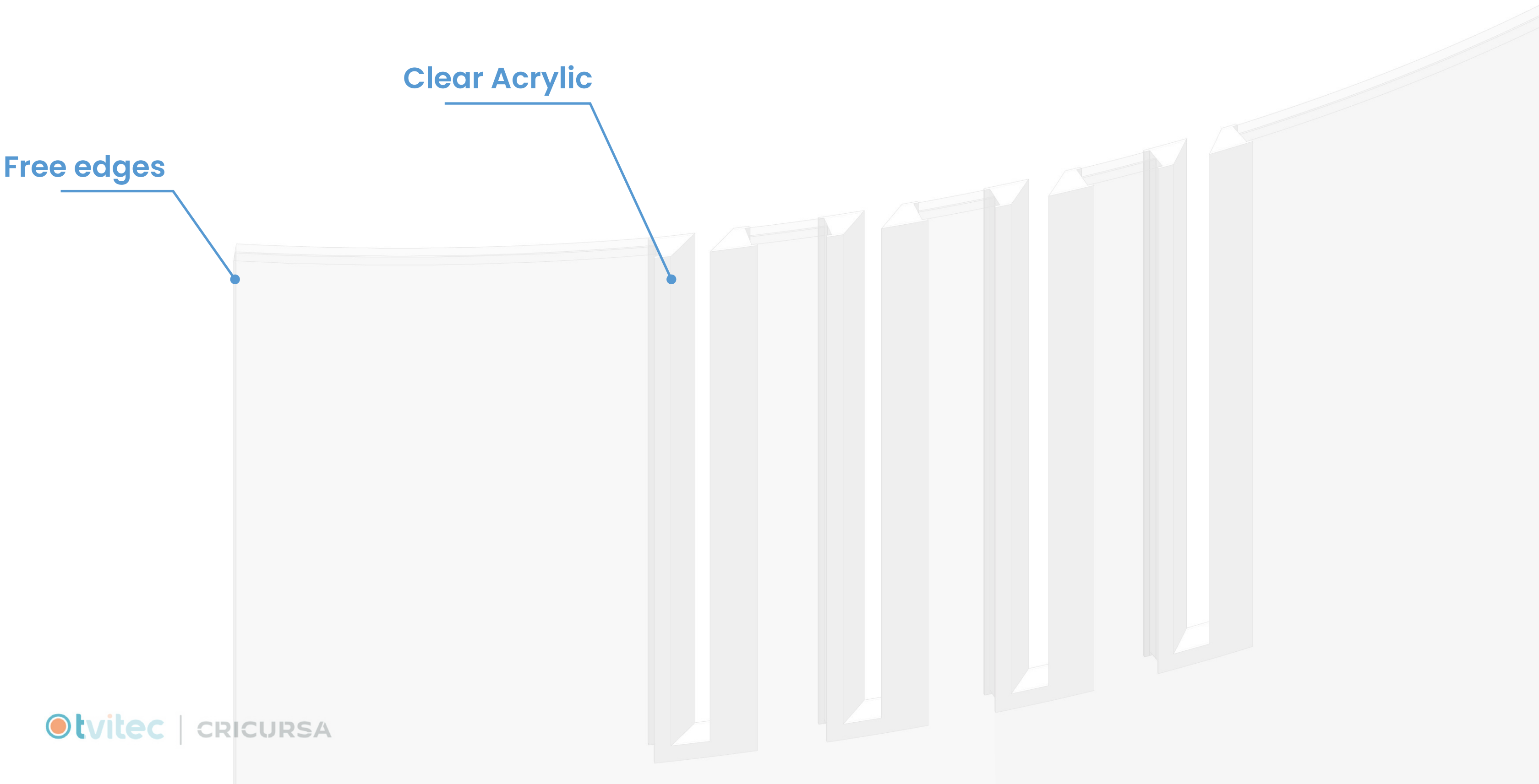
Lab tests confirm that a 1-meter-long, 0.5-meter-high module of 2×6 mm fully toughened glass is structurally feasible, withstanding at least 7.5 kN per slot under compression.



Final design

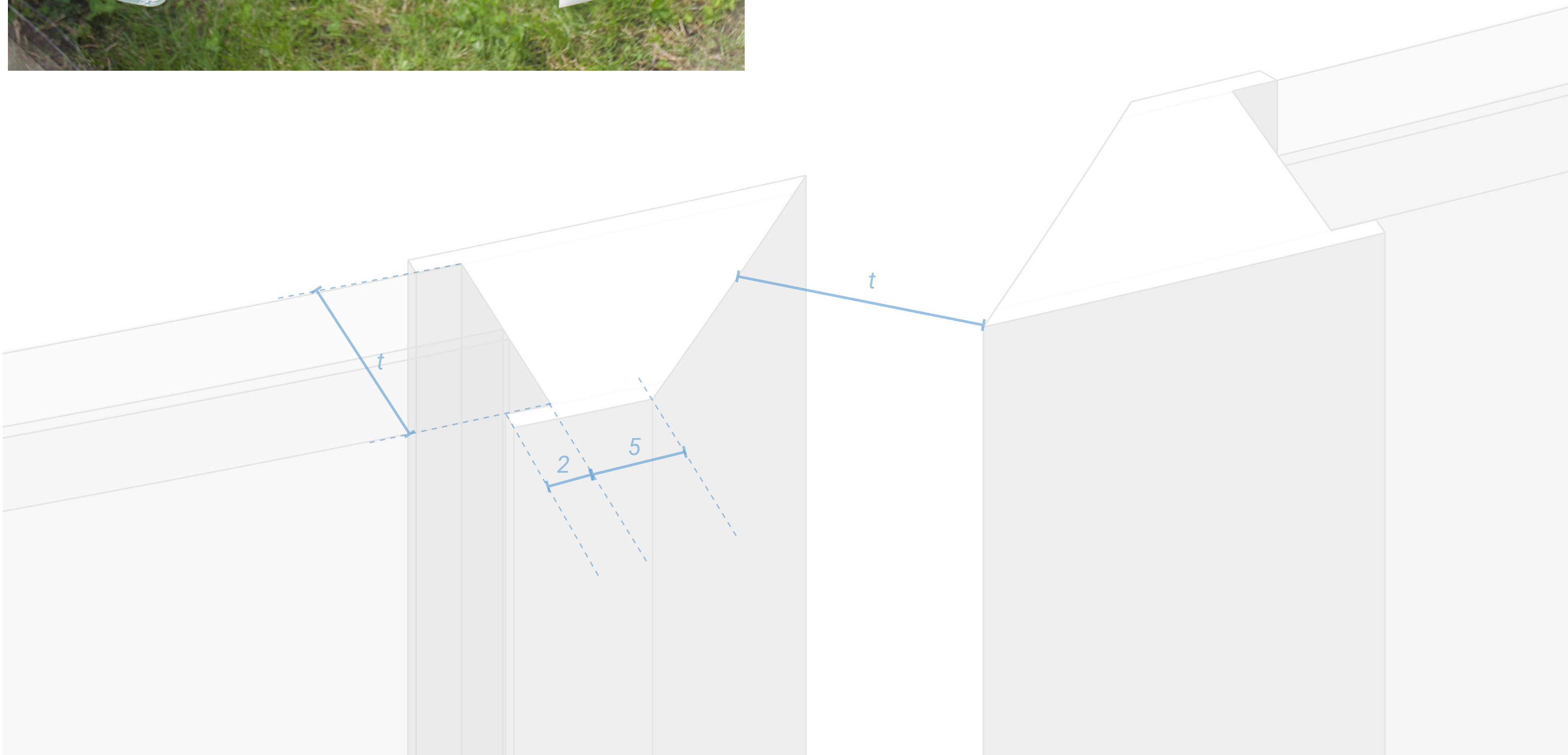
The position of the slots keeps the module edges clear, enhancing the visual transparency and lightness of the structure.





Final design

Transparent acrylic inserts are proposed, that clamp the modules slightly and prevent glass-to-glass contact. This creates pinned-like joints, enabling force transfer through compression and allowing for thinner modules while preserving system transparency.



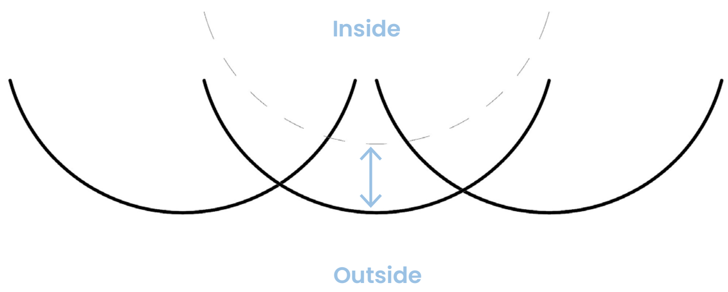
Discussion

- Basic protection against rain: certain height sequences can create gaps in the structure due to the shorter module's limited interlocking depth. So the water tightness varies for each configuration.

- Basic protection against overheating: It is assumed in this research that integrating transparent solar control in the interlayer or at the top as coating would work.

- Optimization of span performance is not based on variable slot locations: it is assumed in the parametric model that each interlocking angle is located at the same location.

- It is not investigated how the various slot angles, who are inclined at a specific angle, can be best distributed along the module's length.



Further research

- Investigate if the angle differences between modules, mostly arising in a more freeform geometry - are not a thread to the structural performance.

- Assessment of overall structural stability and the effects of asymmetric loading conditions.

- Further refinement of the slot infill:

    1. Geometry will slightly differ for different slots facilitating different interlocking angles.

    2. Test compressive strength of slot infill and capability of mitigating excessive internal stresses caused by manufacturing or installation tolerances.

- Testing of the bending resistance of the modules in freeform configurations, where force transfer through compression is not optimal.

- Design of supports for the first and last rows of modules. Adjustable supports may be required, as the algorithm can generate design solutions that slightly deviate from the predefined spatial constraints.

- Exploration of larger spans

- Structural exploration of using the system in a different way, for example, by by rotating a generated arch onto its side, allowing it to function as a transparent partition wall.

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