TO3DPGS - The Future Of Glass

2024 | 06 | 21

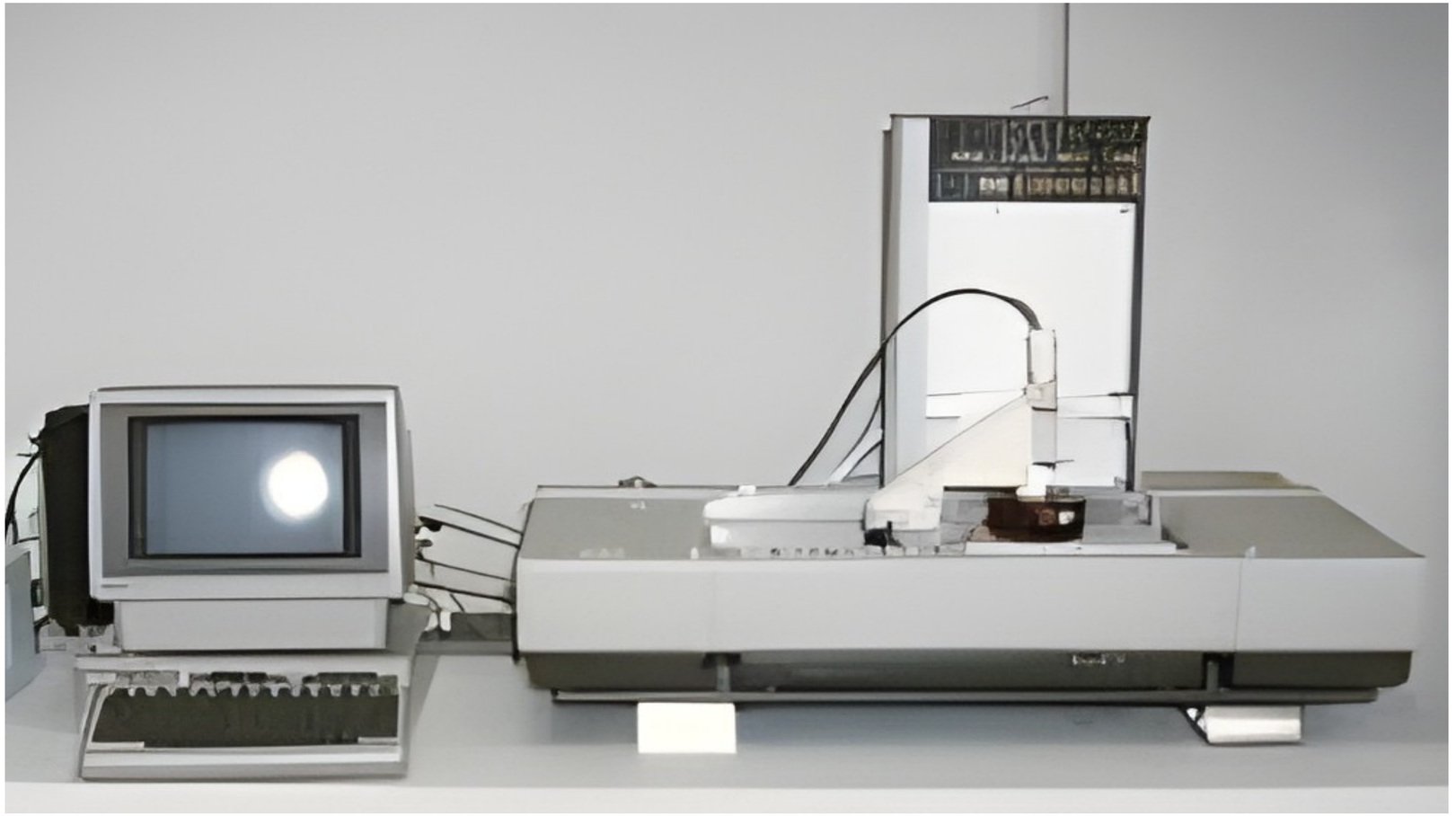
Pim Brueren

*'Development of an Algorithm for **T**opology **O**ptimized **3D P**rinted **G**lass **S**tructure'*

Mentors:
Faidra Oikonomopoulou (SDM)
Charalampos Andriotis (AI)

Creating an **algorithm** that ensures the **manufacturability** of a **monolithic 3D printed glass bridge**

Introduction



First 3D printer ‘80

https://www.sculpteo.com/en/3d-learning-hub/basics-of-3d-printing/the-history-of-3d-printing/ - AI upscaled

Introduction

ETH Zurich developmend of concrete 3D printing

https://www.archdaily.com/921635/eth-zurich-develops-3d-printed-concrete-columns

Introduction

3D printed steel bridge

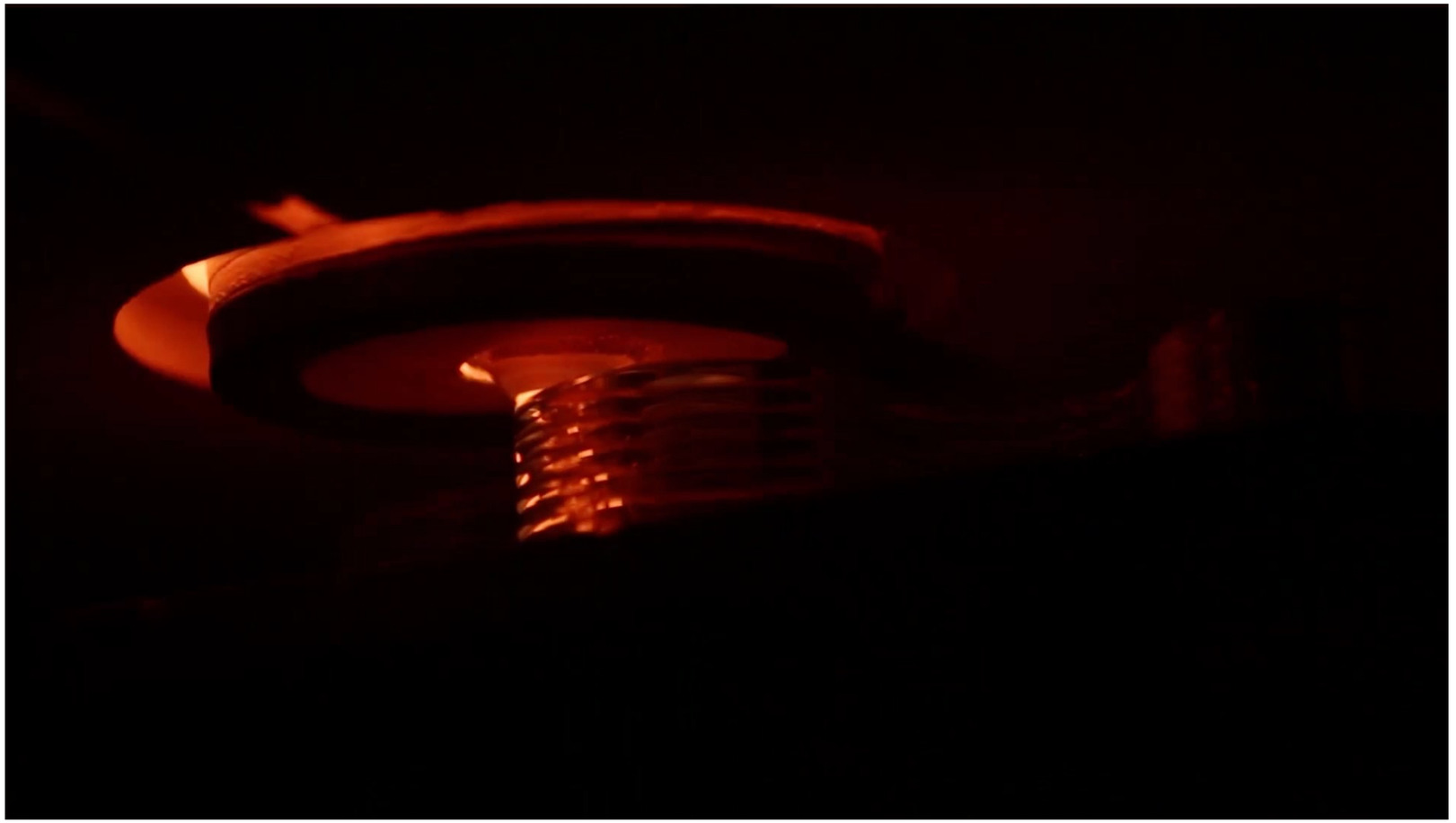
https://www.3dnatives.com/en/3d-printed-steel-bridge260420184/

Introduction

DBT non planar printing in plastic

https://dbt.arch.ethz.ch/project/fluid-forms/

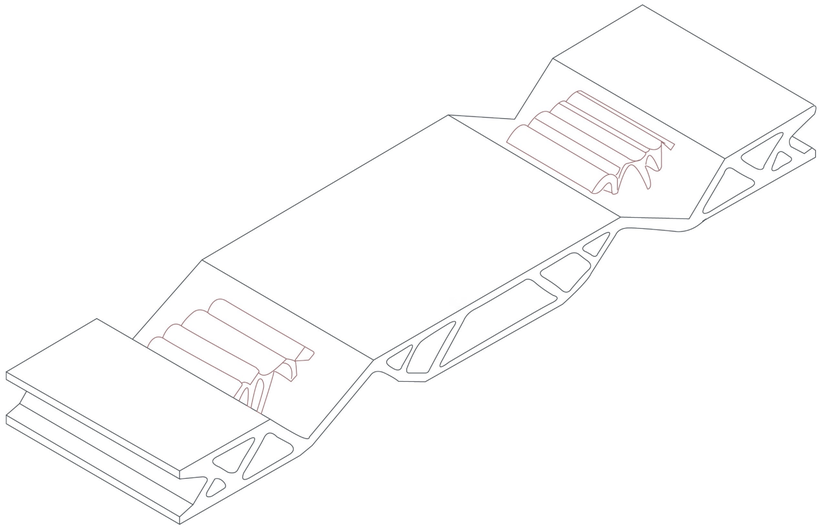
Introduction



G3DP2

https://oxman.com/projects/glass-3d-printing

Introduction



Anna Maria Koniari 2022

Eva Schoenmaker 2023

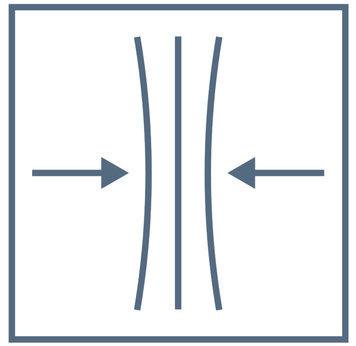
why glass?

Glass

Transparent

Recyclable

Durable



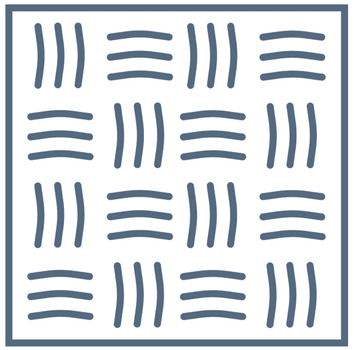
Compressive-resistant

Glass

Glass

420 - (1000) MPA

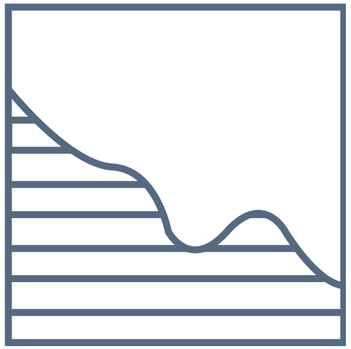
35 - (45) MPA
120-200MPa (toughened)



Steel

250 - 400 MPa

400 - 700 MPa



Epoxy (resin)

124 - 275 MPa

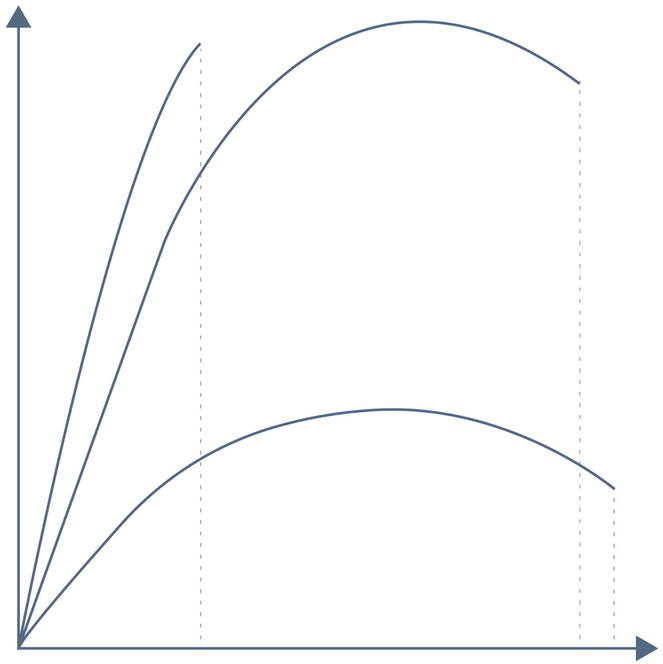
34 - 137 MPa

Unreinfoced Concrete

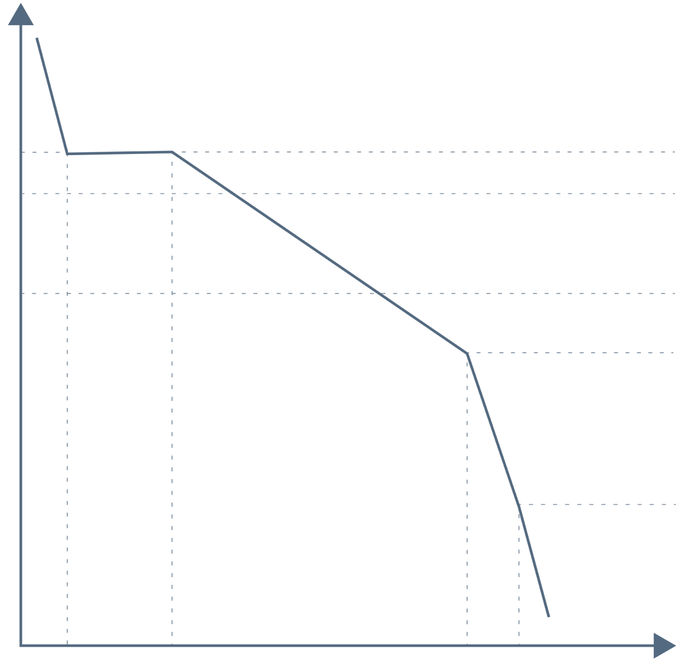
20 - 70 MPa

1.4 - 4.1 MPa

Glass

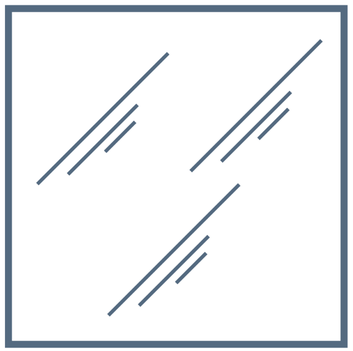


Brittle



Annealing

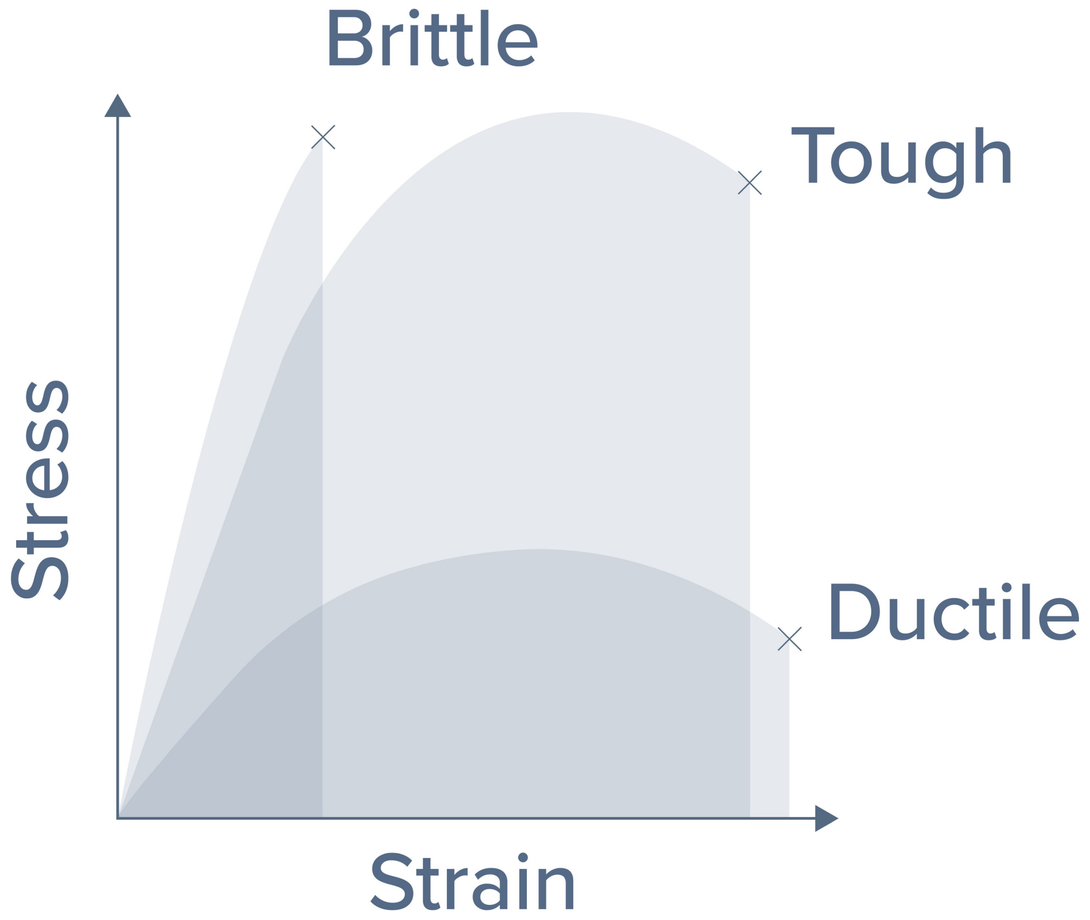
Glass



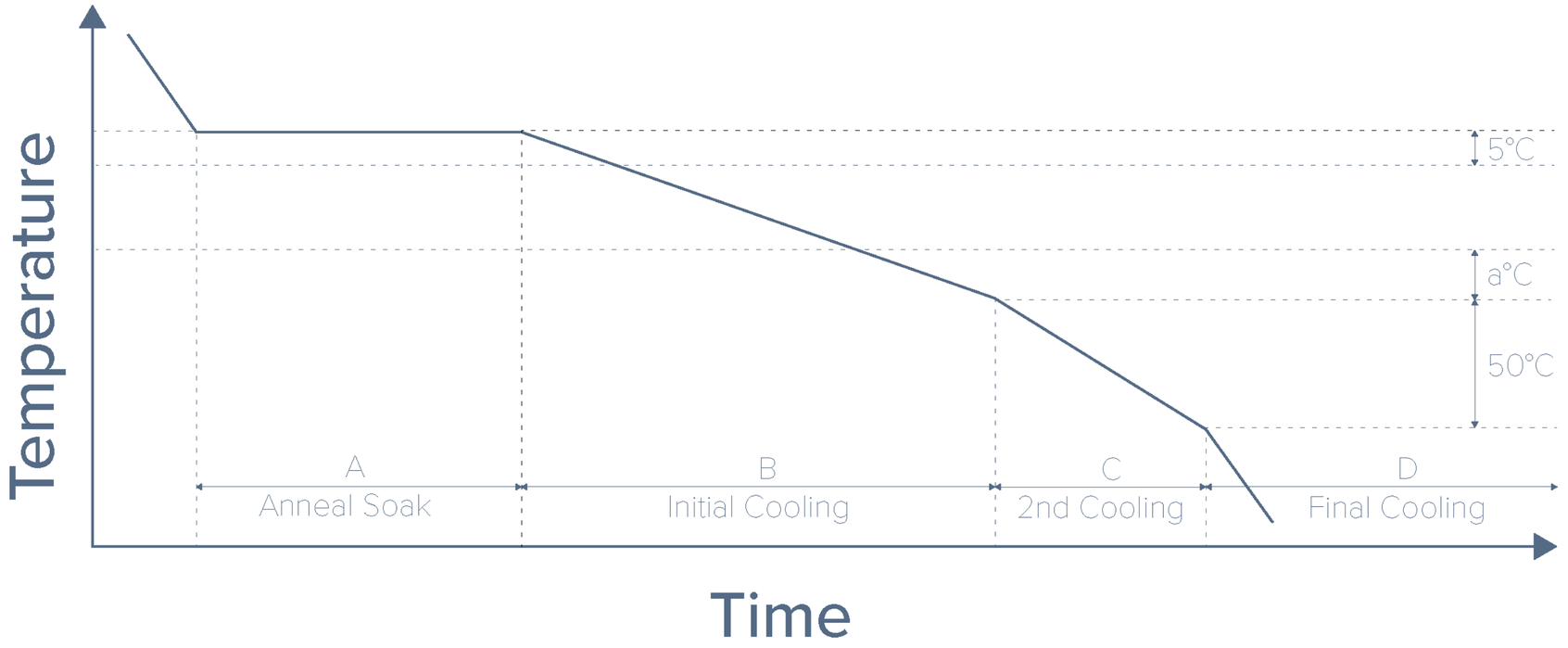
Glass

compressive strength
420 - (1000) MPA

Tensile strength
35 - (45) MPA
120-200MPa (toughened)

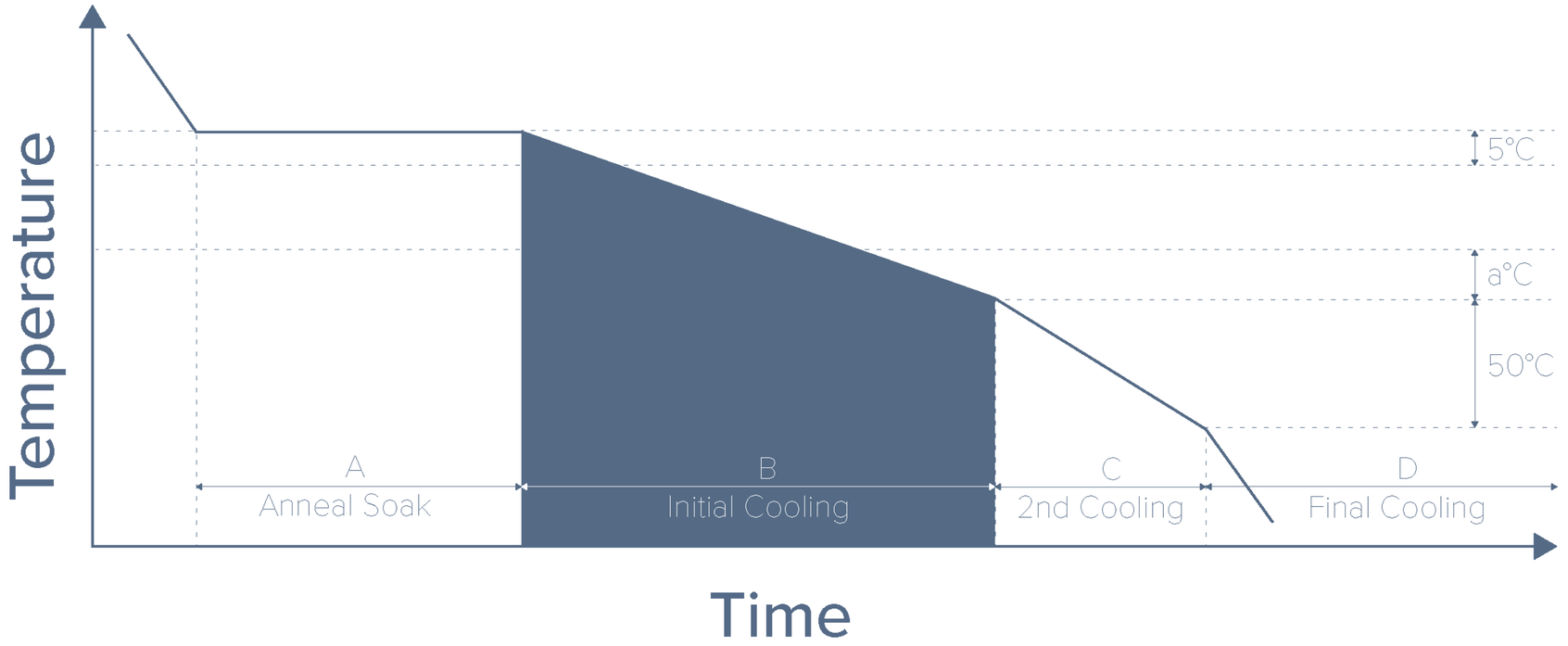


Glass



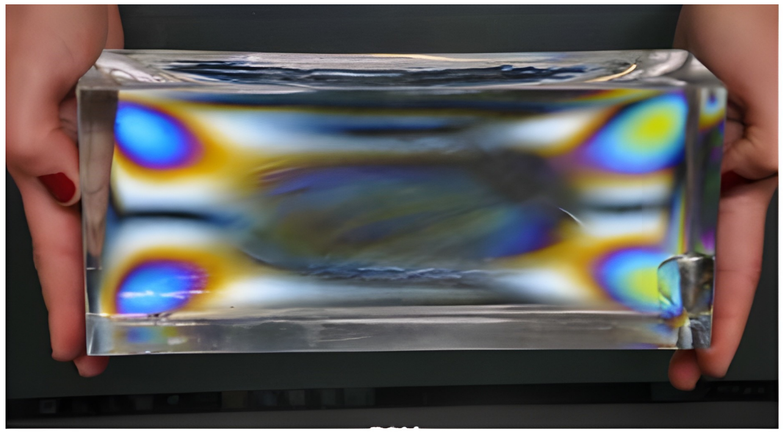
Based on F. Oikonomopoulou (2019)

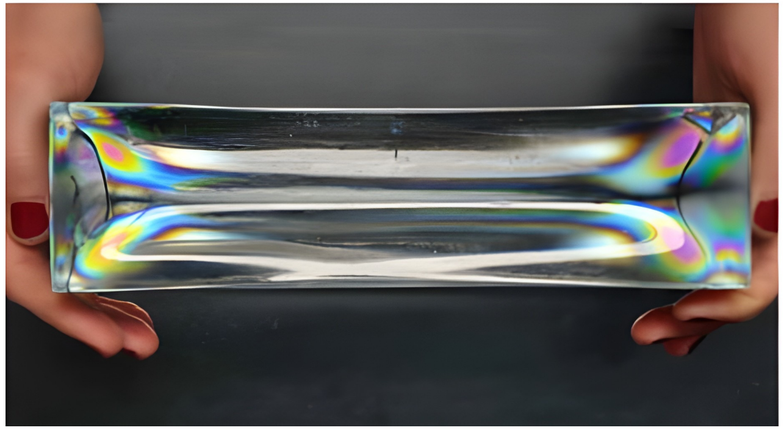
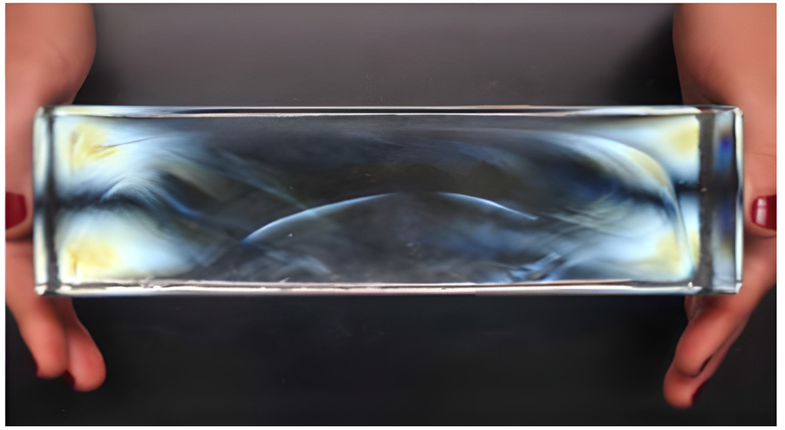
Glass



Based on F. Oikonomopoulou (2019)

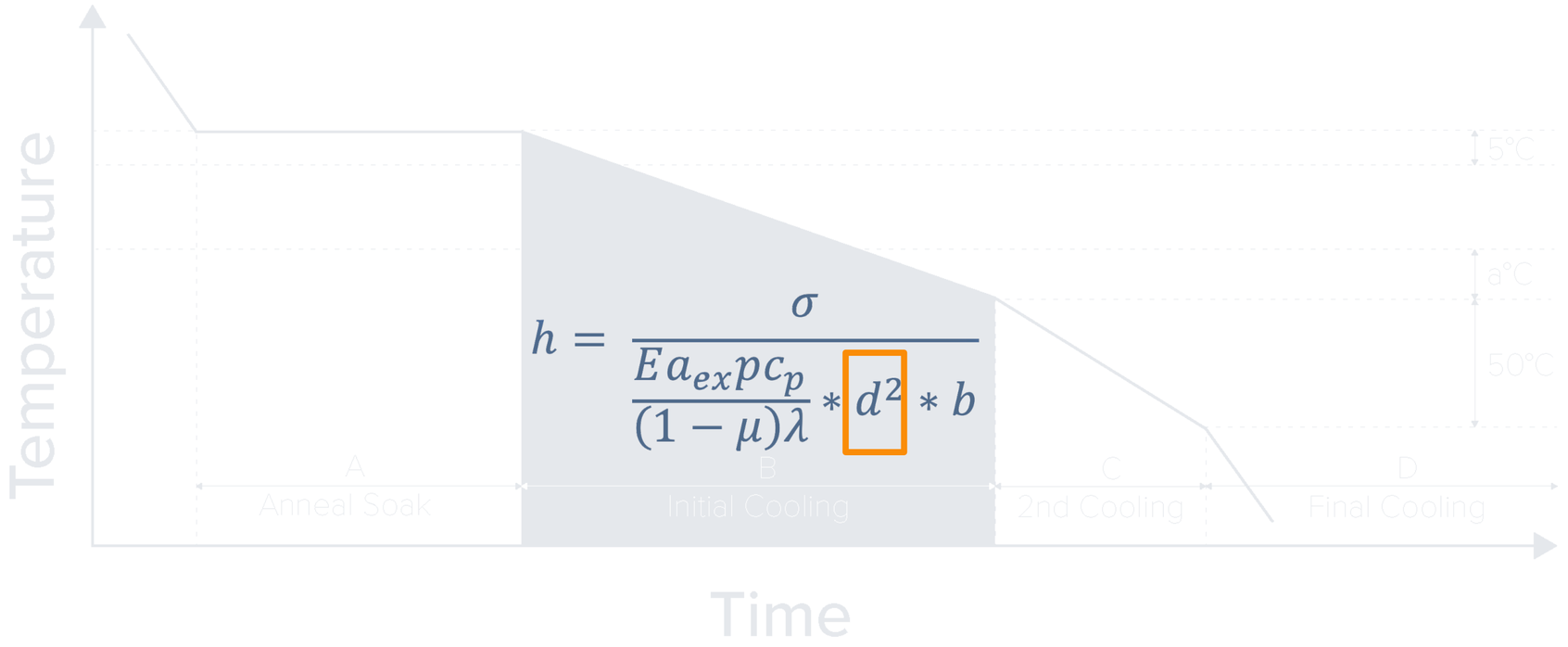
Glass



F. Oikonomopoulou (2019) AI upscaled

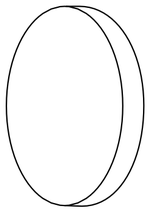
Glass



$$h = \frac{\sigma}{\frac{E a_{ex} p c_p}{(1-\mu)\lambda} * d^2 * b}$$

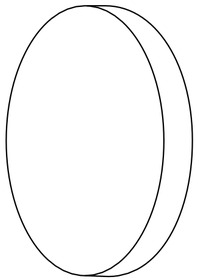
Based on F. Oikonomopoulou (2019) & Koniari (2022)

Glass



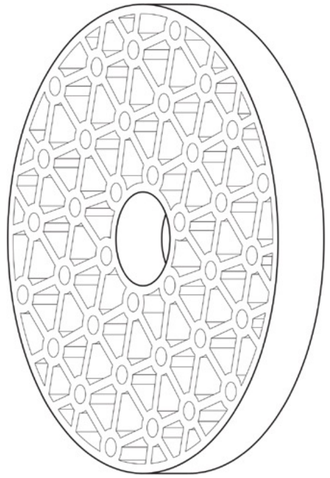
Hale - Mount Wilson Telescope
Ø 1.5m / 60 Inch
d = 190 mm
860 kg
4 months annealing

consist of 1 layer



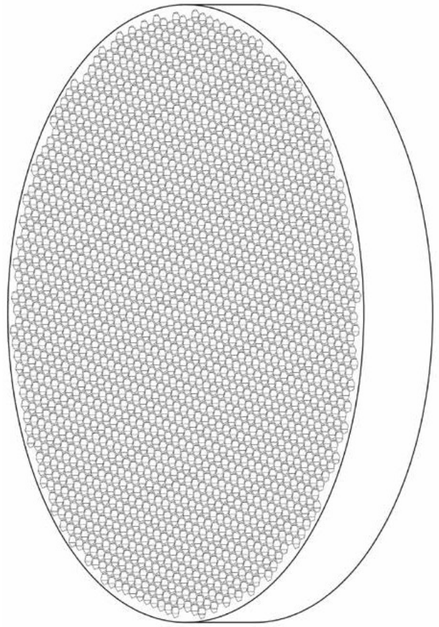
Hale - Mount Wilson Telescope
Ø 2.5m / 100 Inch
d = 325 mm
4500 kg
12 months annealing

consist of 3 layers



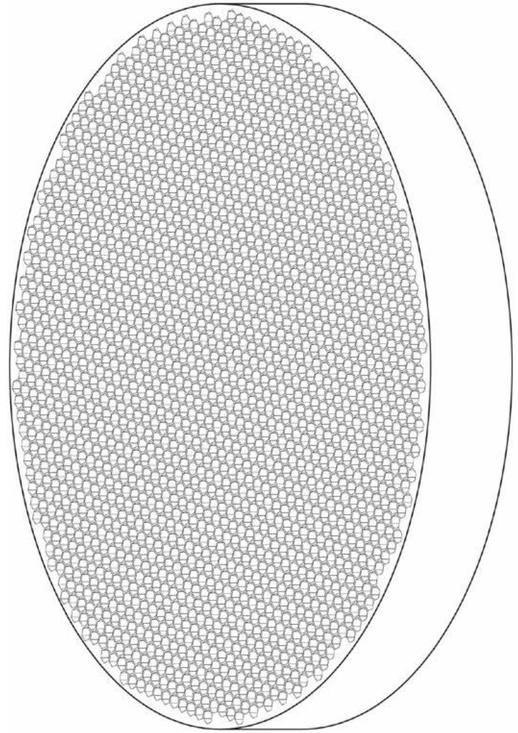
Hale - Palomar observatory
Ø 5.1m / 200 inch
d = 660 mm
20000 kg
10 months annealing

Honeycomb structure



Magellan Telescope
Ø 6.5m / 256 inch
d = 910 mm
9500 kg
3 months annealing

Spin casting - Thinner ribs

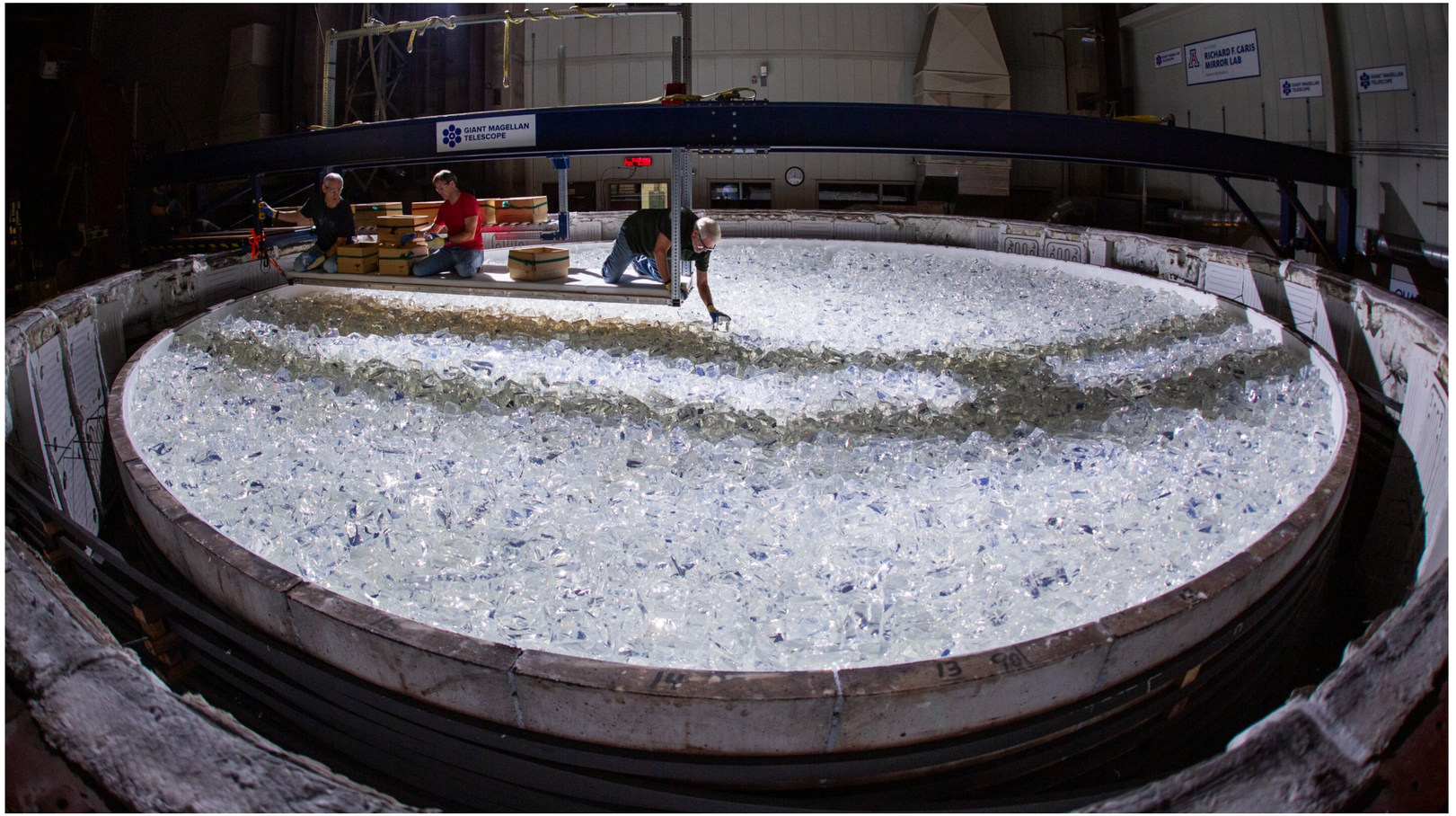


(Giant) Magellan Telescope
Ø 8.417m / 331 inch
d = 894 mm
17481 kg
3 months annealing

Spin casting - Thinner ribs

Evolution of cast mirror blanks used for telescopes
Based on: F. Oikonomopoulo et al., The university of Tokyo, Mtwilson

Glass



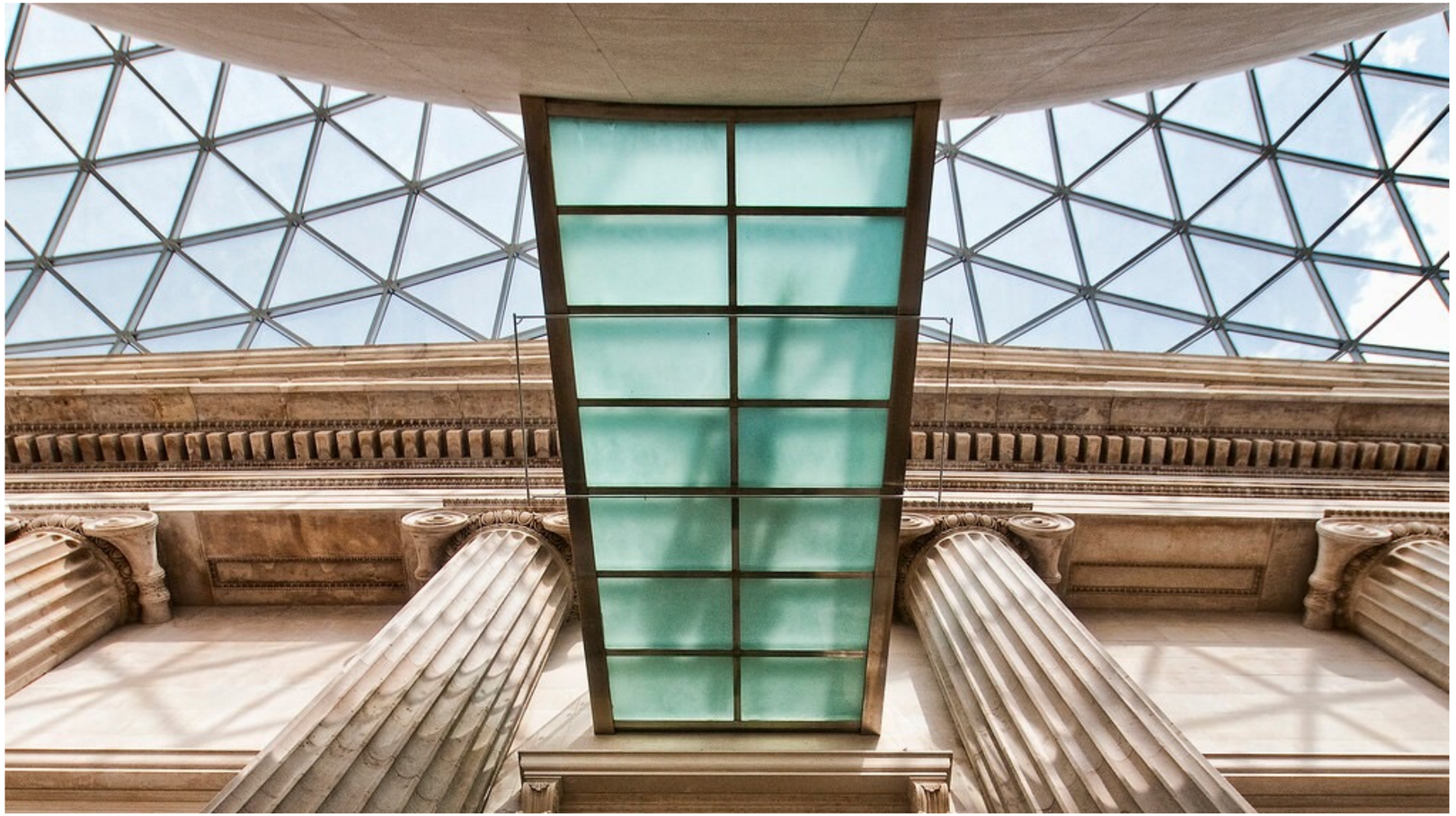
Giant Meggalan Telescope

https://encrypted-tbn2.gstatic.com/images?q=tbn:ANd9GcRfsq5mMxmqcIP5kmOdLg0ty1ux49rj99YISXRt-bVfHtZavEtX

Topology optimization is a mathematical algorihm that **optimizes the shape on a set of load cases within a given domain**.

The algorithm finds the most lightweight design while ensuring the required strength.

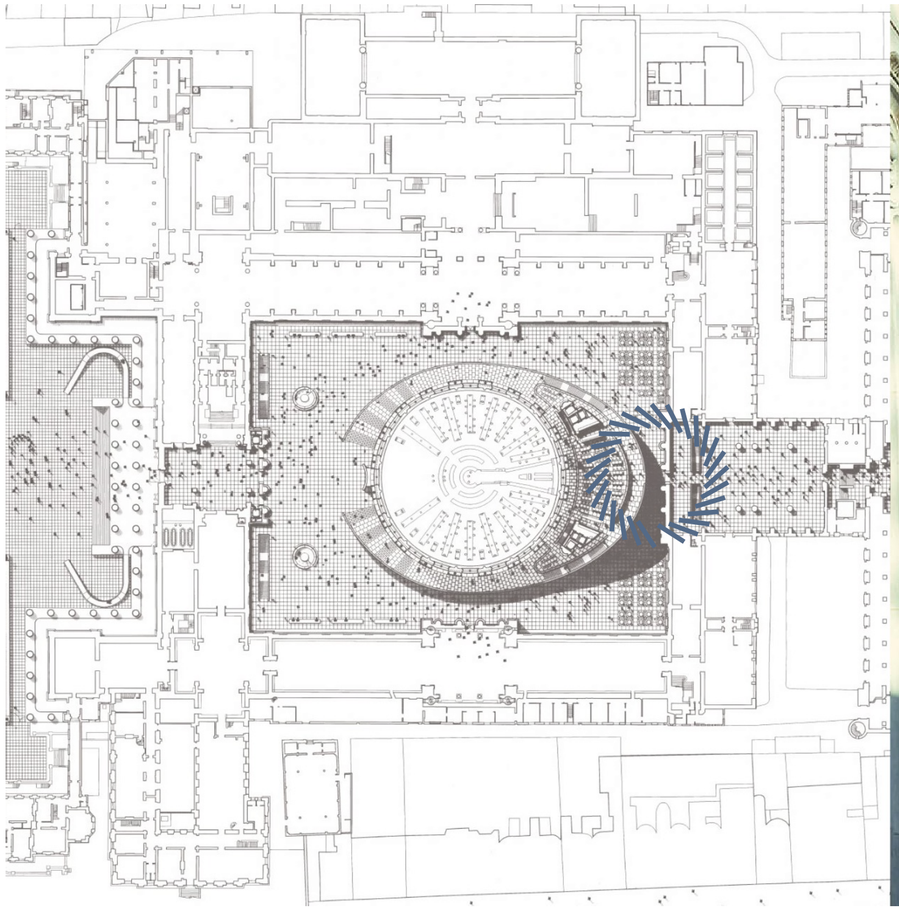
Topology optimization



Bridge connecting the atrium and gallery spaces - The britisch museum

https://www.flickr.com/photos/darrellg/7172296625

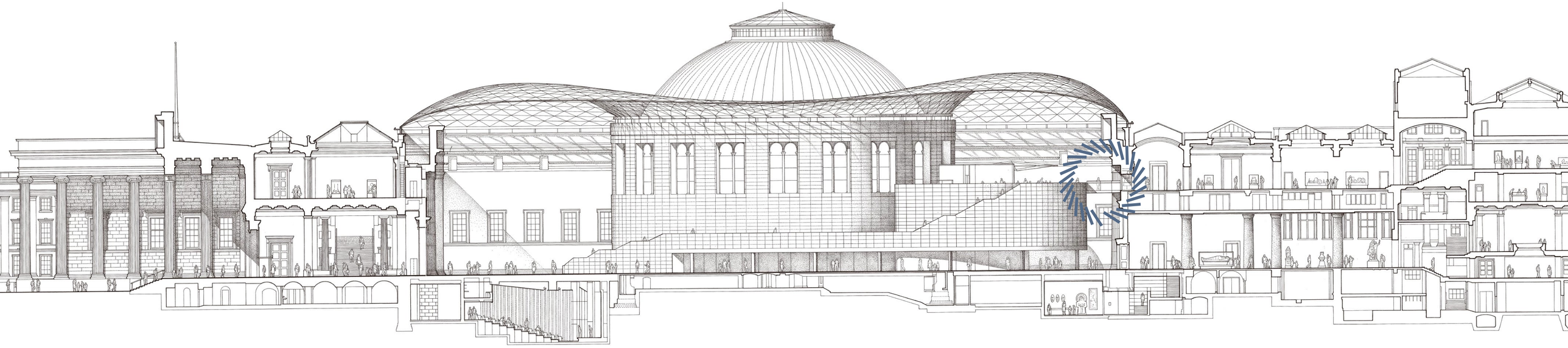
Topology optimization



Bridge connecting the atrium and gallery spaces - The britisch museum

https://arquitecturaviva.com/works/renovacion-del-british-museum-2

Topology optimization



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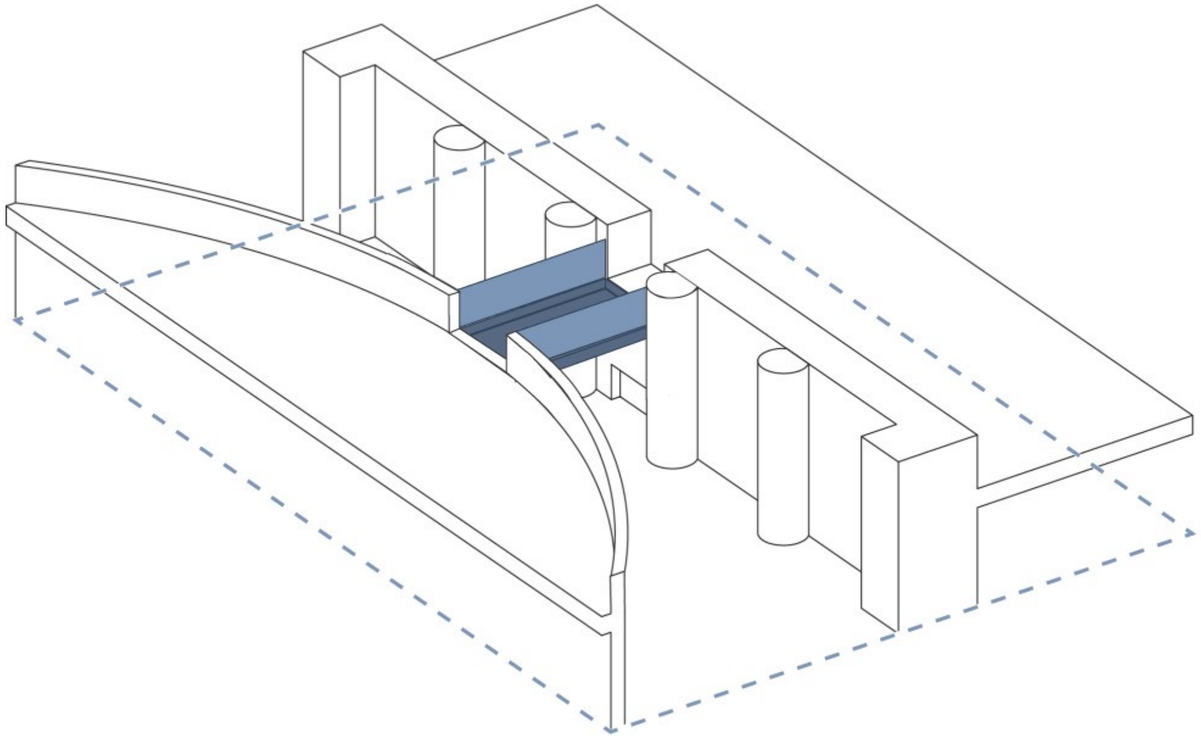
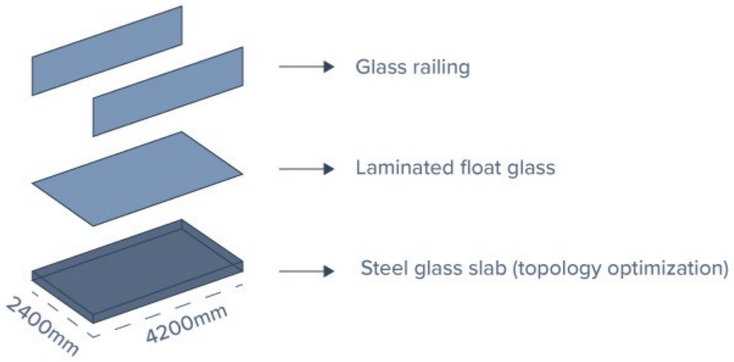
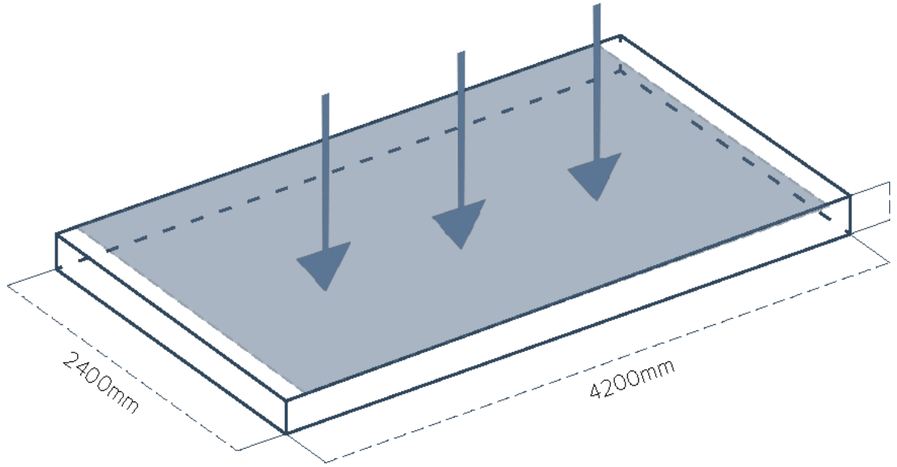
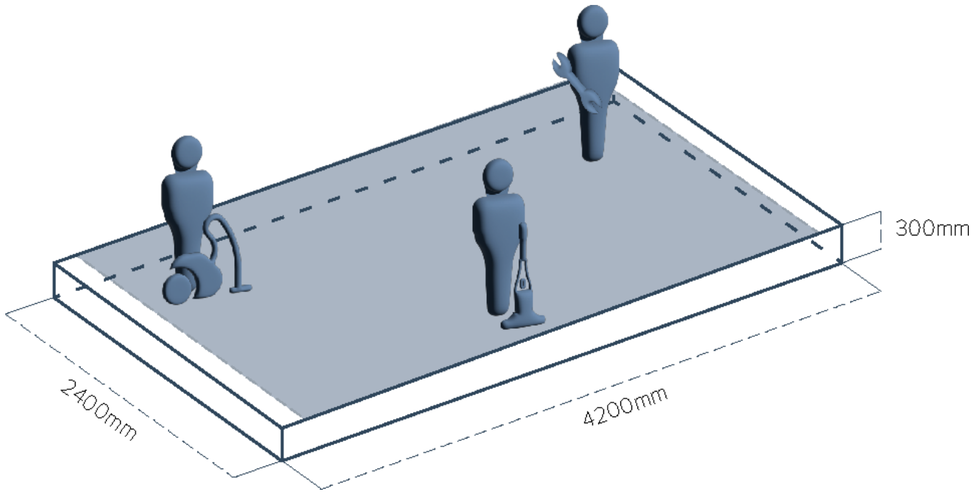
Topology optimization

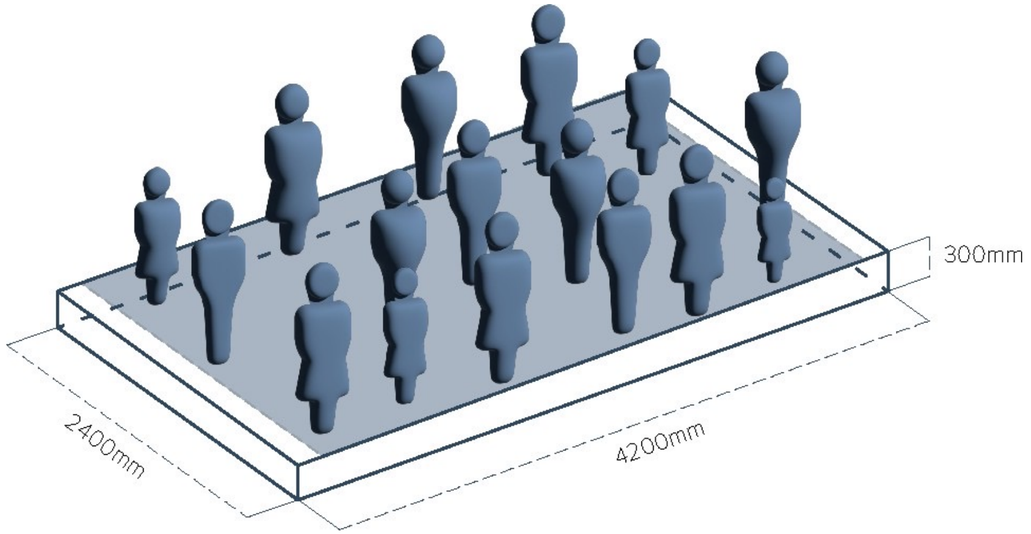




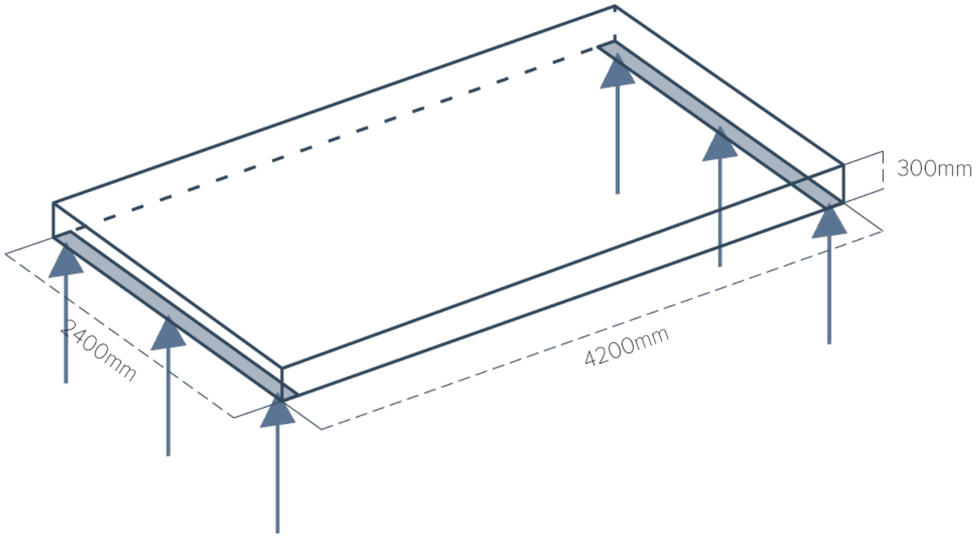
Topology optimization



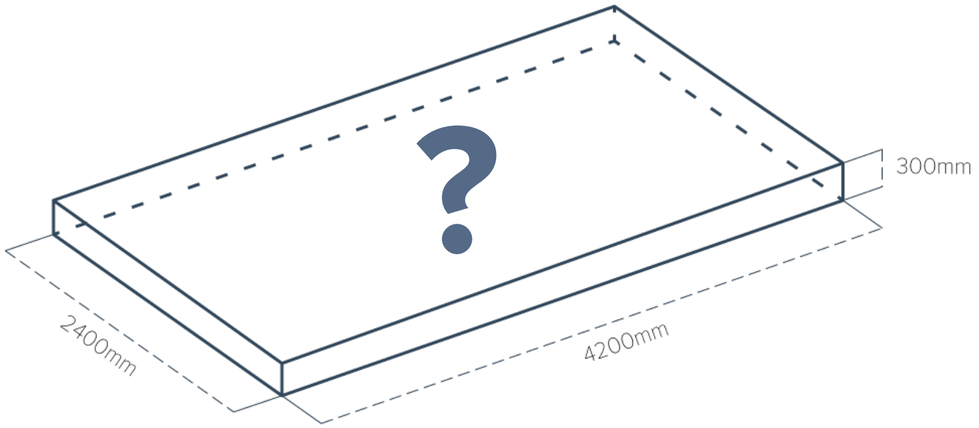




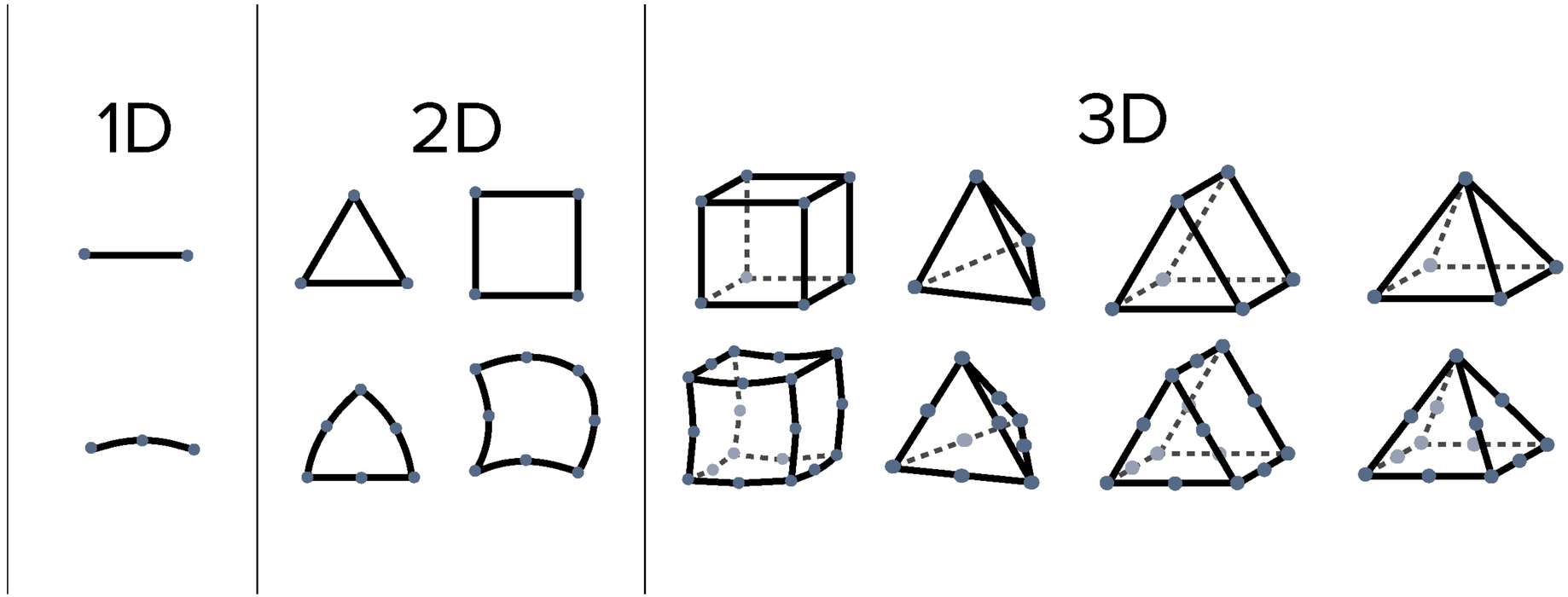
Topology optimization



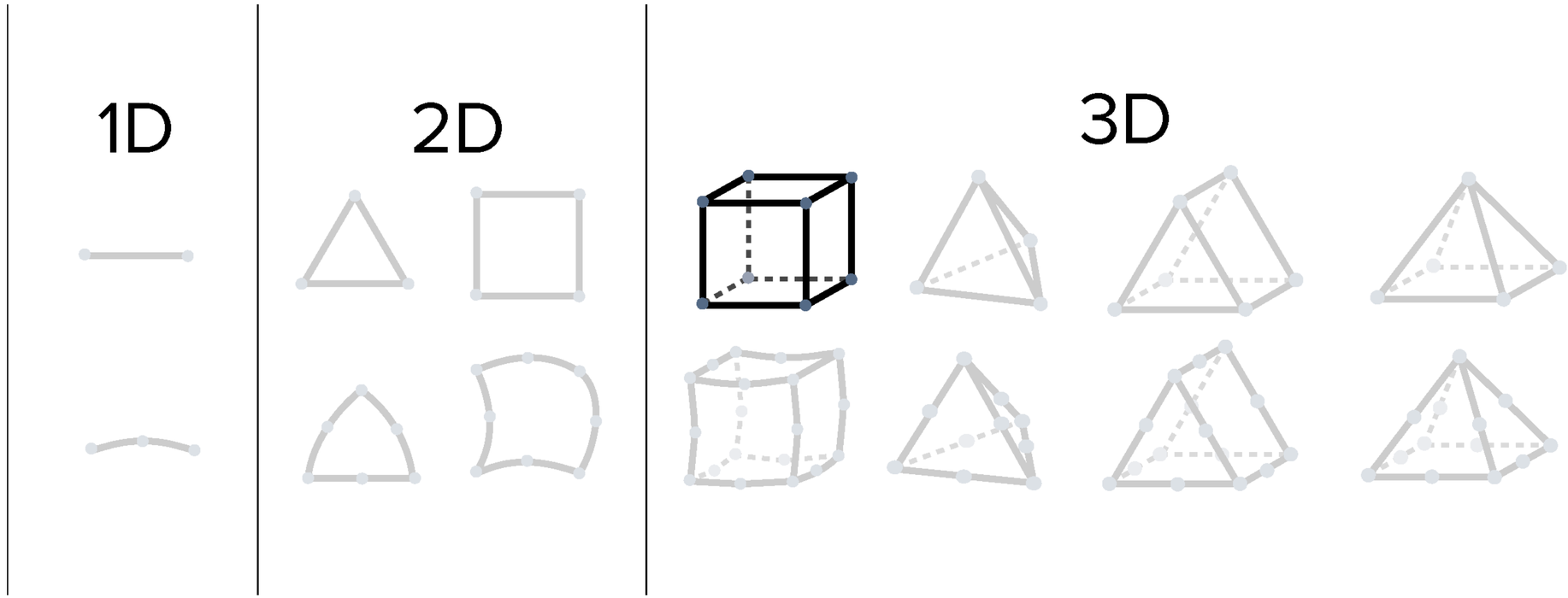
Topology optimization



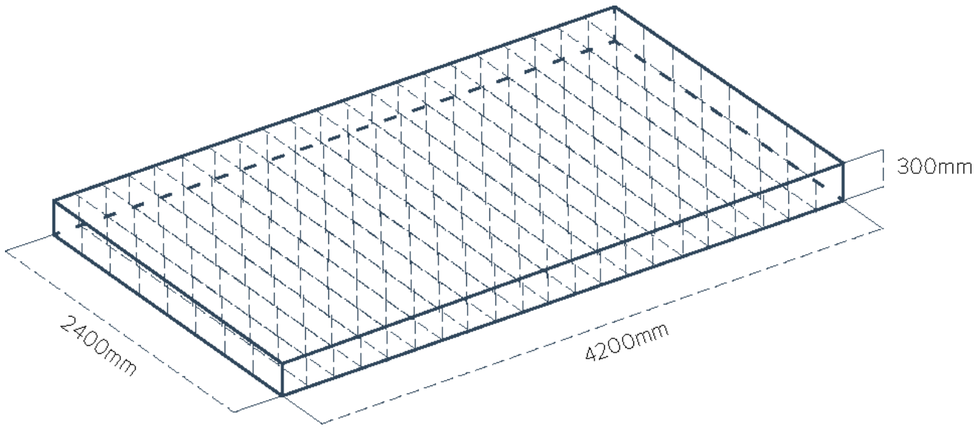
Topology optimization



Topology optimization

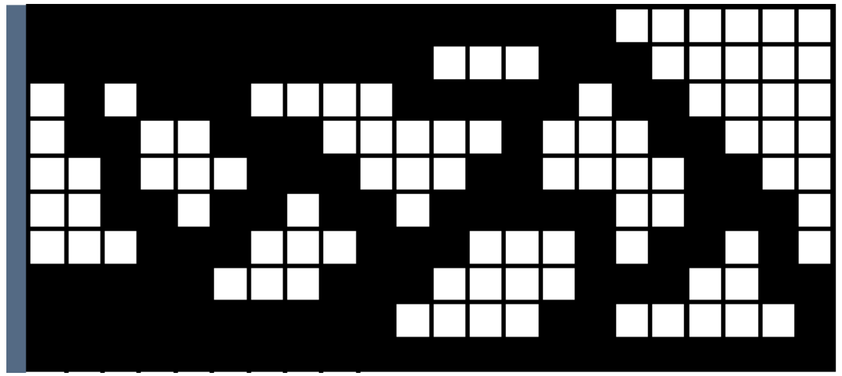


Topology optimization



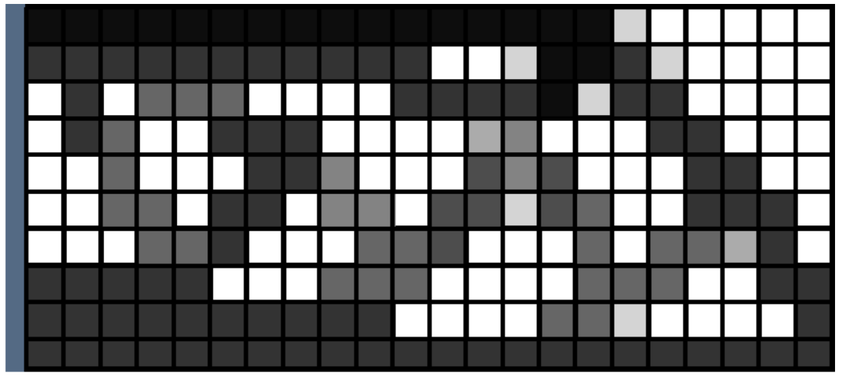
Topology optimization

Direct-Search methods



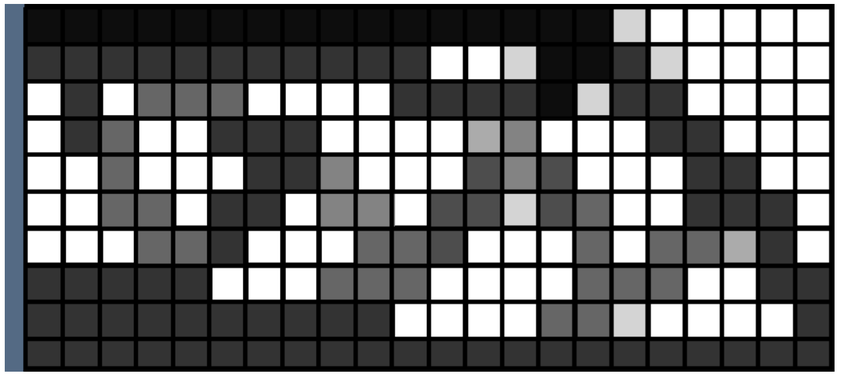
- Evolutionary Algarithms
- Moving Morphable Components (MMC)
- Bi - Directional Evolutionary Structural Optimization ((B)ESO)

Gradient - Based Methods



- SIMP (Solid Isotropic Material Penalization)
- Level Set Method (LSM)
- Homogenization Method

Topology optimization



$$Maximize: \; c(\rho_e) = \{F\}^T(u)$$

$$Subject\ to: \; \left[\sum_{e=1}^{N} \rho_e^p \, K_e\right]\{u\} = \{F\}$$

$$\sum_{e=1}^{N} v_e \rho_e \leq \overline{V_s}$$

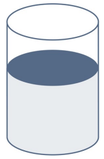
$$0 < \rho_{min} \leq \rho_e \leq 1 : e = 1,2,\dots,N$$

$$p = 1,2,\cdots, \; p_{max} : p_{max} > 3$$

Topology Optimization

Volume

Minimize the sum of all denisties



$$
\begin{aligned}
min_x \quad & : V(x) = \sum_N x_e v_e \\
Subject\ to & : KU = F \\
& : \frac{c}{c_{l,}} \leq 1 \\
& : x_e^{(p-q)} \frac{\sigma_e}{\sigma_{Lt}} \leq 1, \qquad e = 1, \dots, N \\
& : 0 < x_{min} \leq x \leq 1
\end{aligned}
$$

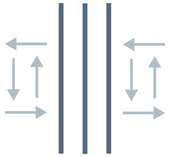
Compliance

Minimize the sum of all deformations

$$
\begin{aligned}
min_x \quad & : c(x) = U^T K U \\
subject\ to & : \frac{V(x)}{V_0} = f \\
& KU = F \\
& 0 < xmin \leq x \leq 1
\end{aligned}
$$

Stress

Minimize the peak sstresses



$$
\begin{aligned}
min \quad & : G_{(x)} \\
subject\ to & : \int_\Omega^\infty \mathrm{x d}\Omega \leq M_0
\end{aligned}
$$

$$
\begin{aligned}
& minimize: \ f_O(x) \\
& g_i(x) \leq 0, for\ i = 1, 2, \dots, m \\
& h_j(x) = 0, for\ j = 1, 2, \dots, p
\end{aligned}
$$

Topology Optimization

Volume

Minimize the sum of all denisties

$$
\begin{aligned}
min_x \quad & : V(x) = \sum_N x_e v_e \\
Subject\ to : \ & KU = F \\
& : \frac{C}{C_{l.}} \leq 1 \\
& : x_e^{(p-q)} \frac{\sigma_e}{\sigma_{Lt}} \leq 1, \qquad e = 1, \ldots, N \\
& : 0 < x_{min} \leq x \leq 1
\end{aligned}
$$

Compliance

Minimize the sum of all deformations

$$
\begin{aligned}
min_x \quad & : c(x) = U^T K U \\
subject\ to \ & : \frac{V(x)}{V_0} = f \\
& KU = F \\
& 0 < xmin \leq x \leq 1
\end{aligned}
$$

Stress

Minimize the peak sstresses

$$
\begin{aligned}
min \quad & : G_{(x)} \\
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\end{aligned}
$$

$$
\begin{aligned}
& minimize: \ f_O(x) \\
& g_i(x) \leq 0, for\ i = 1, 2, \ldots, m \\
& h_j(x) = 0, for\ j = 1, 2, \ldots, p
\end{aligned}
$$

Topology optimization

Compliance

Minimize the sum of all deformations

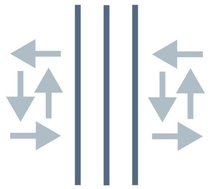
$$\begin{aligned} min_x \quad & : c(x) = U^T K U \\ subject\ to \ & : \frac{V(x)}{V_0} = f \\ & KU = F \\ & 0 < xmin \leq x \leq 1 \end{aligned}$$

Equilibrium

Filtering

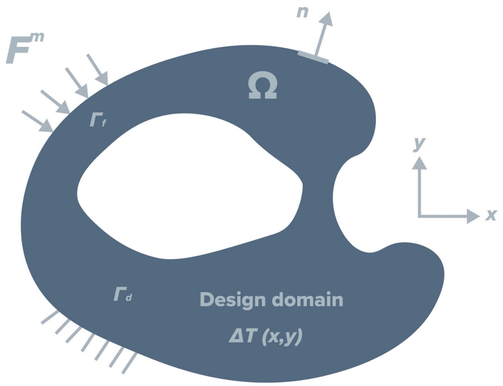
Volume

Principal stress



Deflection

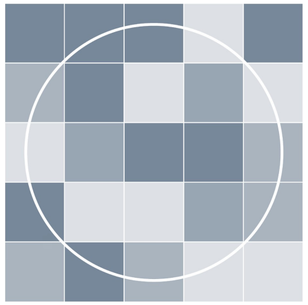
Topology optimization



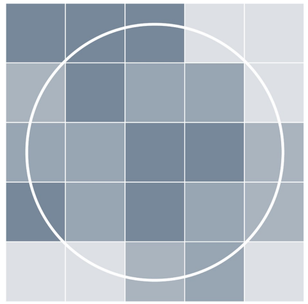
$$\mathrm{II} = \frac{1}{2}\int_V^\infty \sigma^t \varepsilon \, dV - \int_V^\infty u^T f \, dV - \int_s^\infty u^T T \, dS - \sum_i u_i^T P_i$$

Equilibrium	Filtering	Volume	Principal stress	Deflection

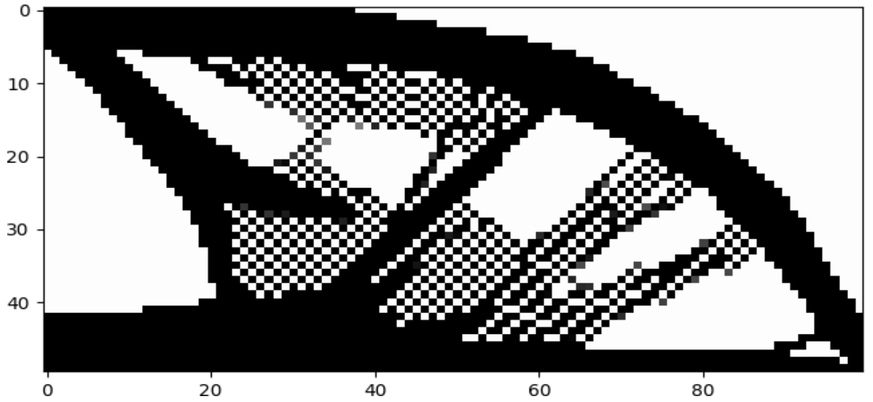
Topology optimization



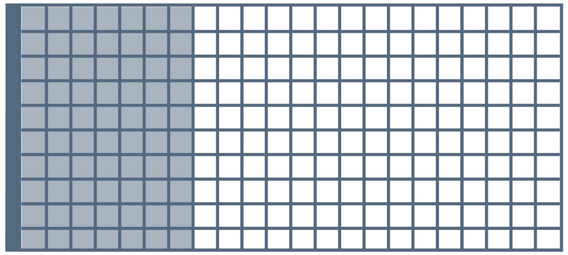
Unfiltered densities



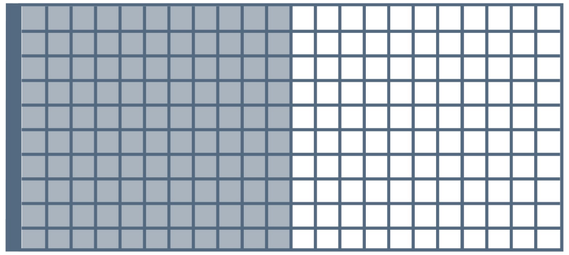
Weighted average densities neighbourhood



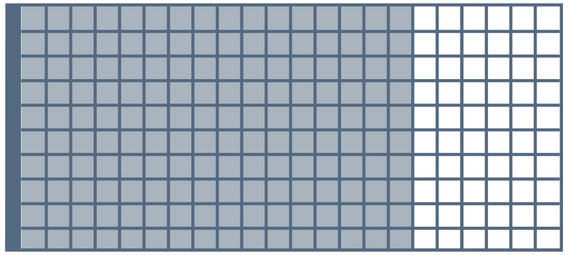
Topology optimization



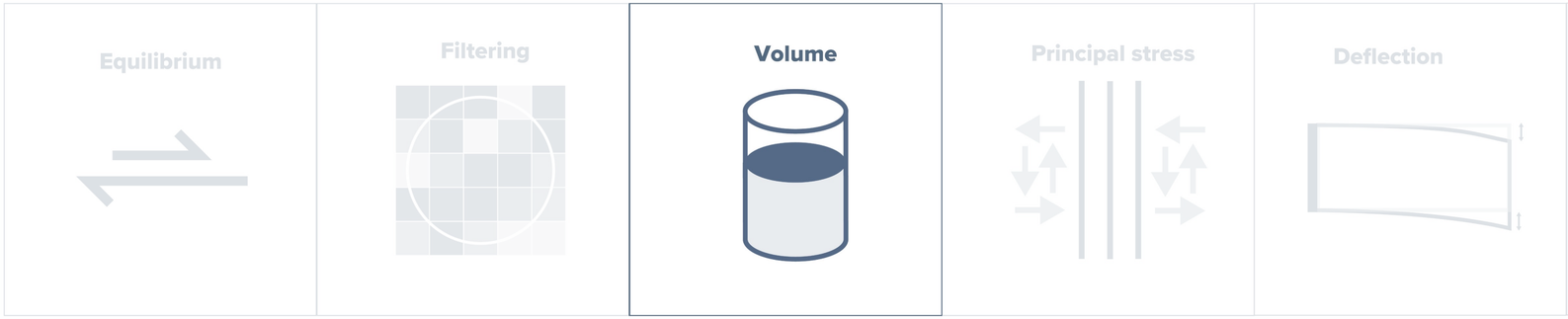
V = 30%



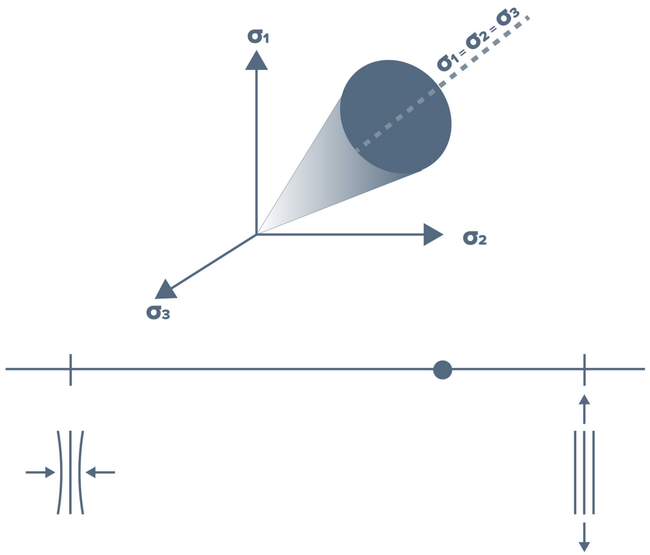
V = 50%

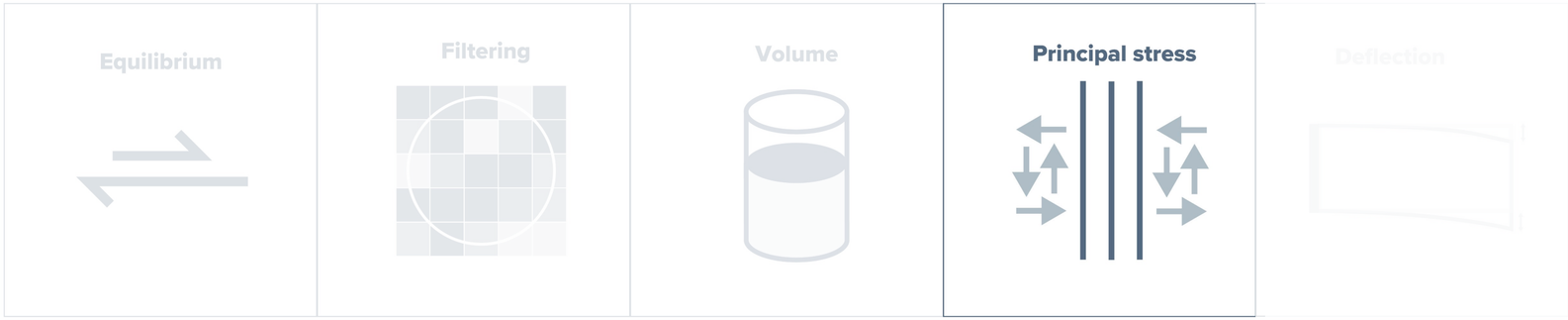


V = 70%



Topology optimization





Topology optimization

Deformation
Critical point

<

Allowed
Deformation

Equilibrium

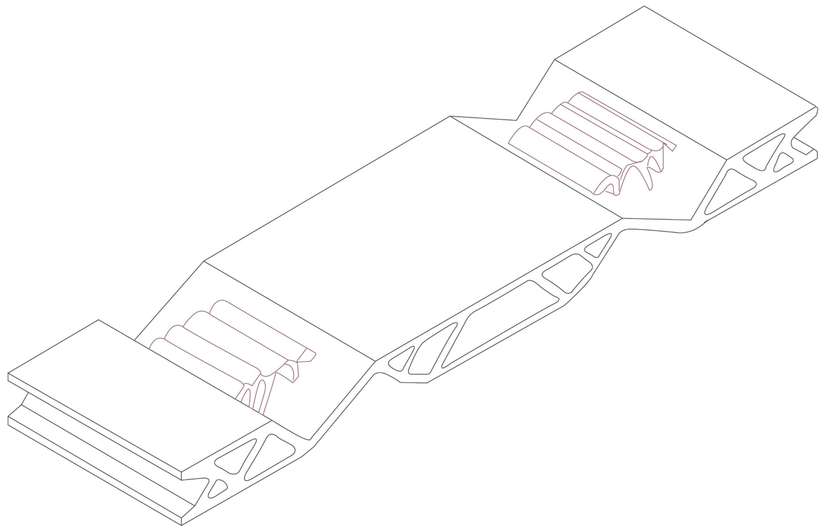
Filtering

Volume

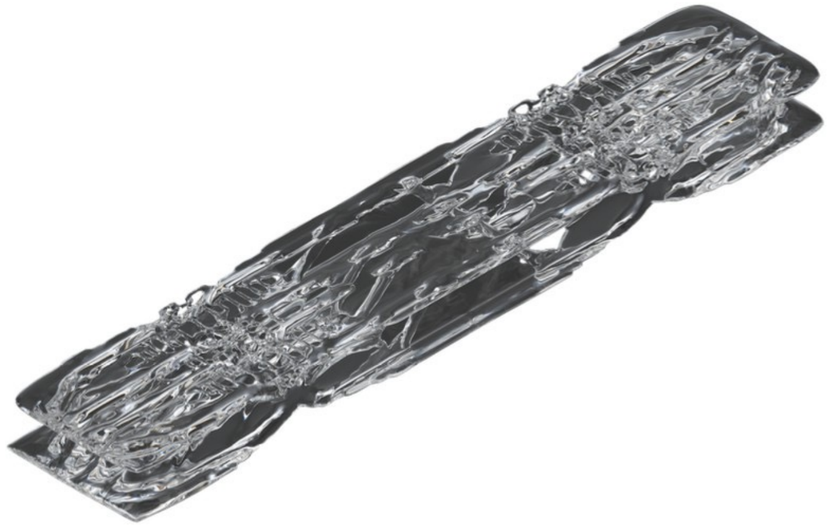
Principal stress

Deflection

Topology optimization

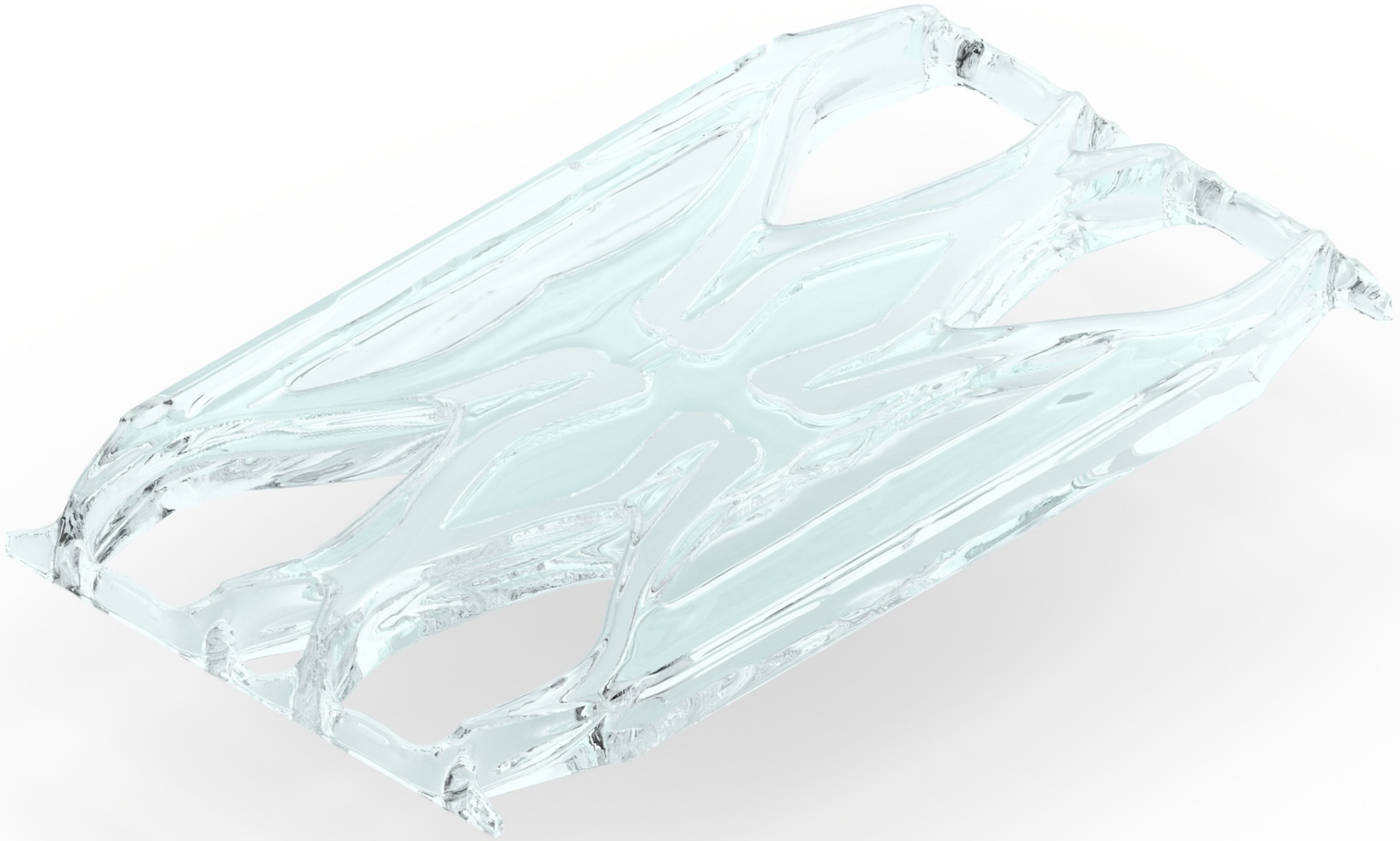


Anna Maria Koniari 2022



Eva Schoenmaker 2023

Topology optimization



Research question

How can the **manufacturing** process be **tailored** to fabricate a **topology-optimized 3D printed monolithic glass structure** while ensuring **effective production** constraints?

Topology Optimization

Compliance

Minimize the sum of all deformations

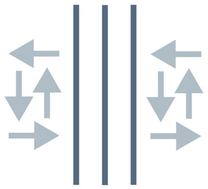
$$
\begin{aligned}
min_x \quad & : c(x) = U^T K U \\
subject\ to \ & : \frac{V(x)}{V_0} = f \\
& \quad KU = F \\
& \quad 0 < xmin \leq x \leq 1
\end{aligned}
$$

Equilibrium

Filtering

Volume

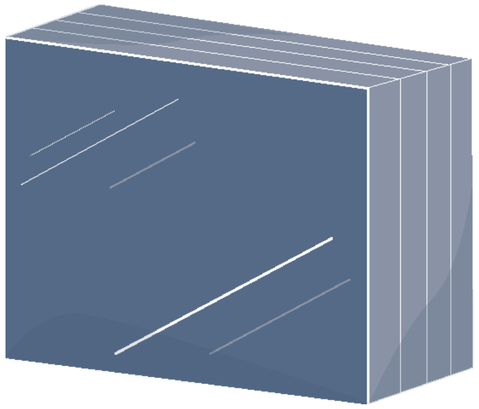
Principal stress

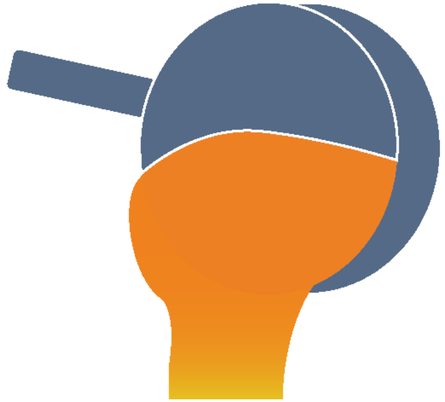


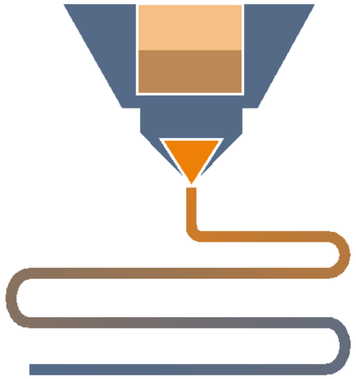
Deflection

Manufacturing

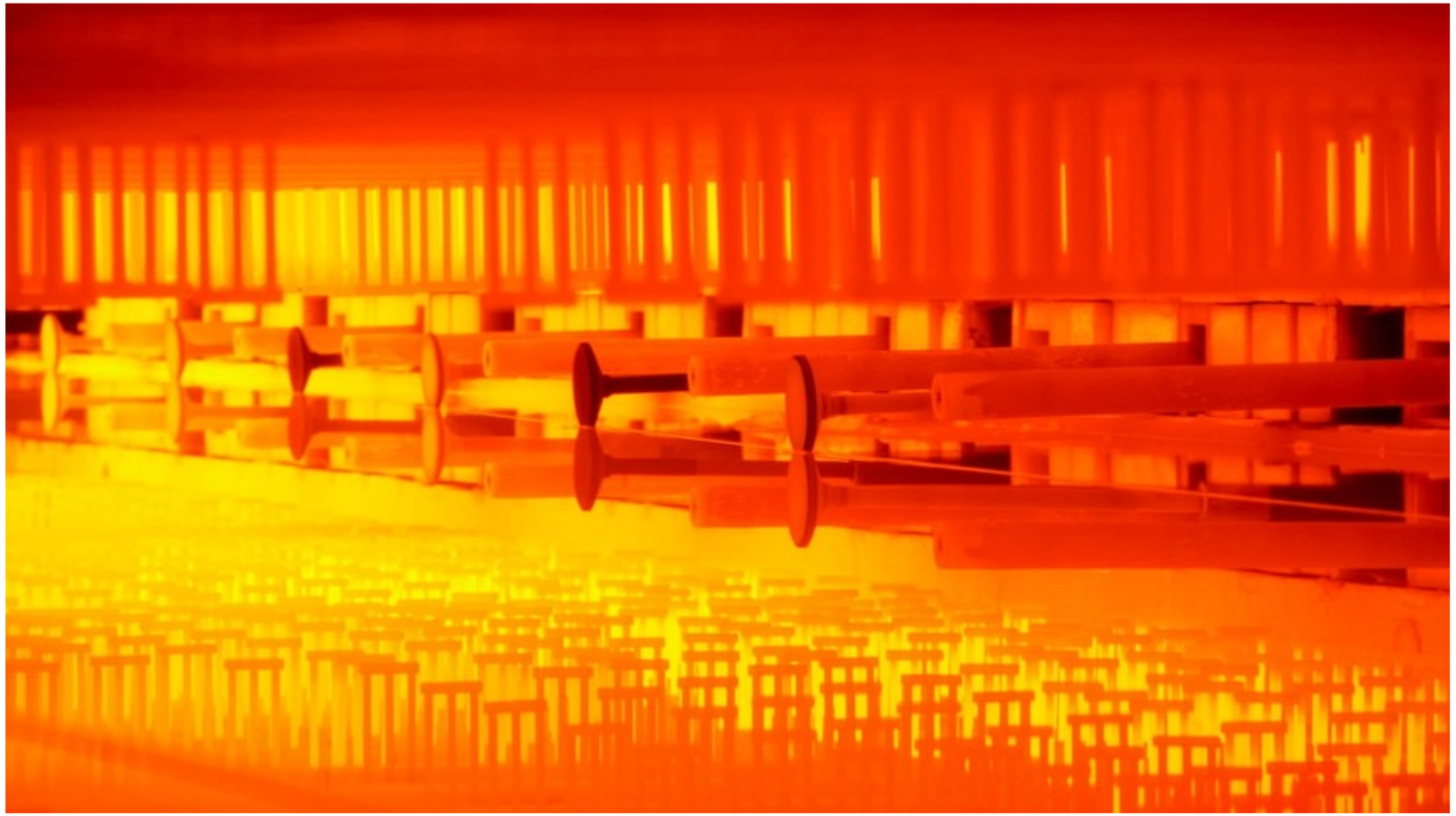
Manufacturing







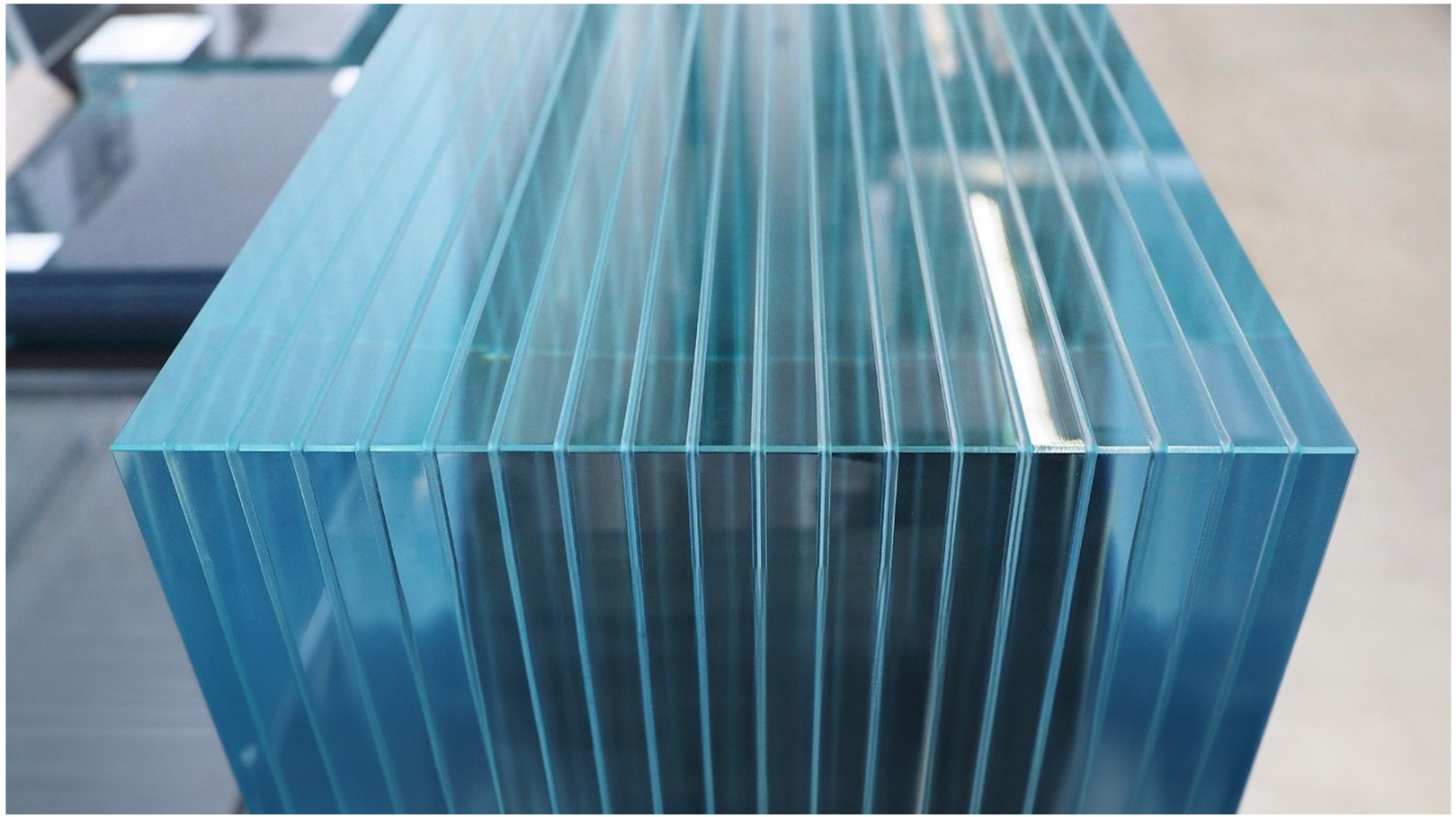
Manufacturing



Melting furnace of the float glass process, pilkington

https://www.gw-news.eu/sites/default/files/styles/aurora_default/public/aurora/89467.jpeg?itok=FjUg2A45

Manufacturing



Sedak, 19 layer connection of float glass

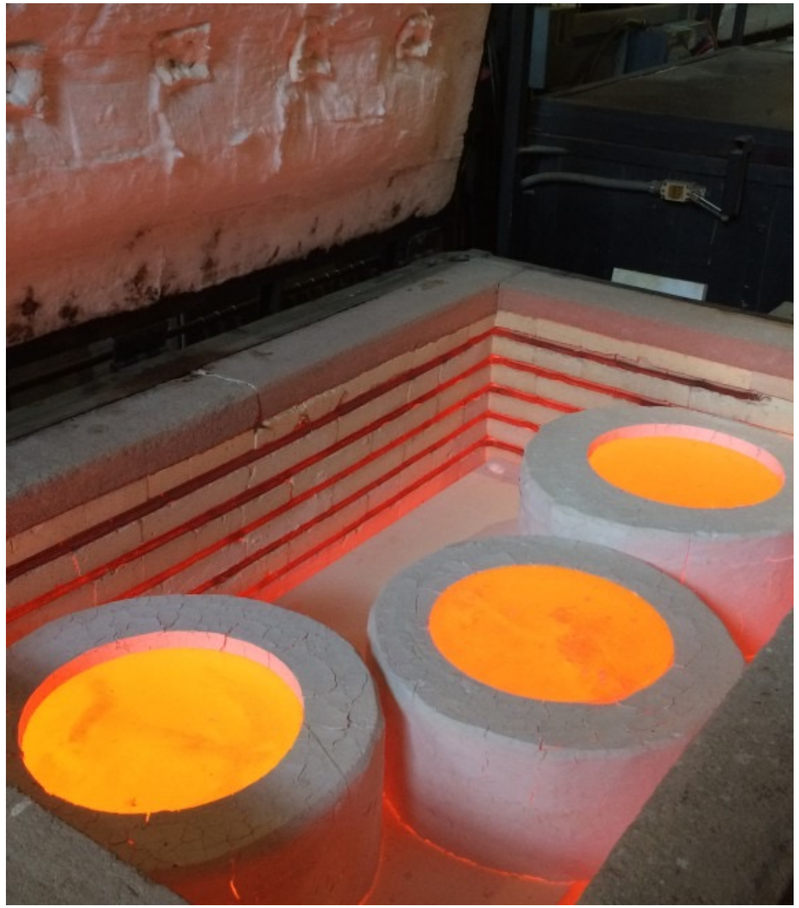
https://www.sedak.com/en/skills/

Manufacturing

Broken glass statue, made with special lamination

https://www.l1.nl/nieuws/2389216/lot-sfinx-venlo-lijkt-bezegeld

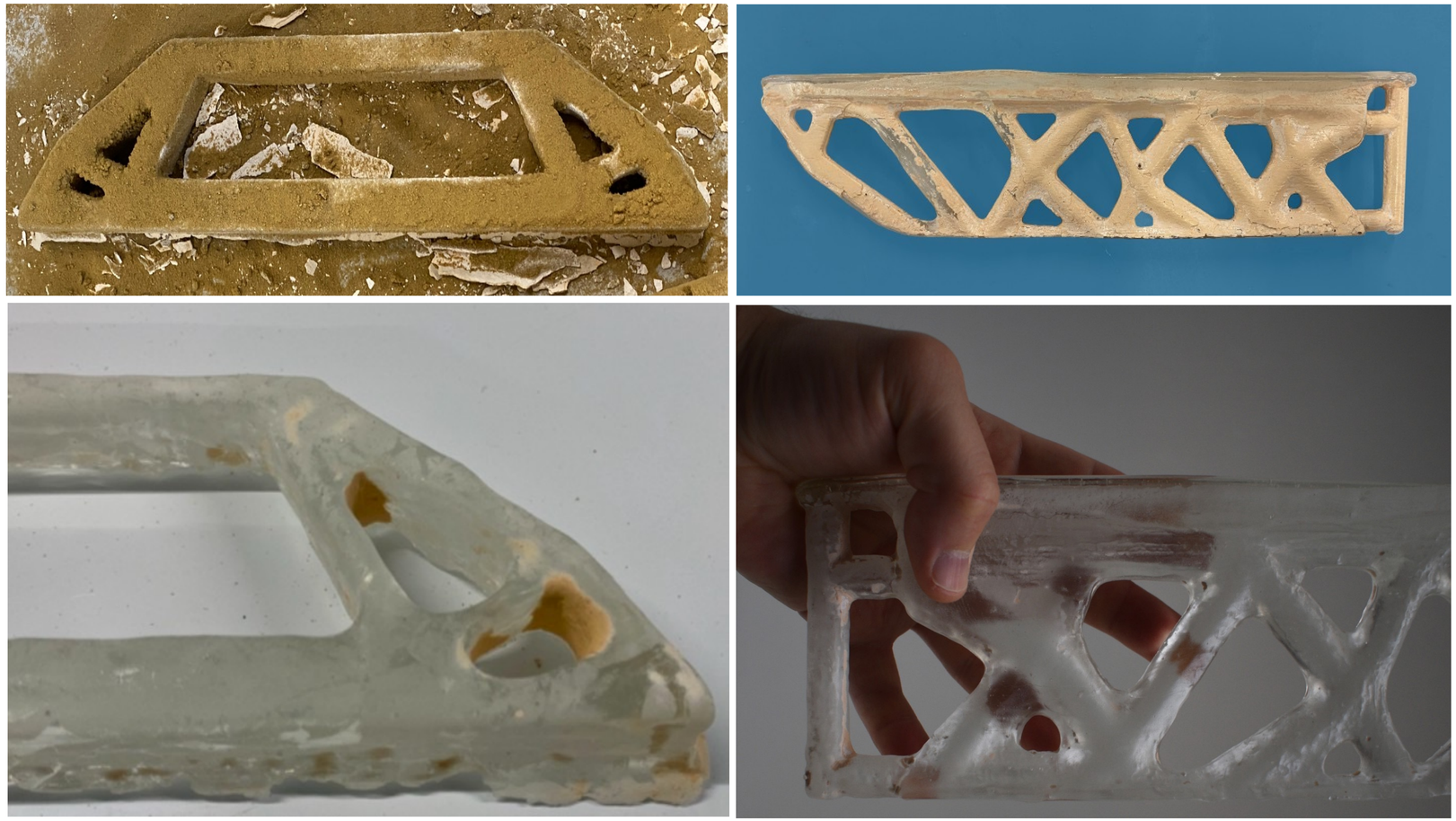
Manufacturing



Hot forming and Kiln Castin

https://opdel.com/golden-decisions-a-guide-to-selecting-the-perfect-melting-furnace-for-your-precious-metal-journey/

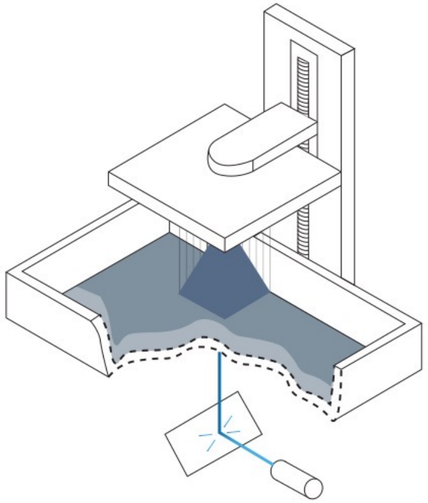
Manufacturing



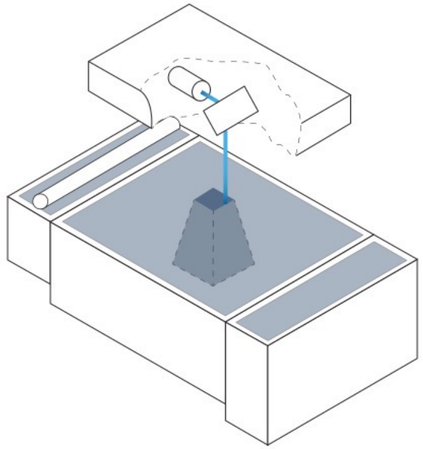
Giesecke and Dillenburger (2022b)
& Ioannidis (2023)

Manufacturing

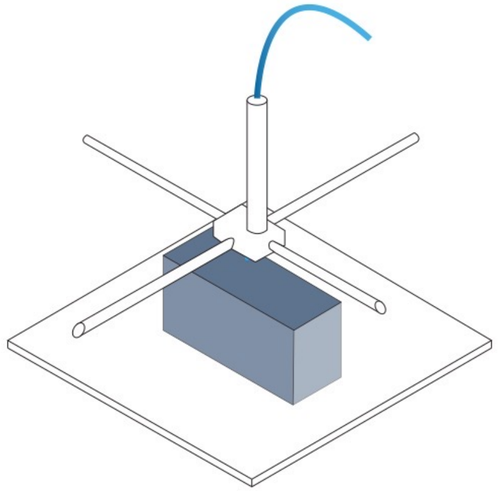
SLA



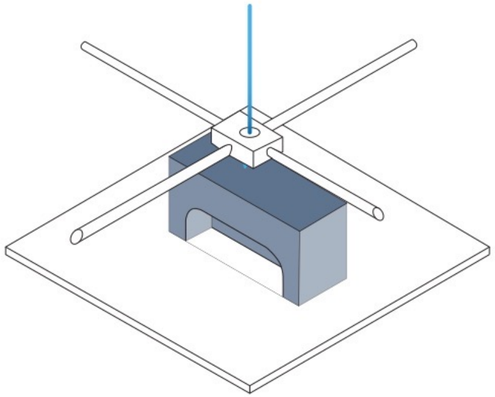
SLS



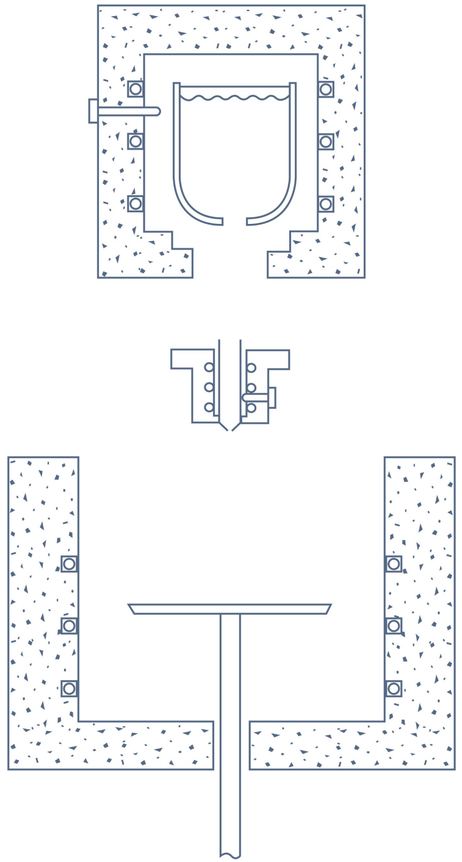
DIW



FDM



Manufacturing



Glass resevoir

Nozzle

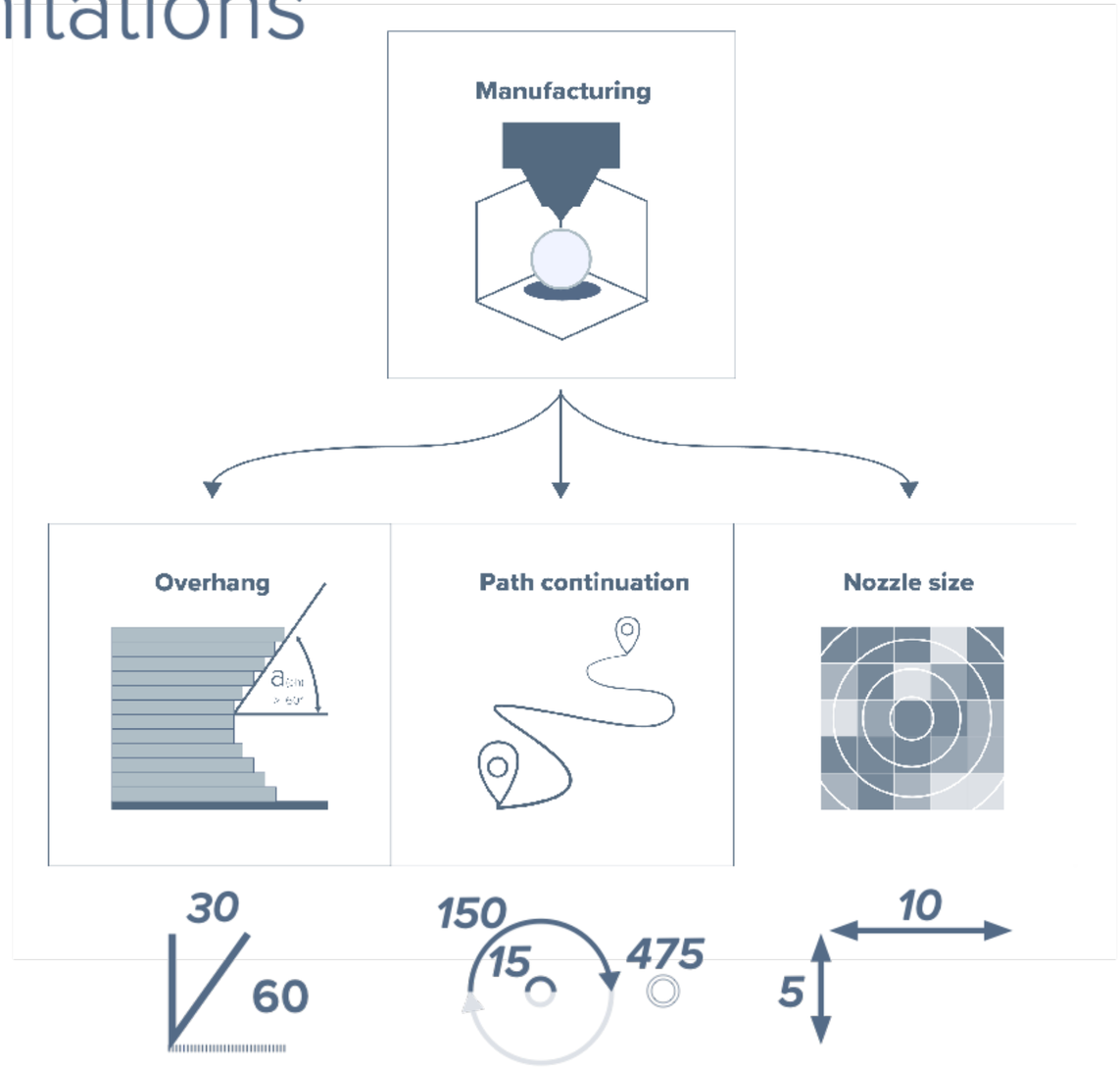
Annealing - xyz control plate

Based on: INAMURA et al., 2018b

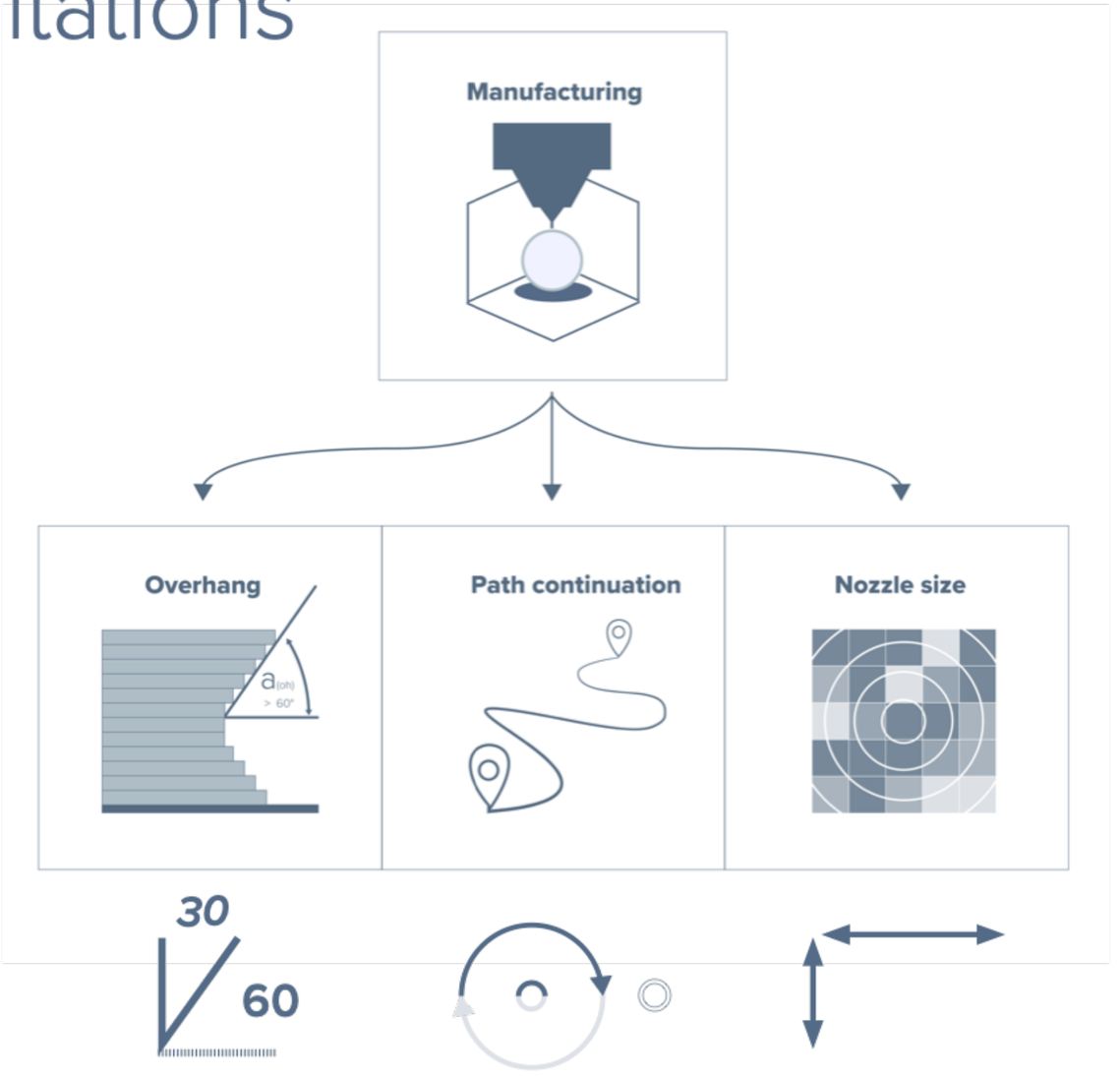
Manufacturing

INAMURA et al., 2018b

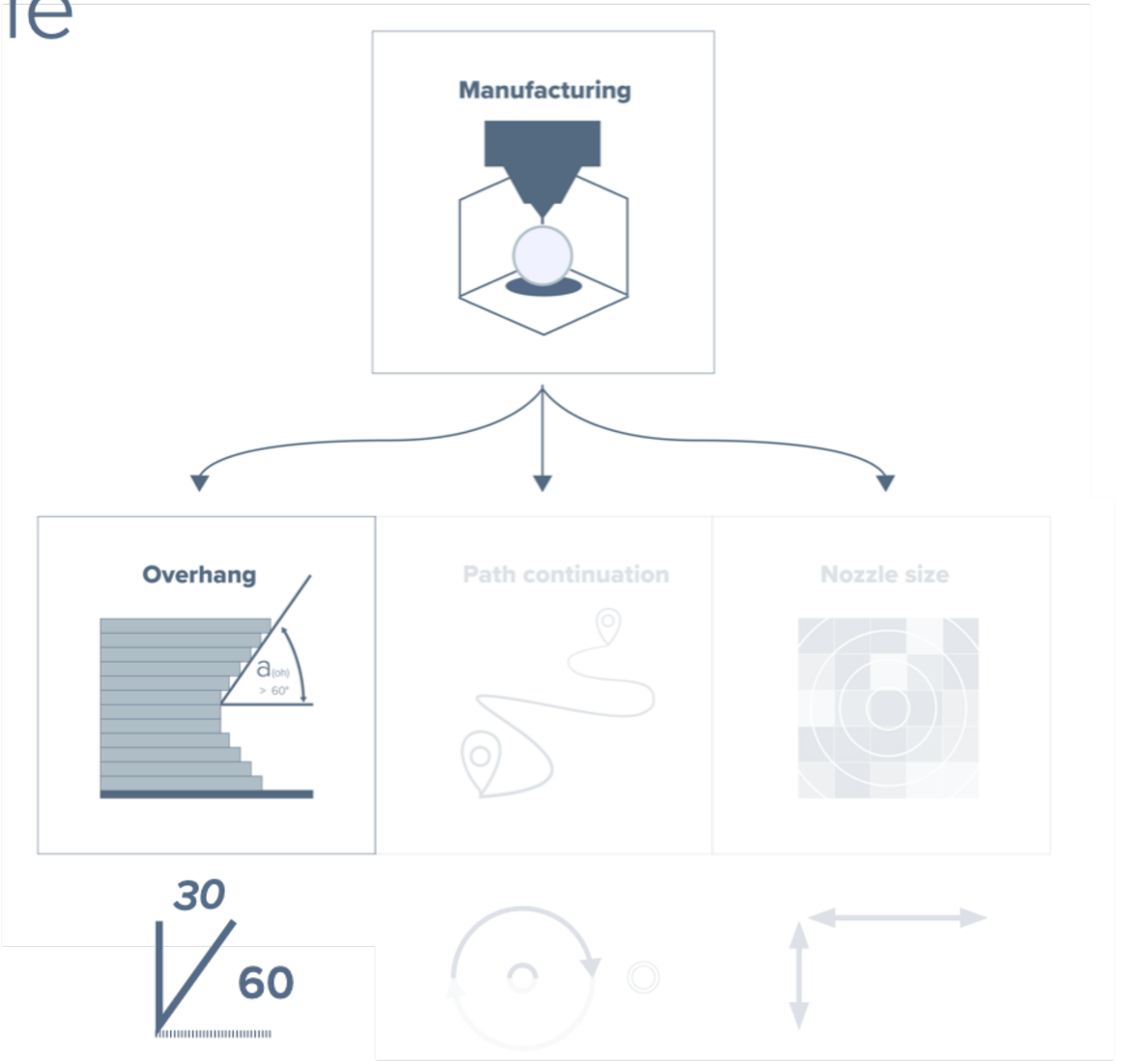
3D printing limitations



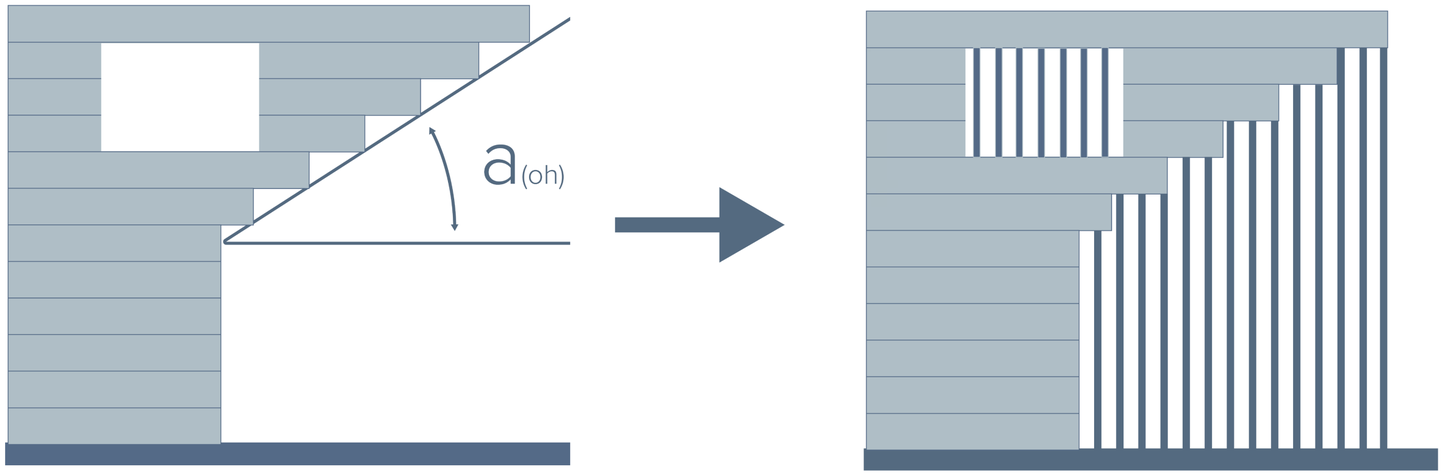
3D printing limitations



Overhang angle

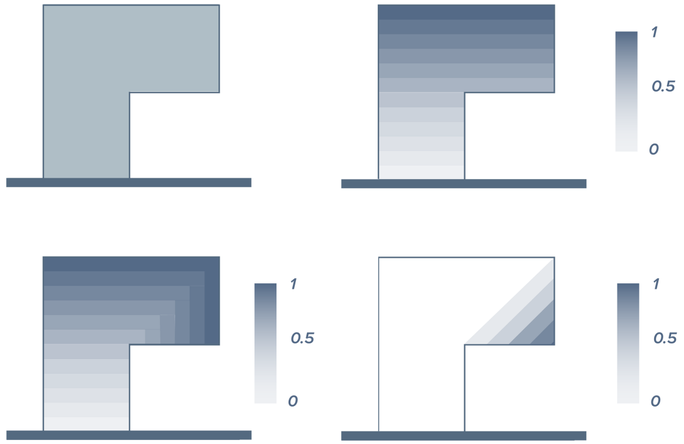


Overhang angle

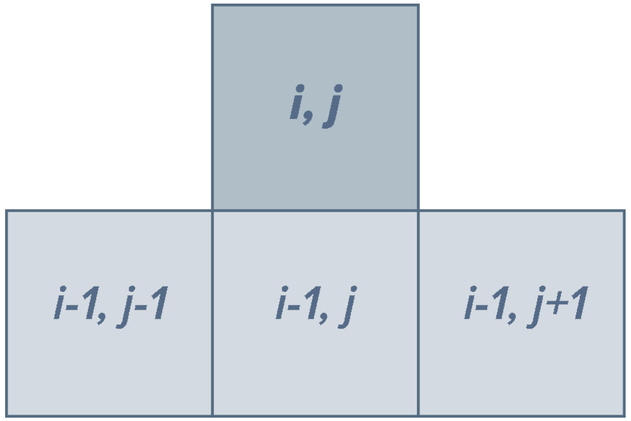


Overhang angle

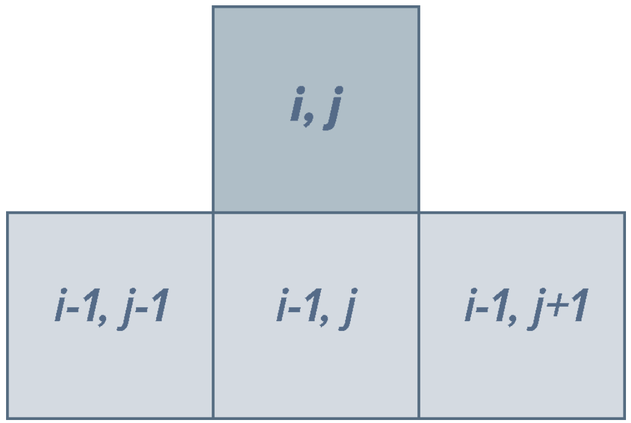
Front propagation filter

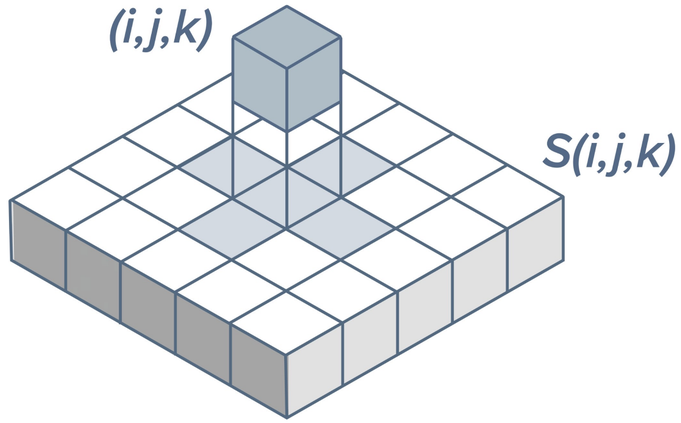


Layer by layer filter

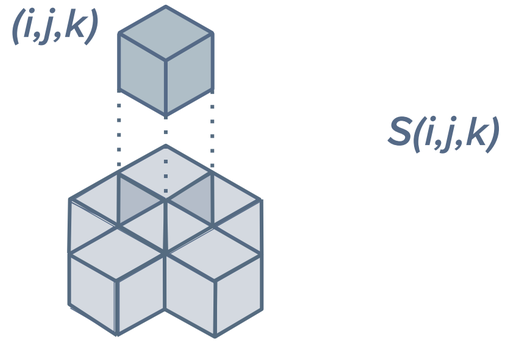


Overhang angle

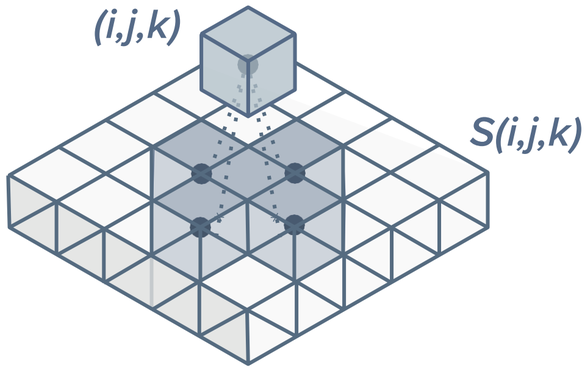




Overhang angle



63.4



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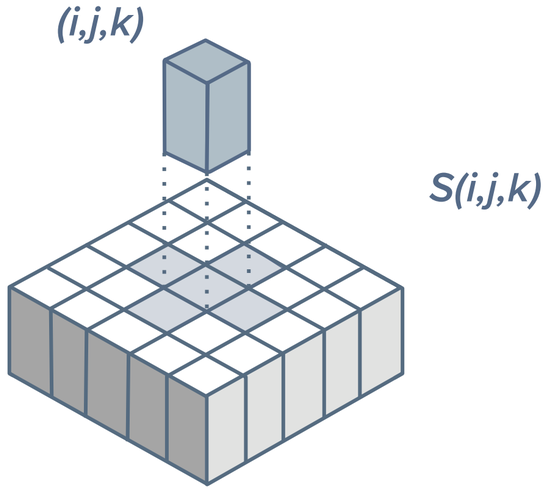
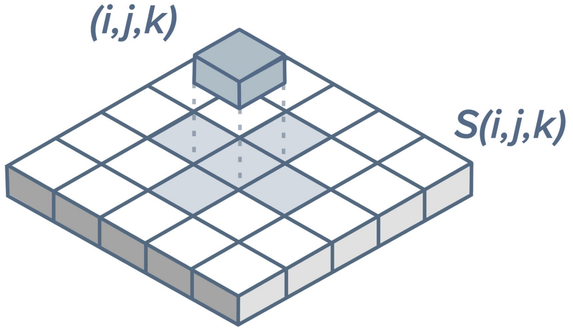
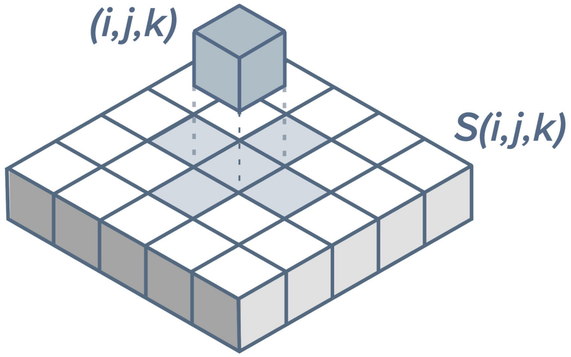


63.4

Overhang angle



26.6



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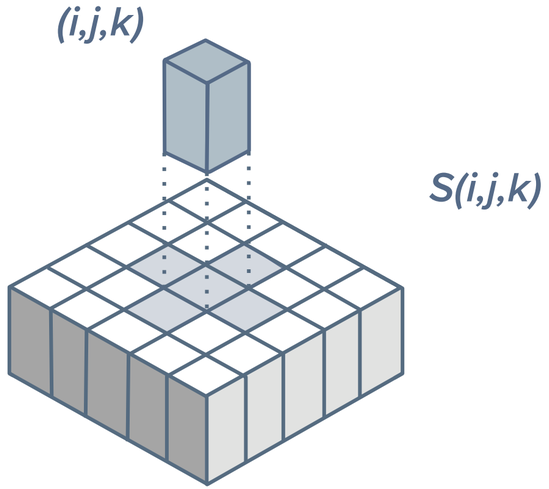
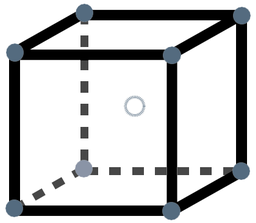
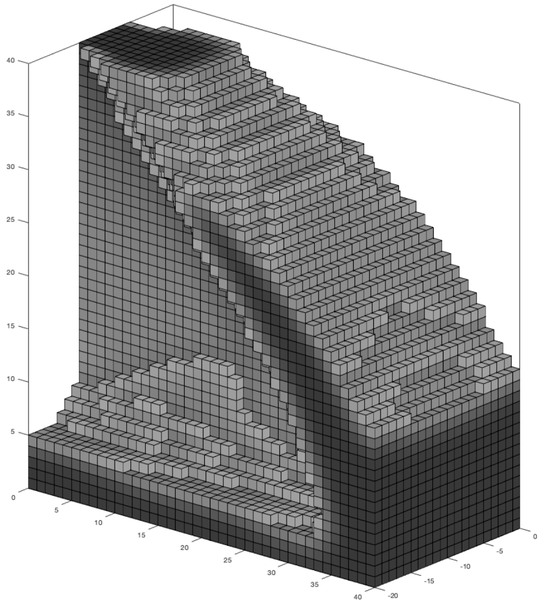


63.4

Overhang angle





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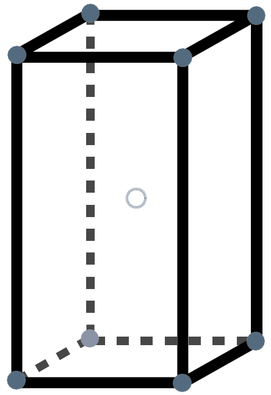

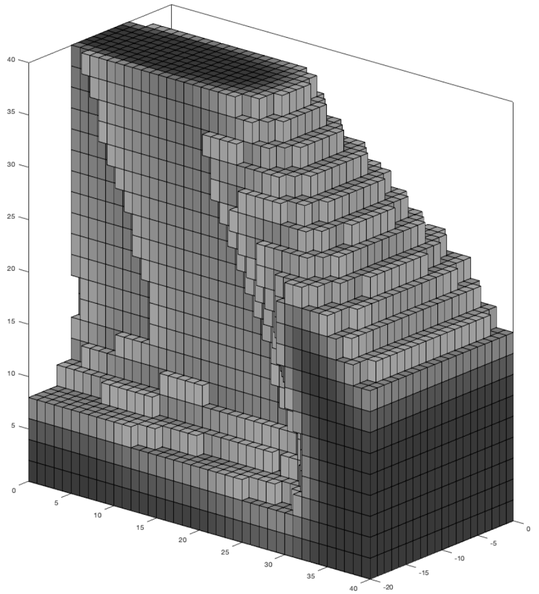

63.4

Islanding function

Islanding function

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Additive Manufacturing

journal homepage: www.elsevier.com/locate/addma

Topology optimization for 3D concrete printing with various manufacturing constraints

Minghao Bi [a], Phuong Tran [a], Lingwei Xia [b], Guowei Ma [b], Yi Min Xie [a,*]

[a] Centre for Innovative Structures and Materials, School of Engineering, RMIT University, Melbourne, Victoria 3001, Australia
[b] Tianjin Key Laboratory of Prefabricated Building and Intelligent Construction, School of Civil and Transportation Engineering, Hebei University of Technology, Tianjin 300401, China

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

An integrated method of topological optimization and path design for 3D concrete printing

Wenwei Yang [a], Li Wang [a,b,*], Guowei Ma [a,b,*], Peng Feng [c]

[a] School of Civil and Transportation Engineering, Hebei University of Technology, 5340 Xiping Road, Beichen District, Tianjin 300401, China
[b] Tianjin Key Laboratory of Prefabricated Building and Intelligent Construction, Hebei University of Technology, 5340 Xiping Road, Beichen District, Tianjin 300401, China

Islanding function

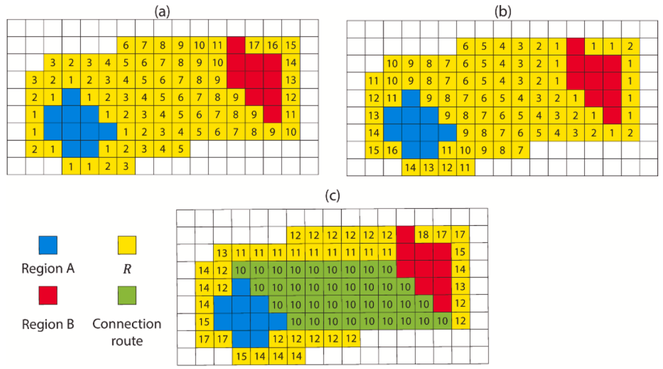
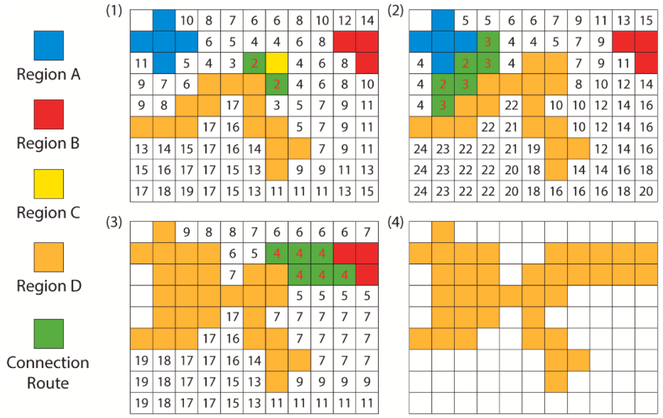
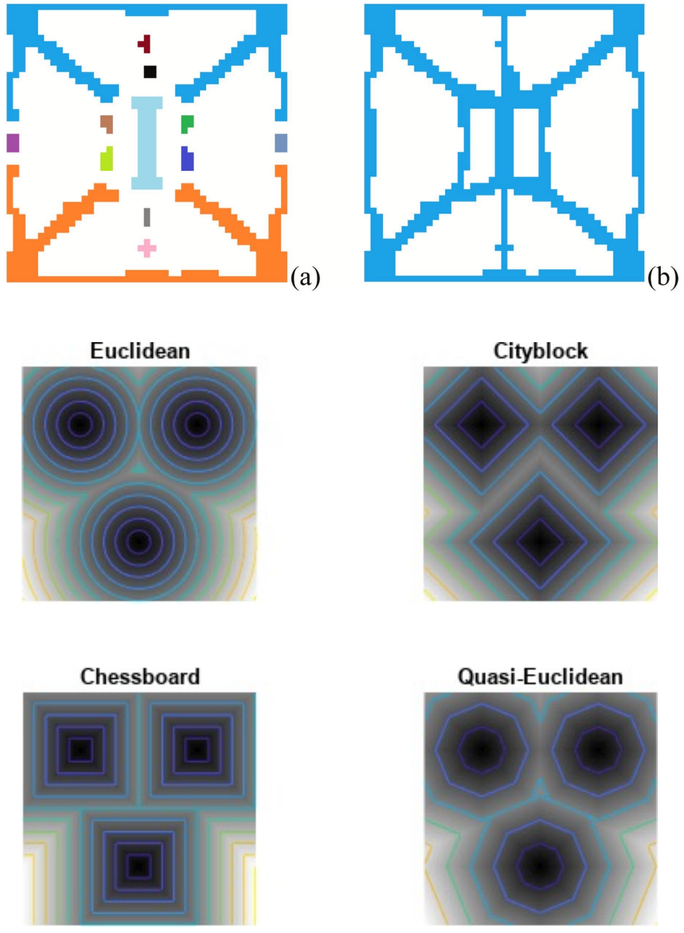
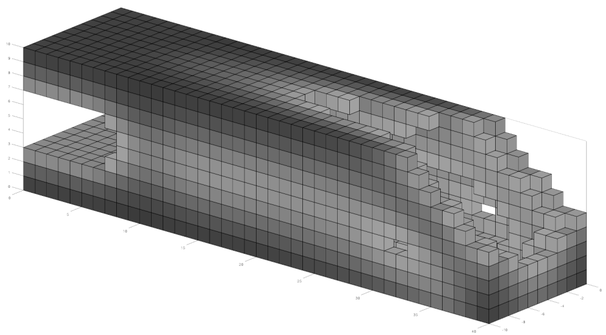


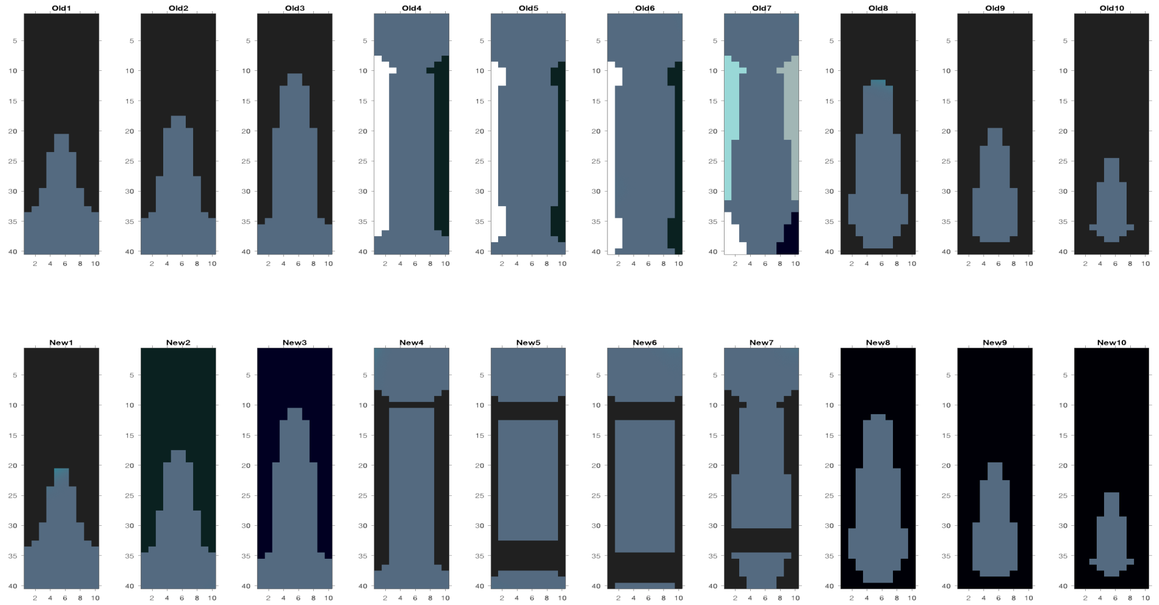
Fig. 3. Demonstration of how the shortest possible route is found within the potential area for reconnection: (a) the distance map of region A; (b) the distance map of region B; (c) the sum of the two distance maps; the shortest connection route is located by adding elements with the lowest summed distance value.

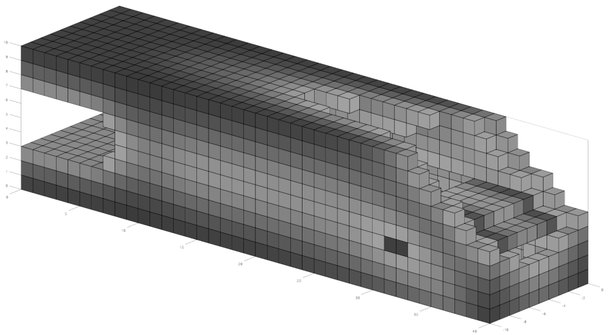




Islanding function

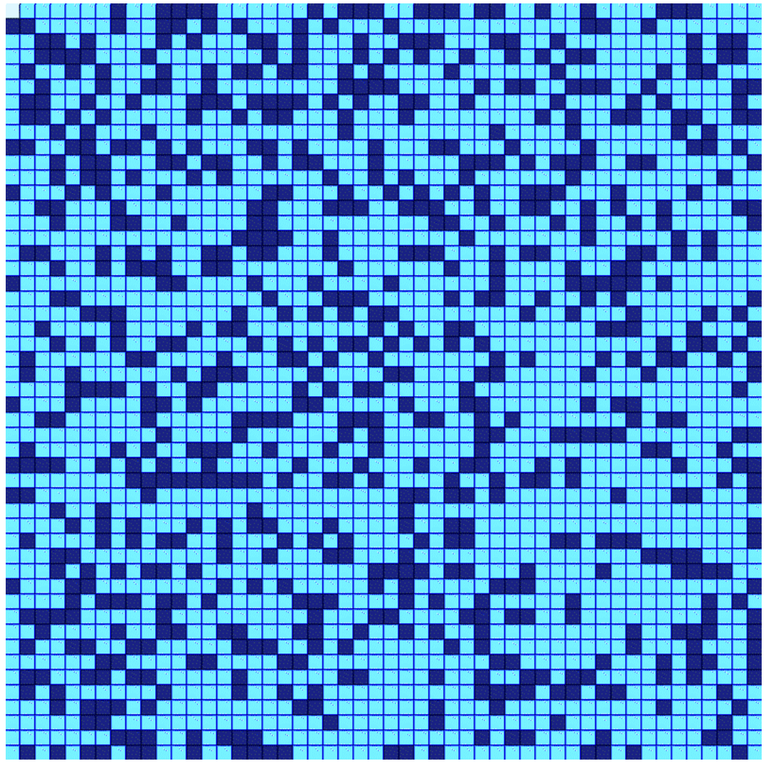






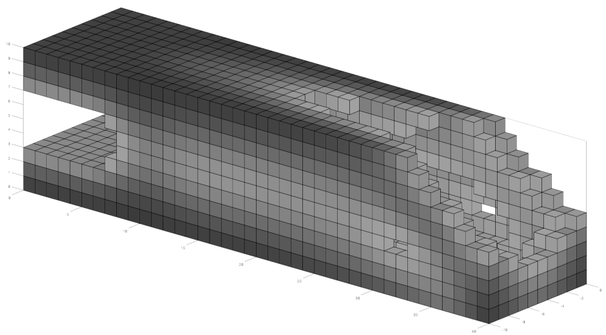
Islanding function

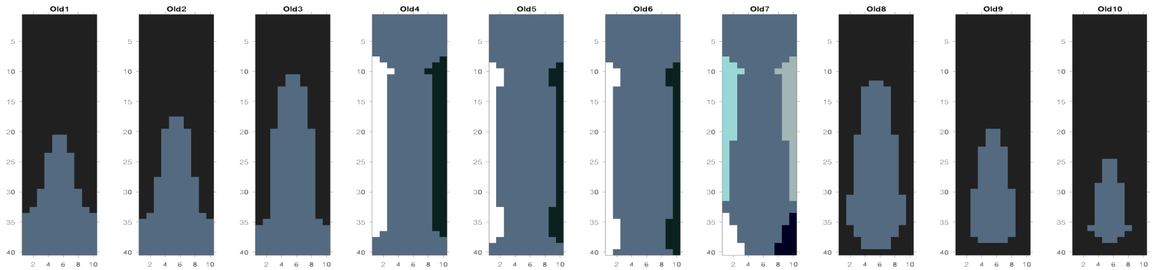
Dijkstra's Algorithm
Bellman-Ford Algorithm
Floyd-Warshall Algorithm
A* Search Algorithm
Bidirectional Search Algorithm
Johnson's Algorithm
Depth-First Search (DFS)
Breadth-First Search (BFS)

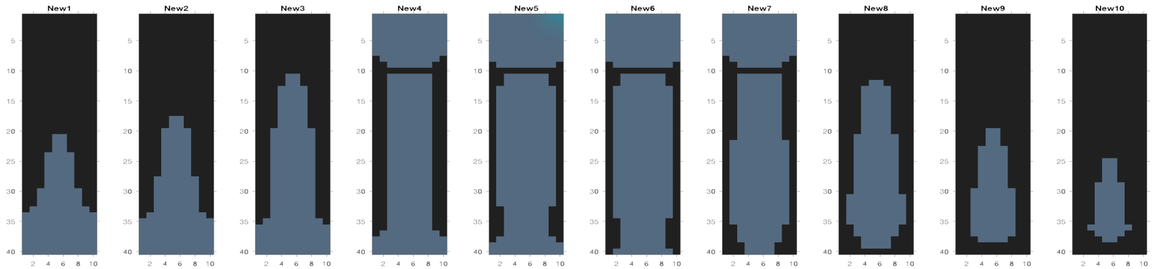


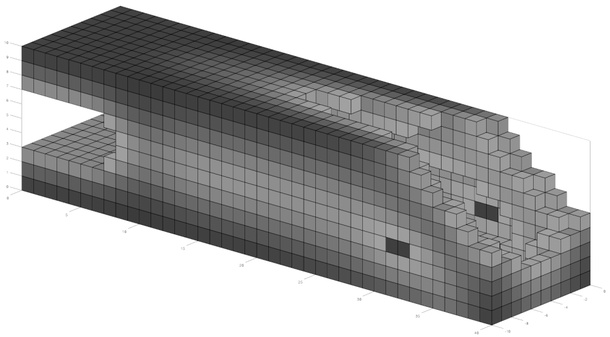
```
function endpoints = find_endpoints(map)
    [N, M] = size(map);
    endpoints = [];
    for i = 1:N
        for j = 1:M
            if map(i, j) == 1
                waters = 0;
                if i-1 < 1 || map(i-1, j) == 0
                    waters = waters + 1;
                end
                if i+1 > N || map(i+1, j) == 0
                    waters = waters + 1;
                end
                if j-1 < 1 || map(i, j-1) == 0
                    waters = waters + 1;
                end
                if j+1 > M || map(i, j+1) == 0
                    waters = waters + 1;
                end
                if waters >= 2 || 3
                    endpoints = [endpoints; [i, j]];
                end
            end
        end
    end
end
```

Islanding function

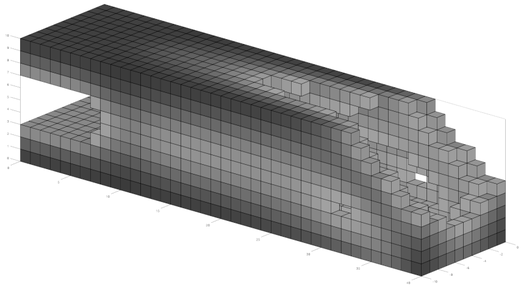


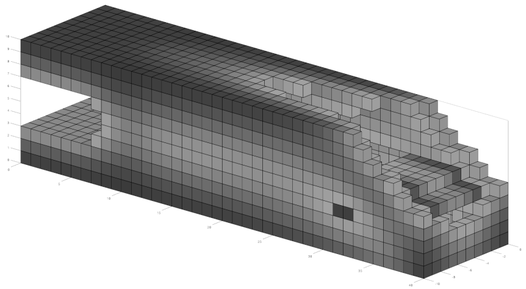


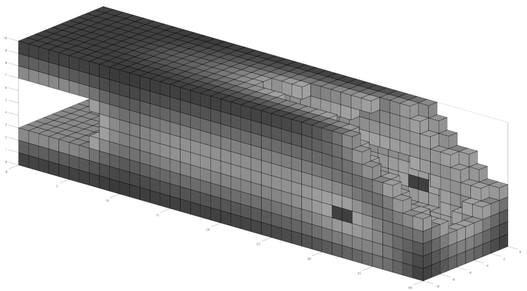




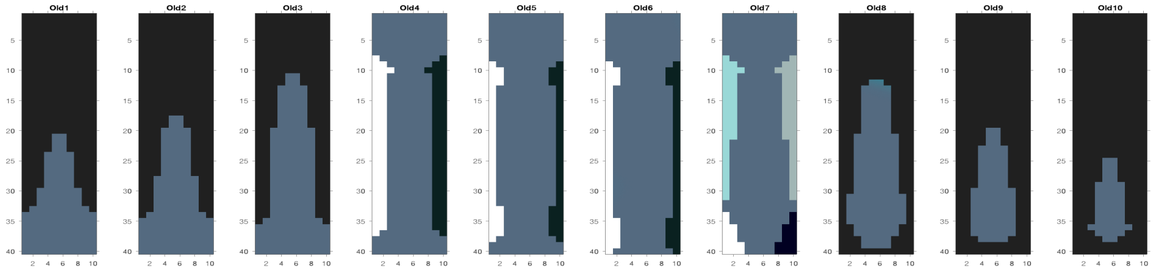
Islanding function



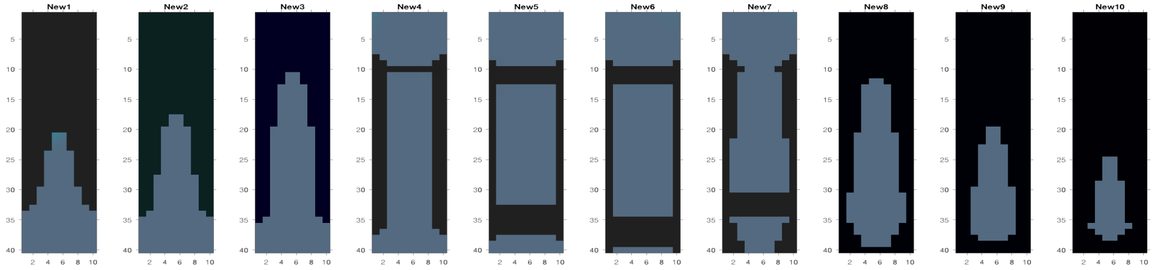




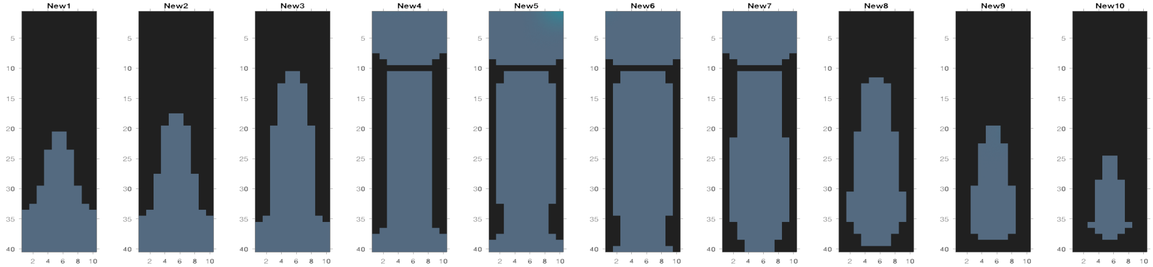
No algorihm



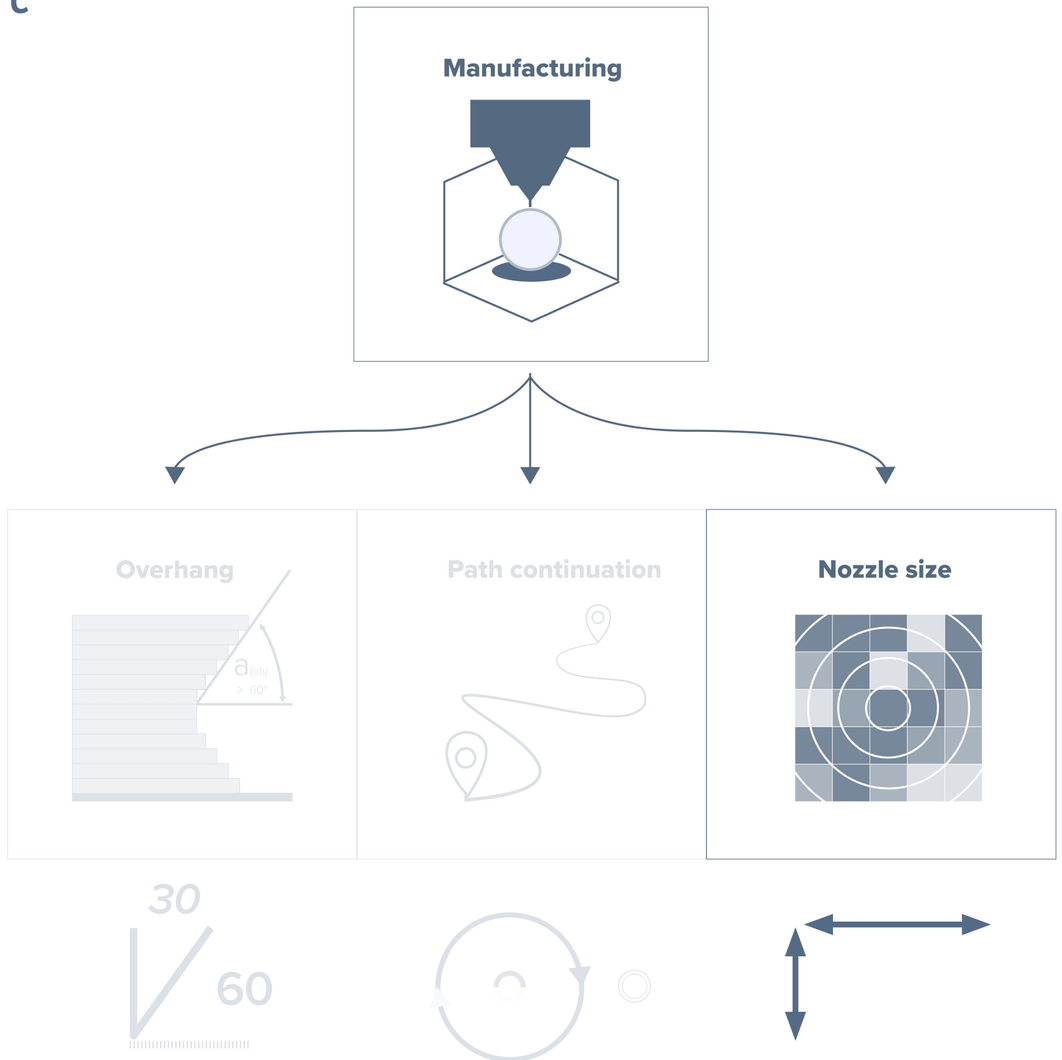
Matlab function



Dijkstra function

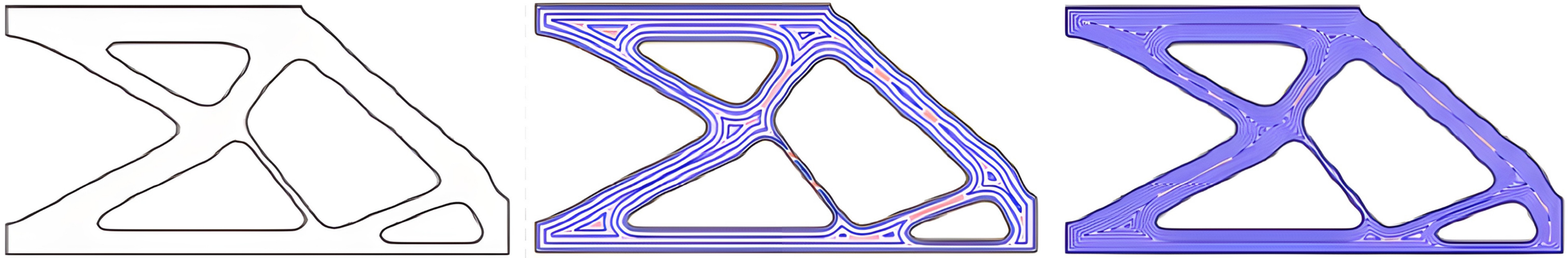


Boundary offset

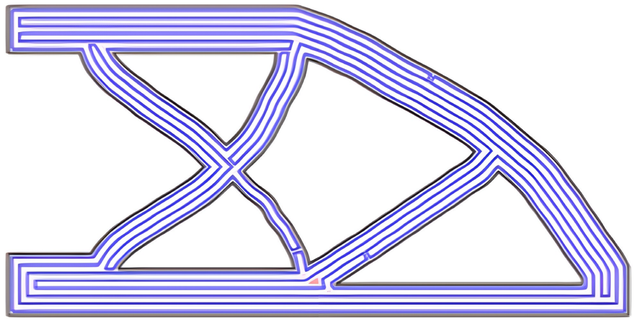


Boundary offset

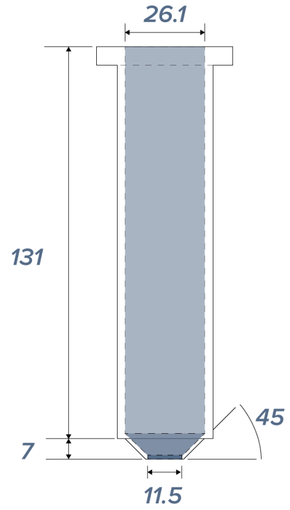
Toolpath generation and planning post-topology optimization

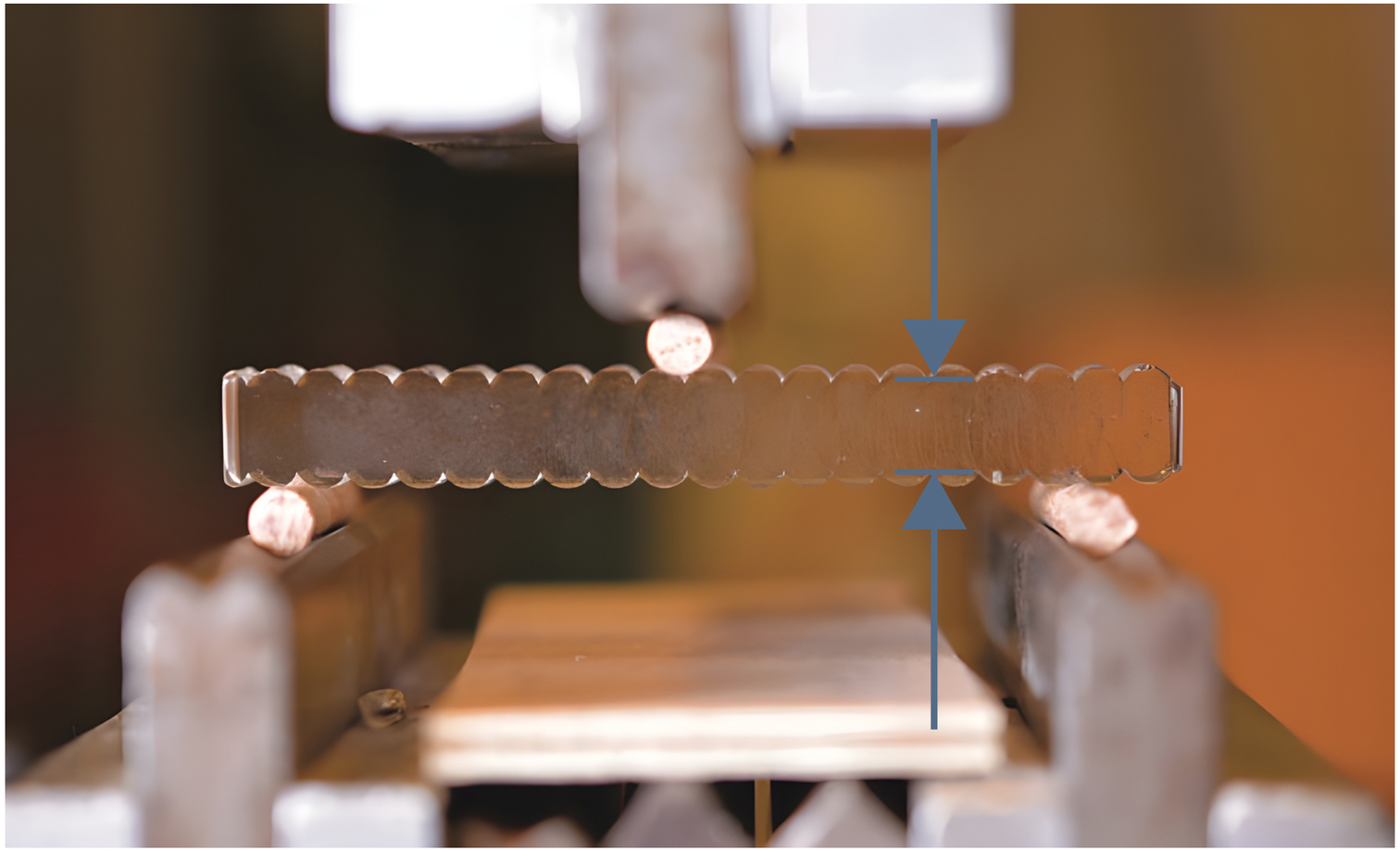


Toolpath generation integrated post-topology optimization



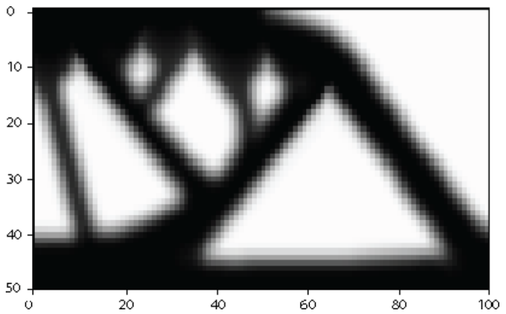
Boundary offset

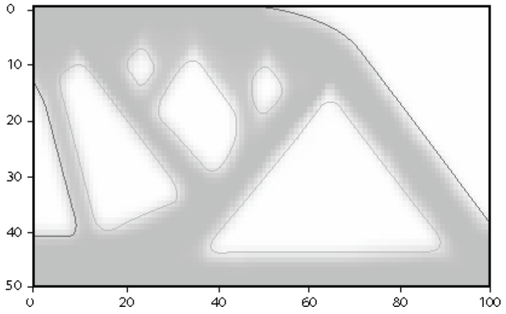


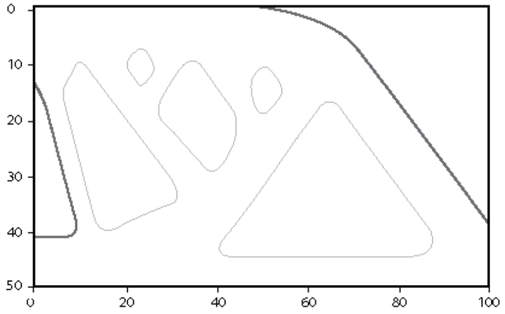


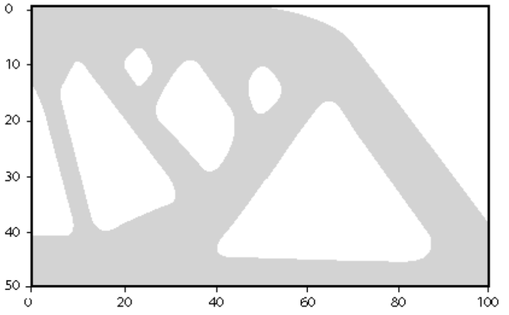
Nozzle and 3 point testing
based on: Inamura et al., 2018

Boundary offset

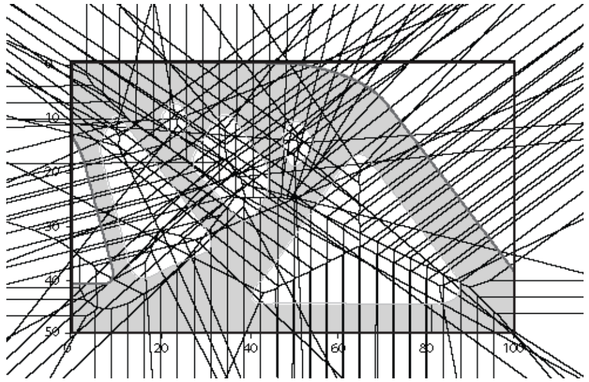


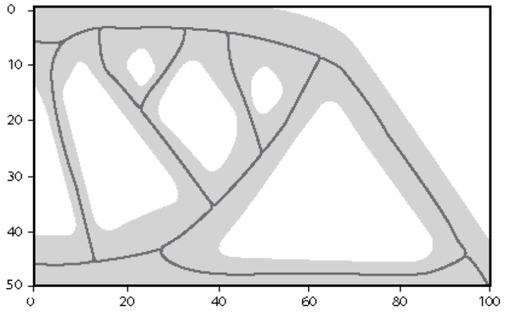




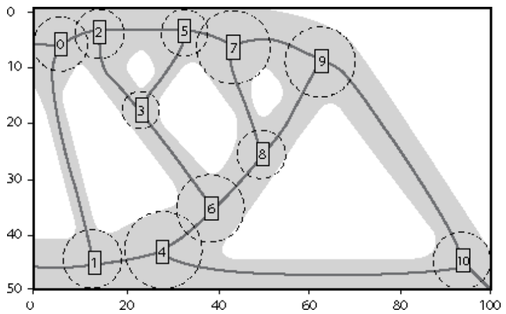


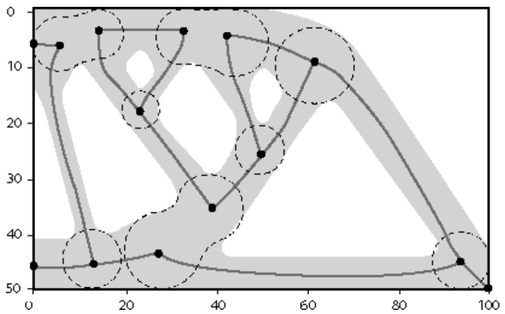
Boundary offset

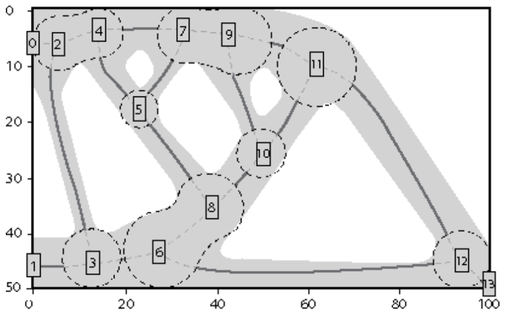


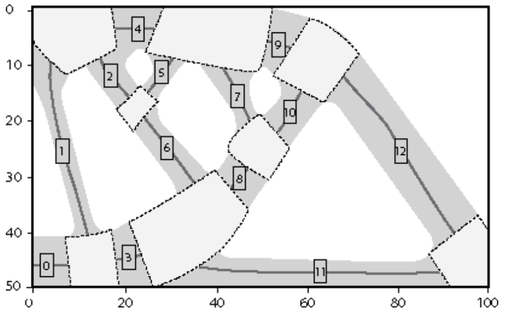


Boundary offset

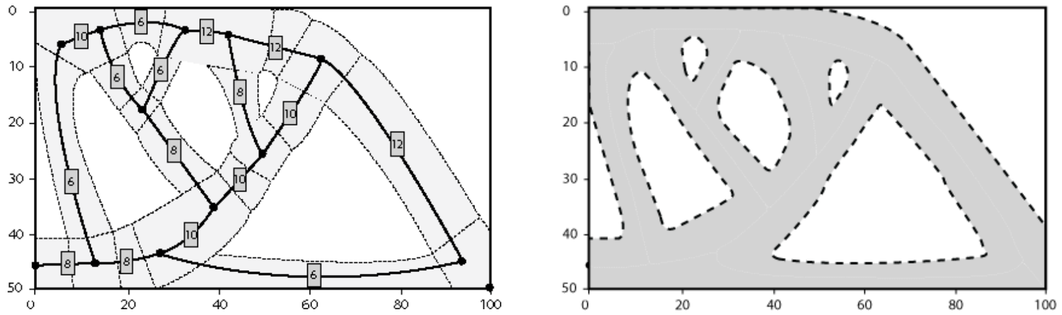








Boundary offset



Final output

Compliance

Minimize the sum of all deformations

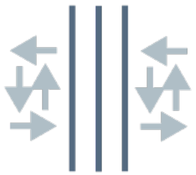
$$
\begin{aligned}
min_x \quad & : c(x) = U^T K U \\
subject\ to \ & : \frac{V(x)}{V_0} = f \\
& KU = F \\
& 0 < xmin \leq x \leq 1
\end{aligned}
$$

Equilibrium

Filtering

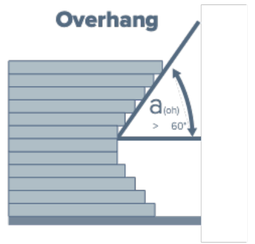
Volume

Principal stress



Deflection

Overhang

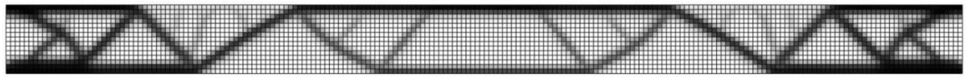


Path adaptions

Nozzle size

Final output

Anna-Maria Koniari 2D (2022)



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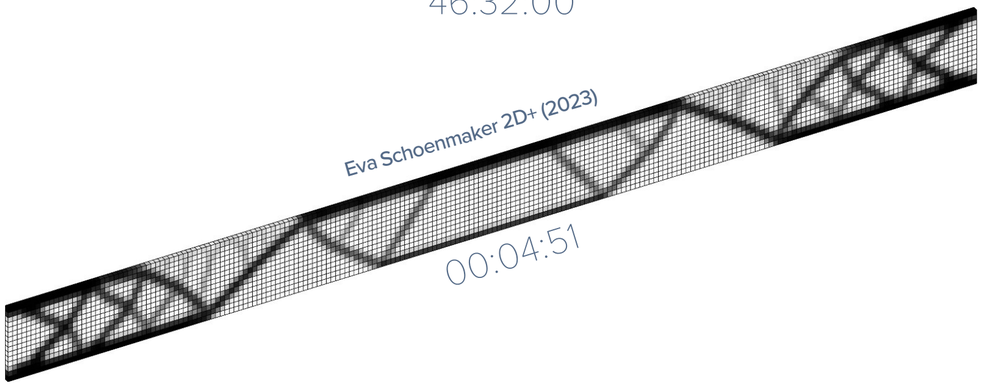
Eva Schoenmaker 2D+ (2023)



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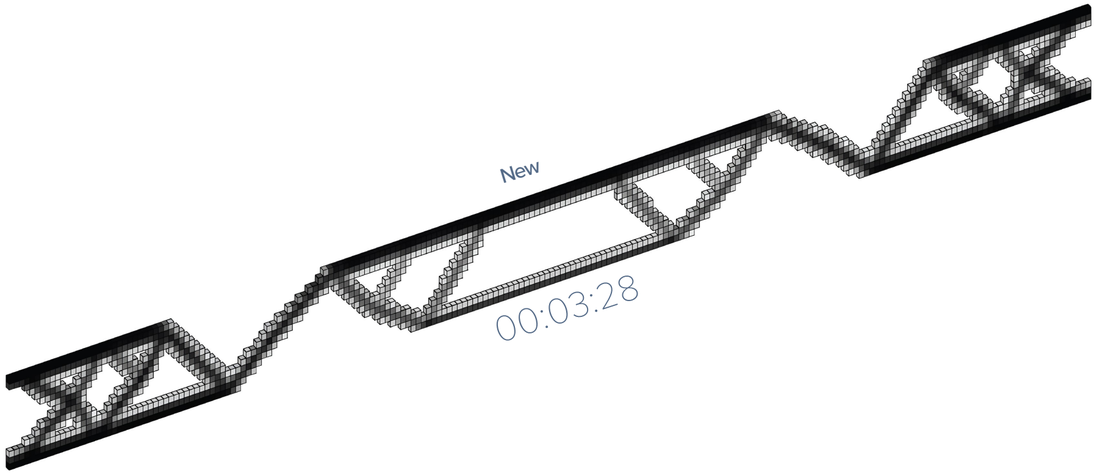
New



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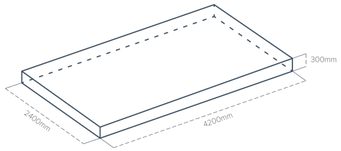
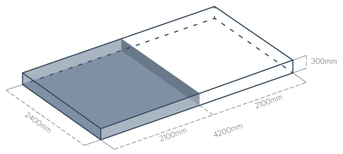
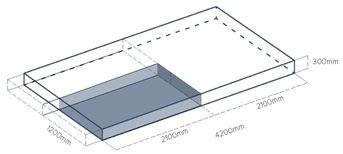
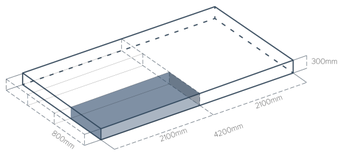
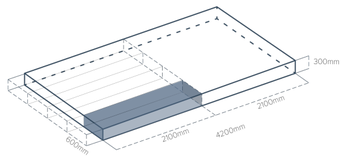
Final output

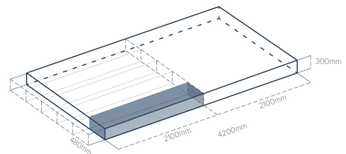


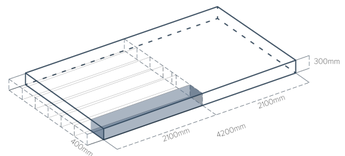






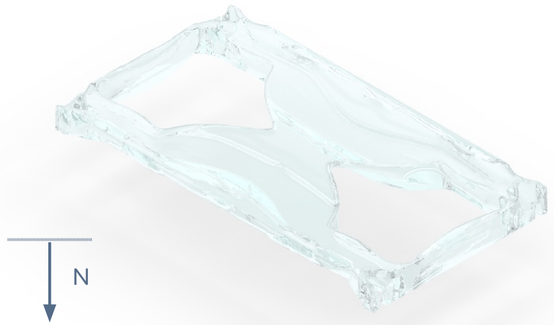


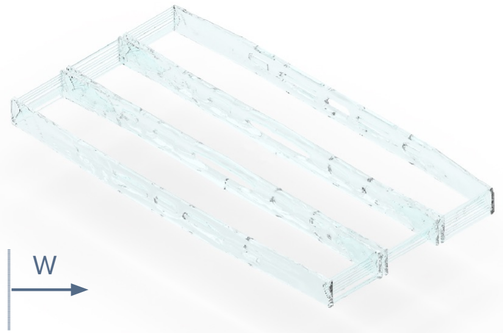


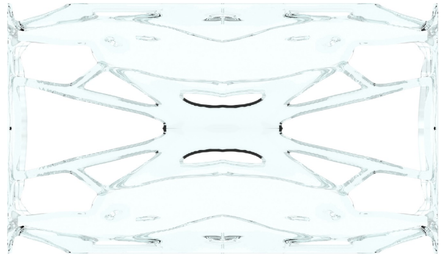


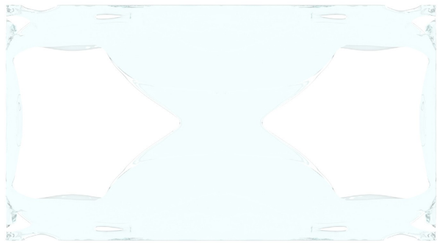
Final output

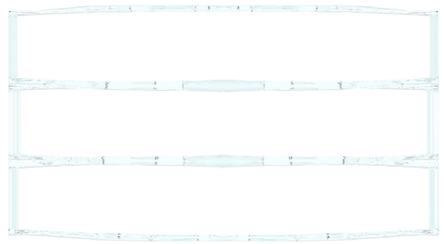
Final output

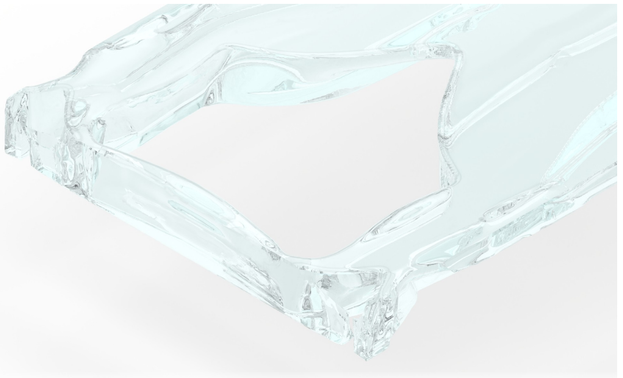


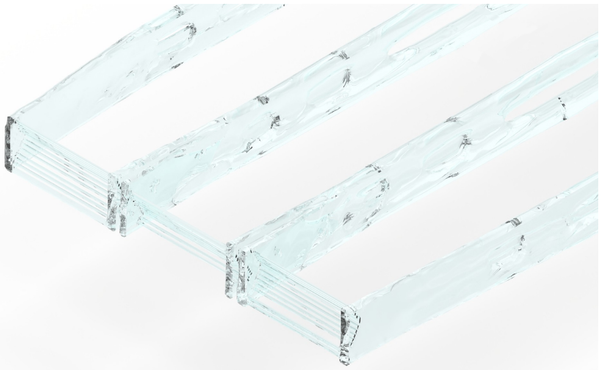




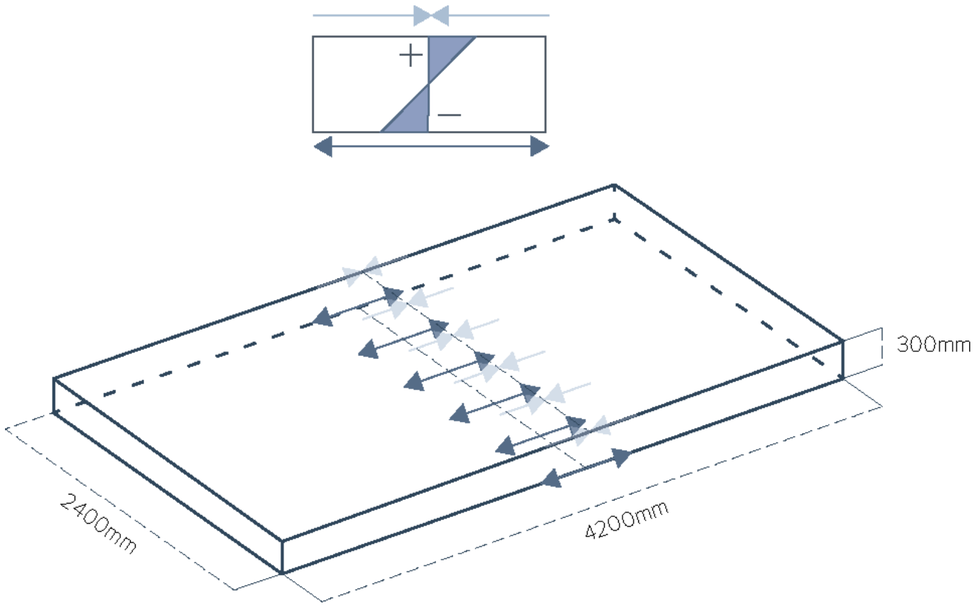




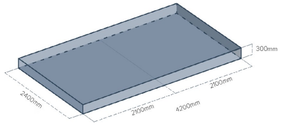


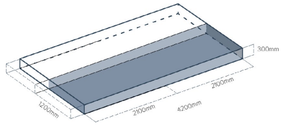


Final output



Final output





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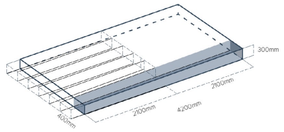

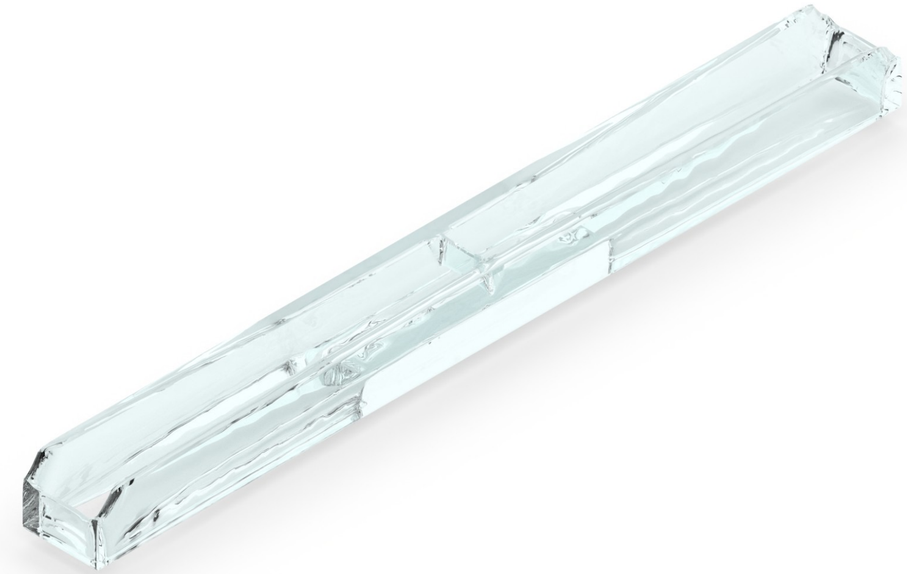

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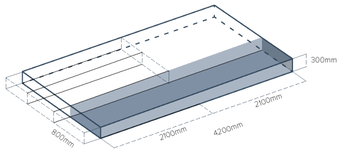

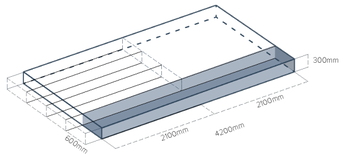

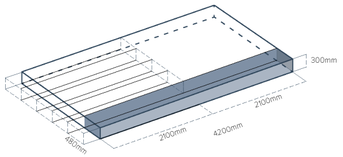

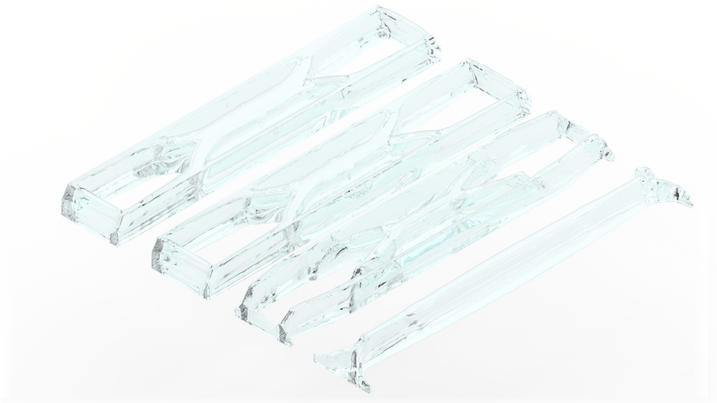

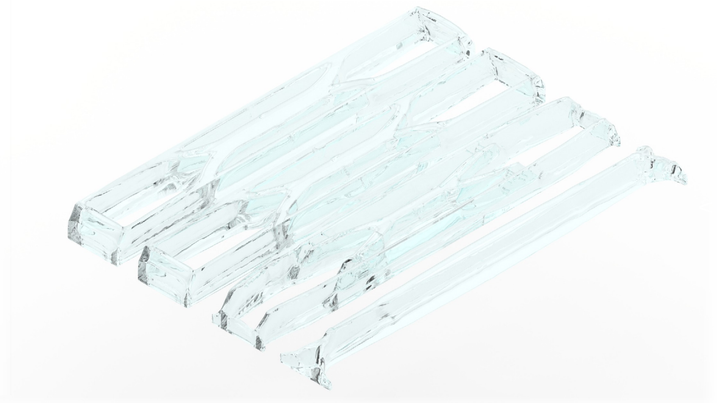

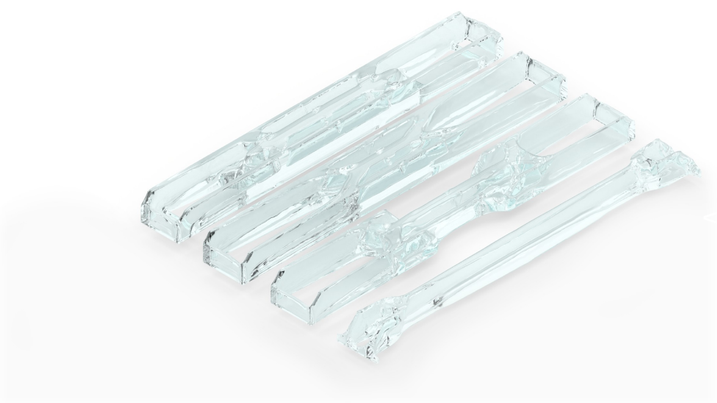

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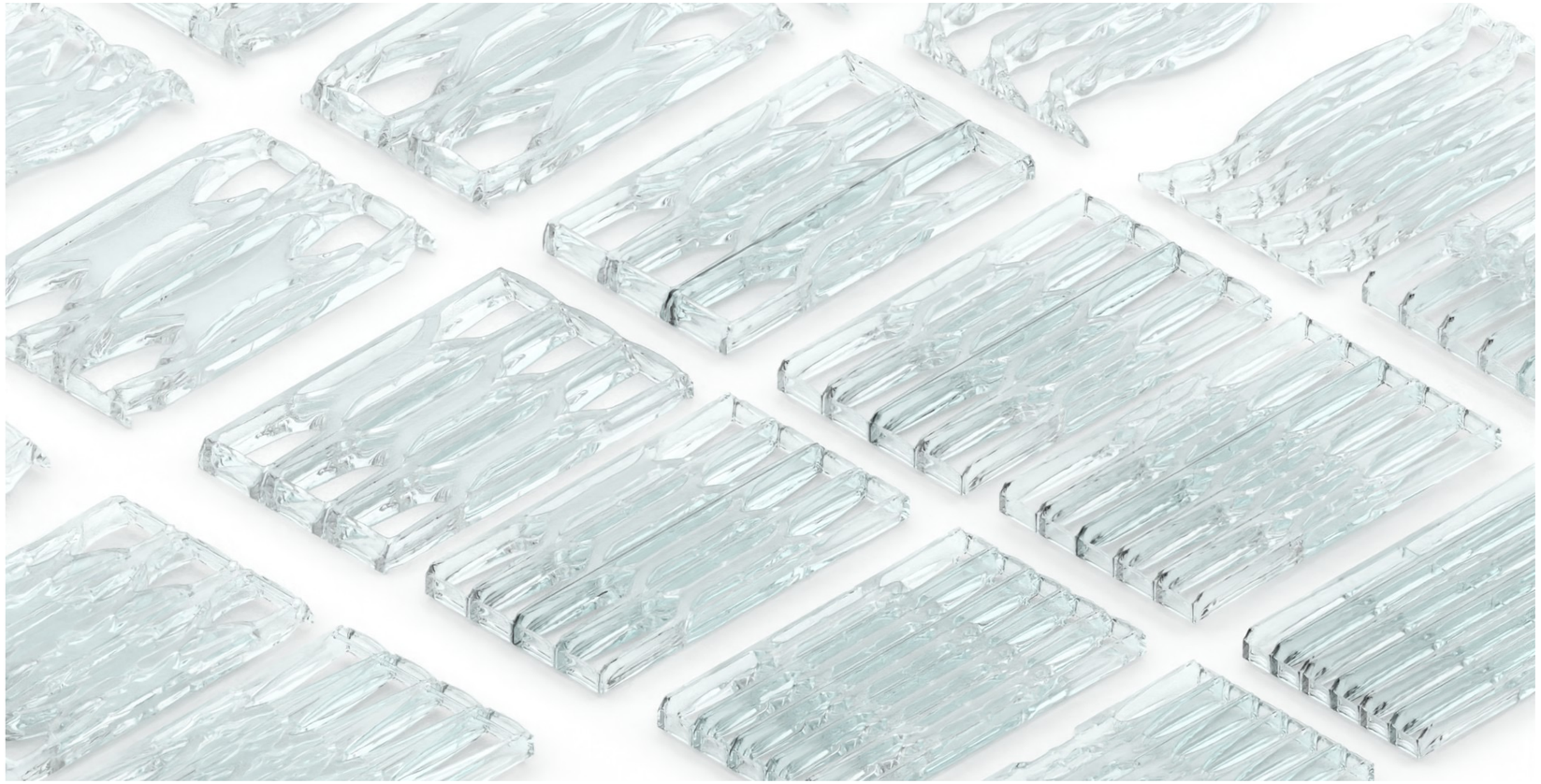
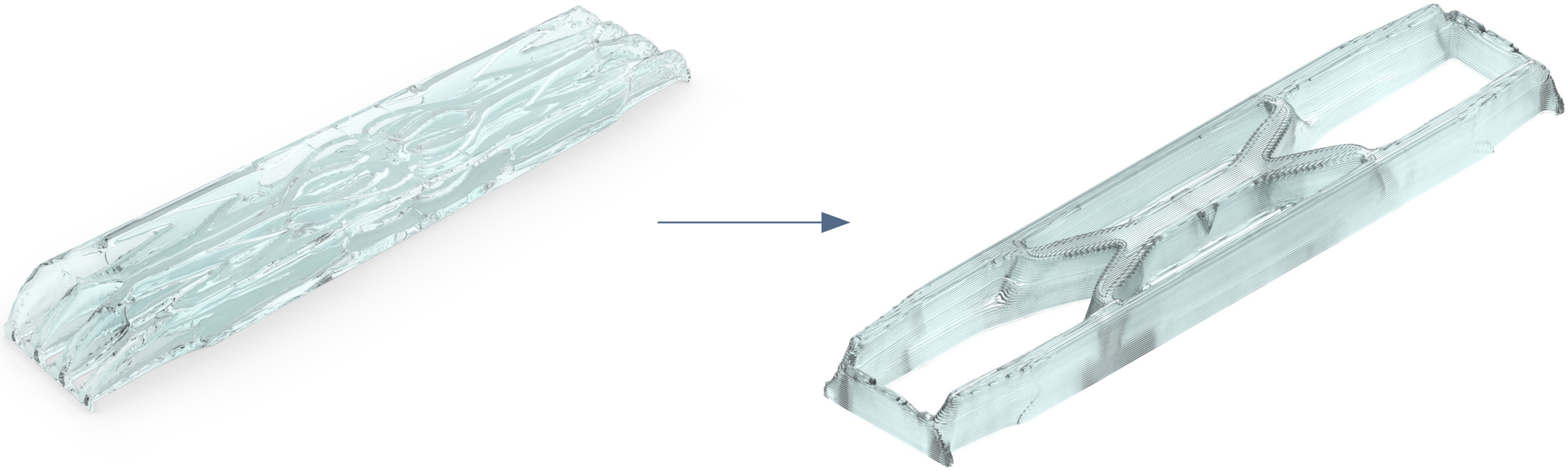
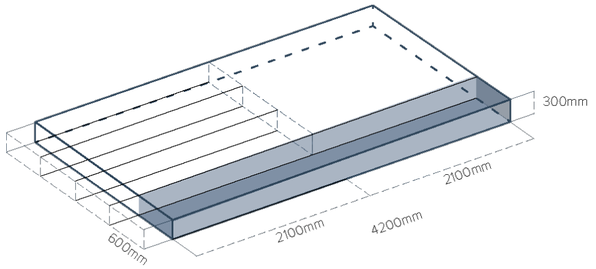


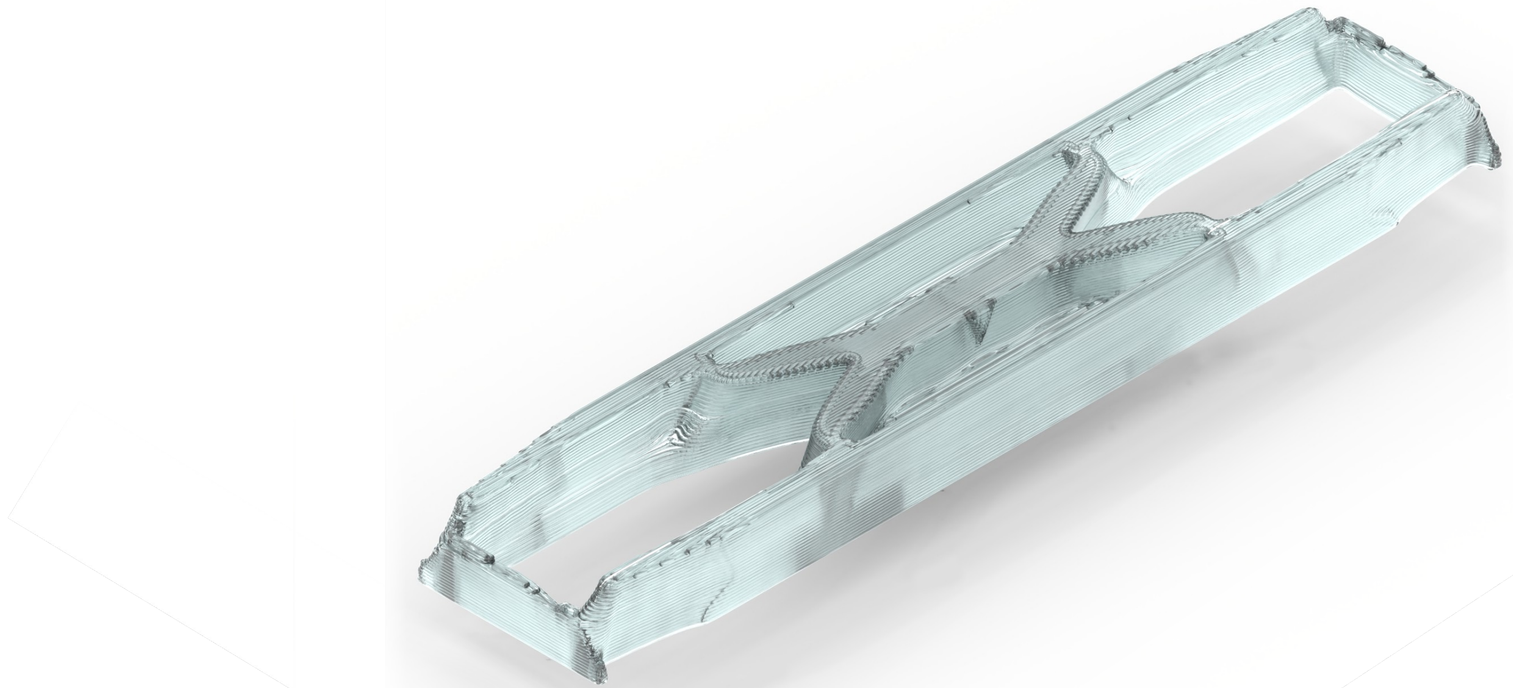
The comparison between TO layed out

Final output

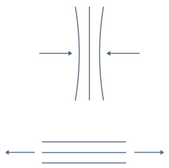


Final output





Vol 0.3
-
vol 0.37

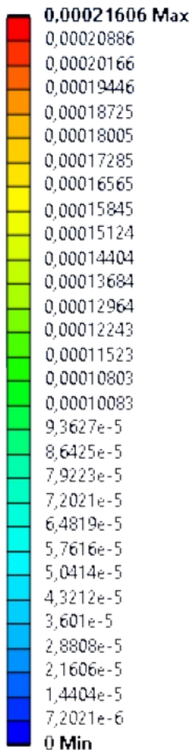


- 4.8N/mm2

3.7N/mm2

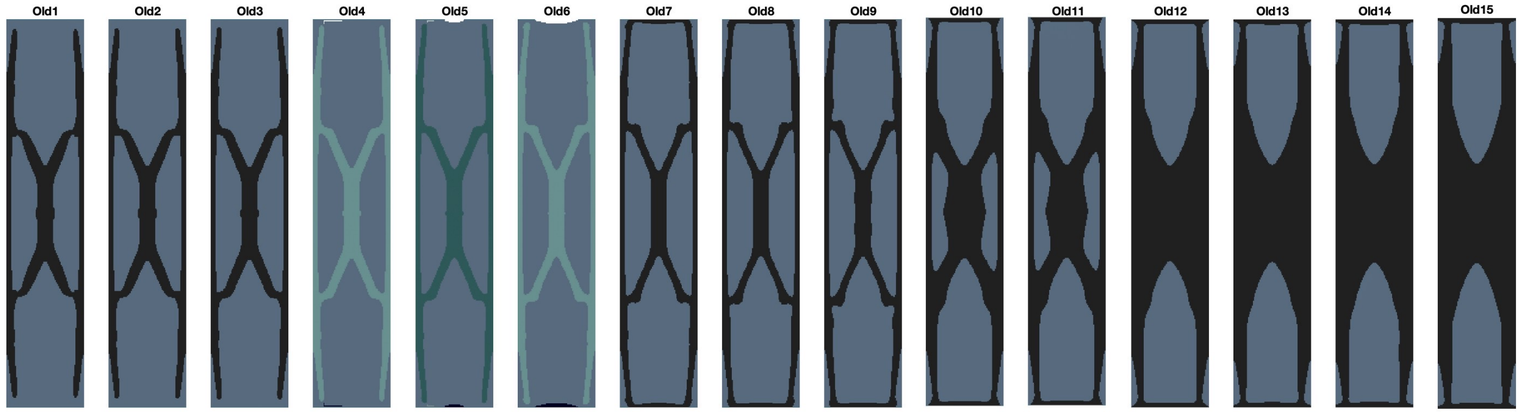
-0.223 mm

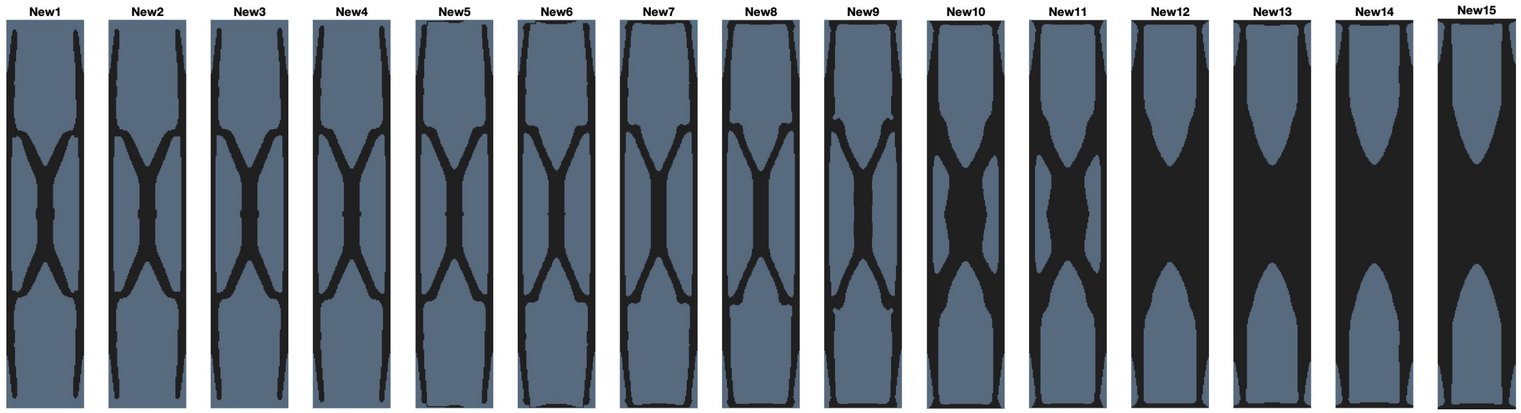
Final output - Ansys



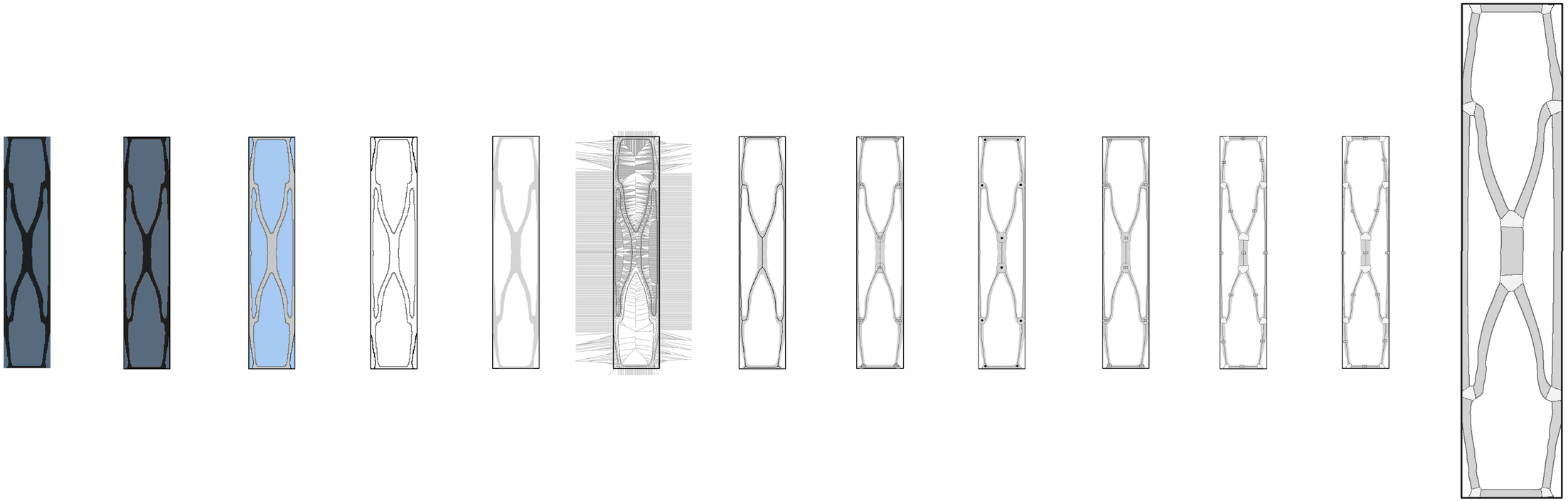
-0.216 mm

Final output





Final output



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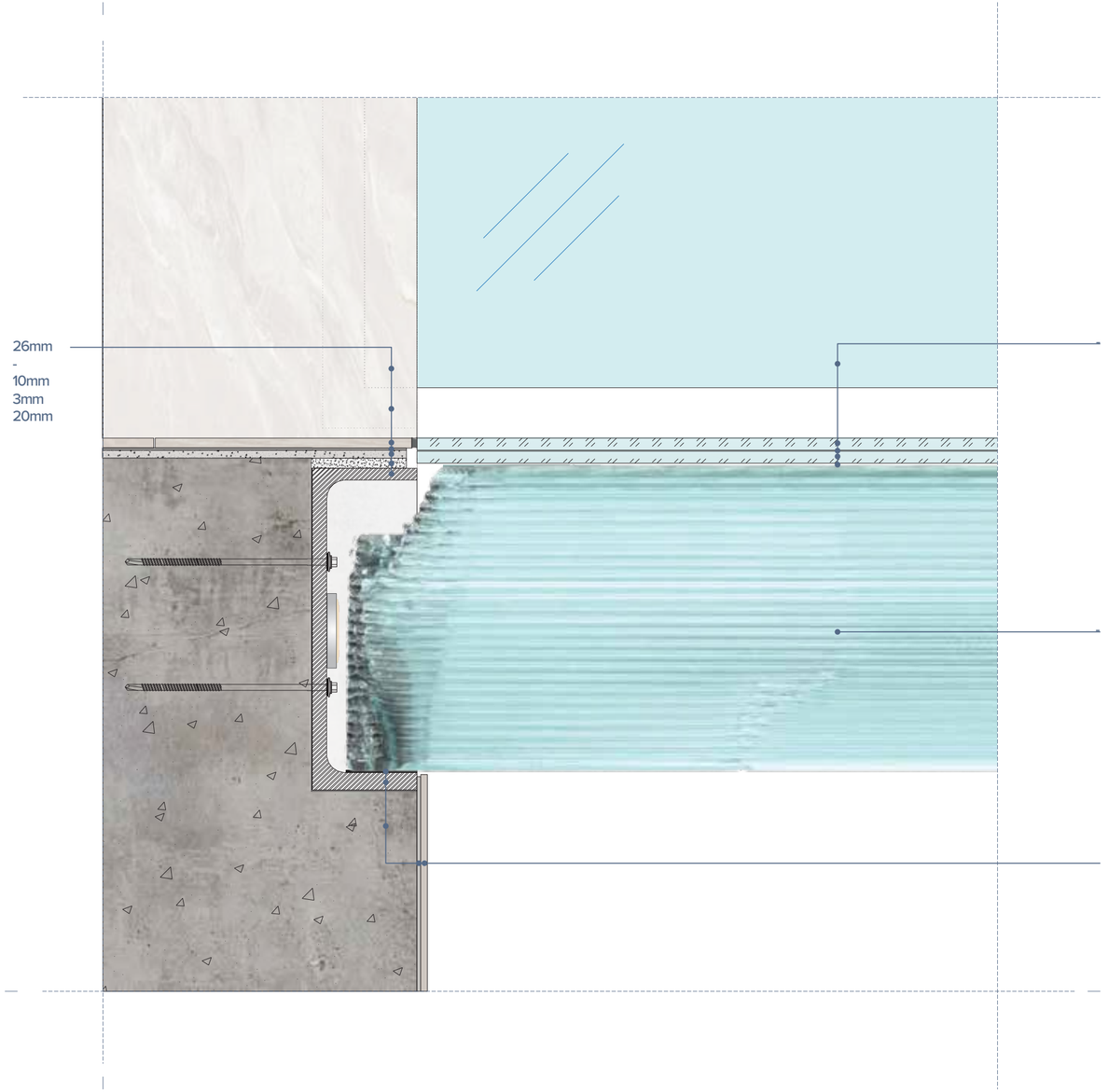


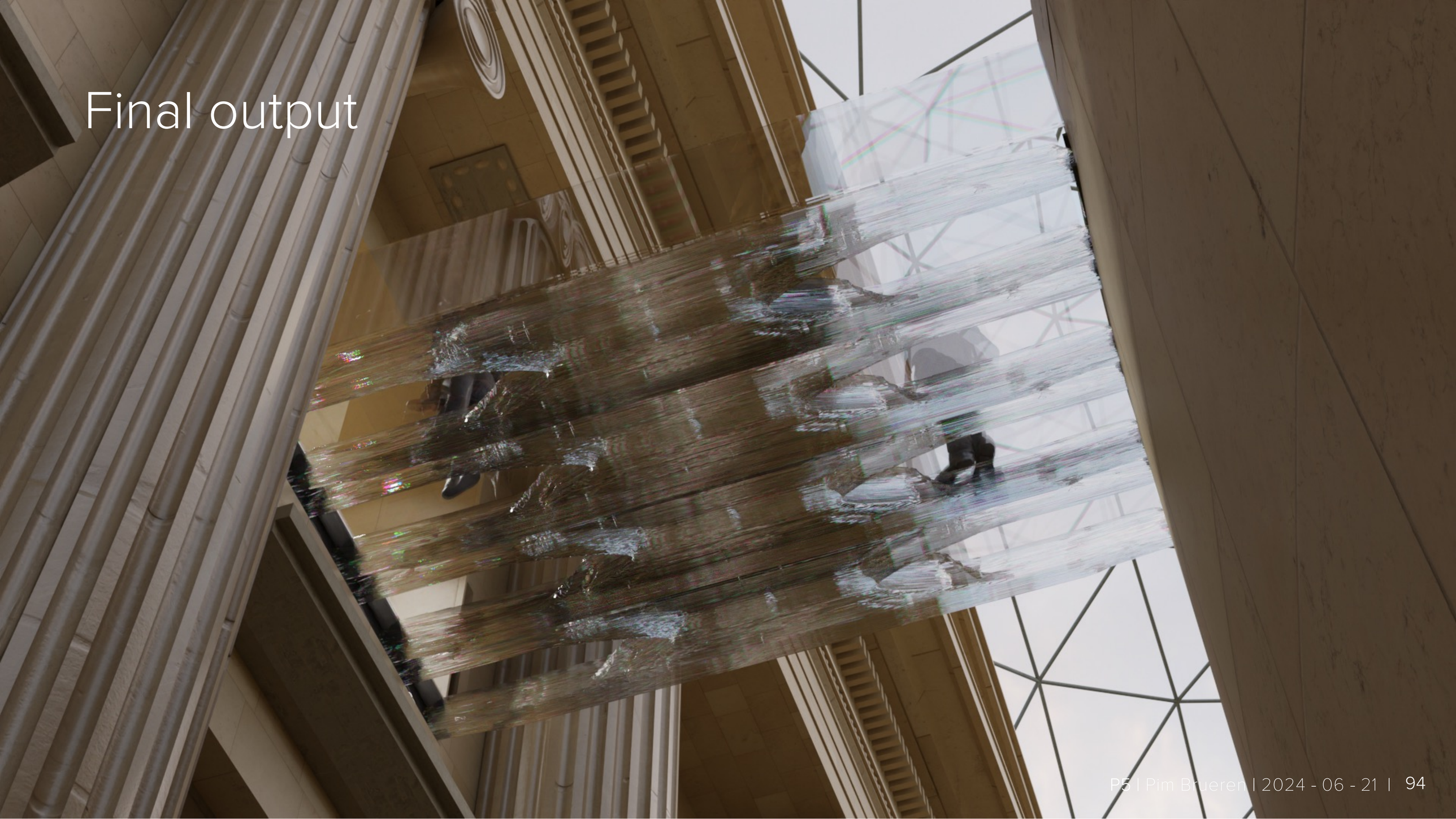
Float glass 2 x 12mm laminated	26mm
Aluminium profile (hidden in wall)	-
Tile	10mm
Tile adhesive	3mm
concrete	20mm

Float glass 2 x 12mm lamintated	26mm
Float glass 12mm laminated	12mm
PVB plastic interlayer	2mm
Float glass 12mm laminated	12mm
PVB Sheet 3*	4.56mm

Monolithic 3D printed glass

Neoprone gasket	5mm
UPN 320 steel profile	320mm
Concrete	-
Tile adhesive	3mm
Tile	10mm

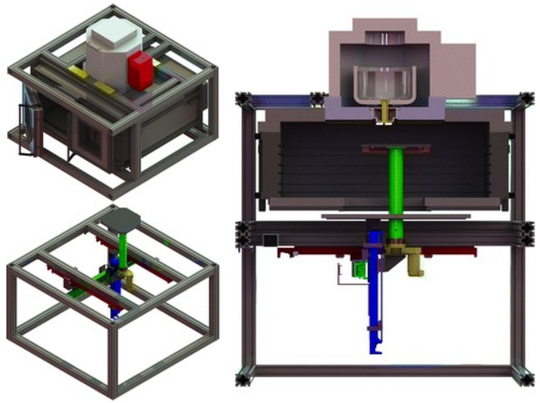
Final output

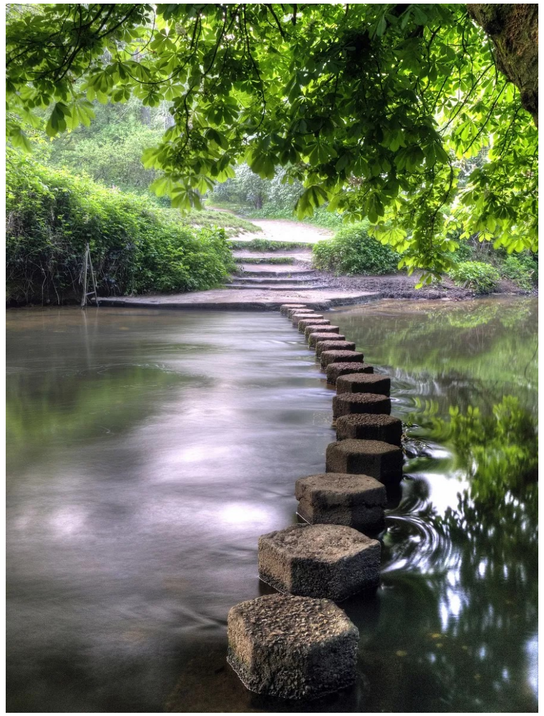


Final output

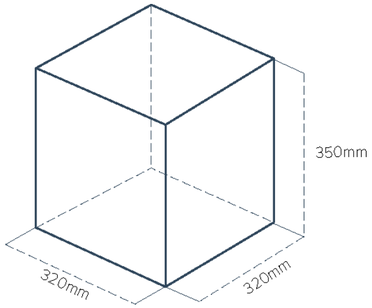
Final output

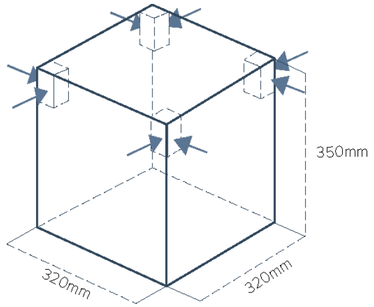
Final output

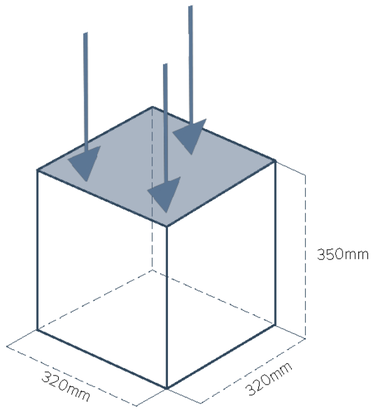


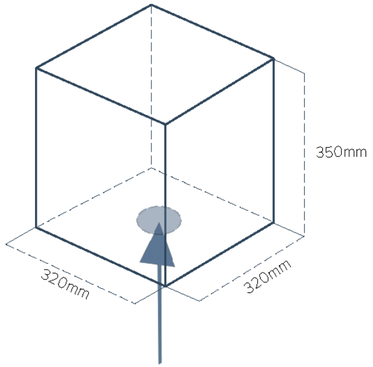


Final output

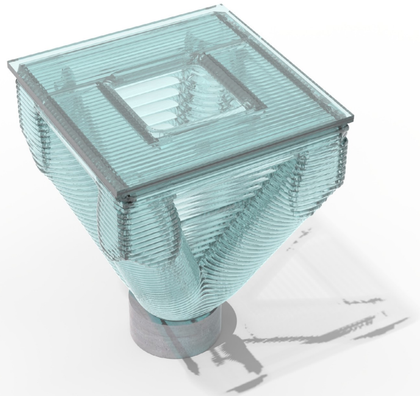


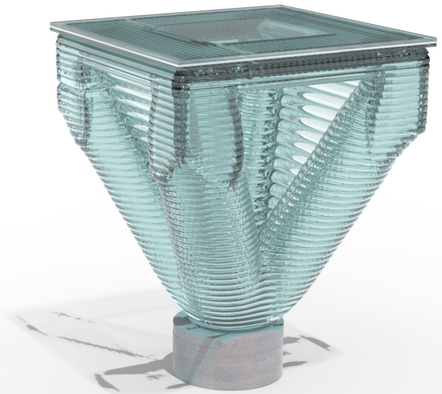






Final output





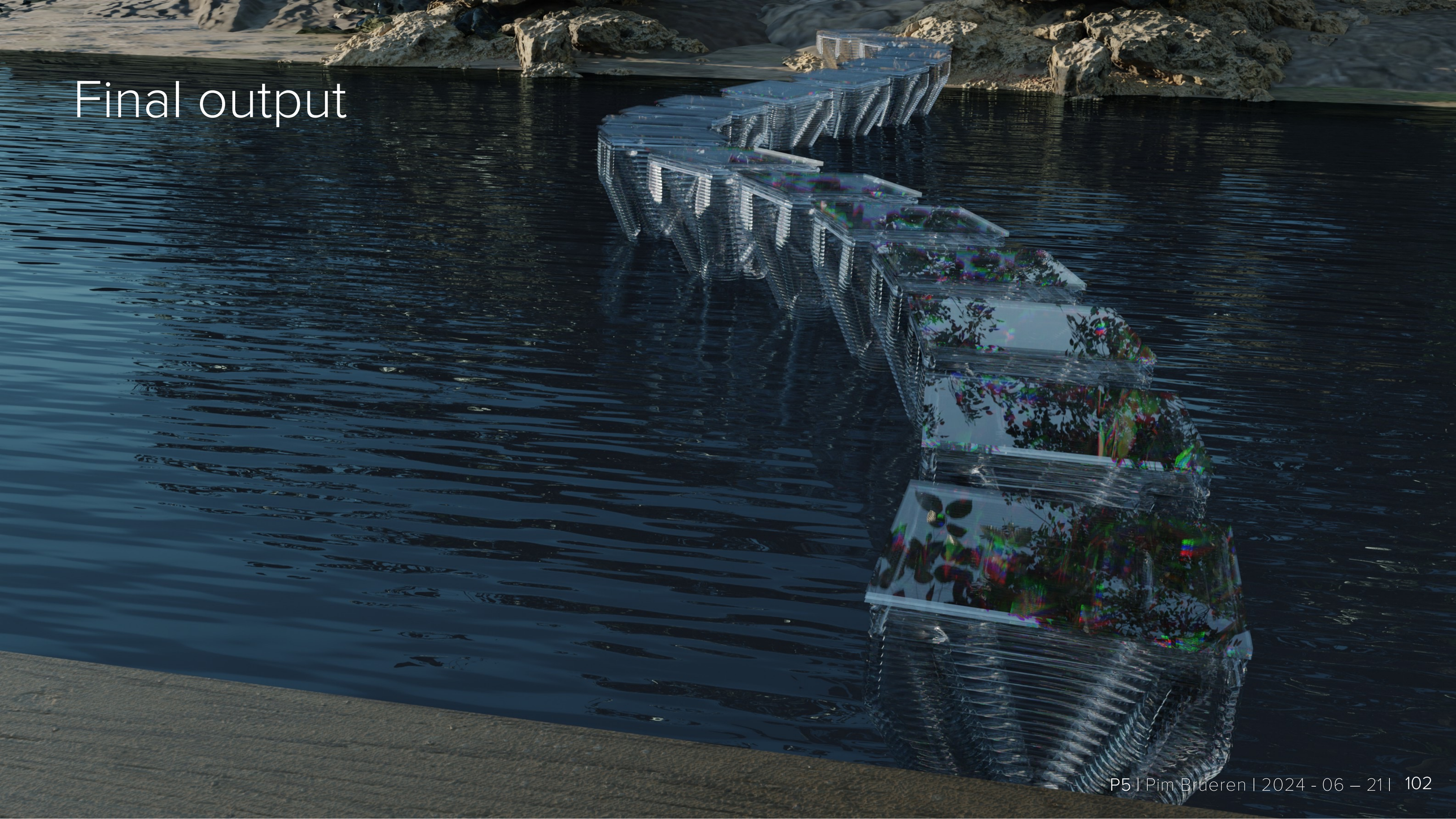
Final output

Stepping stones

https://www.nationaltrust.org.uk/visit/surrey/box-hill/box-hill-stepping-stones-walk

Final output

Final output



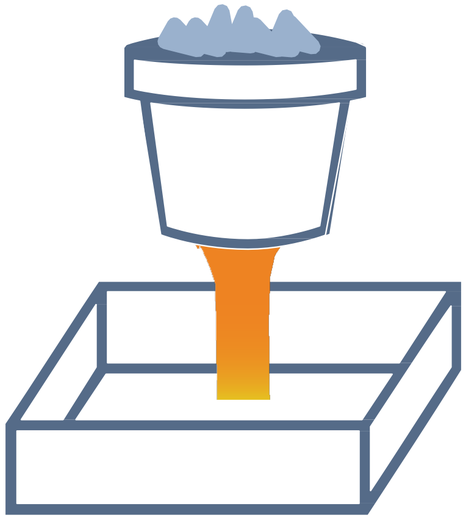
Final output

Yeah, cool, so...

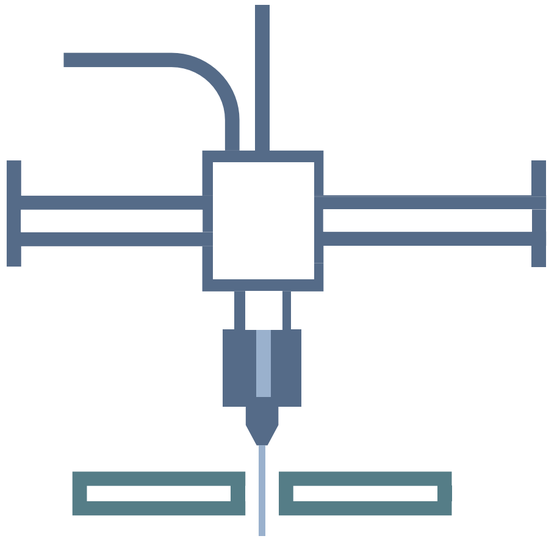
Can we make a prototype out of **glass**?

Production

Large scale 3D printer (plastic)

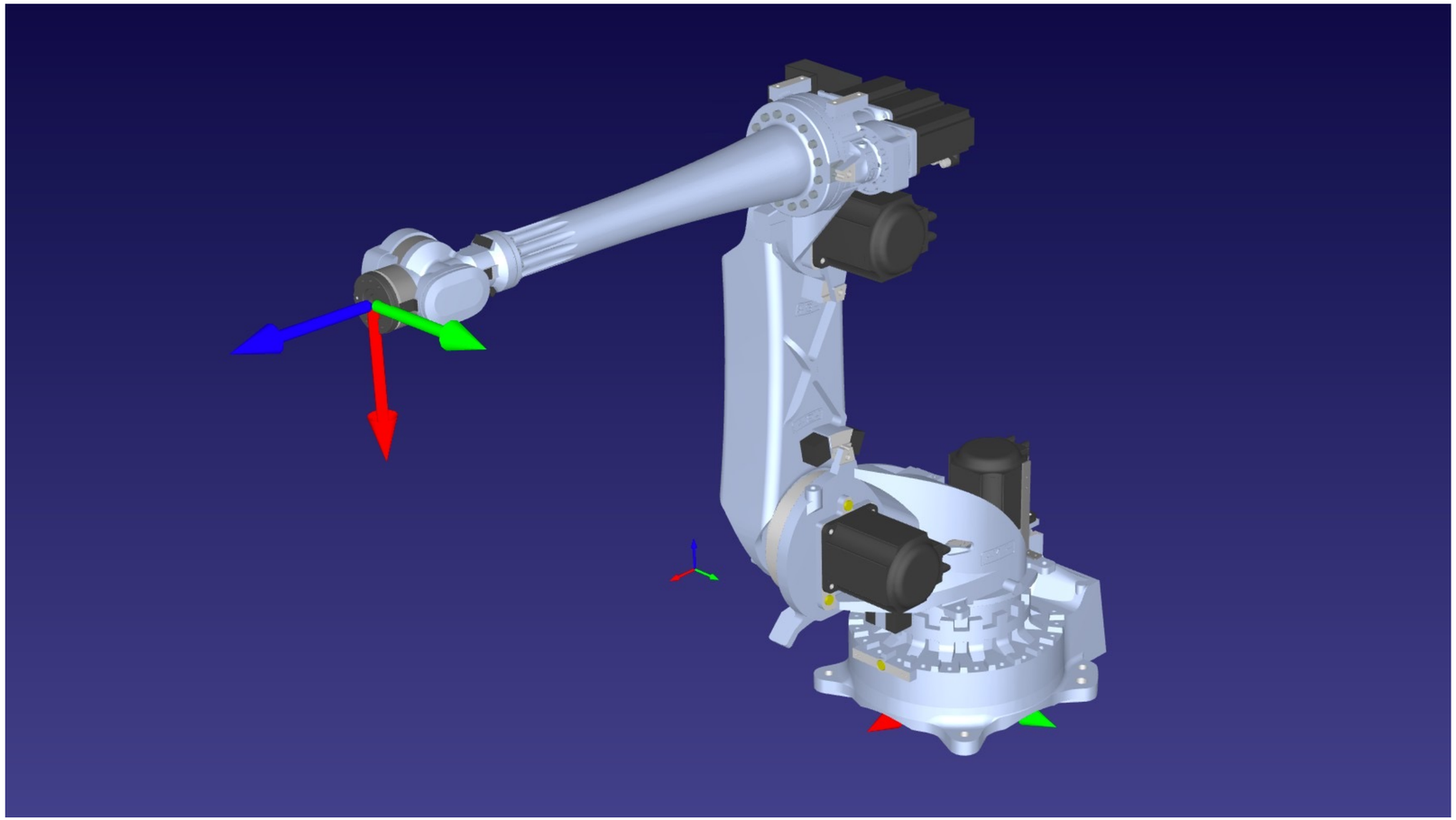


Casting



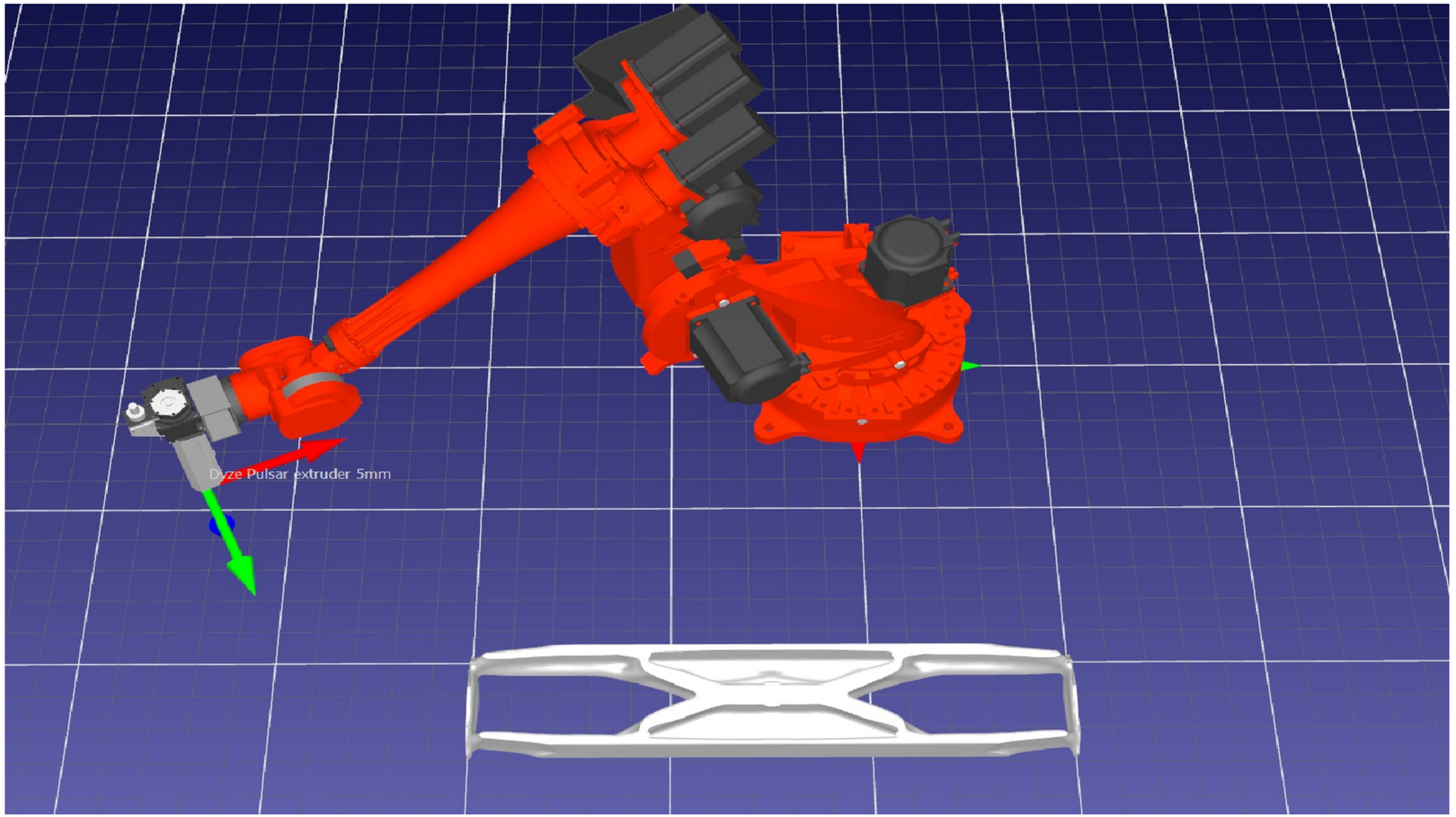
Waterjet cutting

Production



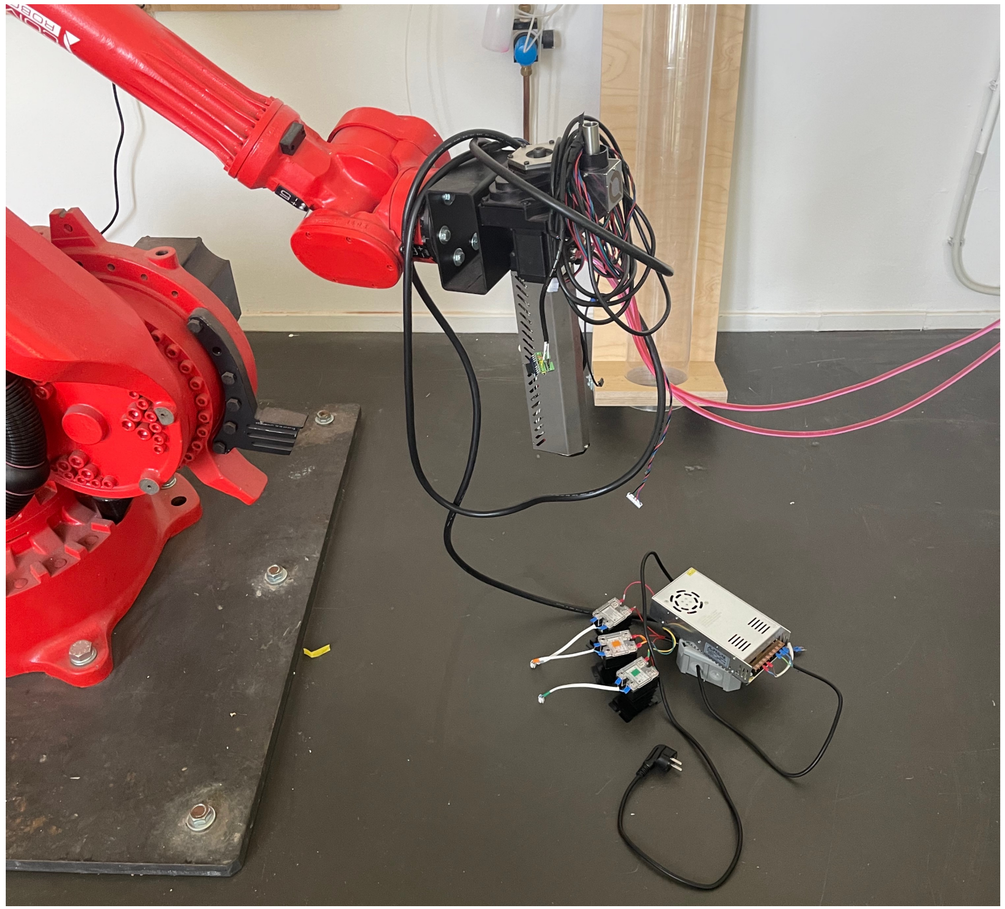
Starting with ROBODK

Production



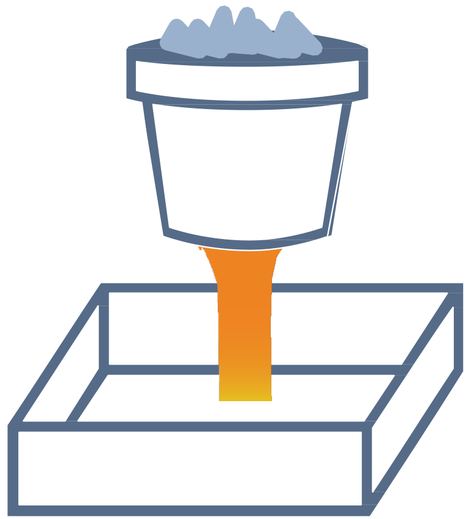
Total setup ROBODK, ready for printing

Production



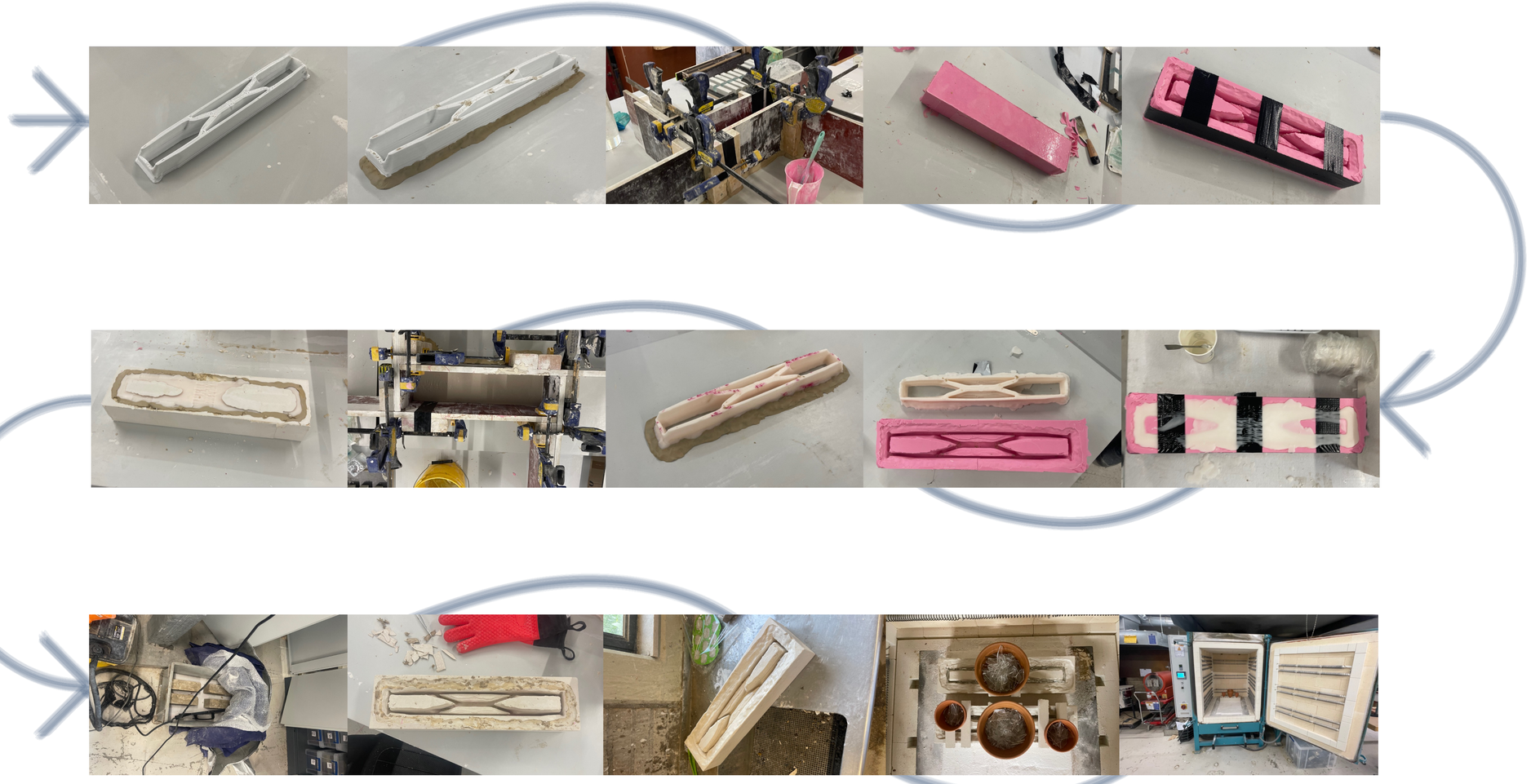
Comau robot with broken Dyze extruder

Production



Casting

Production



Production

Flowerpots broken into the glass prototype

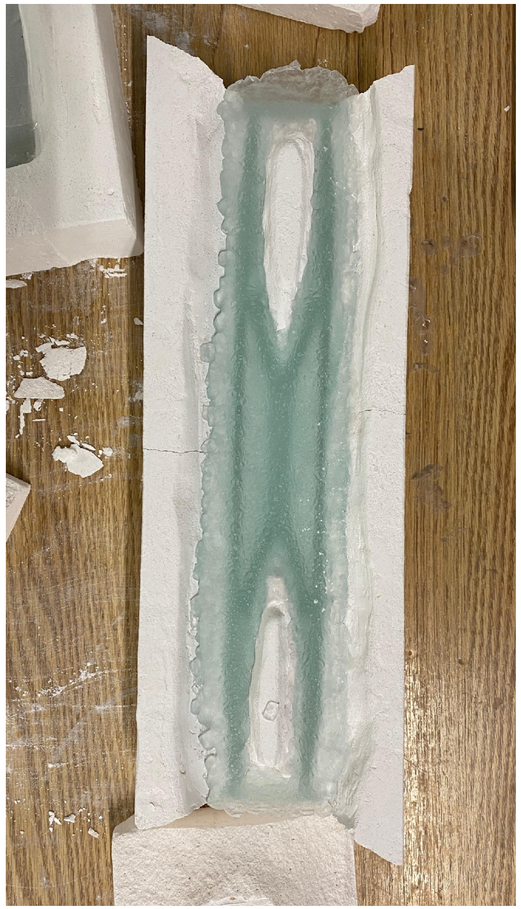
Production

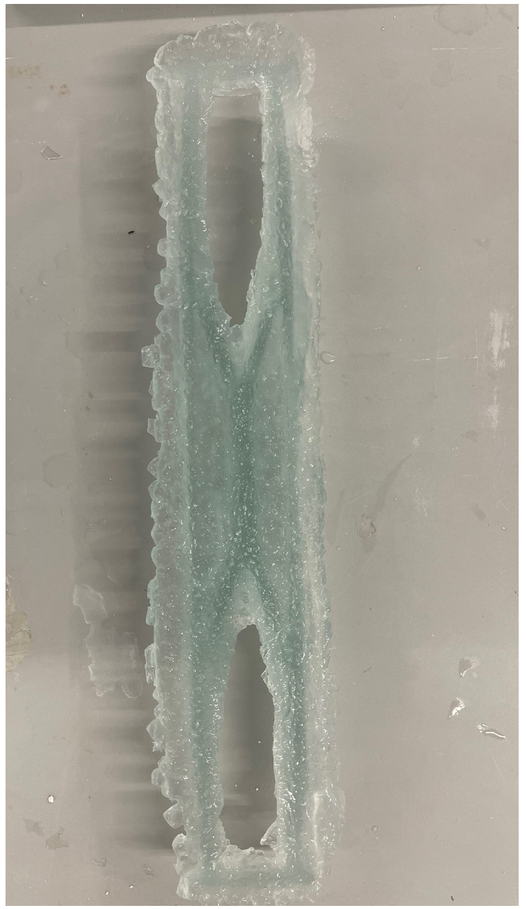
The remaining pieces of the prototype

Production

The new float glass prototype with all glass inside the mold

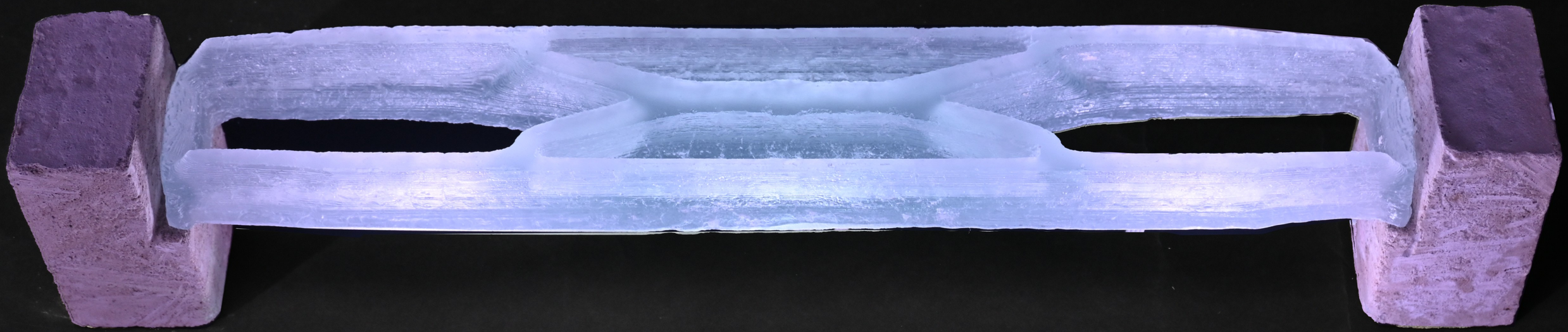
Production



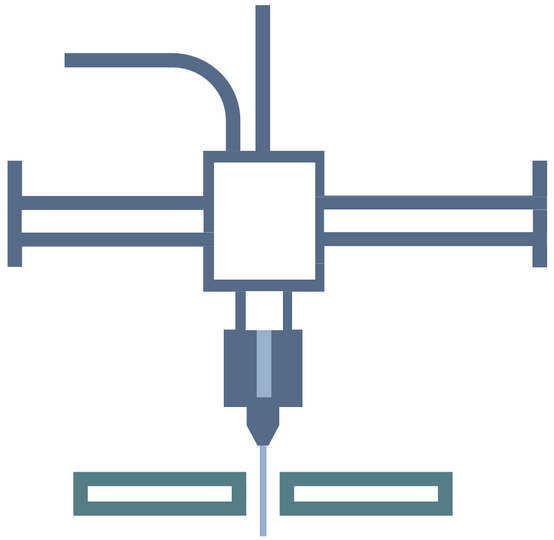


Preparing the mold for final shape

Production



Production

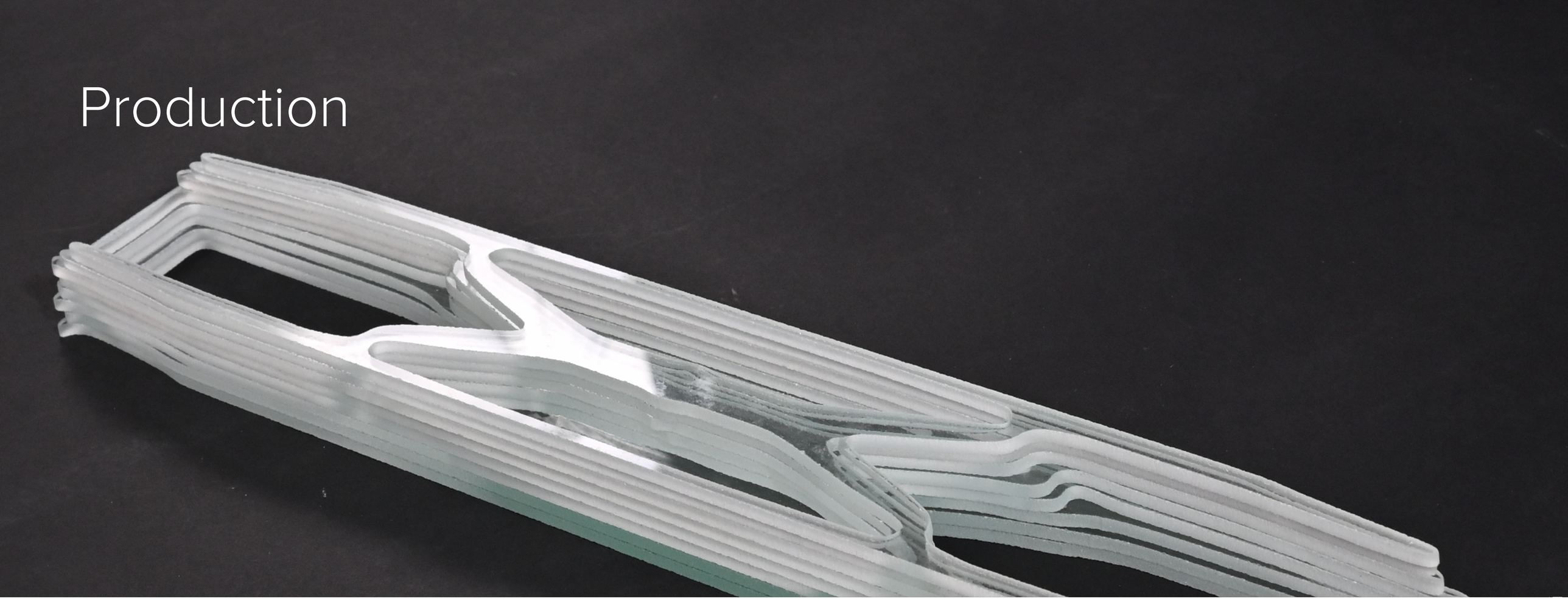


Waterjet cutting

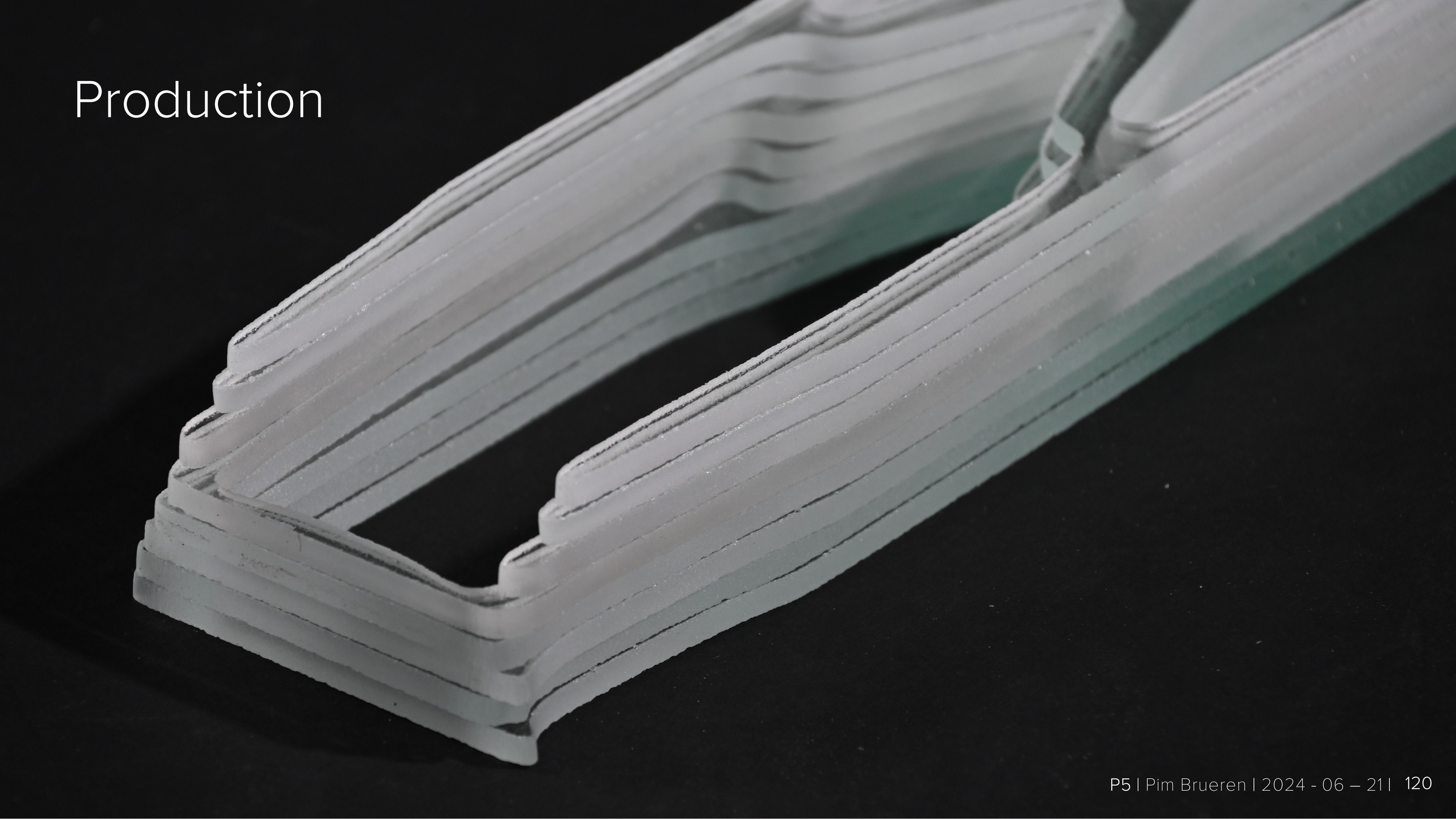
Production

Waterjet Cutter in action

Production



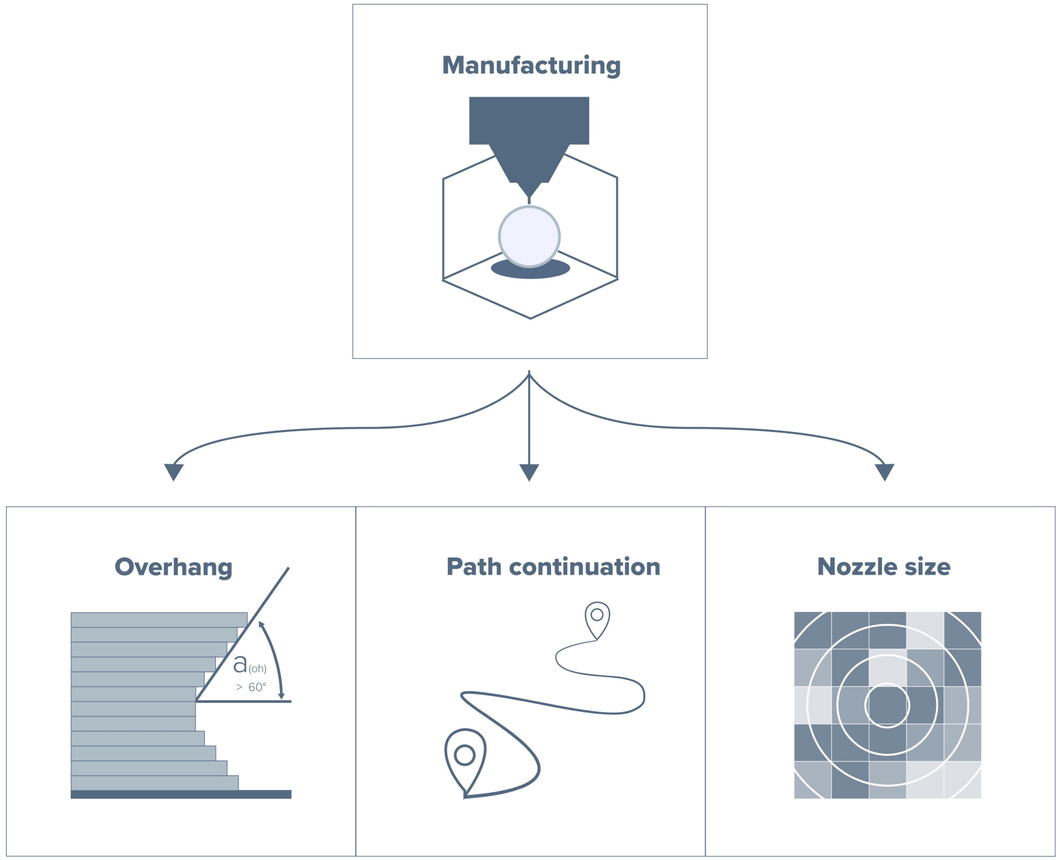
Production



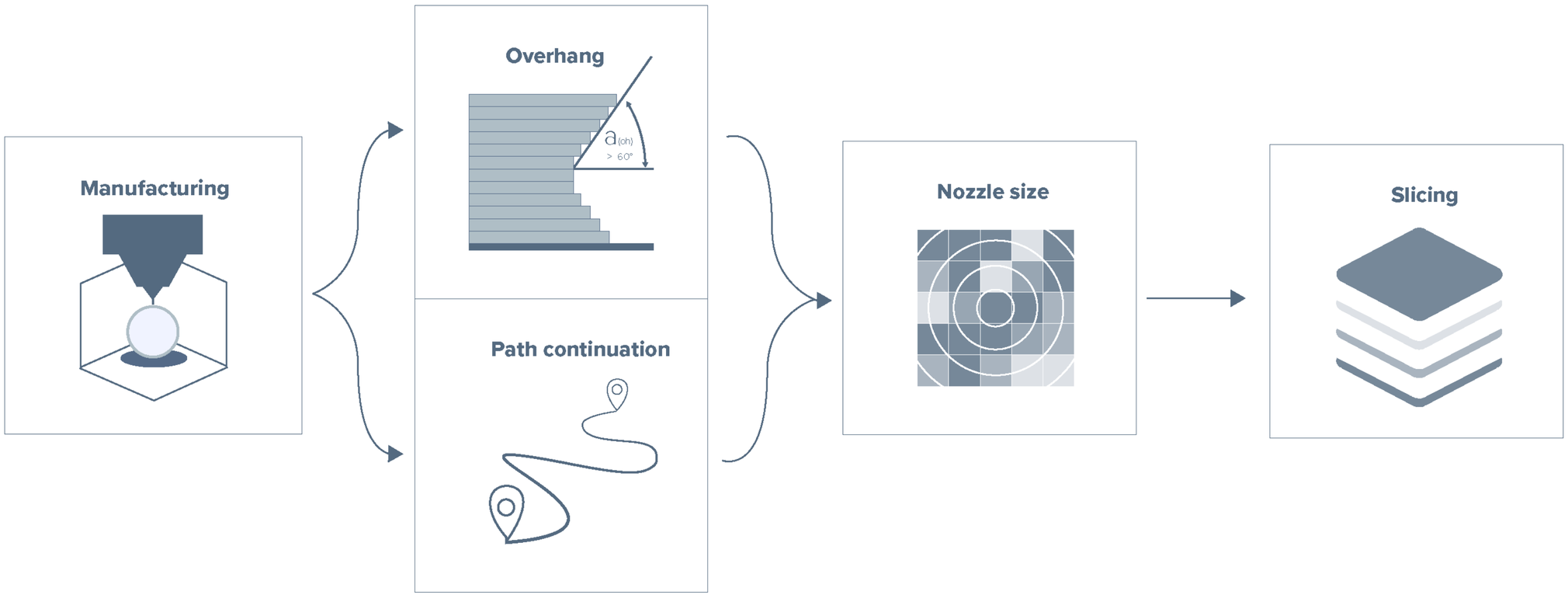
Research question - Concluding

How can the **manufacturing** process be **tailored** to fabricate a **topology-optimized monolithic 3D printed glass structure** while ensuring **effective production** constraints?

Ensuring effective production

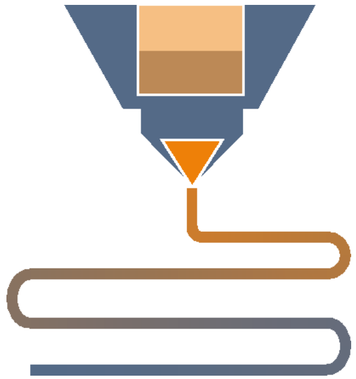


Ensuring effective production



Upsides

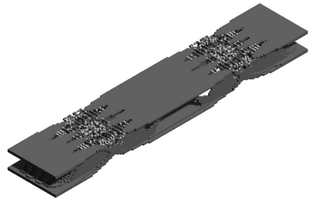
manufacturability



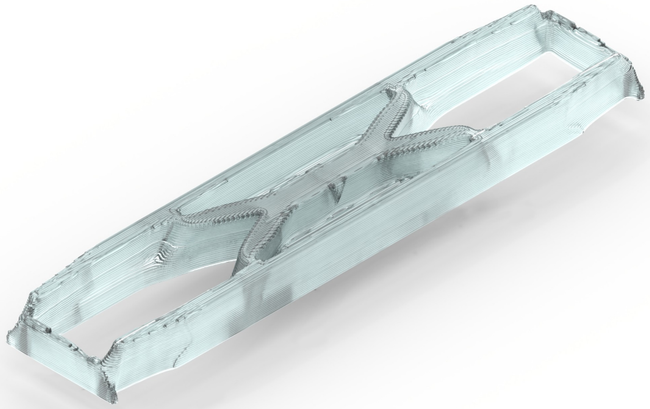
No need for post processing

6.300 elements

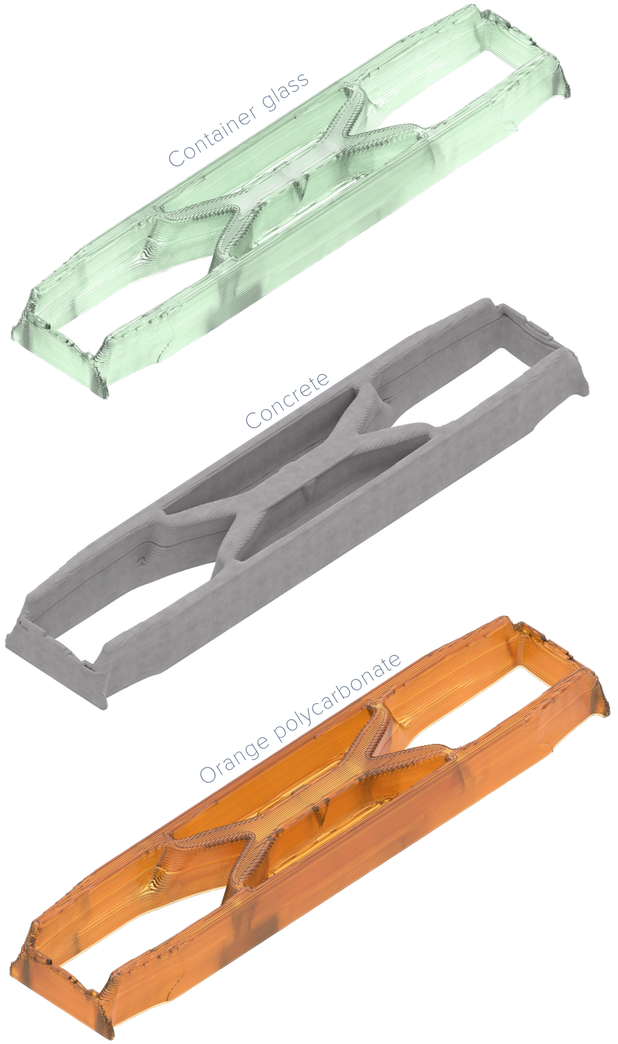
36.000 elements



1.008.000 elements

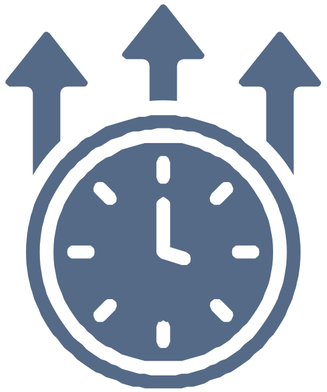


Not limited to soda-lime glass

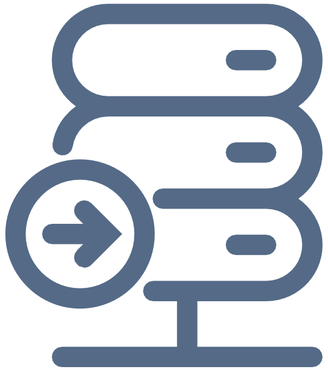


Limitations

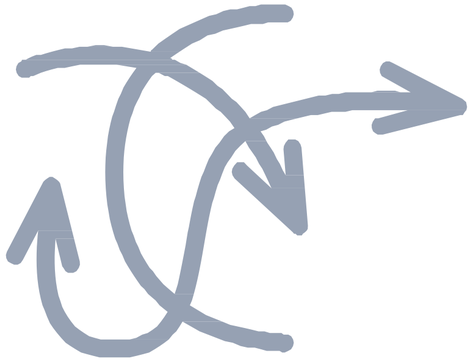
Computational time



More expertise needed to provide the right input



Introduction of more steps, more complex

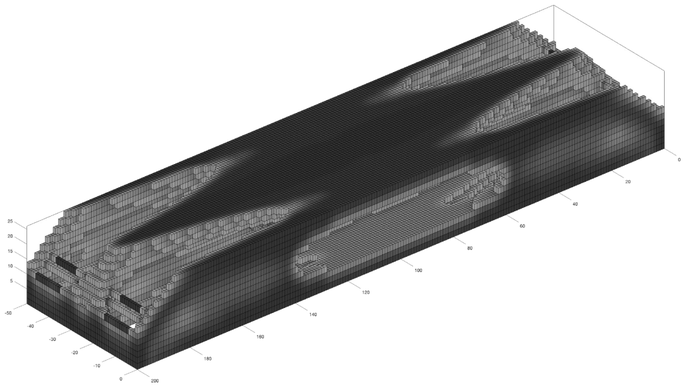


Future research

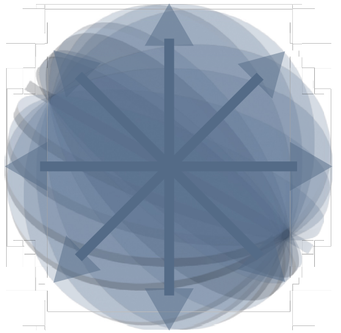
Reflection

Slicing

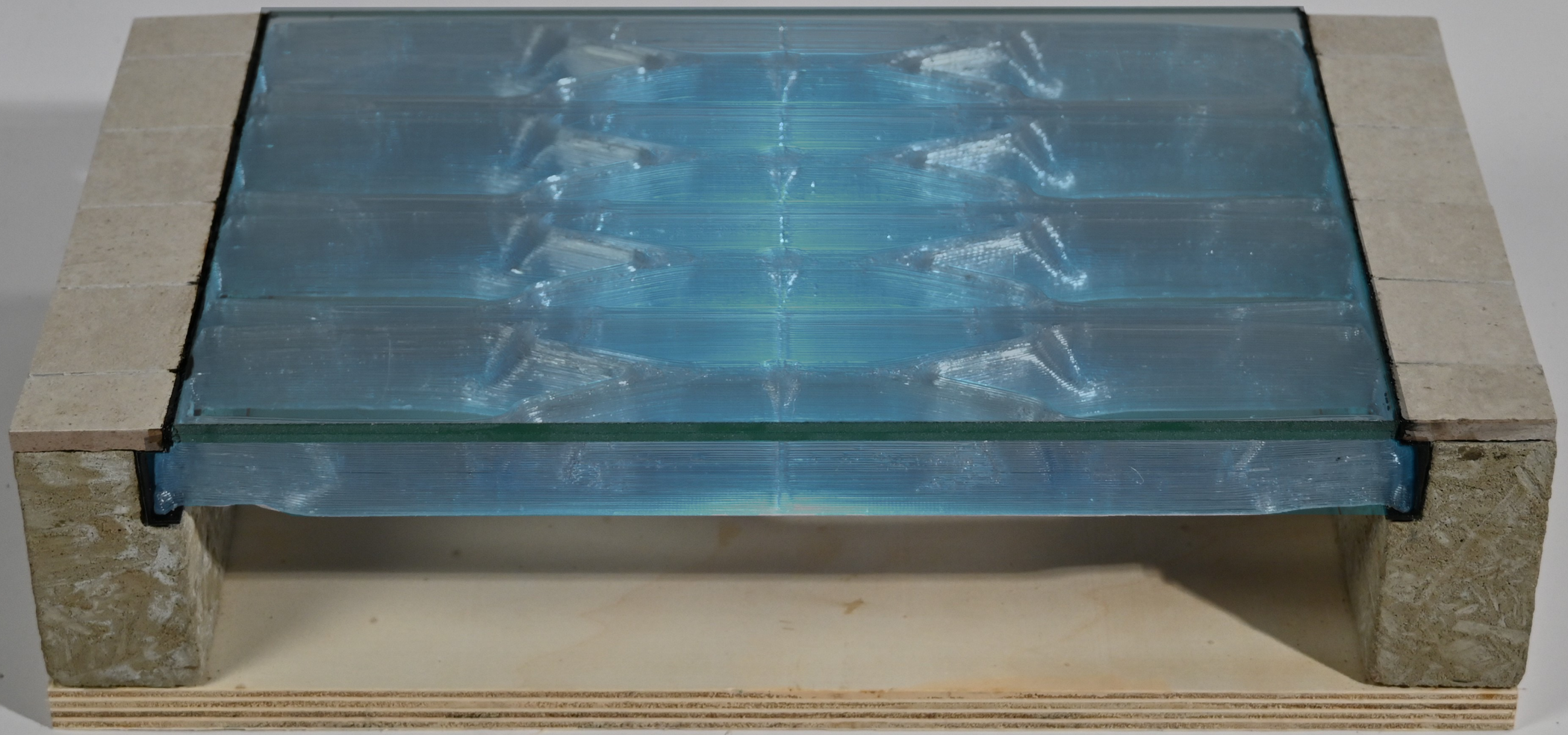
Lost of information due to amount of elements



Anisotropic



Thanks for your attention



TO3DPGS - The Future Of Glass

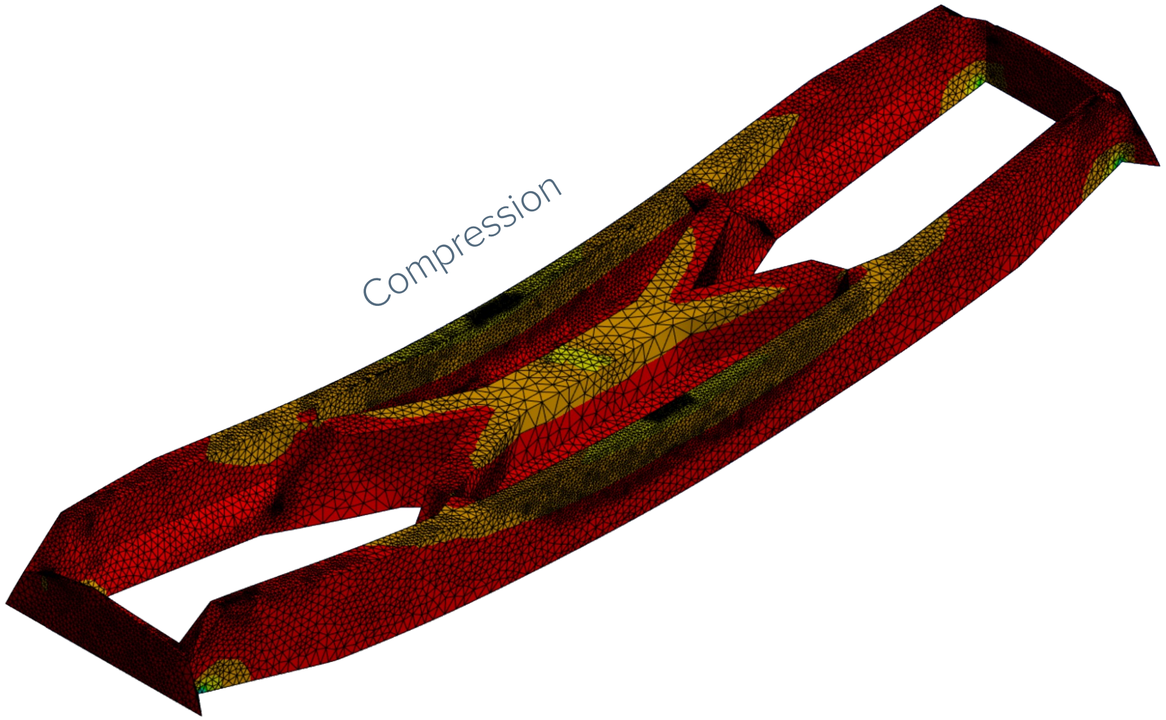
2024 | 06 | 21

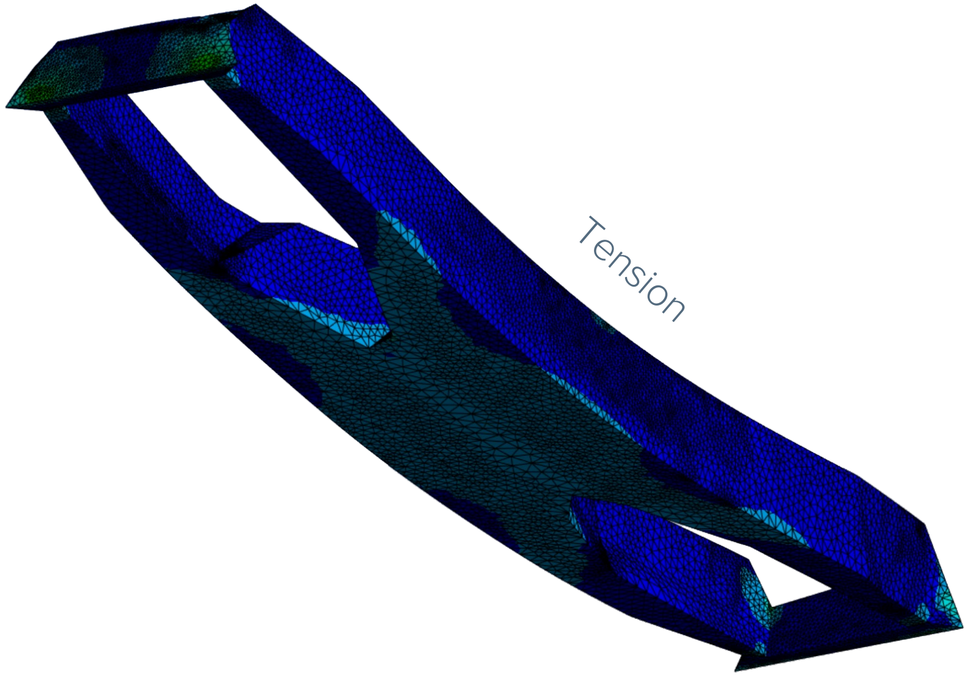
Pim Brueren

*'Development of an Algorithm for **T**opology **O**ptimized **3D P**rinted **G**lass **S**tructure'*

Mentors:
Faidra Oikonomopoulou (SDM)
Charalampos Andriotis (AI)

Appendix

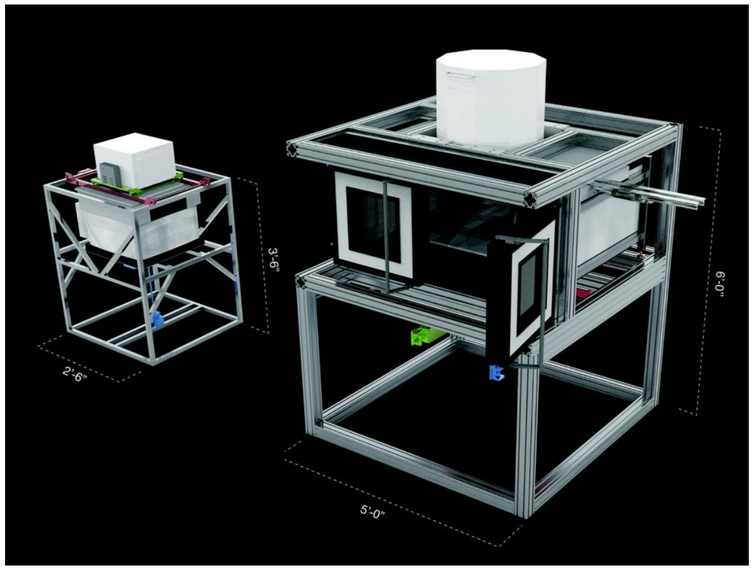




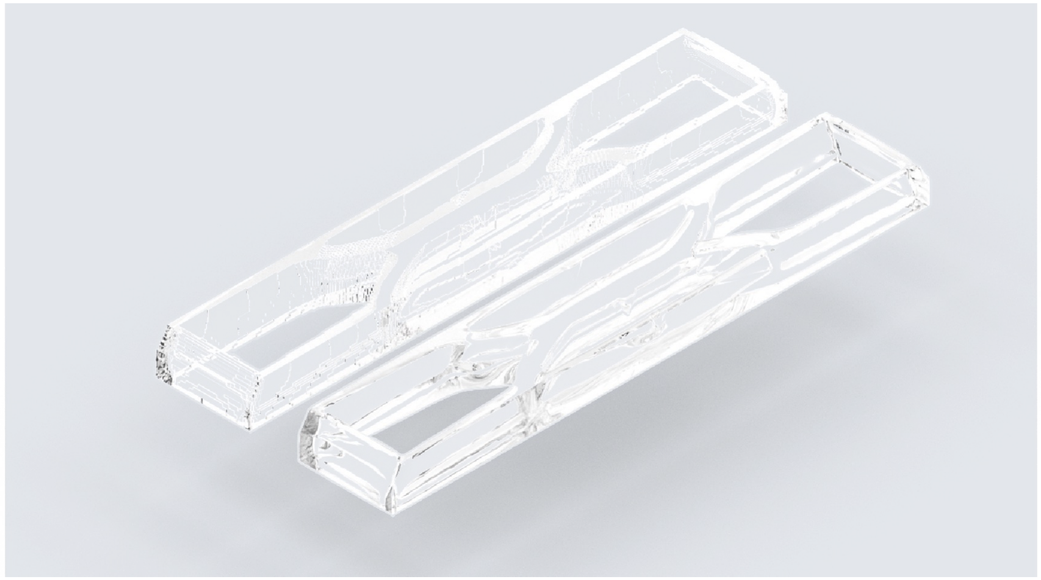
Appendix

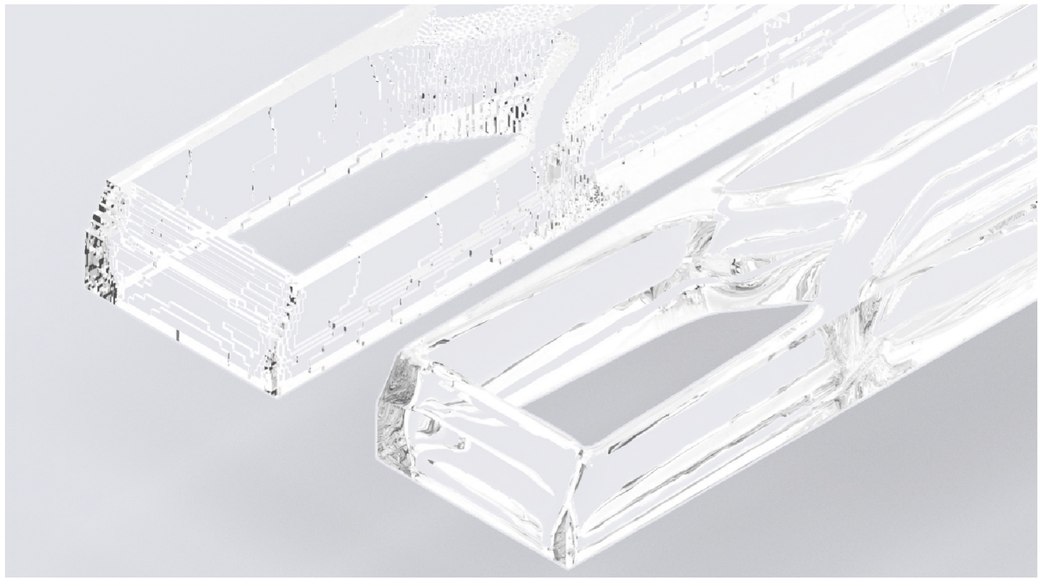
G3DP

G3DP2

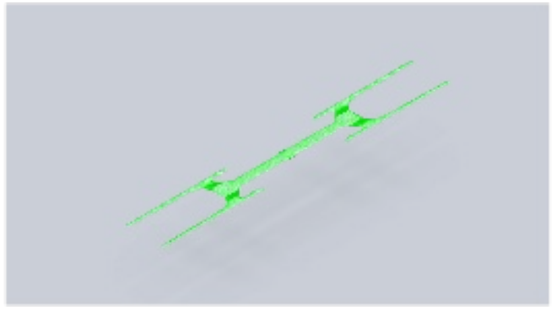


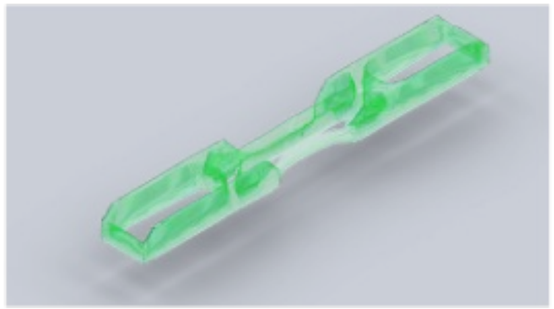
Appendix

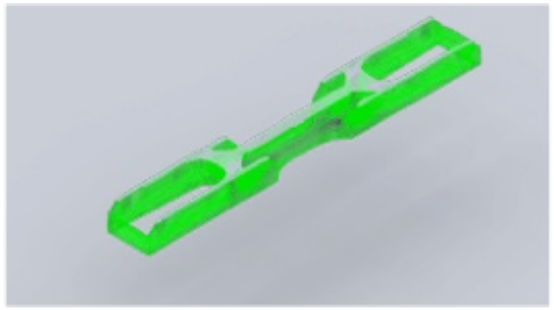


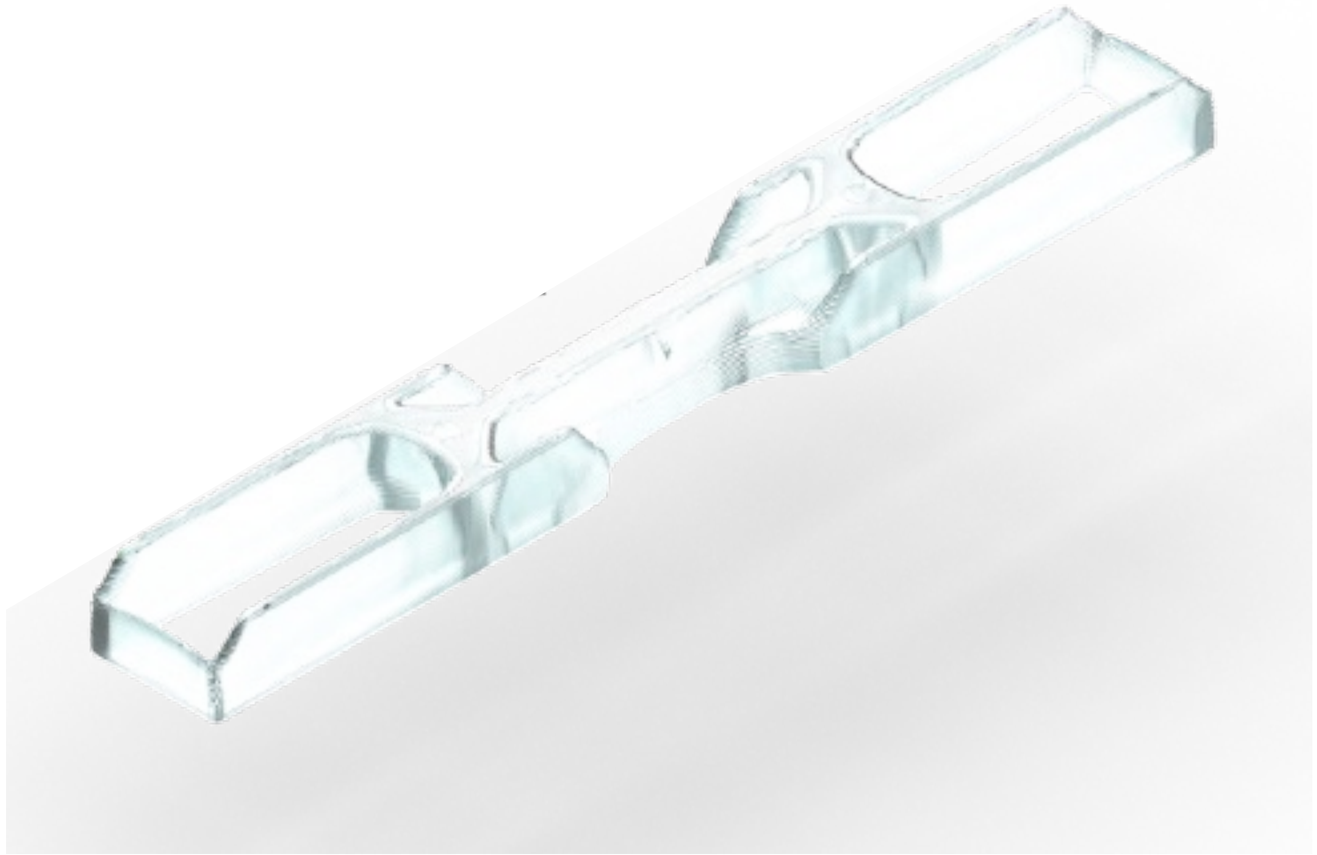


Appendix

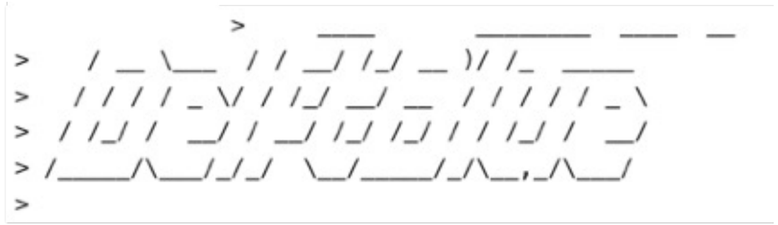








Appendix



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User/Group: pbrueren/domain users
State: COMPLETED (exit code 0)
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Cores per node: 24
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CPU Efficiency: 53.69% of 11-18:49:36 core-walltime
Job Wall-clock time: 11:47:04
Memory Utilized: 94.36 GB
Memory Efficiency: 52.42% of 180.00 GB
```

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Job ID: 3687858
Cluster: delftblue
User/Group: pbrueren/domain users
State: COMPLETED (exit code 0)
Nodes: 1
Cores per node: 36
CPU Utilized: 27-18:40:53
CPU Efficiency: 77.15% of 36-00:05:24 core-walltime
Job Wall-clock time: 1-00:00:09
Memory Utilized: 450.85 GB
Memory Efficiency: 60.11% of 750.00 GB
```
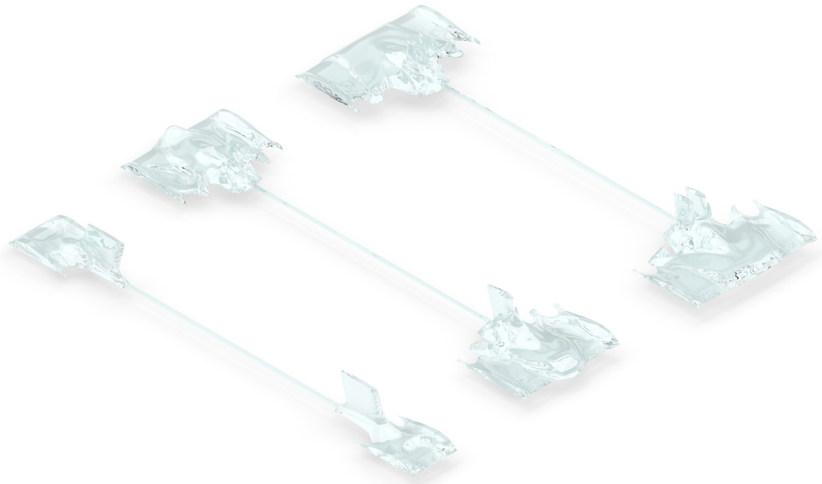

```
Job ID: 3686057
Cluster: delftblue
User/Group: pbrueren/domain users
State: COMPLETED (exit code 0)
Nodes: 1
Cores per node: 36
CPU Utilized: 29-00:02:46
CPU Efficiency: 57.37% of 50-13:19:12 core-walltime
Job Wall-clock time: 1-09:42:12
Memory Utilized: 162.19 GB
Memory Efficiency: 87.67% of 185.00 GB
```

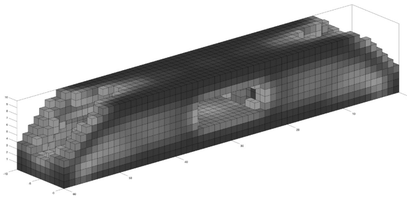
```
Job ID: 3687856
Cluster: delftblue
User/Group: pbrueren/domain users
State: COMPLETED (exit code 0)
Nodes: 1
Cores per node: 36
CPU Utilized: 28-02:32:12
CPU Efficiency: 78.06% of 36-00:05:24 core-walltime
Job Wall-clock time: 1-00:00:09
Memory Utilized: 474.52 GB
Memory Efficiency: 63.27% of 750.00 GB
```

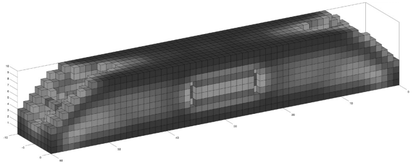
```
[pbrueren@login03 ~]$ squeue -u $USER
             JOBID PARTITION     NAME     USER ST       TIME  NODES NODELIST(REASON)
           3675365 compute-p matlab_t pbrueren  R   11:37:30      1 cmp125
           3675369 compute-p matlab_t pbrueren  R   11:38:03      1 cmp135
           3677240 compute-p matlab_t pbrueren  R    2:17:26      1 cmp035
           3677241 compute-p matlab_t pbrueren  R    2:15:17      1 cmp115
           3677239 compute-p matlab_t pbrueren  R    2:27:04      1 cmp159
           3677238 compute-p matlab_t pbrueren  R    2:30:19      1 cmp086
           3677236 compute-p matlab_t pbrueren  R    2:36:49      1 cmp202
           3677233 compute-p matlab_t pbrueren  R    2:43:14      1 cmp043
           3677235 compute-p matlab_t pbrueren  R    2:42:12      1 cmp053
           3677232 compute-p matlab_t pbrueren  R    2:47:32      1 cmp179
           3677228 compute-p matlab_t pbrueren  R    2:52:49      1 cmp168
           3677229 compute-p matlab_t pbrueren  R    2:50:39      1 cmp036
           3677246    memory matlab_t pbrueren PD       0:00      1 (Resources)
           3671919    memory matlab_t pbrueren  R 1-04:32:10      1 mem009
           3677244    memory matlab_t pbrueren  R      15:48      1 mem007
           3677243    memory matlab_t pbrueren  R      47:40      1 mem006
           3677242    memory matlab_t pbrueren  R    2:50:19      1 mem007
```

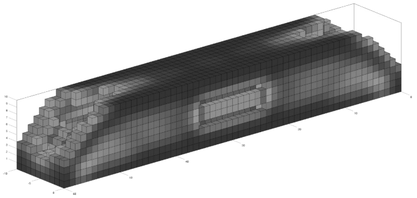
Appendix

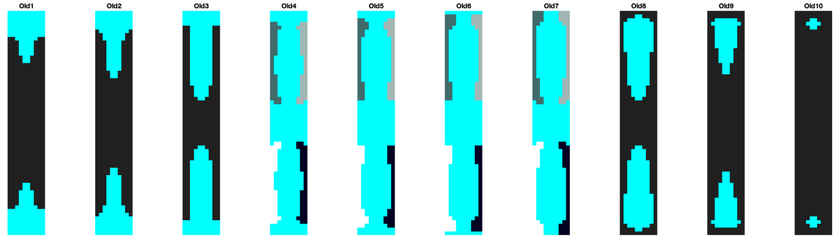


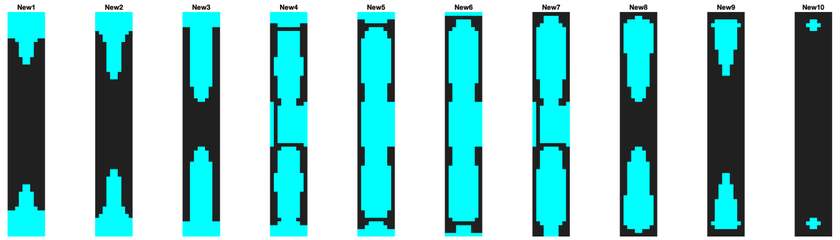
Appendix

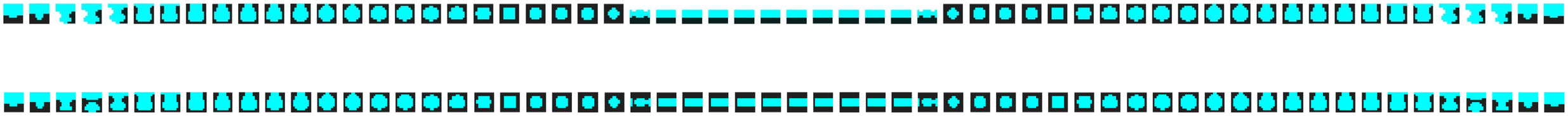







Old1
Old2
Old3
Old4
Old5
Old6
Old7
Old8
Old9
Old10


New1
New2
New3
New4
New5
New6
New7
New8
New9
New10




Old1
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Appendix

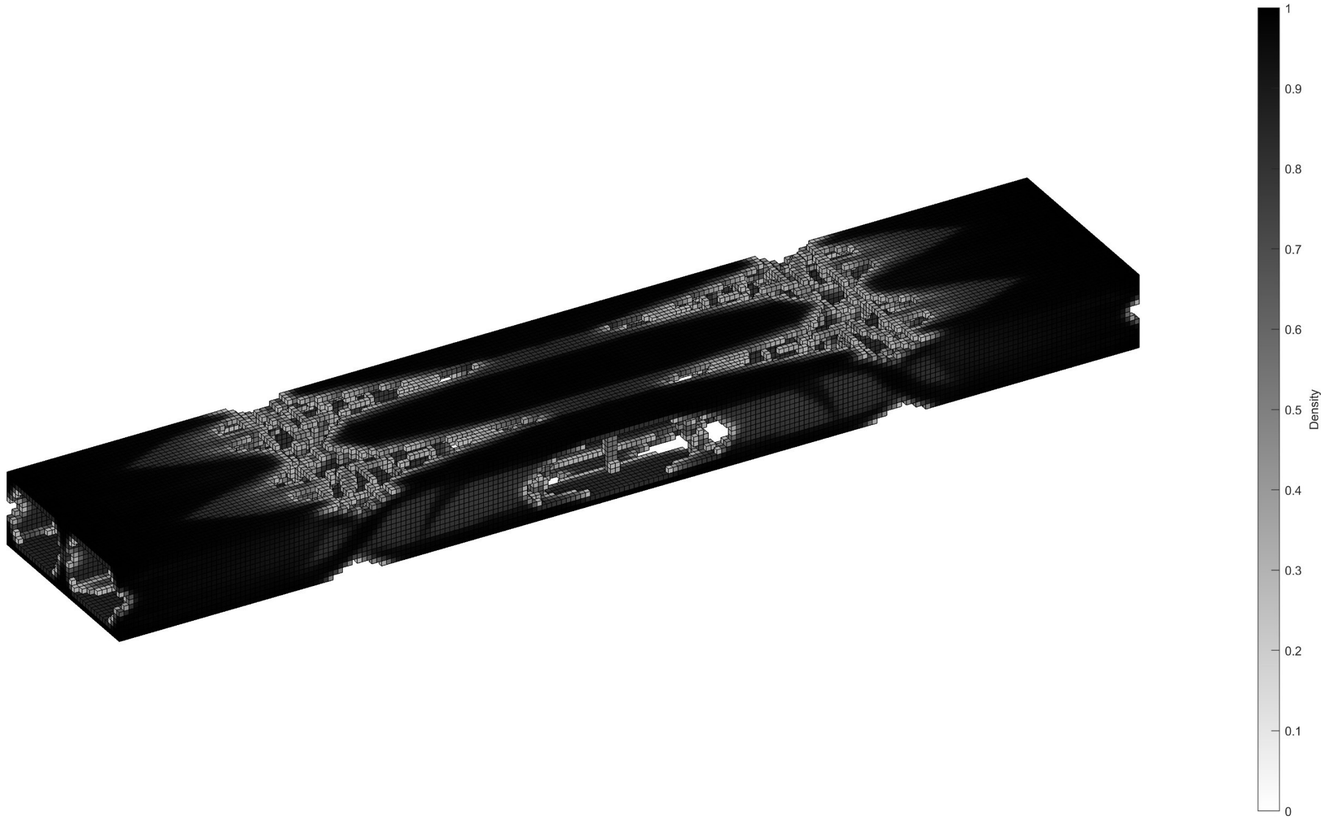

Figure 7.5: Result Compliance Optimization, split domain