

Adding a New Dimension to Glass Giants

Development of a Three-Dimensional
Topology Optimization Algorithm for Mass-
Optimized Cast Glass Components

Eva Schoenmaker | 4693906 | 10/11/2023

Mentors | Charalampos Andriotis (AI)

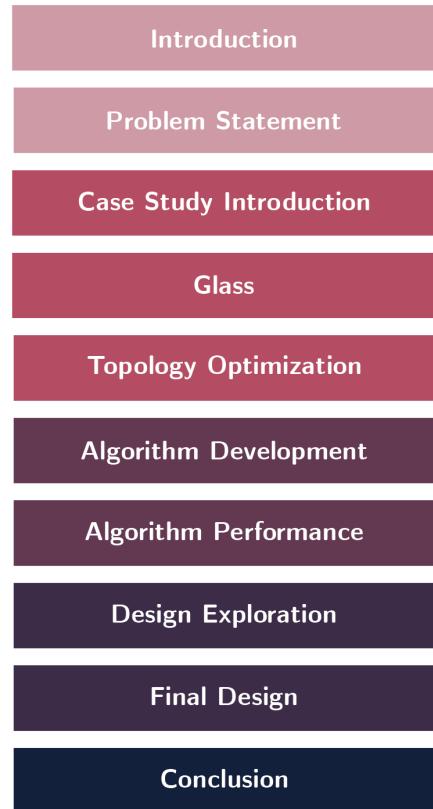
Faidra Oikonomopoulou (SDM)



In a Nutshell

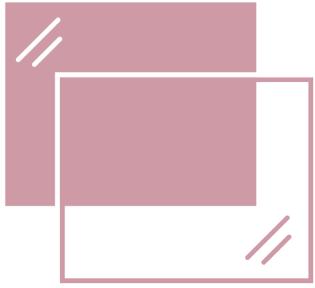
Aiming to create an algorithm that can find the best material layout for a load carrying member made from cast glass

Presentation Overview



Why Cast Glass for Structures?

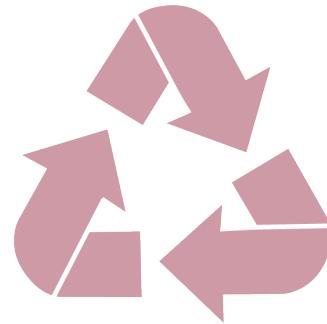
Why Glass?



Transparent



Durable

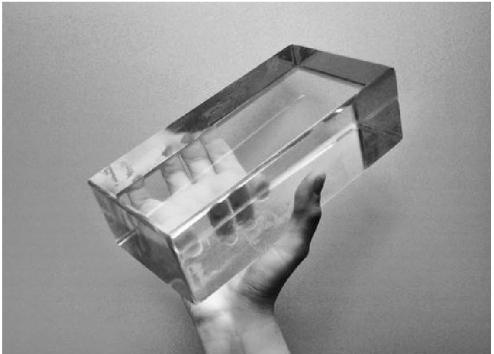


Recyclable



High compressive strength

Strength Glass



Glass



Compression
500 MPa



Tension
45 MPa



Unreinforced Concrete



Compression
17-50 MPa



Tension
2-5 MPa



Structural Steel



Compression
250-500 MPa



Tension
250-500 MPa

Structural Glass in Buildings

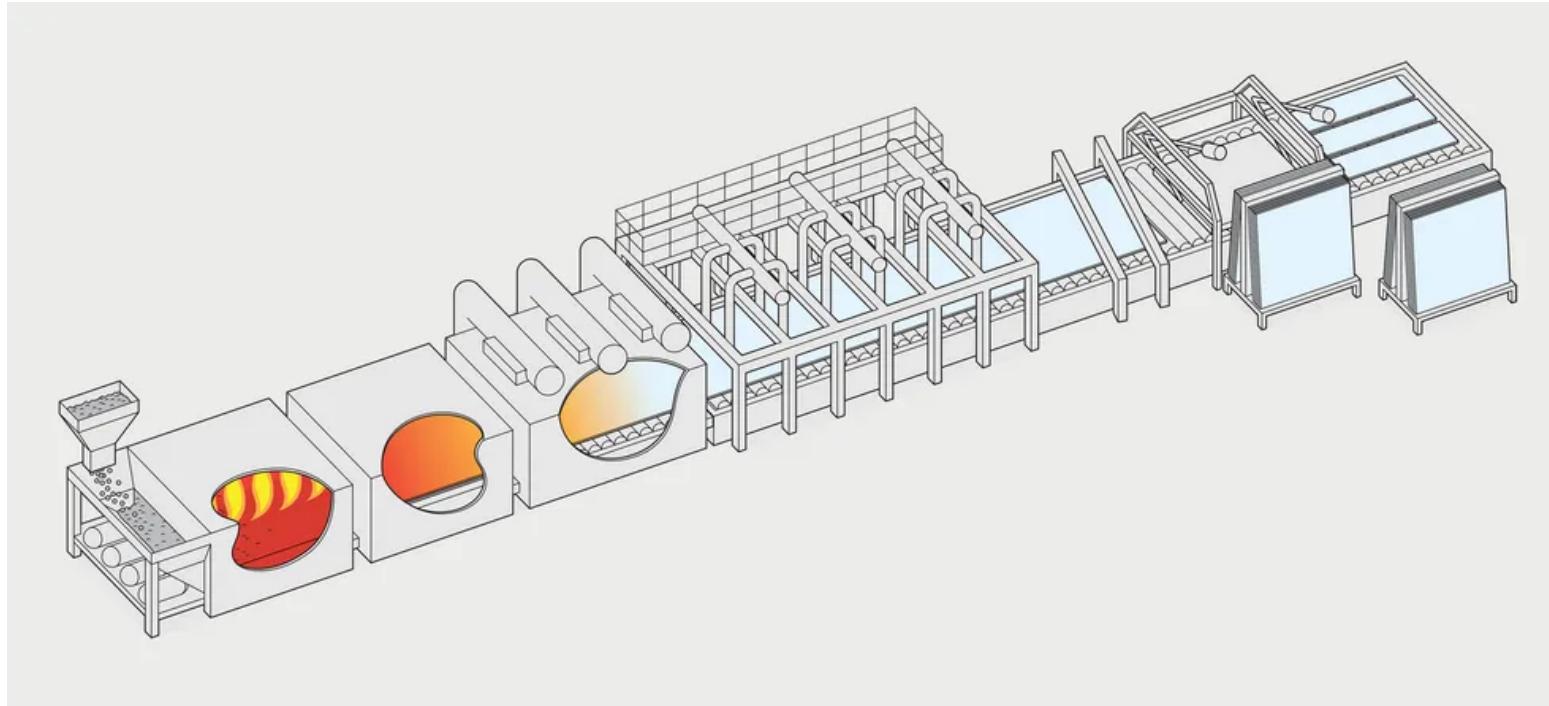


Apple store Fifth Avenue, New York

Design by Foster + Partners, cube developed by EOC engineers

Introduction

Production Process | Float Glass

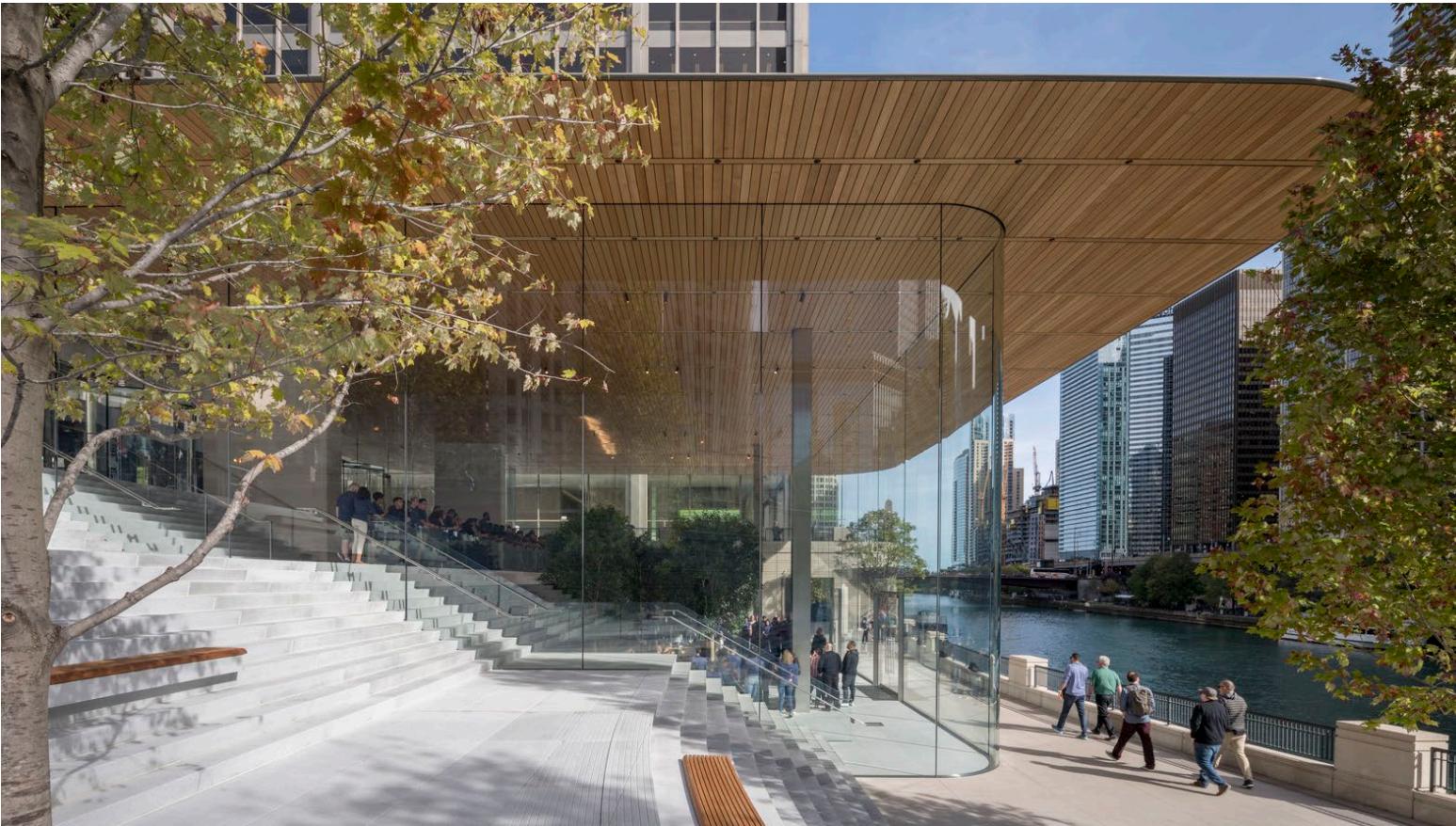


Float Glass Production Method

IEEE-Spectrum

Introduction

Structural Glass in Buildings

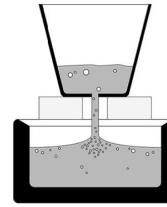
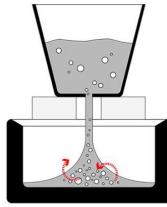
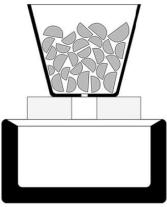


Apple Store, Michigan Avenue Chicago

Design by Foster + Partners, developed by EOC engineers

Introduction

Production Method | Kiln Casting



Introduction

Cast Glass | Potential



Glass Dresses

Artist: Karen La Monte

Introduction

Cast Glass | Possibilities

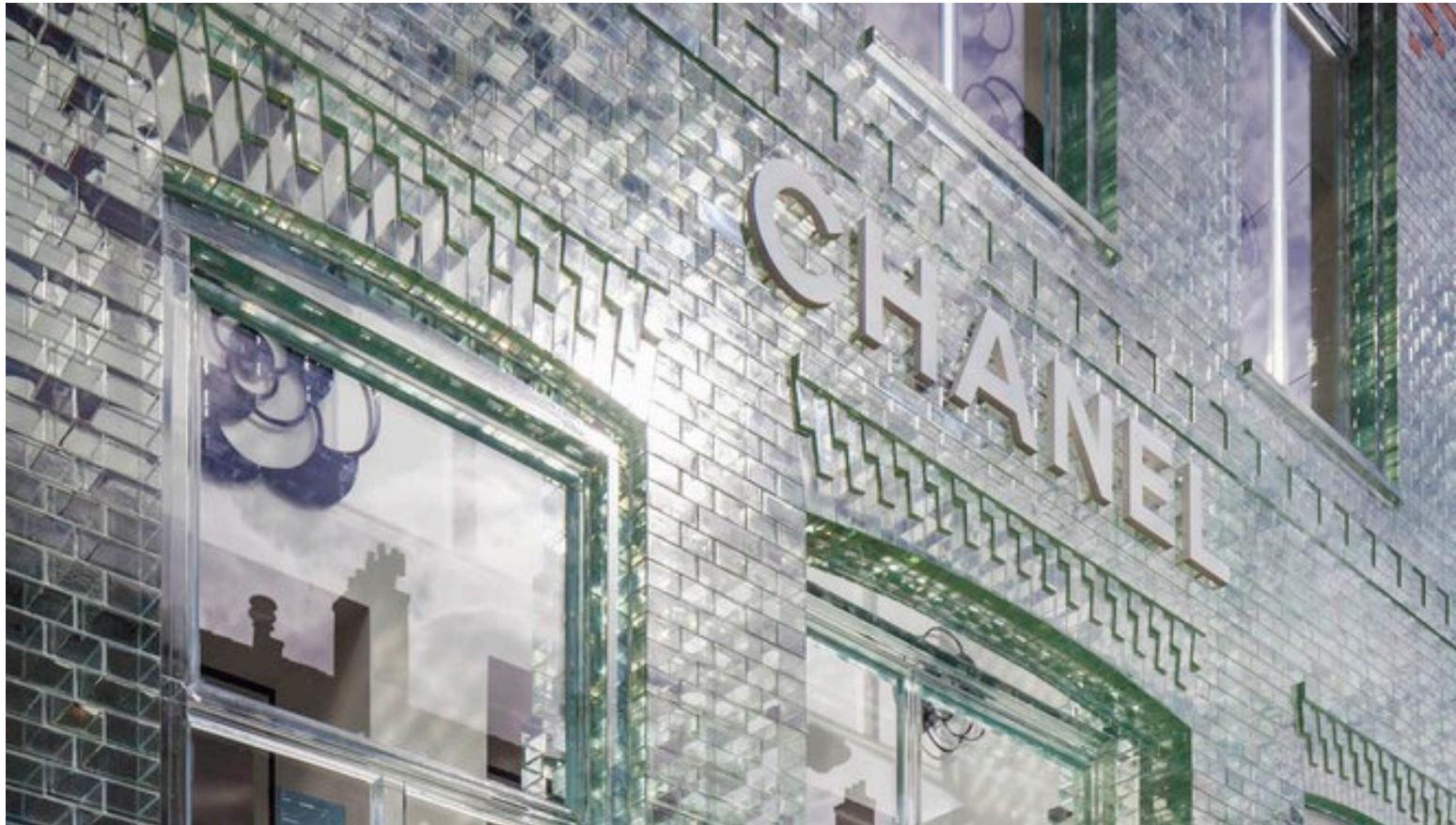


Re3 Glass: new generation of Recyclable and Reusable cast glass components

Research from F. Oikonomopoulou and T Bristogianni

Introduction

Cast Glass in Buildings

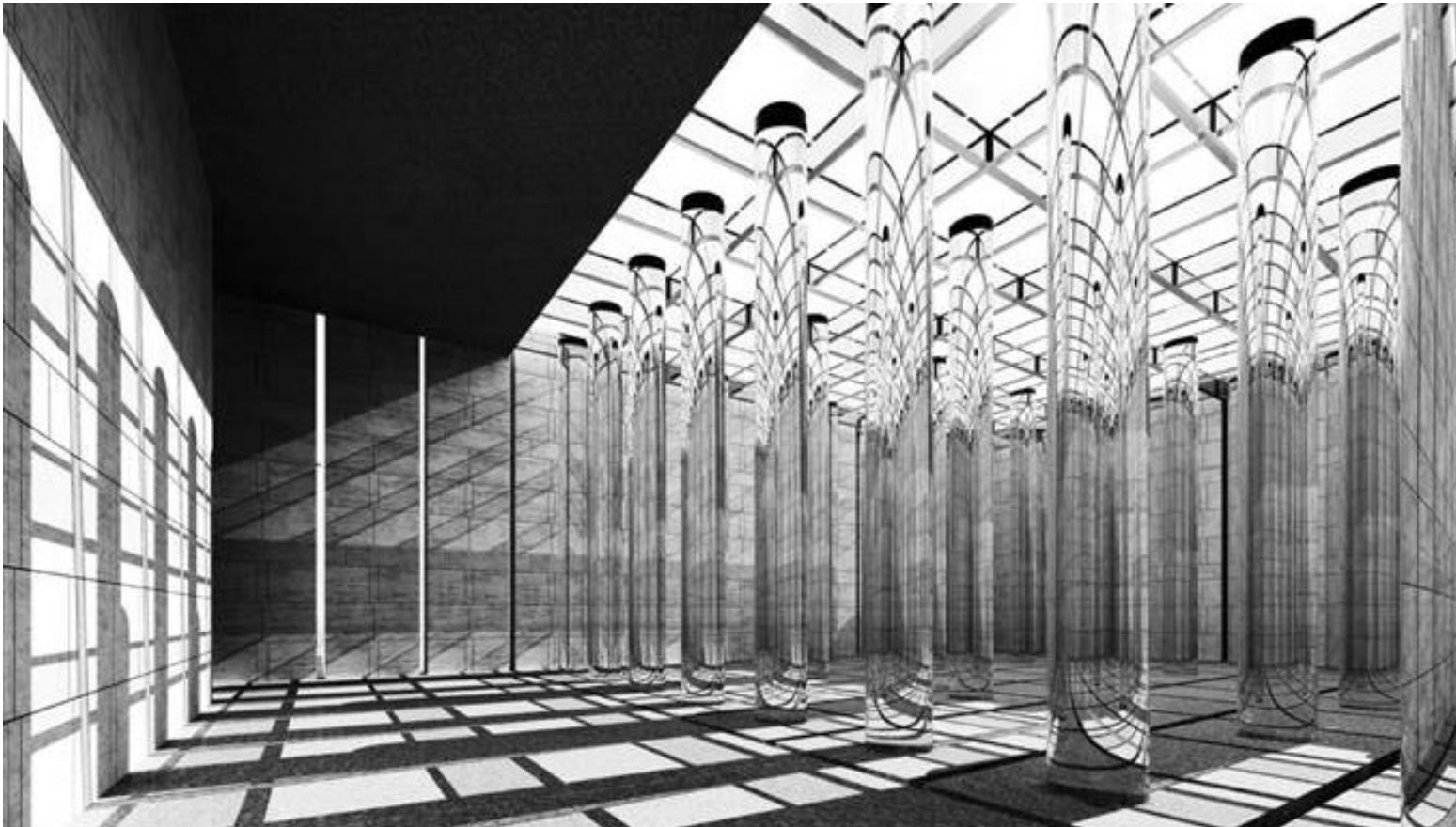


Crysal Houses Façade, Amsterdam

Design: MVRDV Developed by TU Delft Glass & Transparency group

Introduction

Cast Glass | Constraints

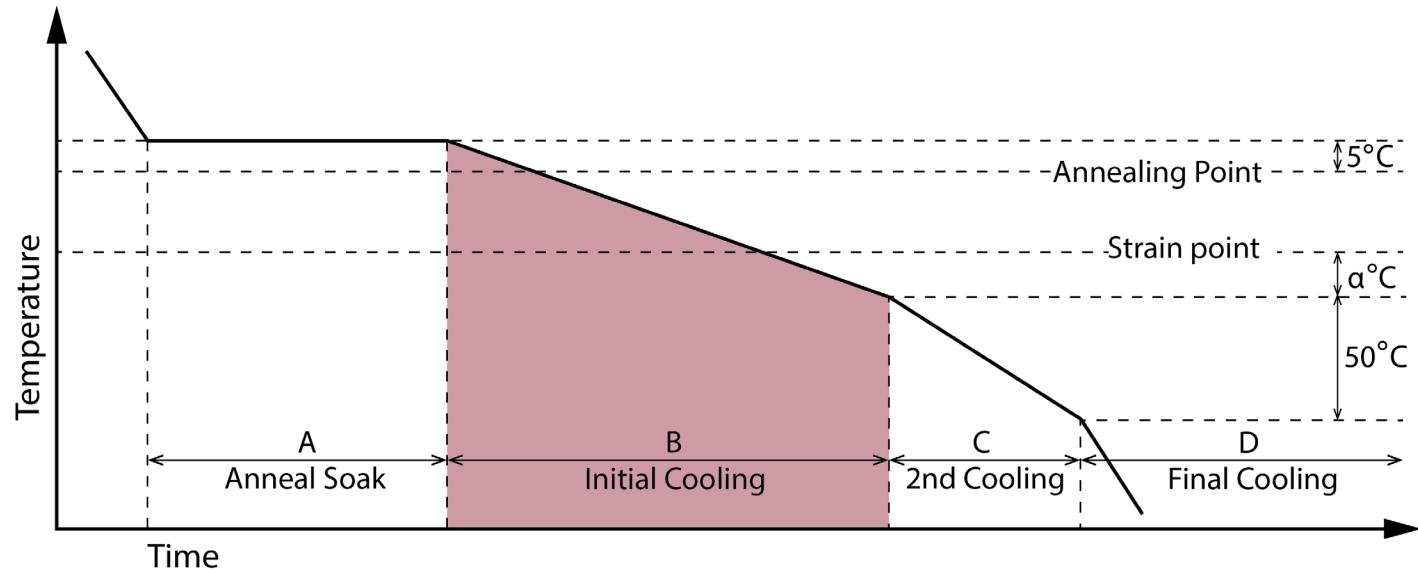


Drawing of Danteum

Giuseppe Terragni, 1939

Introduction

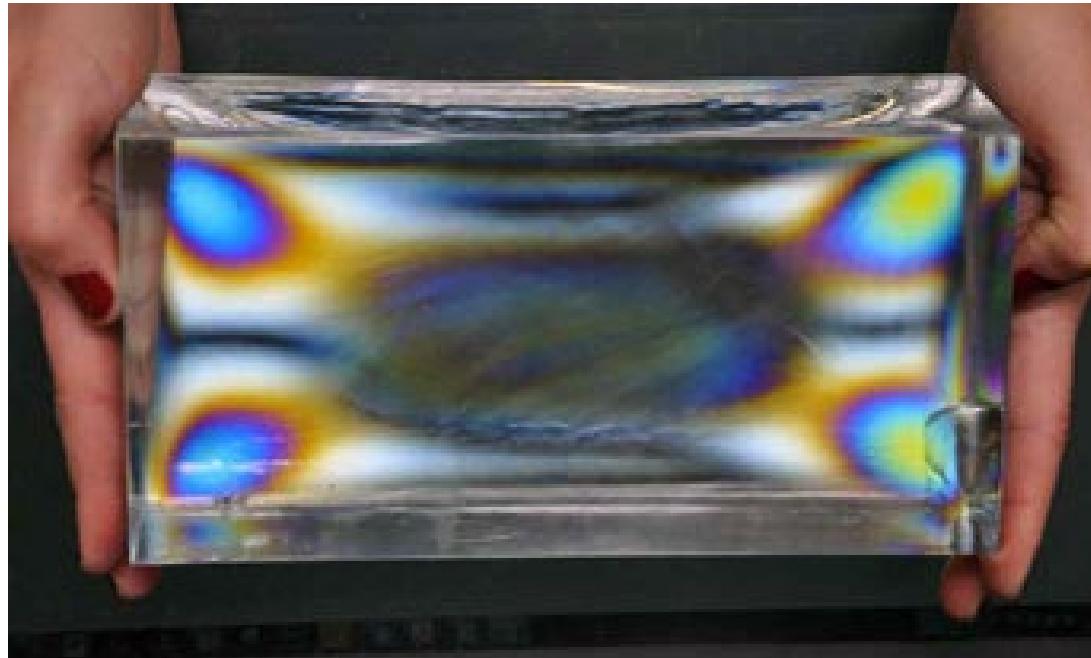
Cast Glass | annealing process



Annealing Process

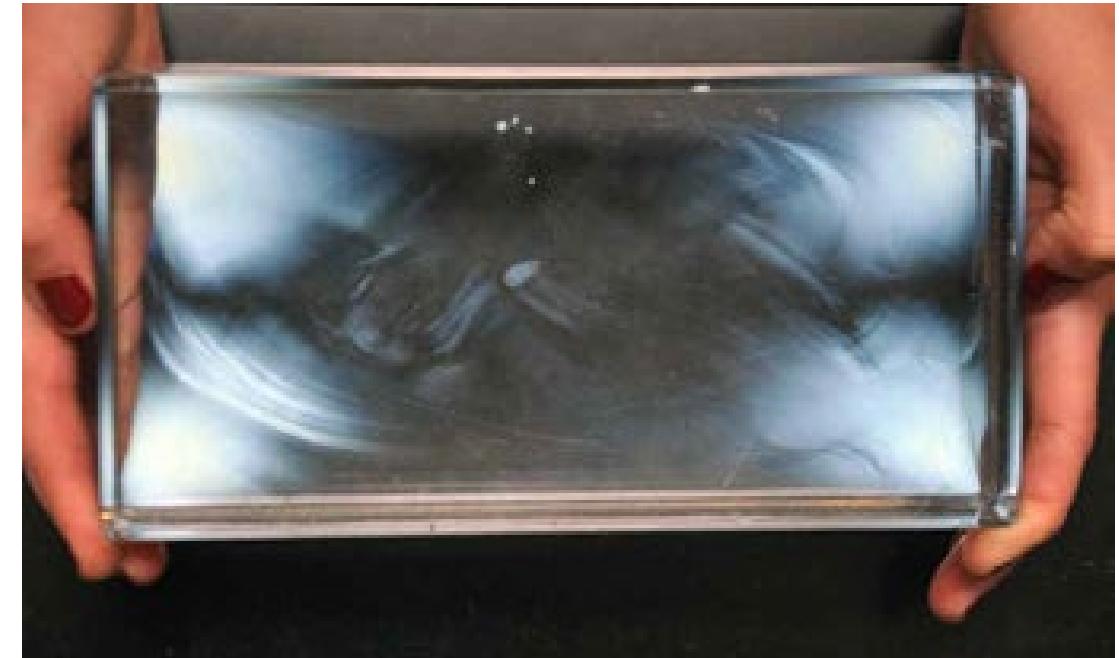
From: F. Oikonomopoulou (2019)

Cast glass | Annealing Process



Glass Brick with residual stresses shown with Polarization Test

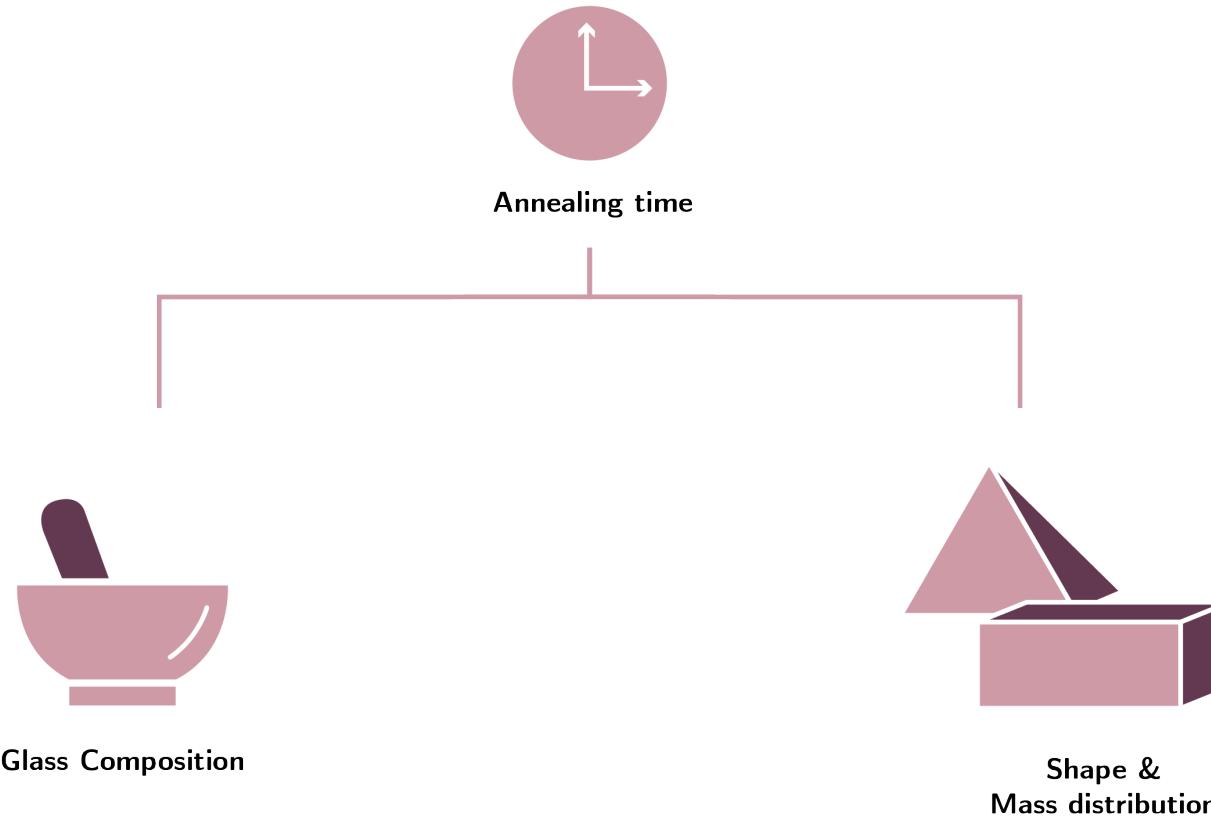
Research from F. Oikonomopoulou



Glass Brick without residual stresses shown with Polarization Test

Research from F. Oikonomopoulou

Cast glass | Annealing process



Cast Glass | Constraints

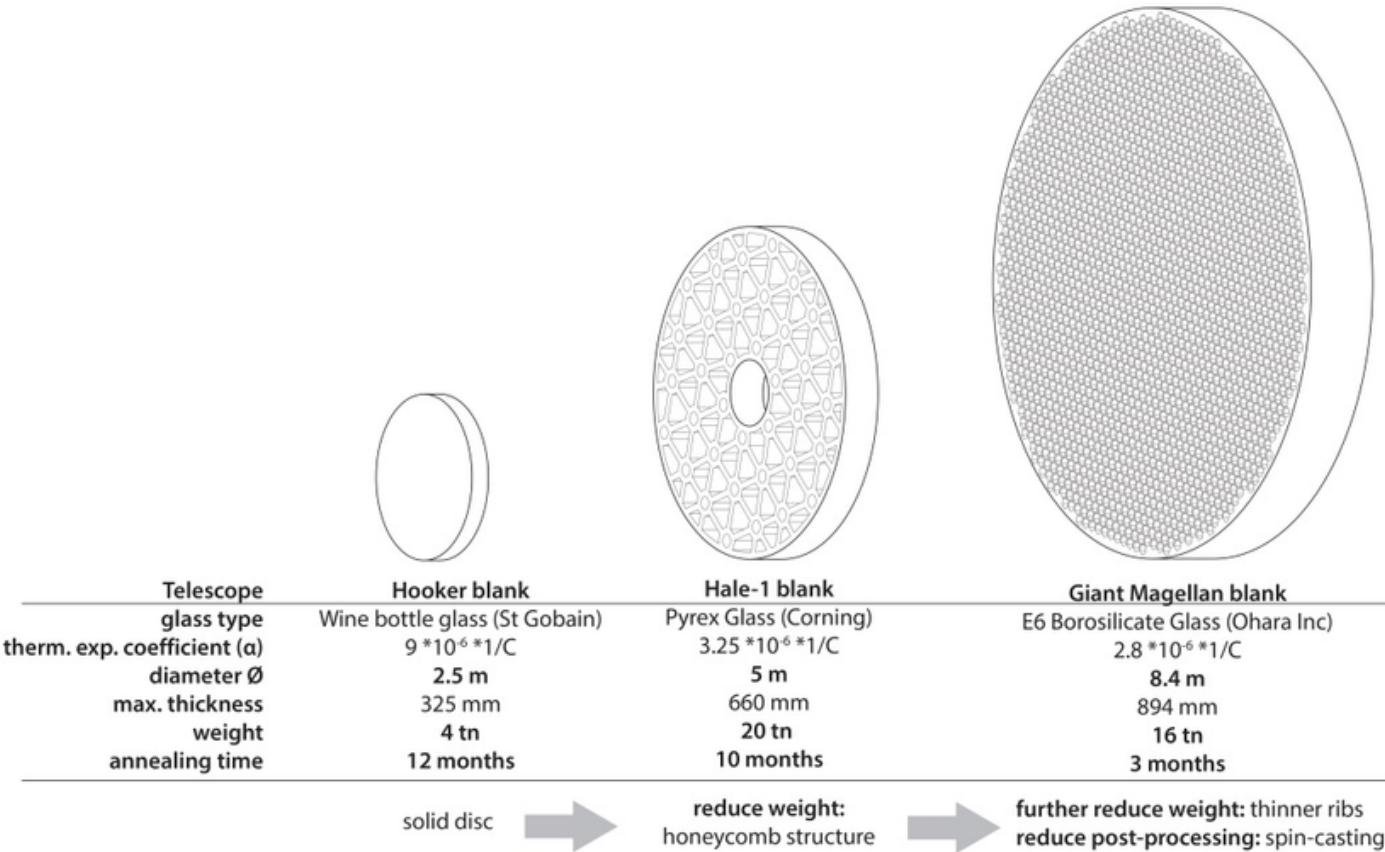


Opposites of White

Roni Horn | size: 50,8 x 142 cm

Introduction

Cast Glass | Constraints

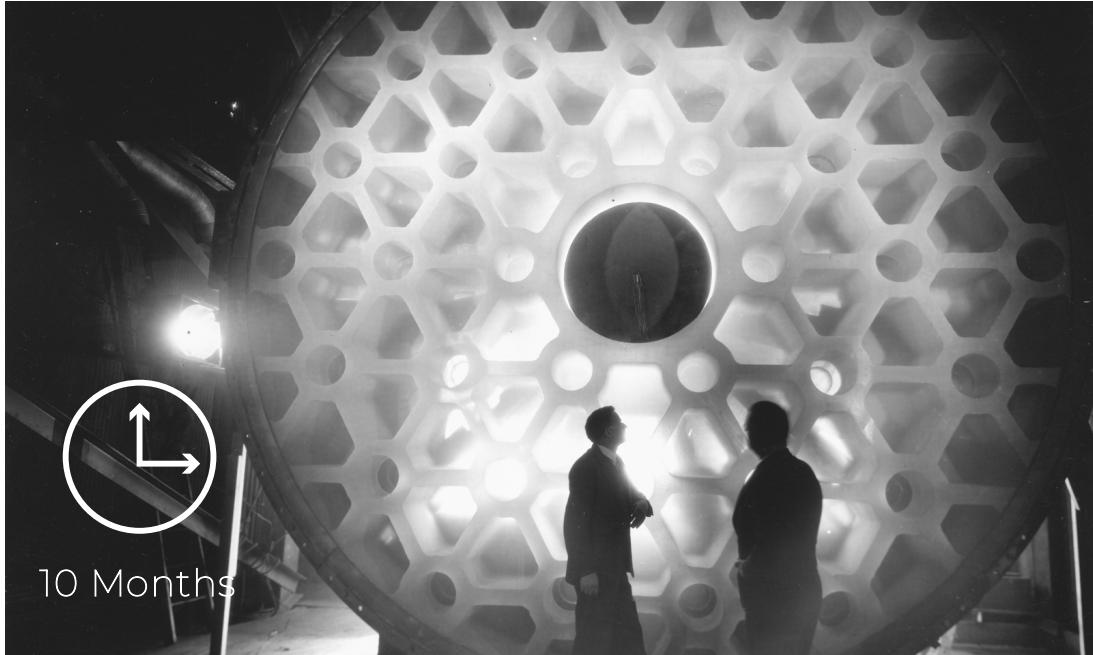


Evolution of the cast glass mirror blanks

Derived from (Oikonomopoulou 2019), based on data from (zirker 2005)

Introduction

Glass Constraints | Annealing



Hale-1 Blank



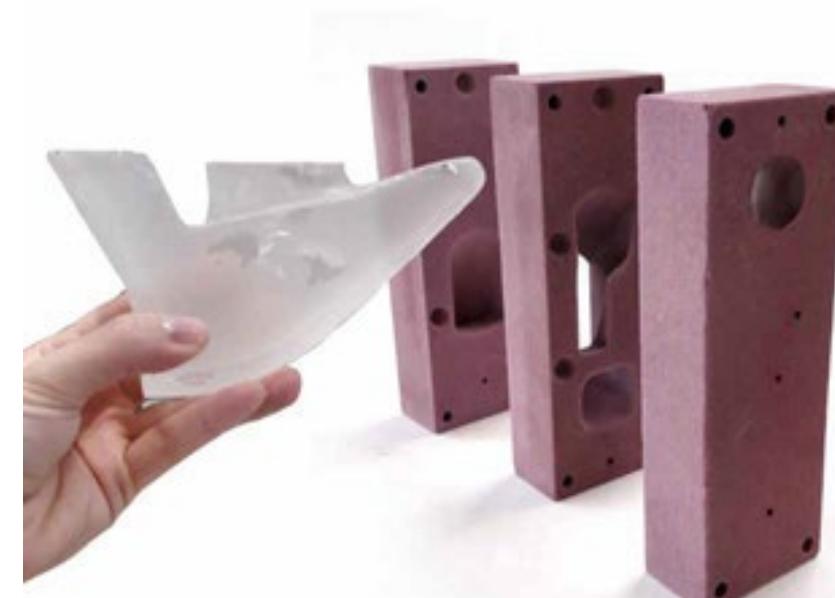
Giant Magellan Blank

Predecessors



Topologically Optimised Cast Glass Grid Shell Node

W. Damen (2019)

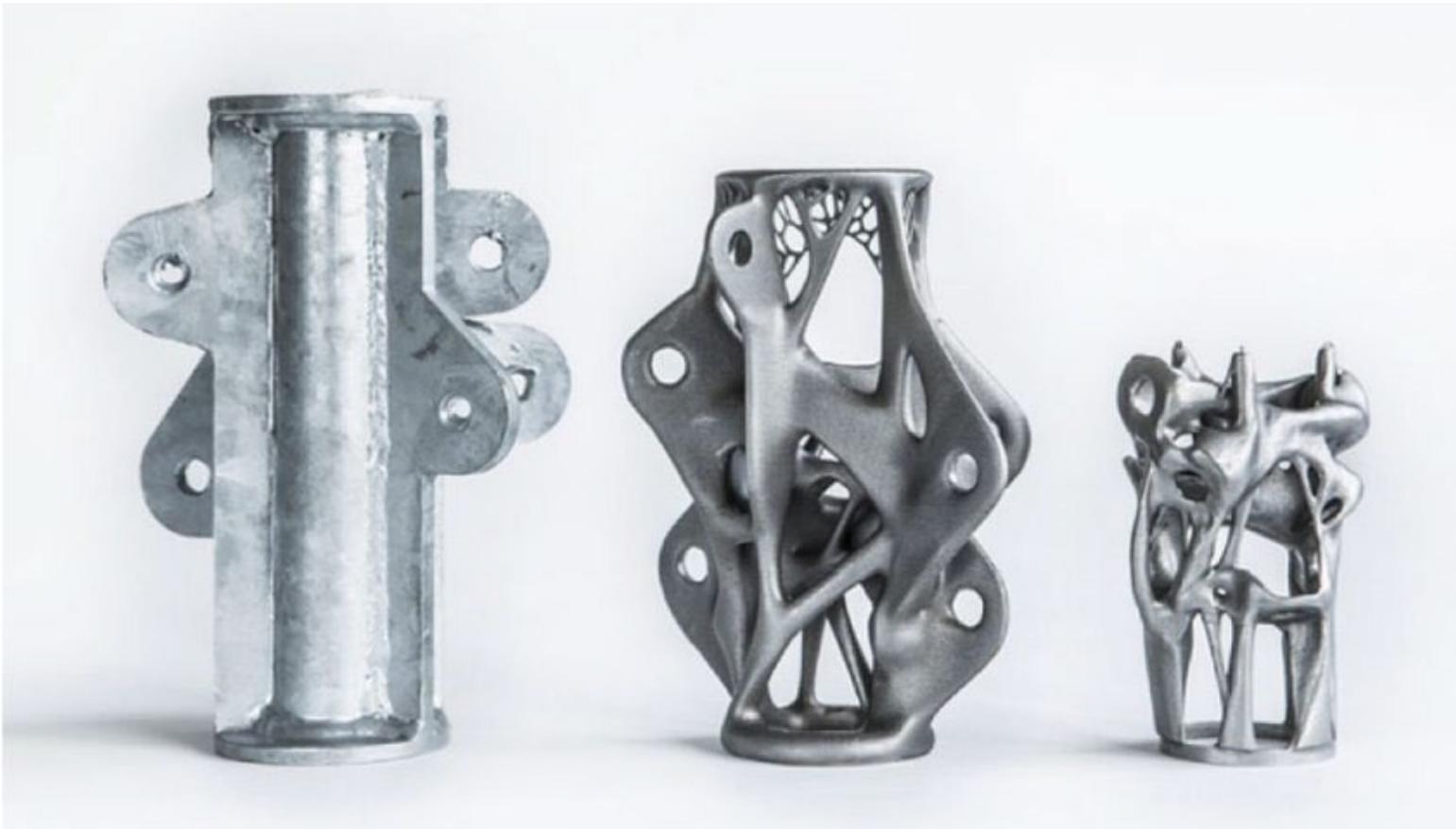


Section Topology Optimized Column

I. Bhatia (2019)

Introduction

Structural Optimization



Topologically optimized tensile node

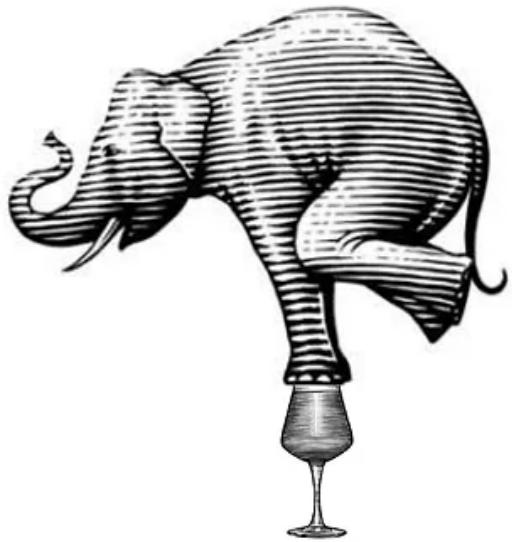
Project from ARUP

Introduction

Software limitations

Strength Glass

<



Strong in Compression

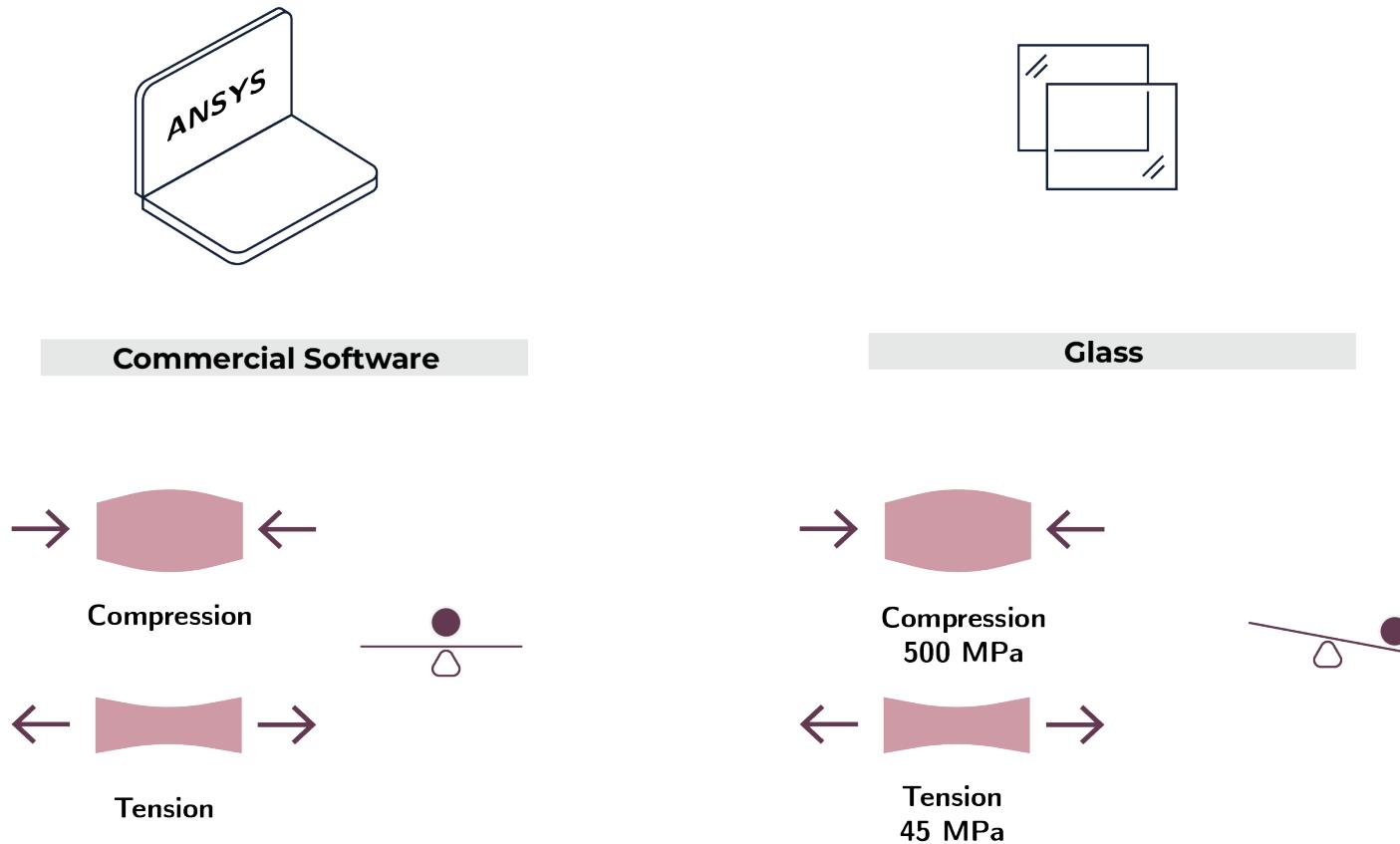


Weak in Tension

Anisotropy Glass
Steven Noble

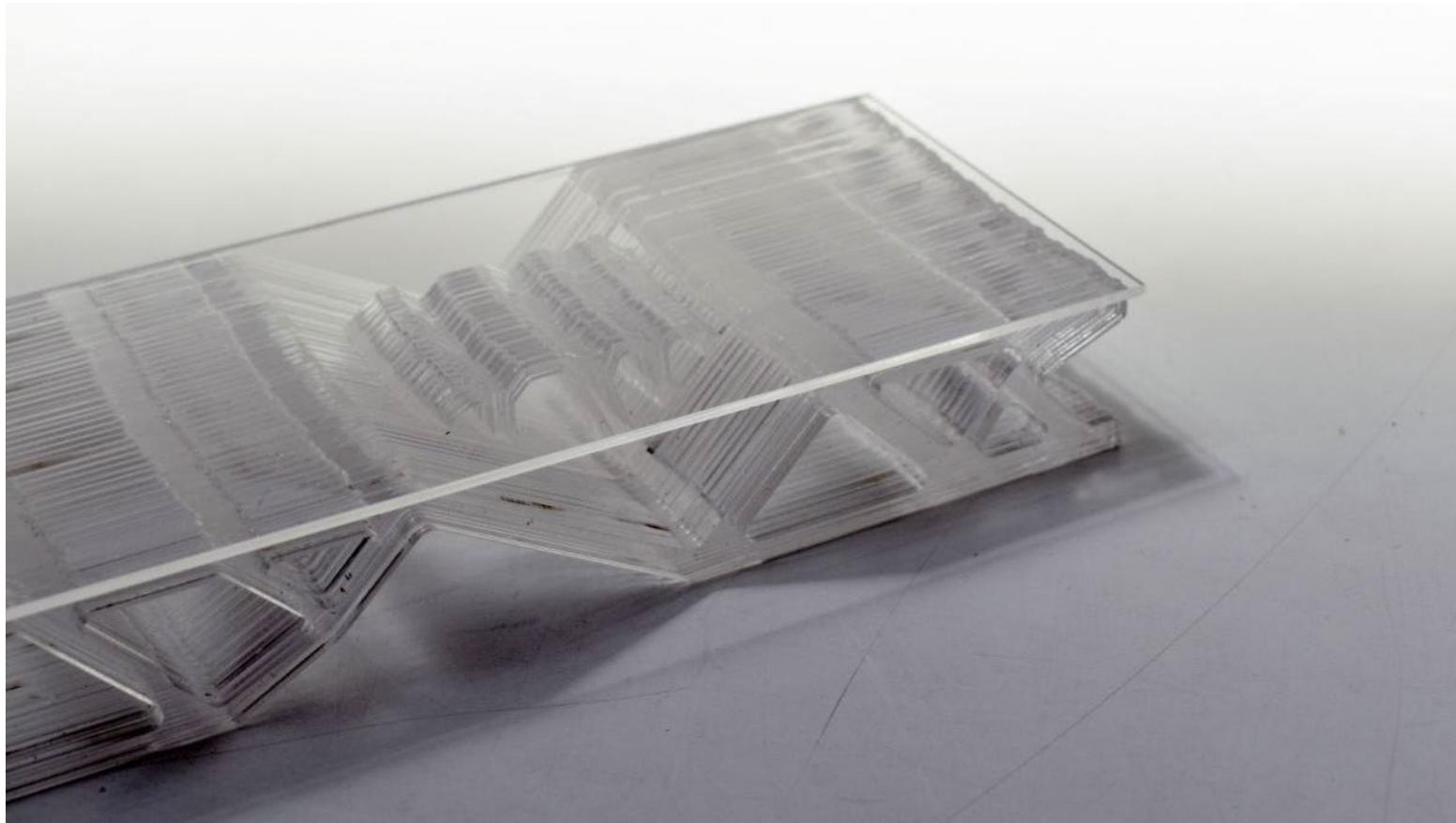
Introduction

Software Limitations



Problem Statement

Predecessors

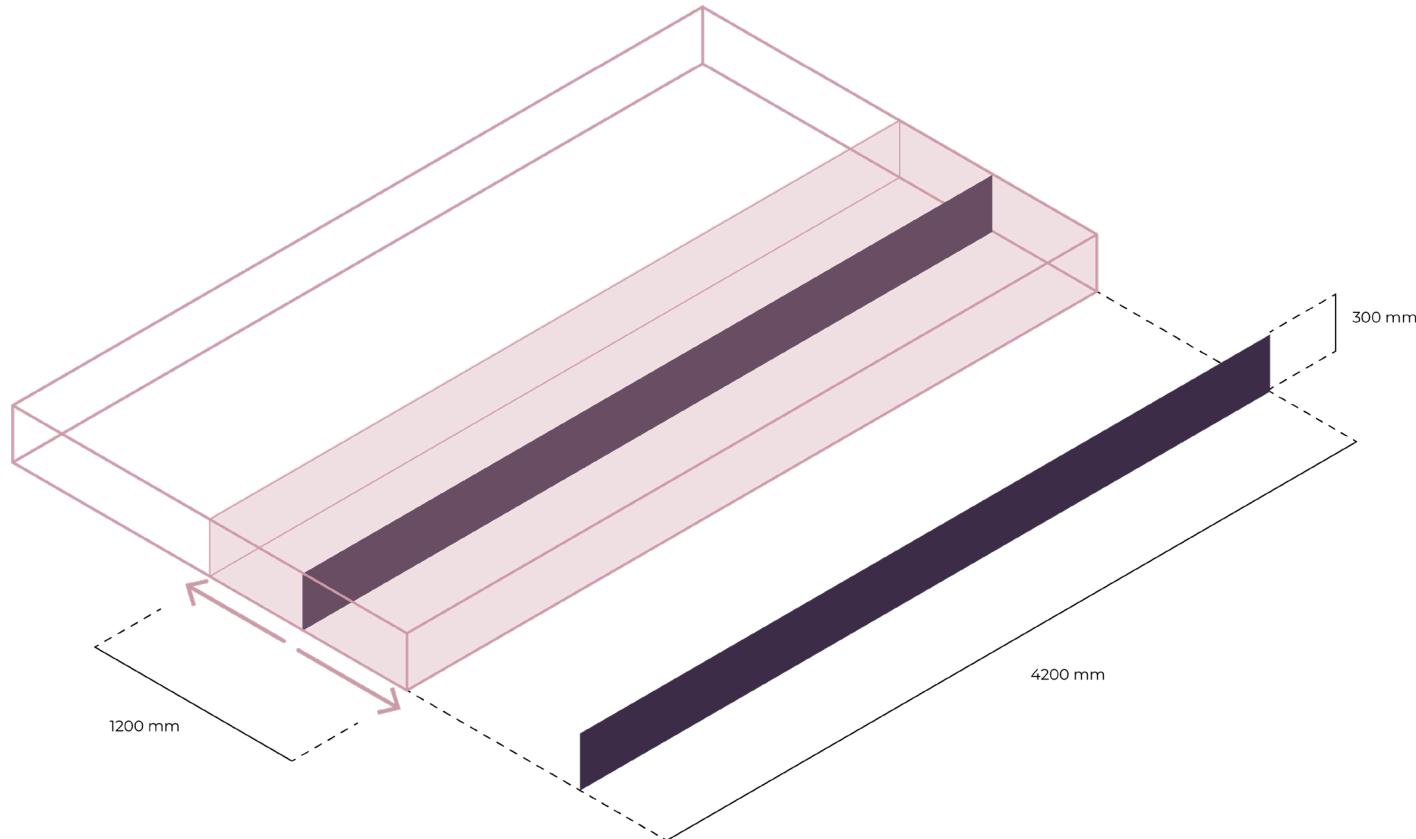


Anna Maria Koniari

"Just glass: Development of a topology optimization algorithm for a mass-optimized cast glass component" 2022

Problem Statement

Predecessors



Anna Maria Koniari

"Just glass: Development of a topology optimization algorithm for a mass-optimized cast glass component" 2022

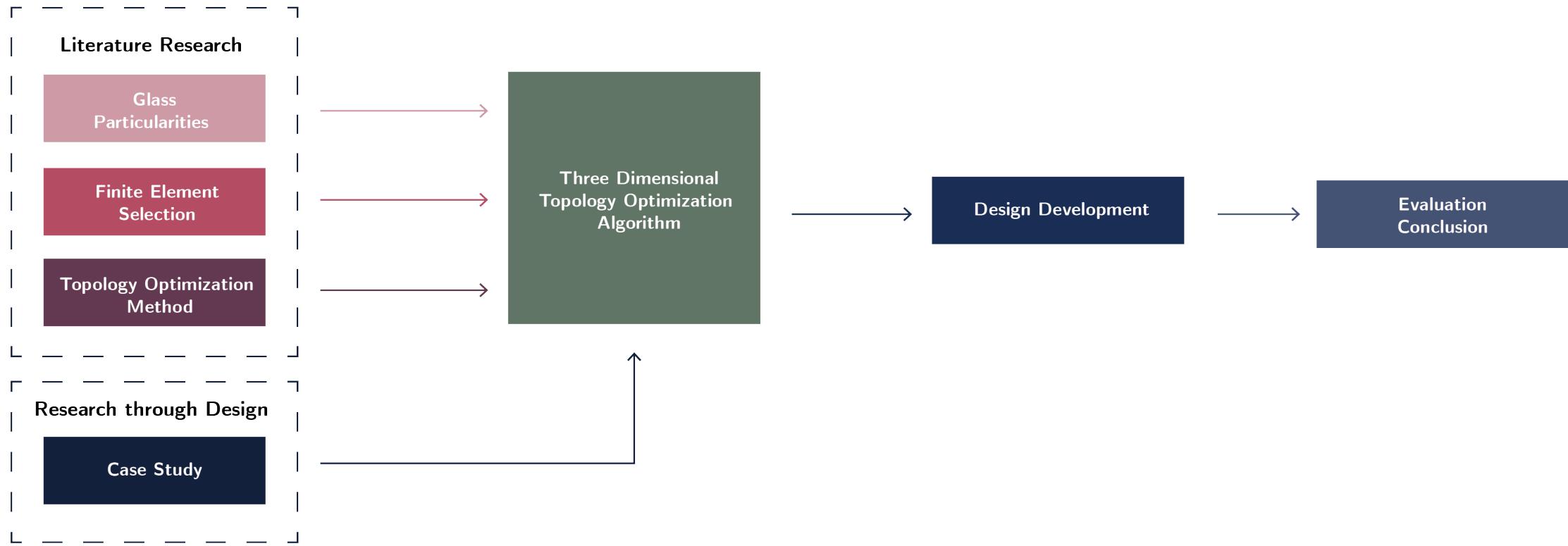
Problem Statement

Research question

*What are the main aspects and limitations of a *three-dimensional* topology optimization for the design of a *massive cast glass structure*?*

Problem Statement

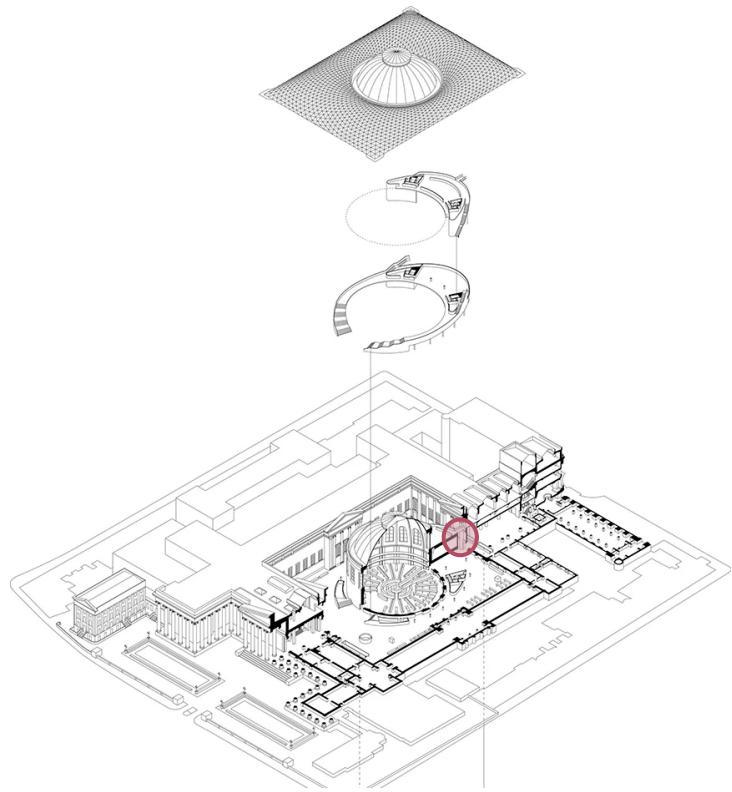
Methodology



Problem Statement

Case Study Introduction

Case Study



Great Court British Museum

Picture from A.M Koniaris

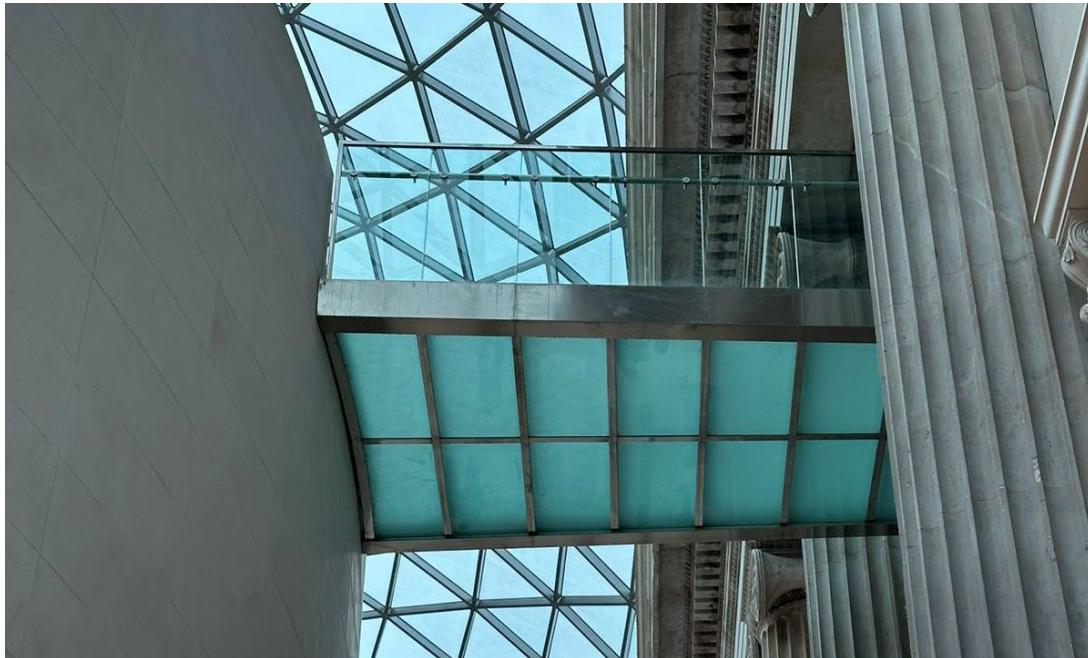


Glass Bridge British Museum

Picture from A.M Koniaris

Introduction Case Study

Case Study



Glass Bridge British Museum

Picture: Daniela Martinez

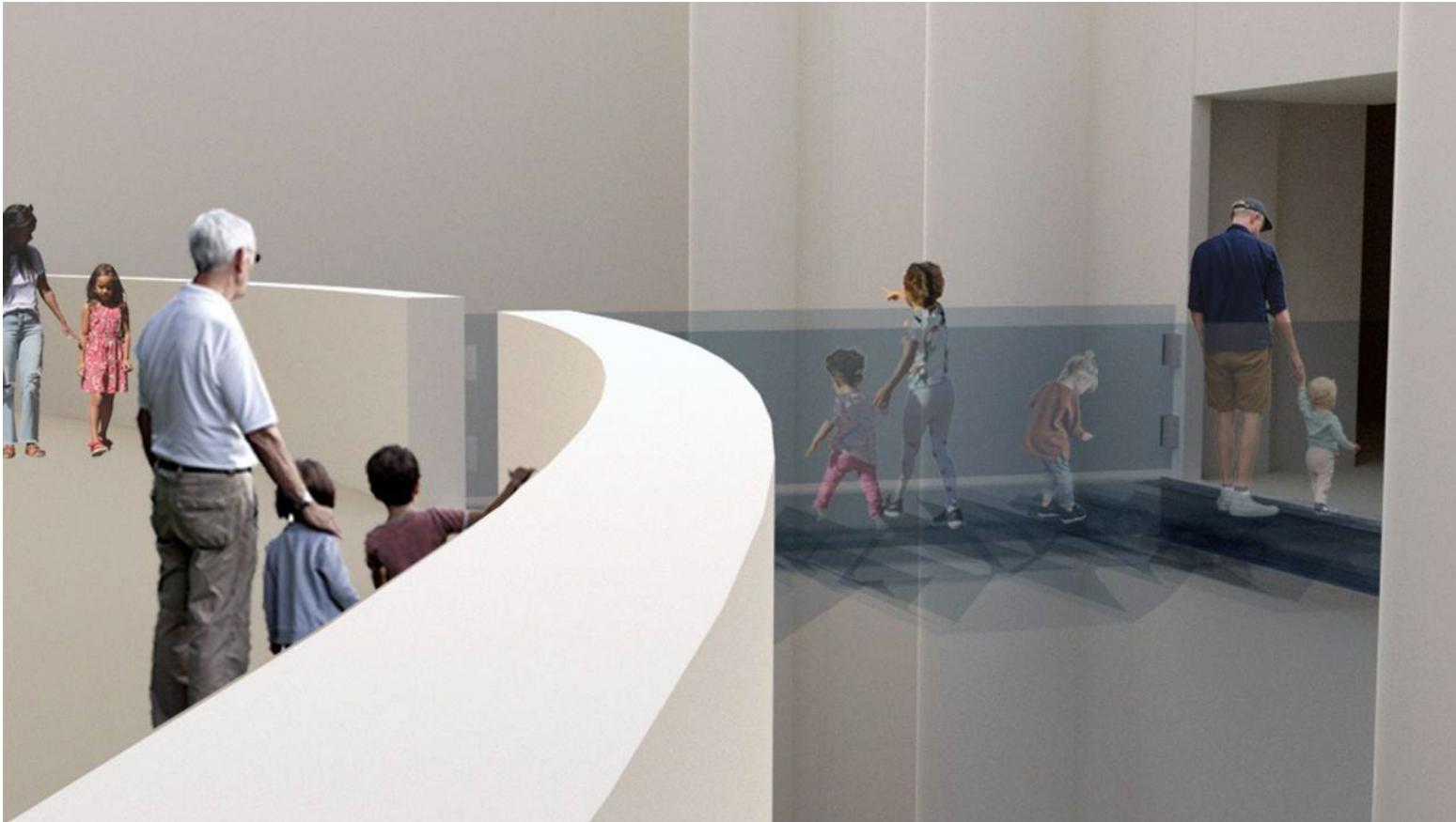


Glass Bridge British Museum

Picture: Daniela Martinez

Case Study Introduction

Redesign 2D Algorithm

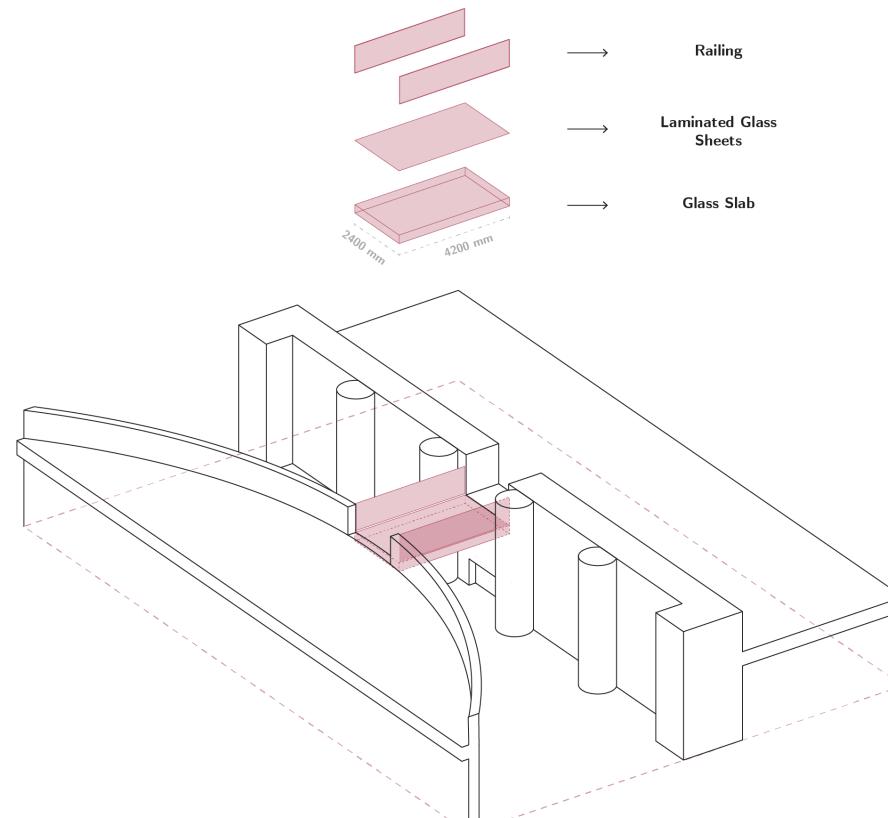


Anna Maria Koniari

"Just glass: Development of a topology optimization algorithm for a mass-optimized cast glass component" 2022

Case study Introduction

Case Study



Overview Elements Design

Introduction Case Study

Glass

Glass
Shaping freedom

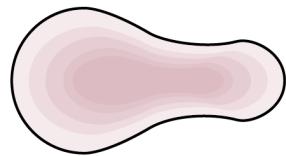
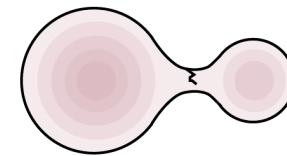
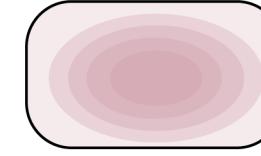
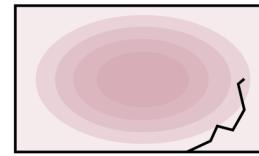
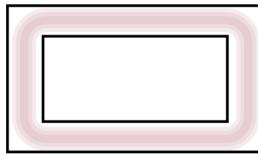
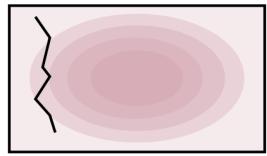


Glass

P5 | Eva Schoenmaker | 10.11.2023

36

Glass Design Criteria



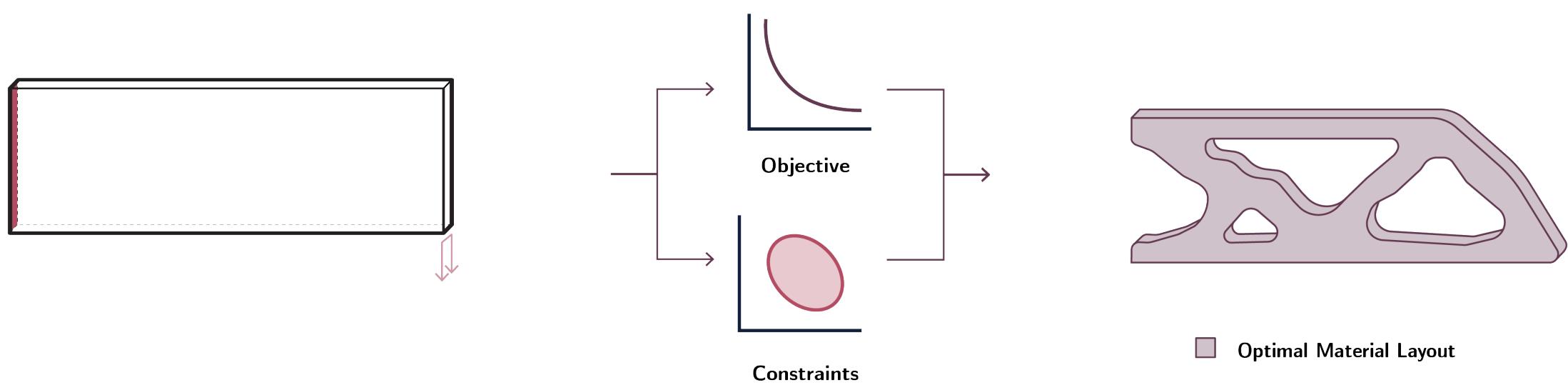
Avoid Large Cross Sections

Avoid Sharp Corners

Avoid Large Differences Size

Topology Optimization

Topology Optimization



Topology Optimization

Topology Optimization | Architecture

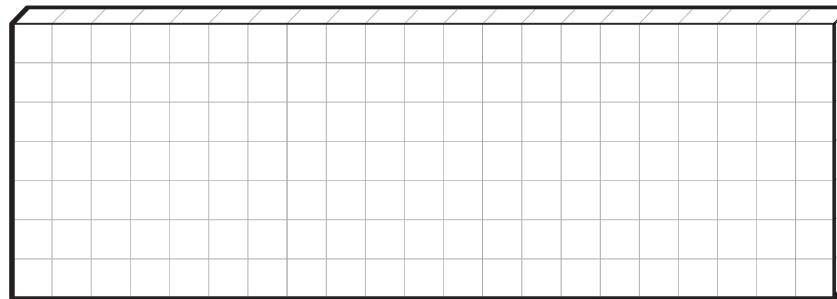


Qatar National Convention Centre

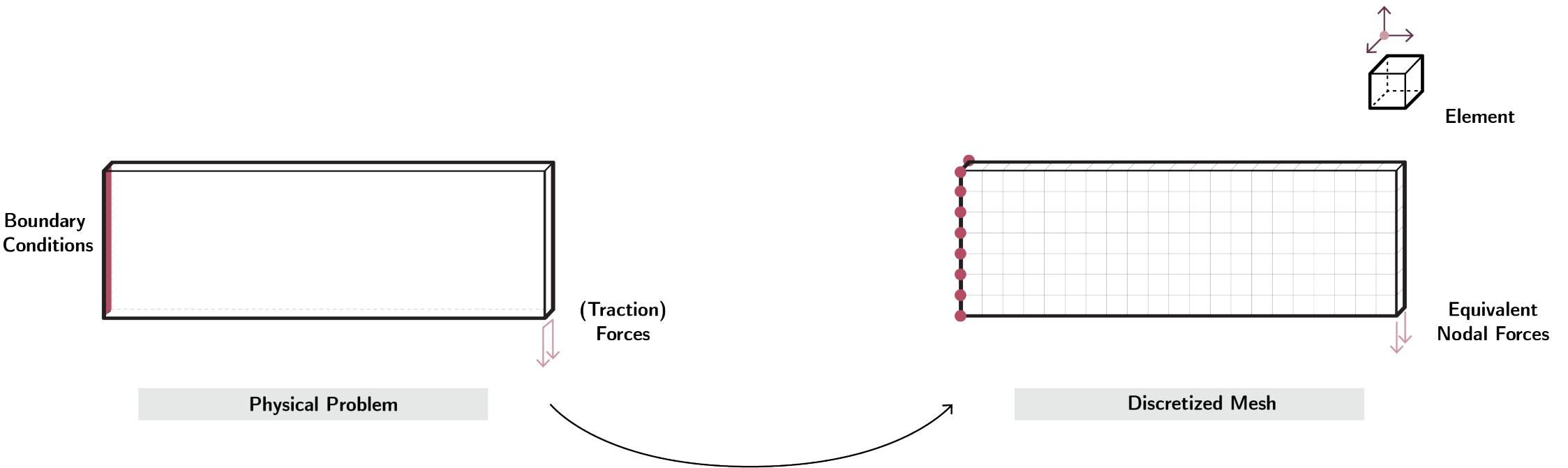
Arata Isozaki & Andrea Maffei Associati

Topology Optimization

Topology Optimization | SIMP

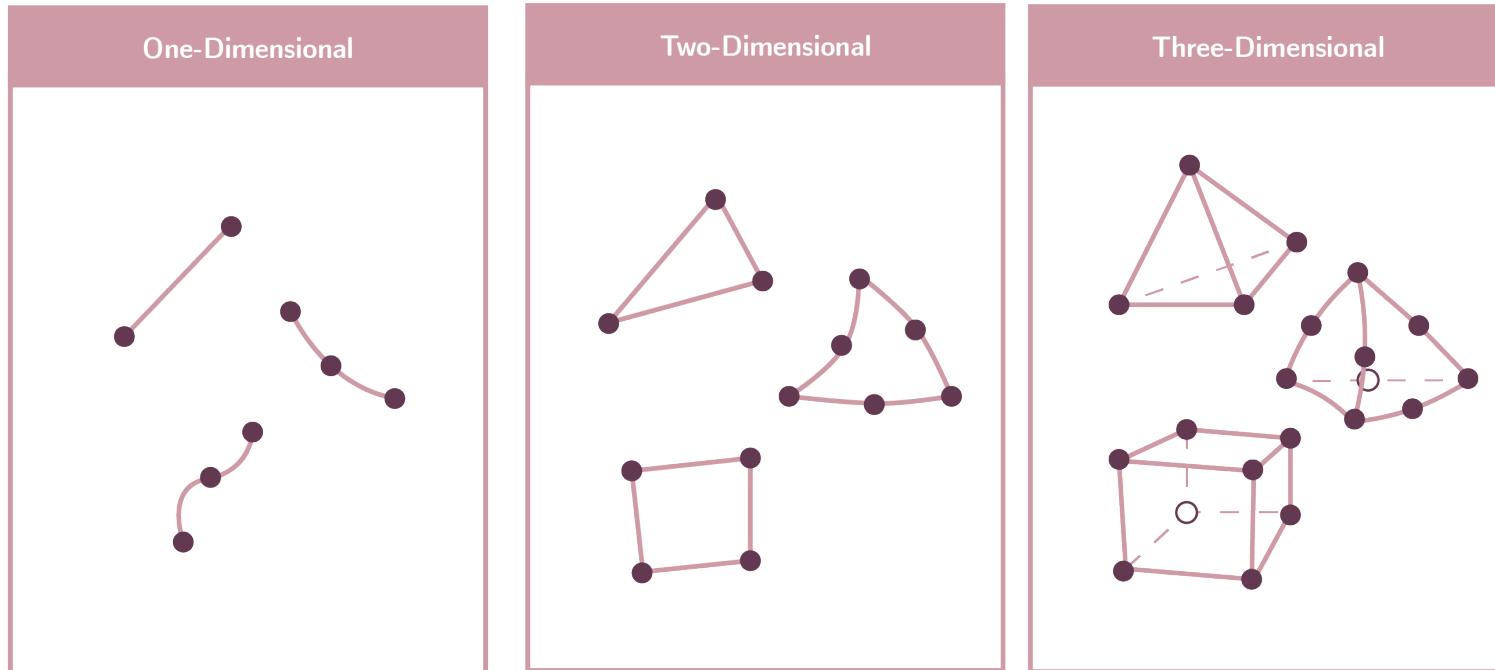


Finite Element Analysis

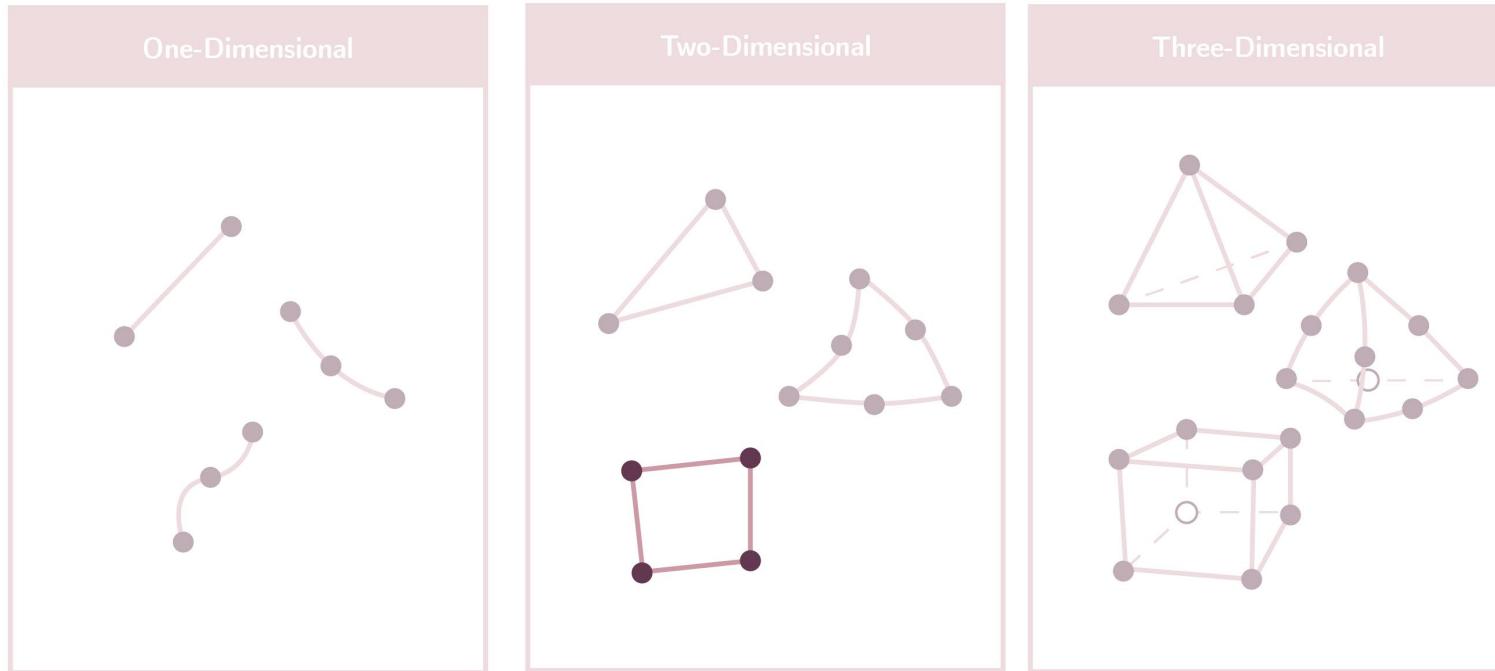


Topology optimization

Finite Elements

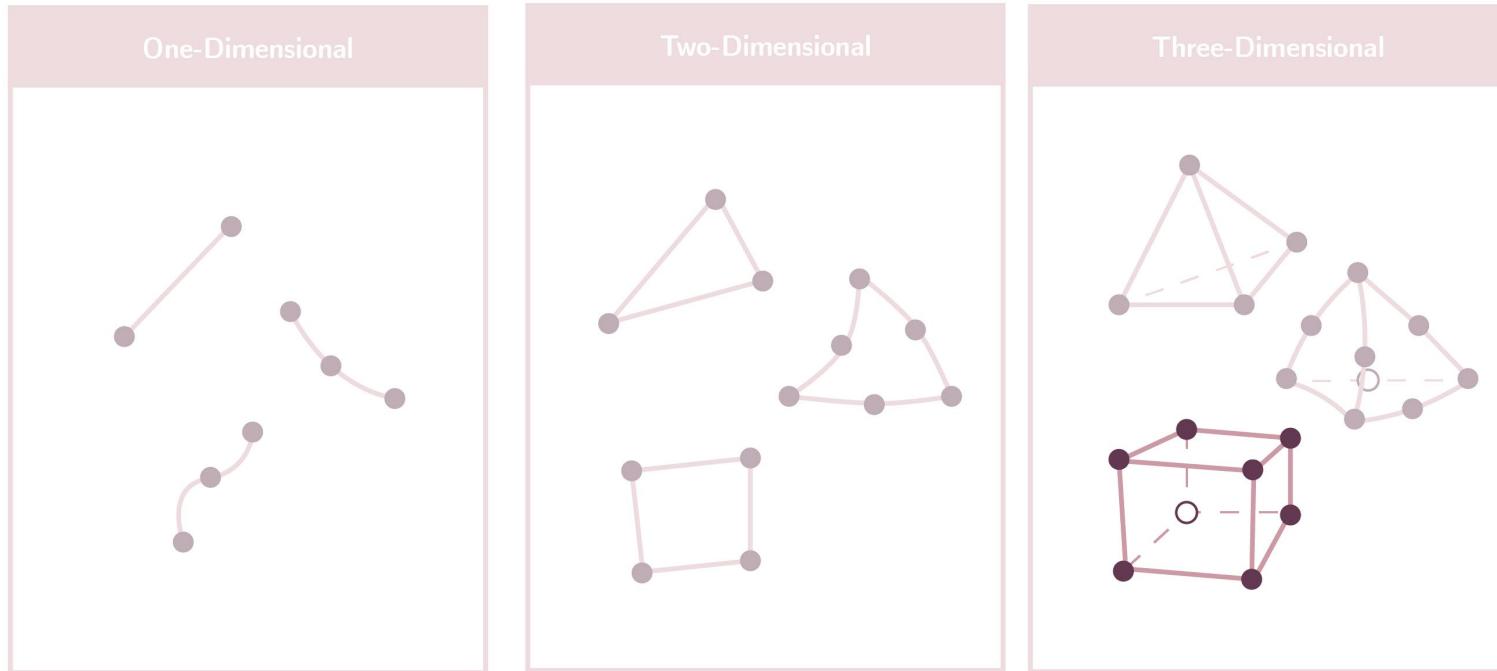


Finite Elements



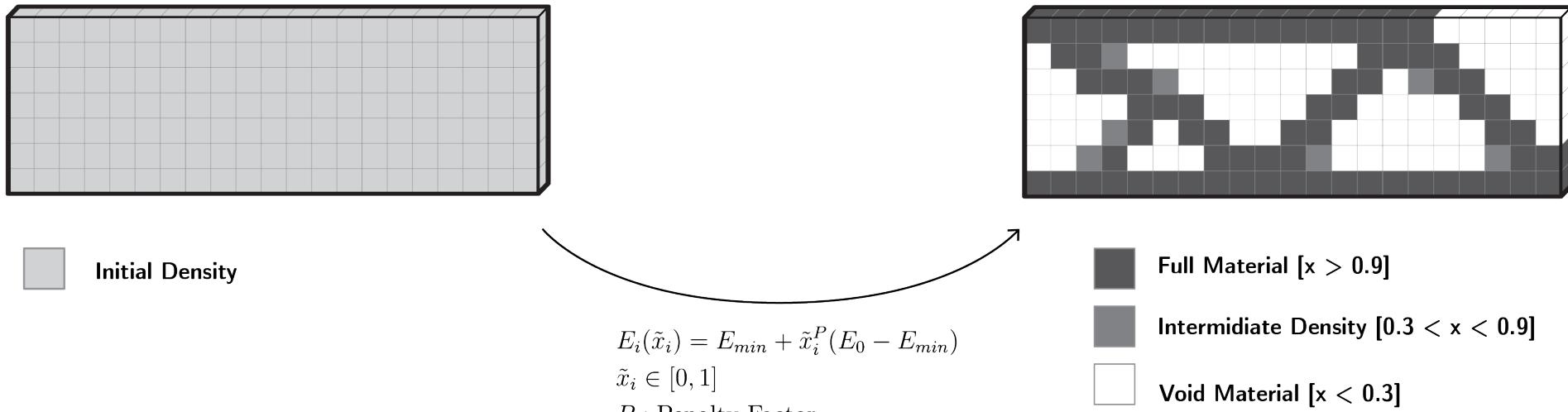
Topology Optimization

Finite Elements



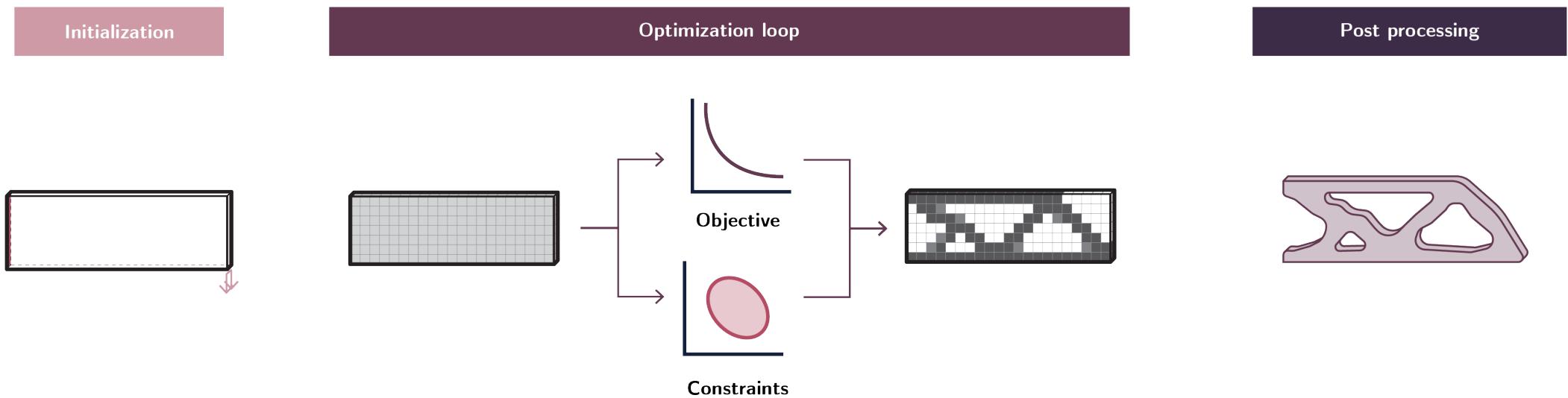
Topology Optimization

Topology Optimization | SIMP

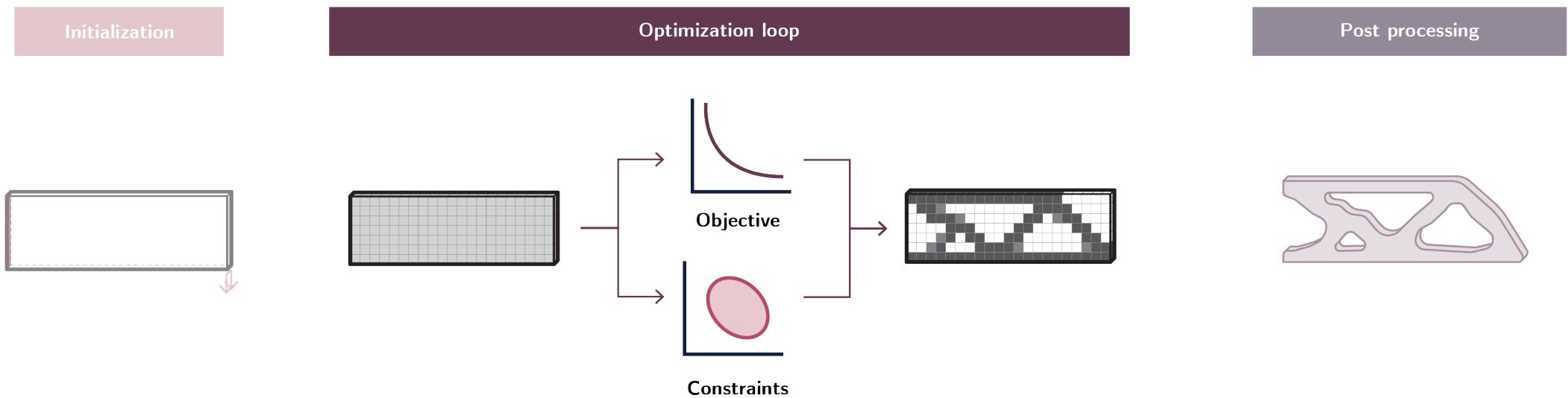


Algorithm Development

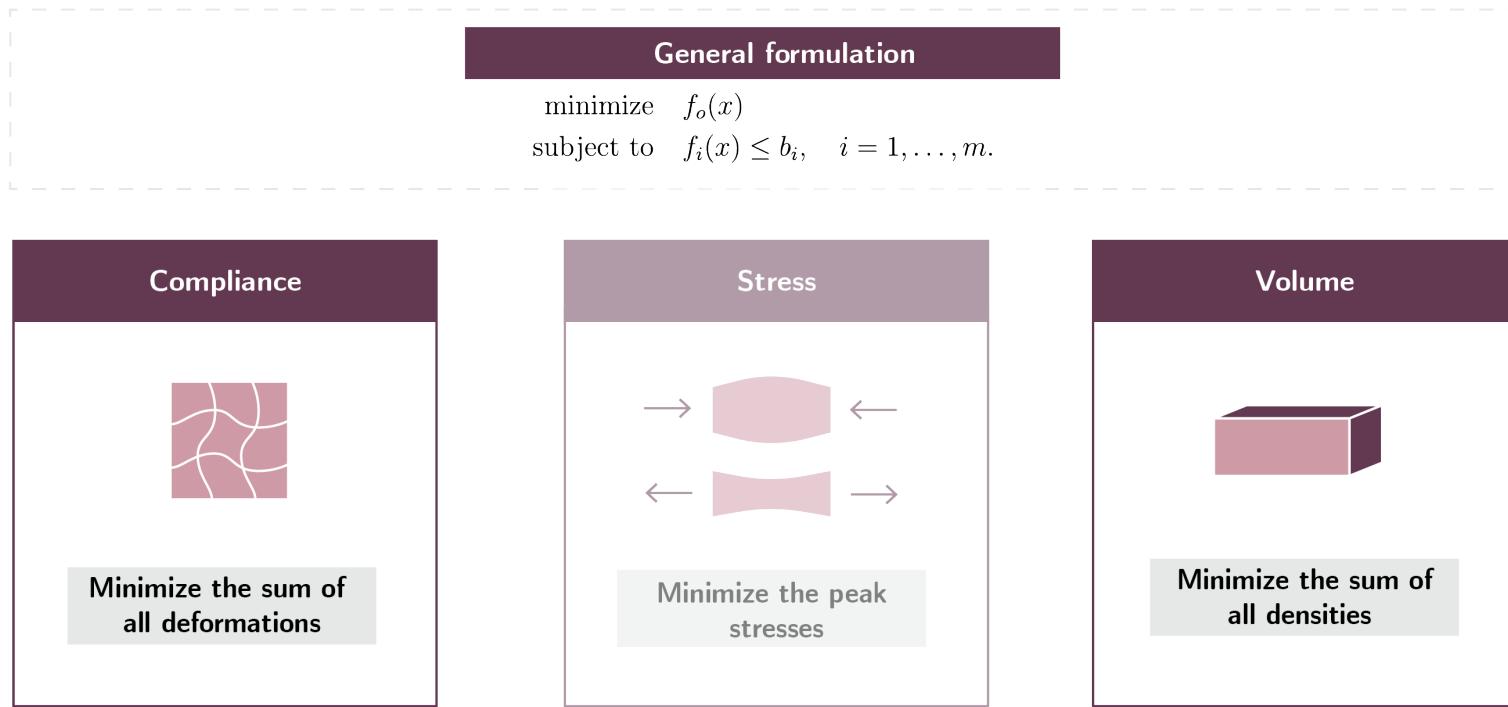
Phases Algorithm



Phases Algorithm



Objectives



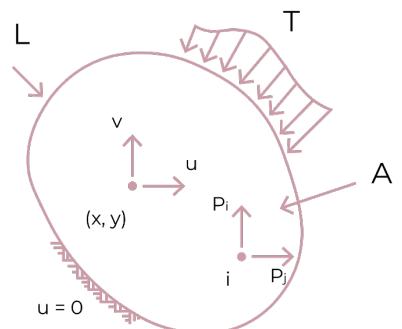
Constraints

SIMP Related Constraints		Basic TO Constraints		Cast Glass Constraints		
Equilibrium	Filtering	Compliance	Volume	Principal Stress	Annealing	Deflection
✓	✓		✓	✓	✓	✓
✓	✓	✓		✓	✓	✓

Constraints

SIMP related constraint

	Compliance	Volume
Equilibrium	✓	✓
Filtering		
Compliance		
Volume		
Principal Stress		
Annealing		
Deflection		

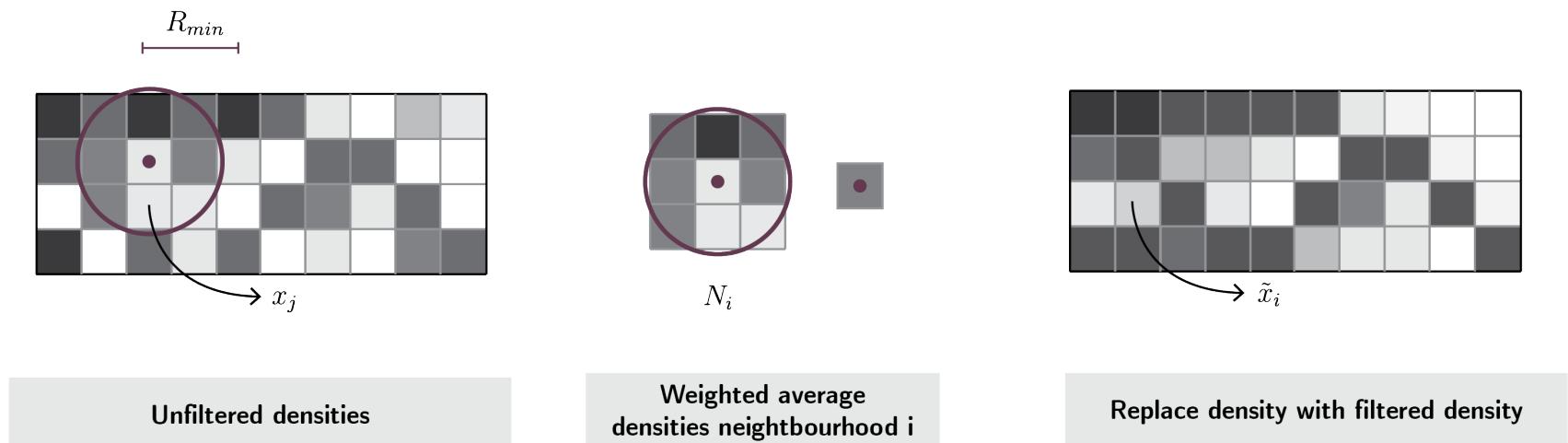


$$\Pi = \frac{1}{2} \int_V \sigma^T \varepsilon dV - \int_V u^T f dV - \int_s u^T T dS - \sum_i u_i^T P_i$$

Constraints

SIMP related constraint

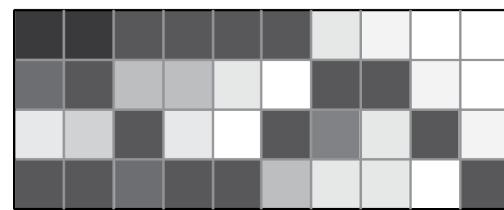
	Compliance	Volume
Equilibrium		
Filtering	✓	✓
Compliance		
Volume		
Principal Stress		
Annealing		
Deflection		



Constraints

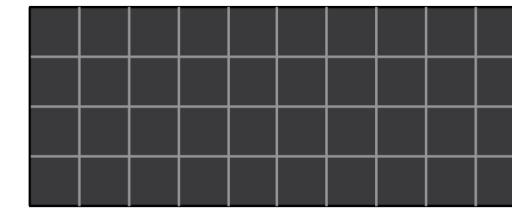
Basic TO constraint

	Compliance	Volume
Equilibrium		
Filtering		
Compliance		✓
Volume		
Principal Stress		
Annealing		
Deflection		



$$c(\tilde{x})$$

Compliance of current iteration



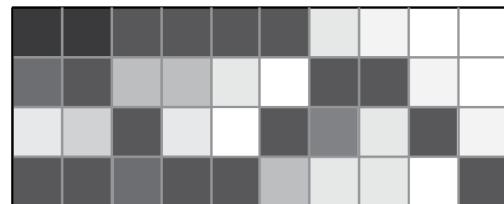
$$c_0$$

Imposed compliance constraint as
percentage of initial compliance ($c_0 a_c$)

Constraints

Basic TO constraint

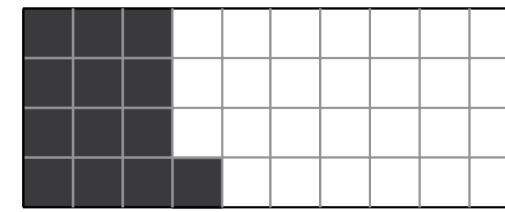
	Compliance	Volume
Equilibrium	grey	grey
Filtering	grey	grey
Compliance	grey	grey
Volume	grey	grey
	✓	
Principal Stress	grey	grey
Annealing	grey	grey
Deflection	grey	grey



$$\sum_{e=1}^N \tilde{x}_e v$$

Volume of current iteration

<



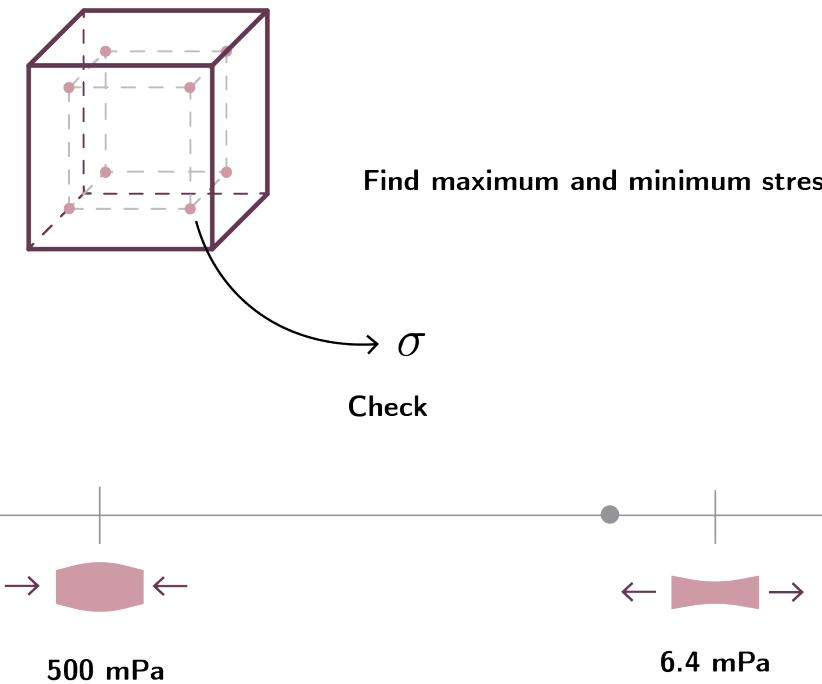
$$\bar{v}$$

Imposed volume constraint as
percentage of total volume (\bar{v})

Constraints

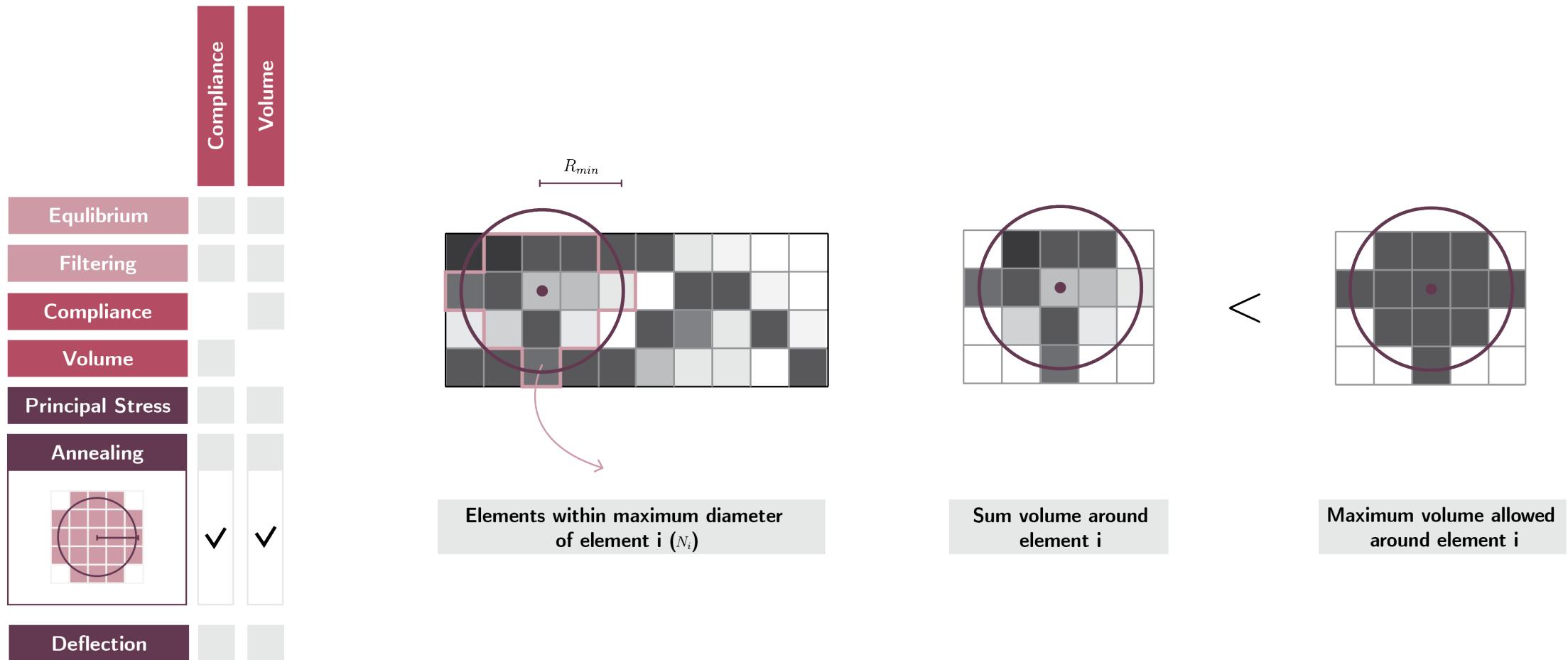
Glass related constraint

	Compliance	Volume
Equilibrium		
Filtering		
Compliance		
Volume		
Principal Stress		
Annealing		
Deflection		



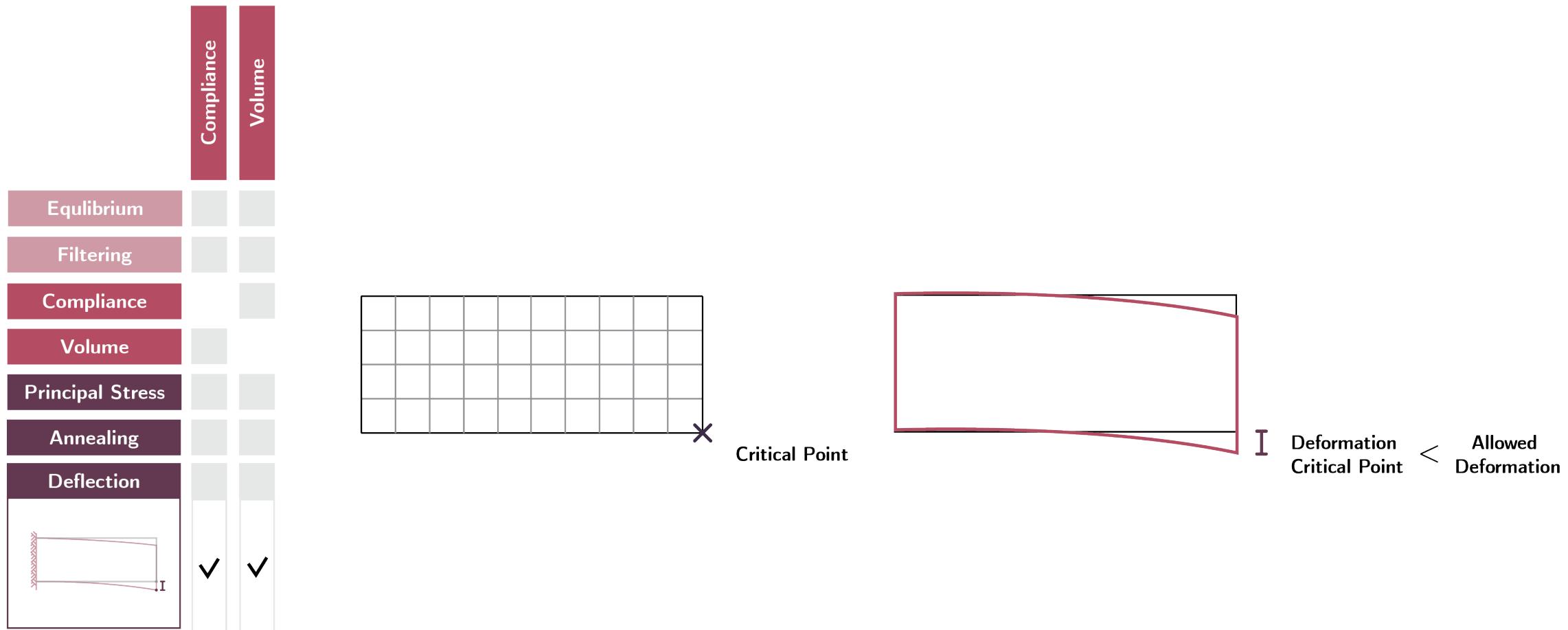
Constraints

Glass related constraint

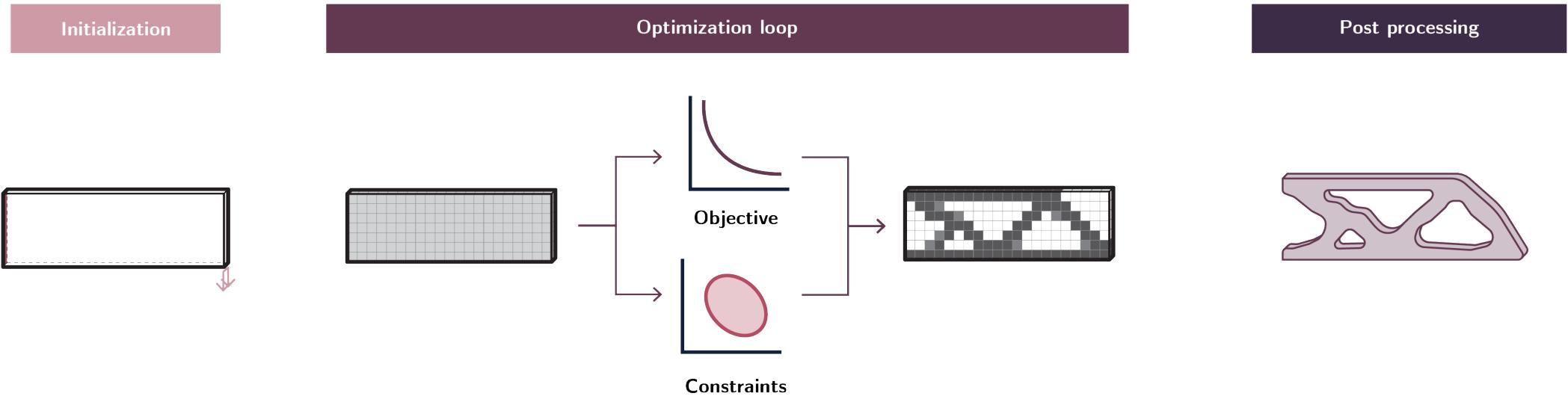


Constraints

Glass related constraint



Algorithm Performance

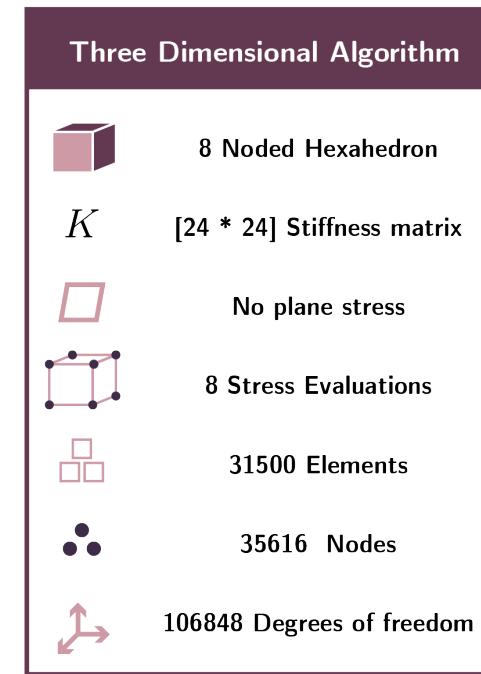
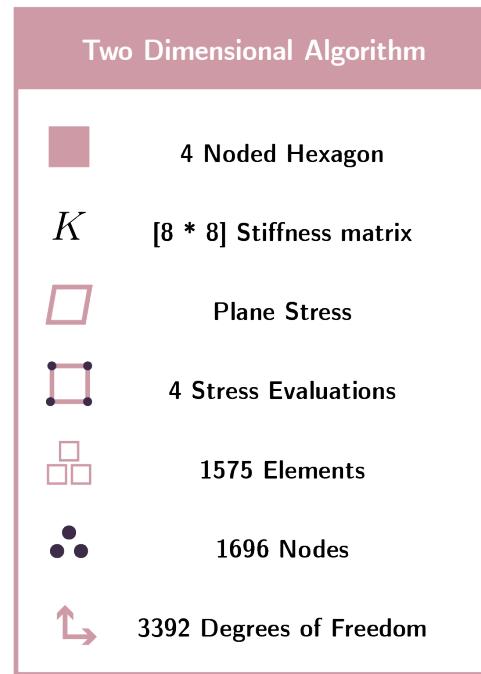


Computational time

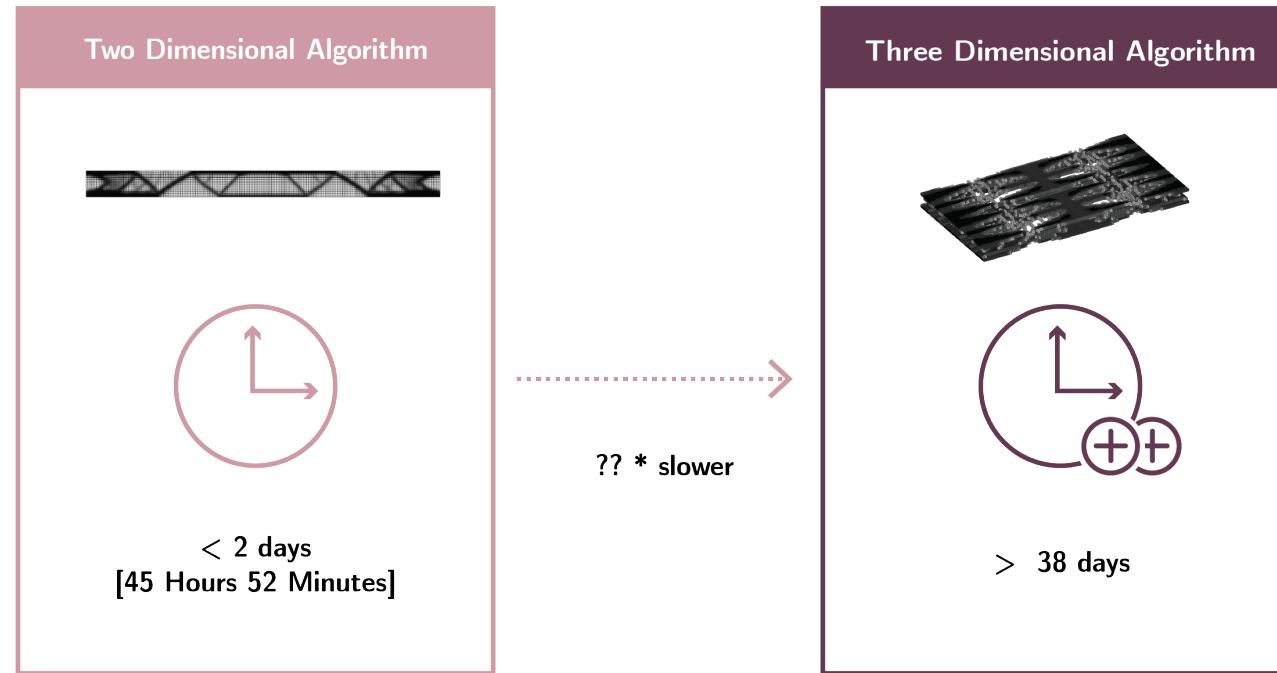


Algorithm Performance

Challenges 3D algorithm



Challenges 3D algorithm

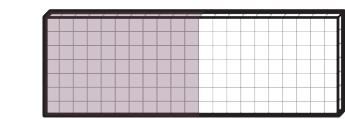


Improving performance Algorithm

Limiting Size

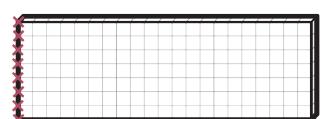


Symmetric boundary
conditions

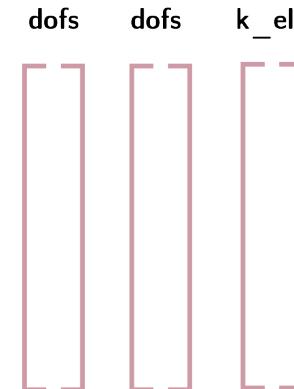


Calculate half

Pre-processing



Vectorized



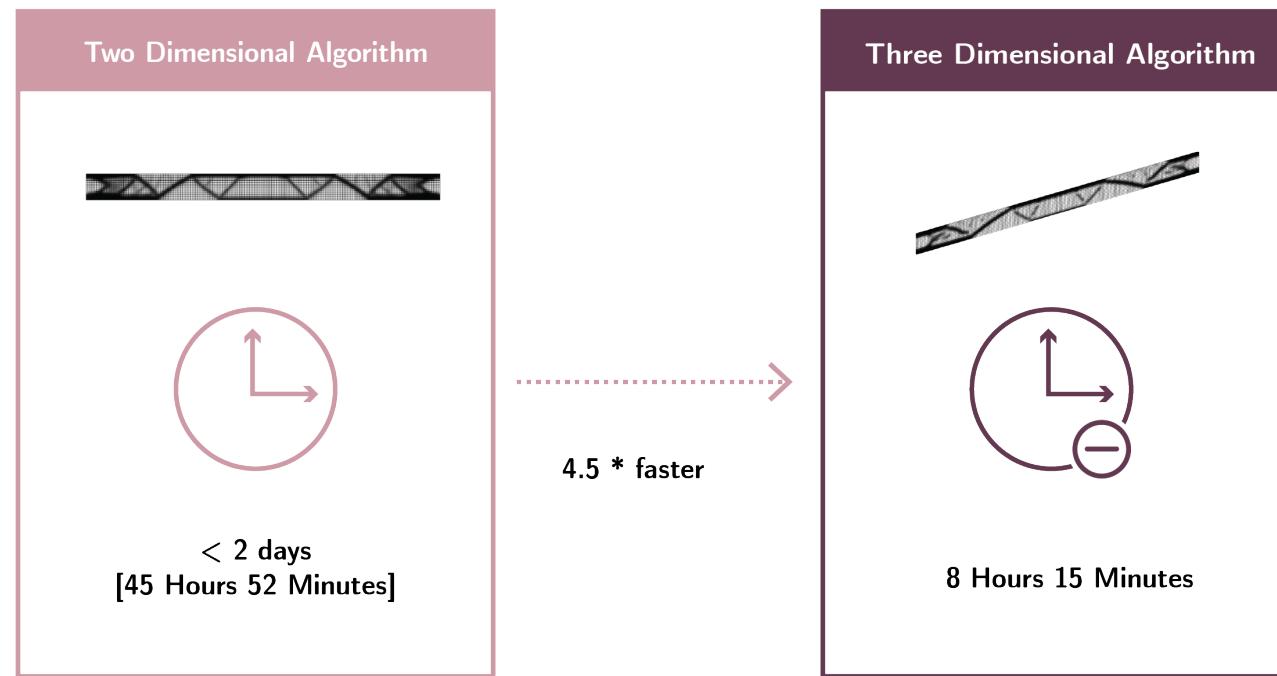
$K = \text{Sparse}(\text{dofs}, \text{dofs}, \text{k_el})$

Iterative Solver

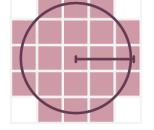


preconditioned conjugate
gradients method

First Time Reduction

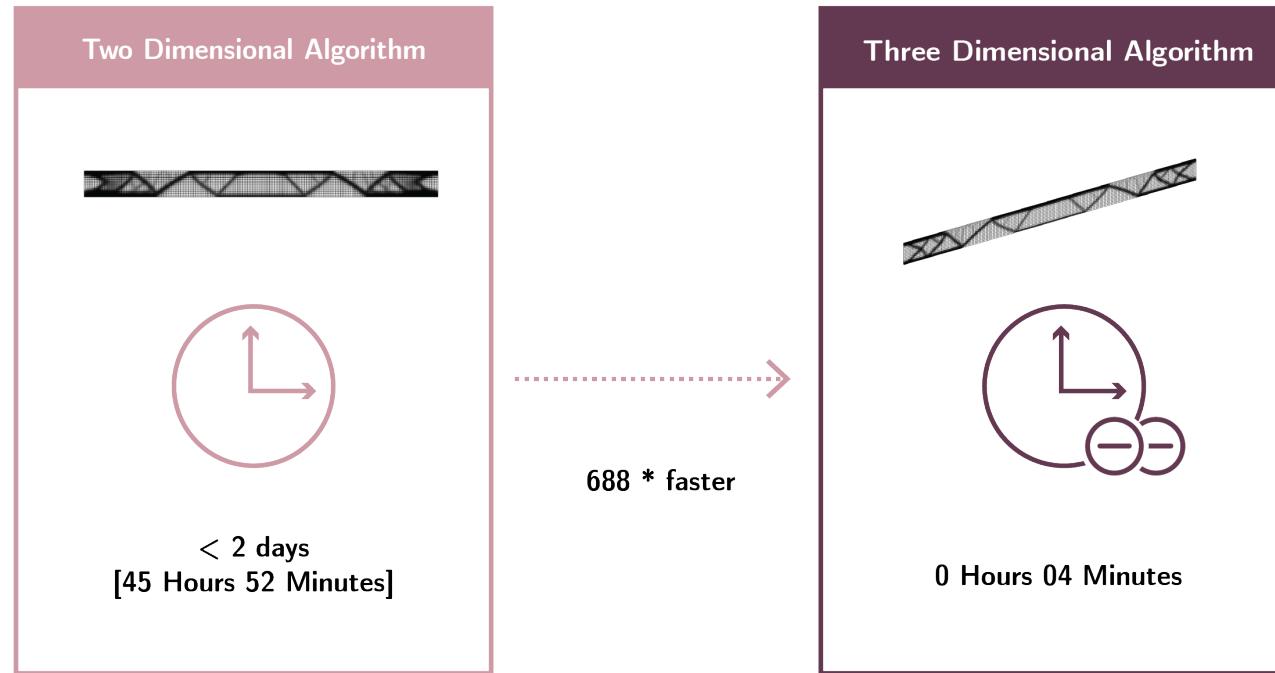


Gradient Functions

Compliance	Volume	Principal Stress	Annealing	Deflection
 $-\frac{u_i(\tilde{x})^T [p\tilde{x}_i^{p-1}(E_o - E_{min})K_i^0] u_i(\tilde{x})}{c_0 a_c}$	 $\sum_{i \in N_e} \frac{\partial V(\tilde{x})}{\partial \tilde{x}_i} \frac{\partial \tilde{x}_i}{\partial x_e}$	 $(p - q)\tilde{x}^{(p-q-1)} \left(\frac{\sigma_e(\tilde{x})}{\sigma_{lm}} \right)$	 $\frac{v_e}{\sum_{j \in N_i} v_j * a_v}$	 $-U(\tilde{x})[p\tilde{x}_i^{p-1}(E_0 - E_{min})K_i^0]K(\tilde{x})^{-1}$

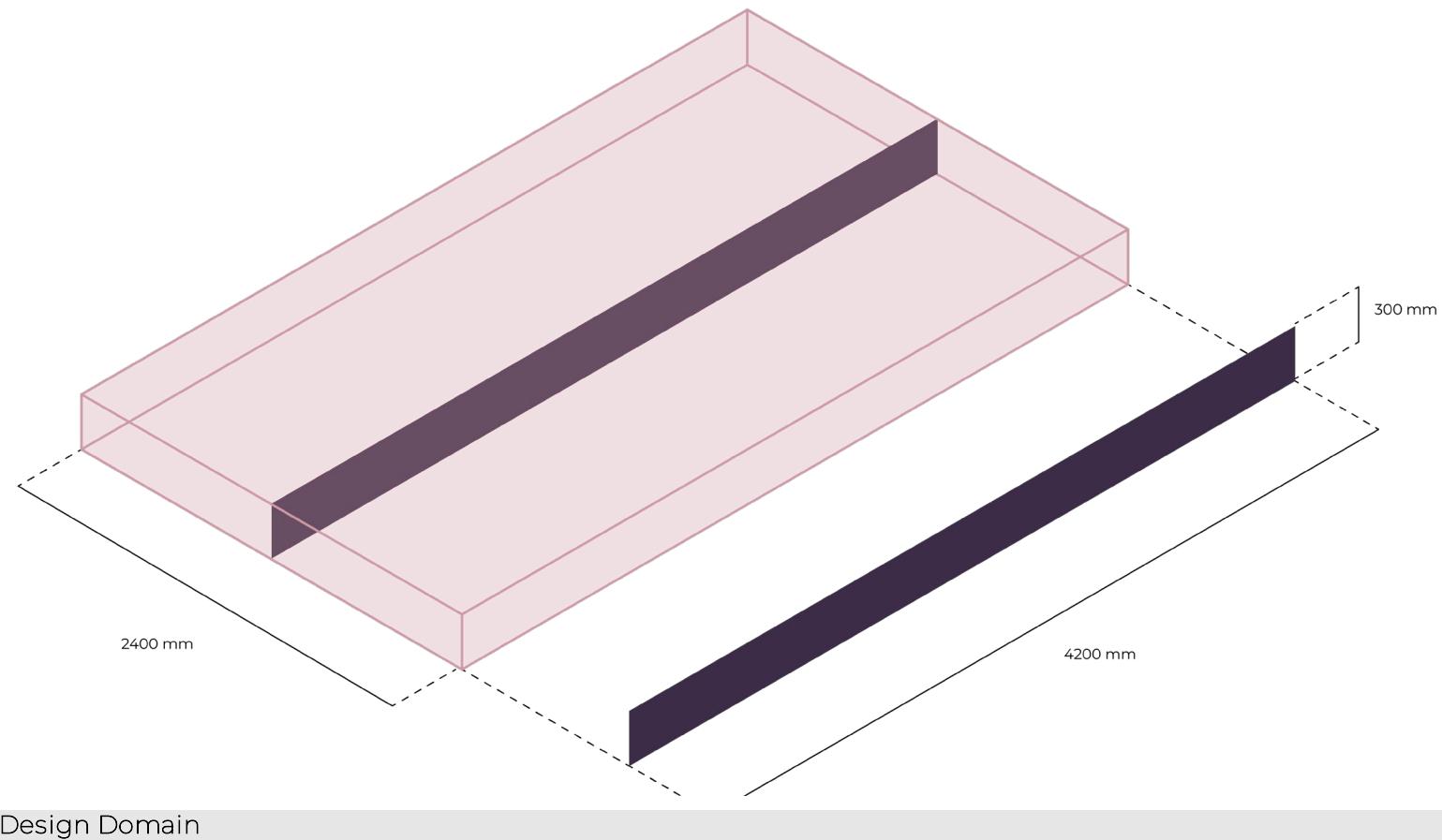
Algorithm Performance

Final Computational Performance



Calibration Algorithm

Two Dimensional Calculation



Calibration Algorithm

Two Dimensional Domain
Supports



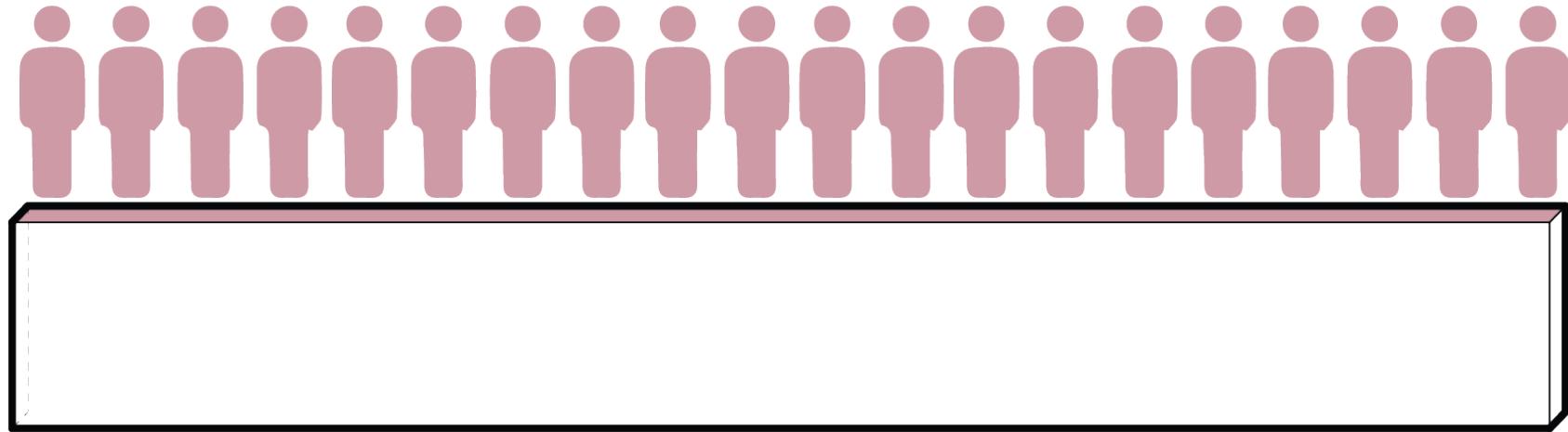
Supports: Fully Fixed Sides

Two Dimensional Domain Loads



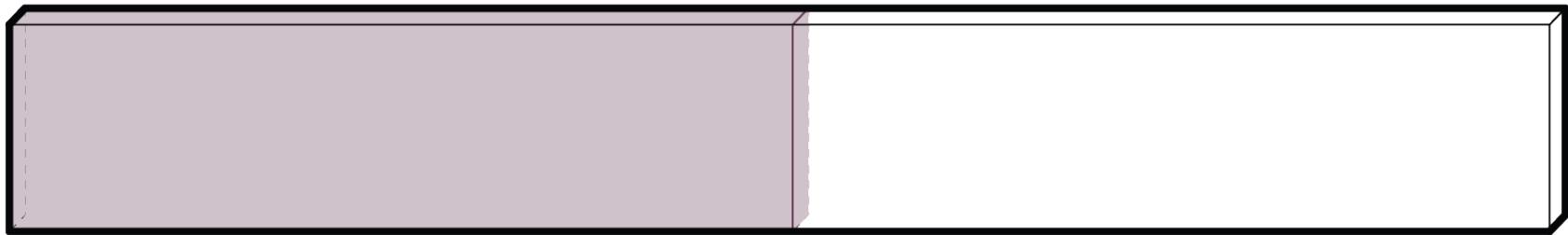
Loads: Distributed Load

Two Dimensional Domain Loads



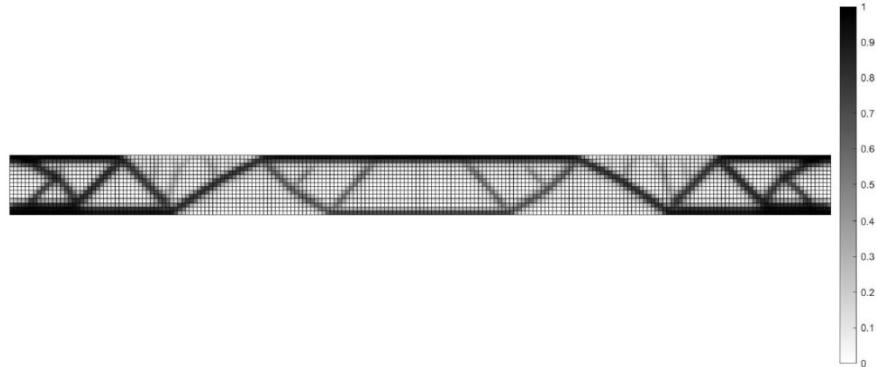
Loads: Distributed Load

Two Dimensional Domain Mirroring



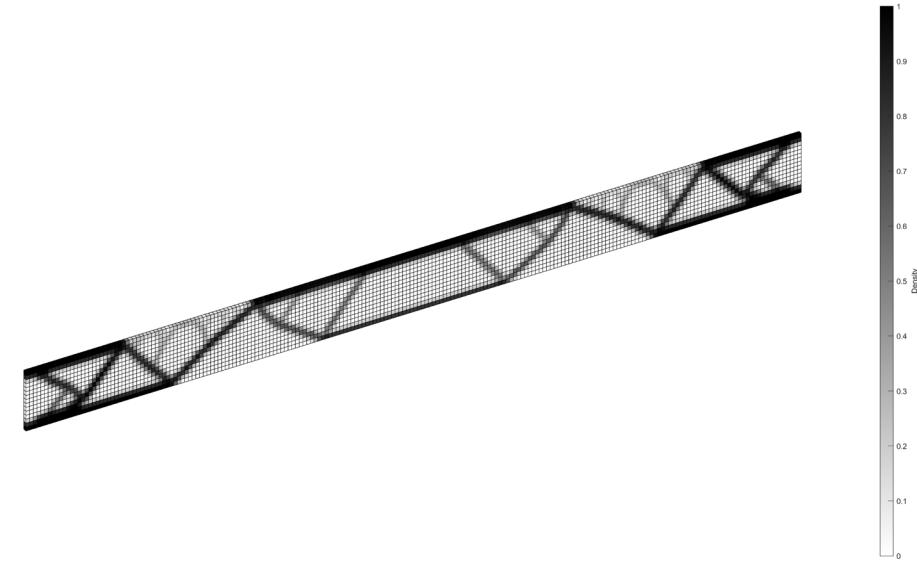
Calculated Domain (l, w, h): 2.1 m * 0.02 m * 0.3 m

Volume optimization 2D



Two-Dimensional Algorithm Result

Anna Maria Koniari



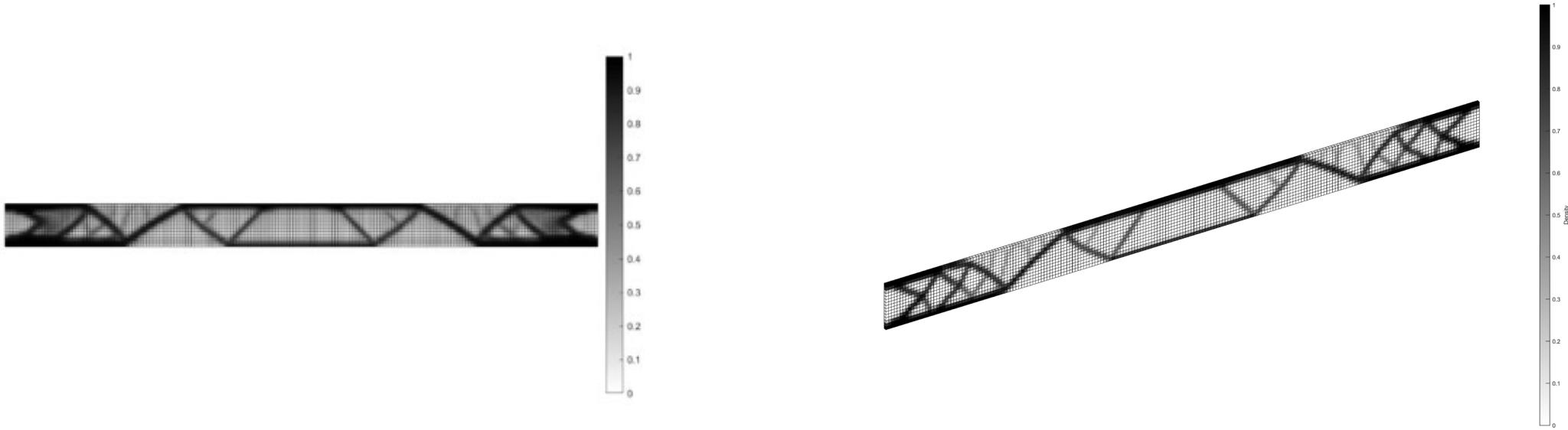
Three-Dimensional Algorithm Result

Me

	Volume percentage	Iterations	Function evaluation	Feasibility	Time (hours:min:sec)
2D	29	231	365727	0	46:32
3D	28.9	149	274	0	00:04:51

Calibrating Algorithm

Compliance optimization 2D



Two-Dimensional Algorithm Result

Anna Maria Koniari

Three-Dimensional Algorithm Result

Me

	Volume percentage	Iterations	Function evaluation	Feasibility	Time (hours:min:sec)
2D	29	231	365727	0	46:32
3D	28.9	149	274	0	00:04:51

Calibrating Algorithm

Case Study Design

Case Study

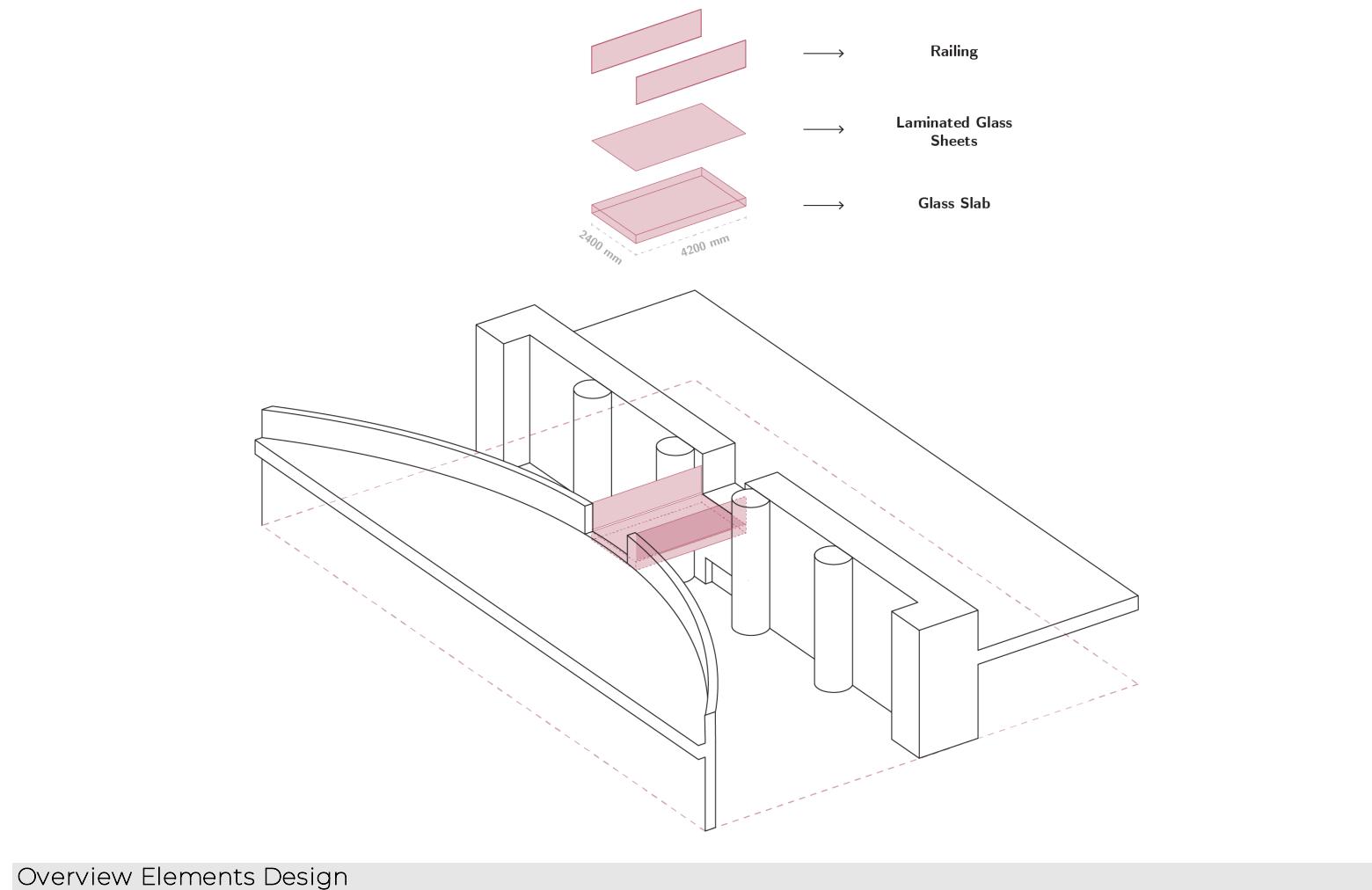


Glass bridge British Museum

Picture from A.M. Koniaris

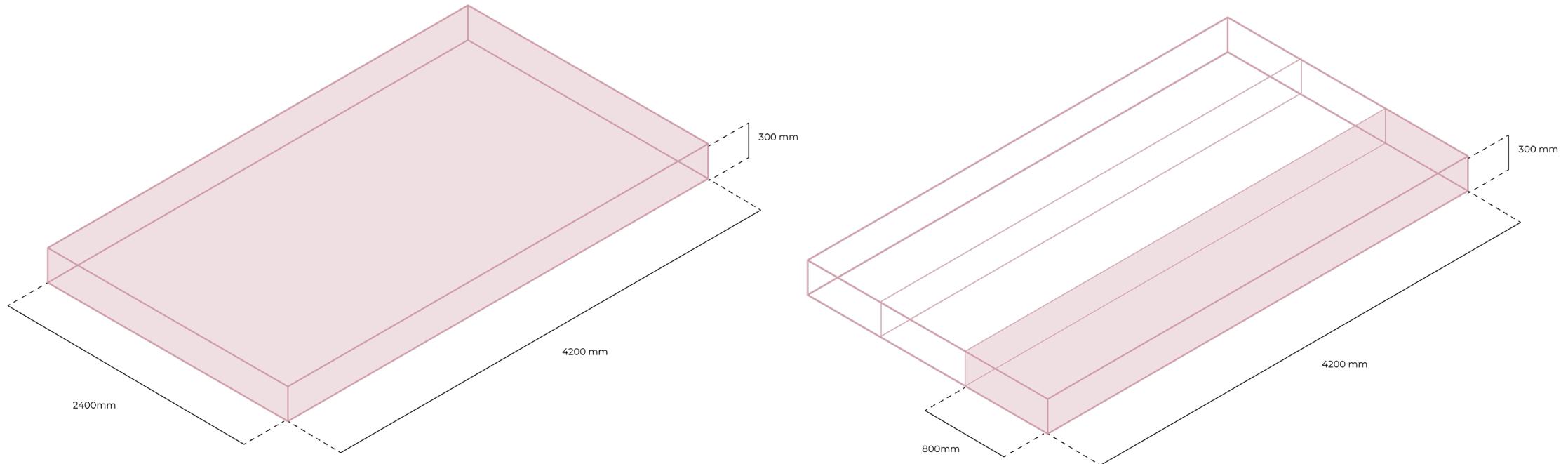
Case Study Design

Case Study



Case Study Design

Case study



Case Study Design

Volume Minimization

All constraint

Design: Three Separate Components



Results:

Volume	Maximum Stress
 23%	-0.0047 0.0047 [Kn/mm ²]
Compliance	Deflection
 2.7 * V initial	 -0.2370 mm

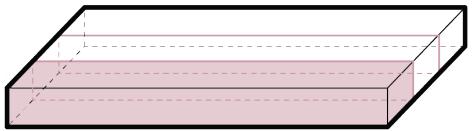


Design Exploration

Compliance Minimization

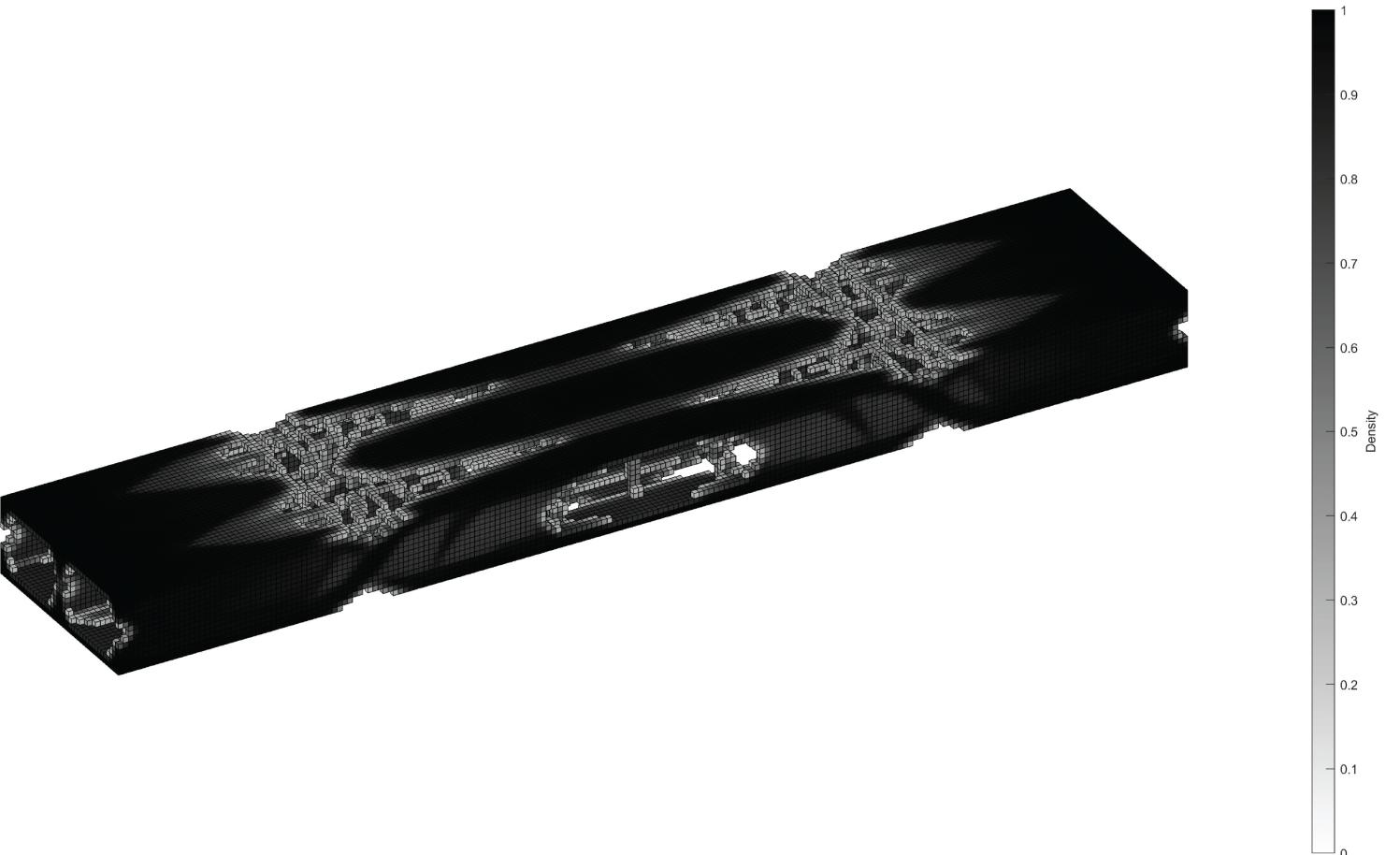
All constraint

Design: Three Separate Components



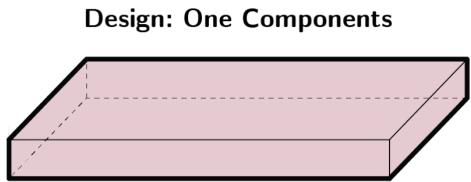
Results:

Volume	Maximum Stress
	-0.0047 0.0047 [Kn/mm ²]
Compliance	Deflection
	-0.2194 mm



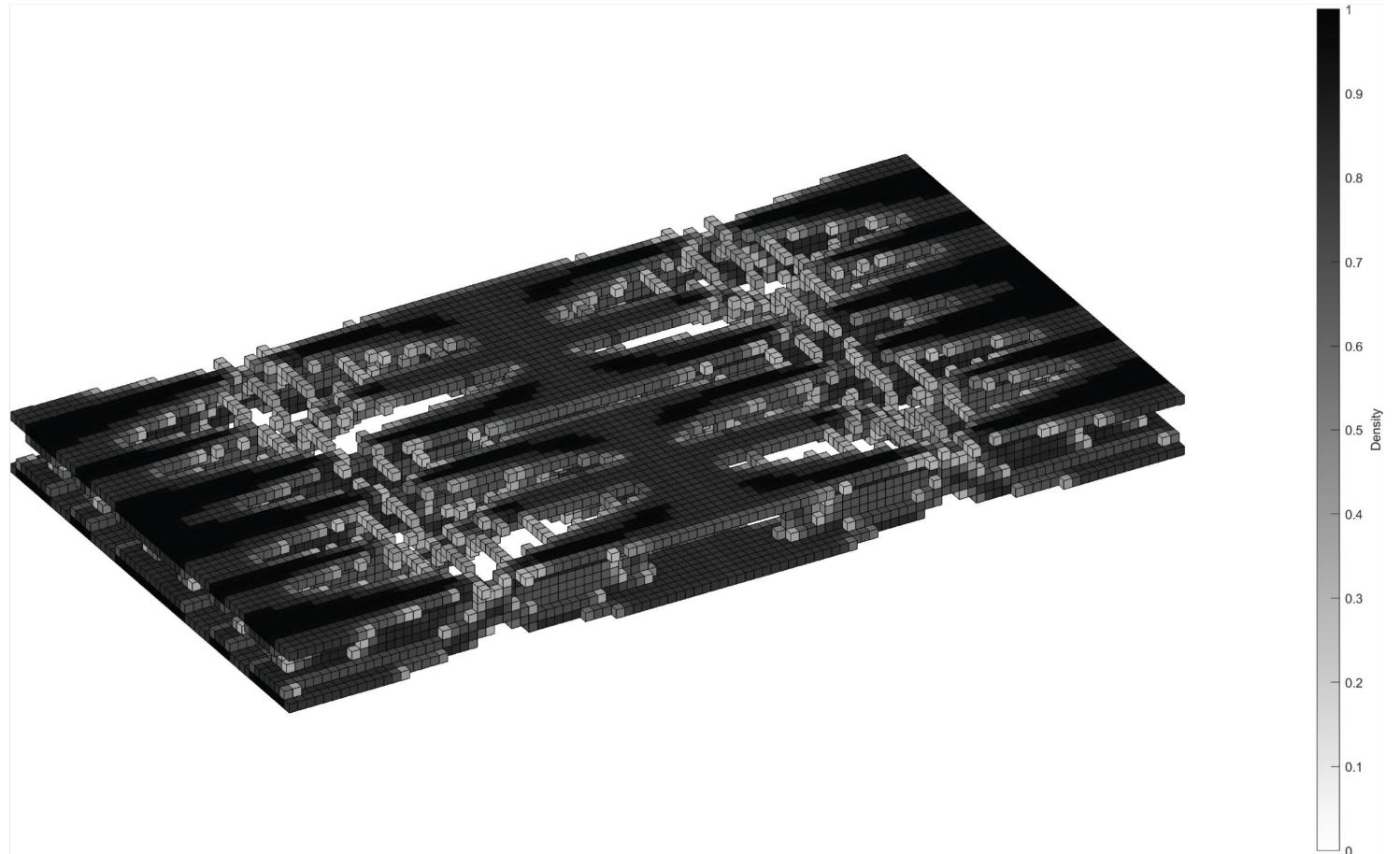
Design Exploration

Volume Minimization All constraint



Results:

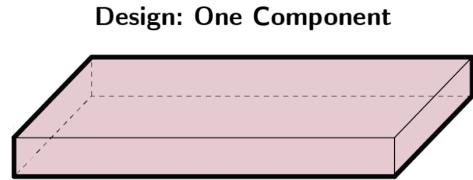
Volume	Maximum Stress
 30%	-0.0036 0.0035 [Kn/mm ²]
Compliance	Deflection
 3.2* V initial	 -0.2358 mm



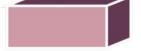
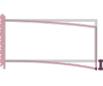
Design Exploration

Compliance Minimization

All constraint



Results:

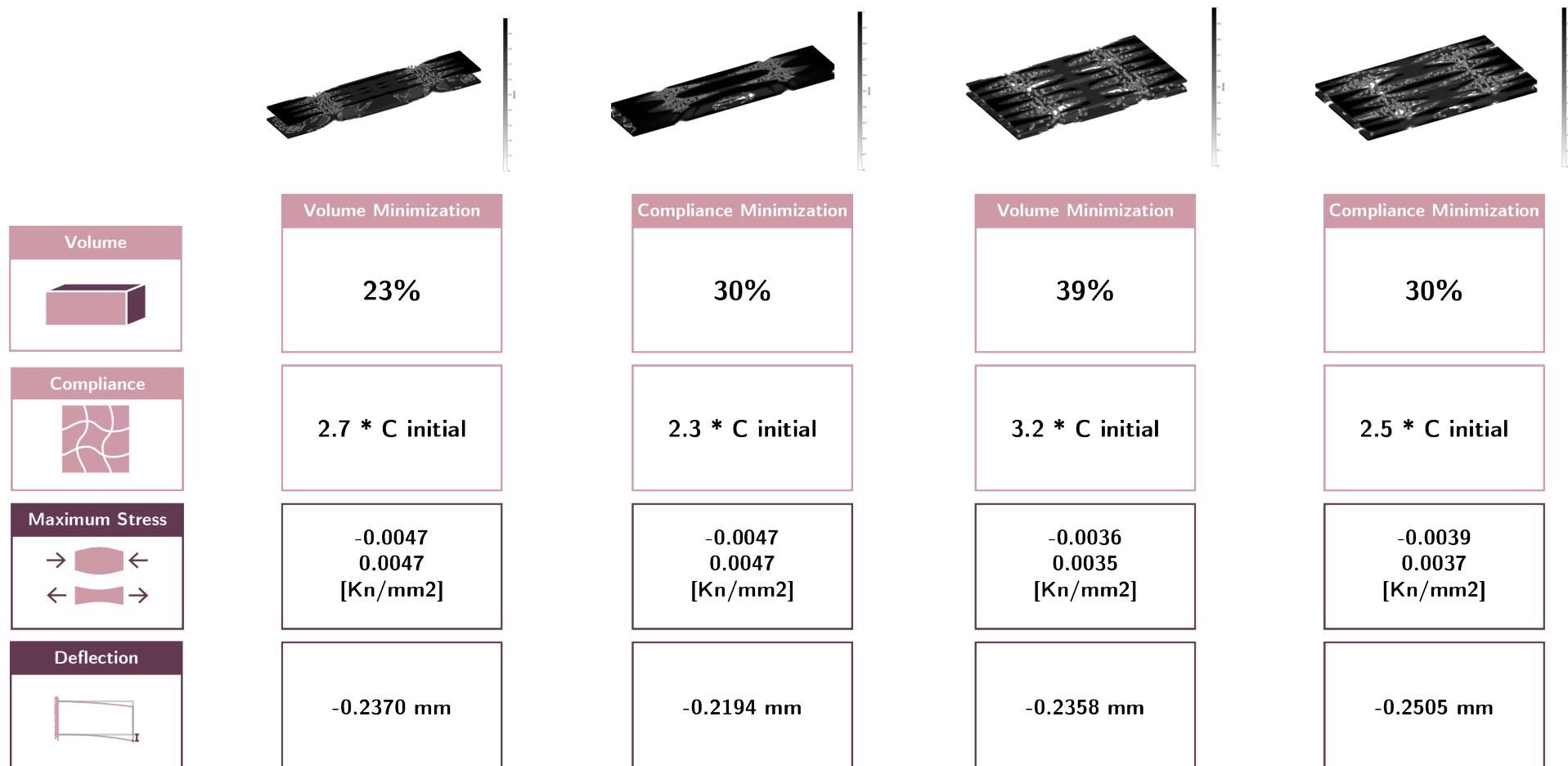
Volume	Maximum Stress
 29%	-0.0039 0.0037 [Kn/mm ²]
Compliance	Deflection
 2.5* V initial	 -0.2505 mm



Design Exploration

Compare the results

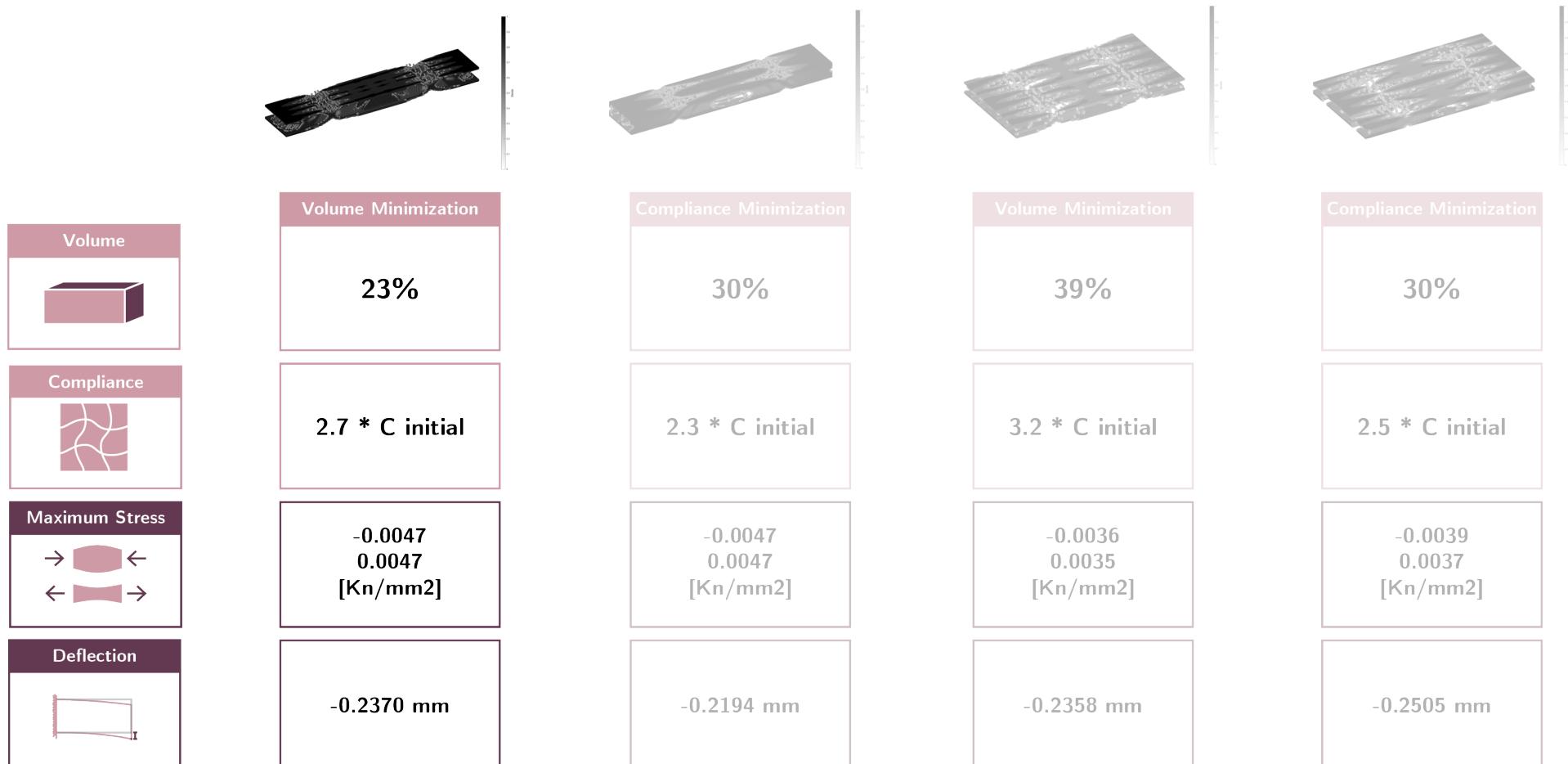
Performance



Design Exploration

Compare the results

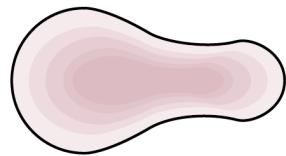
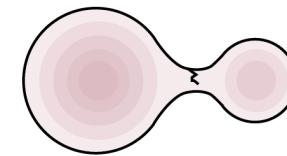
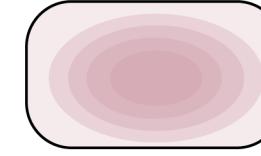
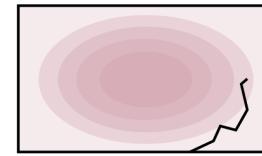
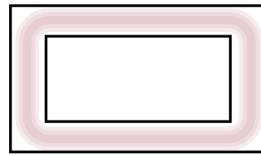
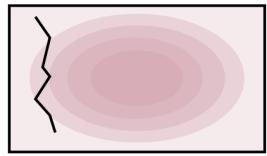
Performance



Design Exploration

Post Processing

Glass Design Criteria



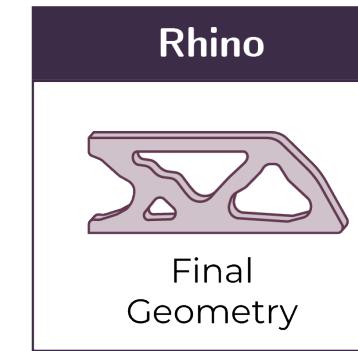
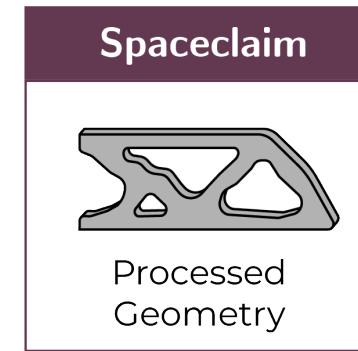
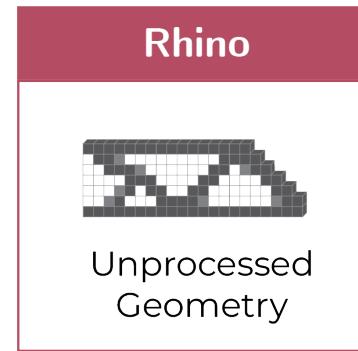
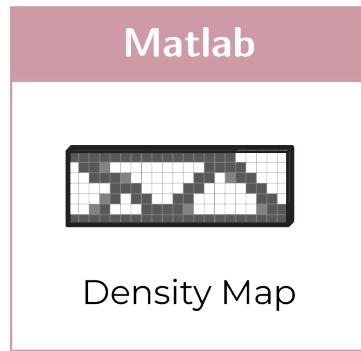
Avoid Large Cross Sections

Avoid Sharp Corners

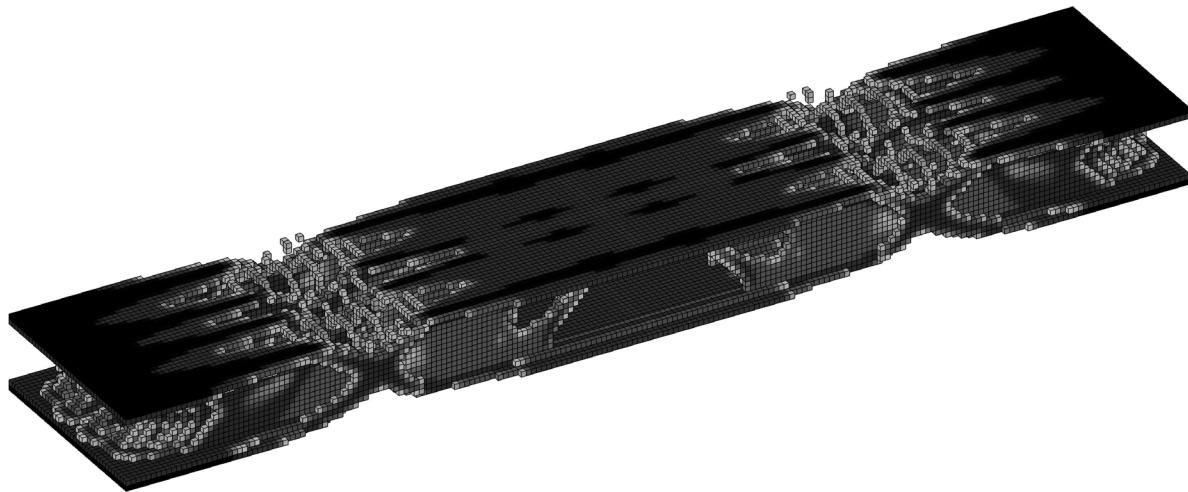
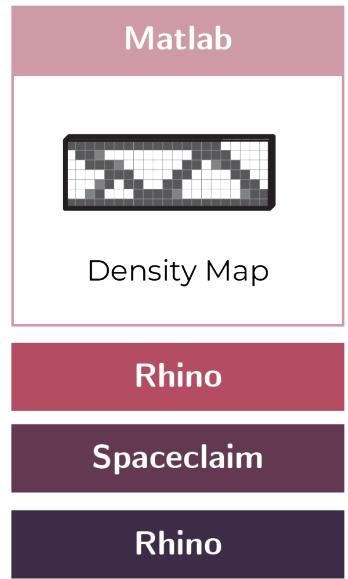
Avoid Large Differences Size

Post Processing

Post Processing

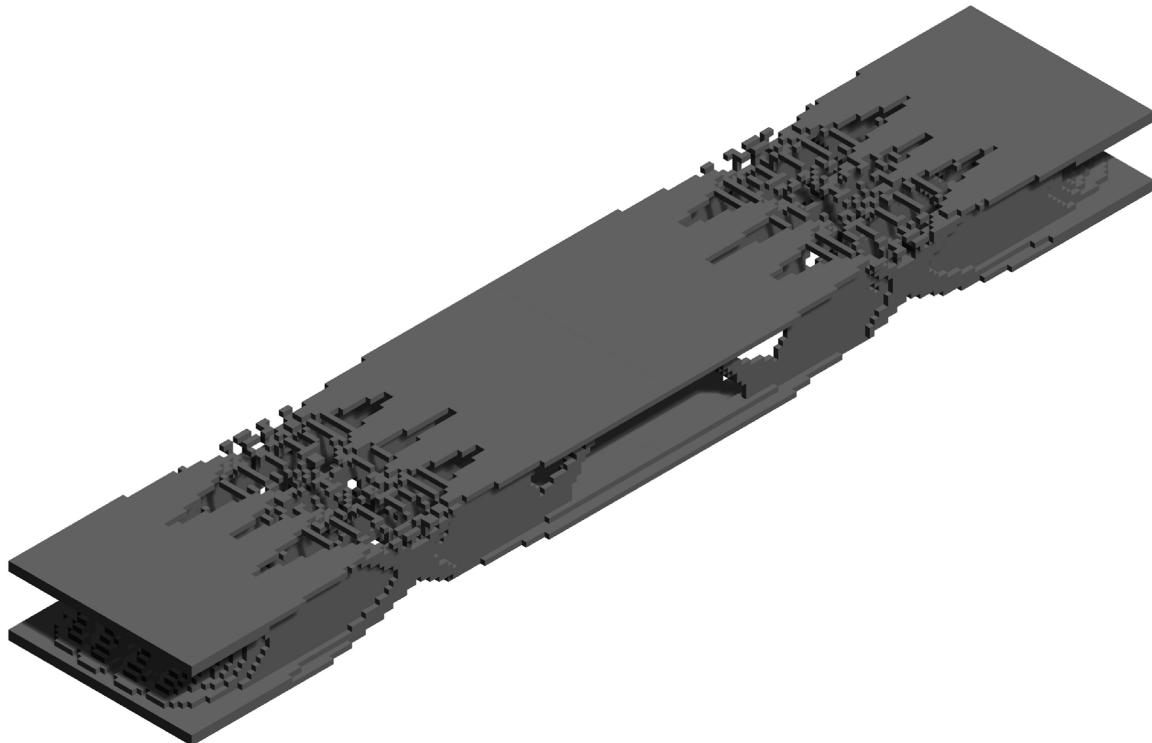
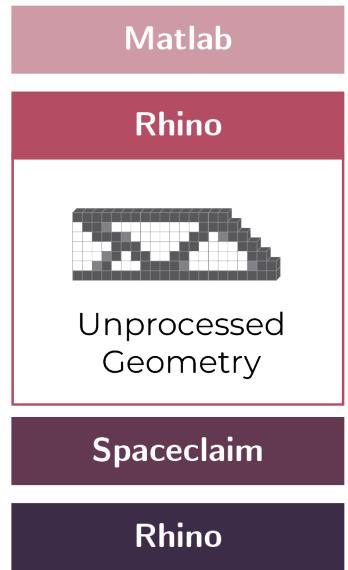


Design Component



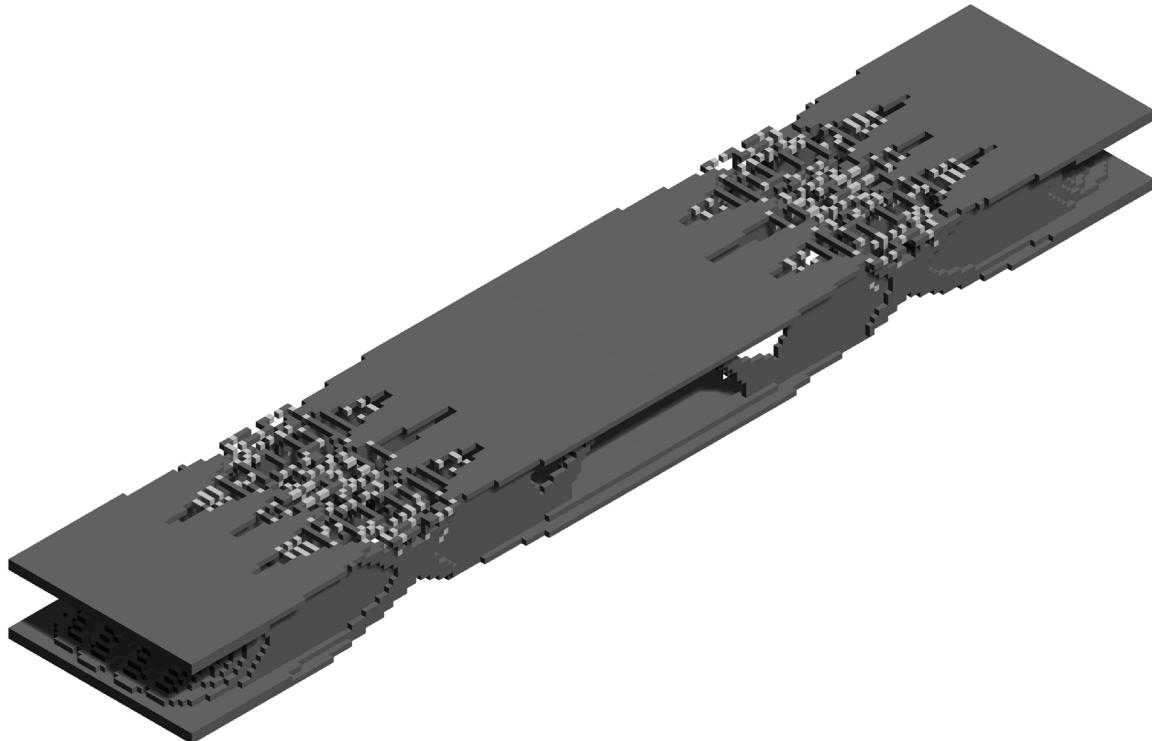
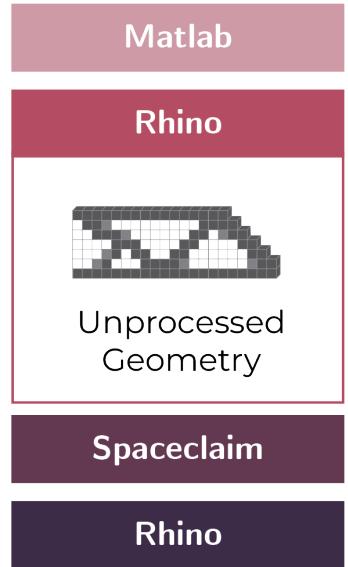
Post Processing

Design Component



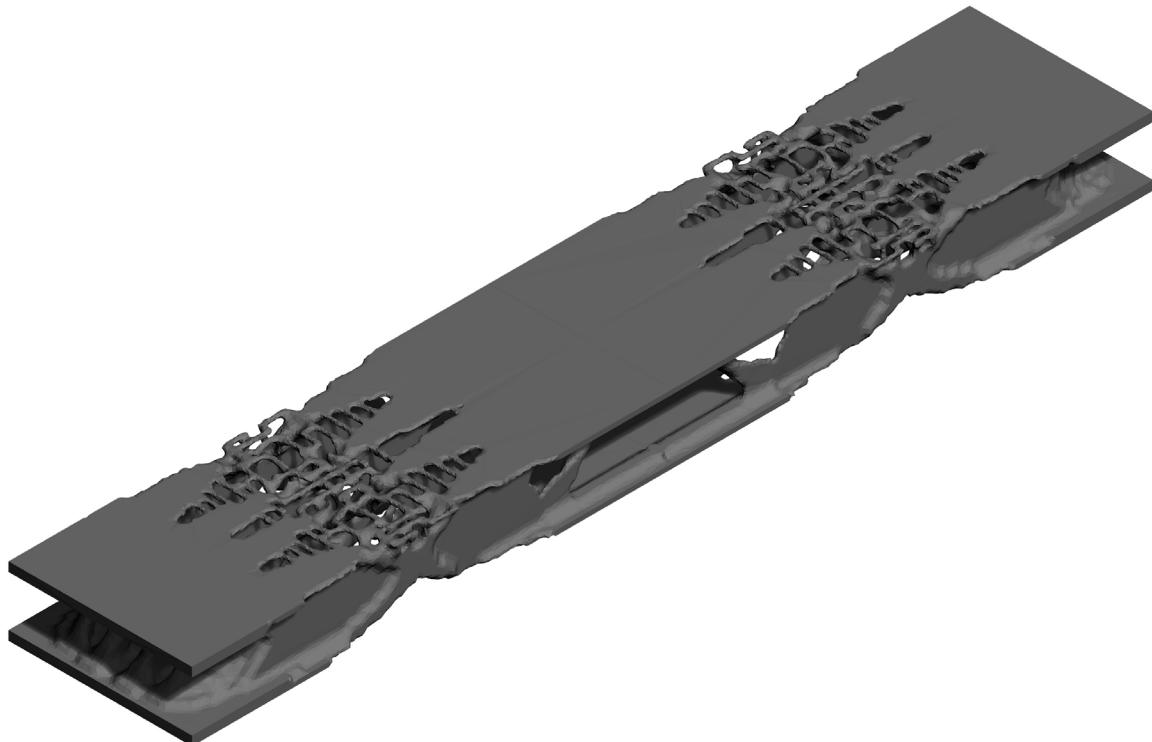
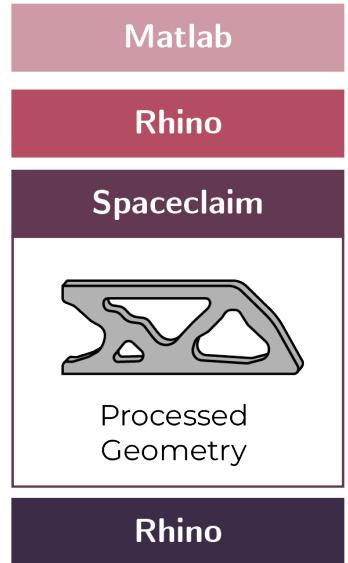
Post Processing

Design Component



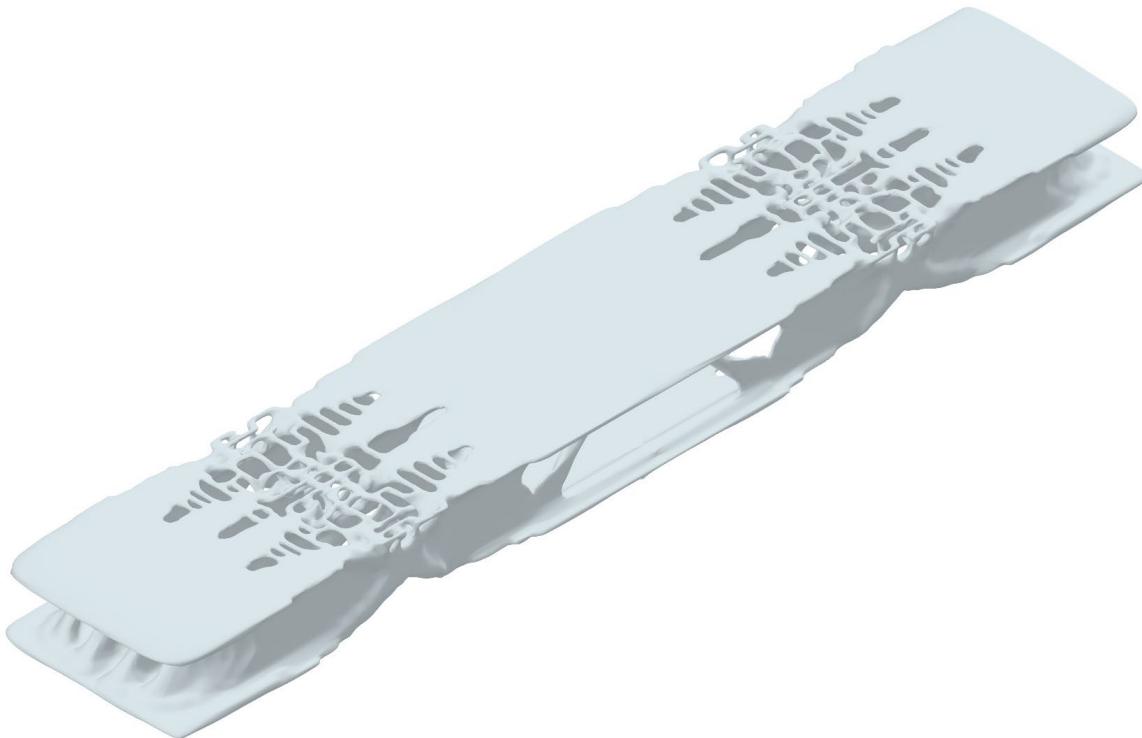
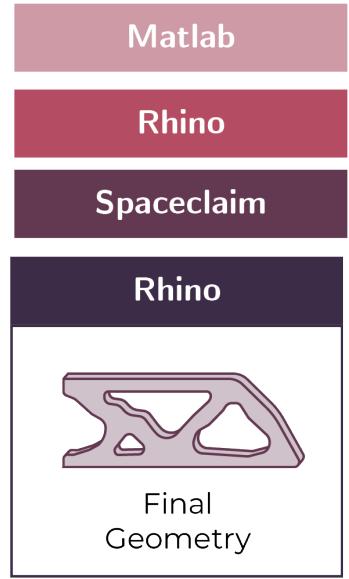
Design Exploration

Design Component



Post Processing

Design Component



Post Processing

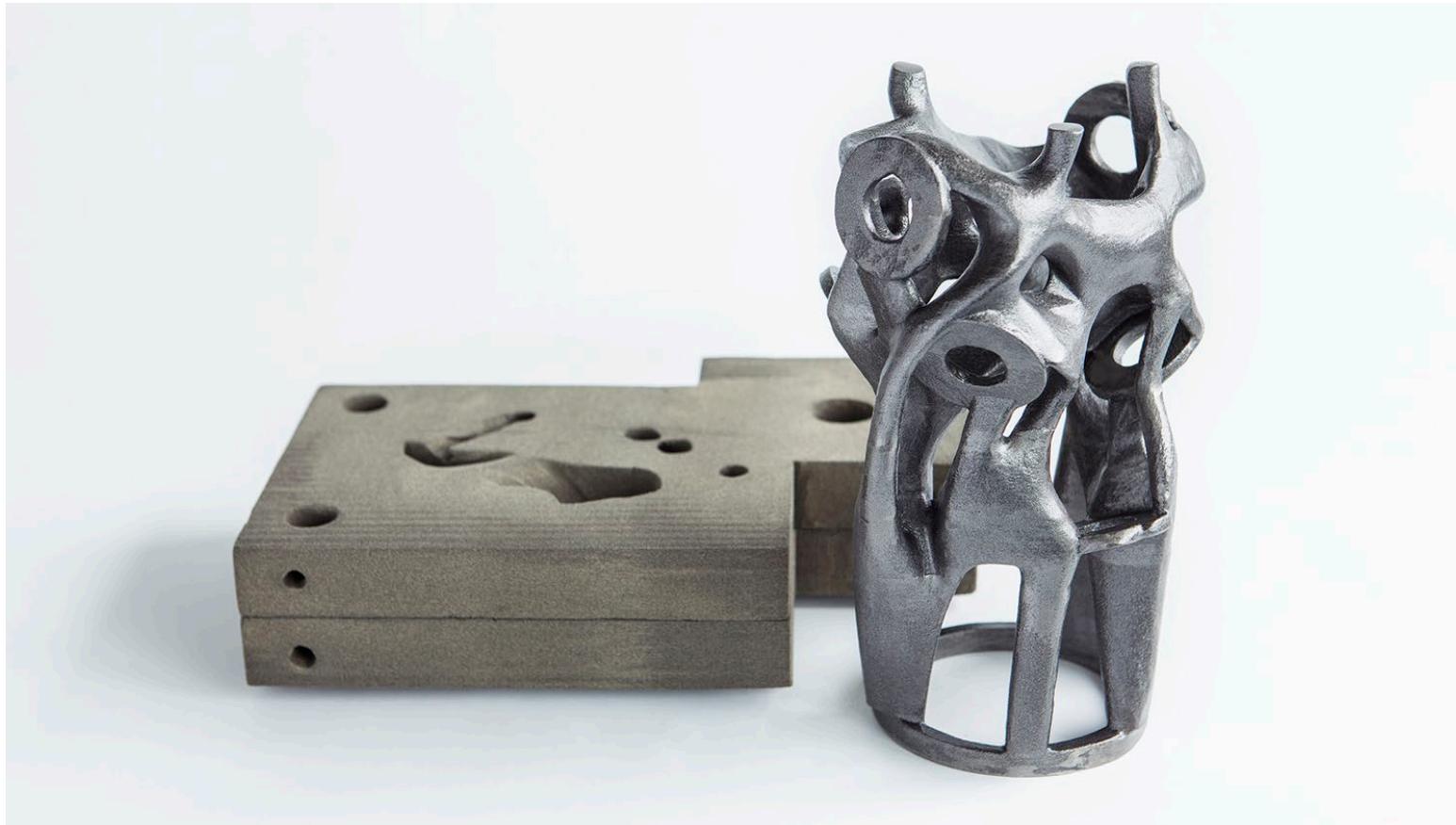
Manufacturing & Building Integration

Production Method | Kiln Casting



Fabrication

3D printed Sand Mould



Example 3D printed Sand Mould for Metal

Example 3D printed Sand Mould for Glass

Manufacturing & Building Integration

Fabrication

Improvement surface quality

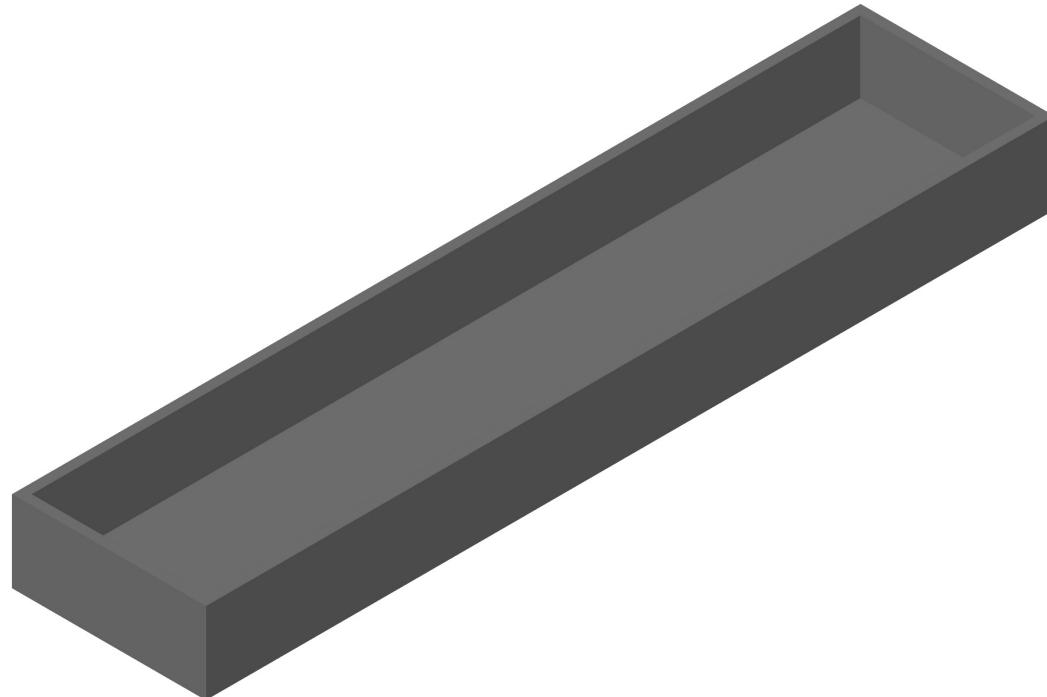


3D printed Sand Moulds
M. Ioannidis And Glass & Transparency Group TU Delft

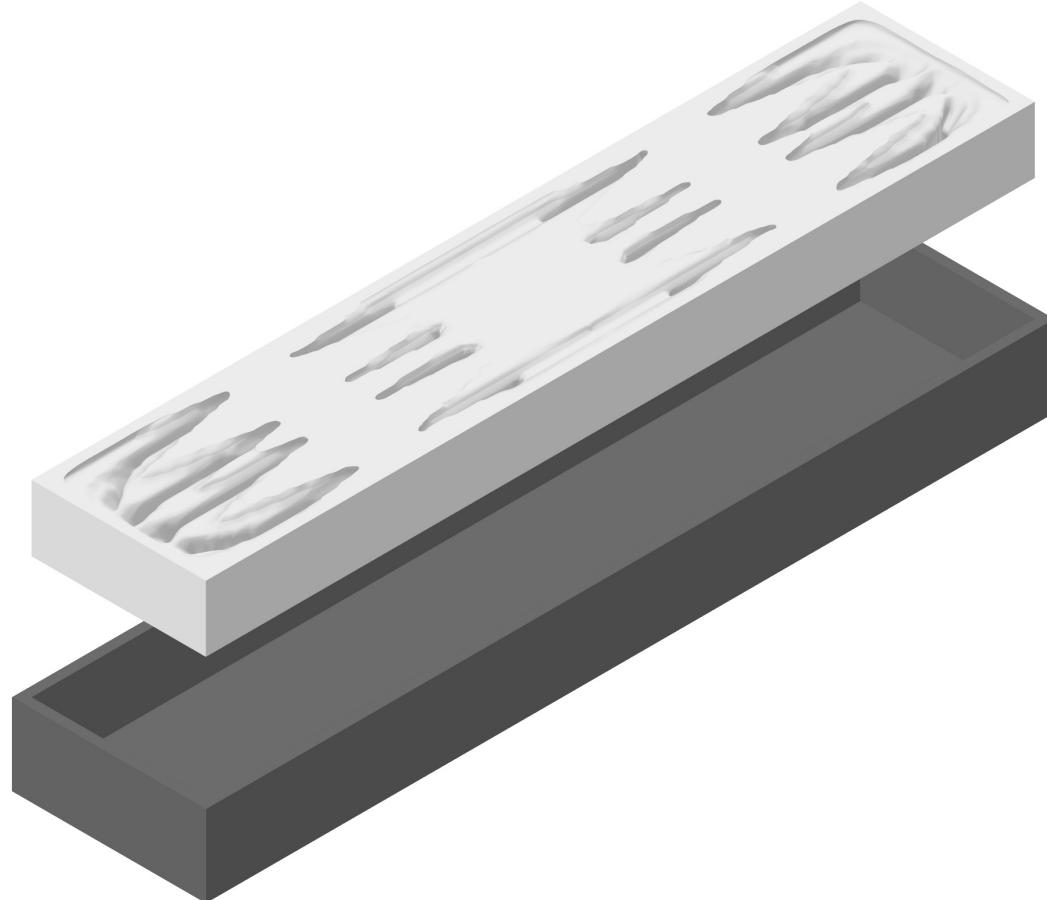


Surface Quality
M. Ioannidis

Manufacturing Component
Concrete Base



Manufacturing Component 3DPSM Pieces



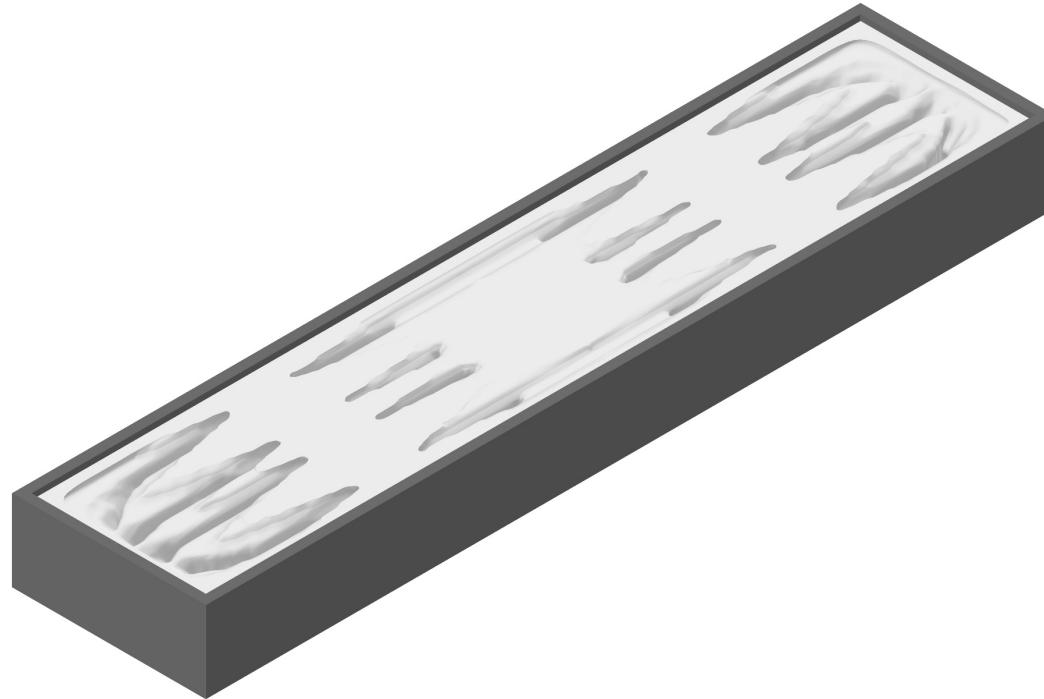
Manufacturing & Building Integration

P5 | Eva Schoenmaker | 10.11.2023

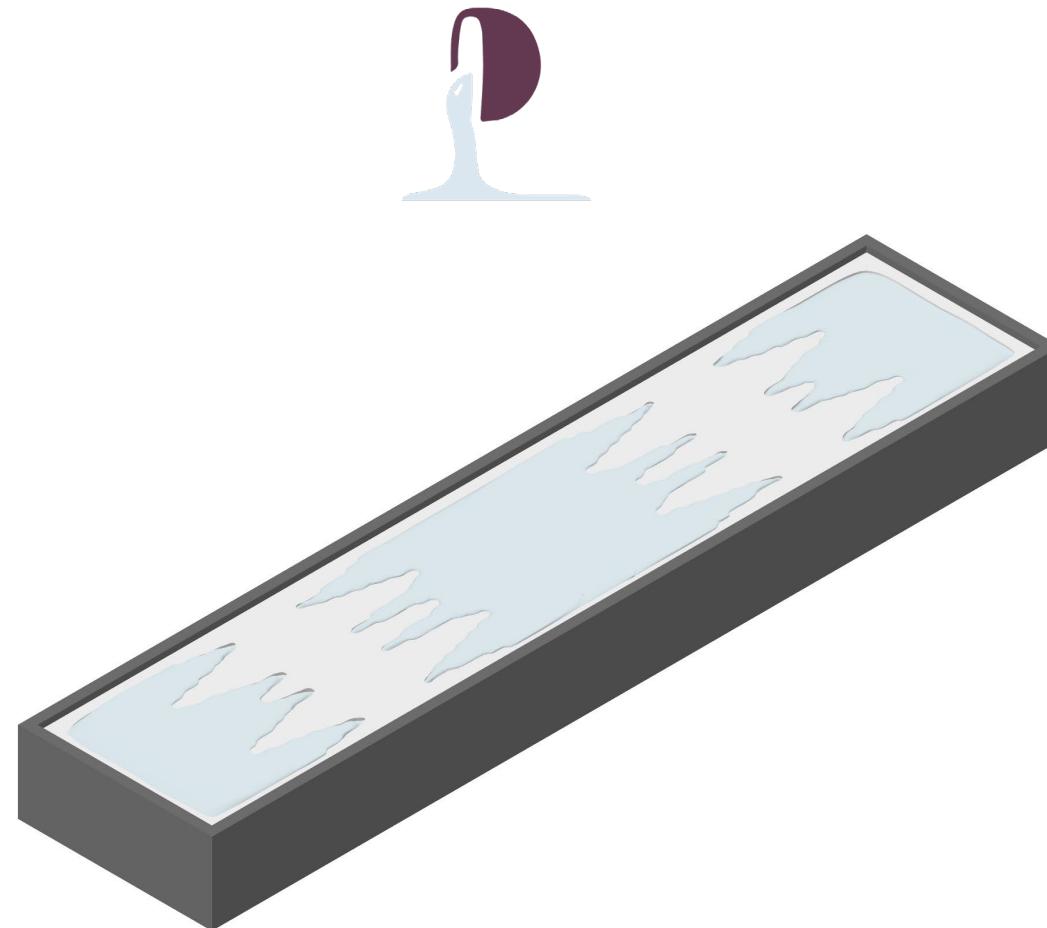
99

Manufacturing Component

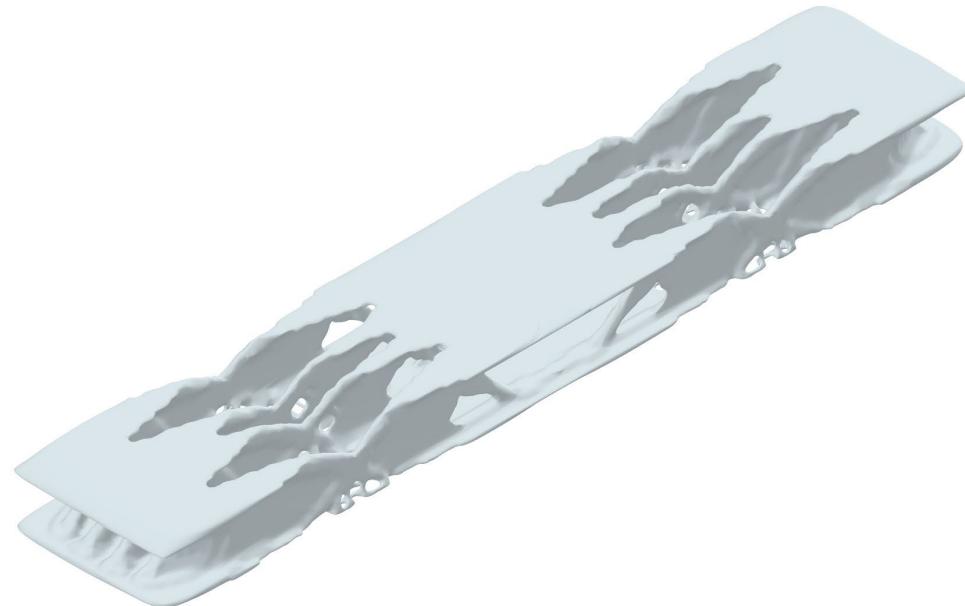
Assembled mould



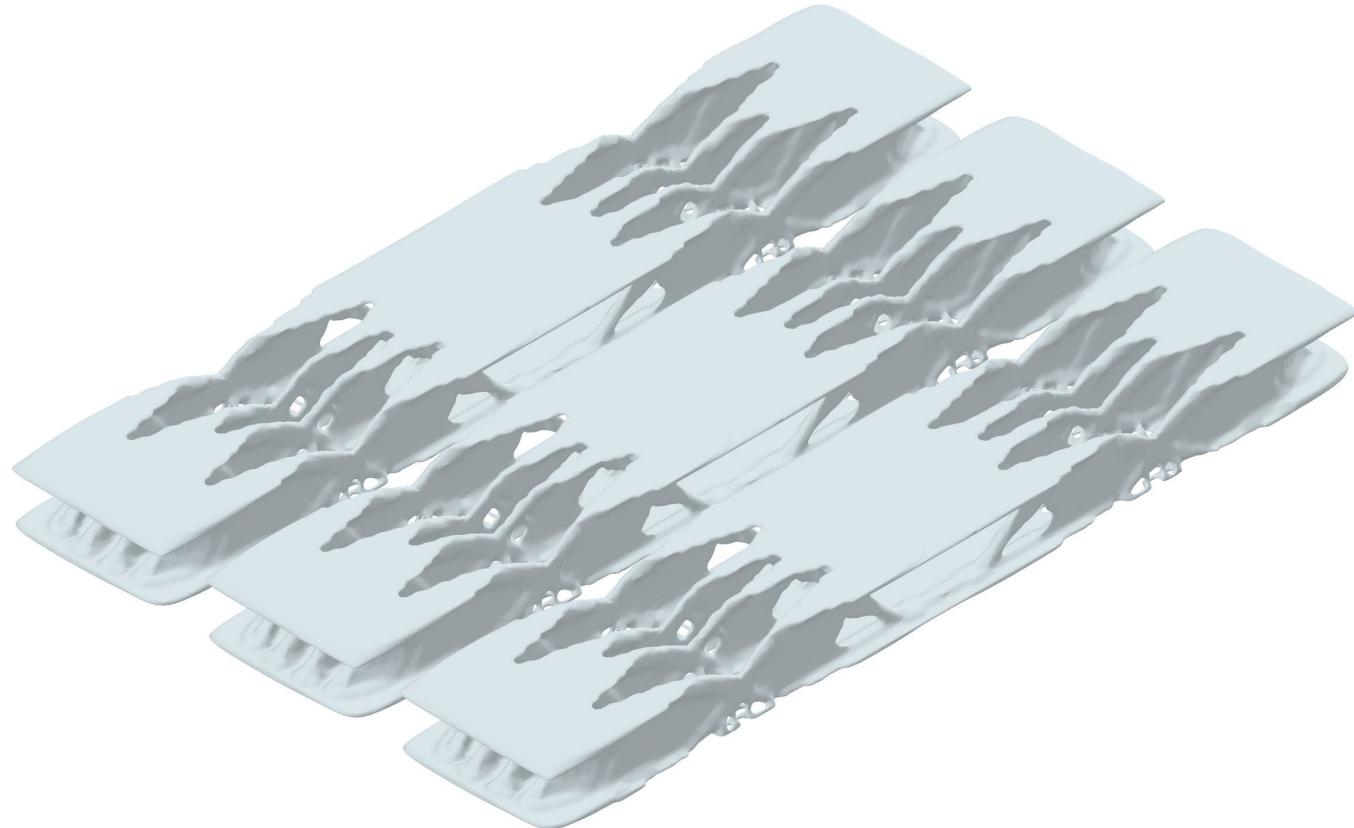
Manufacturing Component Casting Glass



Manufacturing Component Demoulding

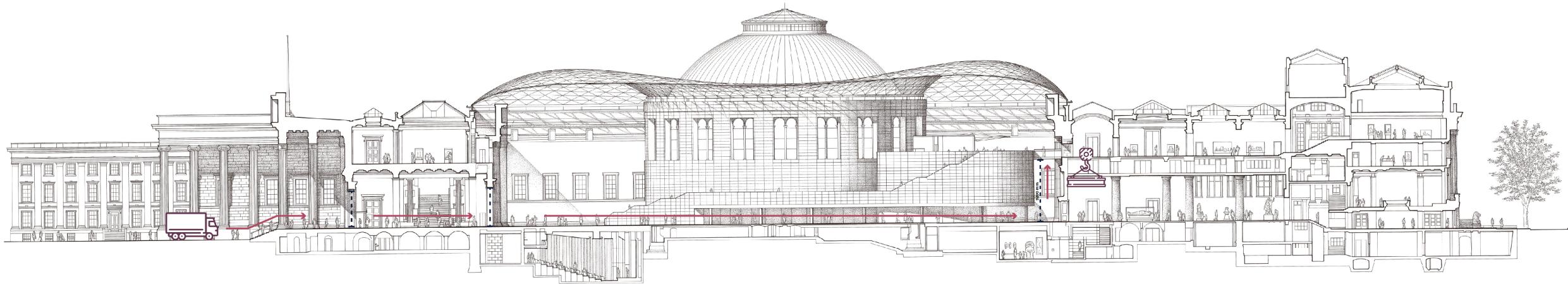


Manufacturing Component Repeat



Manufacturing & Building Integration

Building Integration

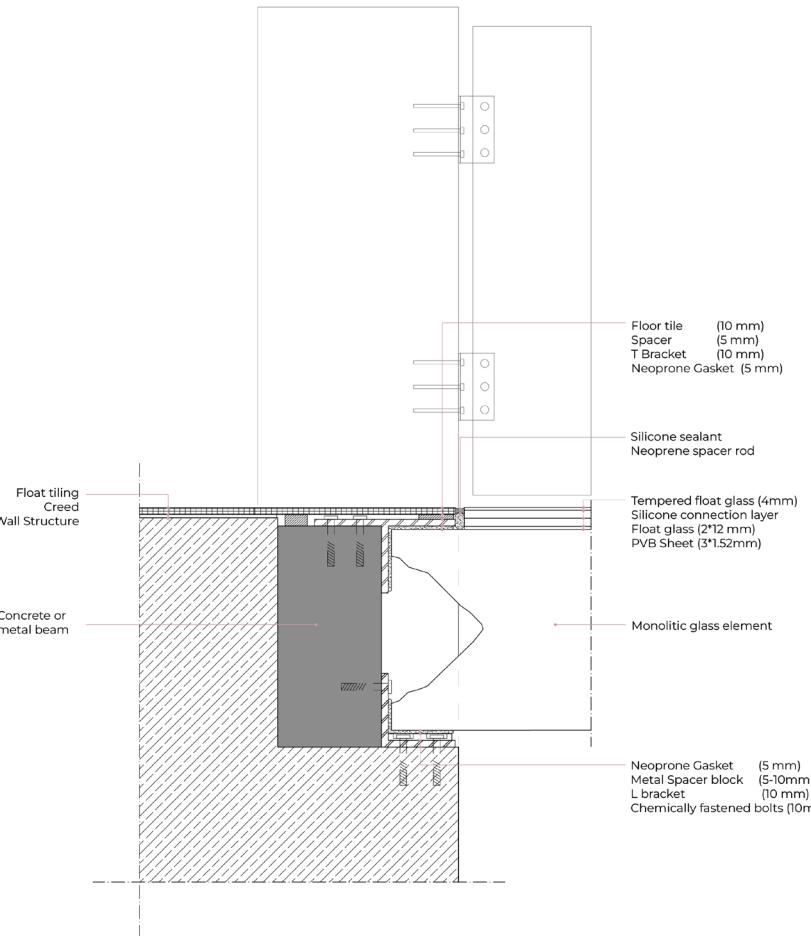


Manufacturing & Building Integration

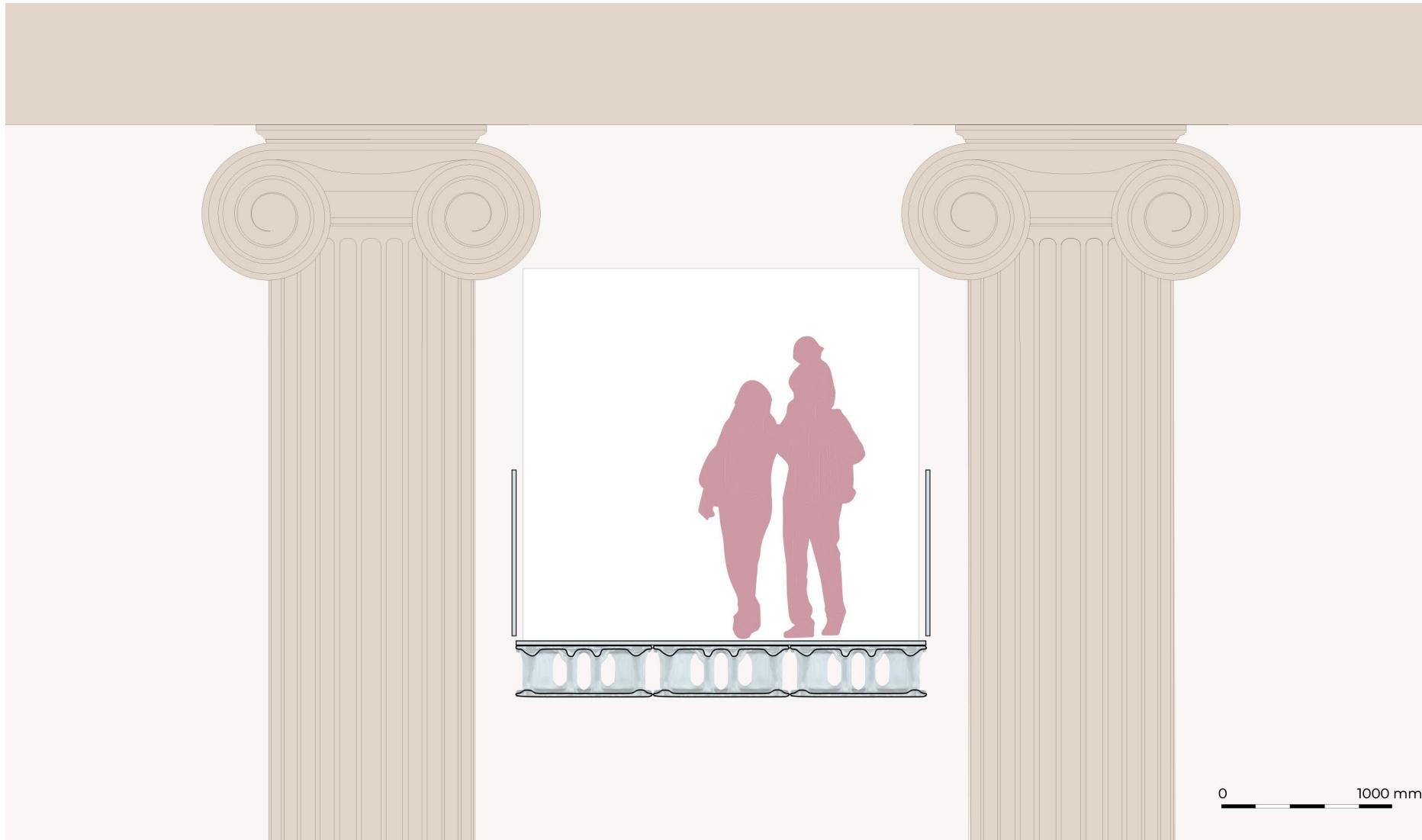
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104

Connection Detail



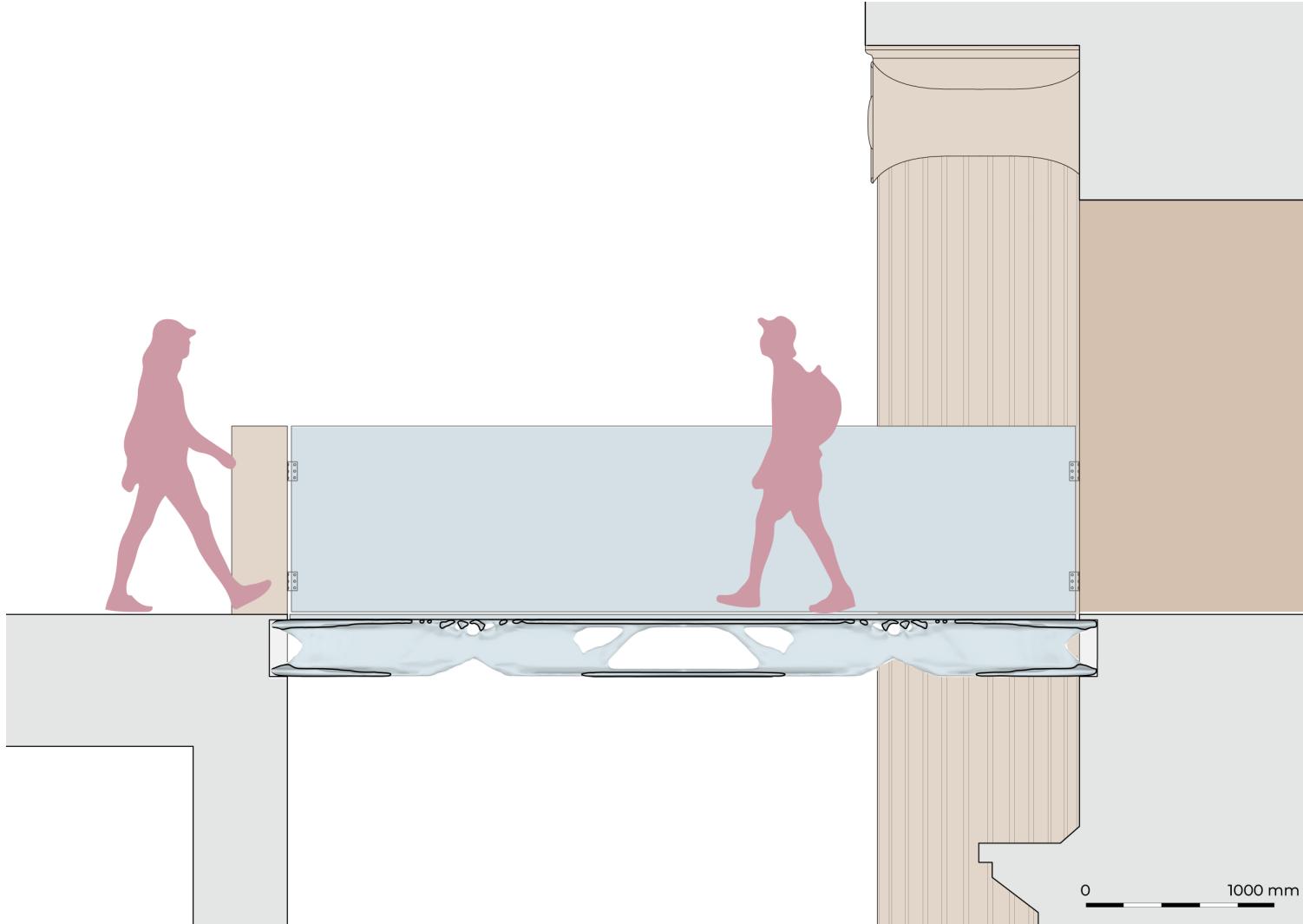




Manufacturing & Building Integration

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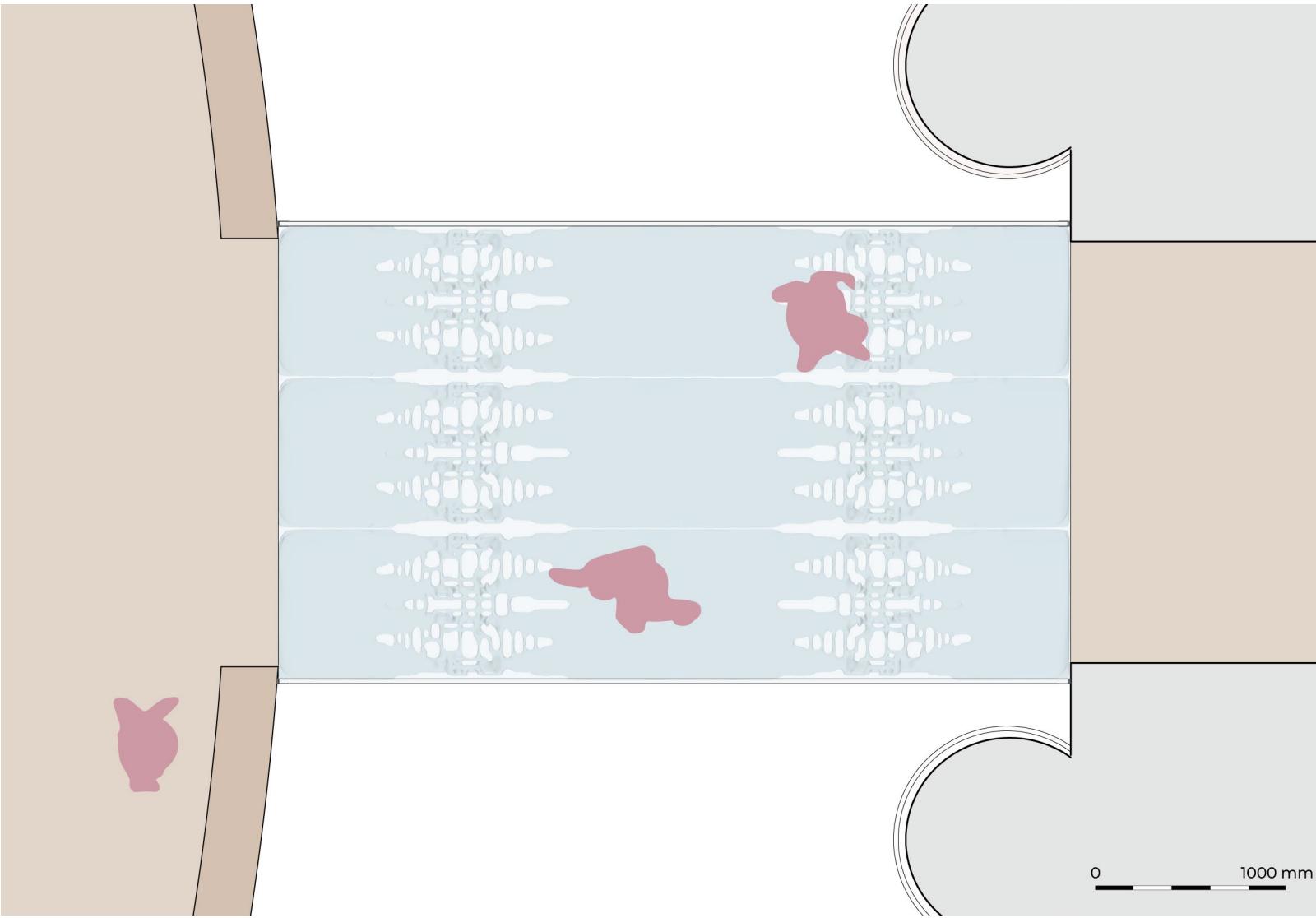
107



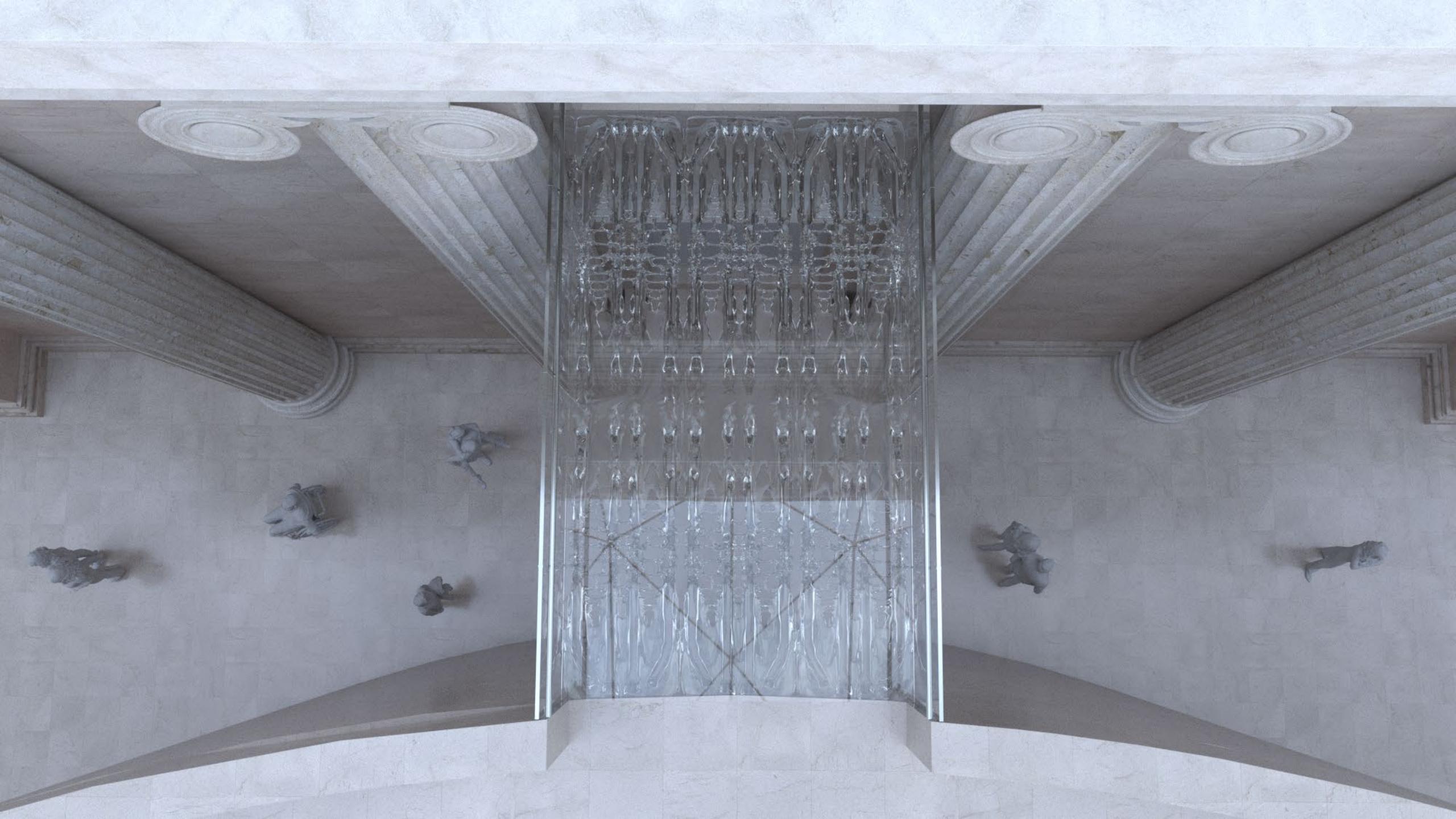
Manufacturing & Building Integration

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108



Manufacturing & Building Integration



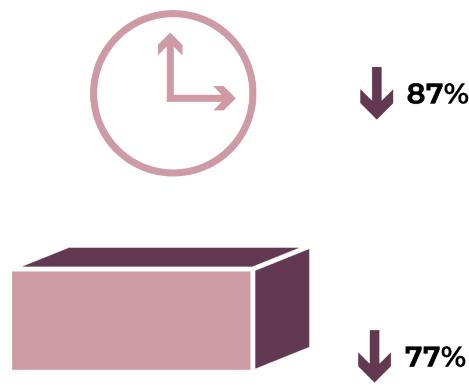
Conclusion and Discussion

Research question

*What are the main aspects and limitations of a *three-dimensional* topology optimization for the design of a *massive cast glass structure*?*

Conclusion and Discussion

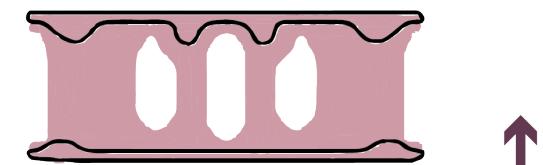
Upsides



Decrease Material Usage and Annealing time



Increased Structural Stiffness

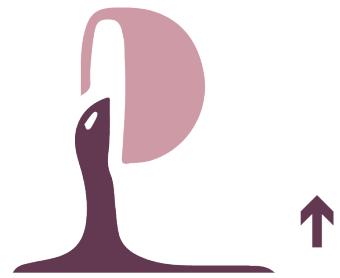


Increased Spatial Insight

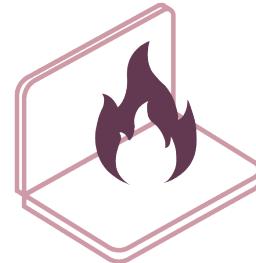
Limitations



Increase Time
Post-Processing



Complex Geometry
For Fabrication



Increased
Computational Need

Conclusion and Discussion

Reflection

Asking the right question...



**Yes, I thought it over
quite thoroughly. It's 42.**

Hitch Hikers Guide to the Galaxy

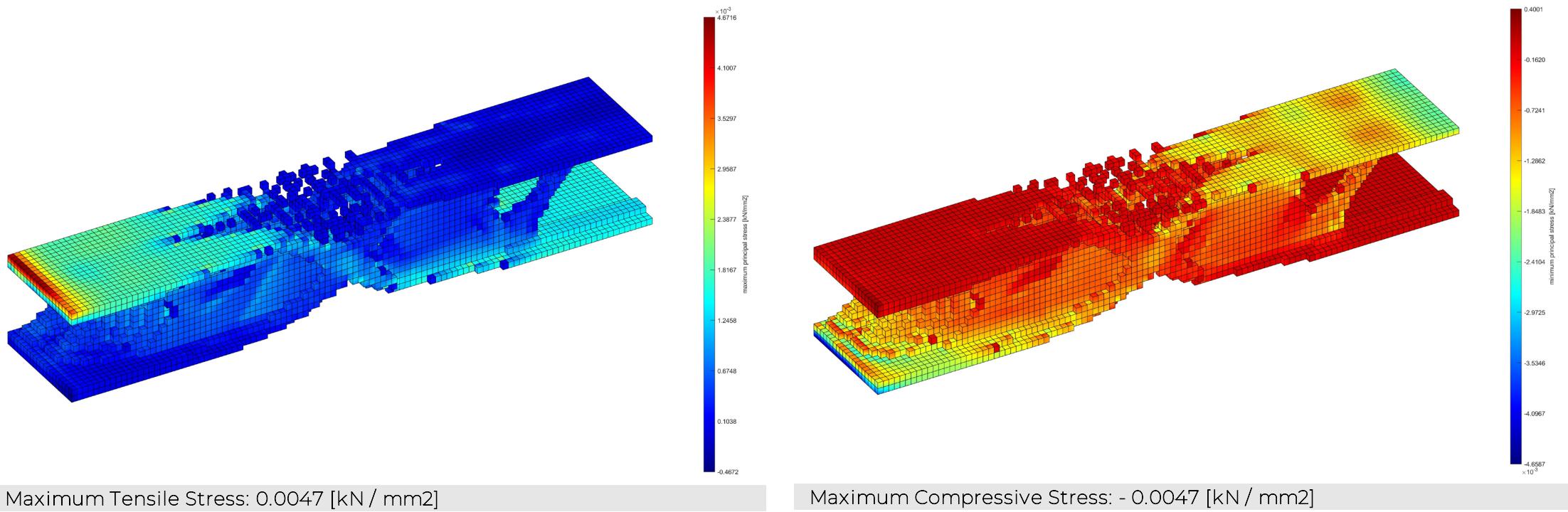
Reflection

Asking the right question...



Reflection

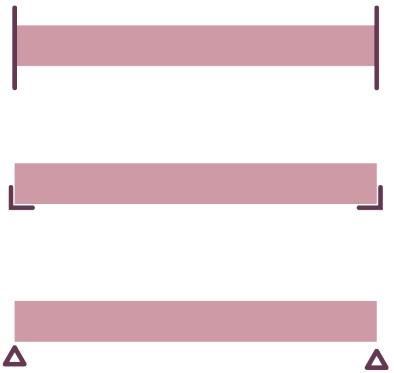
Reflection



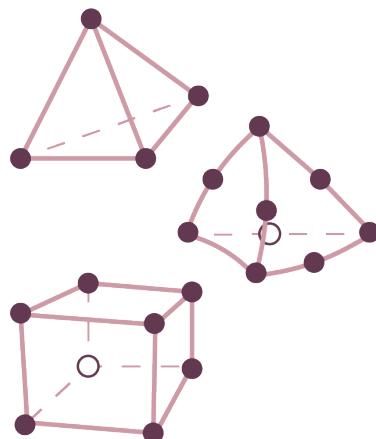
Reflection

Further Research

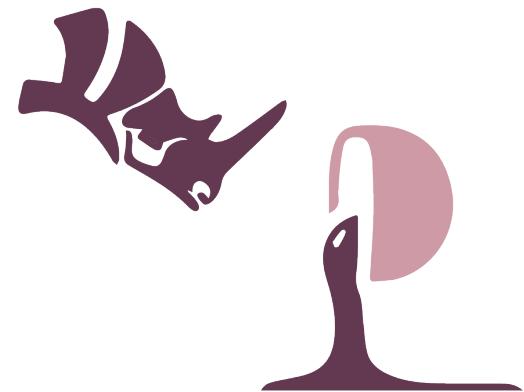
Further Research



**Explore more
Design Options**



**Develop algorithm using
other Finite Element Types**



**Incorporate Post Processing and
Mould Design into Workflow**

Explore Other Material



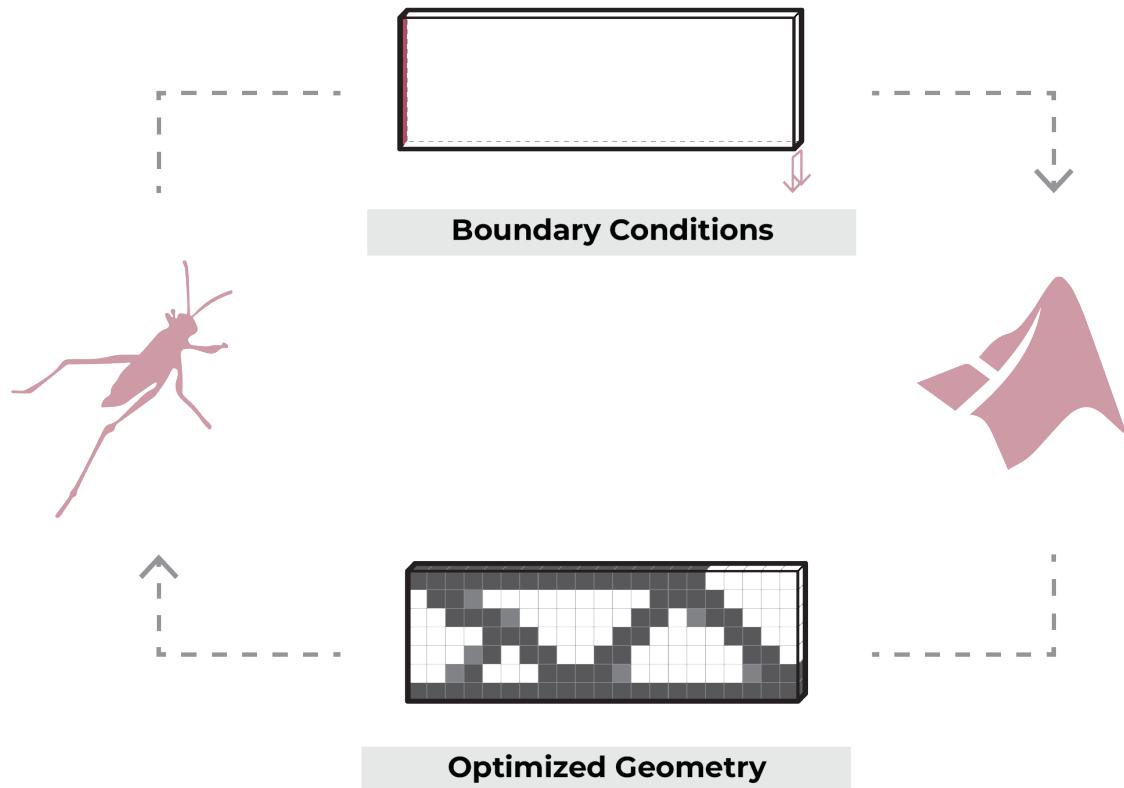
Concrete



Recycled glass

Further Research

Grasshopper Implementation



[https://github.com/ESchoenmaker
/3D_TO_cast_glass](https://github.com/ESchoenmaker/3D_TO_cast_glass)

Further Research

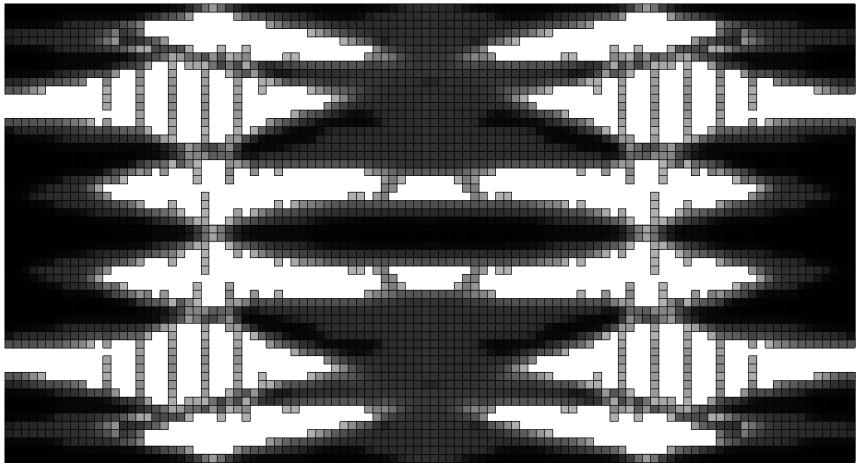
Questions?



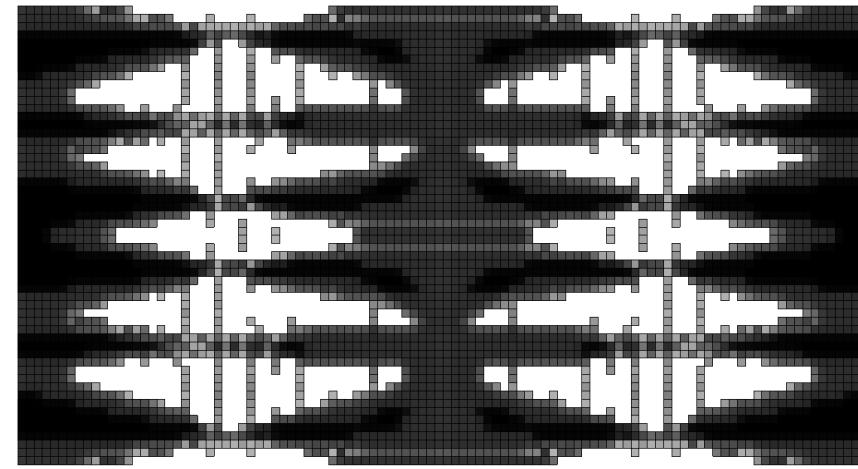
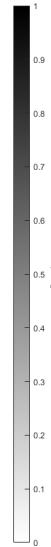
Appendix

Comparison Results

Geometry



Top View Compliance Optimization

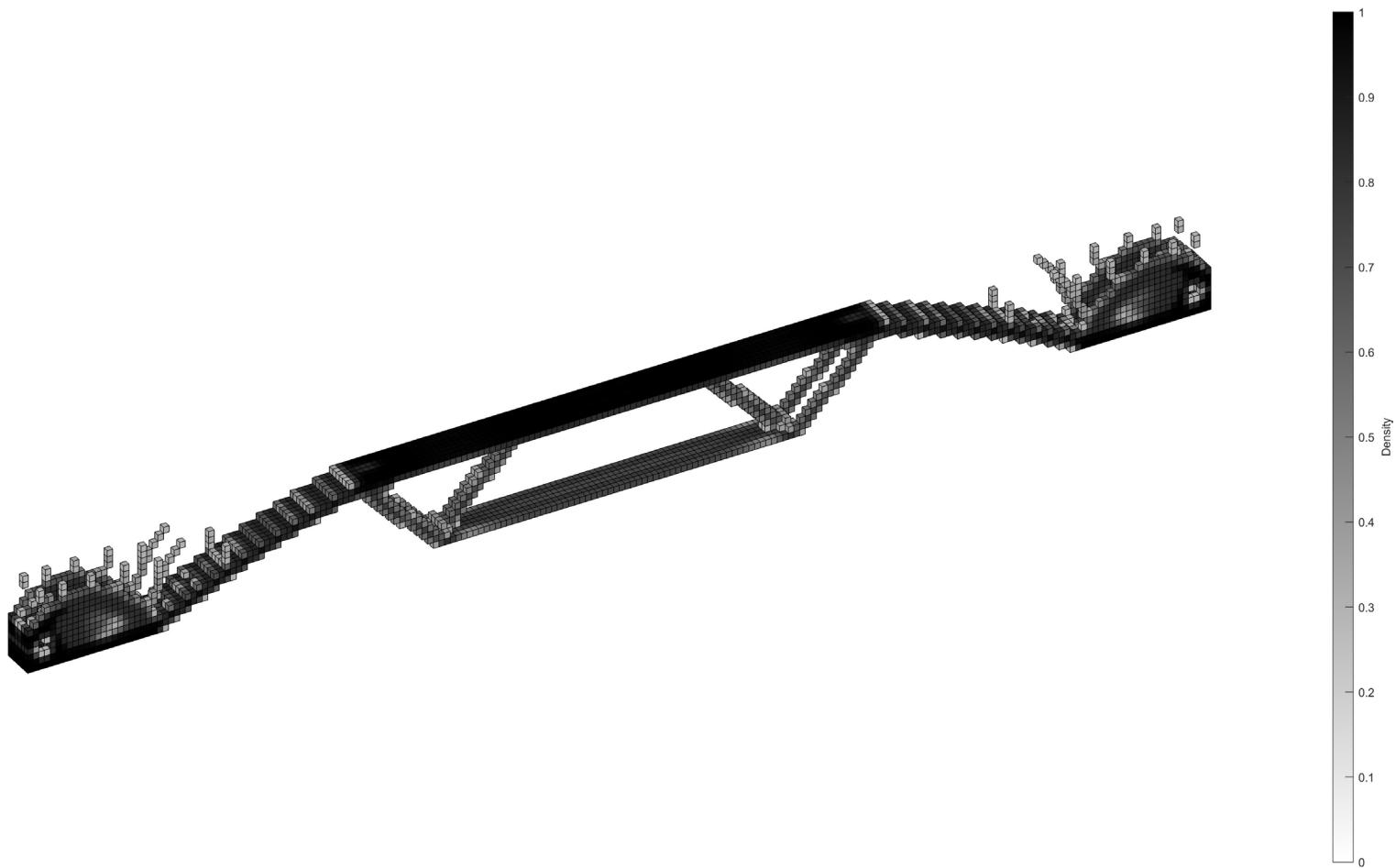


Top View Volume Optimization



Design Exploration

Change in Boundary Conditions



Appendix

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126

Mirroring

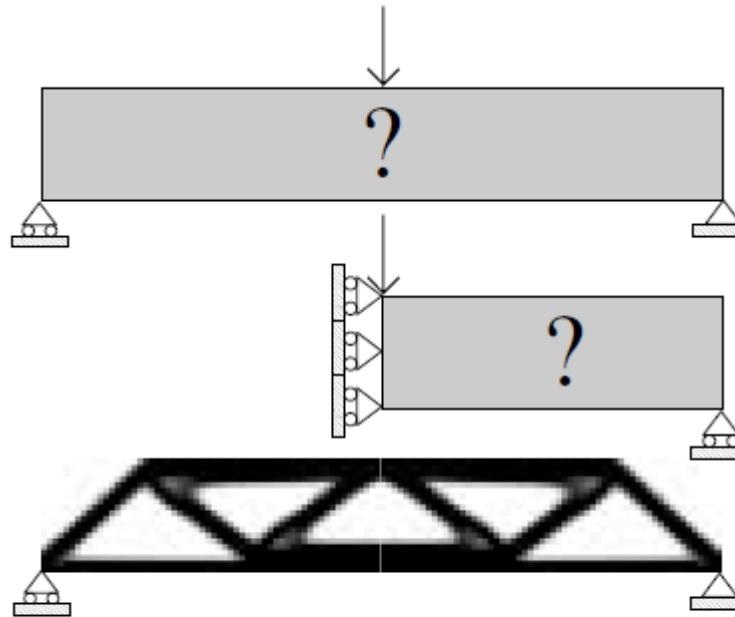
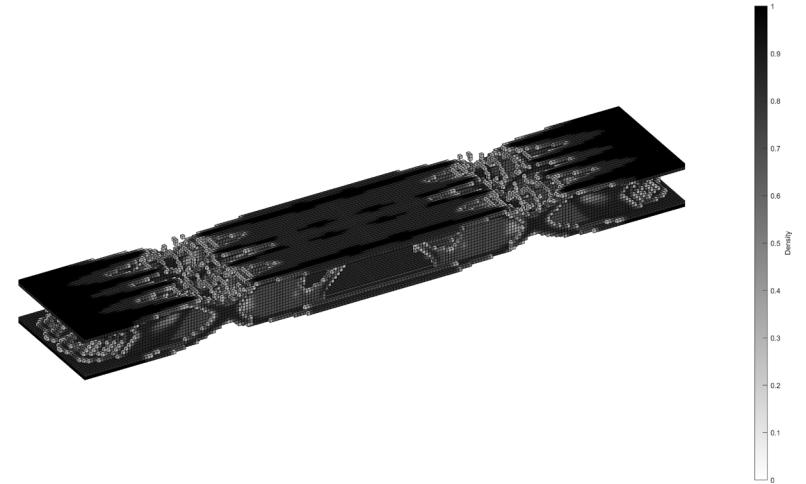
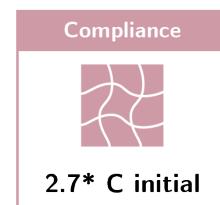
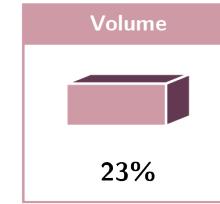
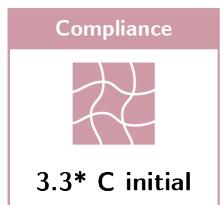
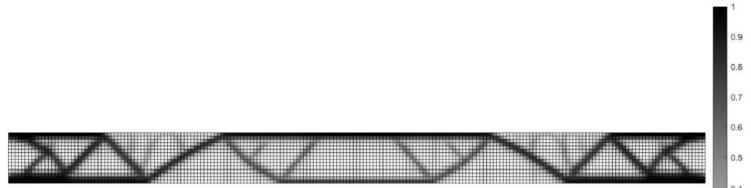
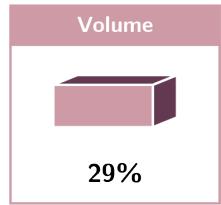


Fig. 1 Topology optimization of the MBB-beam. Top: full design domain, middle: half design domain with symmetry boundary conditions and bottom: resulting topology optimized beam (both halves)

Appendix

Upsides | Decrease Material & Increase Stiffness

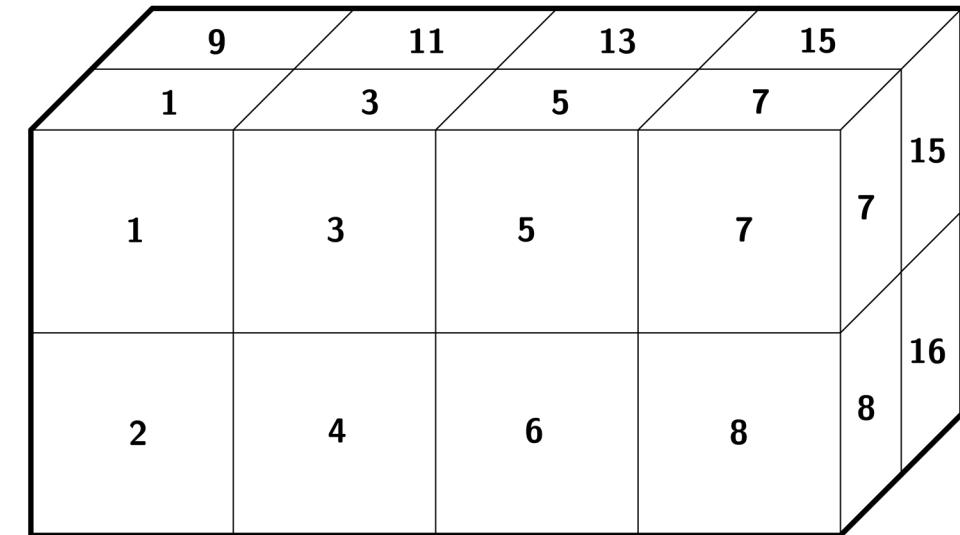
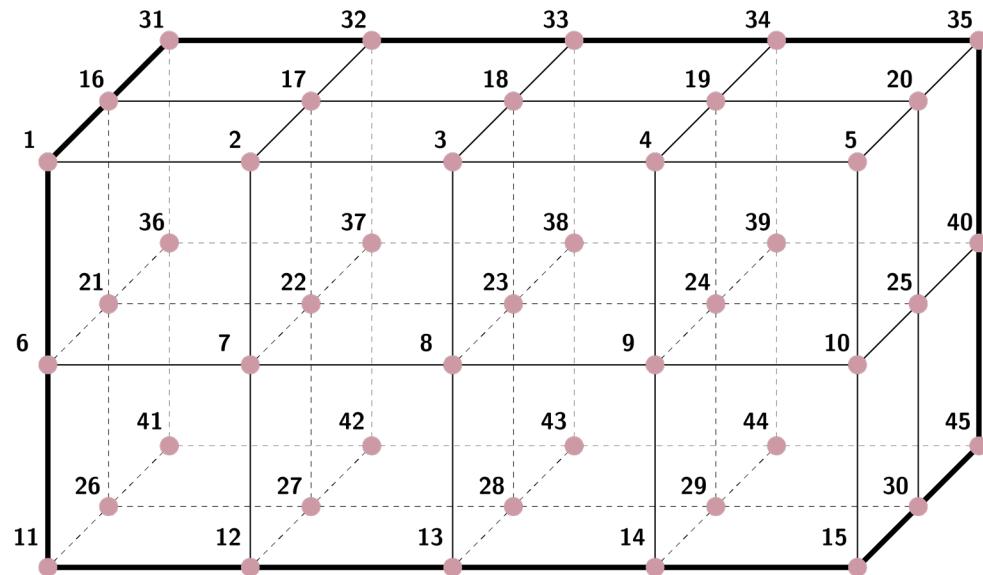


2D Optimization
Anna Maria Koniari

3D Optimization
Eva Schoenmaker

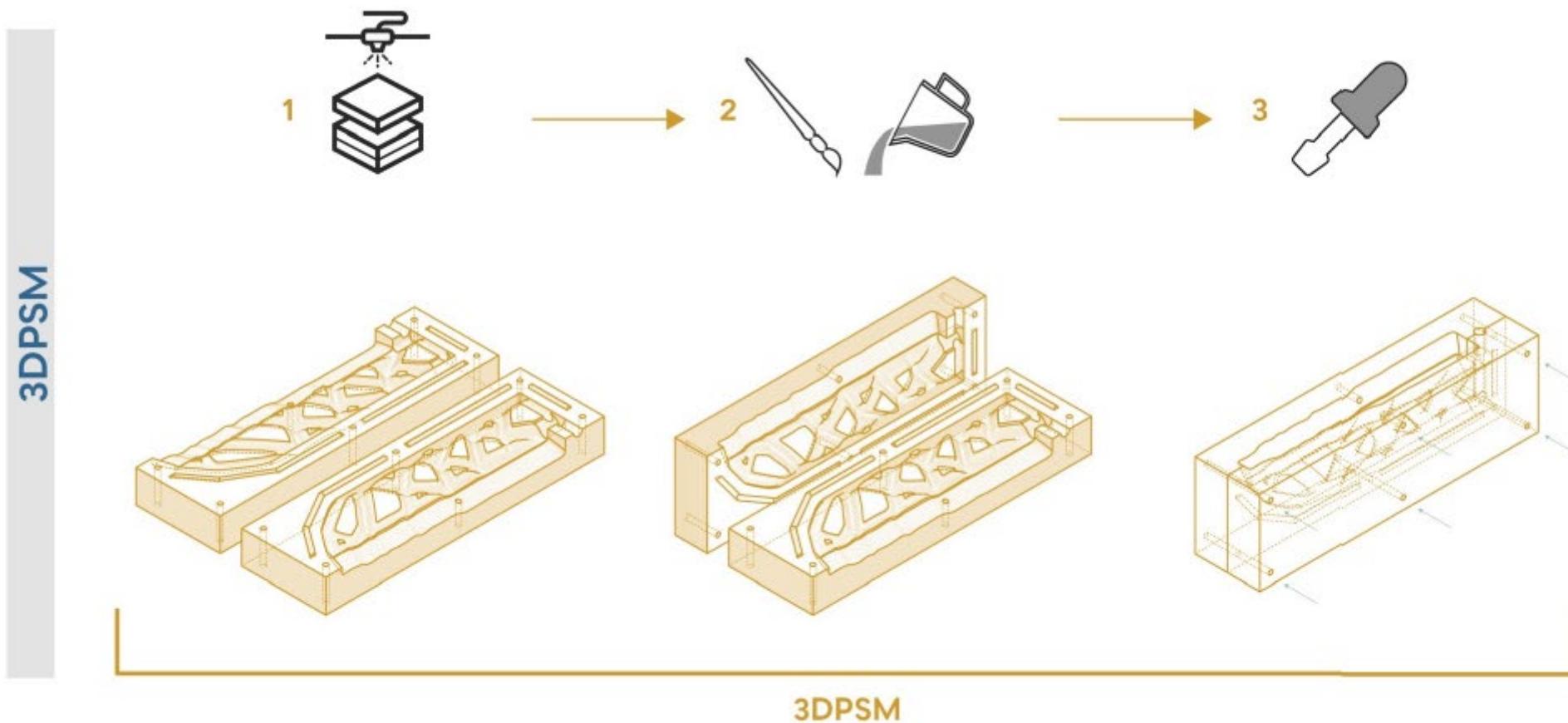
Conclusion and Discussion

Nodal Counting

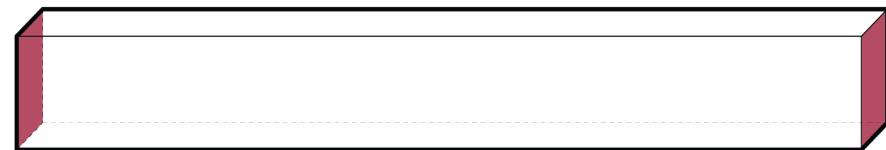


Appendix

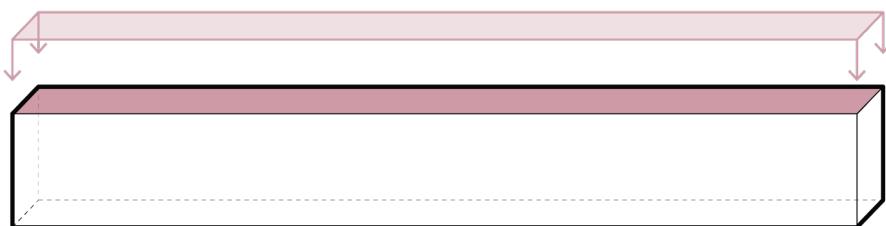
Improvement surface quality



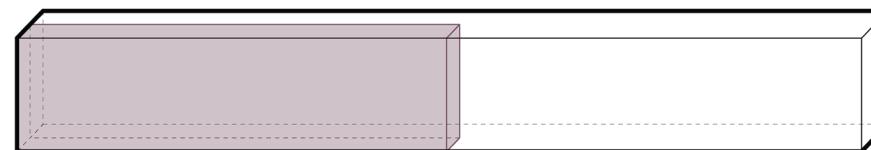
Small Three Dimensional optimization



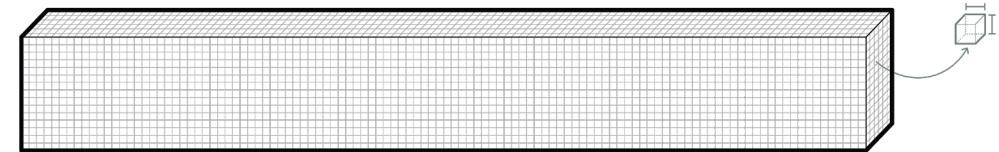
Supports: Fully Fixed Sides



Loads: Distributed Load



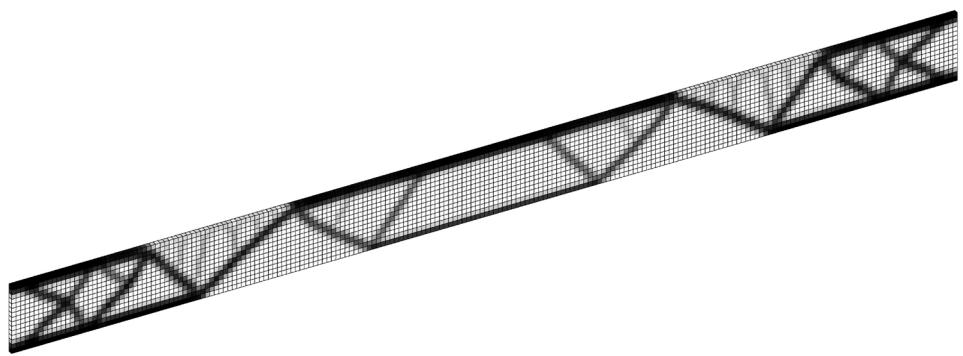
Calculated Domain (l, w, h): 2.1 m * 0.06 m * 0.3 m



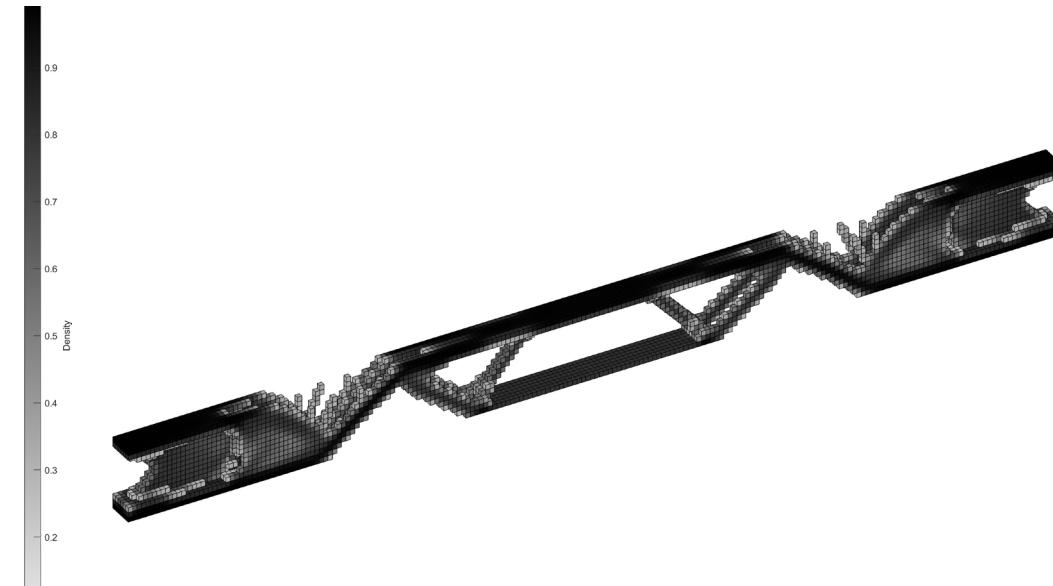
Finite Element Size: 0,02 * 0,02 * 0,02 m

Calibrating Algorithm

3D beam Compliance



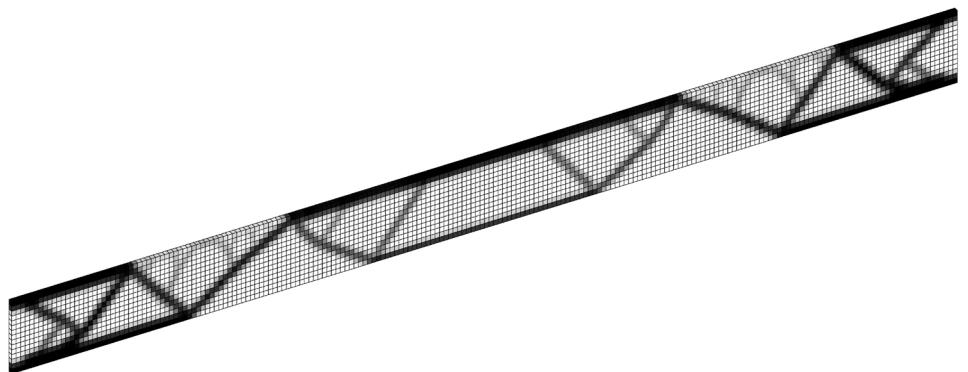
Two Dimensional Compliance Optimization Result



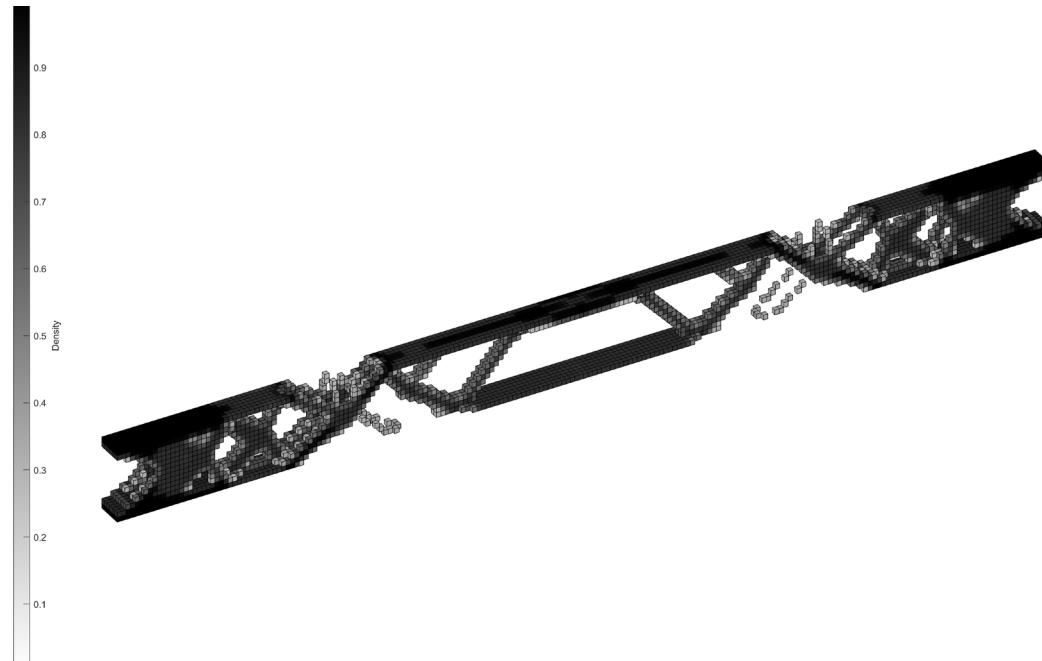
Small Three Dimensional Compliance Optimization Result

Calibrating Algorithm

Volume



Two dimensional Volume Optimization



Small Three Dimensional Volume Optimization

Calibrating Algorithm