Bringing Glass Giants to life

Fabrication of mass-optimized structural glass components of complex form

ONASSIS FOUNDATION

TUDelft

ExOne

HA GROUP

P5 Presentation 05.07.23

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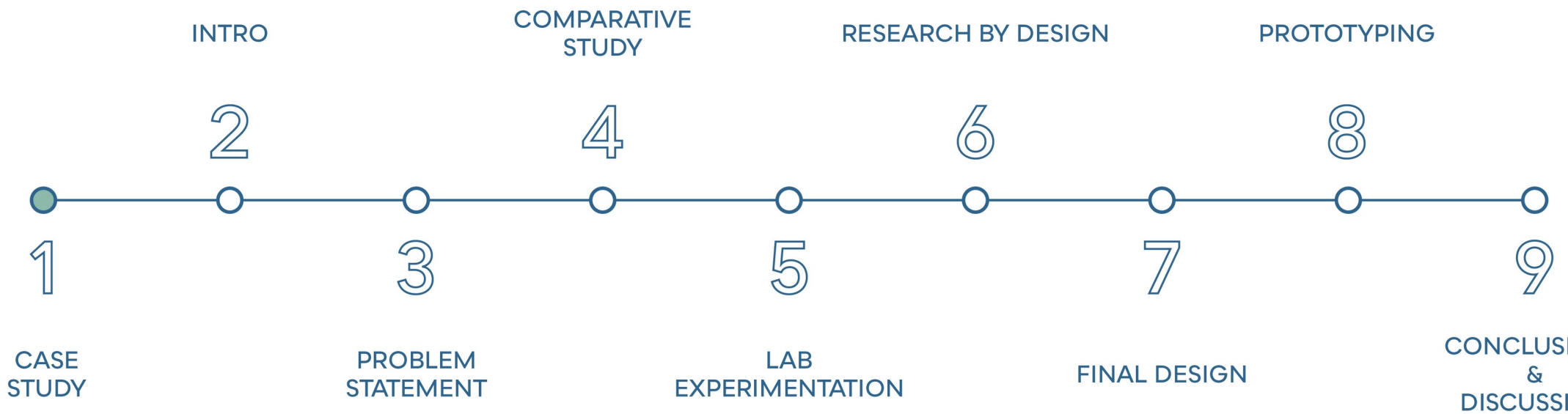
STUDENT: **MENANDROS IOANNIDIS** | 5627338

"I am exploring ways of improving the **surface quality** and **optical transparency** of **complex and customized glass** forms produced via **kiln casting** and the use of **disposable 3D printed sand moulds**"

IN A NUTSHELL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CONCLUSIONS & DISCUSSION

CASE STUDY

ALL-GLASS BRIDGE OBSERVATORY

TOPOGRAPHY AND LOCATION

OXYA VIEW POINT, VIKOS GORGE, GREECE

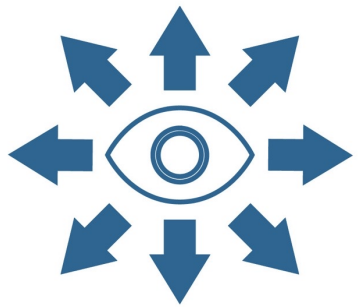
CASE STUDY

SITE: OXYA VIEWPOINT, VIKOS GORGE

Source: Google maps

OPTICAL

Minimal optical footprint



Unobstructed view

DESIGN FREEDOM

Unique structure/ experience

SUSTAINABILITY

Sustainable manufacturing

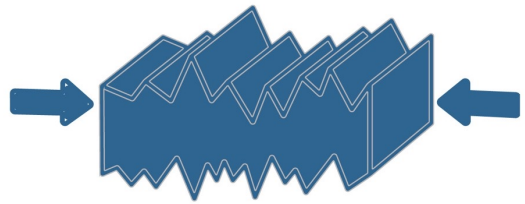
DESIGN PRINCIPLES

WHY GLASS ?

TRANSPARENT

DURABLE

RECYCLABLE



HIGH COMPRESSIVE STRENGTH

WHY GLASS ?

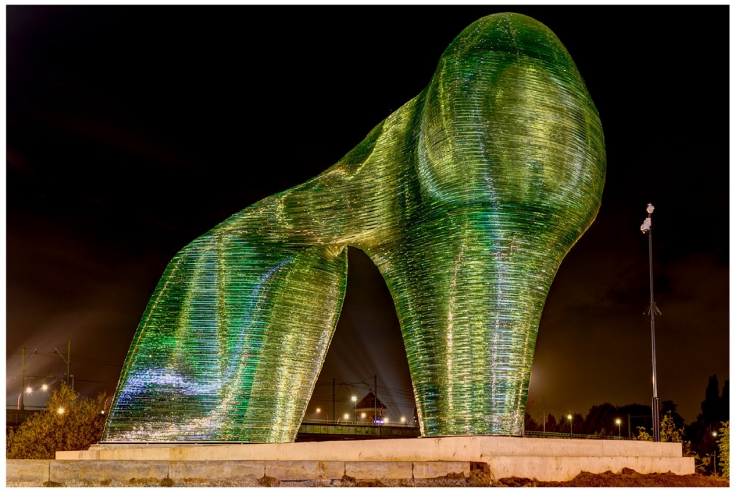
LAMINATION OF FLOAT GLASS

CENTRE ADMINISTRATIF
Brunet Saunier Architecture (1995)

YURAKUCHO CANOPY
Rafael Viñoly Architects (1997)

APPLE STORE FIFTH AVENUE
Bohlin Cywinski Jackson (2006)

LAMINATION OF FLOAT GLASS



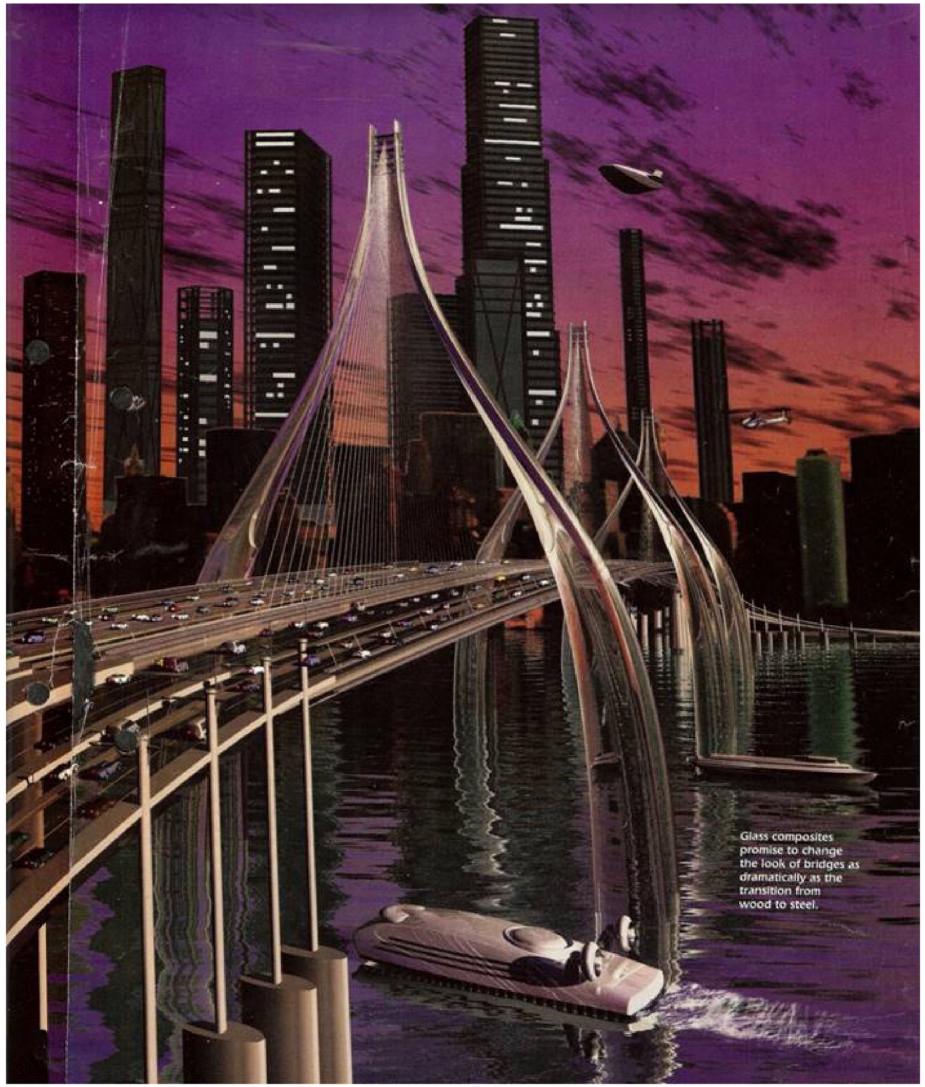
GLASS SPHINX
Schobbers, F. (1993), image credits: Twan van den Hombergh

CAST GLASS

QAAMMAT PAVILION
Konstantin Arkitekter, (2021), image credits: Julien Lanoo

3D PRINTED GLASS

GLASS II
Inamura, C. (2017)



GLASS BRIDGE
Uknown

DANTEUM (GLASS COLUMNS)
Giuseppe Terragni , 1938

COMPLEX SHAPED GLASS: STRUCTURES

CAST GLASS

RECLINING DRESS IMPRESSION WITH DRAPERY
Karen LaMonte

WATER DOUBLE, V.1
Roni Horn, image credits:Ron Amstutz

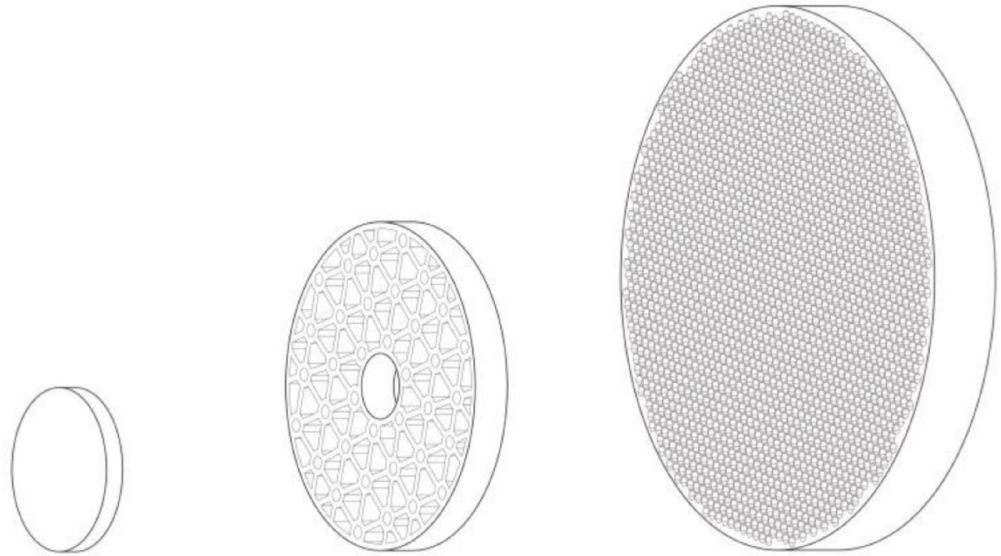
COMPLEX SHAPED GLASS: ART

COMPLEX SHAPED GLASS: SCIENCE

GIANT MAGELLAN TELESCOPE BLANC Ø 8.4 M

WHY DON'T WE SEE GLASS GIANTS IN ARCHITECTURE?

GLASS PARTICULARITIES



Telescope	Hooker blank	Hale-1 blank	Giant Magellan blank
glass type	Wine bottle glass (St Gobain)	Pyrex Glass (Corning)	E6 Borosilicate Glass (Ohara Inc)
therm. exp. coefficient (α)	$9 *10^{-6} *1/C$	$3.25 *10^{-6} *1/C$	$2.8 *10^{-6} *1/C$
diameter Ø	**2.5 m**	**5 m**	**8.4 m**
max. thickness	325 mm	660 mm	894 mm
weight	**4 tn**	**20 tn**	**16 tn**
annealing time	**12 months**	**10 months**	**3 months**

solid disc → **reduce weight:** honeycomb structure → **further reduce weight:** thinner ribs **reduce post-processing:** spin-casting

TOPOLOGY OPTIMIZATION →

Time efficient

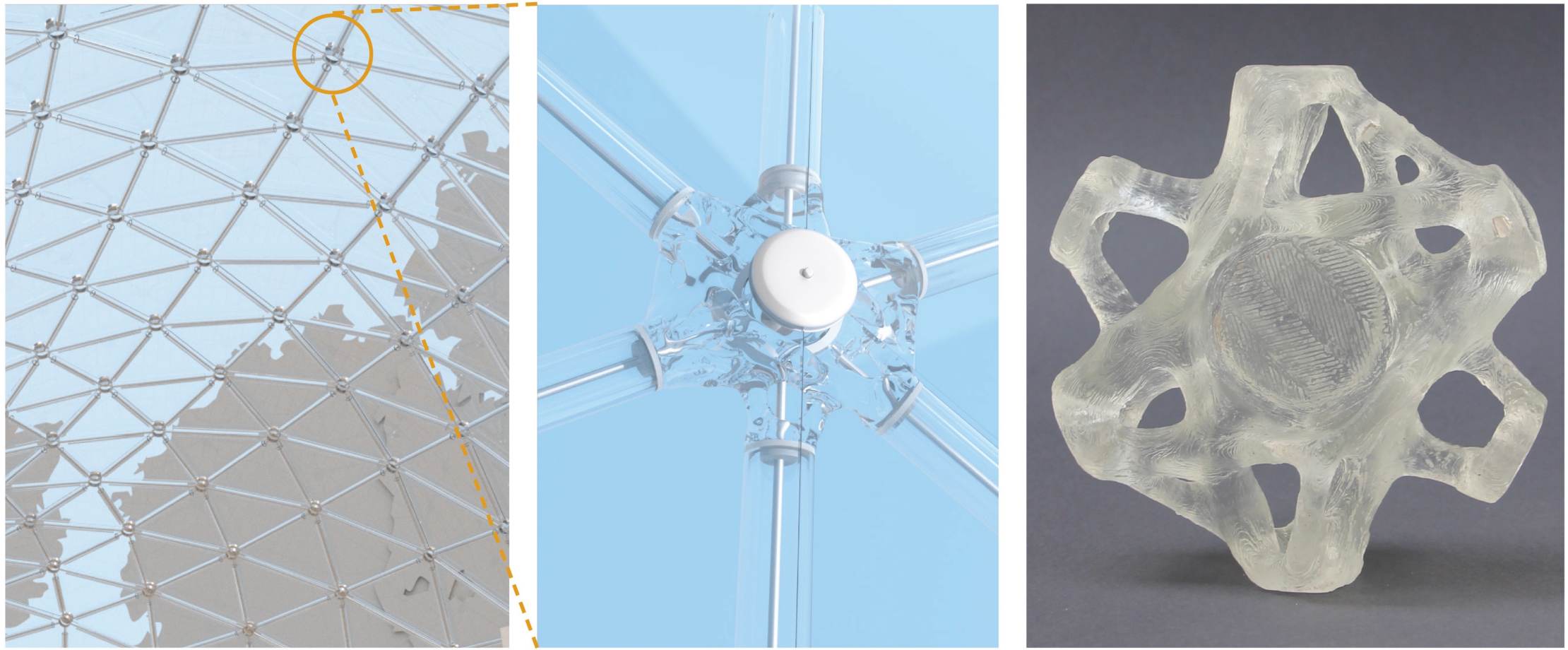
Energy efficient

Cost efficient

ANNEALING TIME

TELESCOPE BLANKS ANNEALING TIME

Oikonomopoulou (2019), Zirker (2005)



TOPOLOGICALLY OPTIMIZED GLASS

GRID SHELL NODE

Damen, W. (2019)

FABRICATION LIMITATIONS

LAMINATION OF FLOAT GLASS

https://glasshape.co.nz/about-us/sustainability/

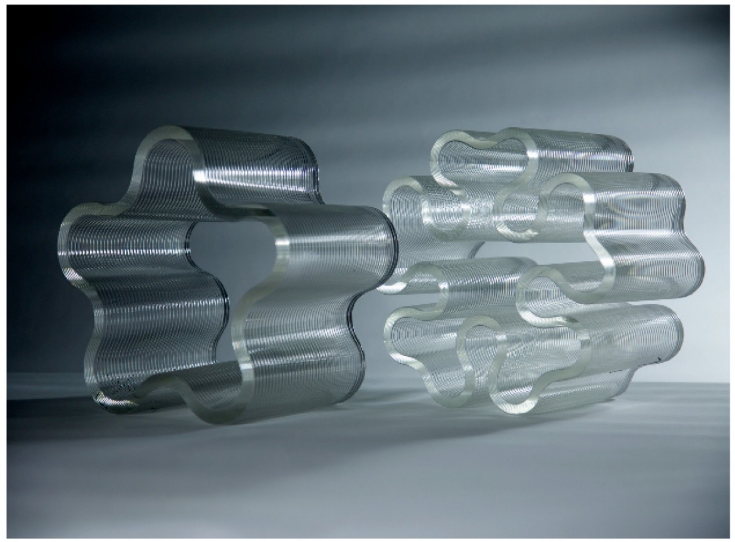
HIGH WASTE GENERATION
LAMINATION CHALLENGES

CAST GLASS

Oikonomopoulou et. al (2020)

COST INEFFICIENT OR
NEED FOR POST PROCESS

3D PRINTED GLASS



https://www.chikara-inamura.com/GLASS/GLASS-II-APPLICATION

SIZE LIMITATIONS

FABRICATION CHALLENGES

ESTABLISHED FABRICATION METHODS

FABRICATION POTENTIAL

CASTING USING 3D PRINTED SAND MOULDS

APPLICATIONS IN CONCRETE

T.O. CONCRETE SLAB/ PROTOTYPE A

Digital Building Technologies (ETH) (2016)

APPLICATIONS IN STEEL

T.O. NODE

Arup, Galjaard, S., Hofman, S., Perry, N., Ren, S. (2015)

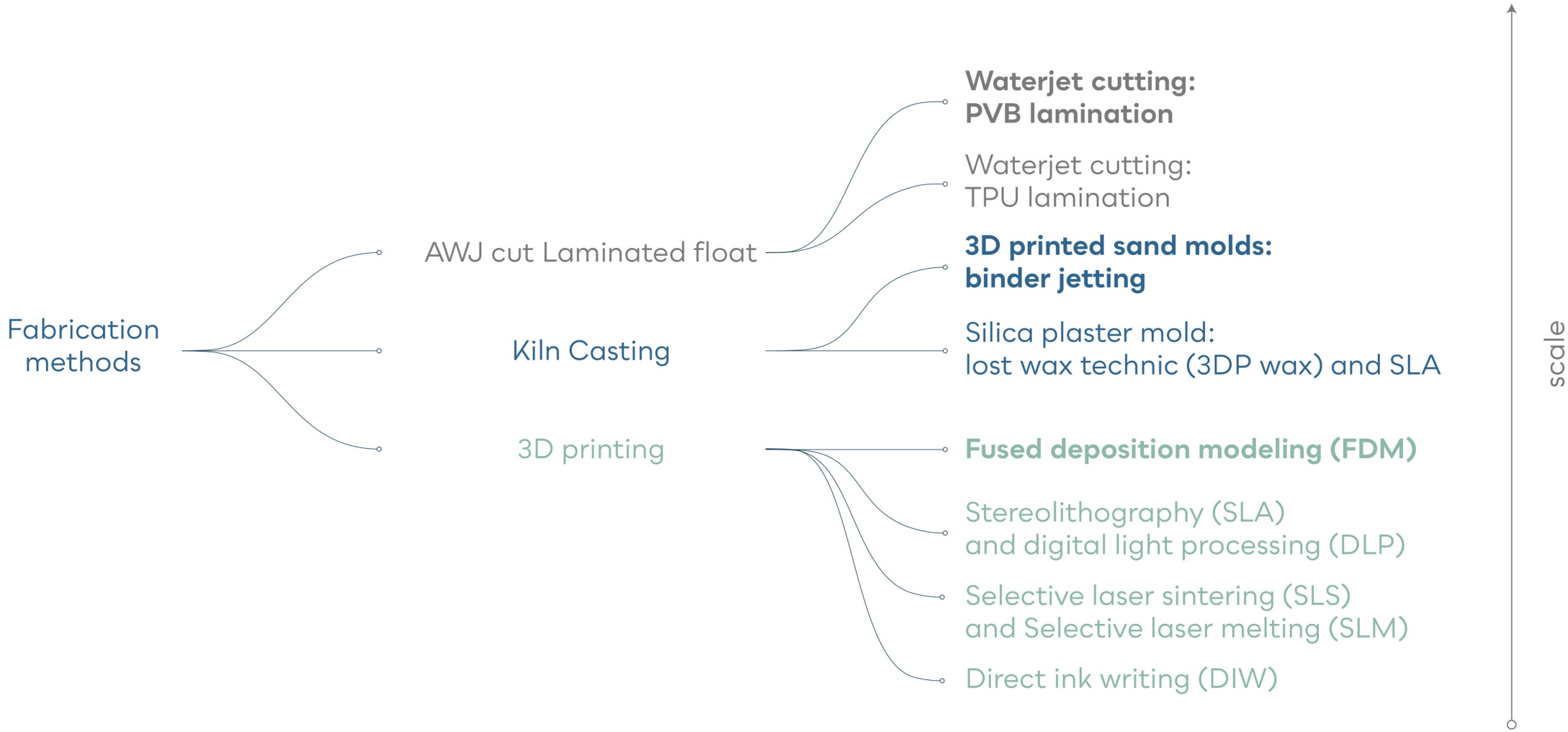
MAIN RESEARCH QUESTION

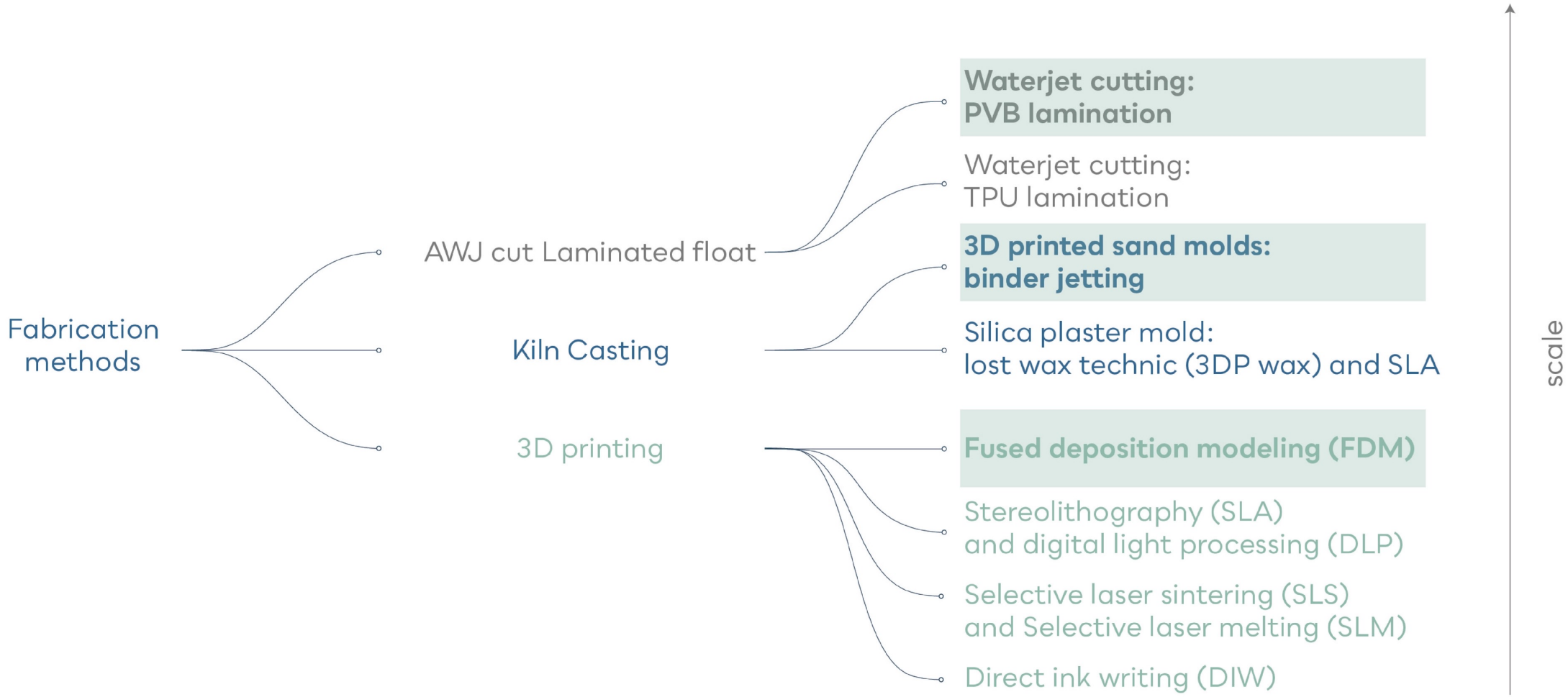
Which fabrication method for glass is **most promising** in terms of:

- **optical quality**,
- **structural performance**,
- **sustainability** and
- **fabrication freedom**?

MAIN RESEARCH QUESTION

COMPARATIVE STUDY


Fabrication methods
AWJ cut Laminated float
Kiln Casting
3D printing
Waterjet cutting: PVB lamination
Waterjet cutting: TPU lamination
3D printed sand molds: binder jetting
Silica plaster mold: lost wax technic (3DP wax) and SLA
Fused deposition modeling (FDM)
Stereolithography (SLA) and digital light processing (DLP)
Selective laser sintering (SLS) and Selective laser melting (SLM)
Direct ink writing (DIW)
scale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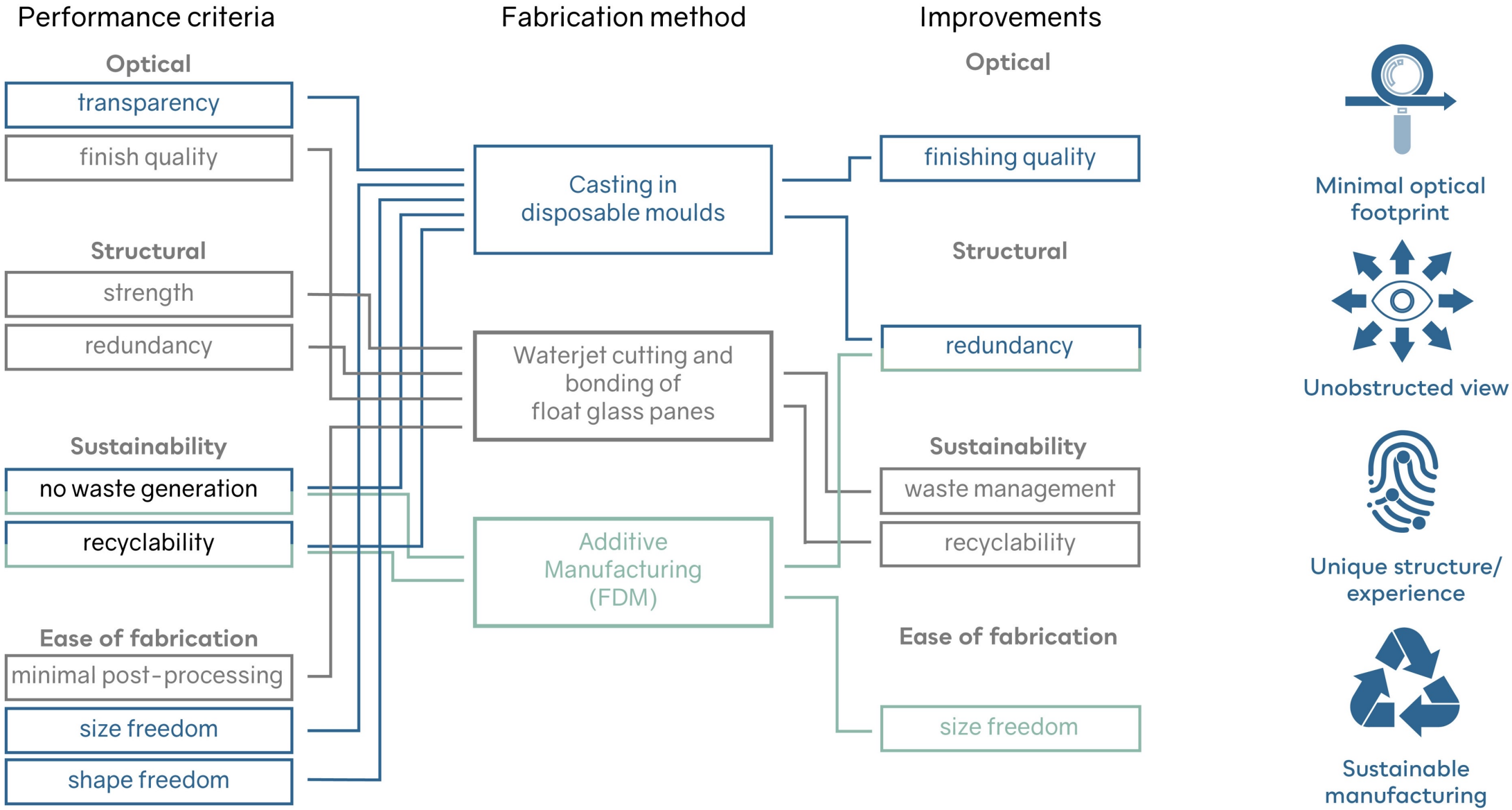
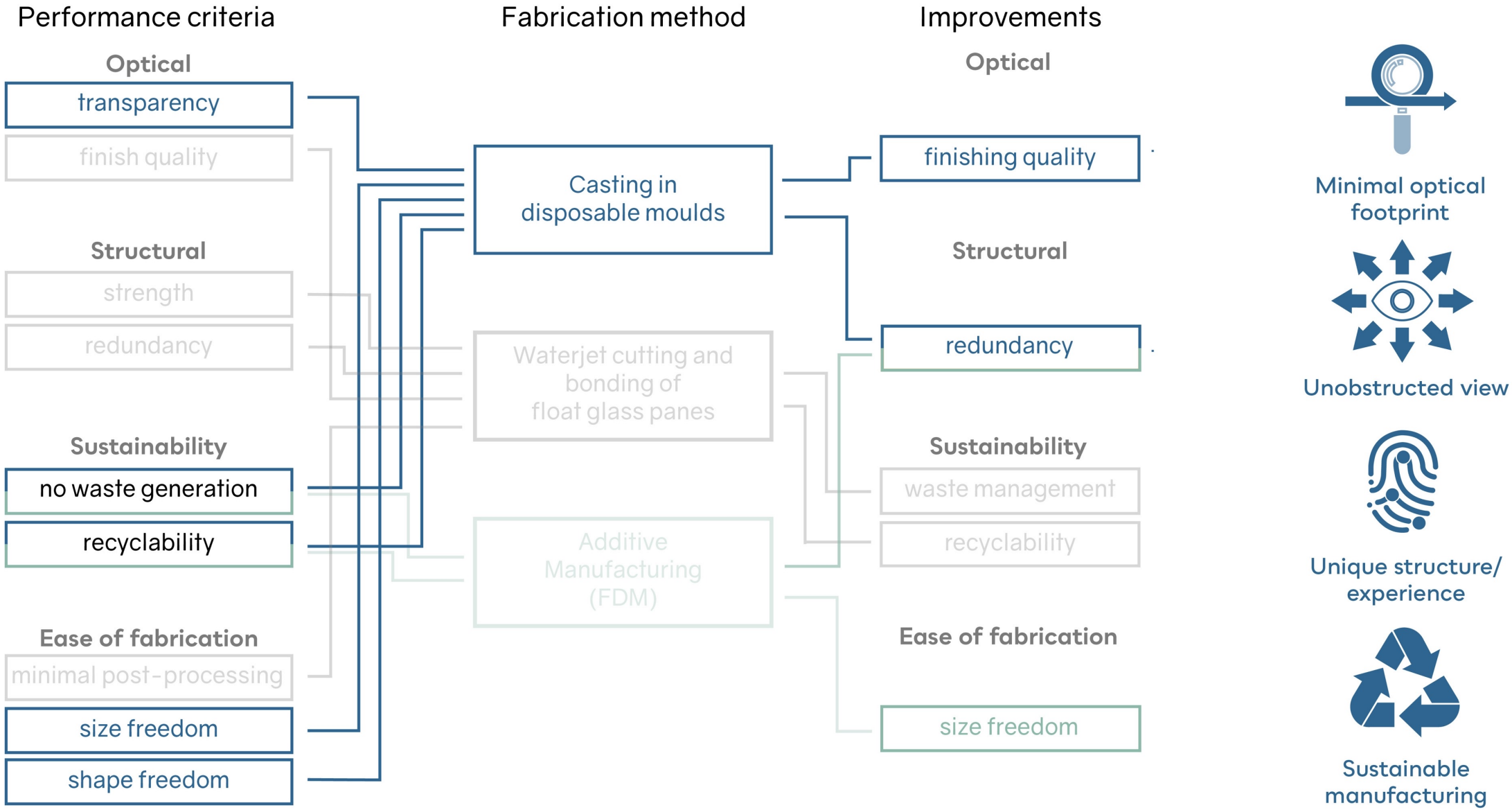

Performance criteria
Optical
transparency
finish quality
Structural
strength
redundancy
Sustainability
no waste generation
recyclability
Ease of fabrication
minimal post-processing
size freedom
shape freedom
Fabrication method
Casting in disposable moulds
Waterjet cutting and bonding of float glass panes
Additive Manufacturing (FDM)
Improvements
Optical
finishing quality
Structural
redundancy
Sustainability
waste management
recyclability
Ease of fabrication
size freedom
Minimal optical footprint
Unobstructed view
Unique structure/ experience
Sustainable manufacturing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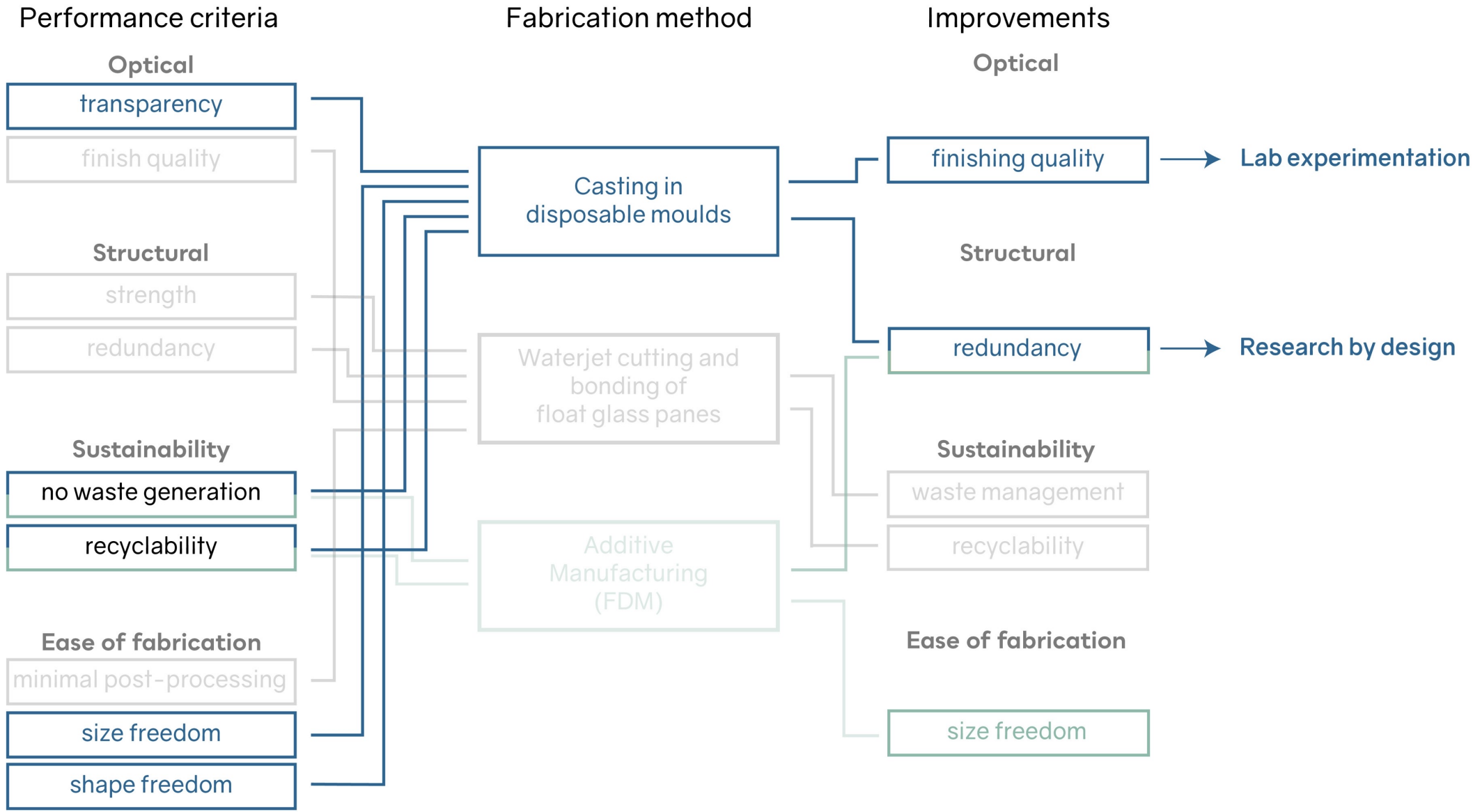
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Waterjet cutting and bonding of float glass panes
Additive Manufacturing (FDM)
Optical
finishing quality
Lab experimentation
Structural
redundancy
Research by design
Sustainability
waste management
recyclability
Ease of fabrication
size freedom

FINISHING QUALITY

LAB EXPERIMENTATION

3DPS mould

(Bhatia, 2019)

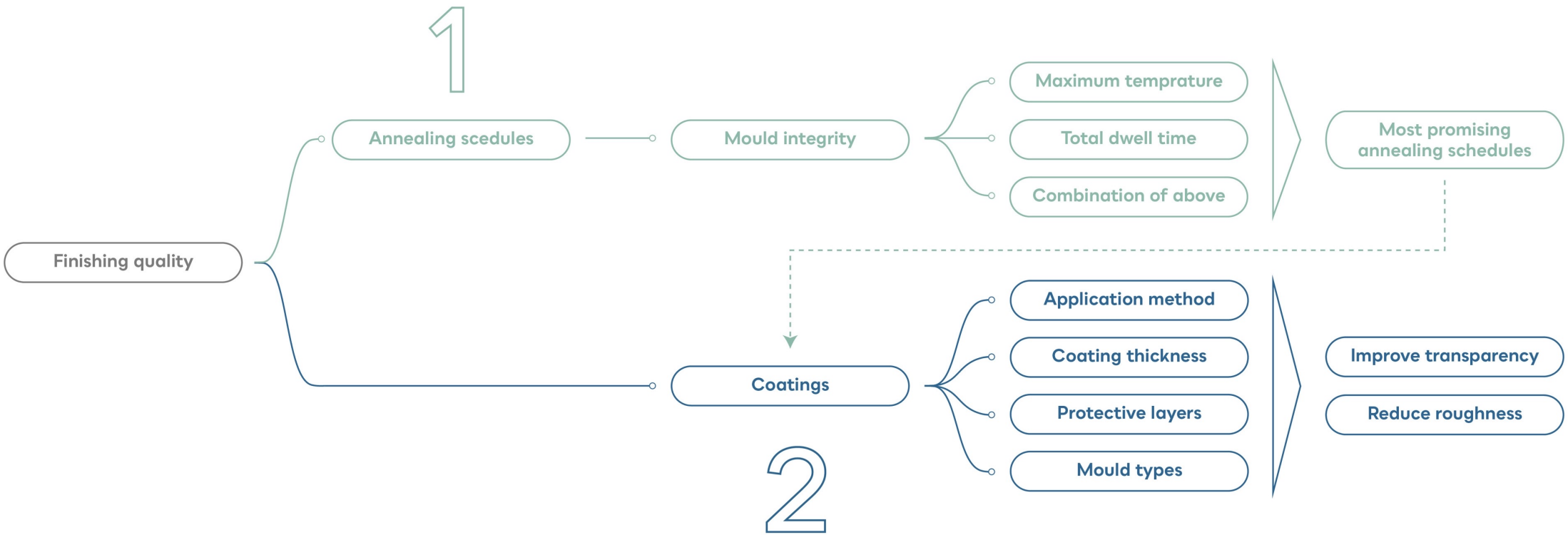
?

Steel mould

Oikonomopoulou, Bristogianni, Veer, et al., (2018)

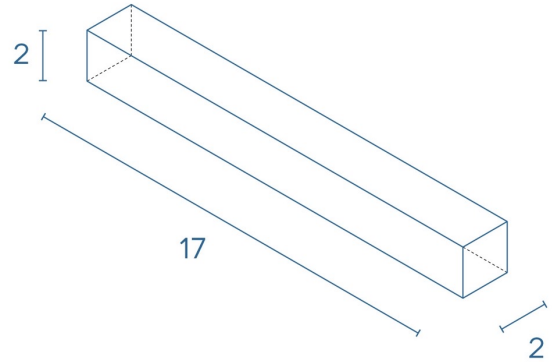
FABRICATION CHALLENGES

SURFACE QUALITY



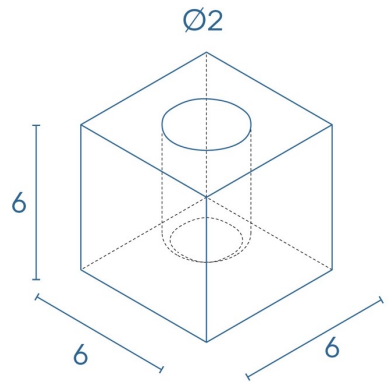
EXPERIMENTS OVERVIEW

1



Bar

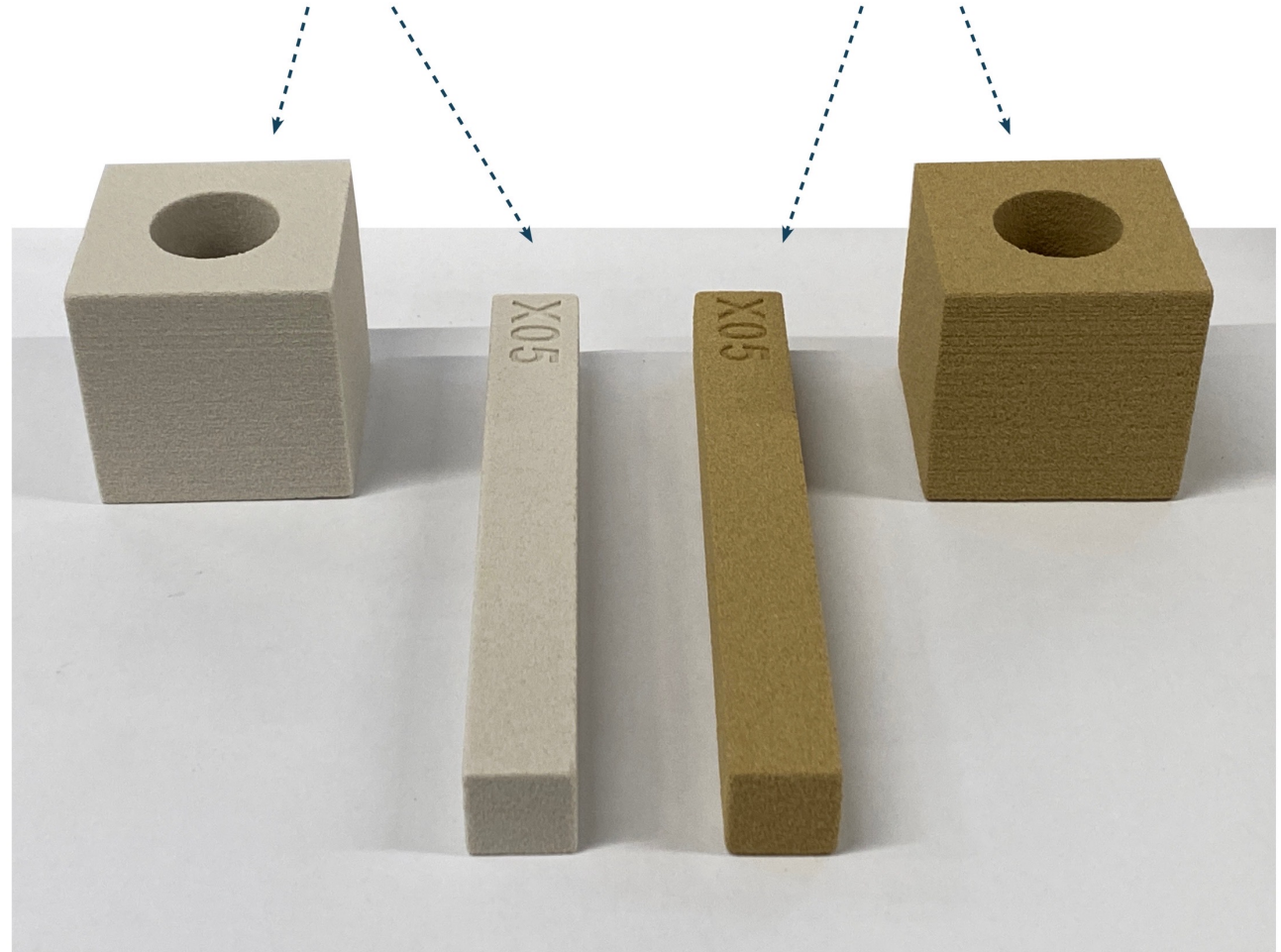
2



Cube

Quartz sand
Inorganic binder

Ceramic sand
Inorganic binder



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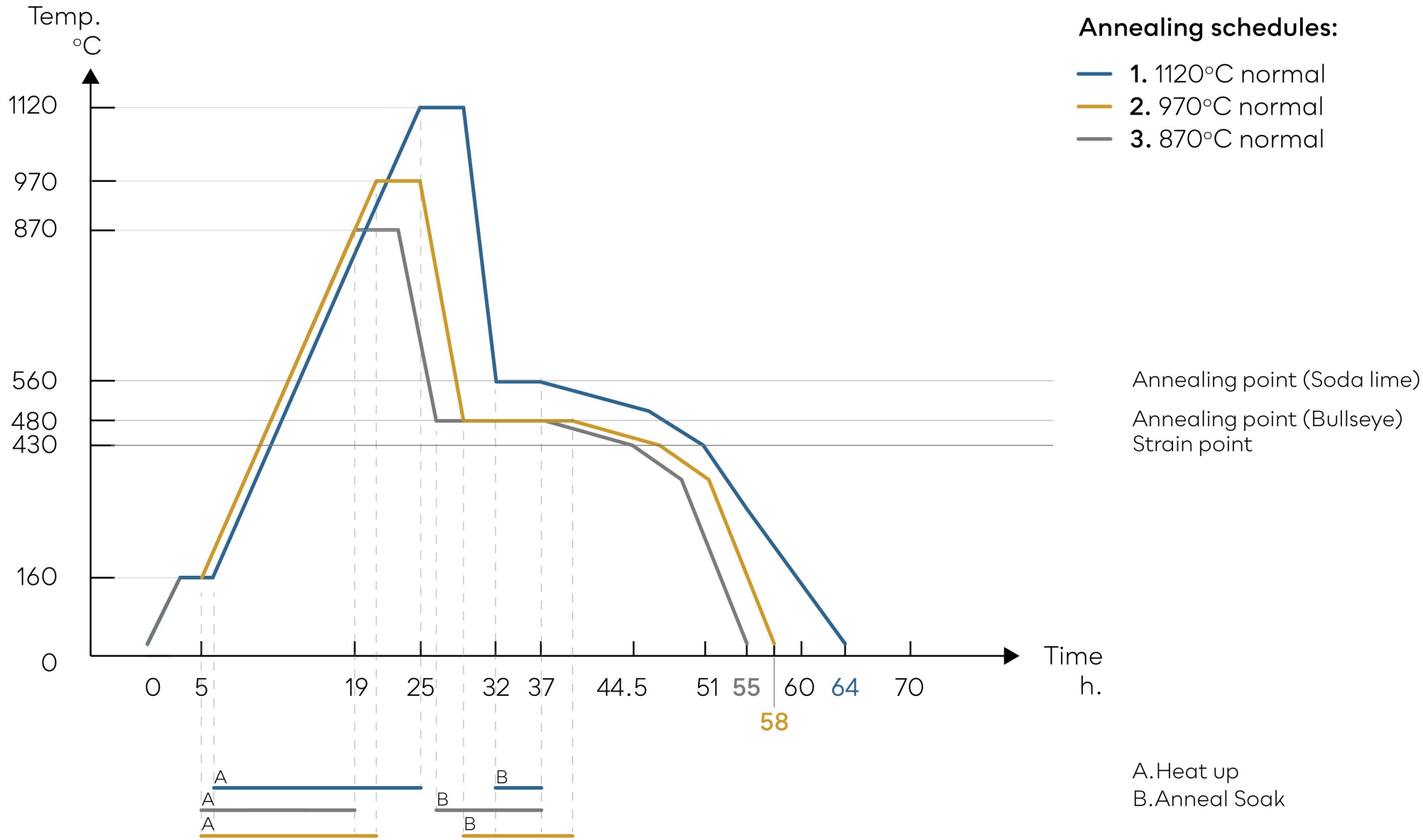
ANNEALING SCHEDULES



Annealing schedules:

- **1.** 1120°C normal
- **2.** 970°C normal
- **3.** 870°C normal

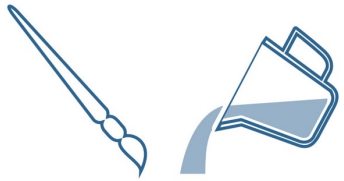
Annealing point (Soda lime)

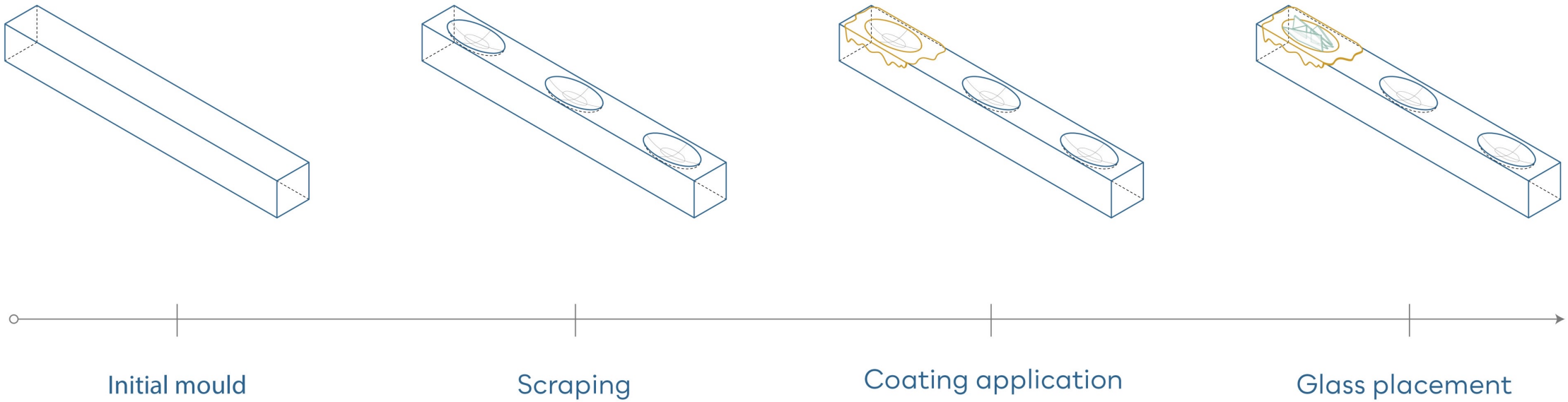
Annealing point (Bullseye)
Strain point

A. Heat up
B. Anneal Soak

ANNEALING SCHEDULES

QUARTZ SAND AND CERAMIC SAND





COATING APPLICATION

Quartz sand

1120°C normal

64 hrs

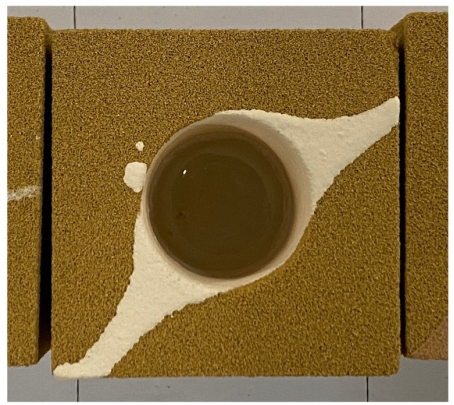
970°C normal

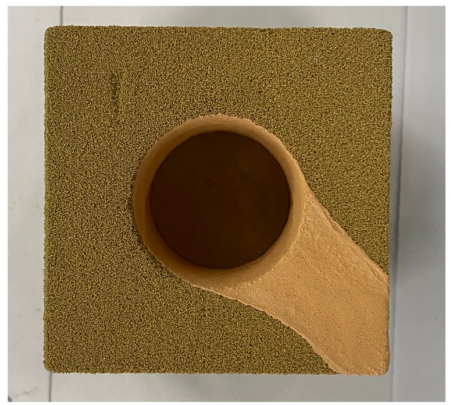
58 hrs

870°C normal

55 hrs

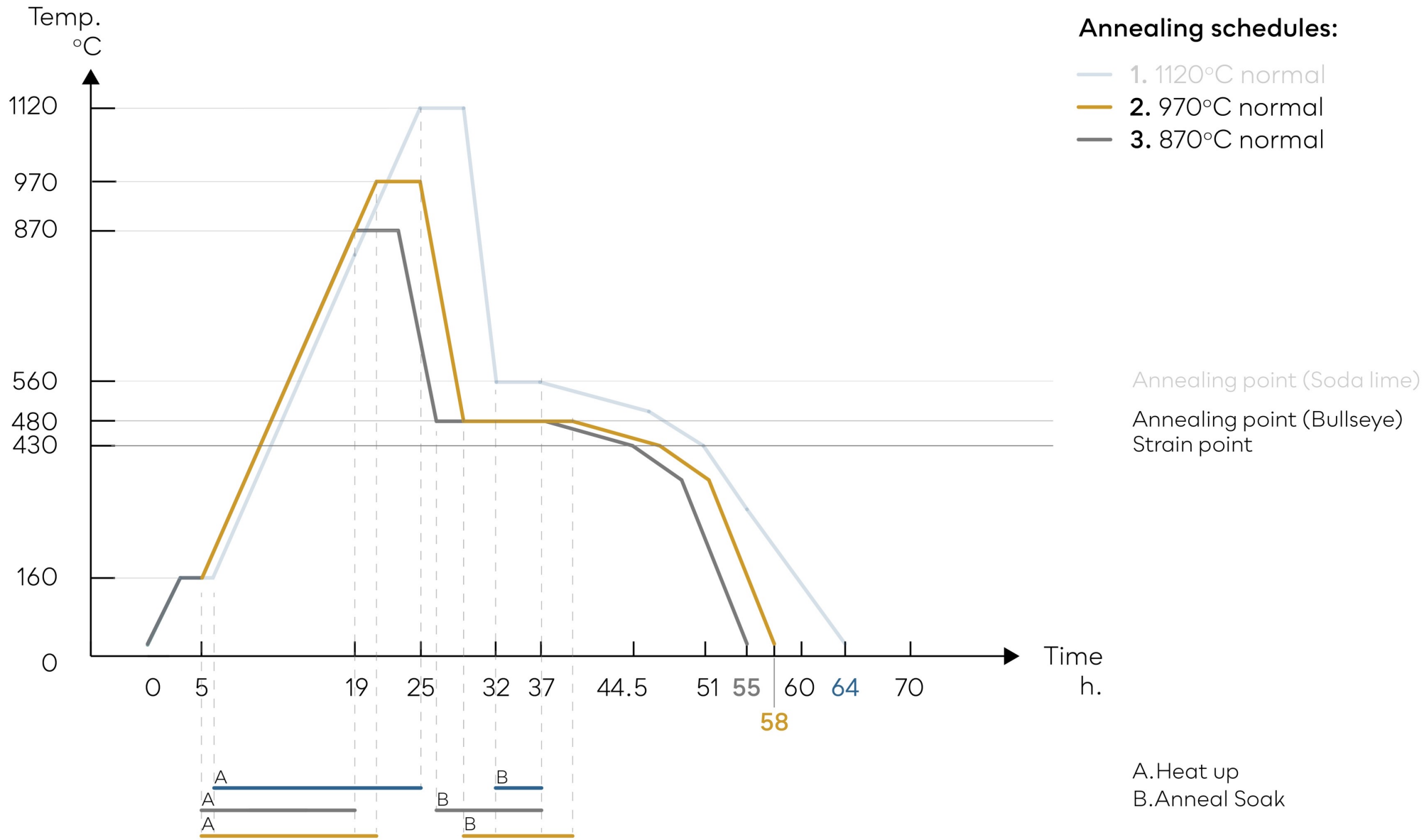
Ceramic sand





OBSERVATION PER SCHEDULE

QUARTZ AND CERAMIC SAND



MOST PROMISING SCHEDULES

QUARTZ SAND AND CERAMIC SAND

COATINGS EXPERIMENTS

COATINGS

	Name	Solvent	Dilution (flow application)	Provider
1	Zirkofluid 1219	Isopropanol	~ 40% wt.	Hüttenes Albertus
2	Zirkofluid 6672	Isopropanol	~ 10% wt.	Hüttenes Albertus
3	Arkopal B 5	Water	~ 30% wt.	Hüttenes Albertus

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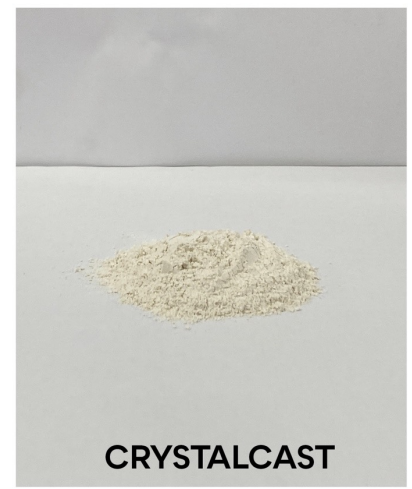
PROTECTIVE LAYER

	Name	Solvent	Dilution (brush application)	Provider
A	Shelf-primer	Water	N/A	Bullseye glass Co.
B	Crystal cast	Water	2:1 w/w	Provetro gruppo



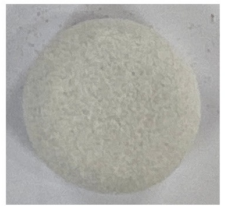
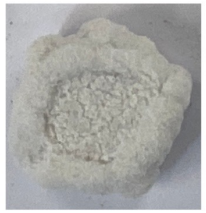
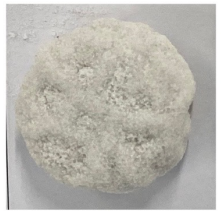
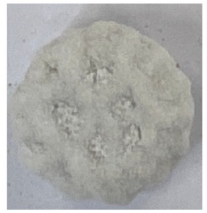
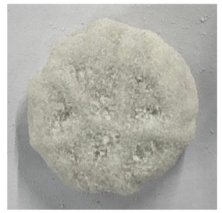
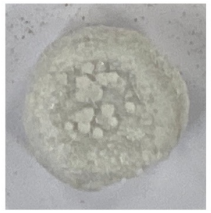
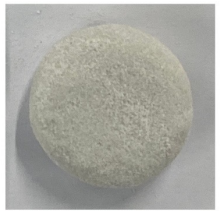
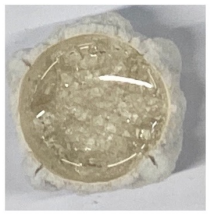
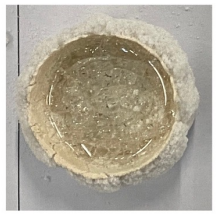
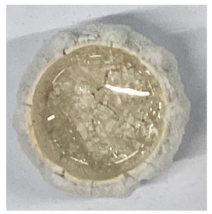
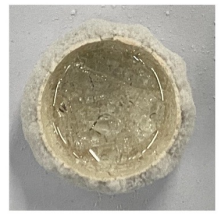
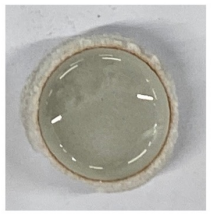
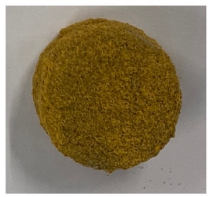
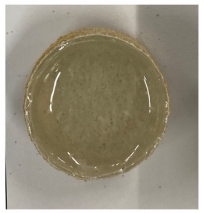
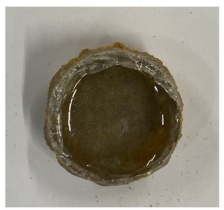
COATINGS & PROTECTIVE LAYER

DILUTION RATIOS OF COATINGS AND PROTECTIVE LAYER

970°C

RESULTS OVERVIEW

970°C

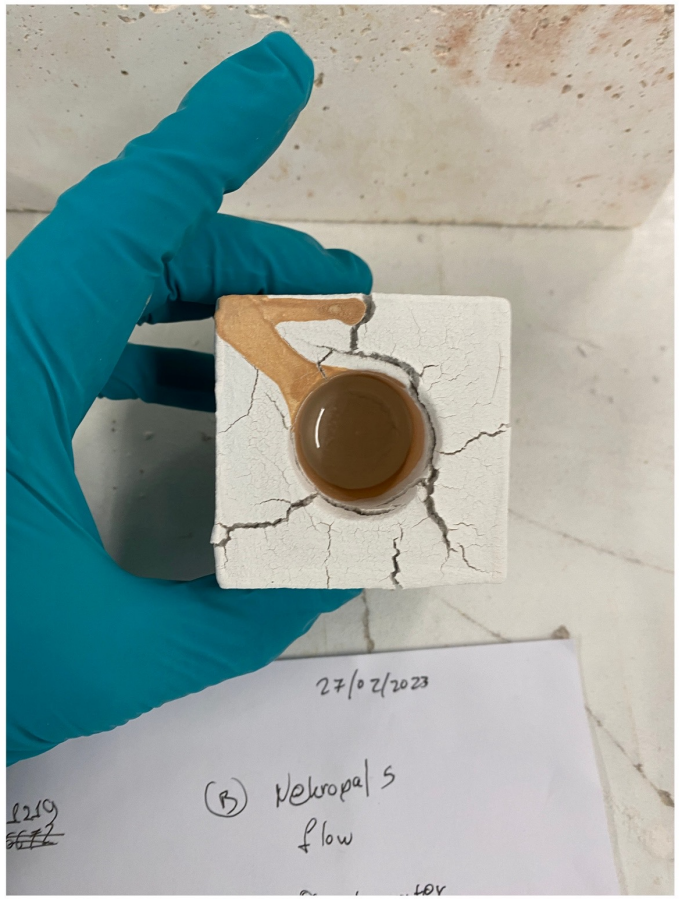
	Annealing schedule	Protective layer	Side	Coatings							
				No	Zirkofluid 1219		Zirkofluid 6672		Arkopal B 5		
					Flow	Brush	Flow	Brush	Flow	Brush	
Quartz sand	970°C normal	No	Contact								X2
			Top								
Ceramic sand	970°C normal	No	Contact								
			Top								

PROTECTIVE LAYER

CRYSTALCAST AND SHELF PRIMER

TOP SURFACE

CONTACT SURFACE

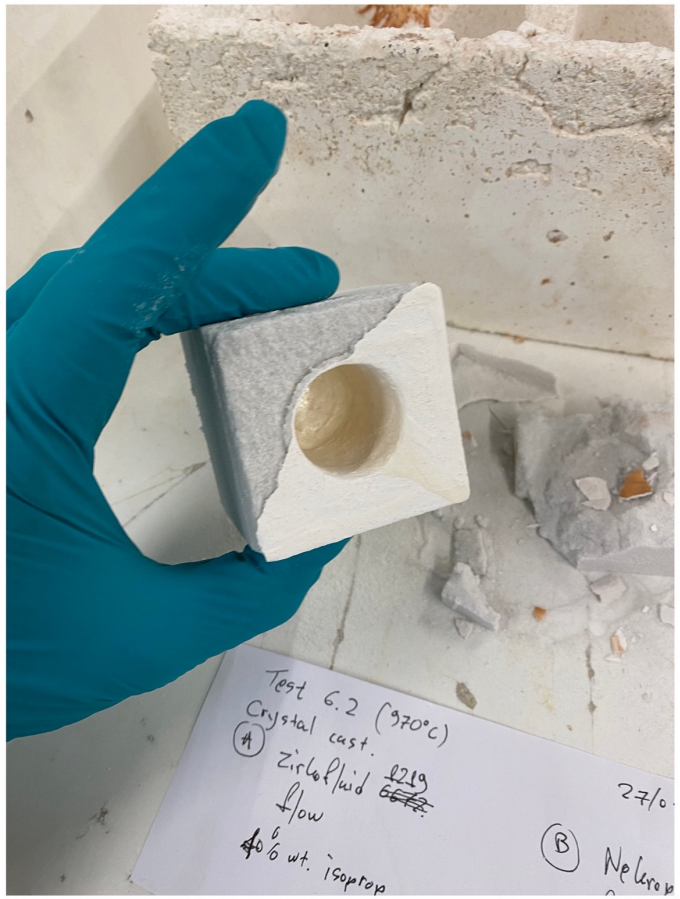


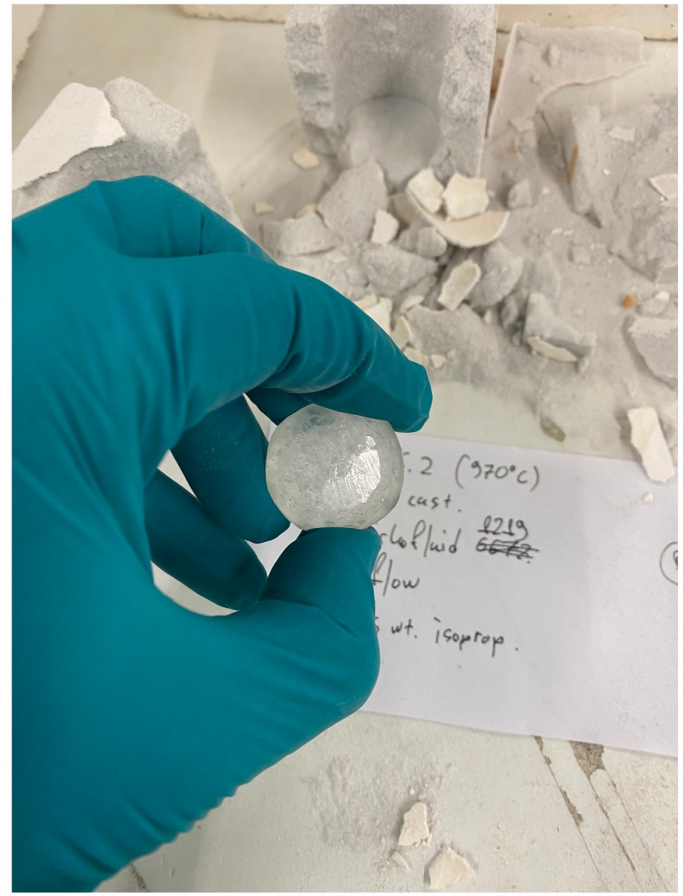
SHELF-PRIMER

970°C

TOP SURFACE

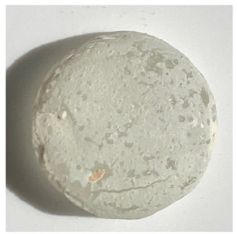
CONTACT SURFACE





CRYSTALCAST

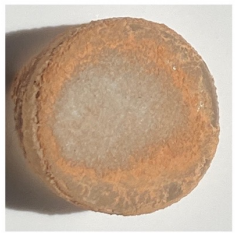
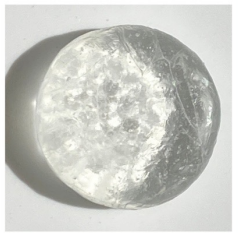
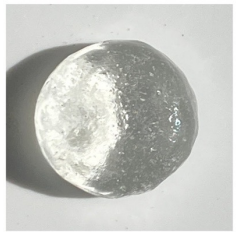
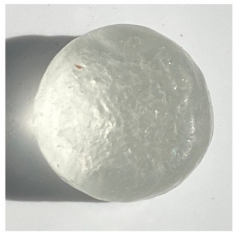
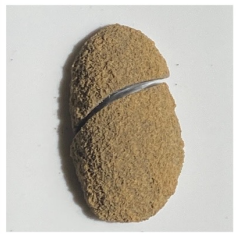
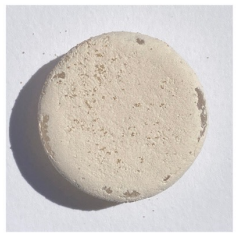
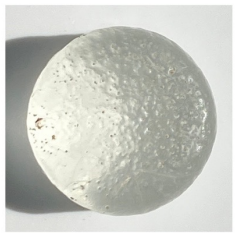
970°C

Annealing schedule	Protective layer	Sand type	Side	Coatings							Coating
				No	Zirkofluid 1219		Zirkofluid 6672		Arkopal B 5		
					Flow	Brush	Flow* (2X)	Brush	Flow	Brush	
	Crystacast 3X Brush	Quartz sand	Contact								X1
		Ceramic sand	Contact								X2

CRYSTALCAST + COATINGS

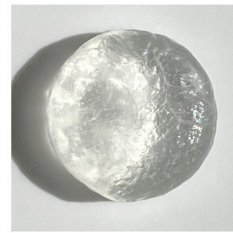
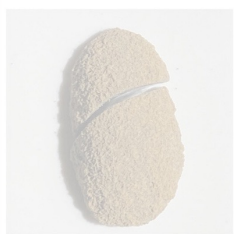
970°C

870°C

Annealing schedule	Protective layer	Sand type	Side	Coatings								Coating
				No	Zirkofluid 1219		Zirkofluid 6672		Arkopal B 5			
					Flow	Brush	Flow	Brush	Flow	Brush		
870°C normal	Crystacast 3X Brush	Quartz sand	Contact									X2
870°C normal	No	Quartz sand	Contact									X2
870°C normal	Crystacast 3X Brush	Ceramic sand	Contact									X2
870°C normal	No	Ceramic sand	Contact									X2

RESULTS OVERVIEW

870°C

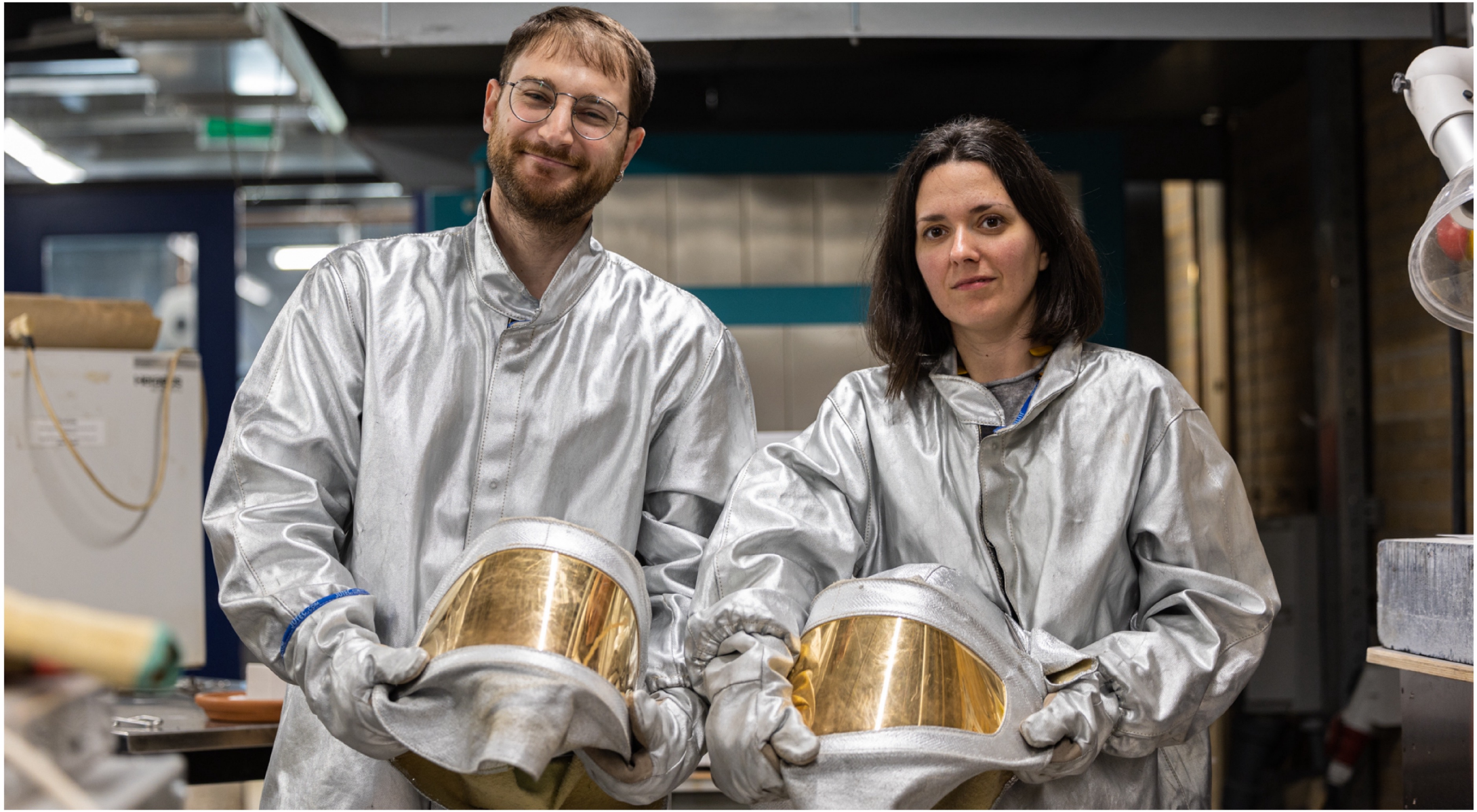
Annealing schedule	Protective layer	Sand type	Side	Coatings								Coating
				No	Zirkofluid 1219		Zirkofluid 6672		Arkopal B 5			
					Flow	Brush	Flow	Brush	Flow	Brush		
870°C normal	Crystacast 3X Brush	Quartz sand	Contact									X2
870°C normal	No	Quartz sand	Contact									X2
870°C normal	Crystacast 3X Brush	Ceramic sand	Contact									X2
870°C normal	No	Ceramic sand	Contact									X2

BEST RESULTS

870°C, MOST PROMISING

1380°C

HOT POURING



HOT POURING

GEAR UP!

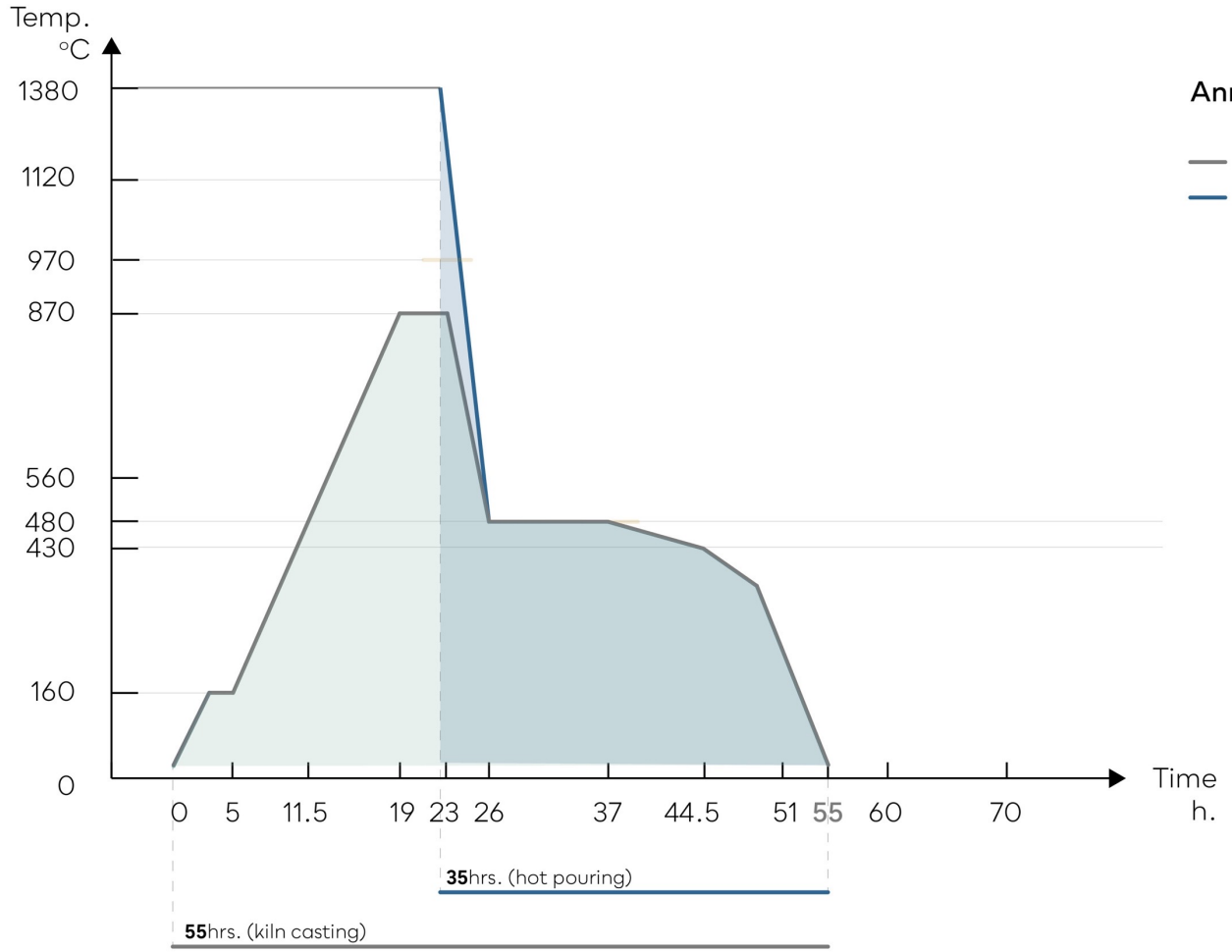
IMAGE CREDITS: MARCEL BILOW

HOT POURING

IMAGE CREDITS: MARCEL BILOW

HOT PROURING

IMAGE CREDITS: MARCEL BILOW

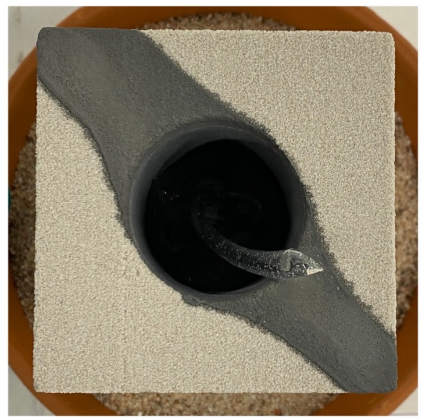


Annealing schedules:

870°C normal
1380°C

Annealing point (Bullseye)
Strain point

Quartz sand
870°C normal



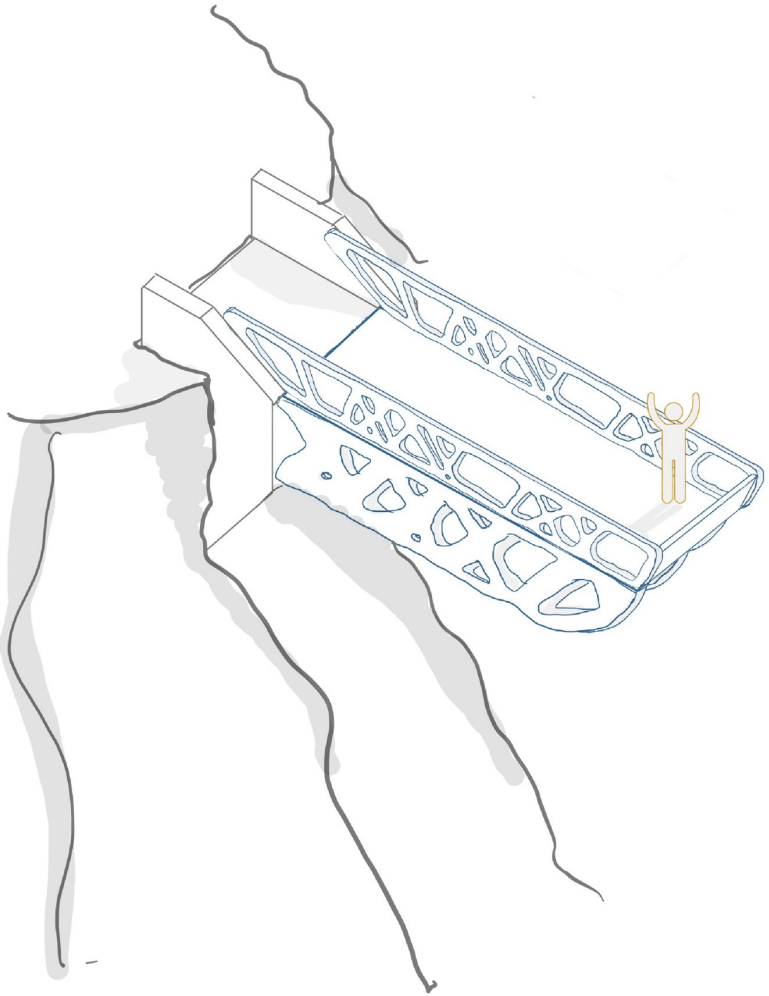
Quartz sand
1380°C

PROLONGED EXPOSURE TO HEAT

COATING EFFECTIVENESS

RESEARCH BY DESIGN

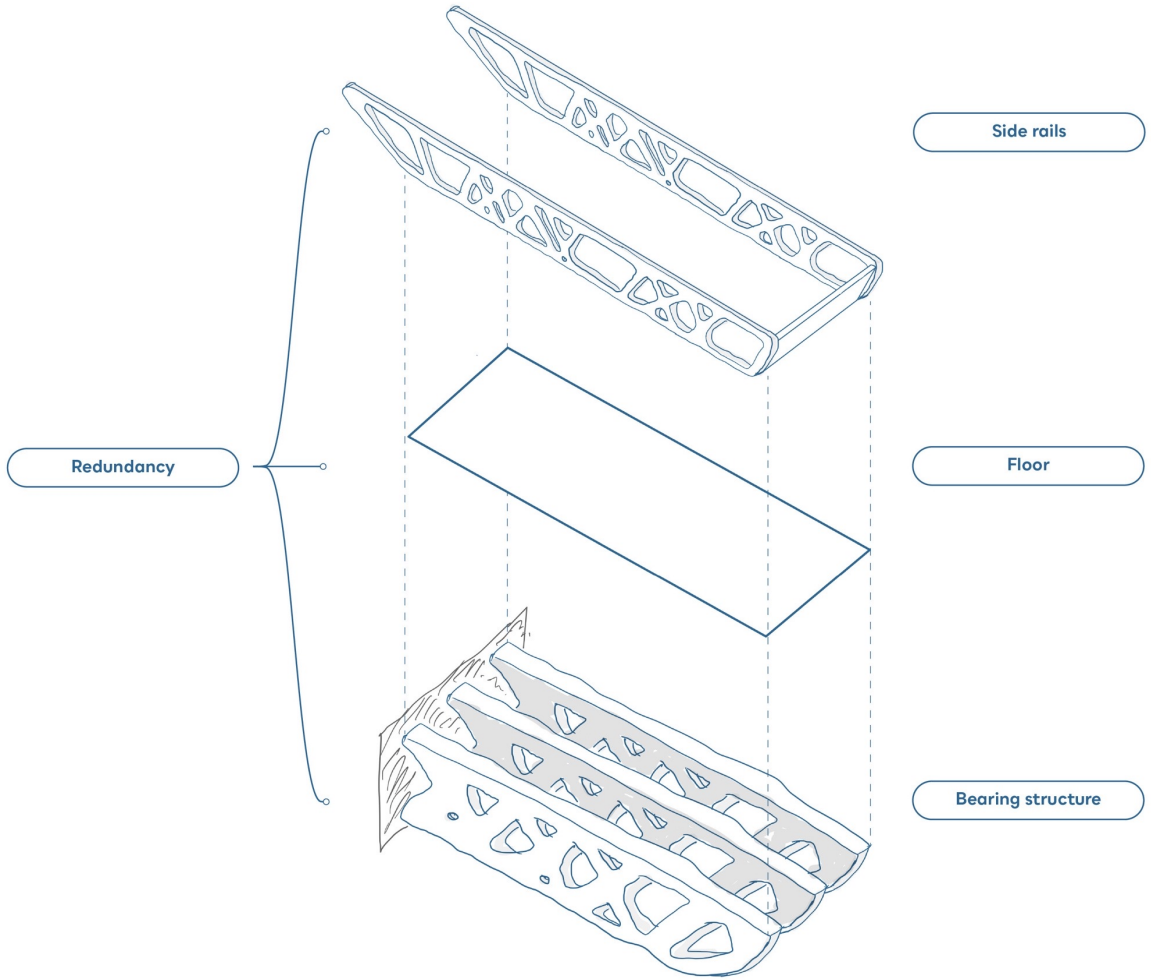
REDUNDANCY



DESIGN OVERVIEW

AXO

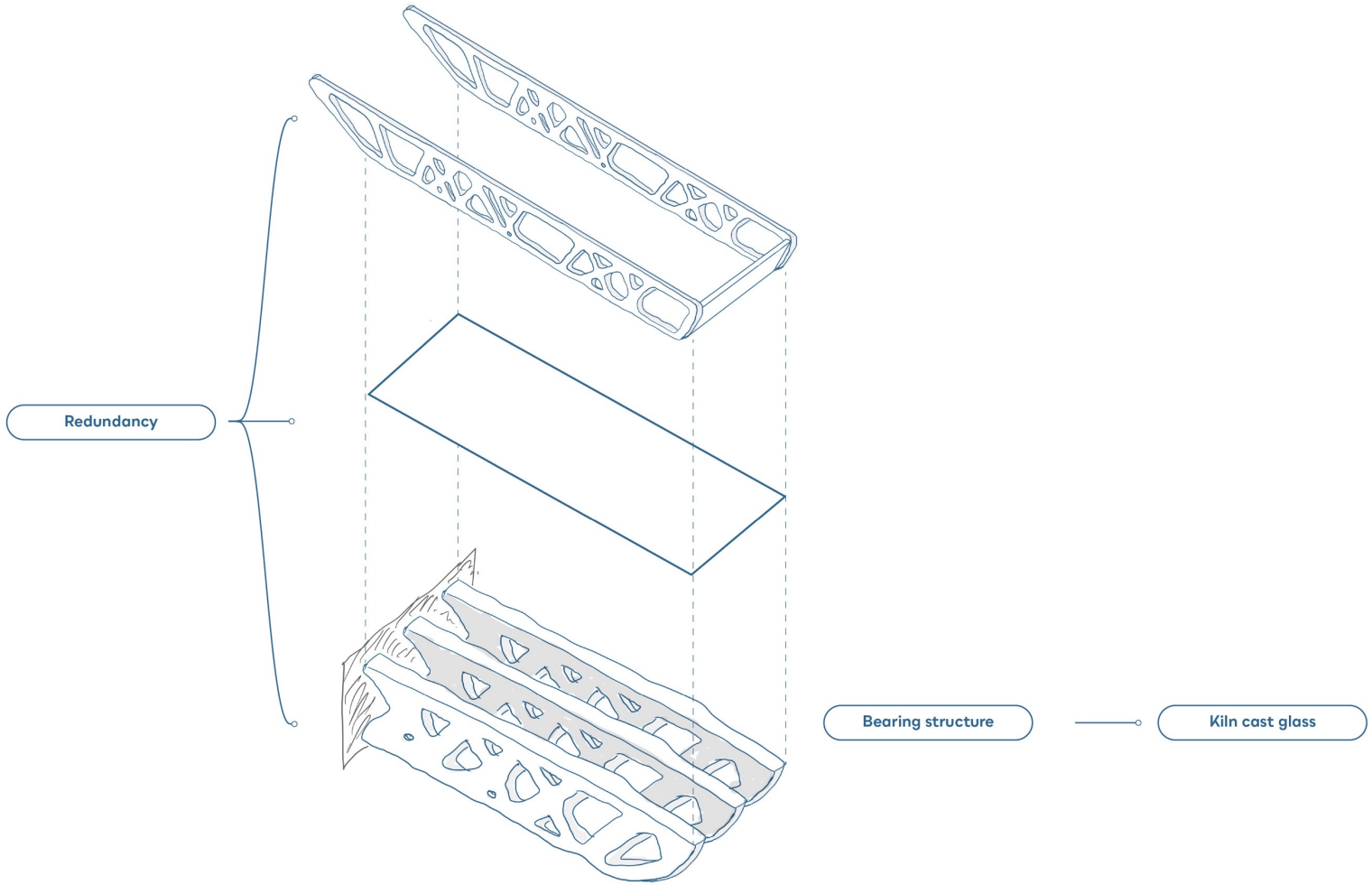
ZONING



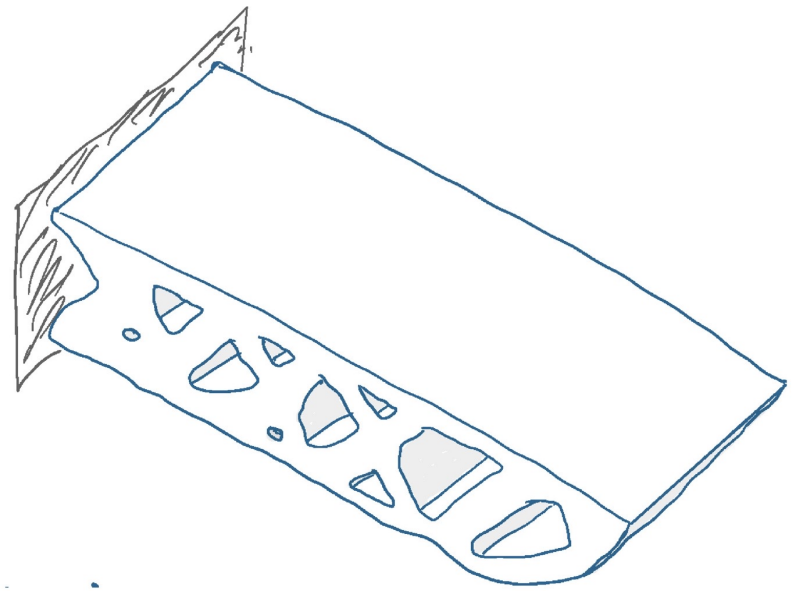
DESIGN OVERVIEW

3 DISCRETE ZONES

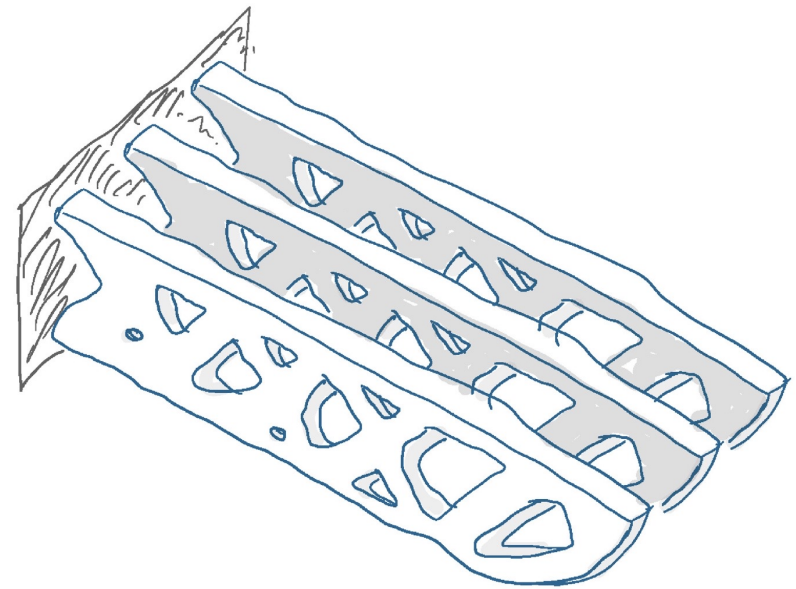
BEARING STRUCTURE



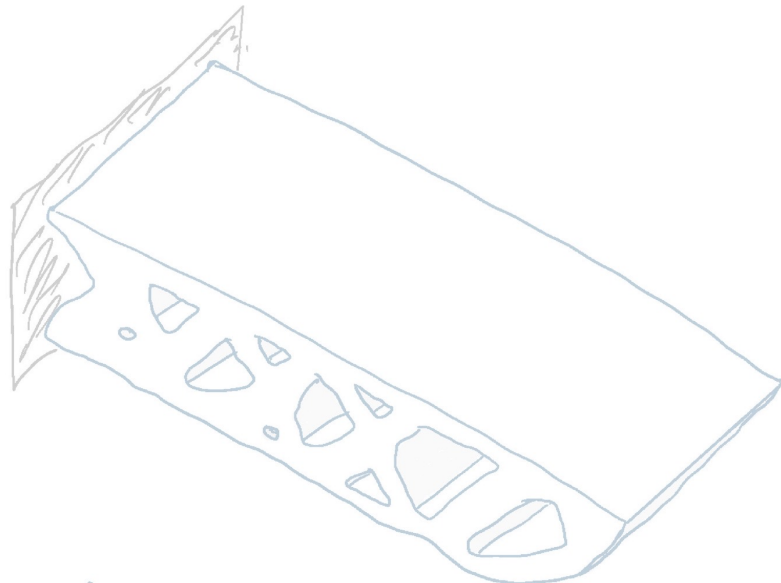
BEARING STRUCTURE



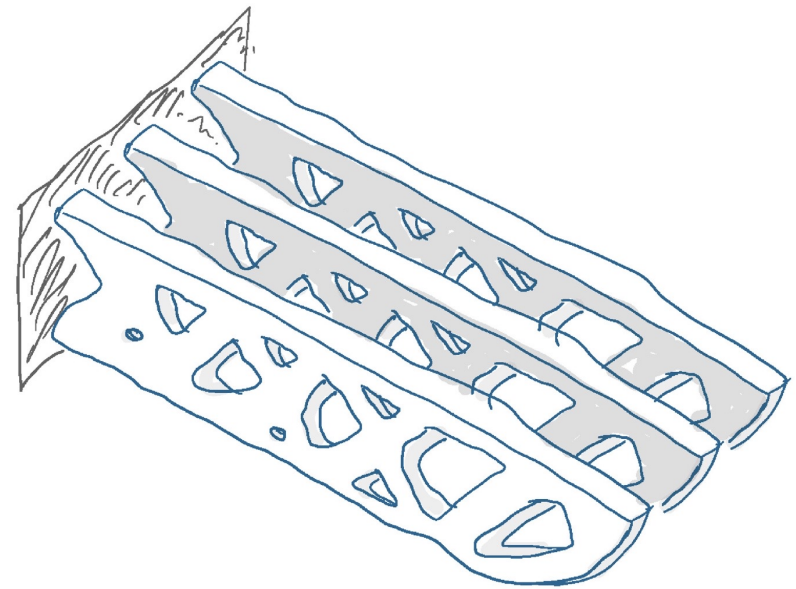
Monolithic design



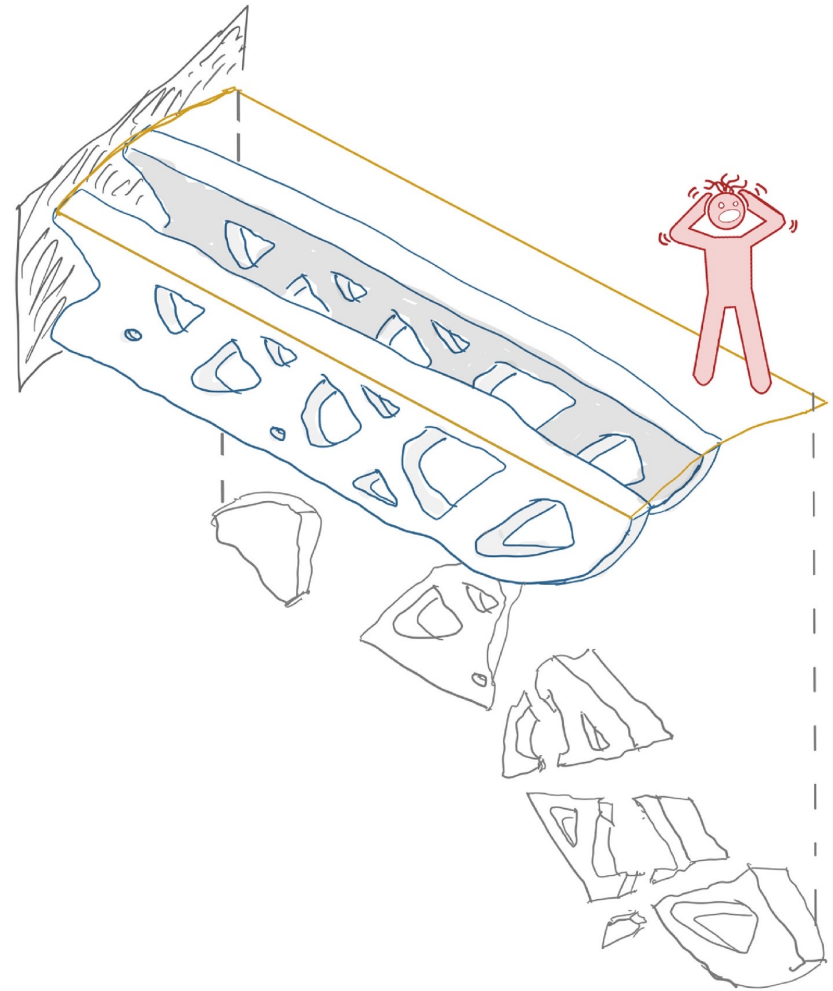
Sliced design



Monolithic design

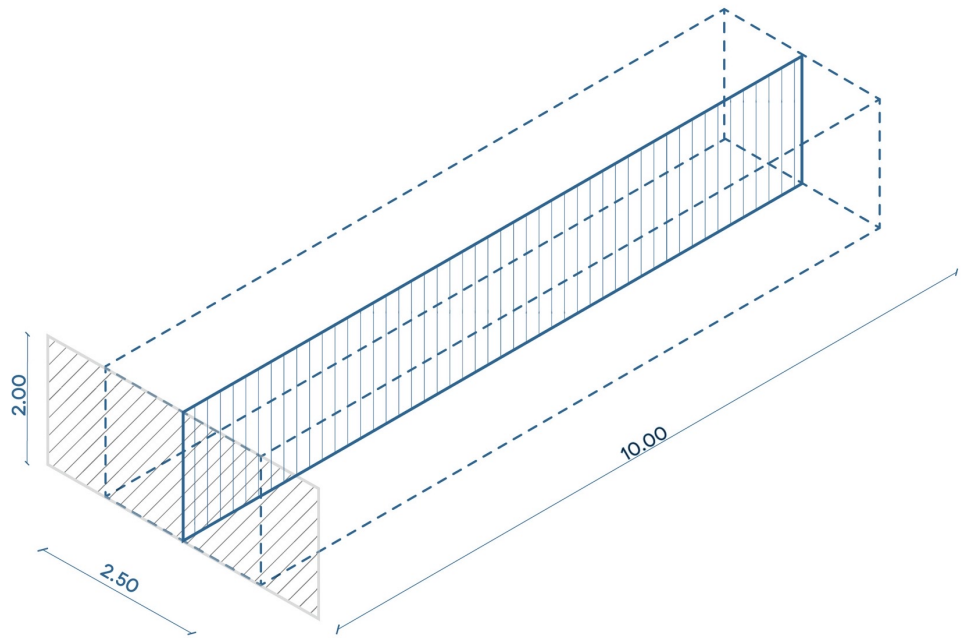


Sliced design



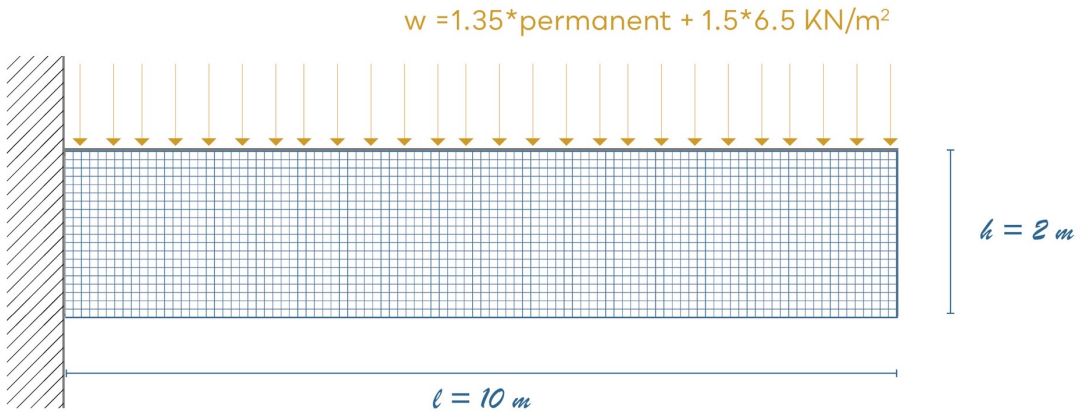
BEARING STRUCTURE

FAILURE



DESIGN DOMAIN

2D SECTION USED FOR OPTIMIZATION



DISCRETIZED DOMAIN

SUPPORT CONDITION

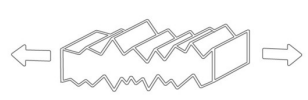
LOAD CASE

OBJECTIVE

MINIMIZE VOLUME

-62%

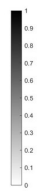
CONSTRAINTS



6.4 MPa

500 MPa

5 days



ALGORITHM OUTPUT

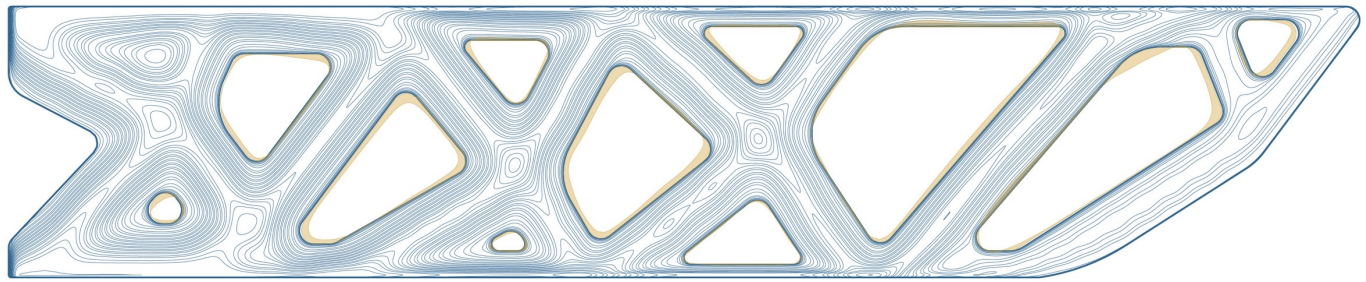
DENSITIES

WHITE = 0 (NO MATERIAL)

BLACK= 1 (FULL MATERIAL)

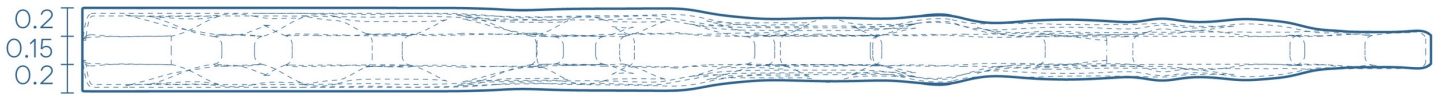
TOPOLOGY OPTIMIZATION

2D ALGORITHM (KONIARI, 2022)

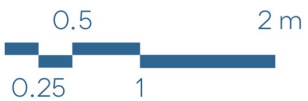


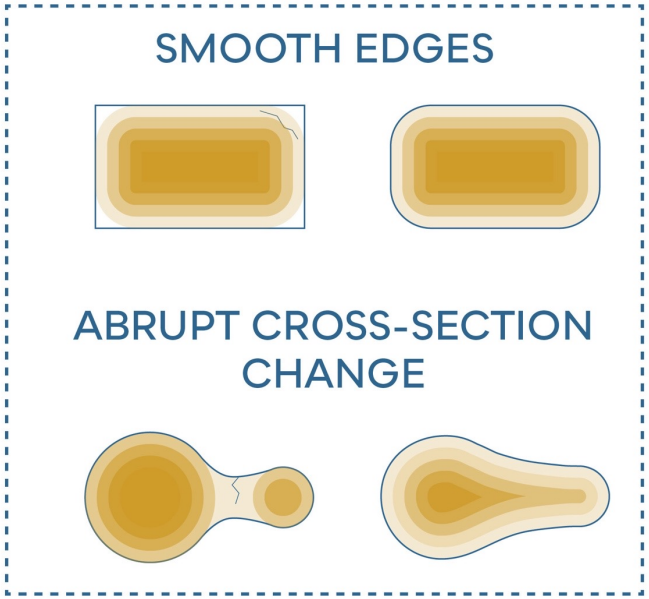
Side view

Manual editing



Top view

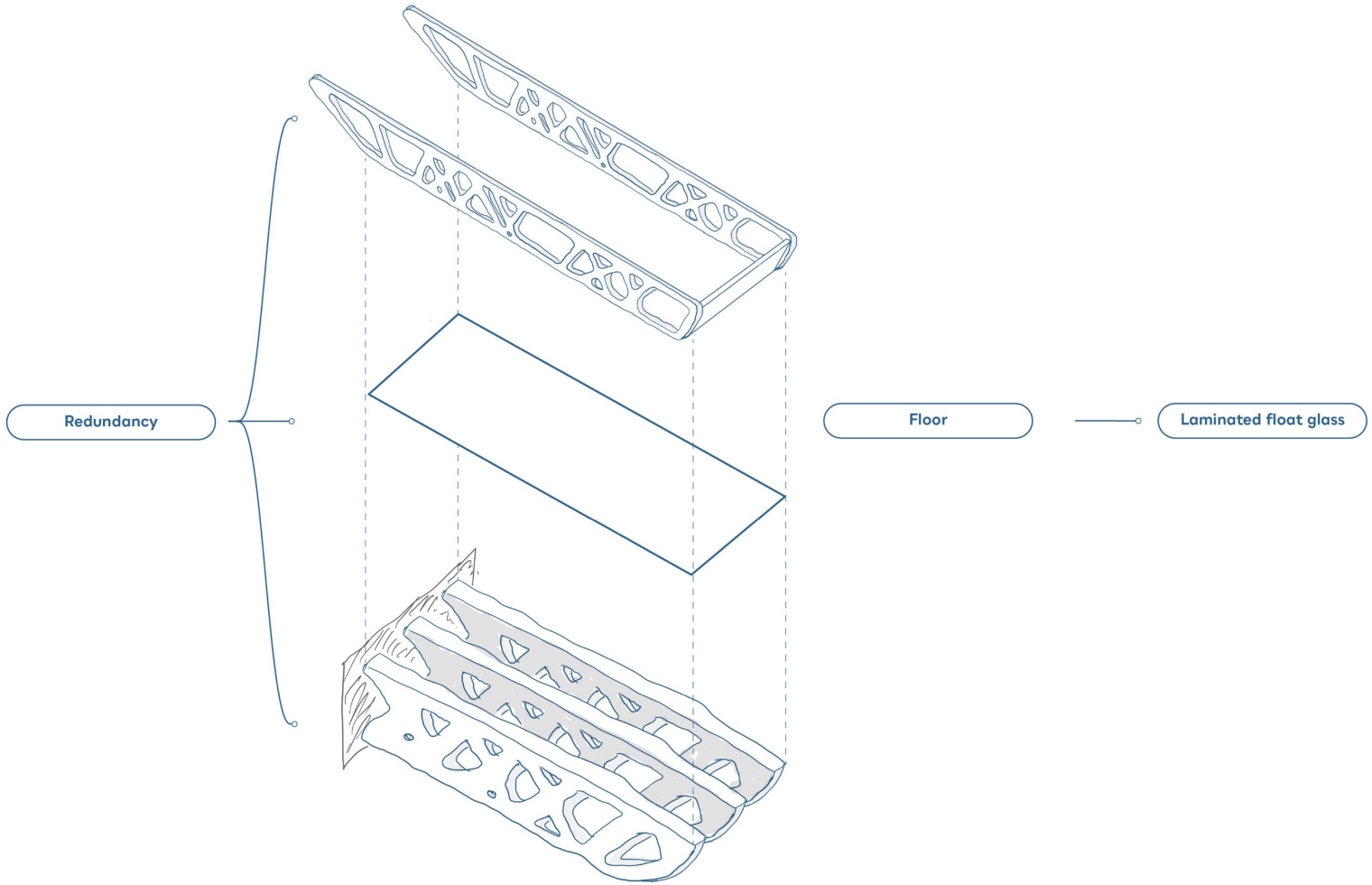




GEOMETRY POST PROCESSING

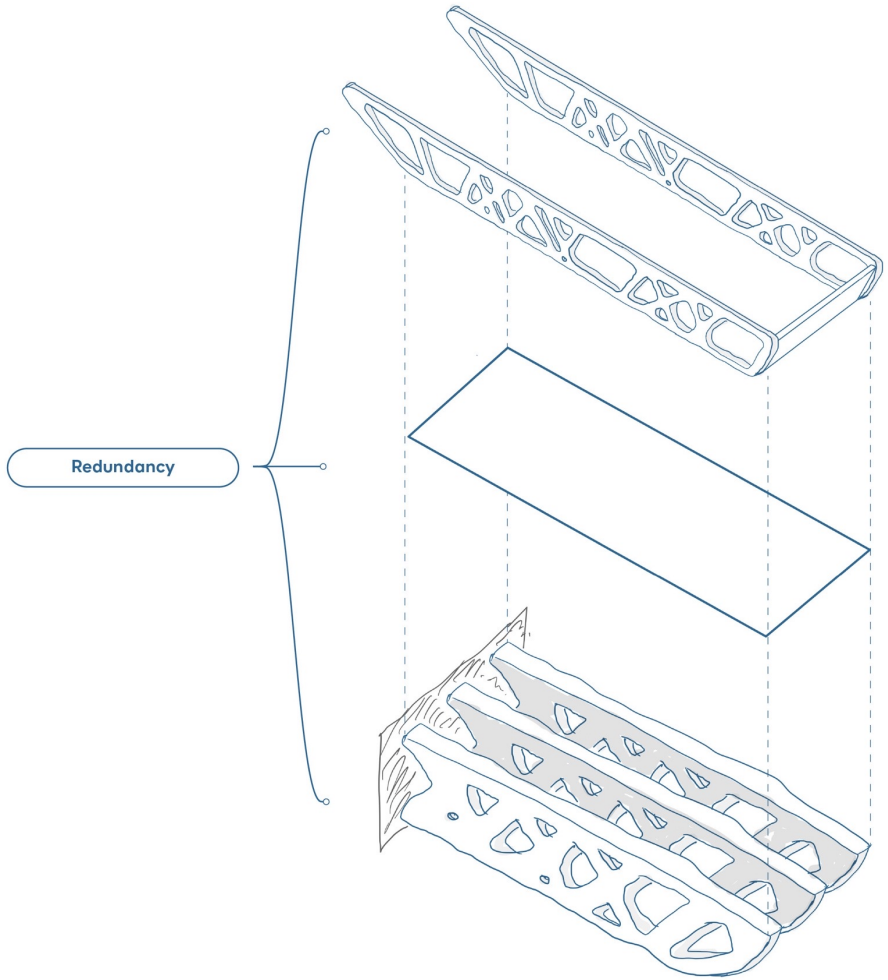
BEARING STRUCTURE

FLOOR



FLOOR

FABRICATION METHOD



Redundancy

Floor

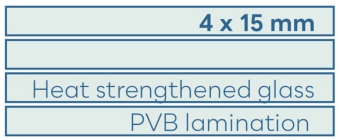
Laminated float glass

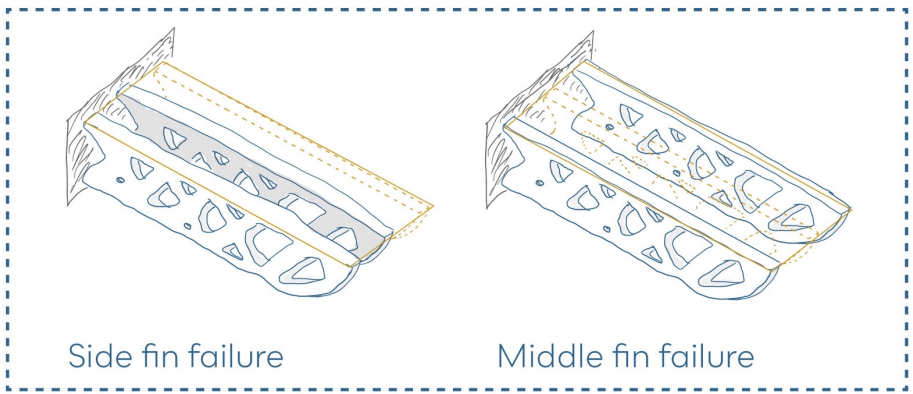
Accident & vandalism

Failure scenarios

Proper dimensioning

Schematic section



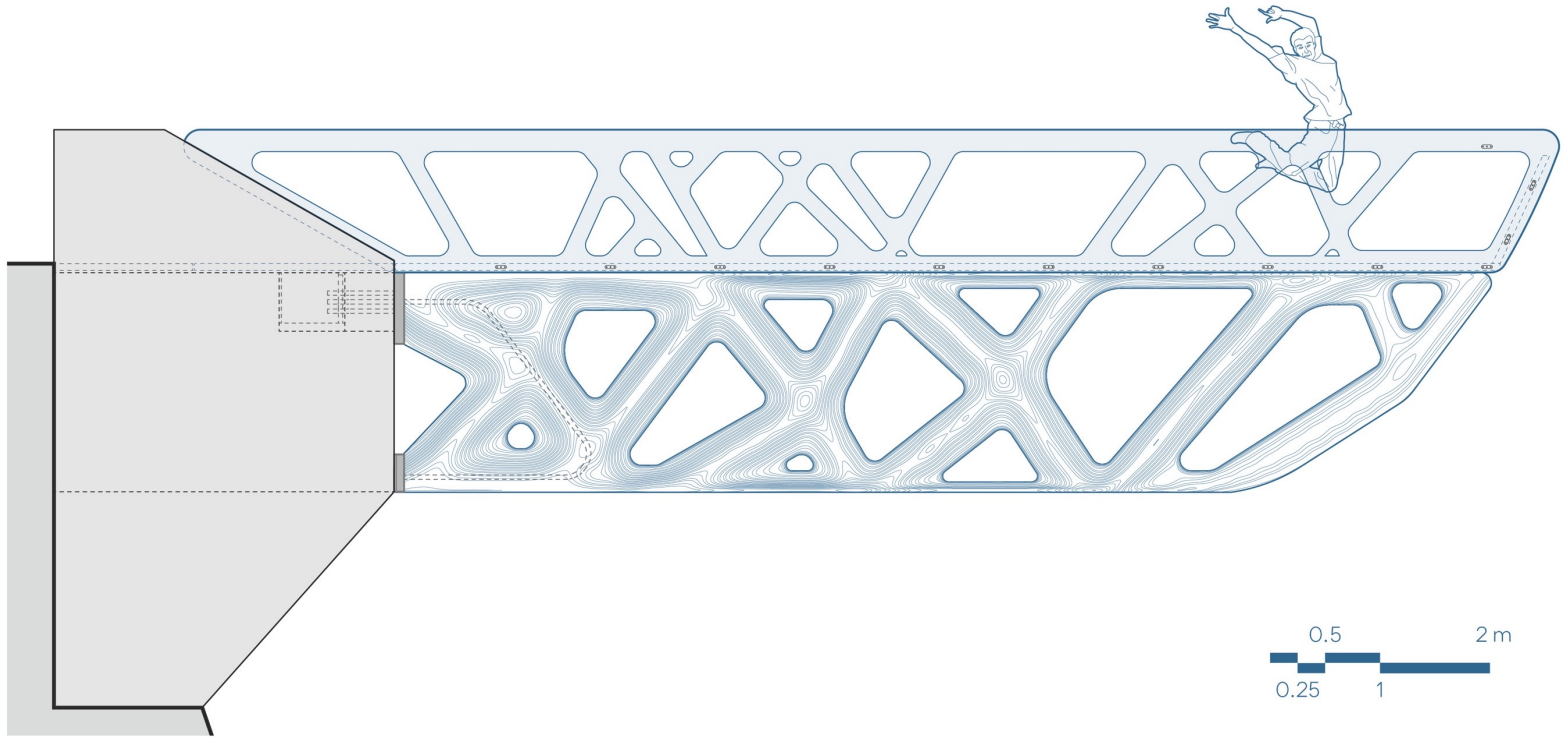


Side fin failure

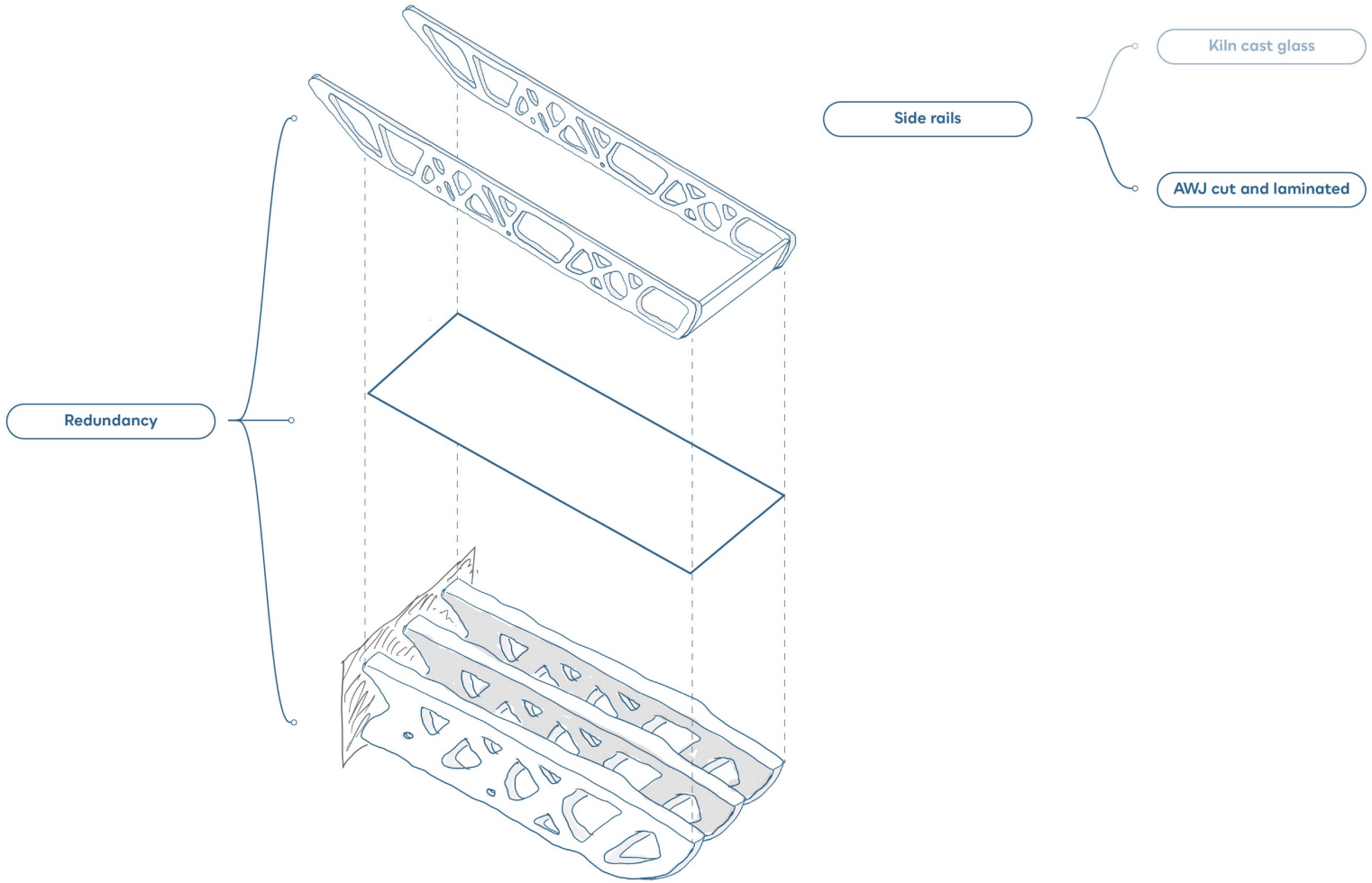
Middle fin failure

FLOOR
OVERVIEW

SIDE RAIL

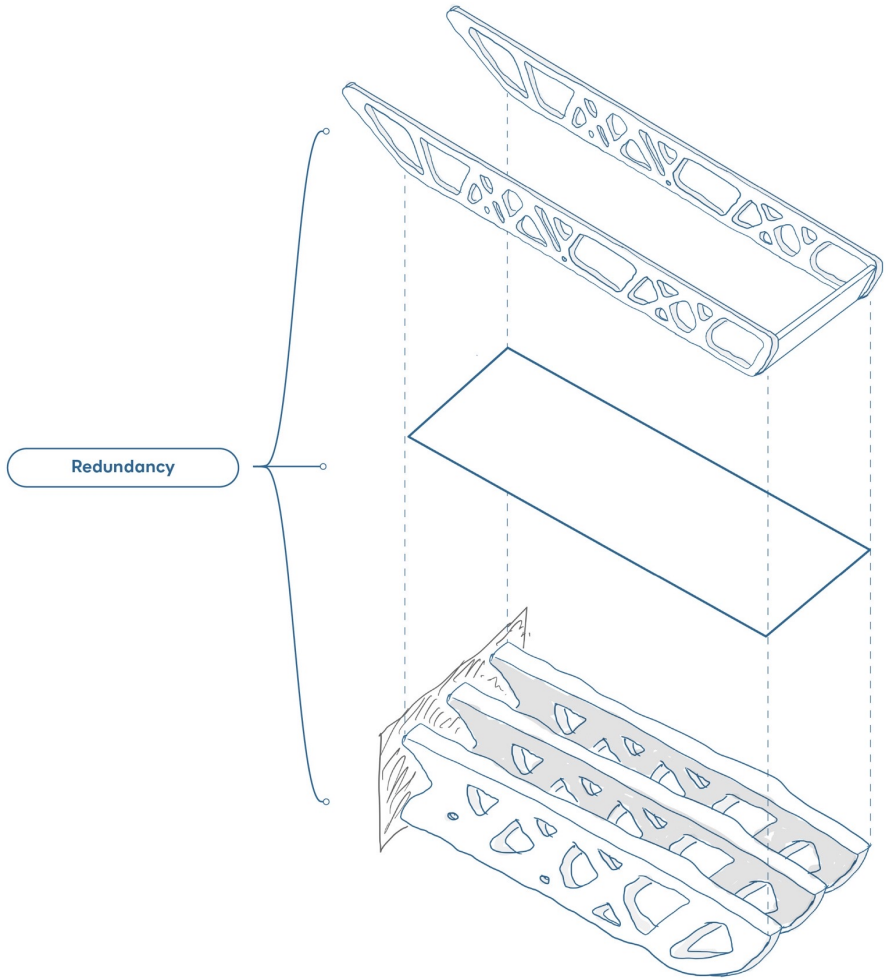


DESIGN CONTINUITY



SIDE RAILS

FABRICATION METHOD



Redundancy

Side rails

Kiln cast glass

Accident & vandalism

Protective layer

Heavier structure

AWJ cut and laminated

Lightweight structure

Post fracture capacity

SIDE RAILS

OVERVIEW

FINAL DESIGN

ANIMATION

FLY OVER

RENDER

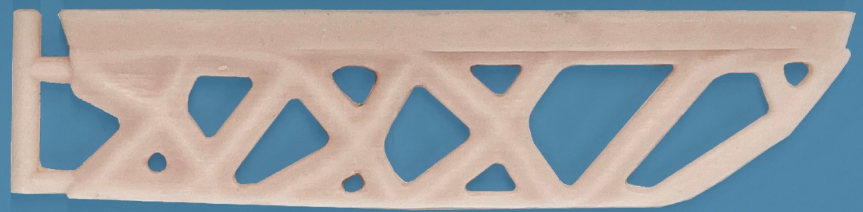
NIGHT VIEW

PROTOTYPING

LOST WAX TECHNIQUE

PETG negative

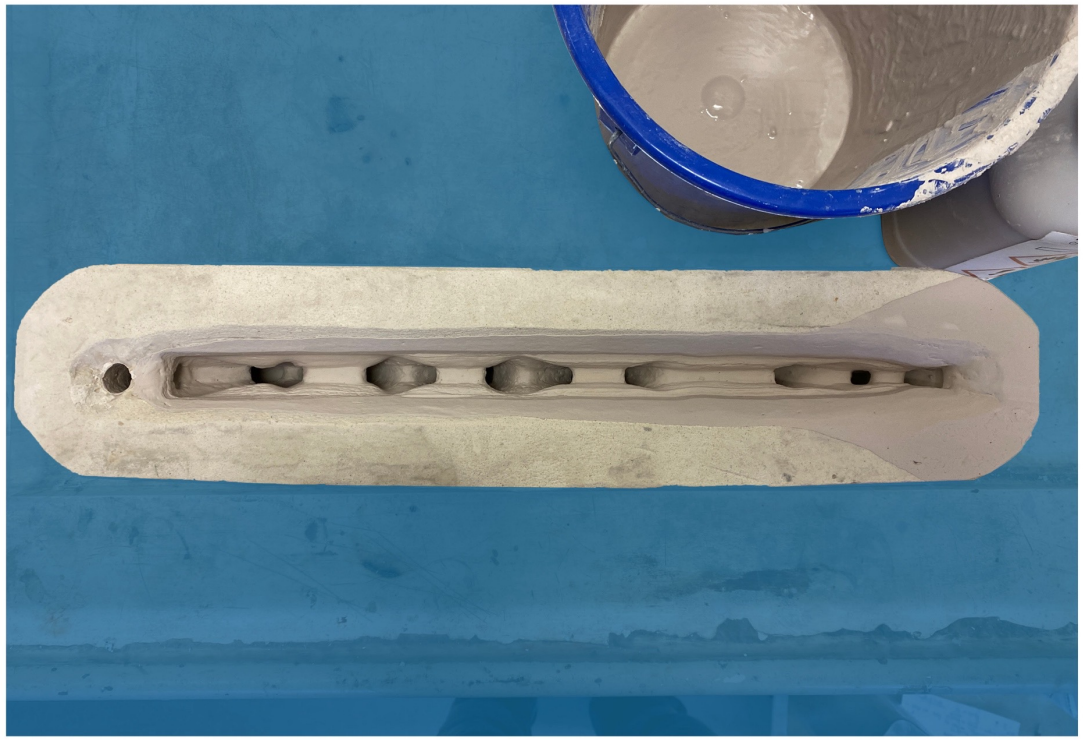
Wax positive



Crystalcast negative

LOST WAX TECHNIQUE

FROM PETG TO CRYSTALCAST NEGATIVE



Coating application
Zirkofluid 6672, X2 Flow

Oven set up

LOST WAX TECHNIQUE

COATING APPLICATION AND OVEN SET UP

PROTOTYPE

BEFORE CLEANING AND CUTTING

PROTOTYPE

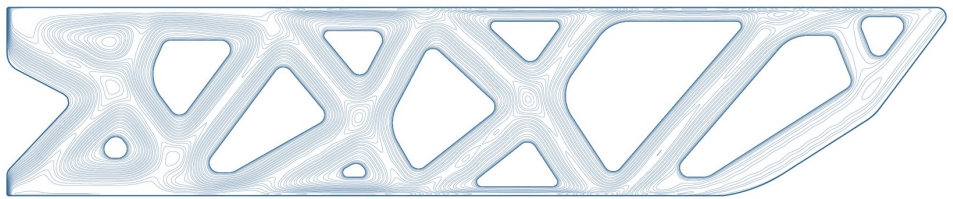
AFTER CLEANING AND CUTTING

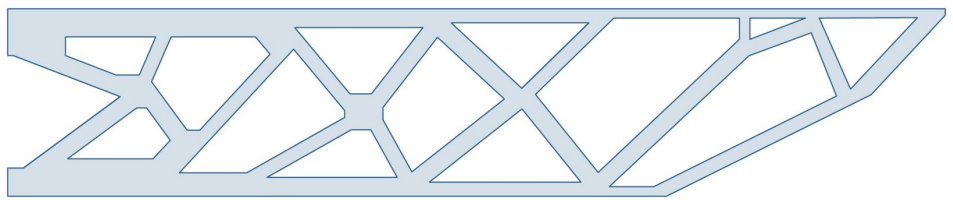
CONCLUSIONS & DISCUSSION

FABRICATION METHOD

ALGORITHM OUTPUT

CAST GLASS





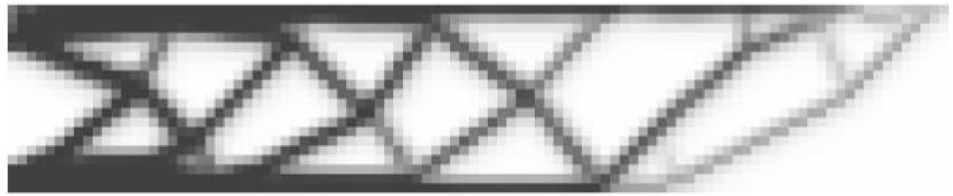
LAMINATION OF FLOAT GLASS

	LOW	MEDIUM	HIGH
STRUCTURAL			
OPTICAL			
SUSTAINABILITY			
FABRICATION FREEDOM			

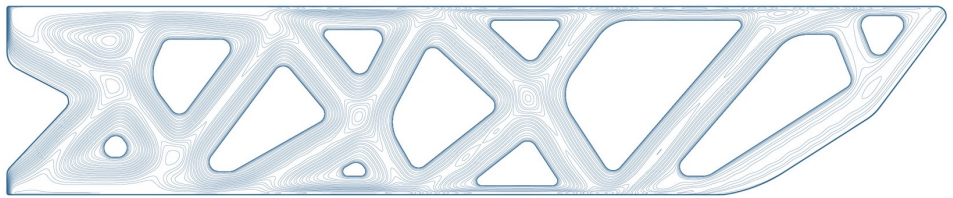
OPTIMIZATION POST PROCESSING

CAST GLASS VS. LAMINATION OF FLOAT GLASS

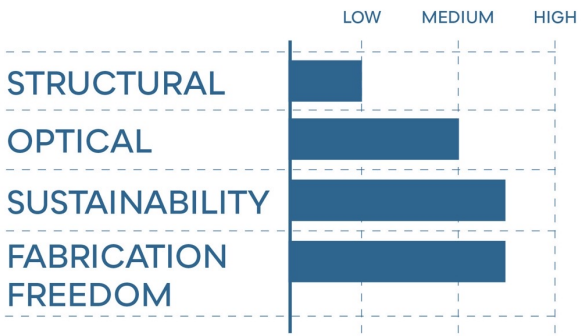
ALGORITHM OUTPUT



CAST GLASS



LAMINATION OF FLOAT GLASS

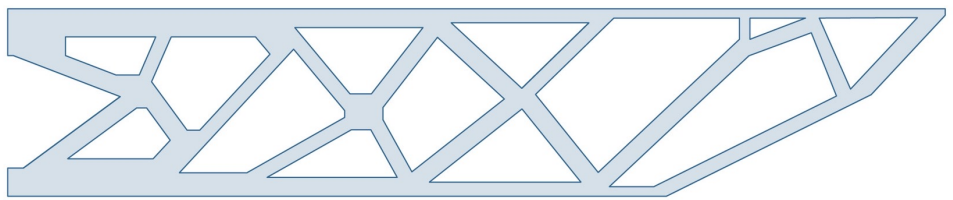


COMPARISON

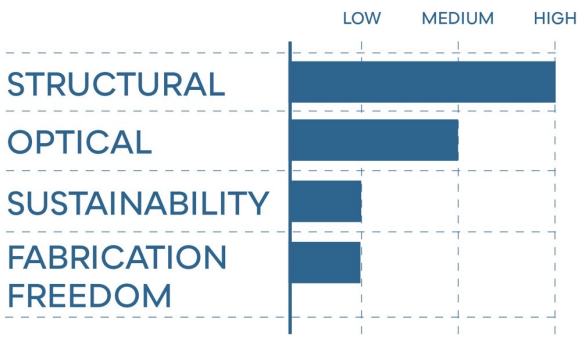
CAST GLASS

ALGORITHM OUTPUT

CAST GLASS

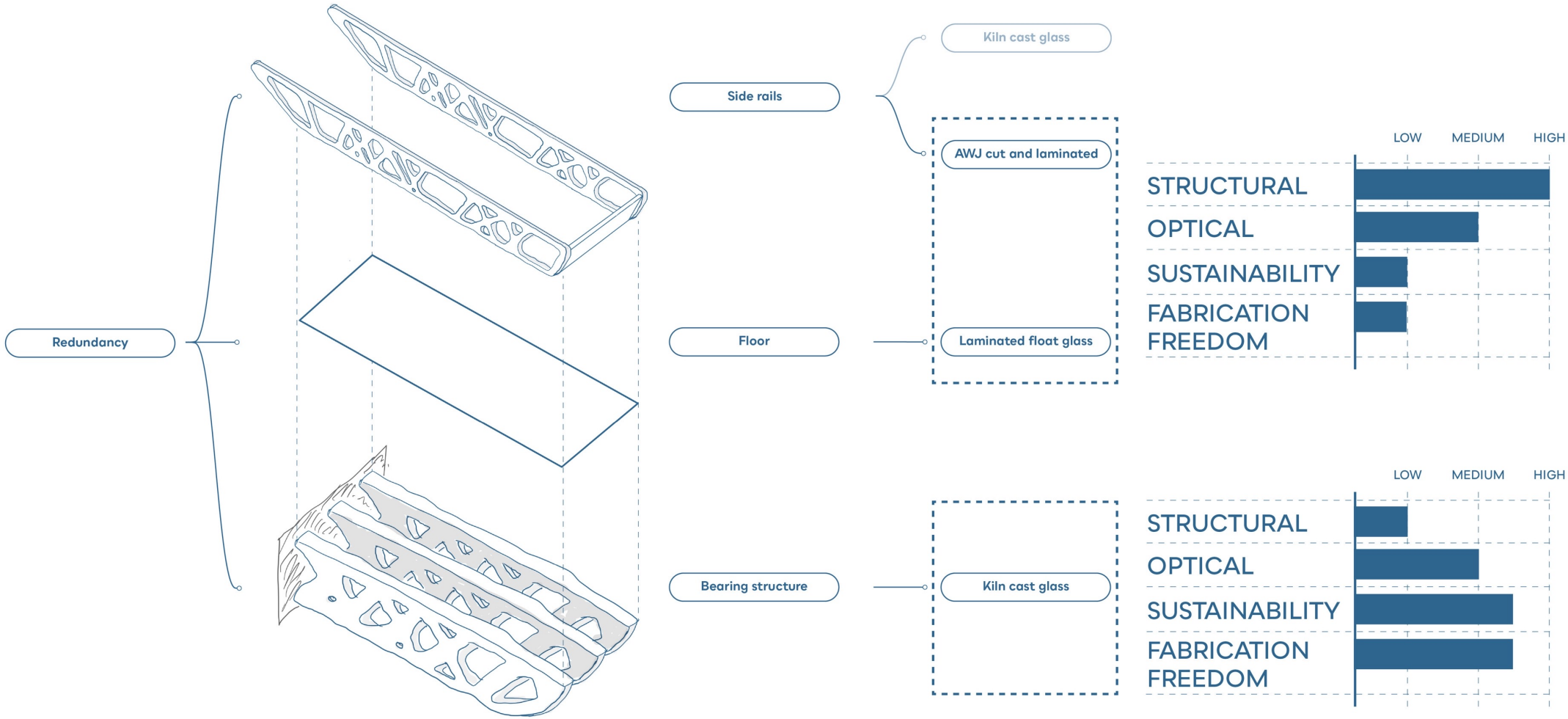


LAMINATION OF FLOAT GLASS



COMPARISON

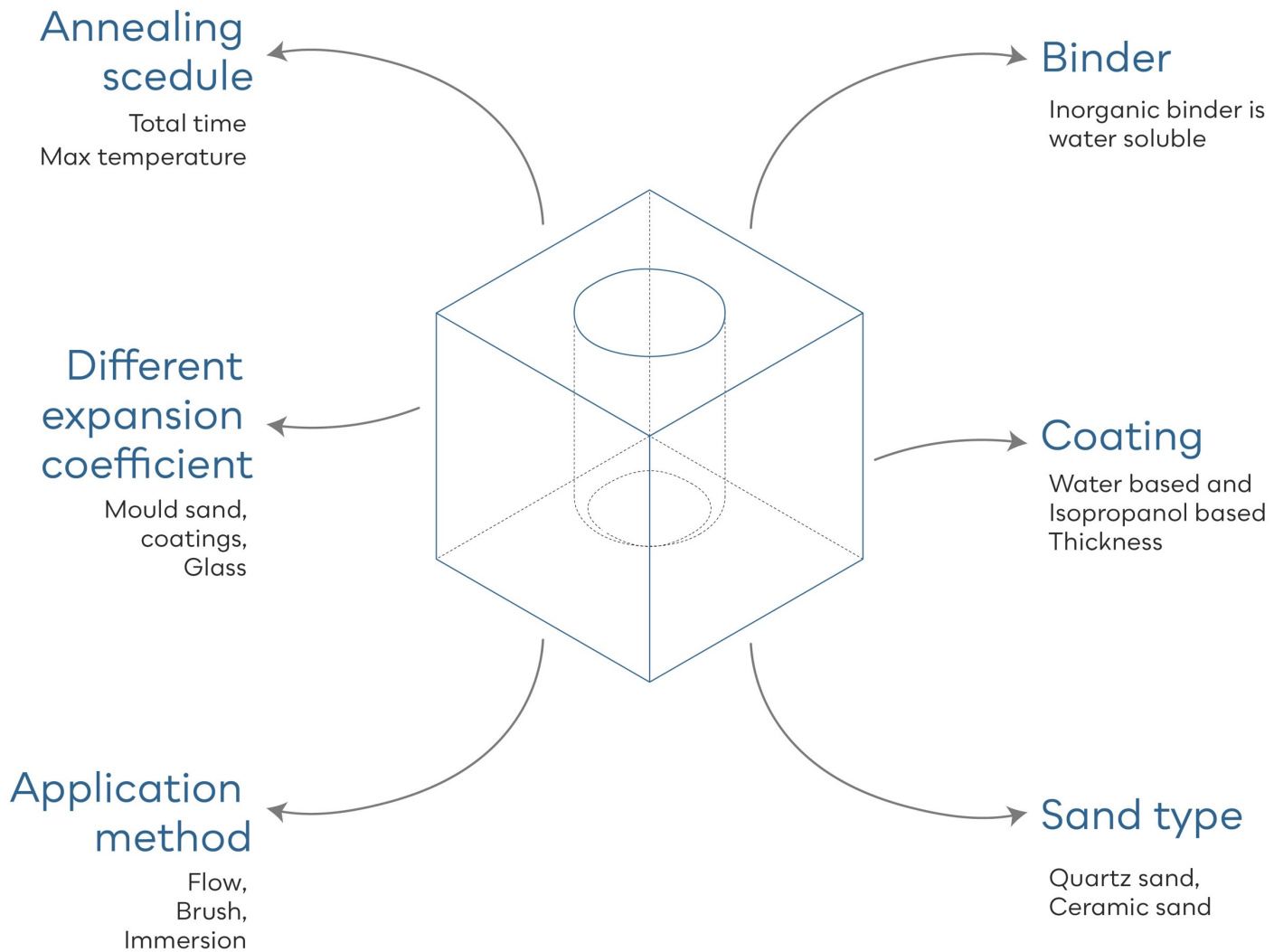
LAMINATED FLOAT



REDUNDANCY OVERVIEW

SUMMARY RESEARCH BY DESIGN

FINISHING QUALITY

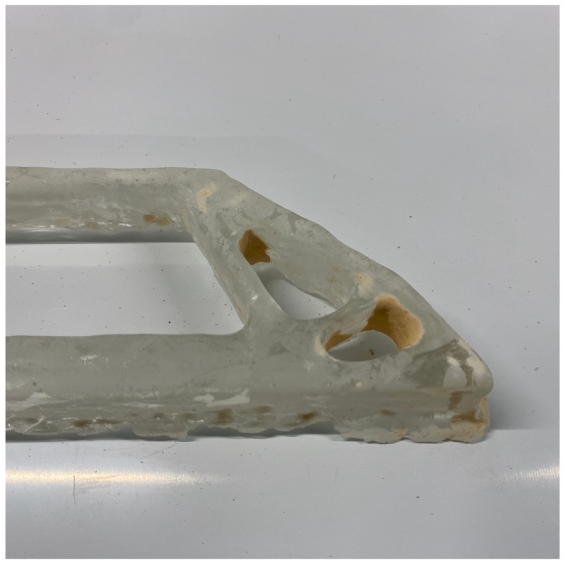


FACTORS AFFECTING FINISHING QUALITY

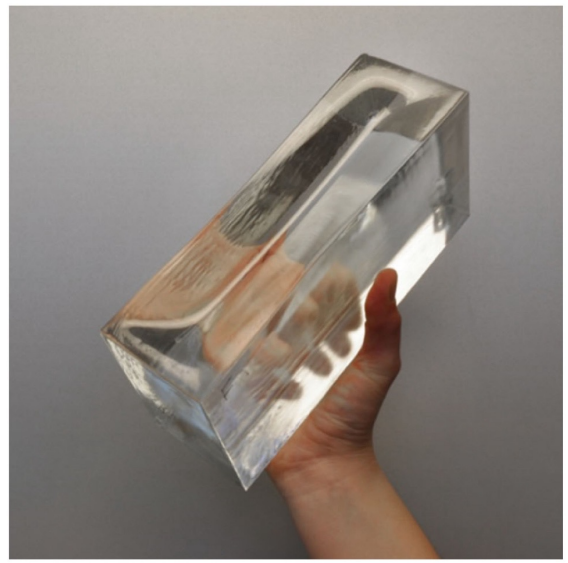
SUMMARY LAB EXPERIMENTS

3DPS mould (previous work)

3DPS mould (current work)



Steel mould

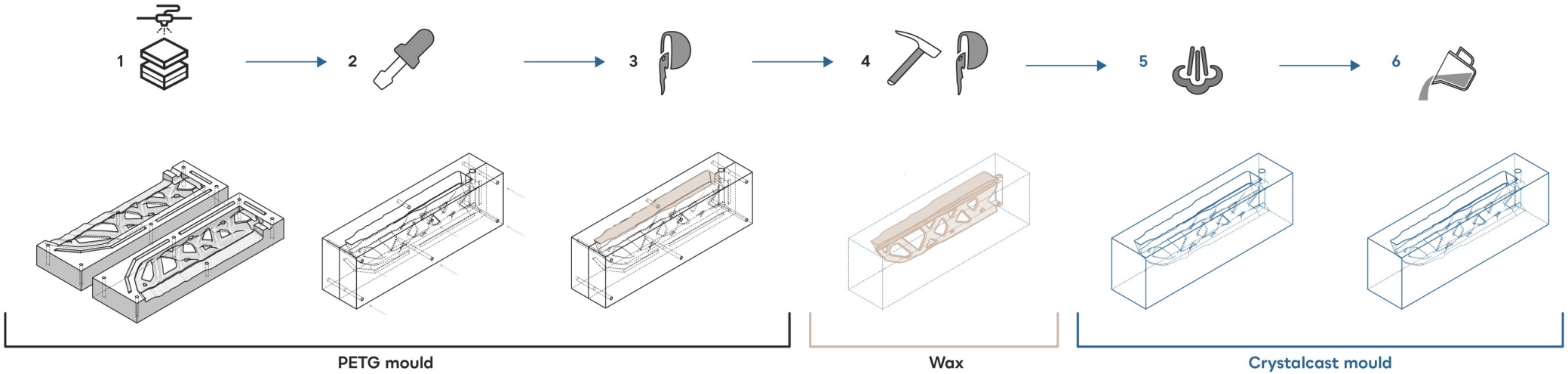


SCALED UP RESULTS

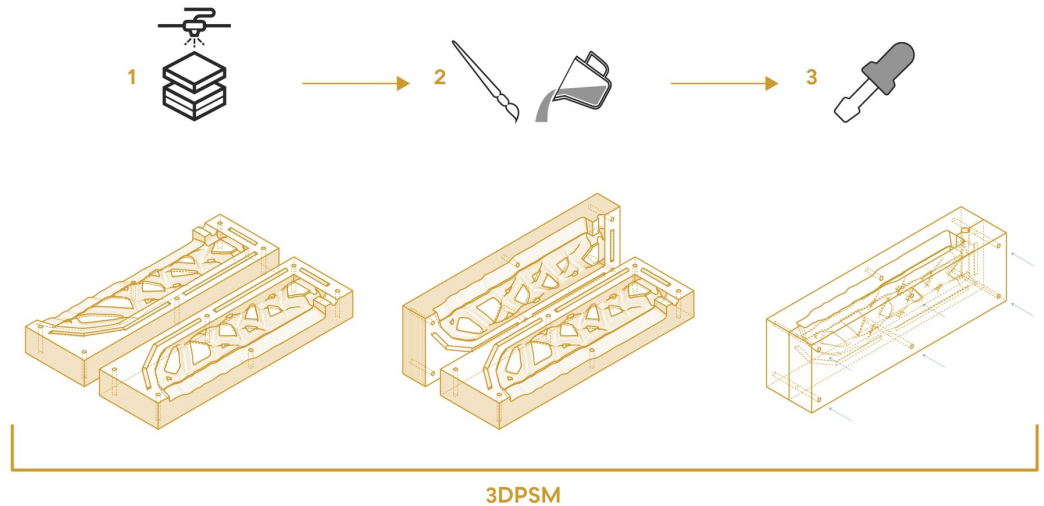
3DPSM

PROTOTYPING

LOST WAX TECHINQUE

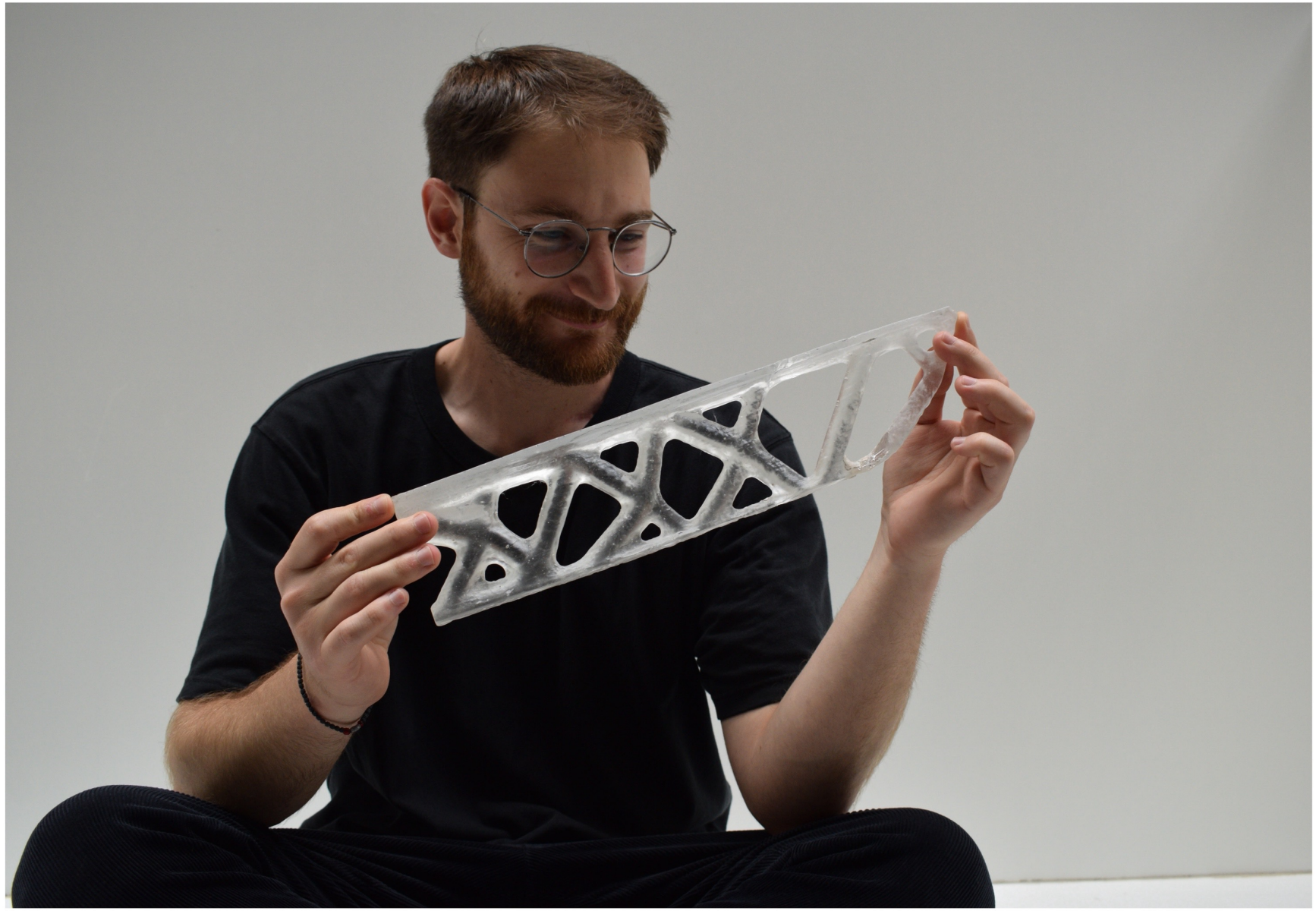


3DPSM



PROTOTYPING METHODS

3D PRINTING OF CRYSTALCAST



REFLECTION

IMAGE CREDITS: MARIALENA TOLIOPOULOU

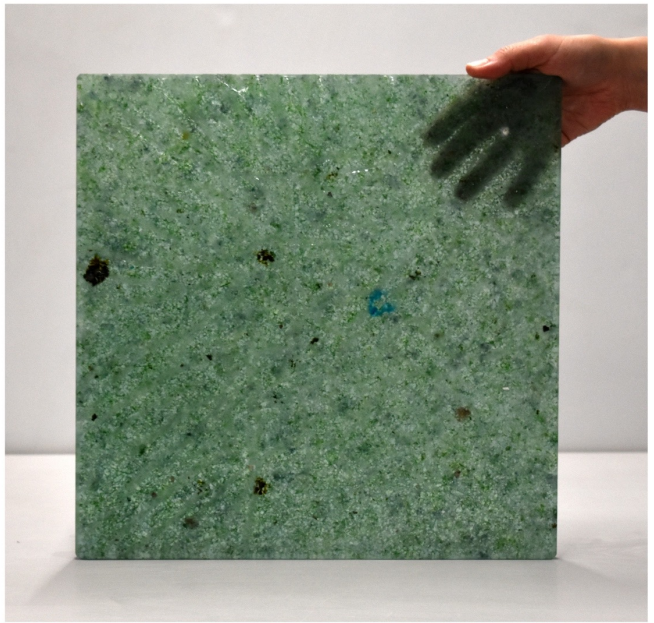
SUSTAINABILITY POTENTIAL

SIDE VIEW RENDER

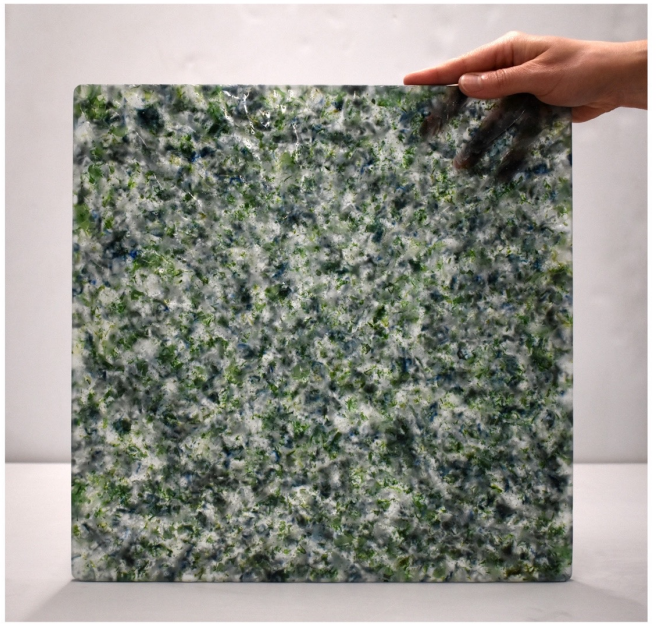
FULL TRANSPARENT GLASS STRUCTURE

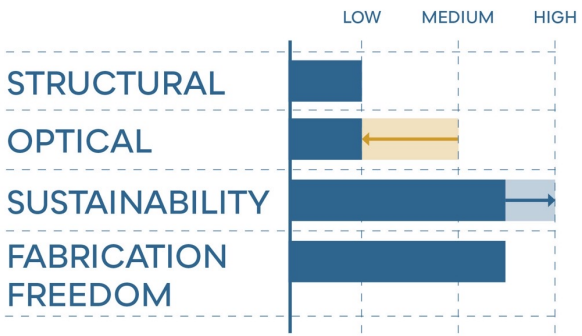
ENAMEL

CAR GLASS



OVEN DOORS





RECOVERED GLASS

CIRCULARITY POTENTIAL

Bristogianni & Oikonomopoulou, 2022

SIDE VIEW RENDER

RECOVER AND RECYCLED GLASS

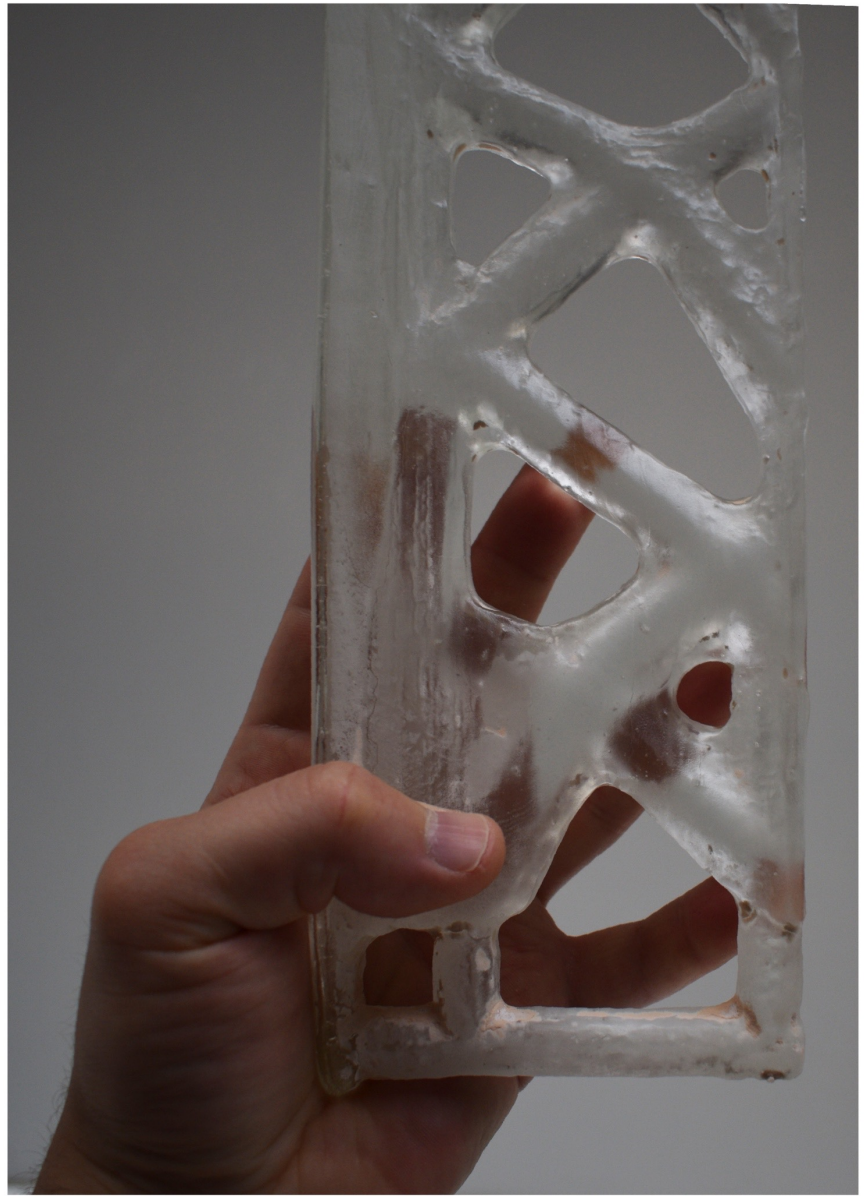
RECYCLED ARTWARE GLASS

CRYSTALLIZATION/ MARBLE LIKE LOOK

Re³ Glass TU Delft Glass lab

SIDE VIEW RENDER

MARBLE LIKE STRUCTURE



EMBRACE OPACITY

SANDBLASTING POST PROCESSING

SIDE VIEW RENDER

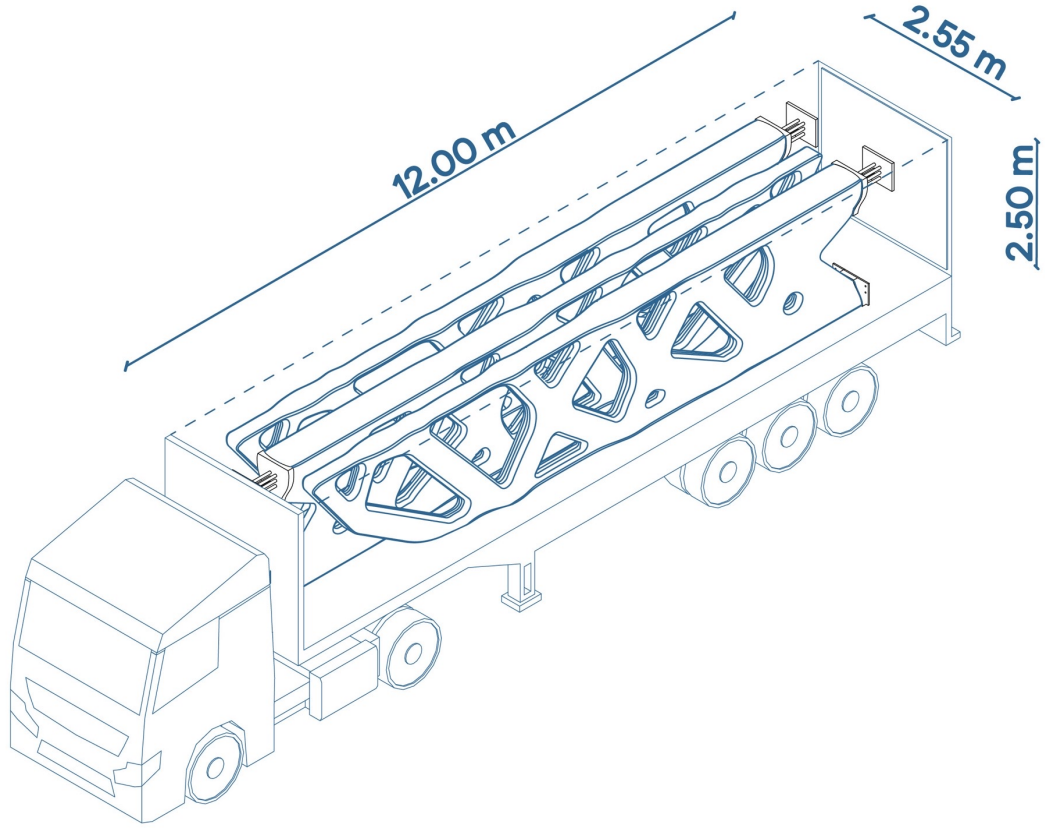
SANDBLASTED SURFACE

QUESTIONS?

FIRST MENTOR: **FAIDRA OIKONOMOPOULOU**, SECOND MENTOR: **MARCEL BILOW** STUDENT: **MENANDROS IOANNIDIS** | 5627338

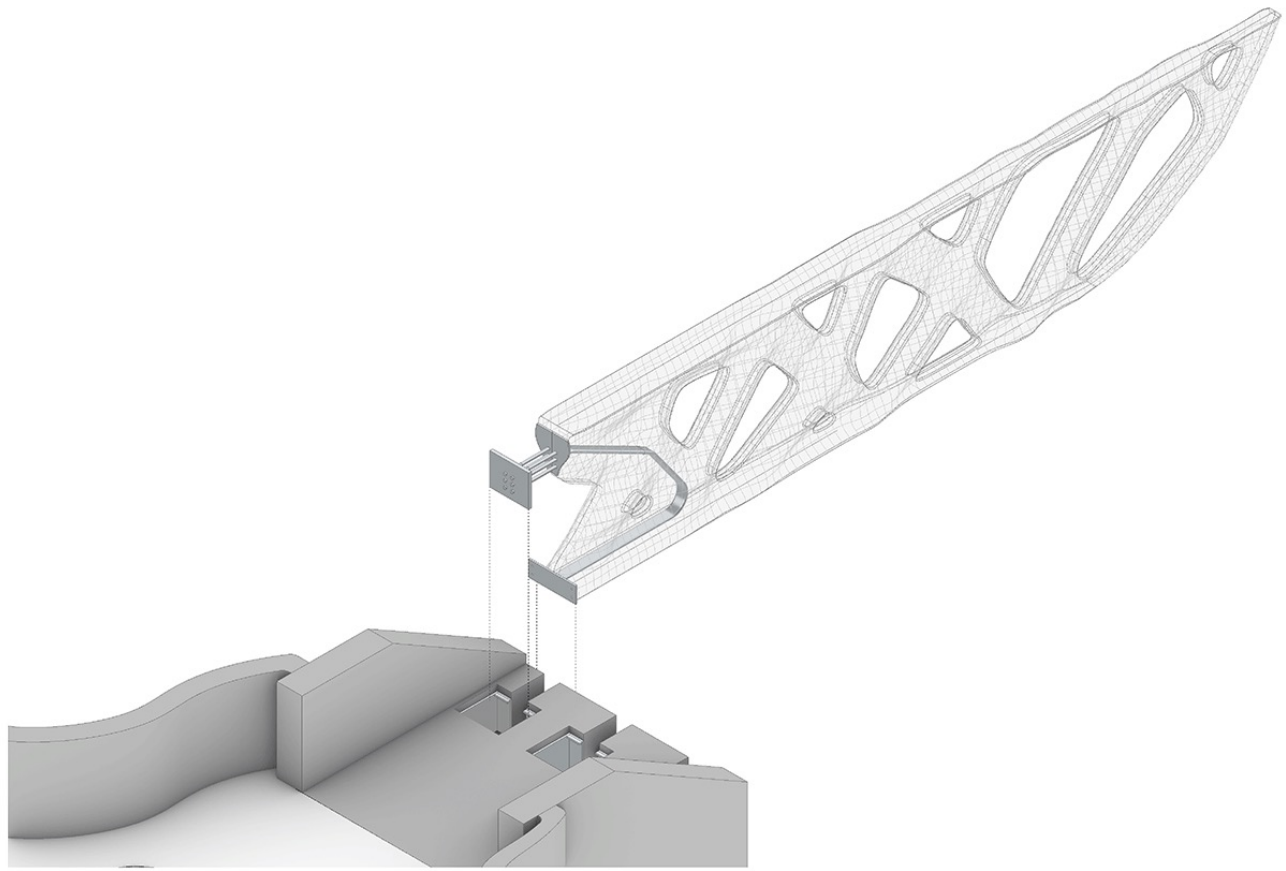
APPENDIX

TRANSPORTATION & ASSEMBLY

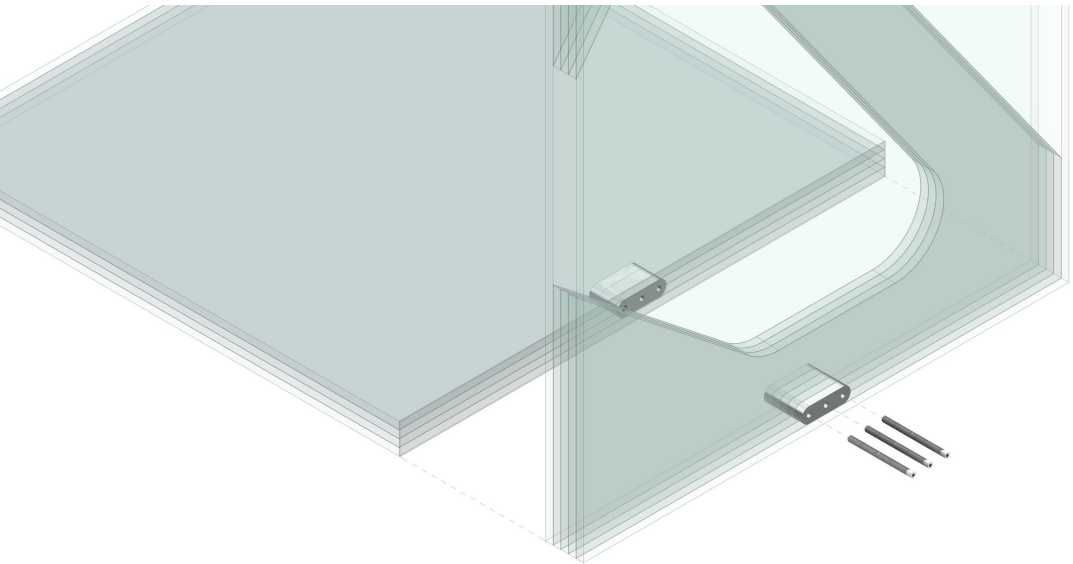


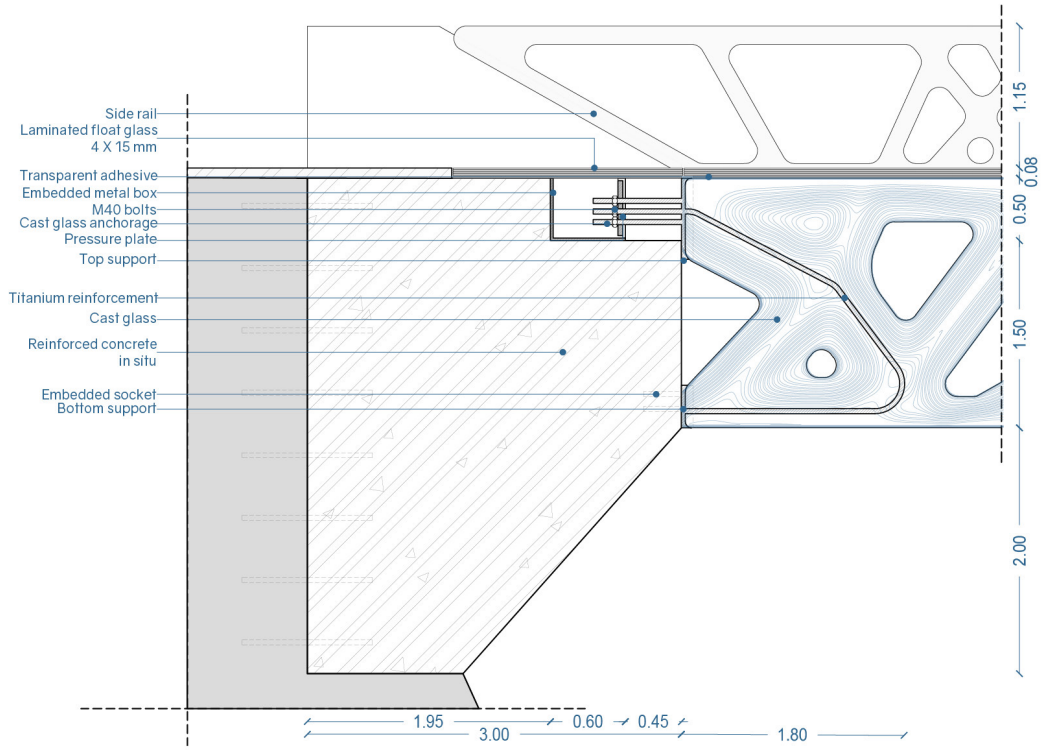
TRANSPORTATION

TRUCK AND HELICOPTER



ASSEMBLY SEQUENCE




Side rail
Laminated float glass
4 X 15 mm
Transparent adhesive
Embedded metal box
M40 bolts
Cast glass anchorage
Pressure plate
Top support
Titanium reinforcement
Cast glass
Reinforced concrete
in situ
Embedded socket
Bottom support
1.15
0.08
0.50
1.50
2.00
1.95
0.60
0.45
3.00
1.80

SCALE UP

3DPSM

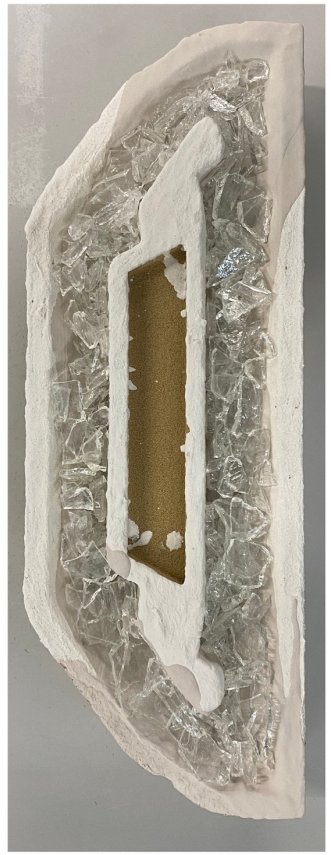
SCALE UP COATINGS RESULTS

AS PART OF PARALLEL RESEARCH AT GLASS LAB

1 Protective layer

2 Coating application

3 Glass placement



4 Mould after firing at 870°C

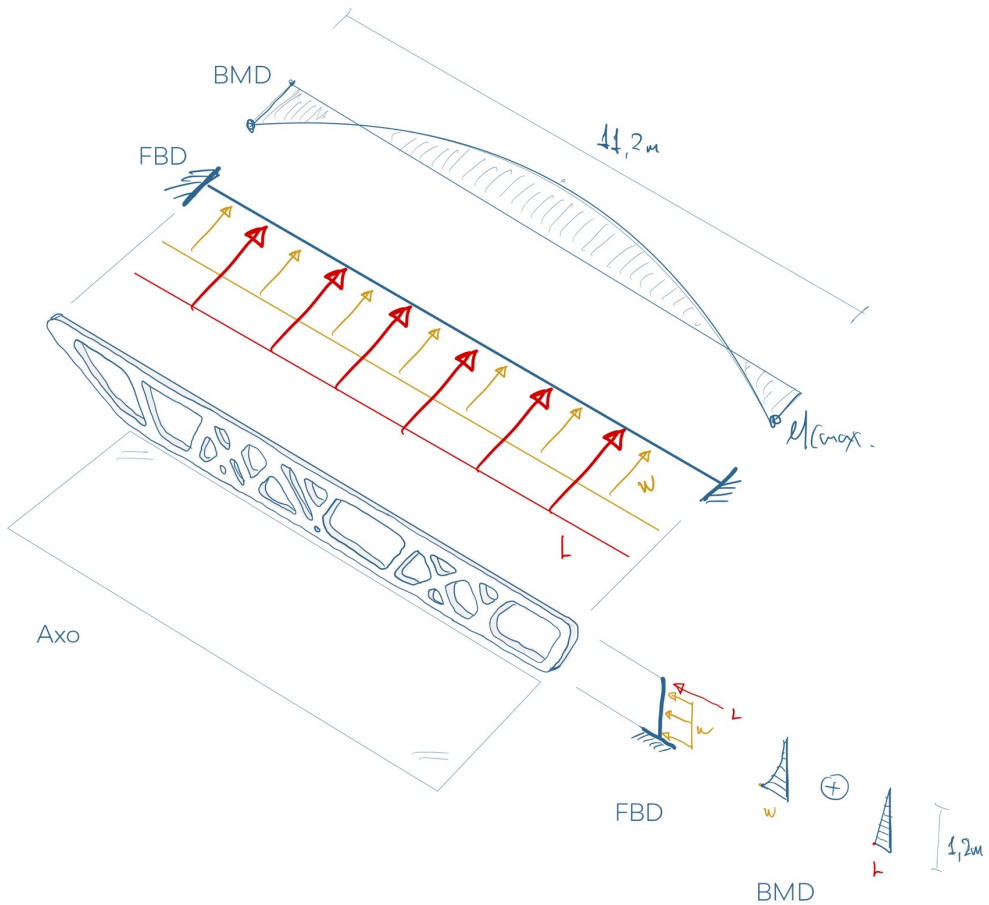
5 Demoulding and cleaning

6 Final glass element

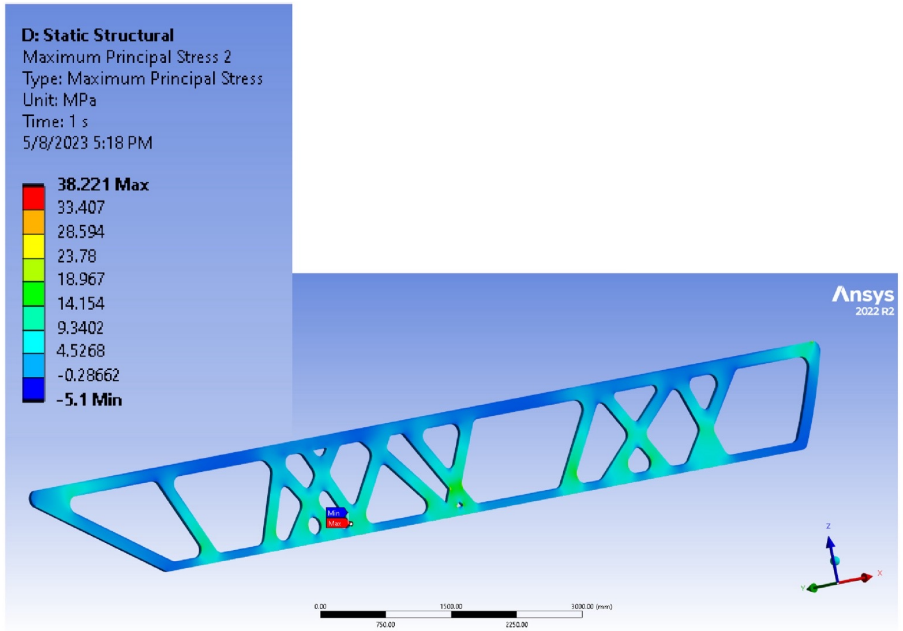
SCALE UP COATINGS RESULTS

FROM 3DPSM TO GLASS

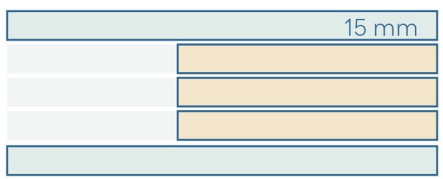
ULS calculations



ANSYS FEM verification



Schematic section

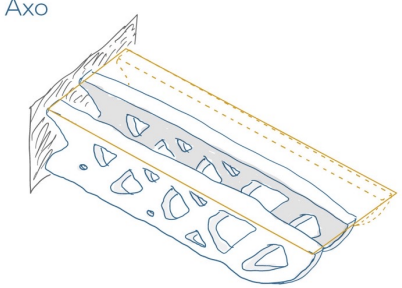


AWJ cut
Heat strengthened glass
PVB lamination

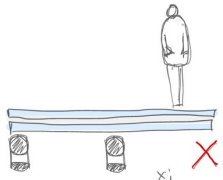
SLS calculations

Side fin failure scenario

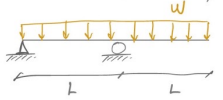
Axo



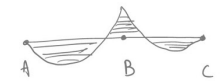
Section



FBD

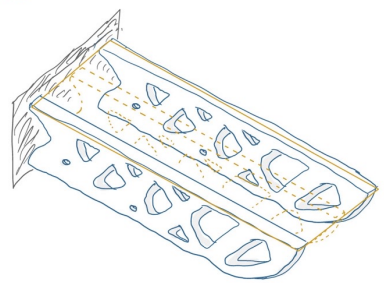


BMD



Middle fin failure scenario

Axo



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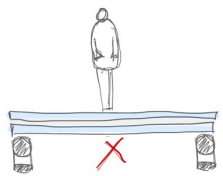

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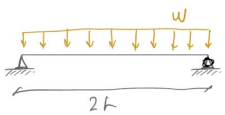
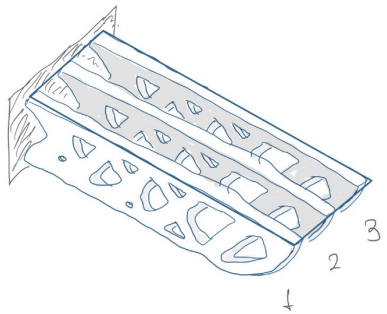


BMD

ULS calculations

Axo



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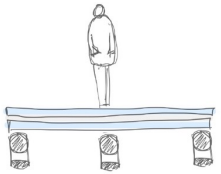

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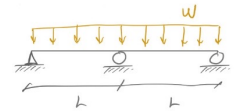

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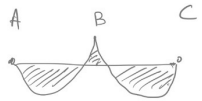
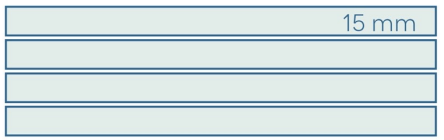
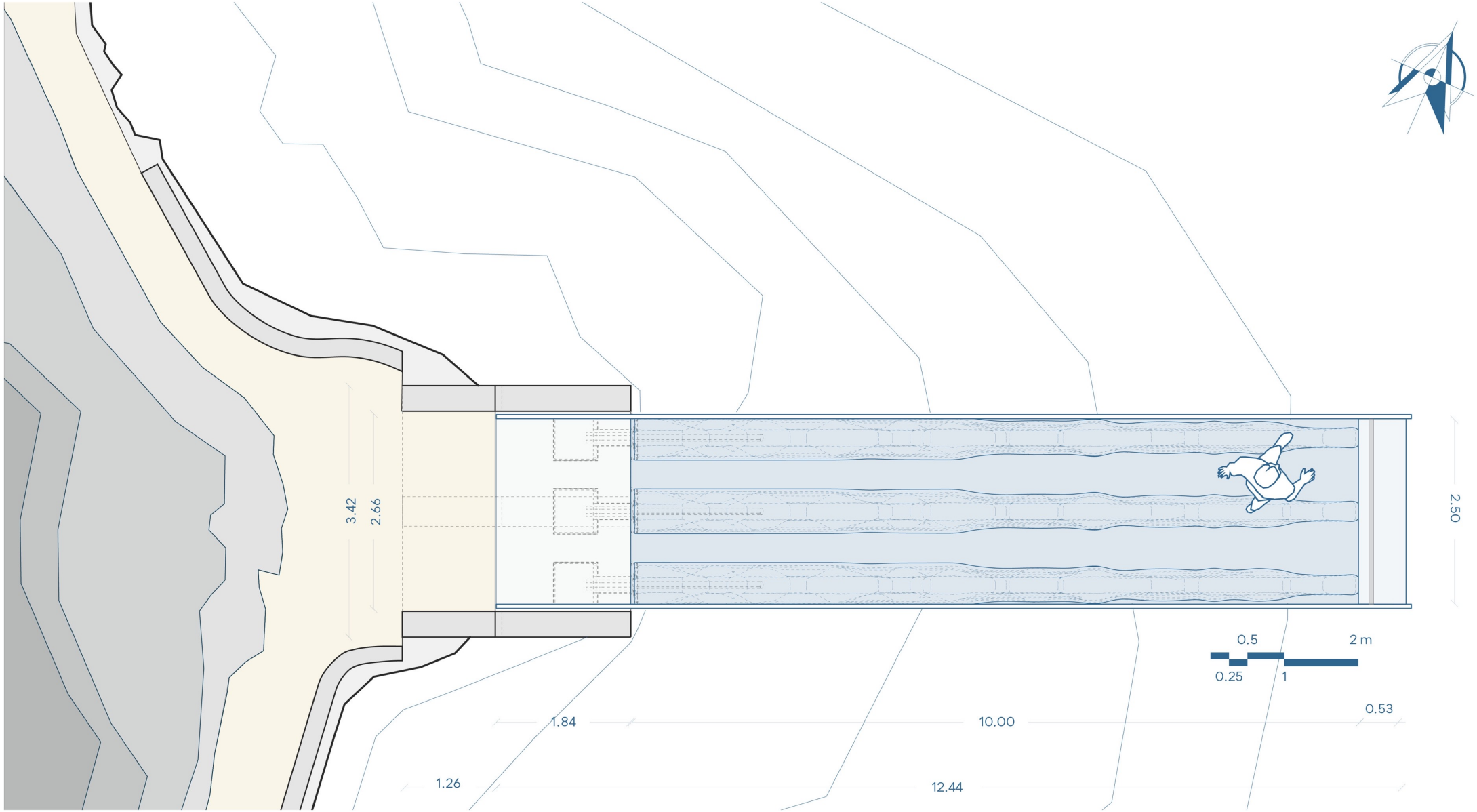
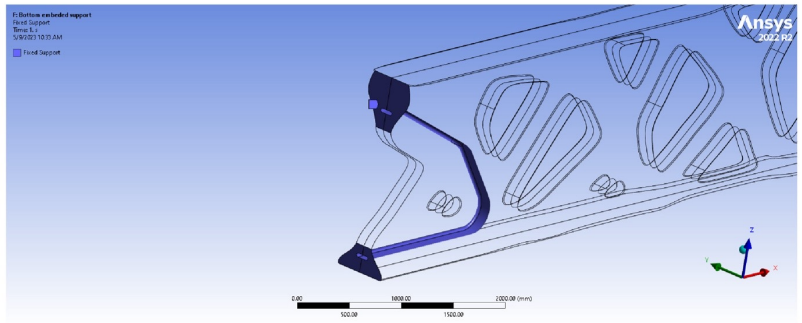


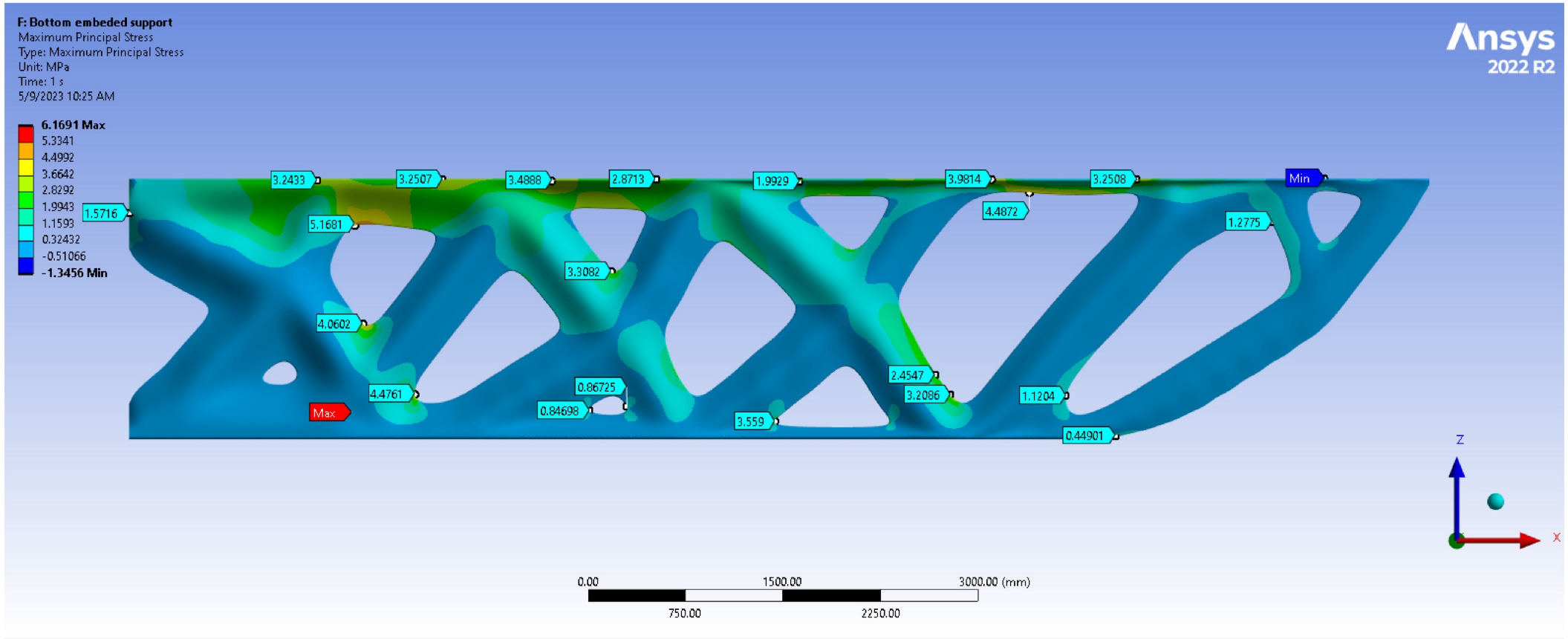
Schematic section



Heat strengthened glass
PVB lamination

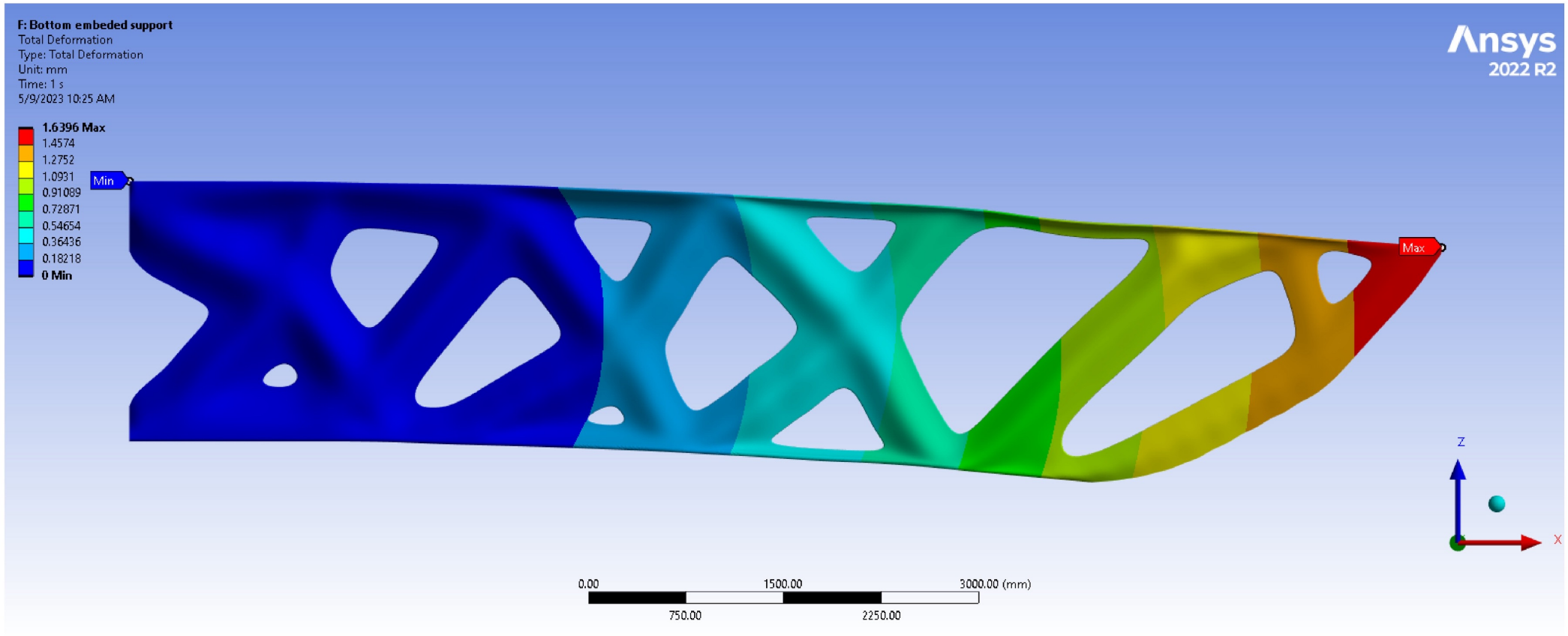

3.42
2.66
2.50
0.5
2 m
0.25
1
1.84
10.00
0.53
1.26
12.44





ANSYS VERIFICATION

MAXIMUM TENSILE STRENGTH



ANSYS VERIFICATION

DEFLECTION

ANIMATION

WALK THROUGH

Skywalk, Bründl Sports

GRAND CANYON SKYWALK

(Giroux Glass, n.d.)

	Structural		Optical		Sustainability		Fabrication limitations					
Criteria	Redundancy	Structural performance	Transparency	Finishing quality	Waste generation	Recyclability	Fabrication cost	Need for post process	Size limitation	Shape limitation	Ease of connection	Transportation
Laminated	High	High	Medium	High	High	Low	High	Low	Medium	High	High	Medium / High
Cast	No	Medium	High	Low	Low	High	Medium	High	Low	Low	Medium	Medium / High
3D printed	No	Low	Low	Medium	No	High	High	Medium	High	Medium	Low	Easy

Disadvantage Neutral Advantage Exceptional

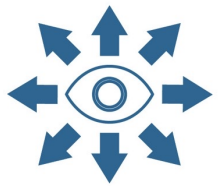
COMPARISON OF FABRICATION METHODS

ASSESMENT CATEGORIES AND CRITERIA

	Structural		Optical		Sustainability		Fabrication limitations					
Criteria	Redundancy	Structural performance	Transparency	Finishing quality	Waste generation	Recyclability	Fabrication cost	Need for post process	Size limitation	Shape limitation	Ease of connection	Transportation
Laminated	High	High	Medium	High	High	Low	High	Low	Medium	High	High	Medium / High
Cast	No	Medium	High	Low	Low	High	Medium	High	Low	Low	Medium	Medium / High
3D printed	No	Low	Low	Medium	No	High	High	Medium	High	Medium	Low	Easy

Disadvantage Neutral Advantage Exceptional

Minimal optical footprint

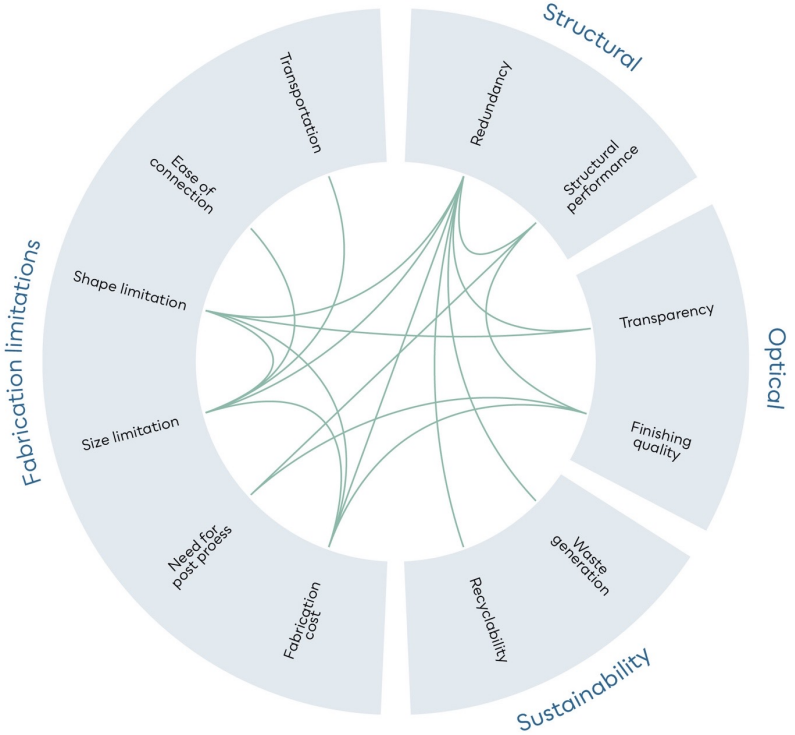


Unobstructed view

Unique structure/ experience

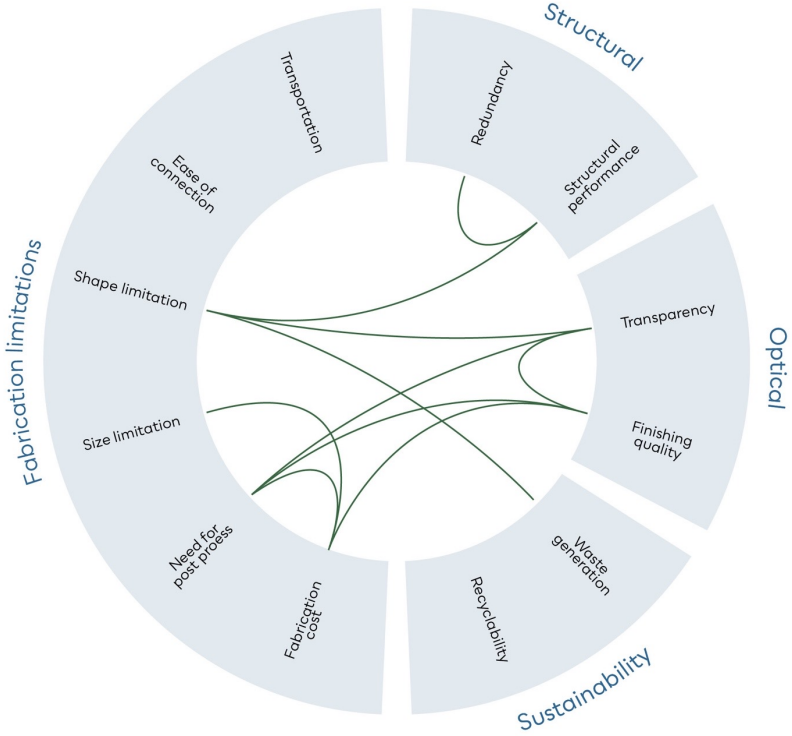
Sustainable manufacturing

AWJ cut laminated float glass



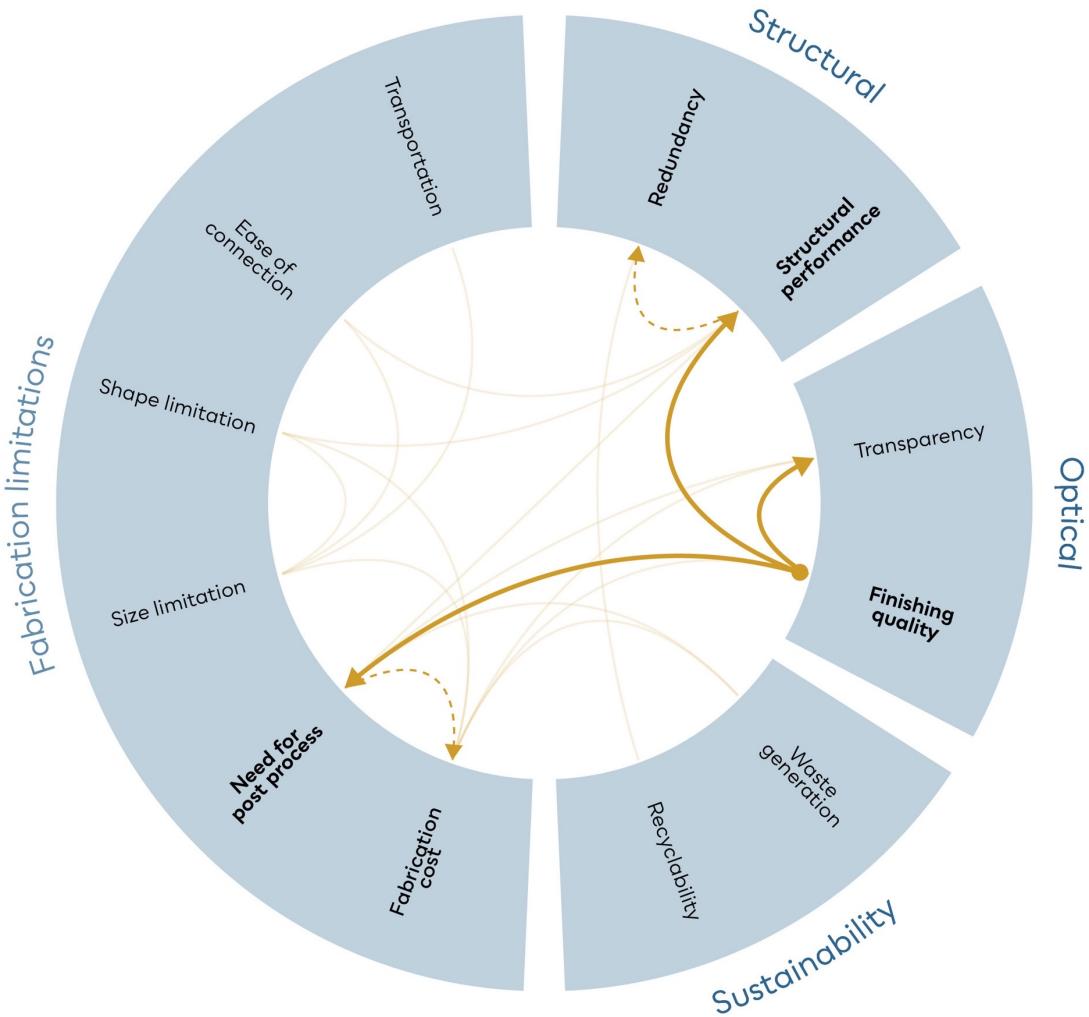
Kiln cast

3D printed glass



CORRELATION DIAGRAMS

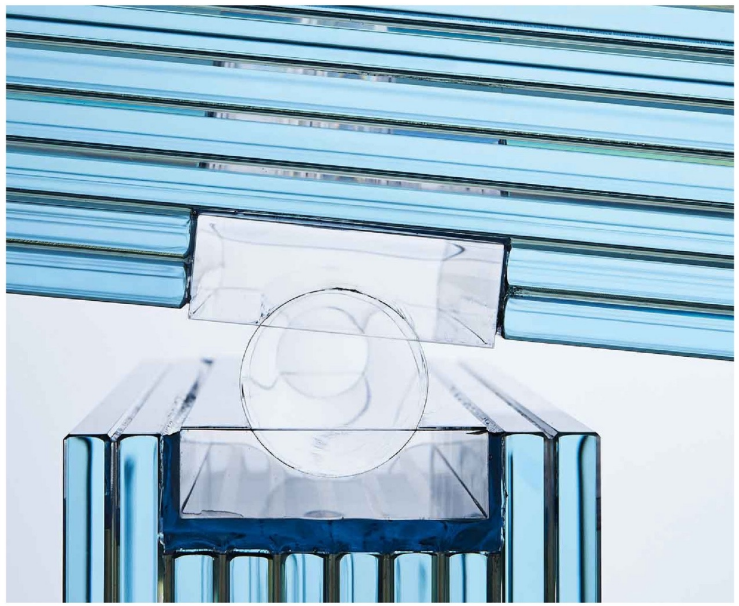
Kiln cast



CORRELATIONS DIAGRAM

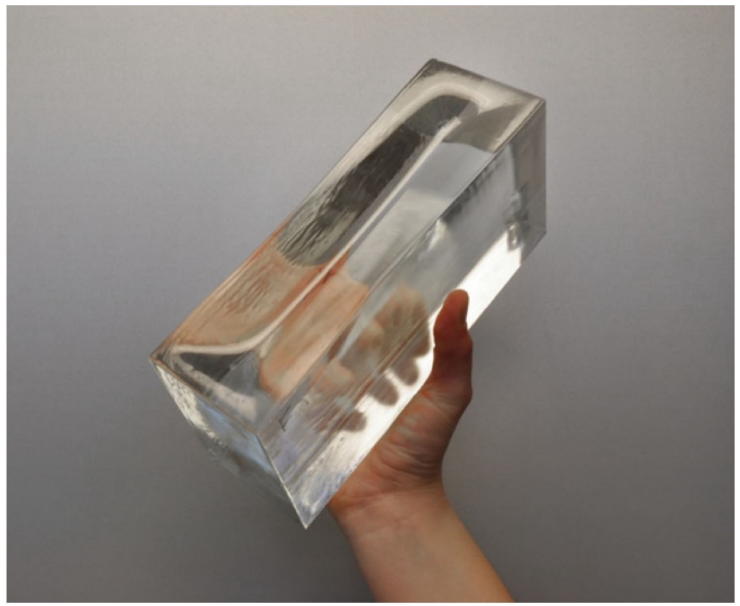
KILN CASTING WITH 3DPSM

Laminated float



Eckersley O'Callaghan, (2018)

Cast



Oikonomopoulou, Bristogianni, Veer, et al., (2018)

3D printed

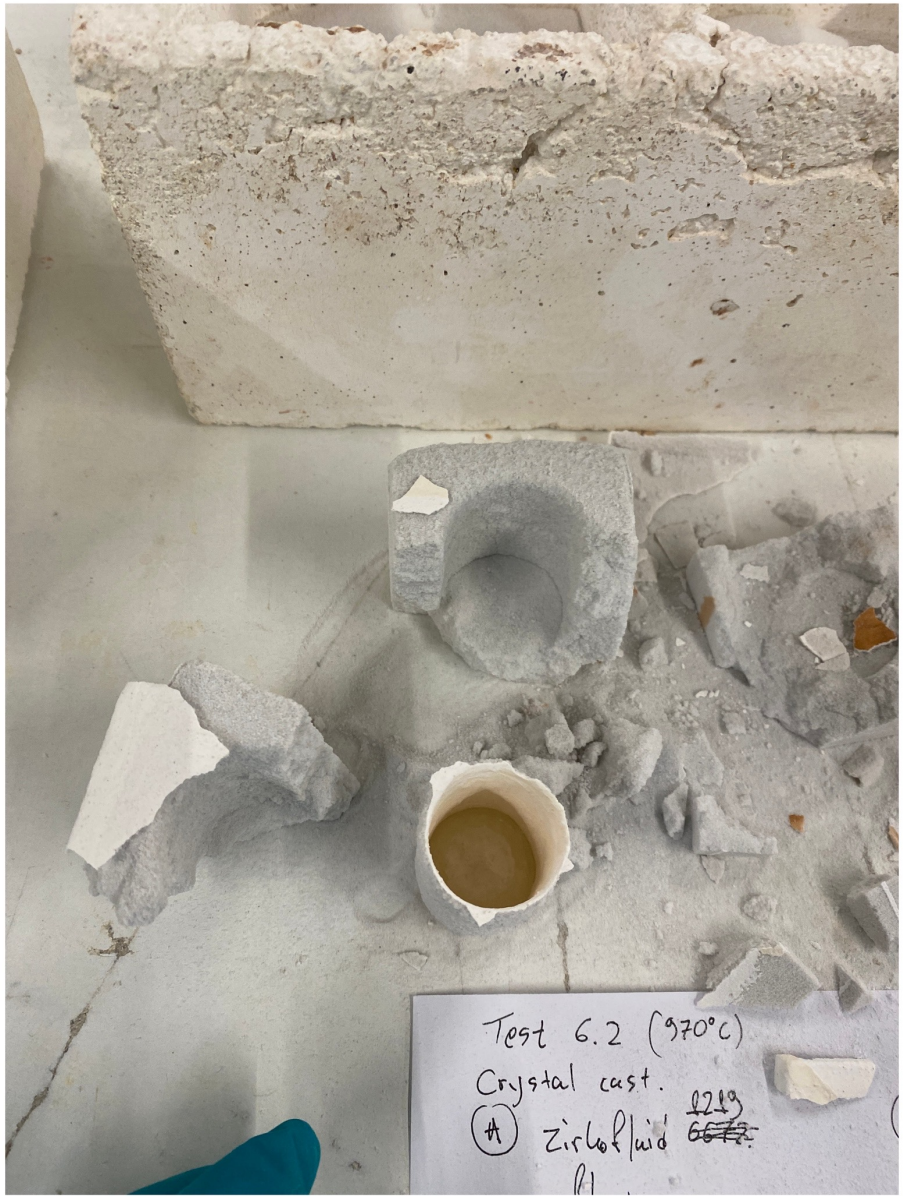
Klein et al., (2015)

COMPARISON

TRANSPARENCY

CRYSTALCAST MOULD

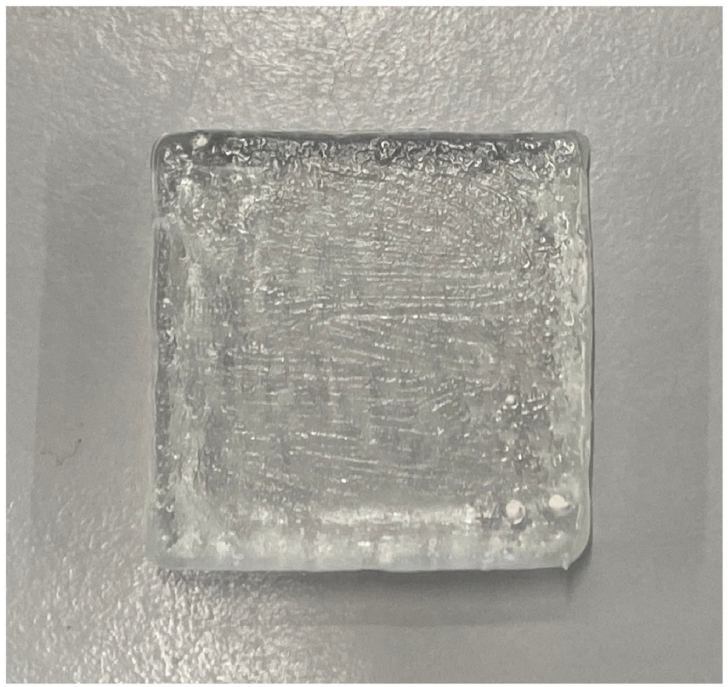
LOST WAX TECHNIQUE



CRYSTALCAST - PROTECTIVE LAYER

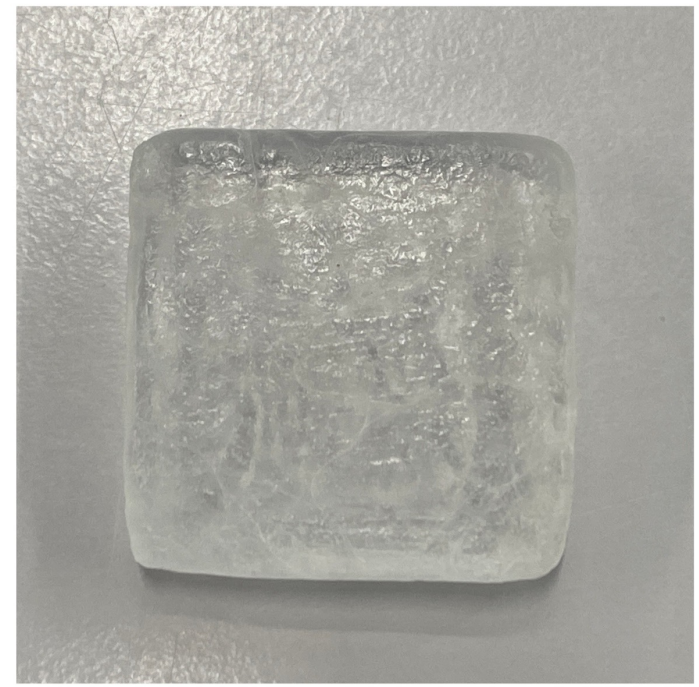
THIN WALLED MOULD

Zirkofluid 1219



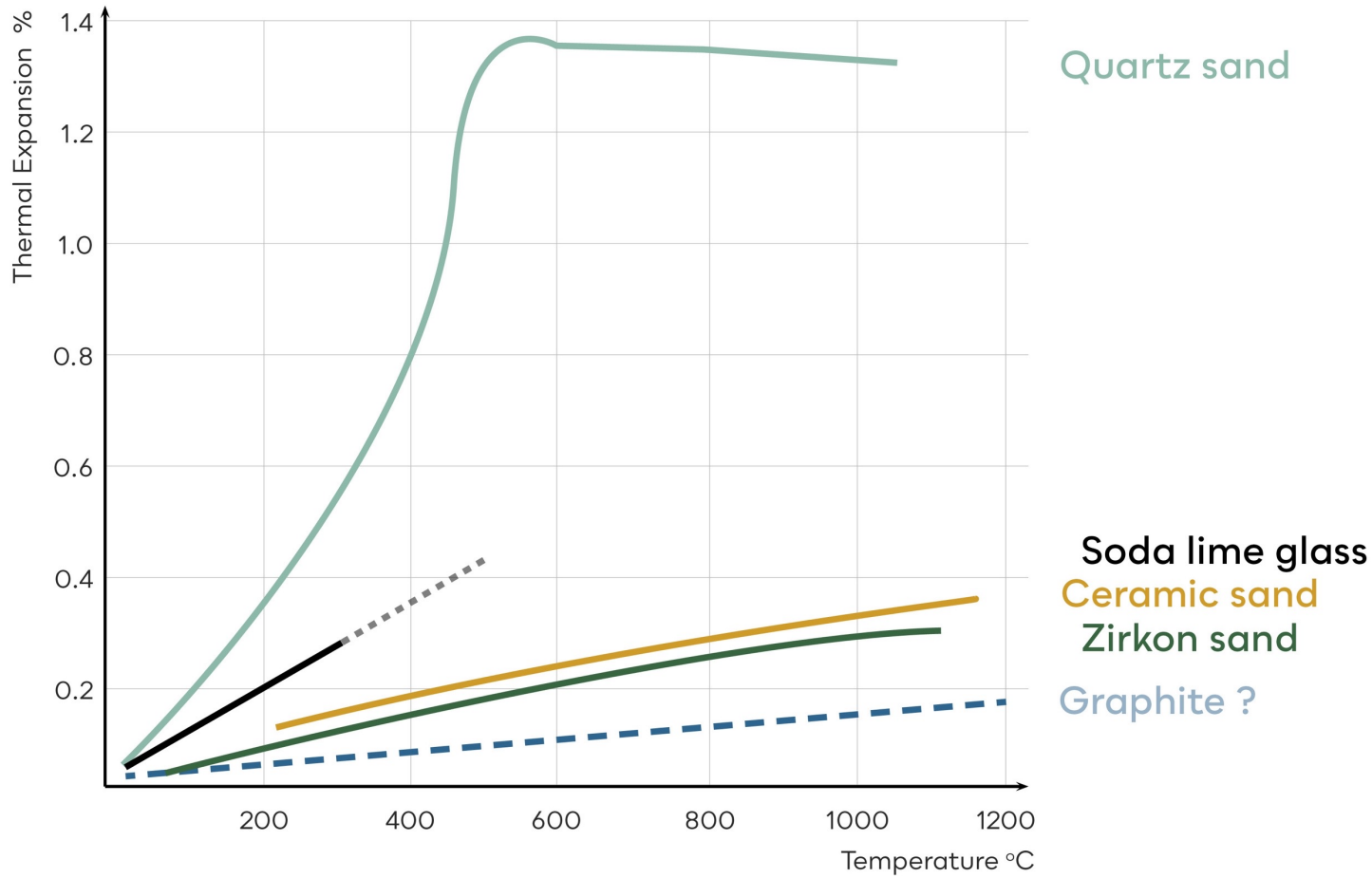
Zirkofluid 6672

Arkopal B 5



CRYSTALCAST MOULDS

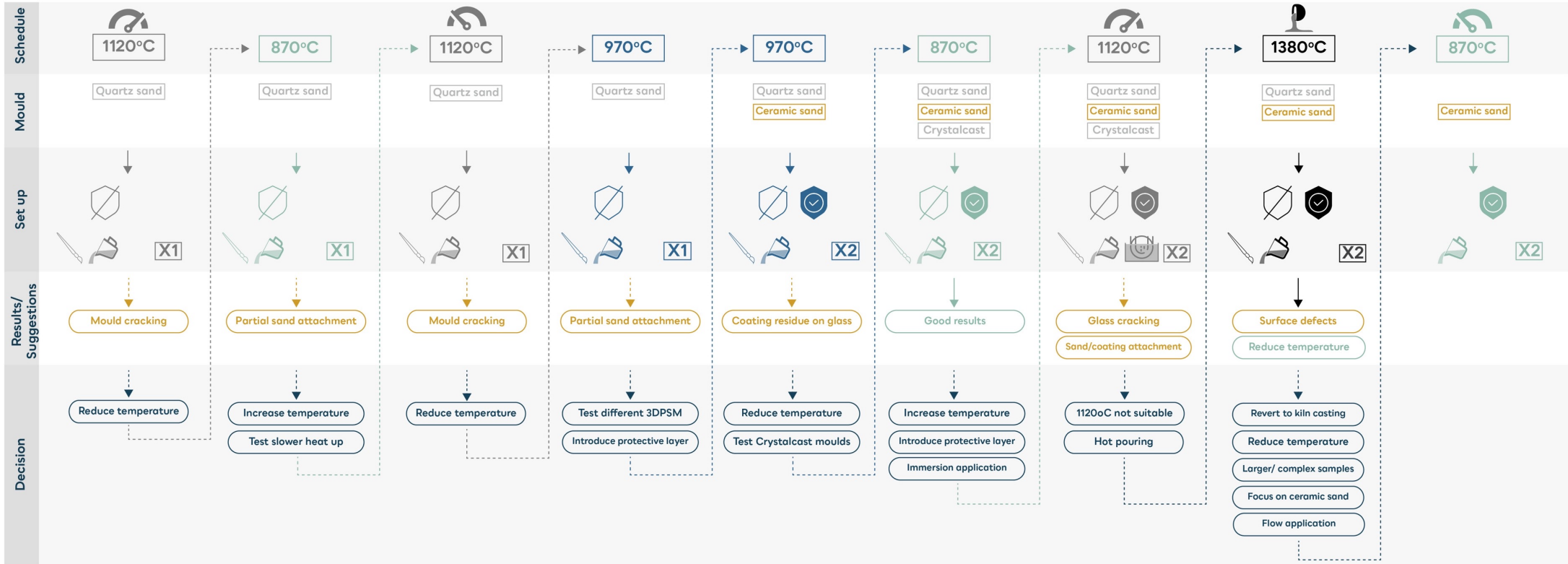
BRUSH APPLICATION 870°C



THERMAL EXPANSION

SAND AND COATINGS APPROXIMATION

Granta EduPack 2022 R1, Roller et al., 2016



DECISION TREE

EXPERIMENTS