BREAKING GROUND WITH BAMBOO

ROBOTIC ADDITIVE MANUFACTURING OF A SELF SUPPORTING WALL WITH BAMBOO

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Delegate of the Board of Examiners: Dr. Arie Romein

P5 I 04.07.2023

AR3B025 2022/23 Q4
Building Technology Graduation Studio

TU Delft Delft University of Technology

made in bamboo

BAMBOODER® BIOBASED FIBER

breaking ground

To do something completely different from what has been done before.

CONTENT

CONTENT

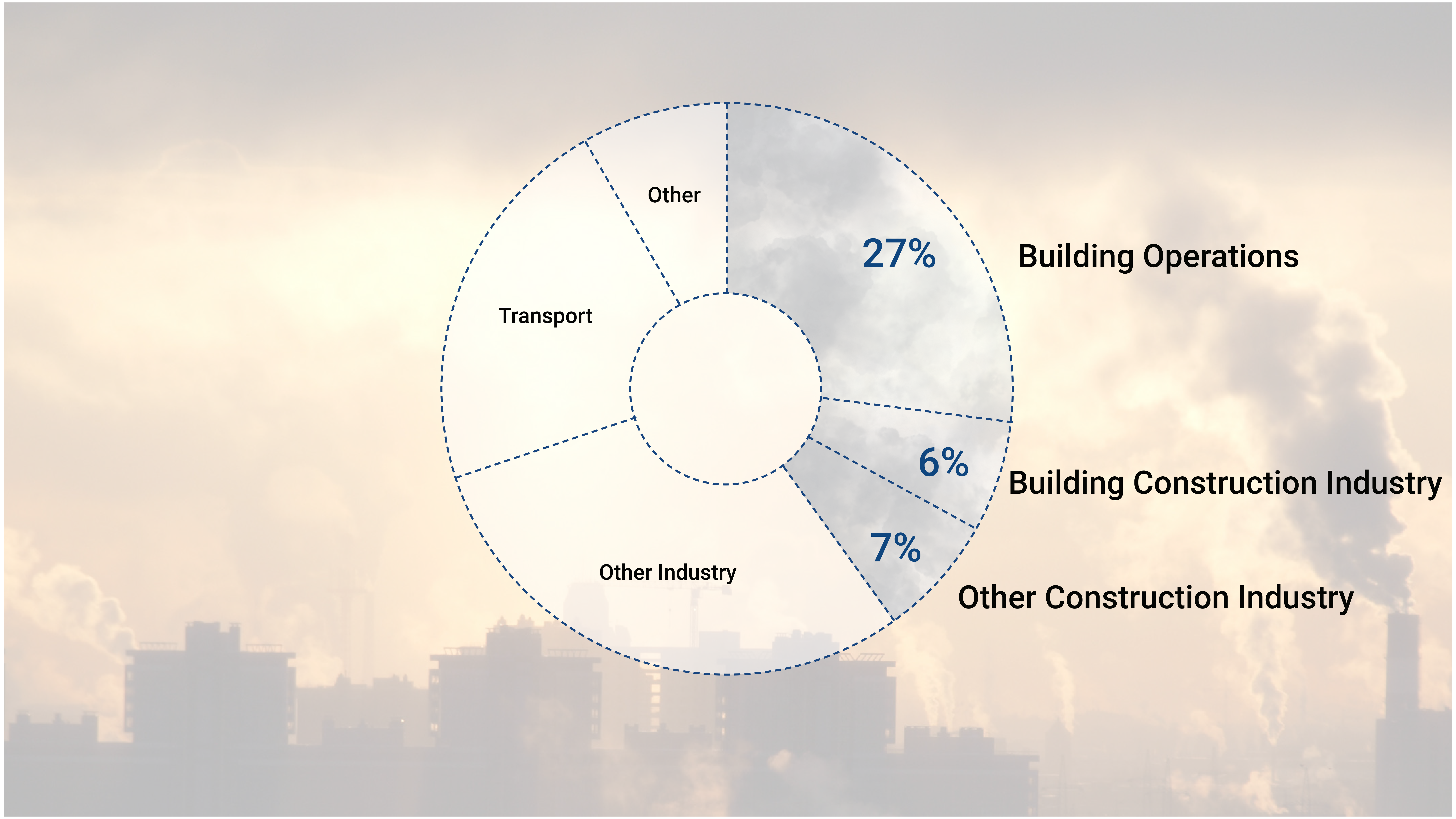
BUILDING INDUSTRY

Source: MunichRE

BUILDING INDUSTRY

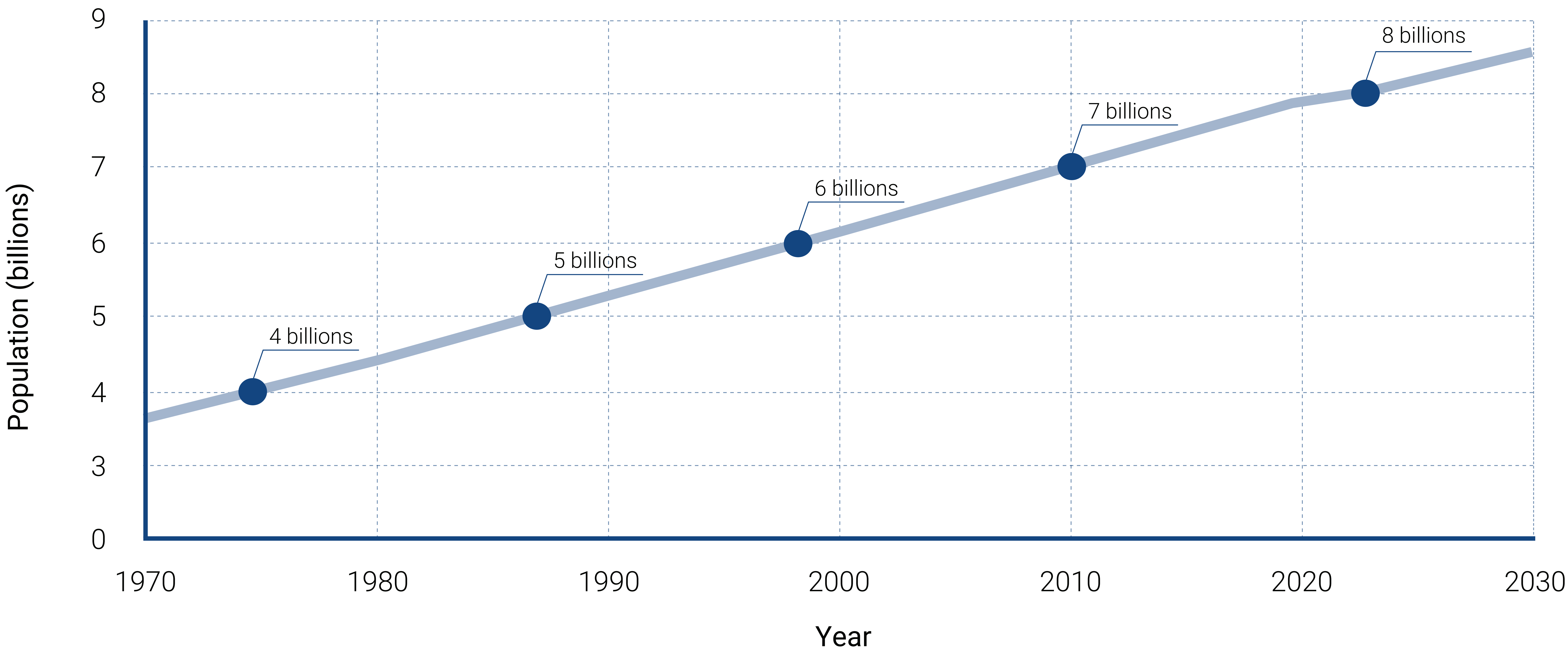
Source: Eumetsat

40% GREENHOUSE GAS EMISSIONS



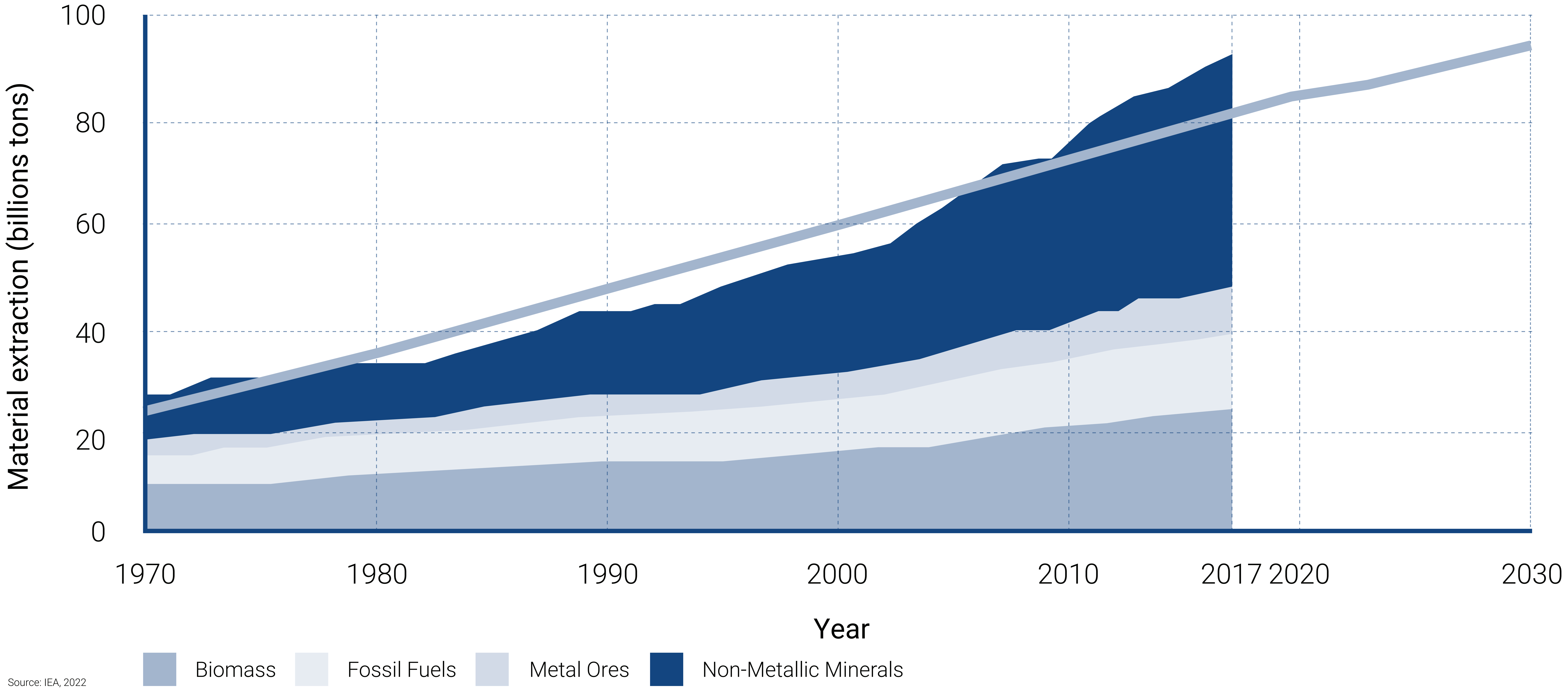
Source: IEA, 2022

8 BILLIONS IN 2022



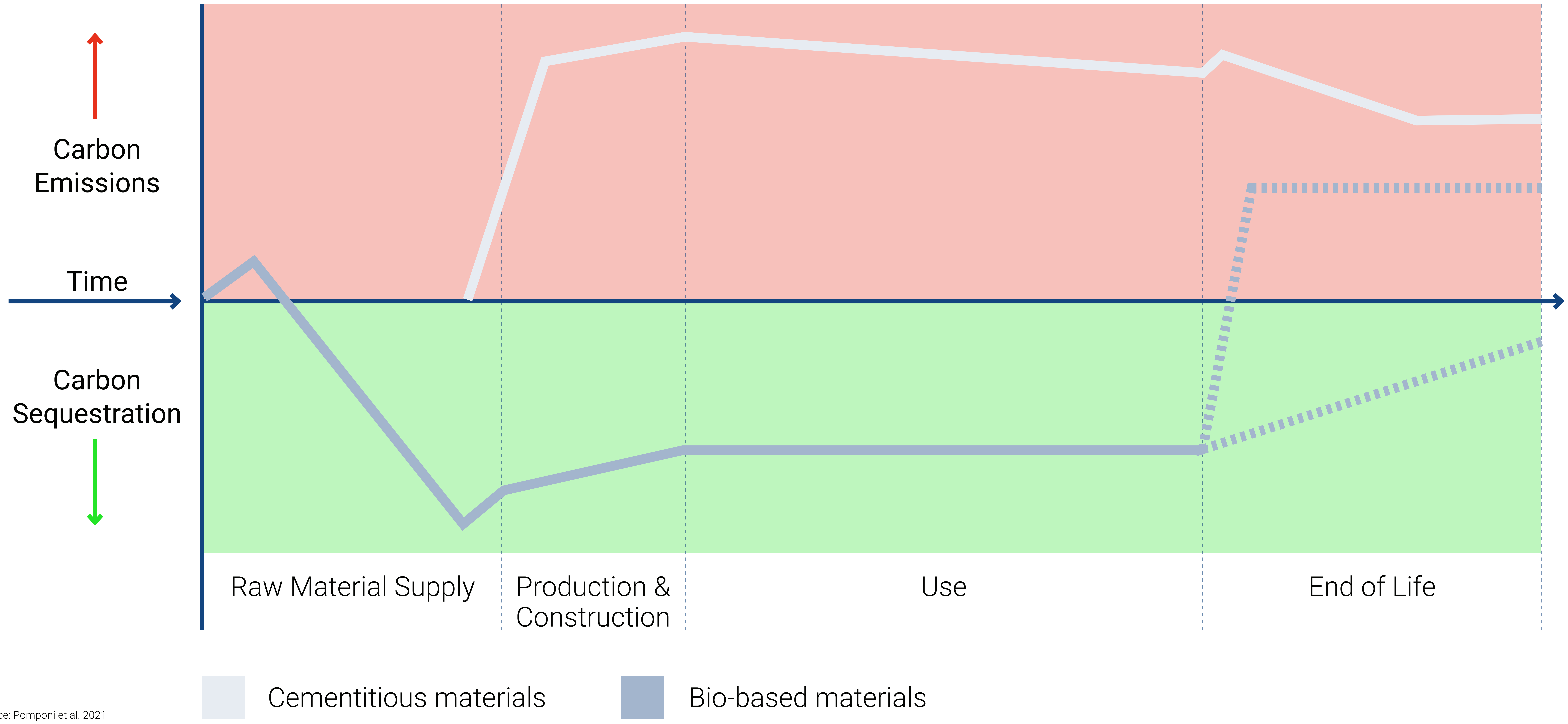
Source: IEA, 2022

MATERIAL EXTRACTION DEMAND



Source: IEA, 2022

CARBON STORAGE



Source: Pomponi et al. 2021

TIMBER


Centre Pompidou Metz, Shigeru Ban. Source: Archdaily


Nest We Grow, Kengo Kuma. Source: Archdaily


The Farmhouse, Studio Precht. Source: Dezeen

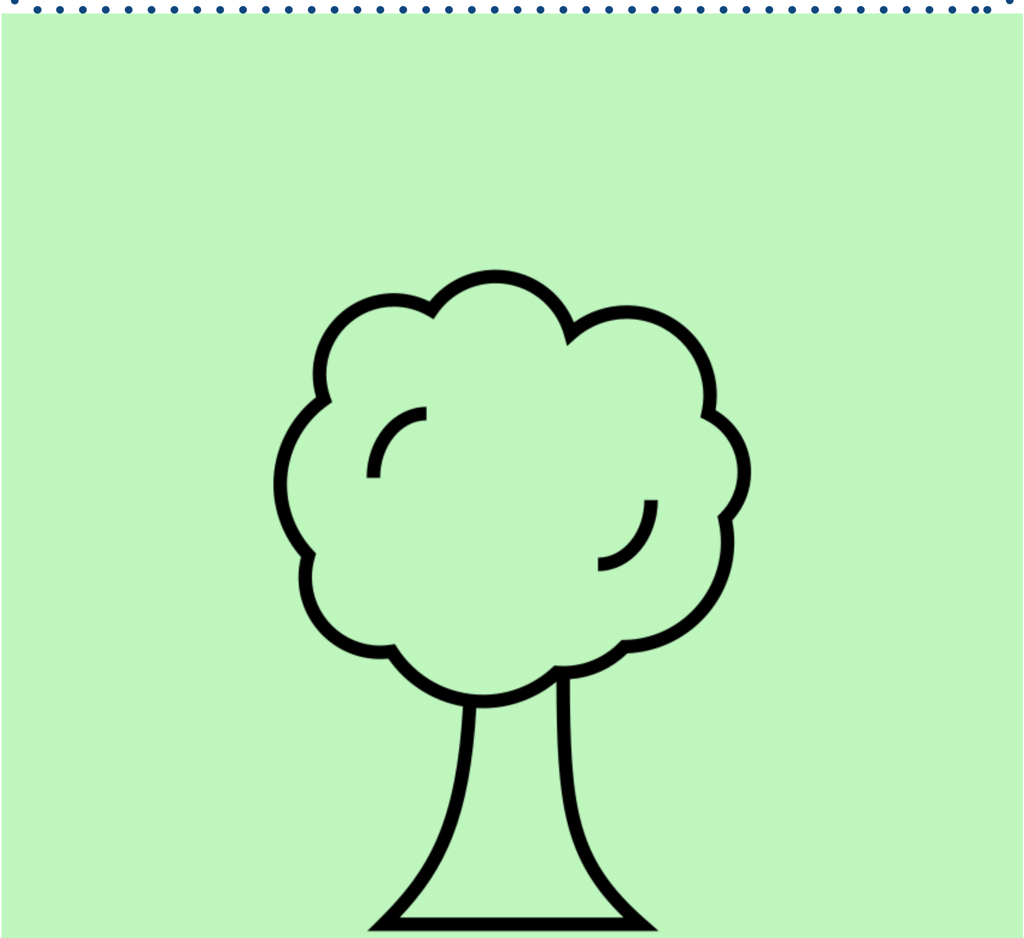

Macquarie University Incubator, ARUP. Source: Arup

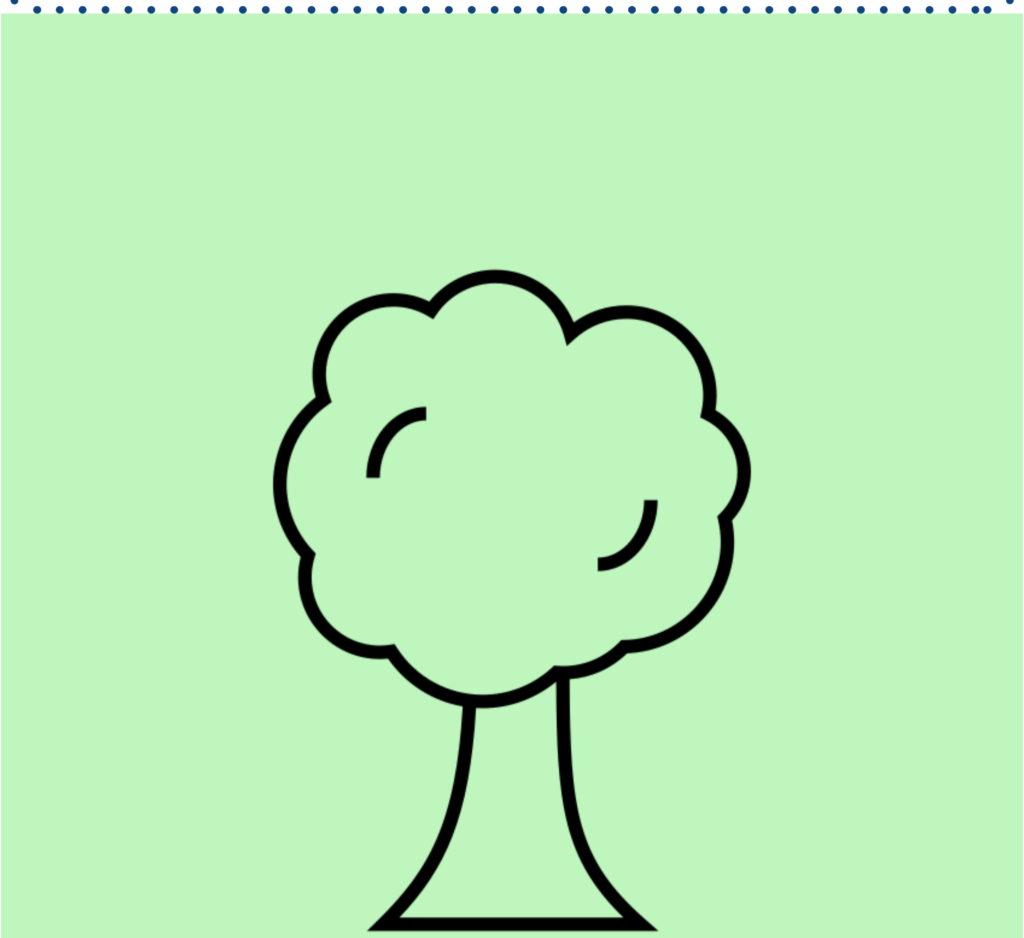

Community Church Knarvik, Reiulf Arkitekter. Source: Archdaily


Timber House, KUHNLEIN Architektur. Source: Archdaily

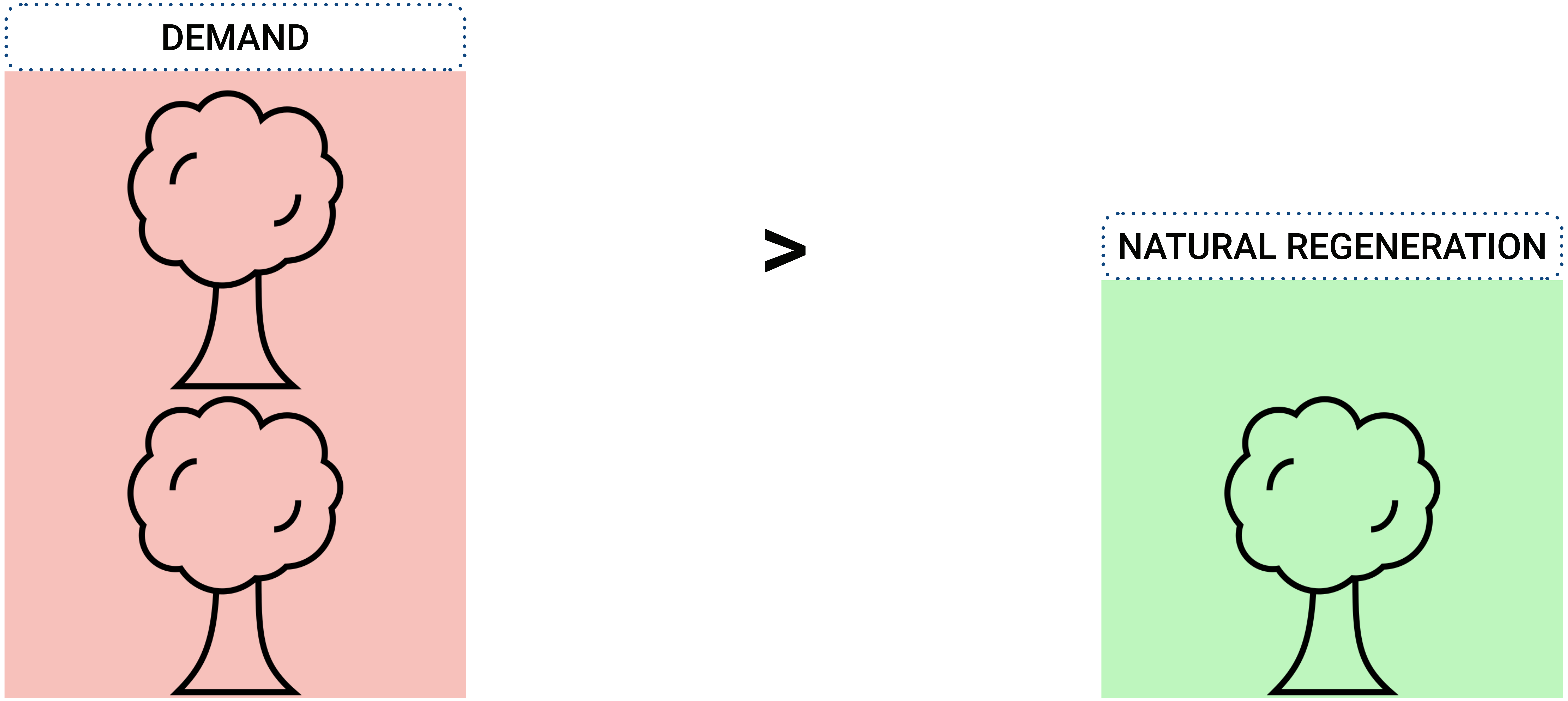
TIMBER LIMITATIONS

DEMAND $\leq$ NATURAL REGENERATION





TIMBER LIMITATIONS



DEFORESTATION

Source: theGuardian

ALTERNATIVES

COMPLEMENT WOOD

affordable

quickly growing

easily accessible

BAMBOO

BAMBOO

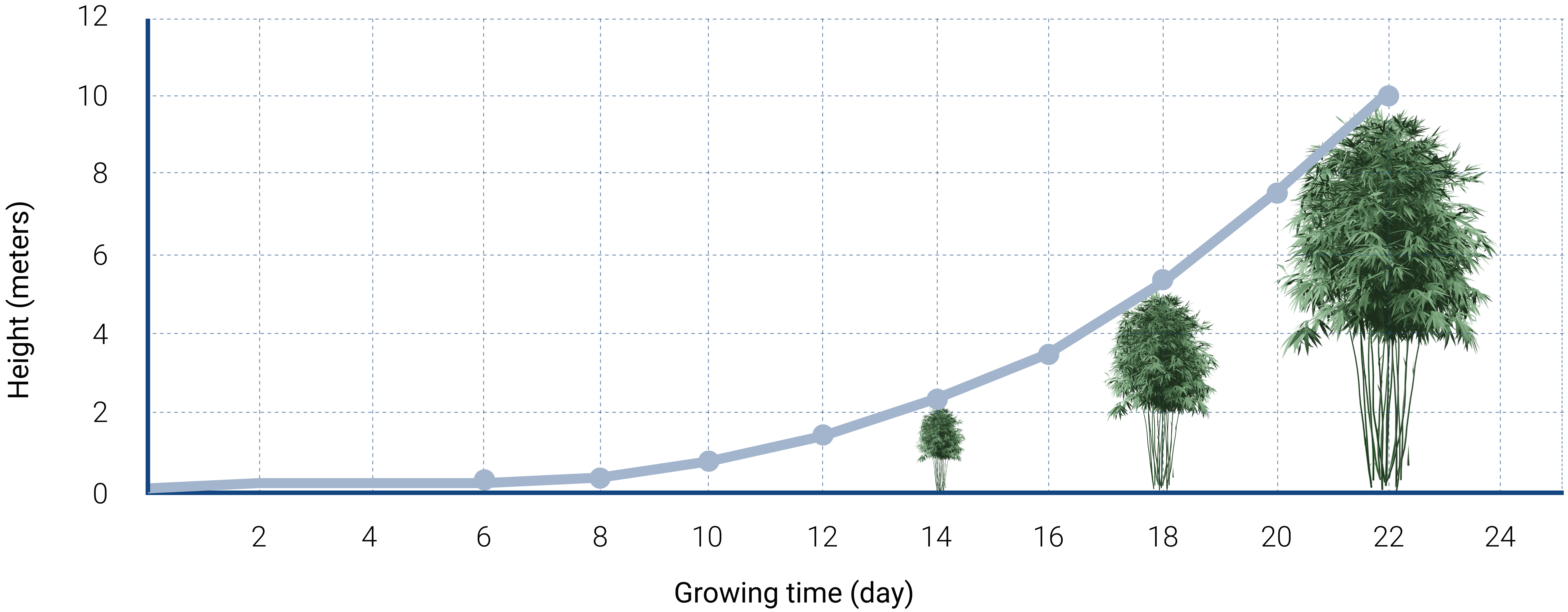
Source: Herald Scotland

BAMBOO AS A CONSTRUCTION MATERIAL

Community Church Knarvik, Reiulf Arkitekter

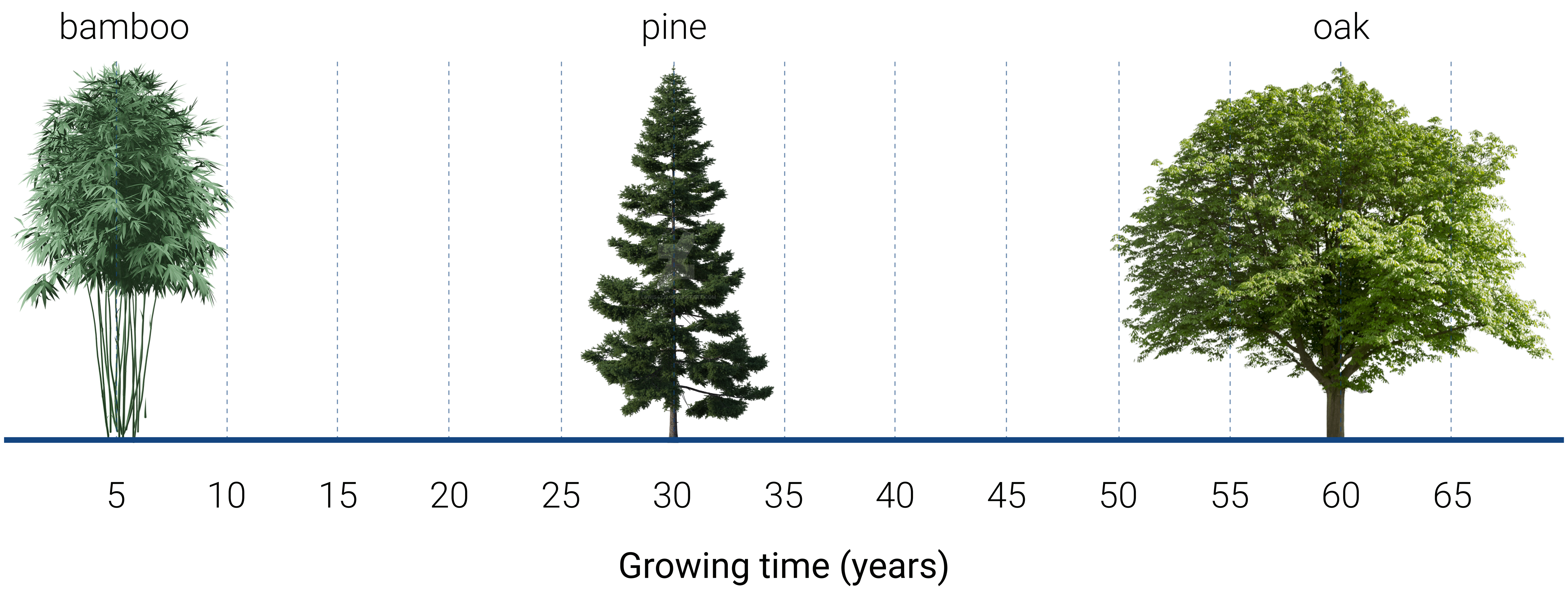
Source: Archdaily

QUICK GROWTH CYCLE



Source: Borowski et al., 2022

QUICK HARVEST

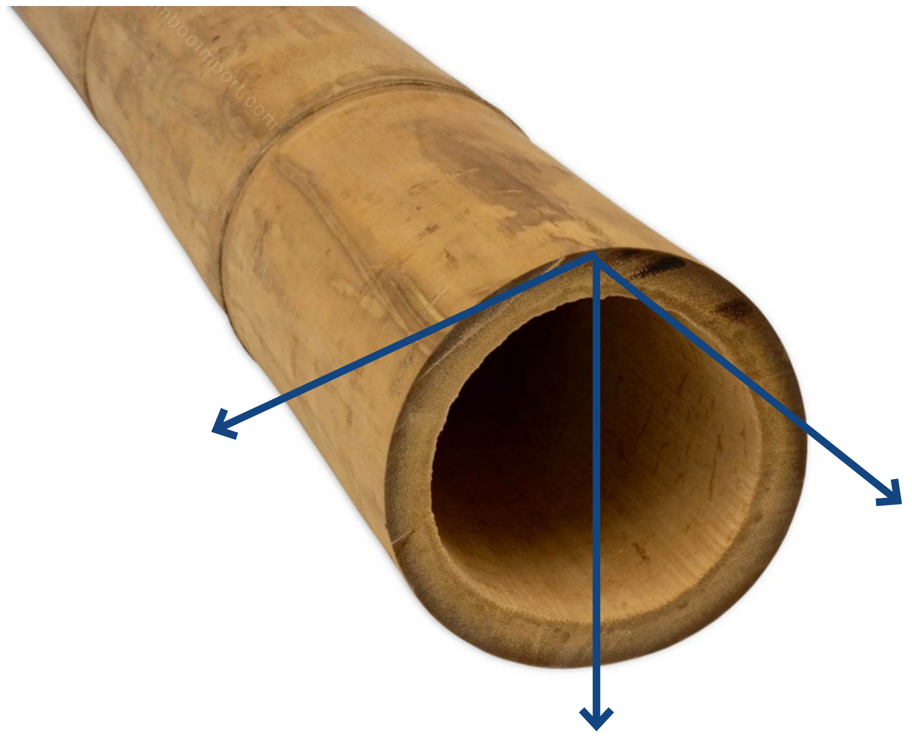


Source: Kampinga et al., 2015

WHY ISN'T IT USED ON A LARGE SCALE?

BAMBOO DISADVANTAGES

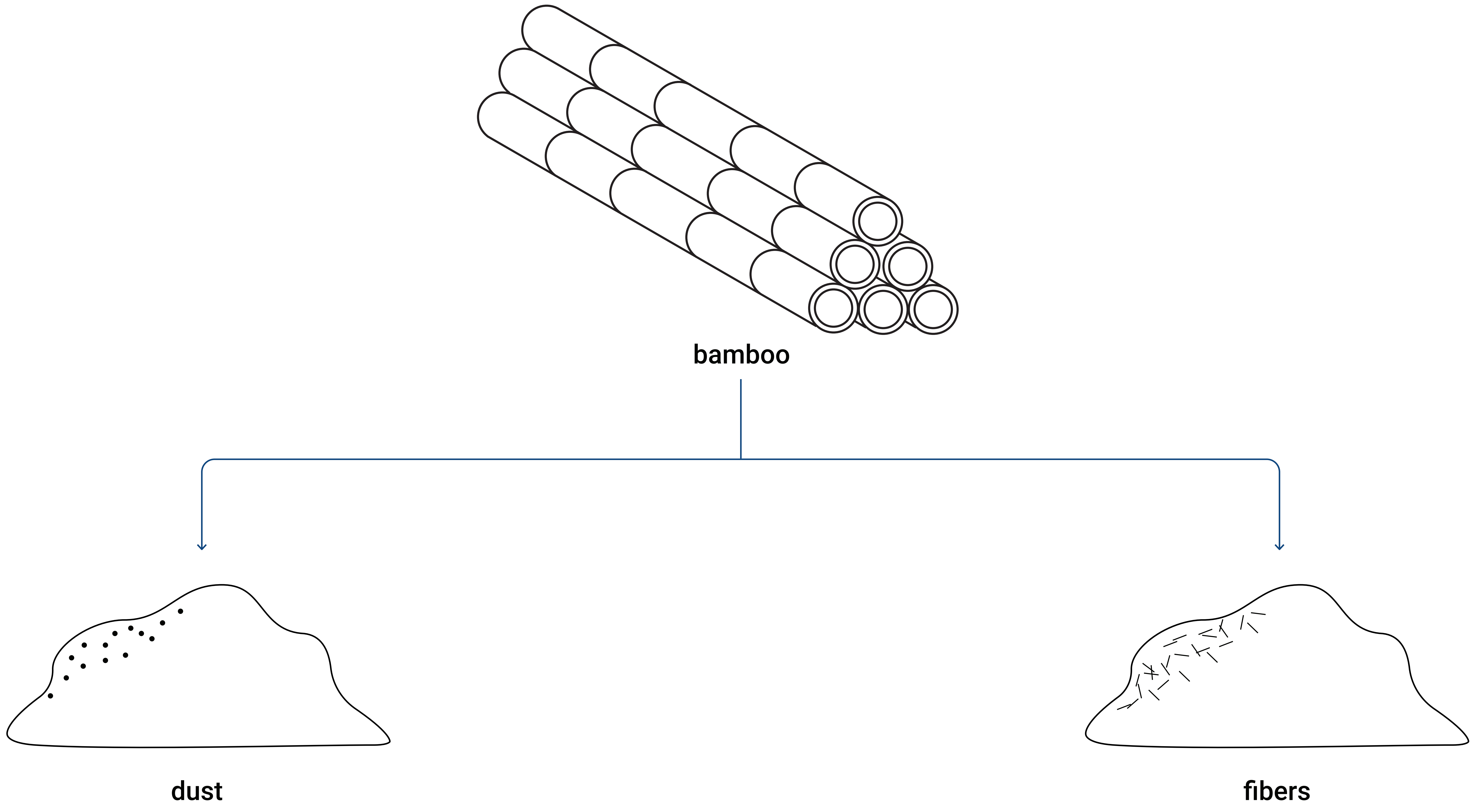

short lifespan


anisotropic material

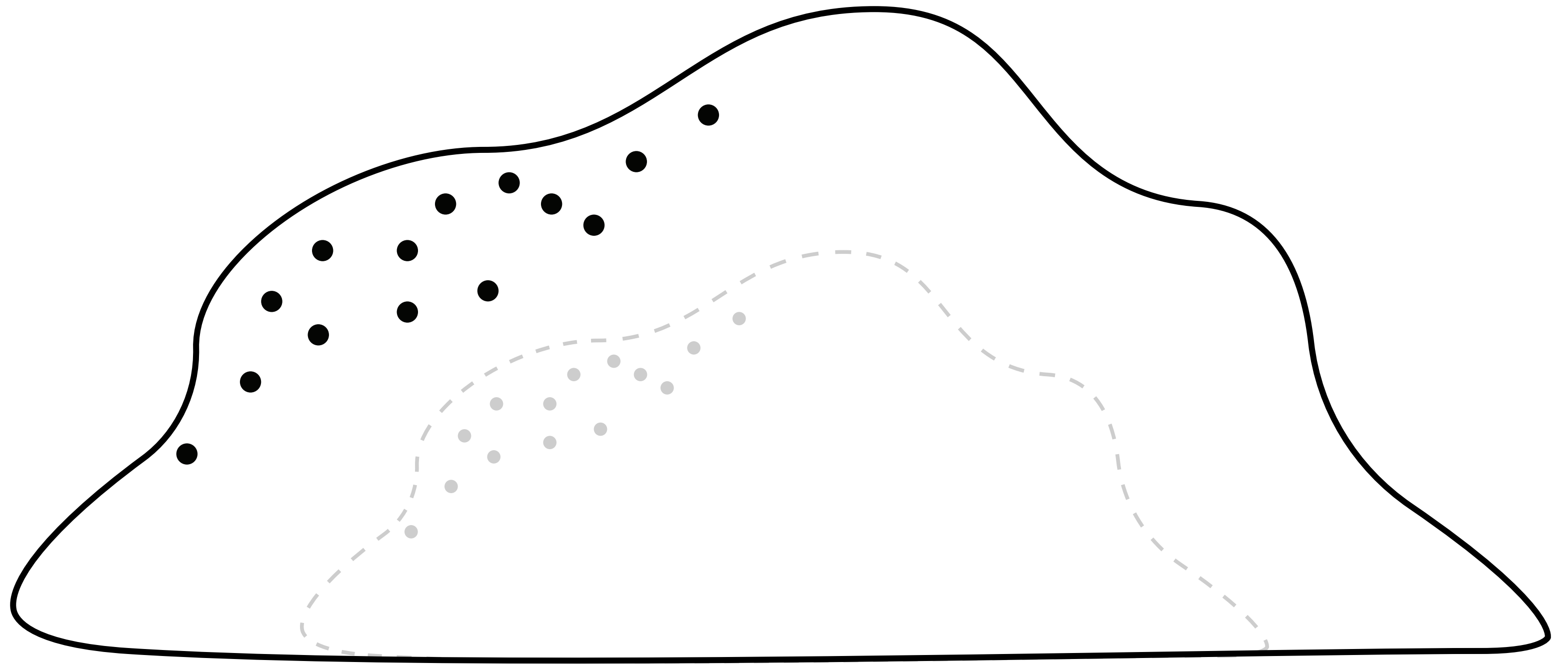

different species = different properties


lack of building codes

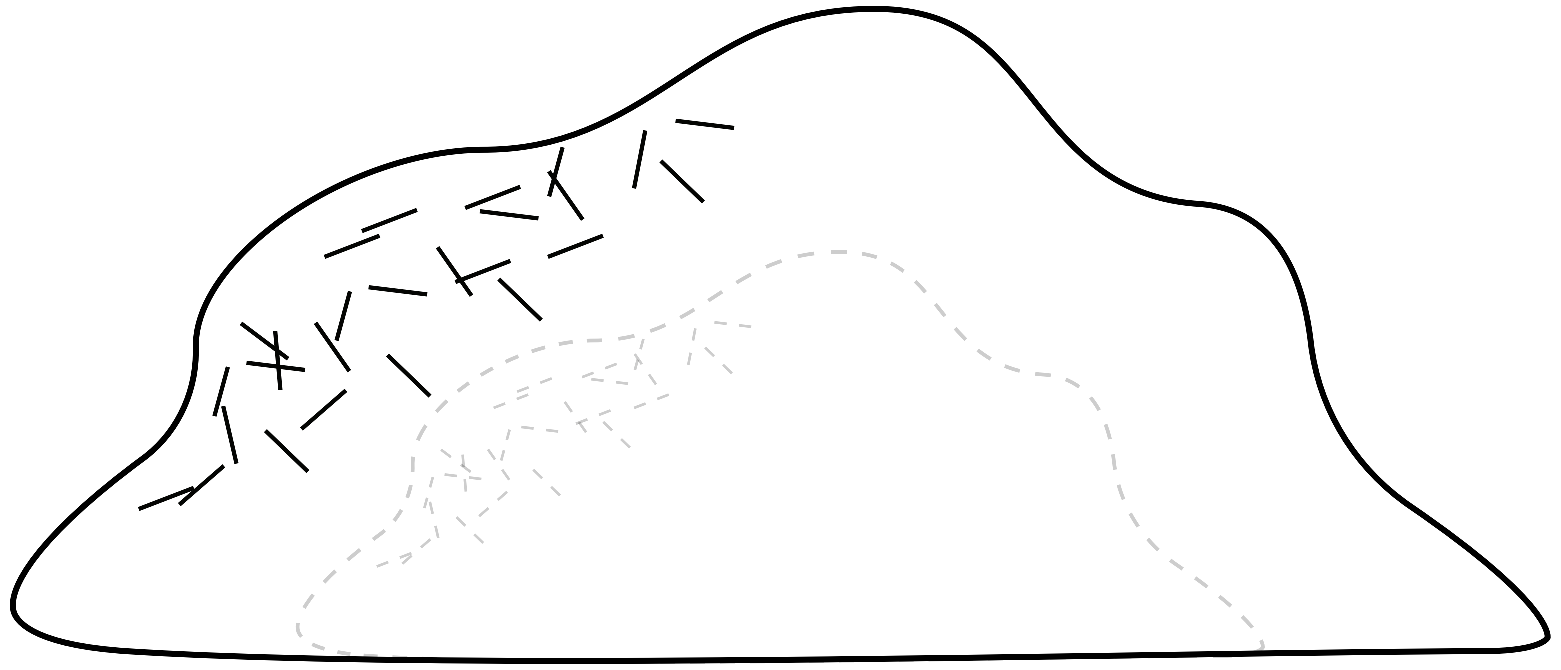
BYPASSING DISADVANTAGES



INCREASING THE UPTAKE



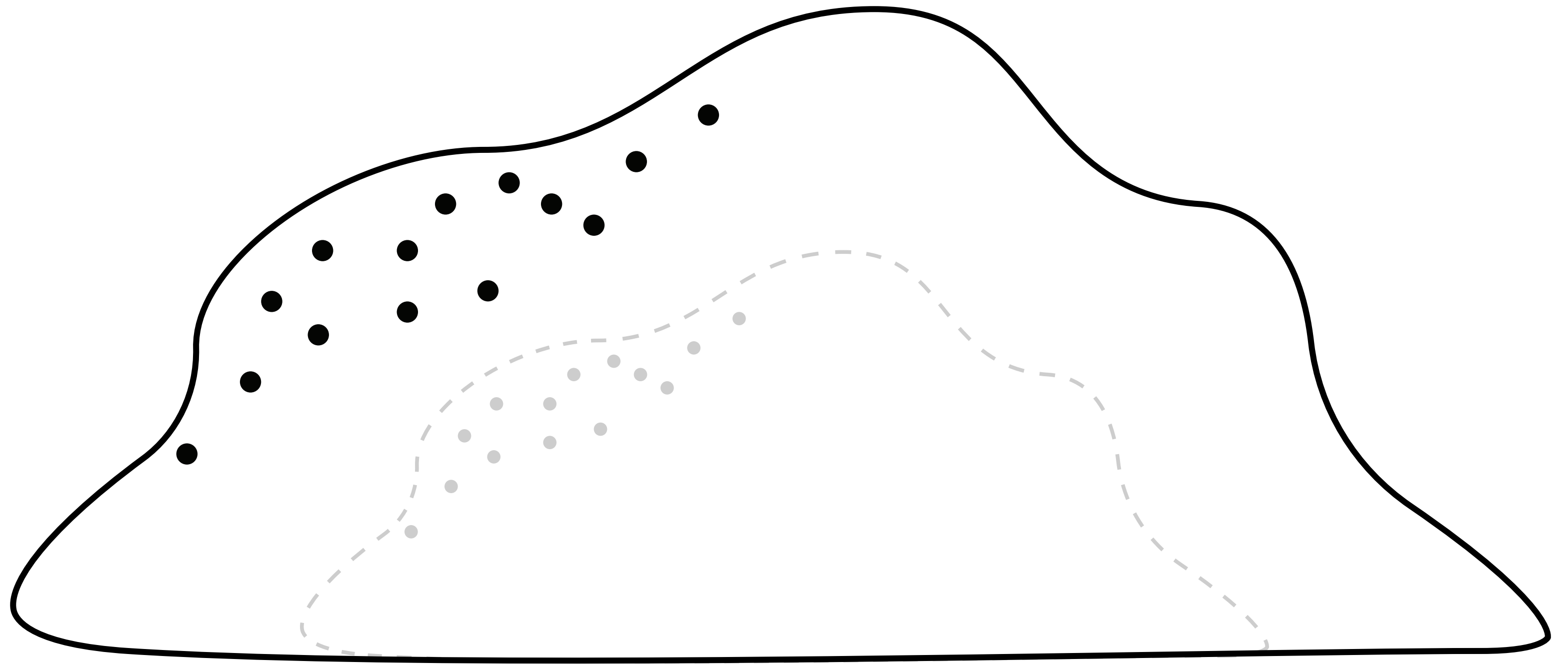
dust



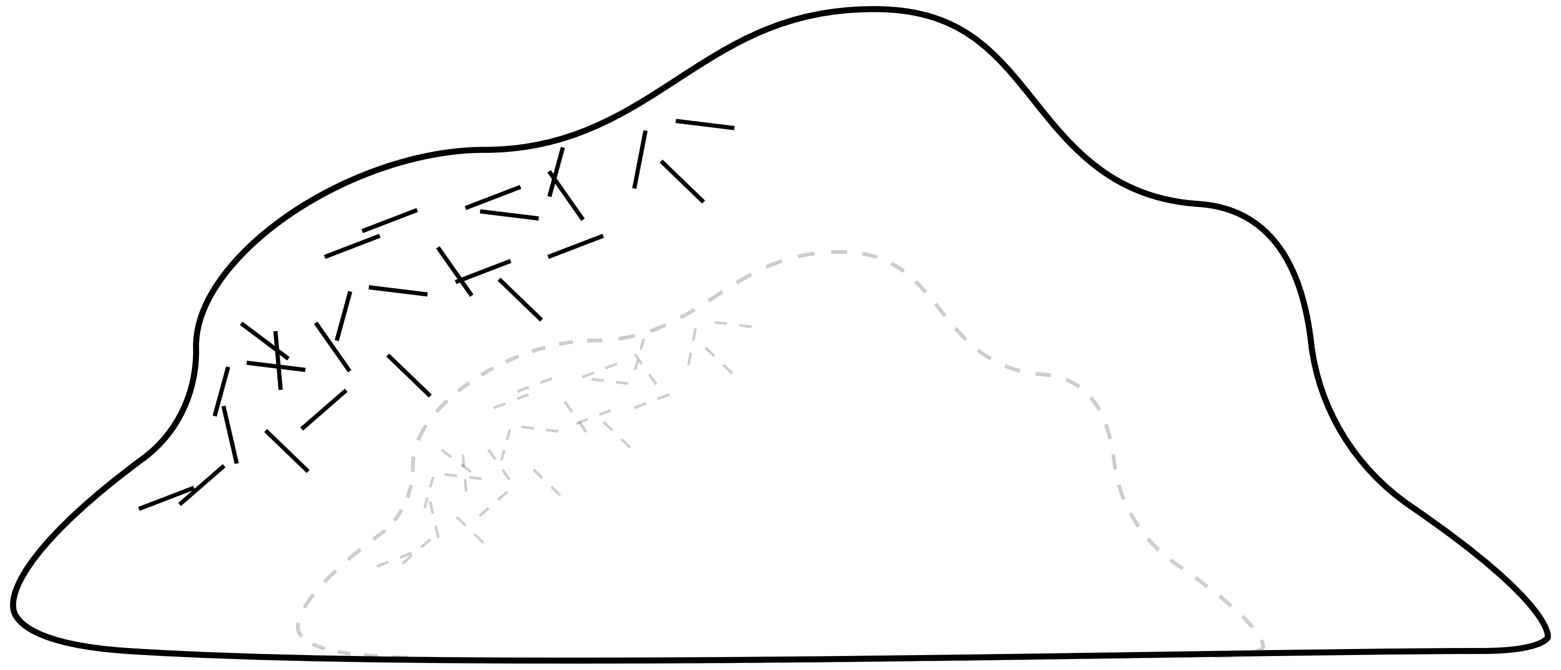
fibers

THE INCREASER

ADDITIVE MANUFACTURING

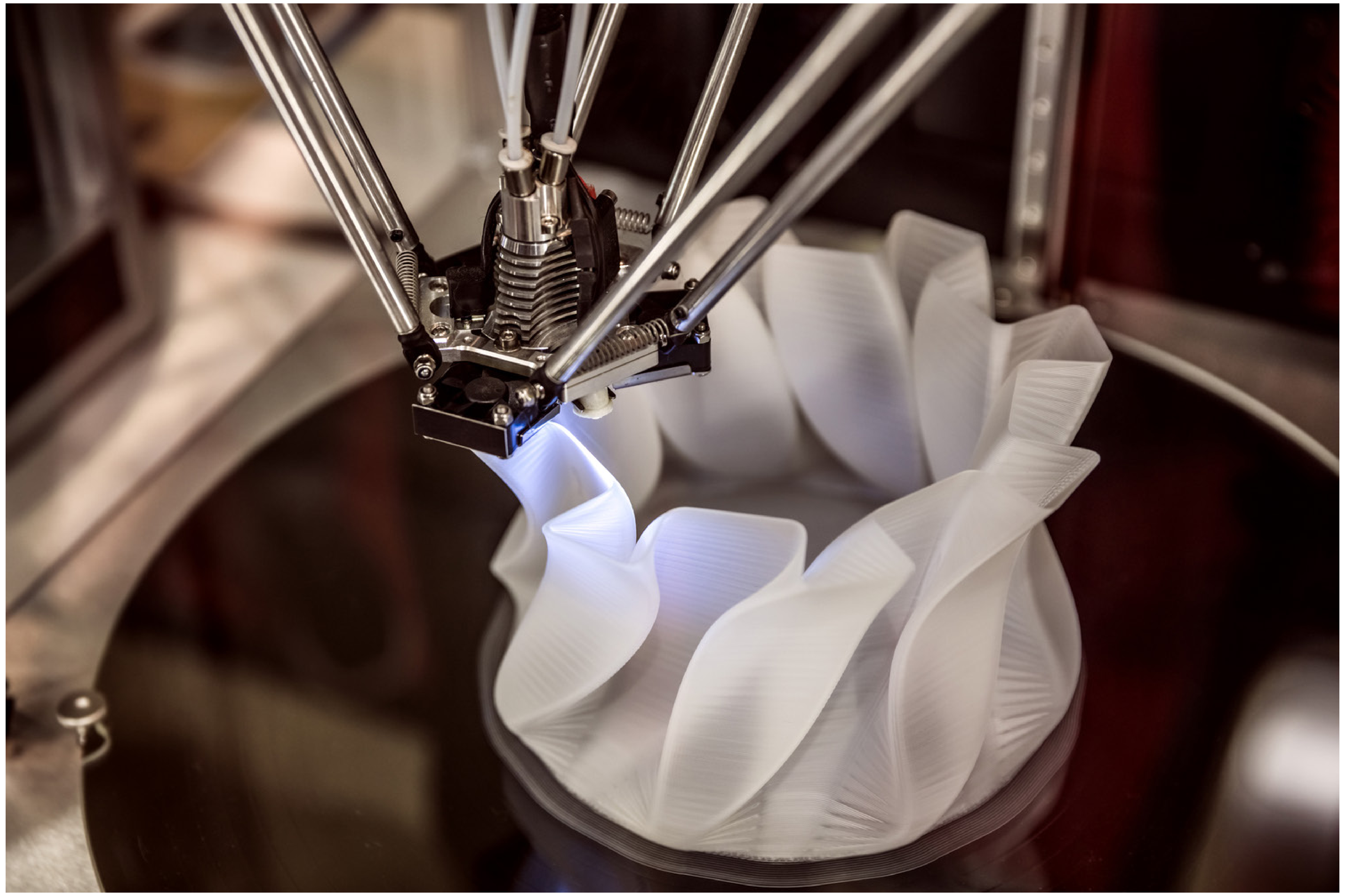


dust



fibers

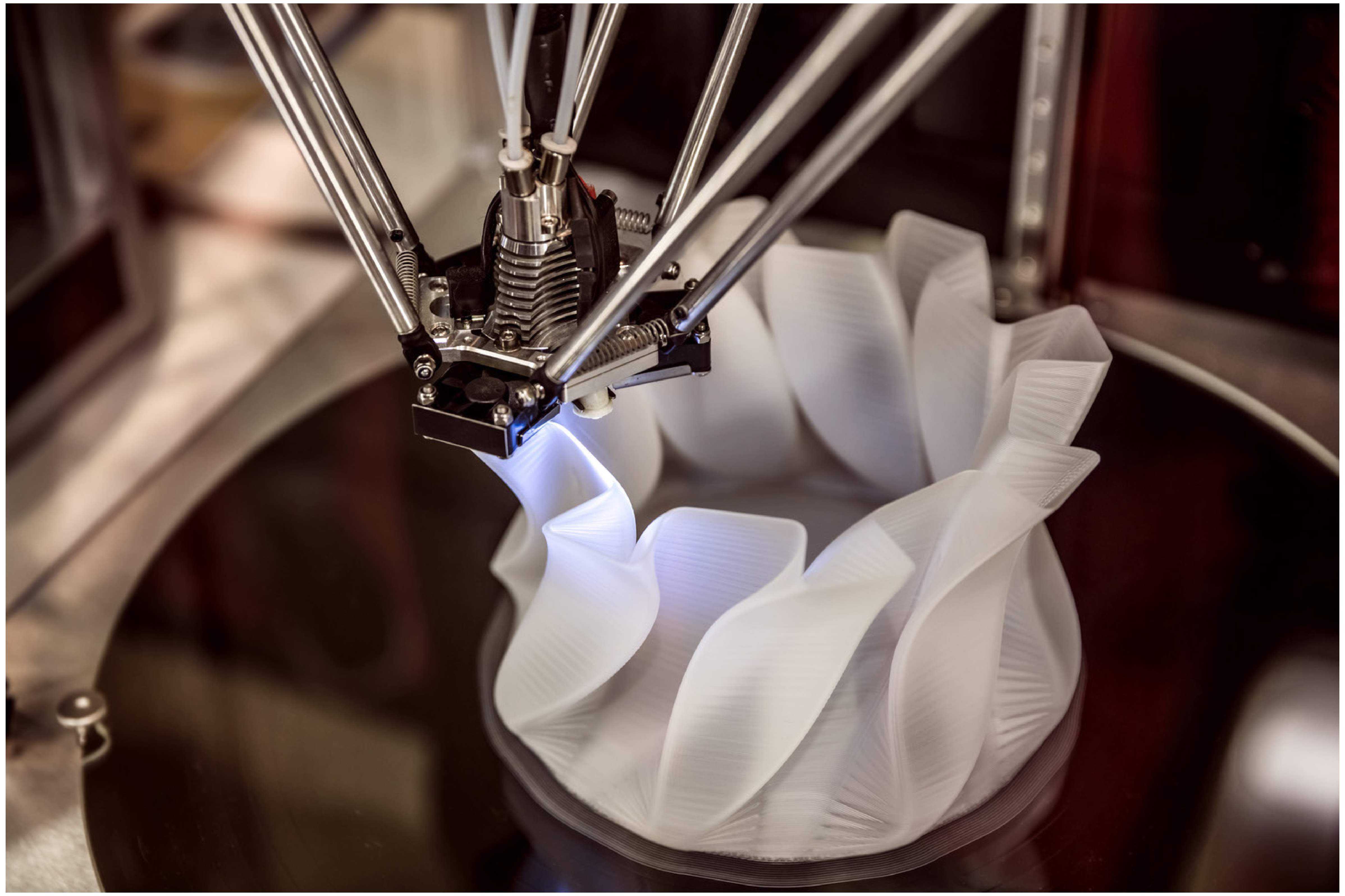
ADDITIVE MANUFACTURING = 3D PRINTING



layer by layer on top of each other

Source: 3deometry

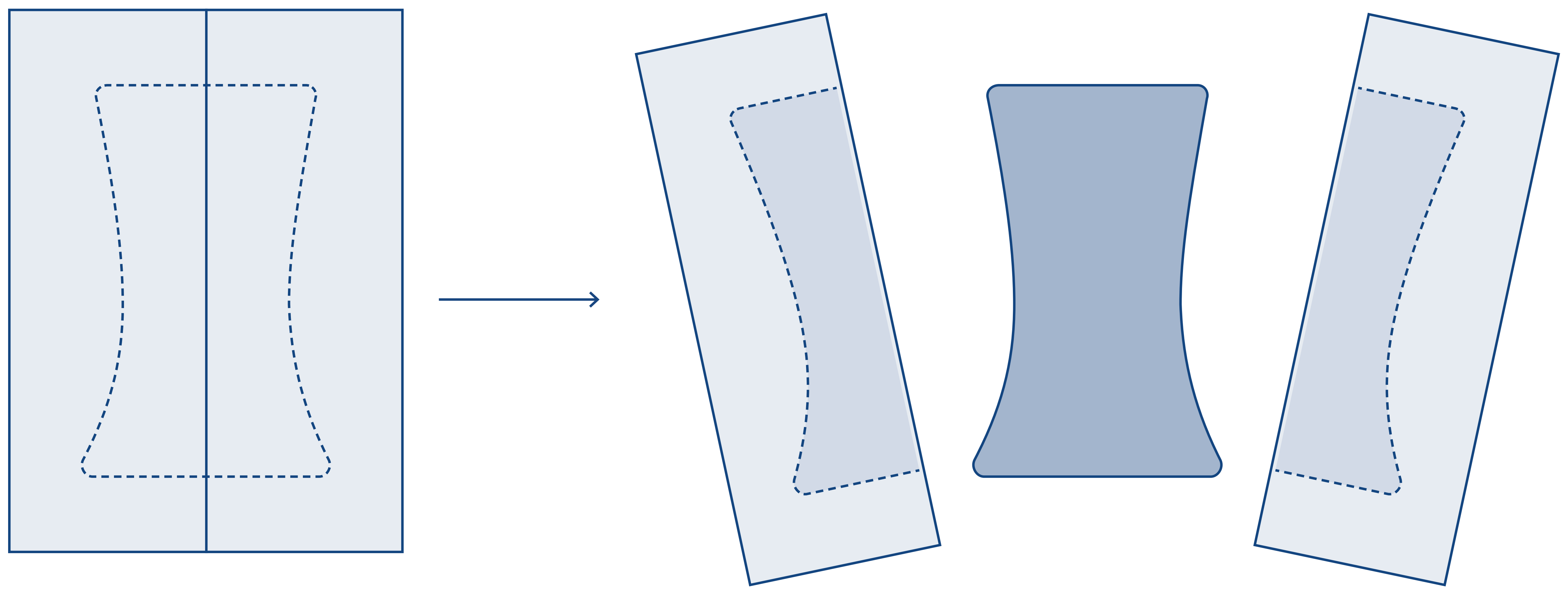
ADDITIVE MANUFACTURING ≠ TRADITIONAL MANUFACTURING



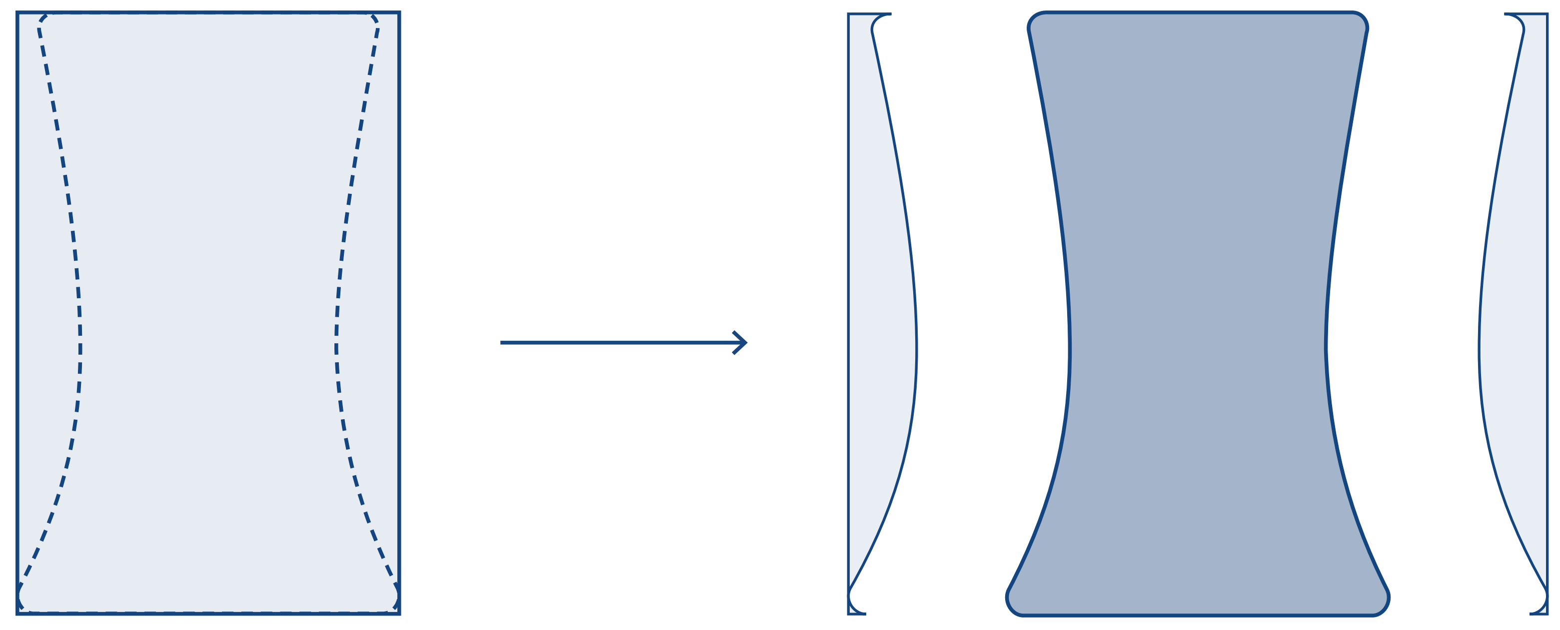
cost effective | flexible design | minimize waste

Source: 3deometry

TRADITIONAL MANUFACTURING

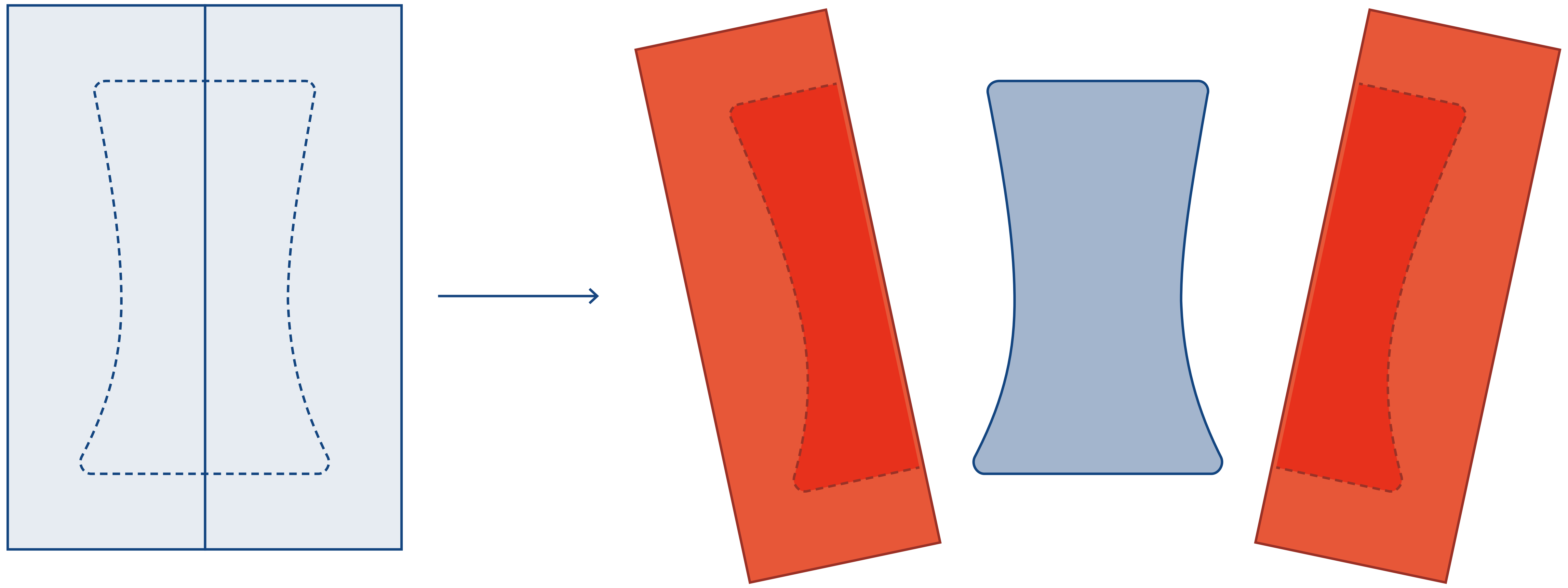


formative process

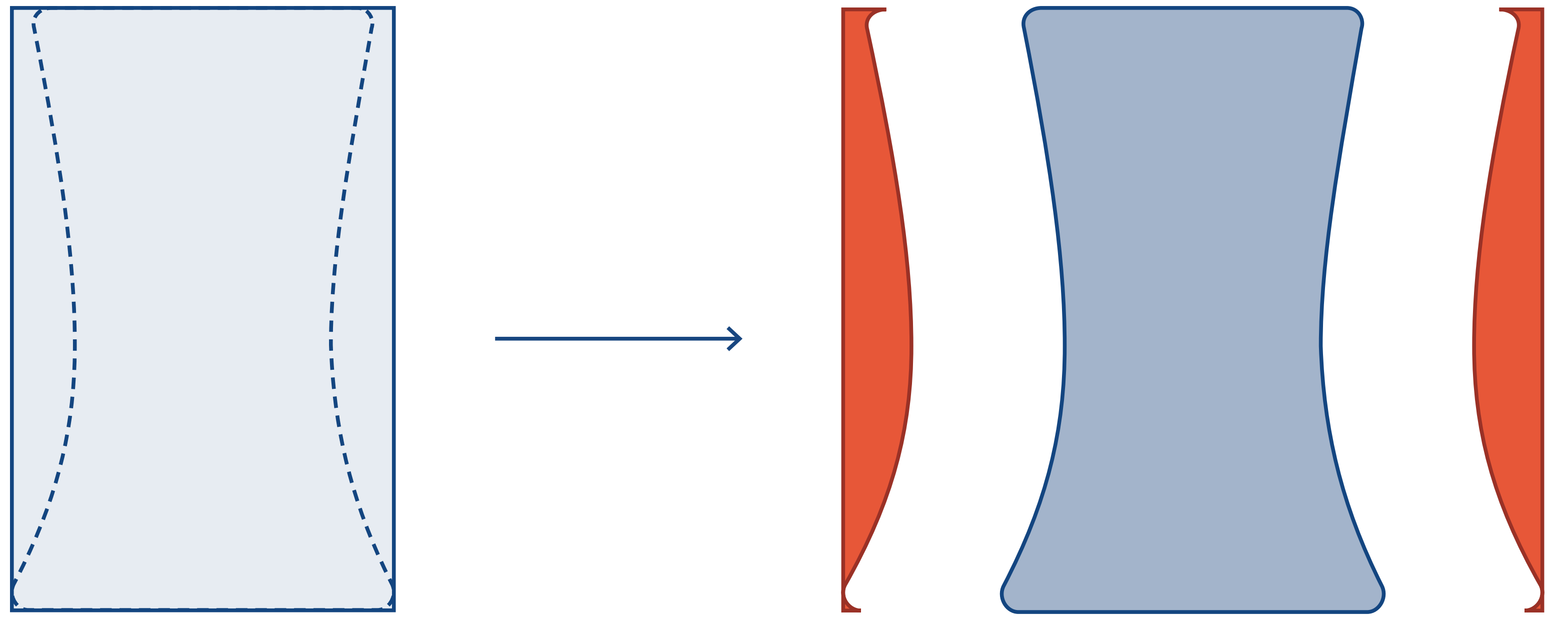


subtractive process

WASTE MATERIALS



formative process



subtractive process

ADDITIVE MANUFACTURING PROCESSES

Directed energy deposition processes (DED)

Material jetting (MJ)

Powder bed fusion processes (PBF)

Vat Photopolymerization (VP)

Sheet lamination processes (SL)

Material extrusion based systems (ME)

Binder jetting (BJ)

MOST USED IN THE BUILT ENVIRONMENT

Directed energy deposition processes (DED)

Material jetting (MJ)

Powder bed fusion processes (PBF)

Vat Photopolymerization (VP)

Sheet lamination processes (SL)

Material extrusion based systems (ME)

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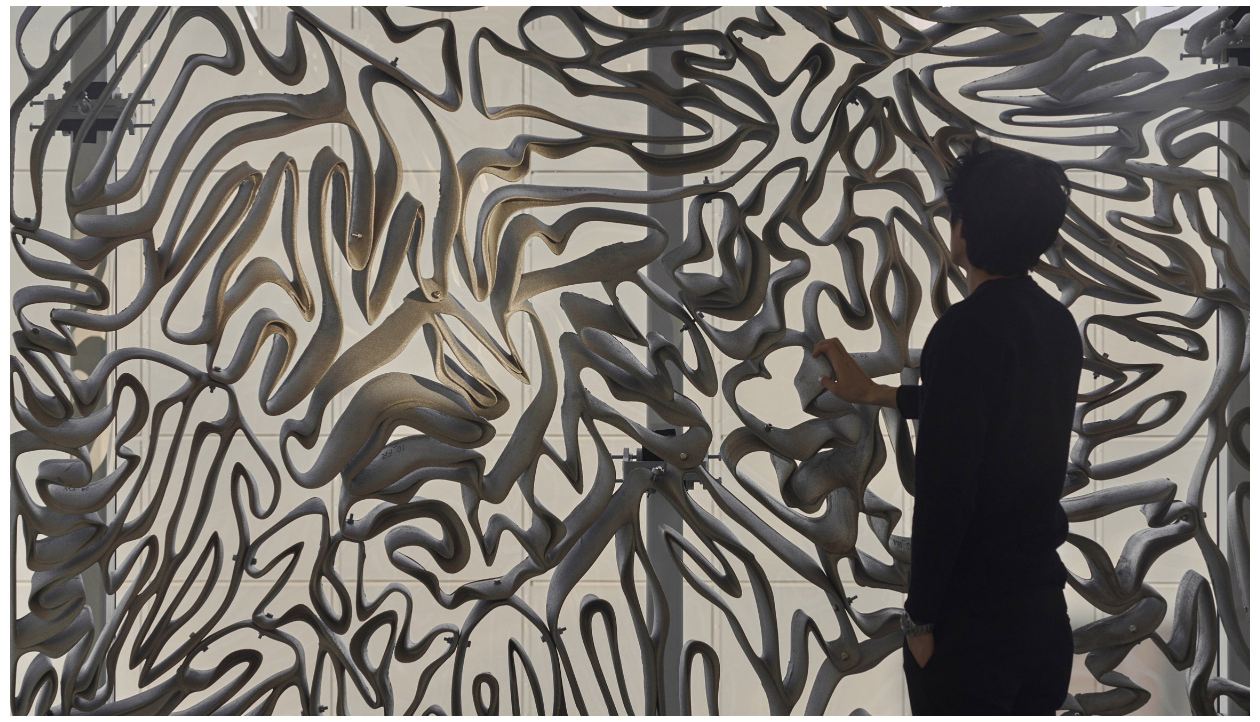
ADDITIVE MANUFACTURING IN THE BUILT ENVIRONMENT


Deep Facade, ETH Zurich


Concrete Choreography, ETH Zurich


Smart Slab, ETH Zurich


Structural joint, ARUP


Radiolaria, Shiro Studio

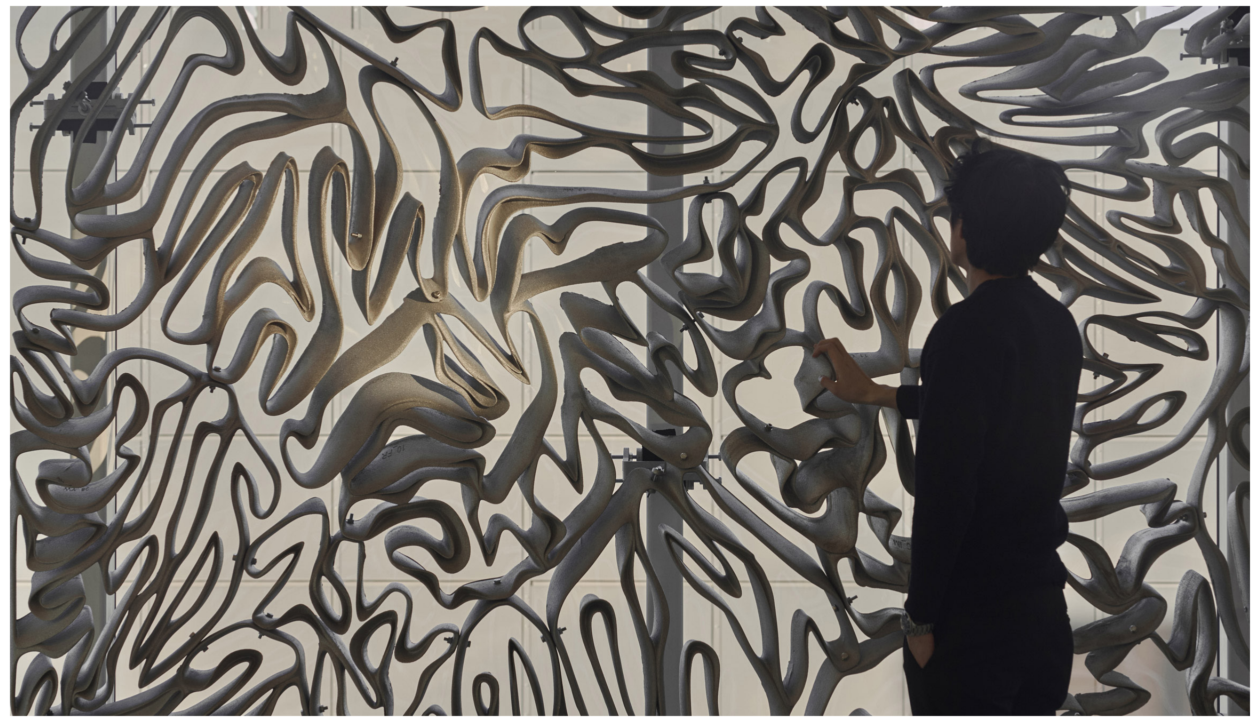

Tecla house, Mario Cucinella

Material extrusion based systems (ME)

Binder jetting (BJ)

Source: Archdaily

PROCESS EMPLOYED



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Tecla house, Mario Cucinella

Material extrusion based systems (ME)

Binder jetting (BJ)

Source: Archdaily

BIO-BASED MATERIAL

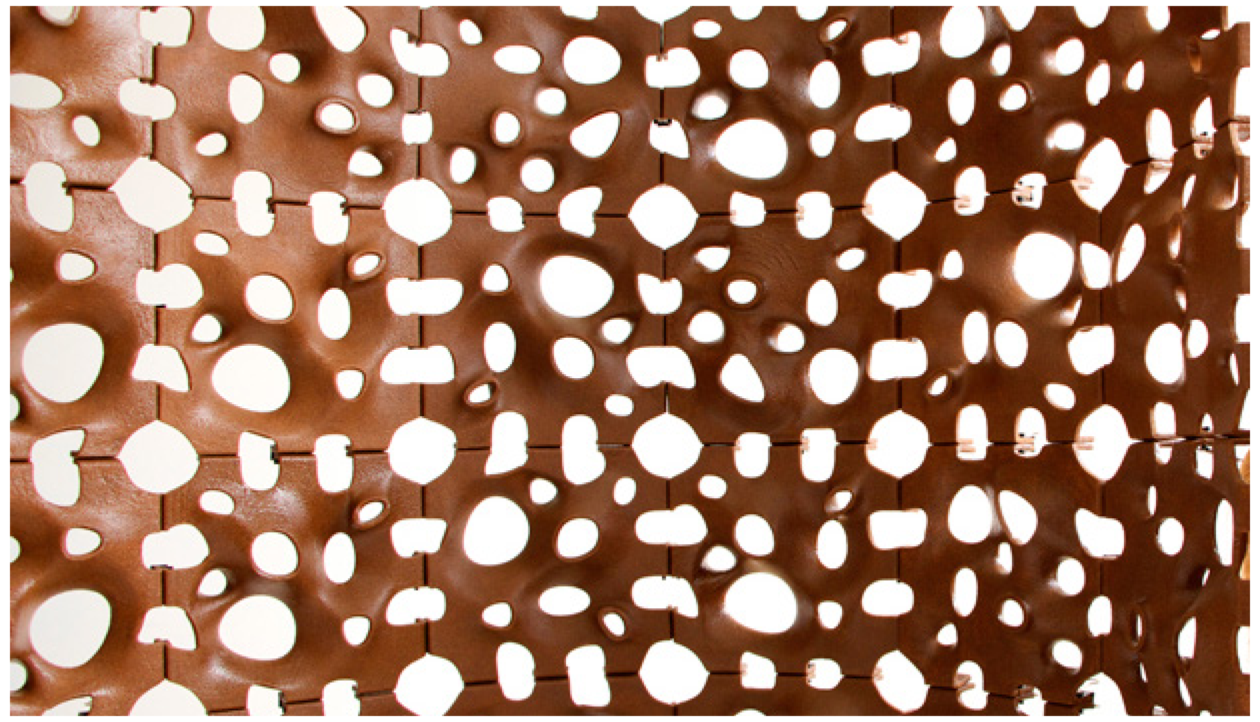
Eggshells

Mycelium

Cellulose

Calcite

Salt



Sawdust

Material extrusion based systems (ME)

Source: Archdaily

STATE OF THE ART OF ADDITIVE MANUFACTURING WITH BAMBOO

Images of the 3D printed species: ABS, ABS-bamboo, ABS-bamboo modified.

Extrusion of mycelium-enriched bamboo fibres-chitoan pastes.

Premixing bamboo powder with PLA and comparison of different adding proportion.

Bambooder 3D printed vase with bamboo short fibers and PLA. Nozzle 0.18 mm.

DESIGN OBJECTIVE

design a building **component** created with **additive manufacturing** by using bamboo **dust** and **fibers** as a **proof** of concept

RESEARCH QUESTION

what is the workflow to develop a building component made of bamboo with additive manufacturing?

RESEARCH SUB-QUESTIONS

what is the workflow to develop a building component made of bamboo with additive manufacturing?

material

- What does make bamboo relevant for additive manufacturing?
- What is the state of the art of additive manufacturing with bio-based materials?
- What is the state of the art of additive manufacturing with bamboo?

mixture

- What are the possible bio-binders that can be used with bamboo to create a printable mixture?
- How does the size of the fiber affect the mixture?

fabrication

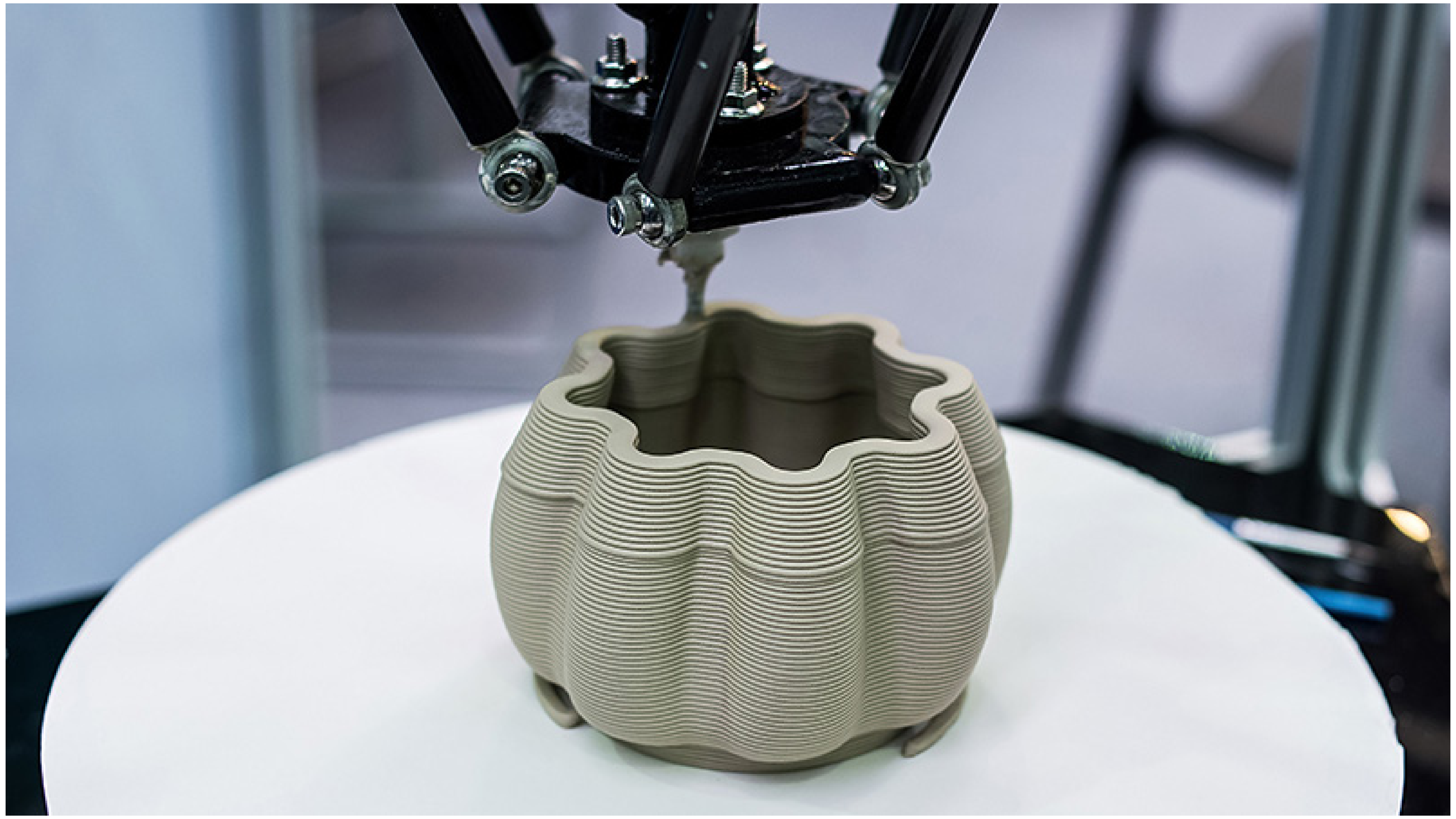
- What are the geometric limitations when printing with bamboo?

design

- What are the design criteria in order to develop a building component with additive manufacturing?
- How to create a mechanically informed infill?

CONTENT

MATERIAL EXTRUSION



Source: Dezeen

COMPOSITE PASTE

FILLERS + BINDERS

COMPOSITE PASTE

FILLERS + BINDERS

Bamboo dust

Bamboo fibers 1-3 mm

Bamboo fibers 6-25 mm

Bamboo “green dust”

BAMBOODER®
BIOBASED FIBER

madeinbamboo

COMPOSITE PASTE

FILLERS + **BINDERS**

BIO-BASED

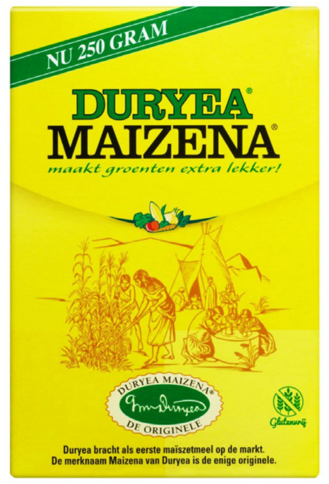
NON BIO-BASED

COMPOSITE PASTE

FILLERS + **BINDERS**

BIO-BASED

NON BIO-BASED



agar agar

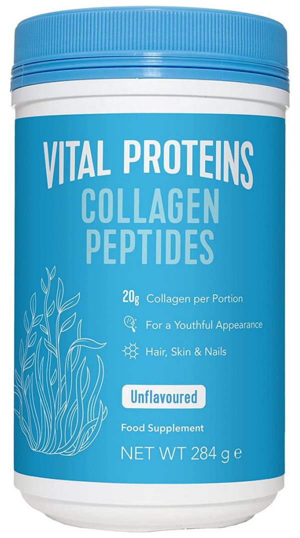
corn starch

potato starch

collagen peptides

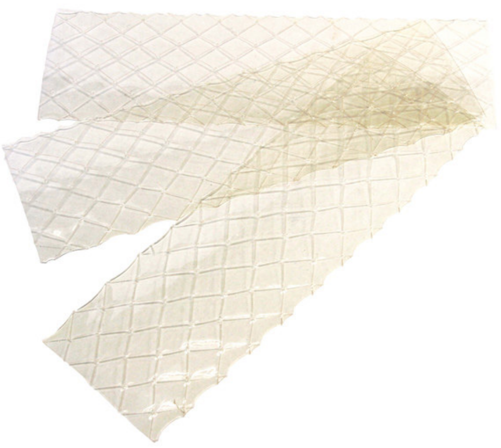
universal glue

paper glue



alginate

tapioca starch



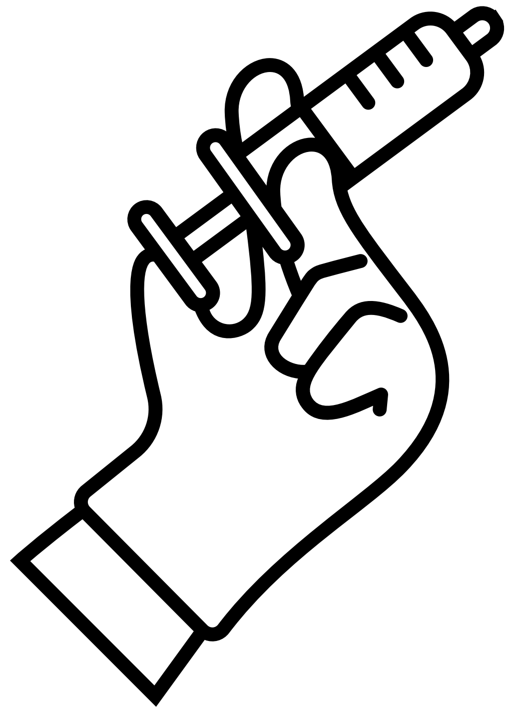
rice flour

bone glue

ethyl alcohol

wood glue

MANUAL EXTRUSION



SYRINGE

ROBOTIC ARM

EVALUATION

negative	indifferent	positive
-1	0	1

Homogeneity

Viscosity

Adhesion

Extrudability

Bio-based

Shrinkage

Brittleness

Curing time

Aesthetics

RESULTS

Mix_1	TOTAL
Water	-5

Mix_2	TOTAL
Ethyl alcoholo	-5

Mix_3	TOTAL
Universal glue	6

Mix_4	TOTAL
Paper glue	6

Mix_5	TOTAL
Potato starch	-2

Mix_6	TOTAL
Tapioca starch	4

Mix_7	TOTAL
Corn starch	1

Mix_8	TOTAL
Corn starch	4

Mix_9	TOTAL
Agar agar	-3

Mix_10	TOTAL
Collagen peptides	8

SECOND MATERIAL EXPERIMENTATION

binders

SECOND MATERIAL EXPERIMENTATION

binders	fillers			
	 bamboo dust	 bamboo green dust	 bamboo dust +  bamboo fibers	 bamboo green dust +  bamboo fibers

COMPARISON

Filler / Binder	Bamboo dust	Bamboo green dust	Dust + Fibers	Green Dust + Fibers
Corn starch				
Potato starch				
Tapioca starch				
Gelatin				
Xantham gum				
Collagen Peptides				
Eco-glue				
Wood glue				

RESULTS

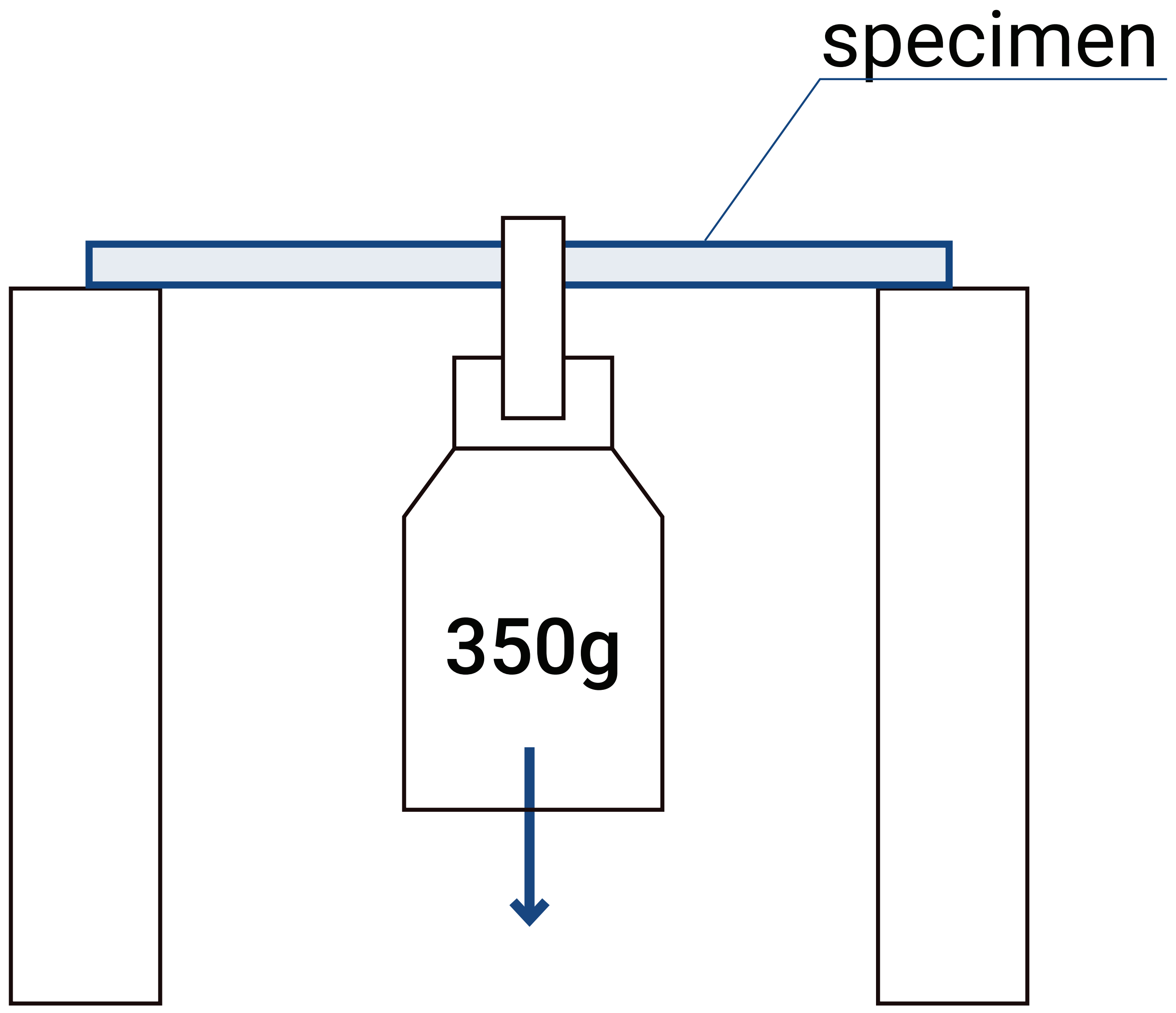
Filler / Binder	Bamboo dust	Bamboo green dust	Dust + Fibers	Green Dust + Fibers
Corn starch				
Potato starch				
Tapioca starch				
Gelatin				
Xantham gum				
Collagen Peptides				
Eco-glue				
Wood glue				

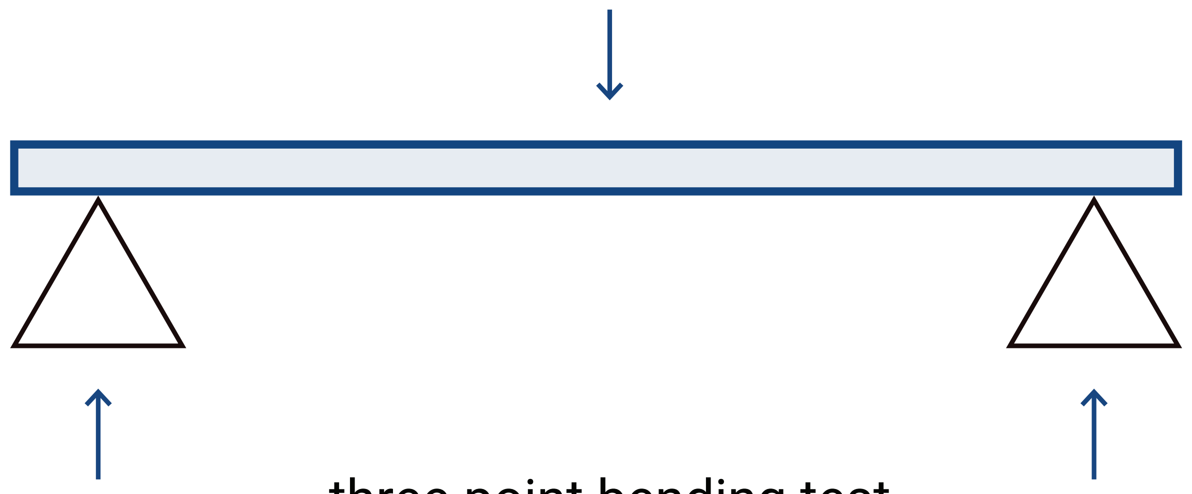
FAULTS DURING DRYING PROCESS

Filler / Binder	Bamboo dust	Bamboo green dust	Dust + Fibers	Green Dust + Fibers
Corn starch				
Potato starch				
Tapioca starch				
Gelatin				
Xantham gum				
Collagen Peptides				
Eco-glue				
Wood glue				

MECHANICAL TESTING

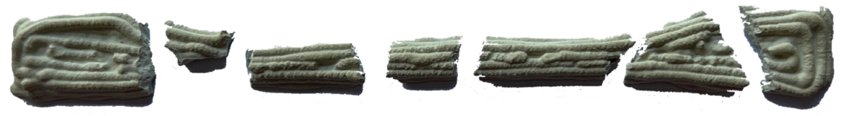
MECHANICAL TESTING





three point bending test

BROKEN SPECIMENS

Binder \ Filler	Bamboo dust	Bamboo green dust	Dust + Fibers	Green Dust + Fibers
Corn starch				
Potato starch				
Tapioca starch				
Gelatin				
Xantham gum				
Collagen Peptides				
Eco-glue				
Wood glue				

REMAINING SPECIMENS

Filler Binder	Bamboo dust	Bamboo green dust	Dust + Fibers	Green Dust + Fibers
Corn starch				
Potato starch				
Tapioca starch				
Gelatin				
Xantham gum				
Collagen Peptides				
Eco-glue				
Wood glue				

POTENTIAL MIXTURES

Binder \ Filler	Bamboo dust	Bamboo green dust	Dust + Fibers	Green Dust + Fibers
Corn starch				
Potato starch				
Tapioca starch				
Gelatin				
Xantham gum				
Collagen Peptides				
Eco-glue				
Wood glue				

BIO-BASED

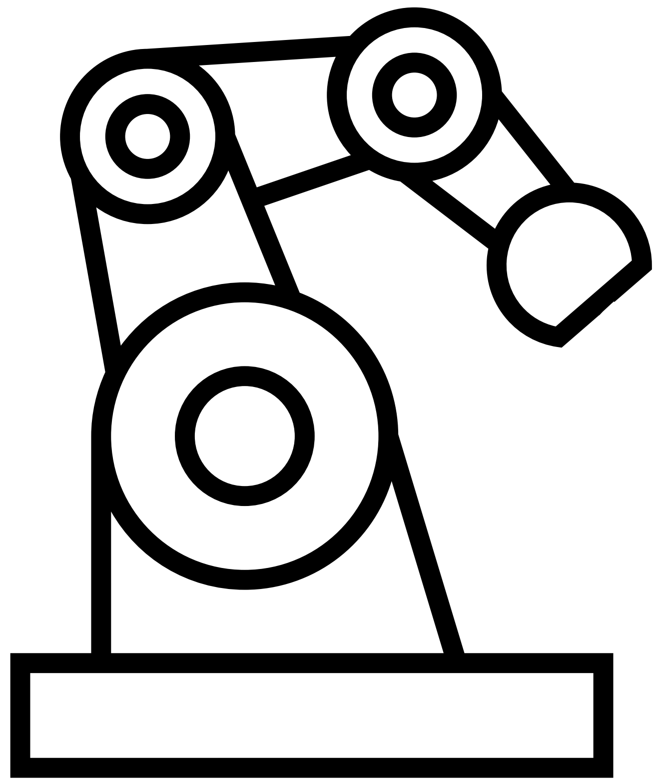
Filler / Binder	Bamboo dust	Bamboo green dust	Dust + Fibers	Green Dust + Fibers
Corn starch				
Potato starch				
Tapioca starch				
Gelatin				
Xantham gum				
Collagen Peptides				
Eco-glue				
Wood glue				

COST

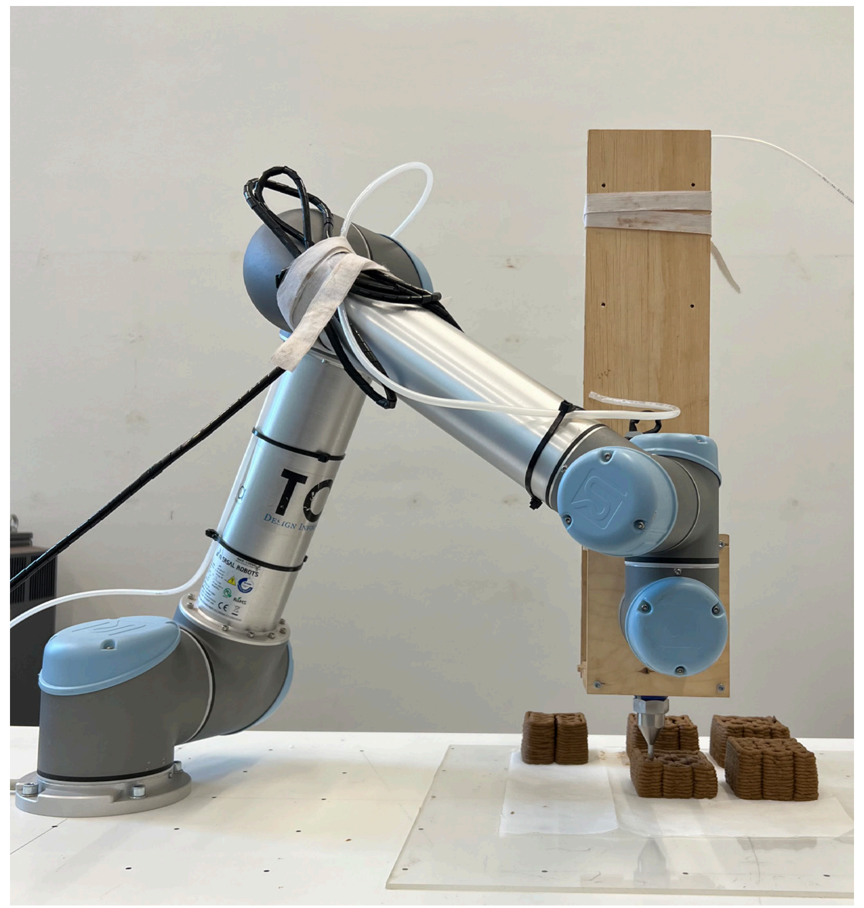
Filler / Binder	Bamboo dust	Bamboo green dust	Dust + Fibers	Green Dust + Fibers
Corn starch				
Potato starch				
Tapioca starch				
Gelatin				
Xantham gum				
Collagen Peptides				
Eco-glue				
Wood glue				

CONTENT

PRINTING EXPLORATION



SYRINGE



ROBOTIC ARM

PRINTING EXPLORATION

CONTROL

EXTRUSION

MOVEMENT

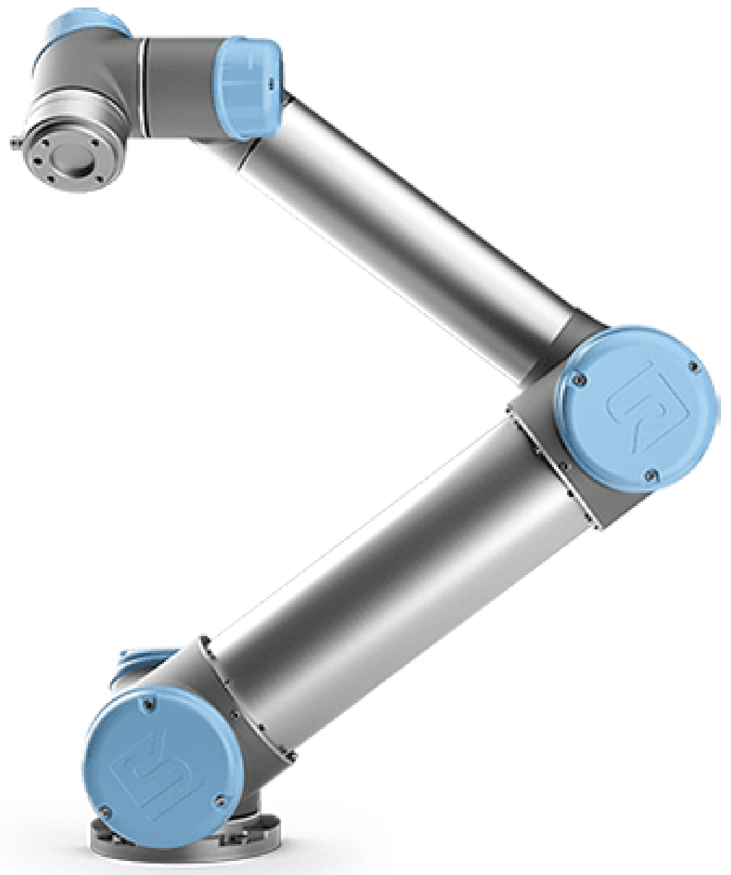
PRINTING EXPLORATION

CONTROL

EXTRUSION

MOVEMENT

WASP LDM extruder



UR5

MATERIAL SETUP

water + potato starch

mix and boil

binder

pour

green bamboo dust

add and mix

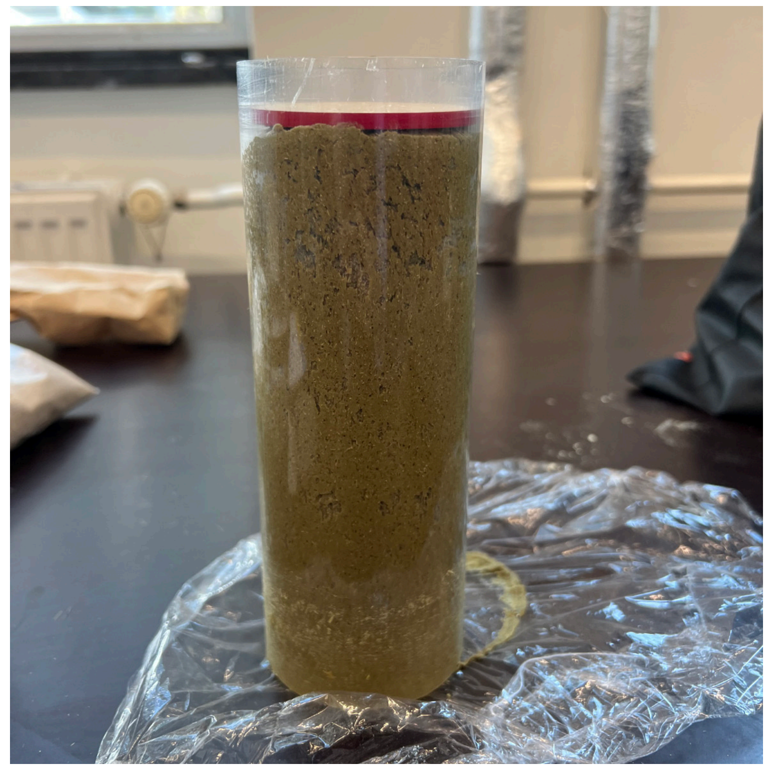
bamboo fibers

add and mix

printing paste

mix

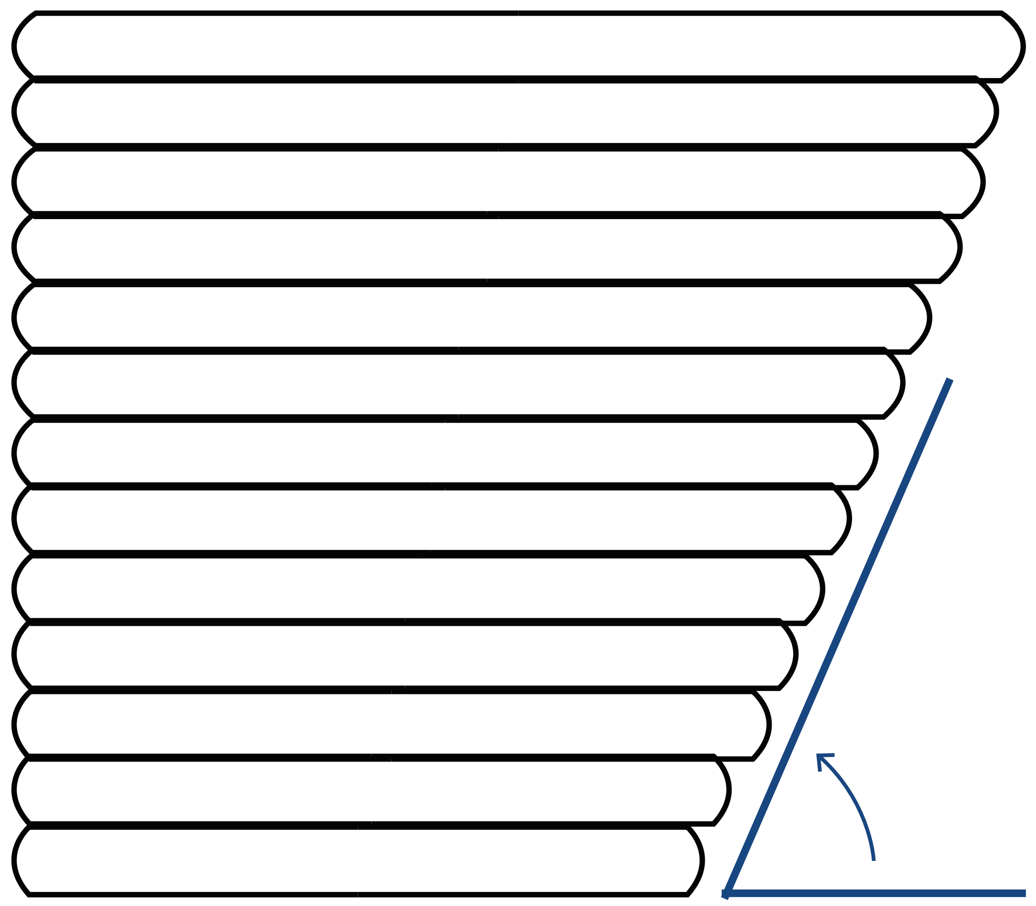
cartridge



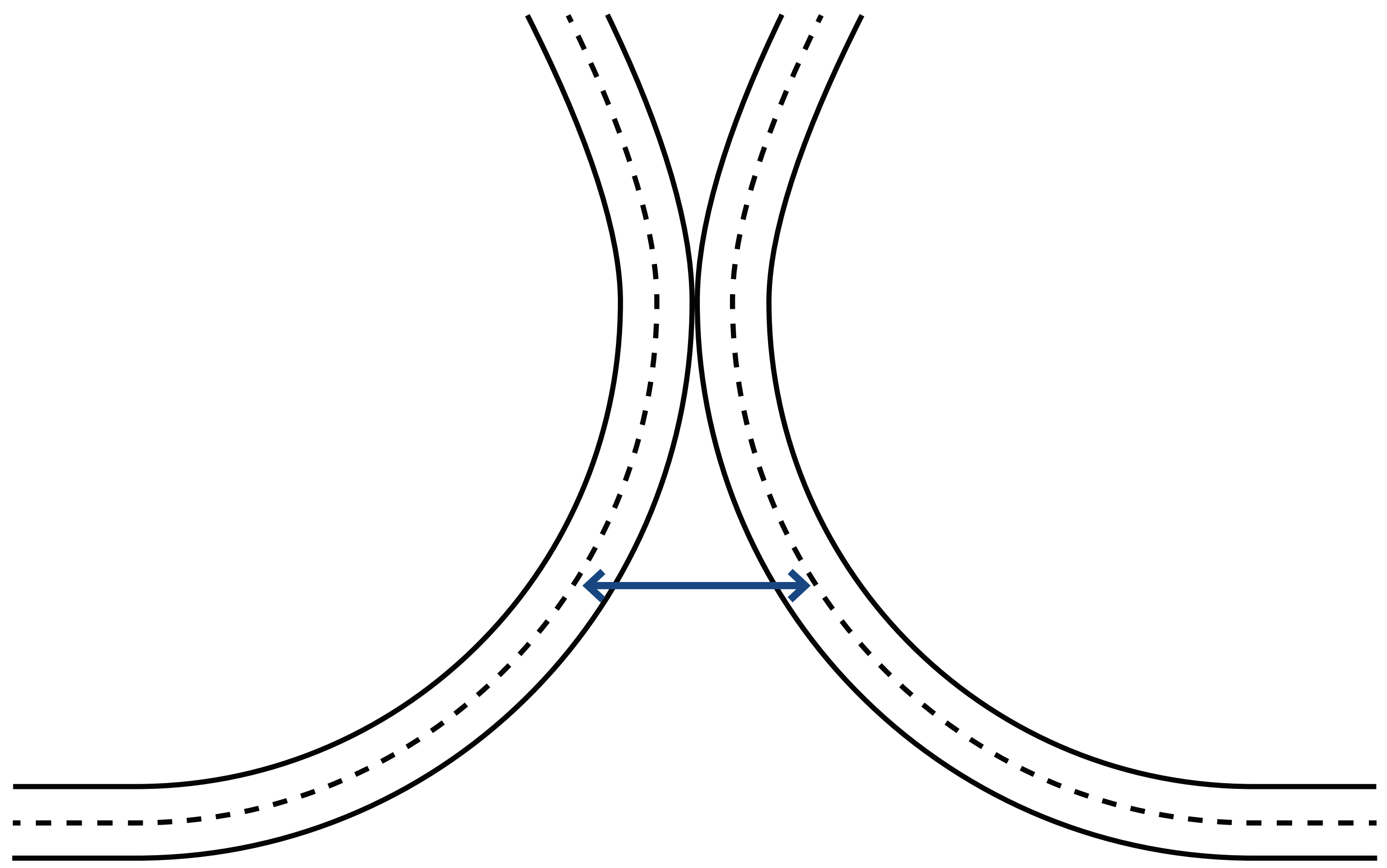
fill

EXPLORATION SETUP

height

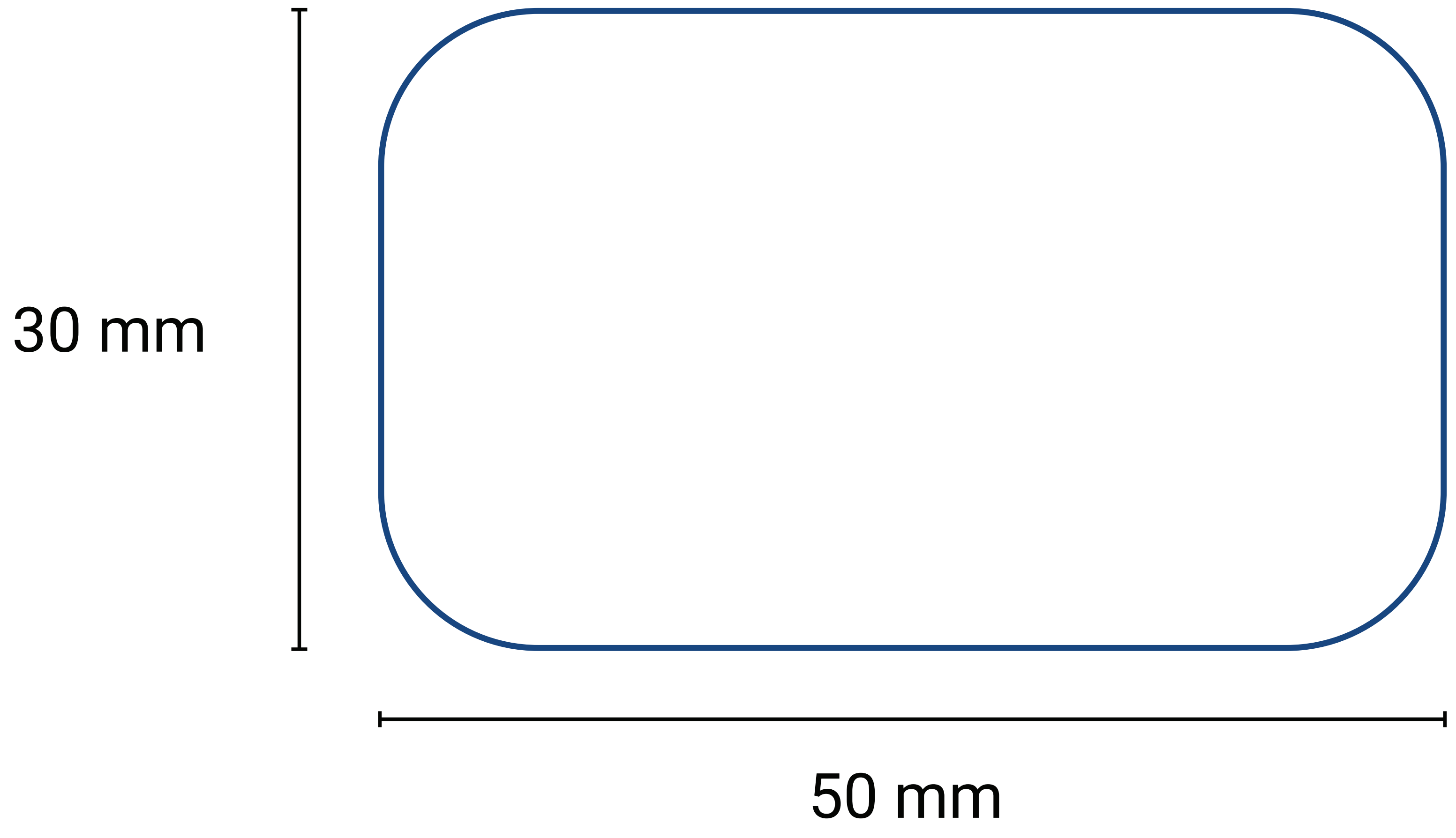


overhang



overlap

HEIGHT



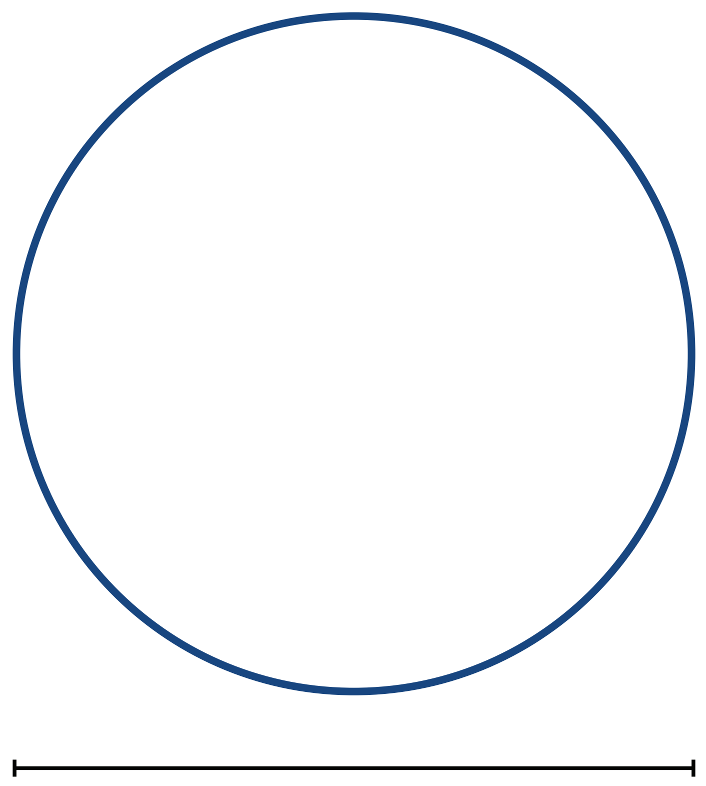
20 mm

50 mm

80 mm

100 mm

HEIGHT

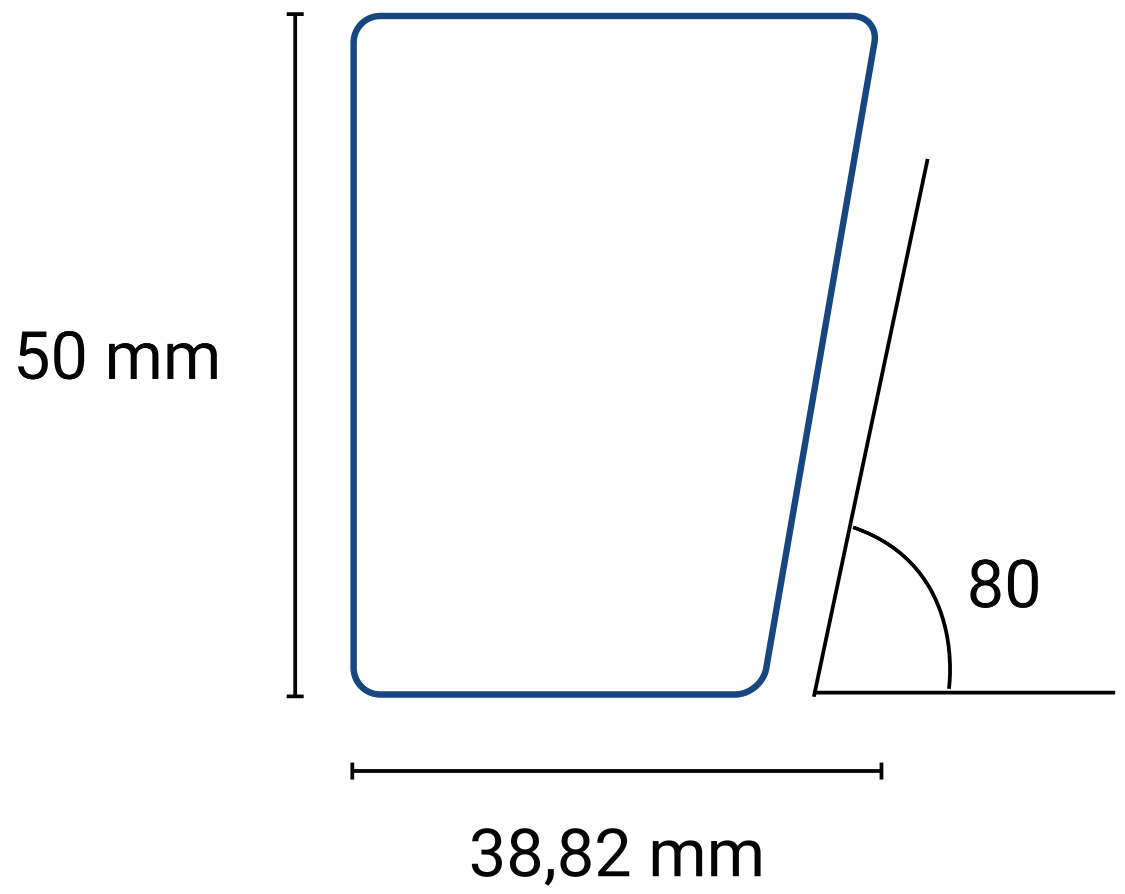


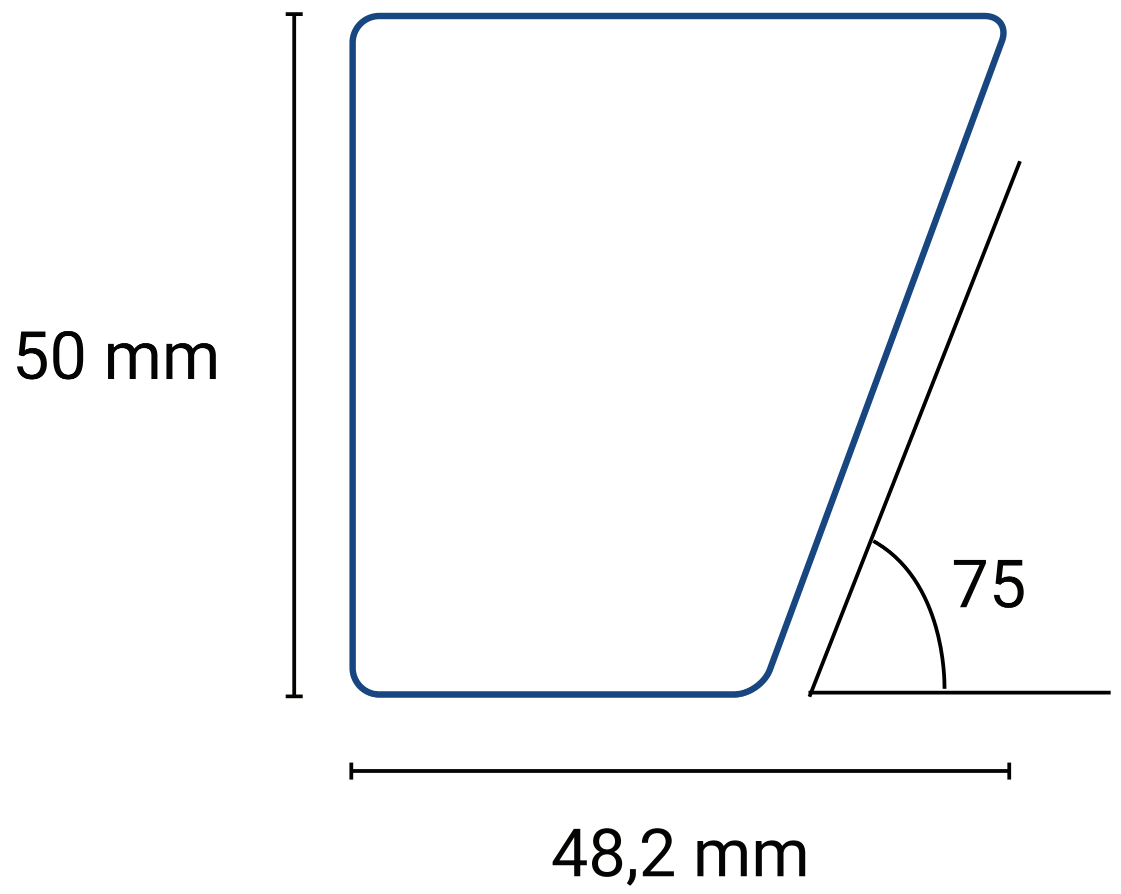
50 mm

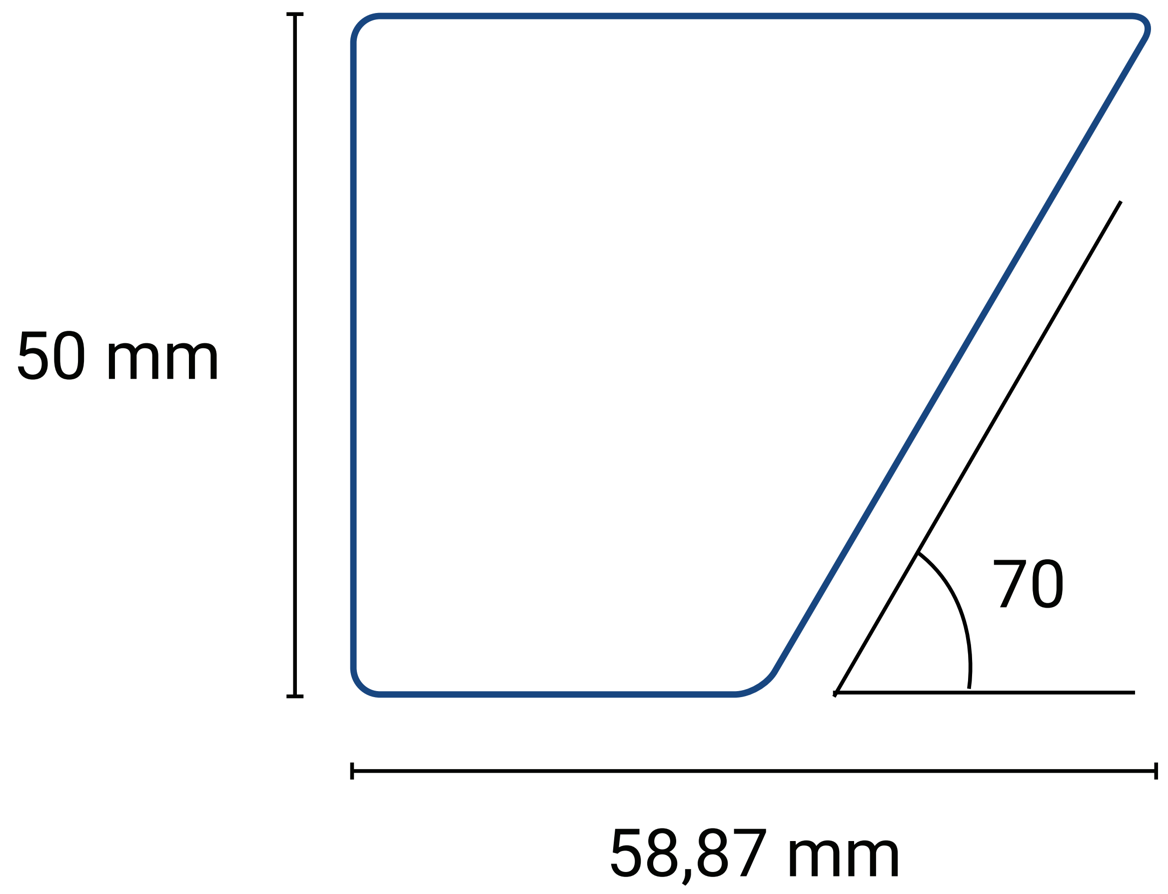
100 mm

120 mm

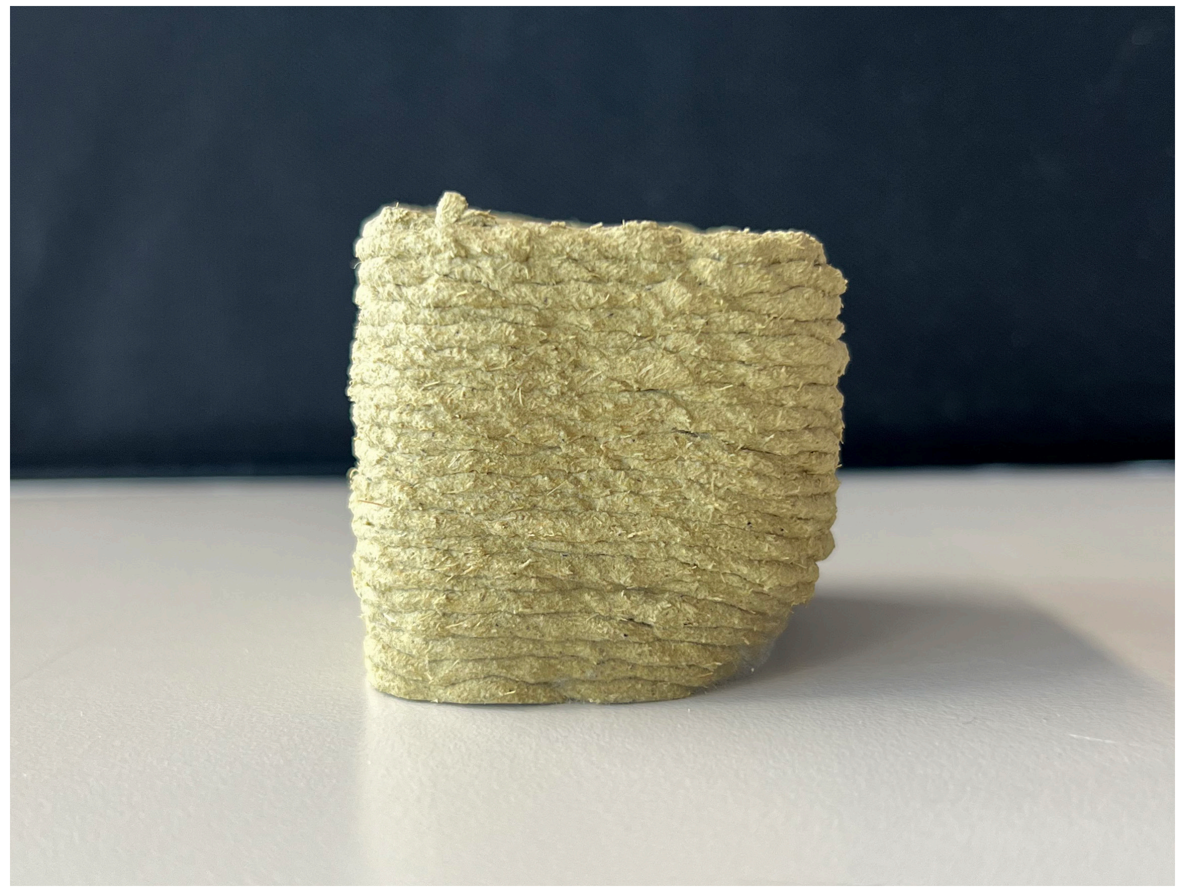
OVERHANG







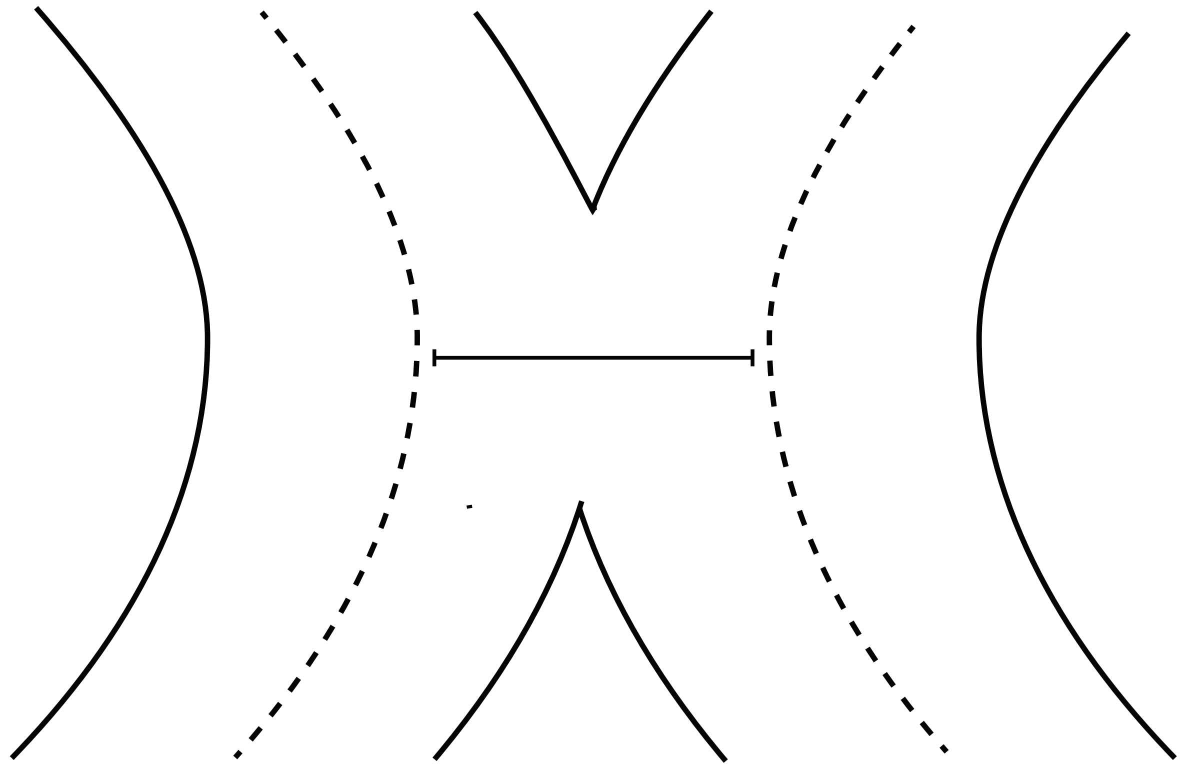
80 degree



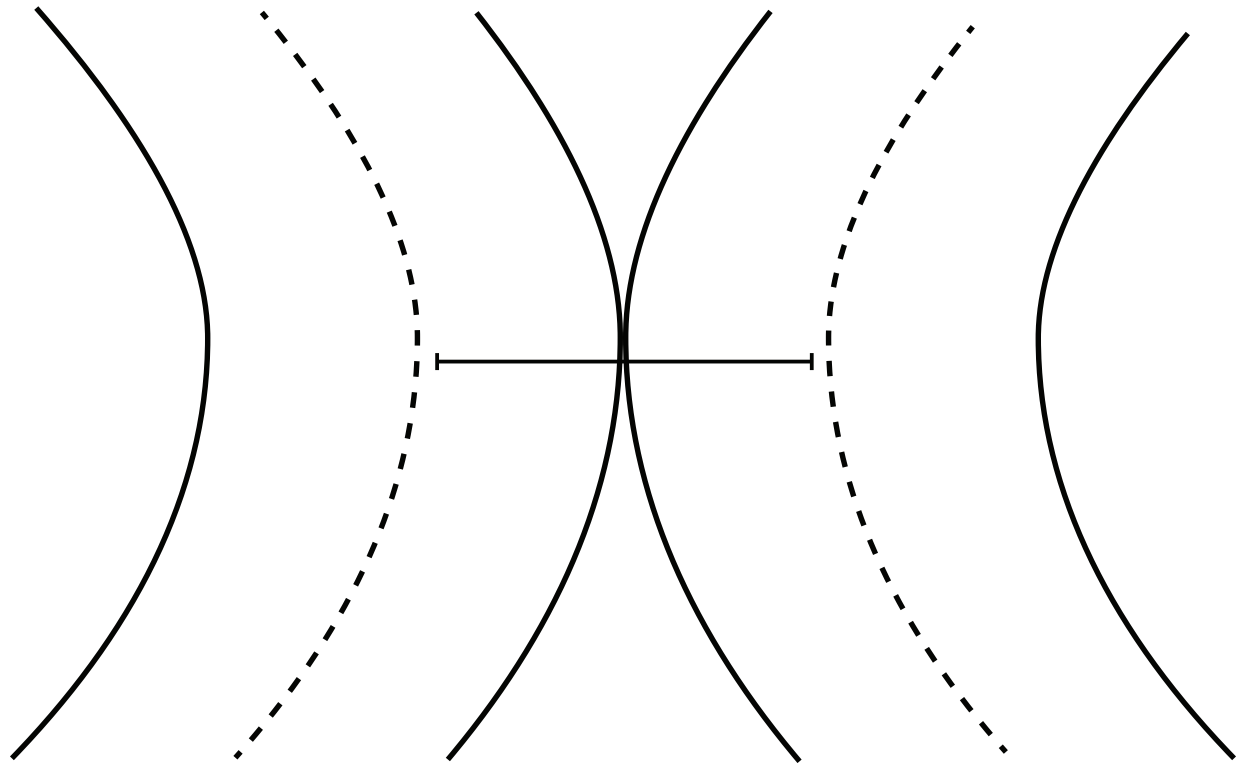
75 degree

70 degree

OVERLAP

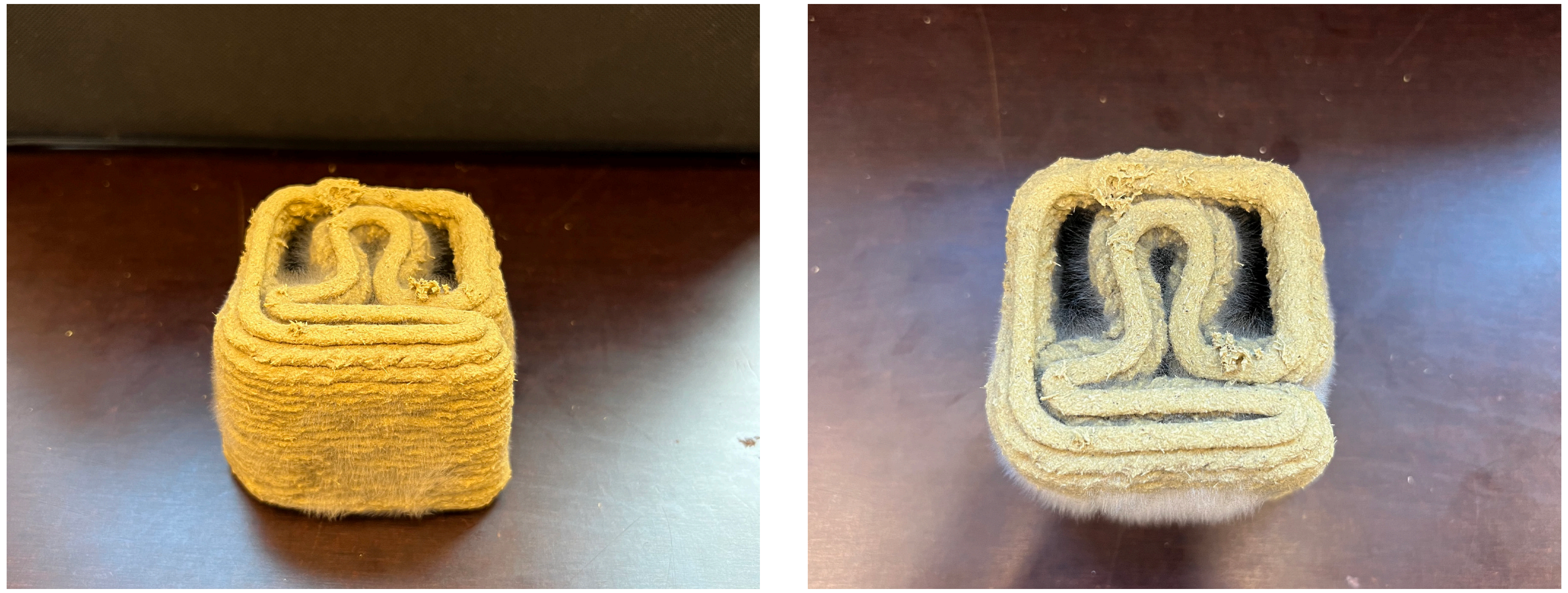


4 mm



6 mm

4 mm



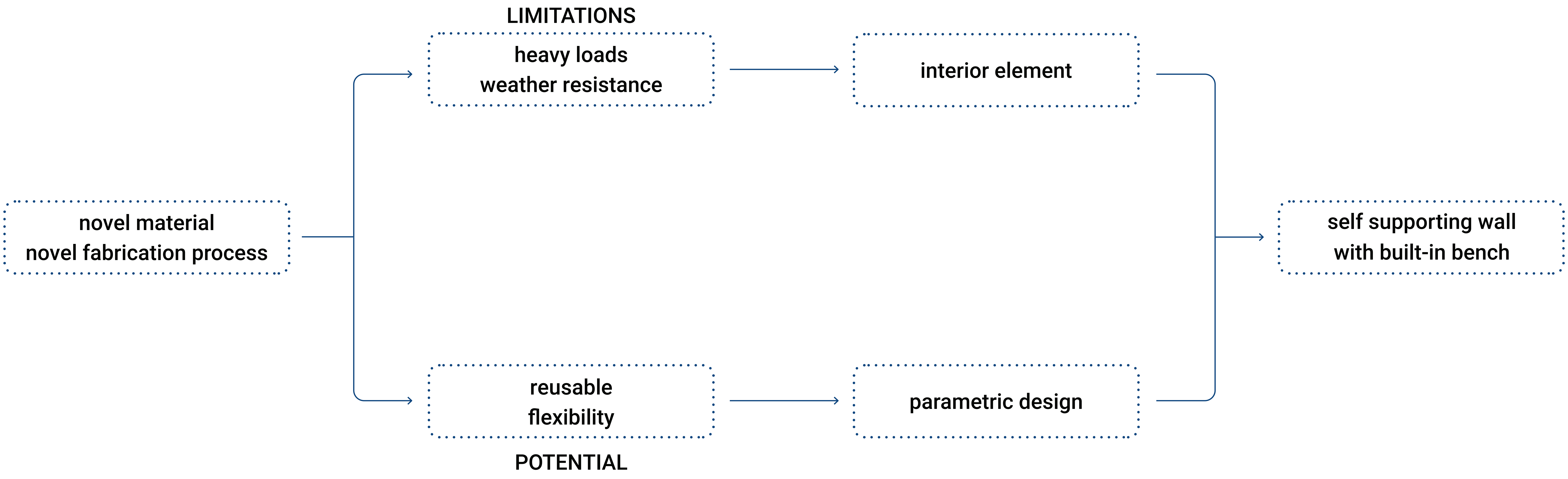
6 mm

CONTENT

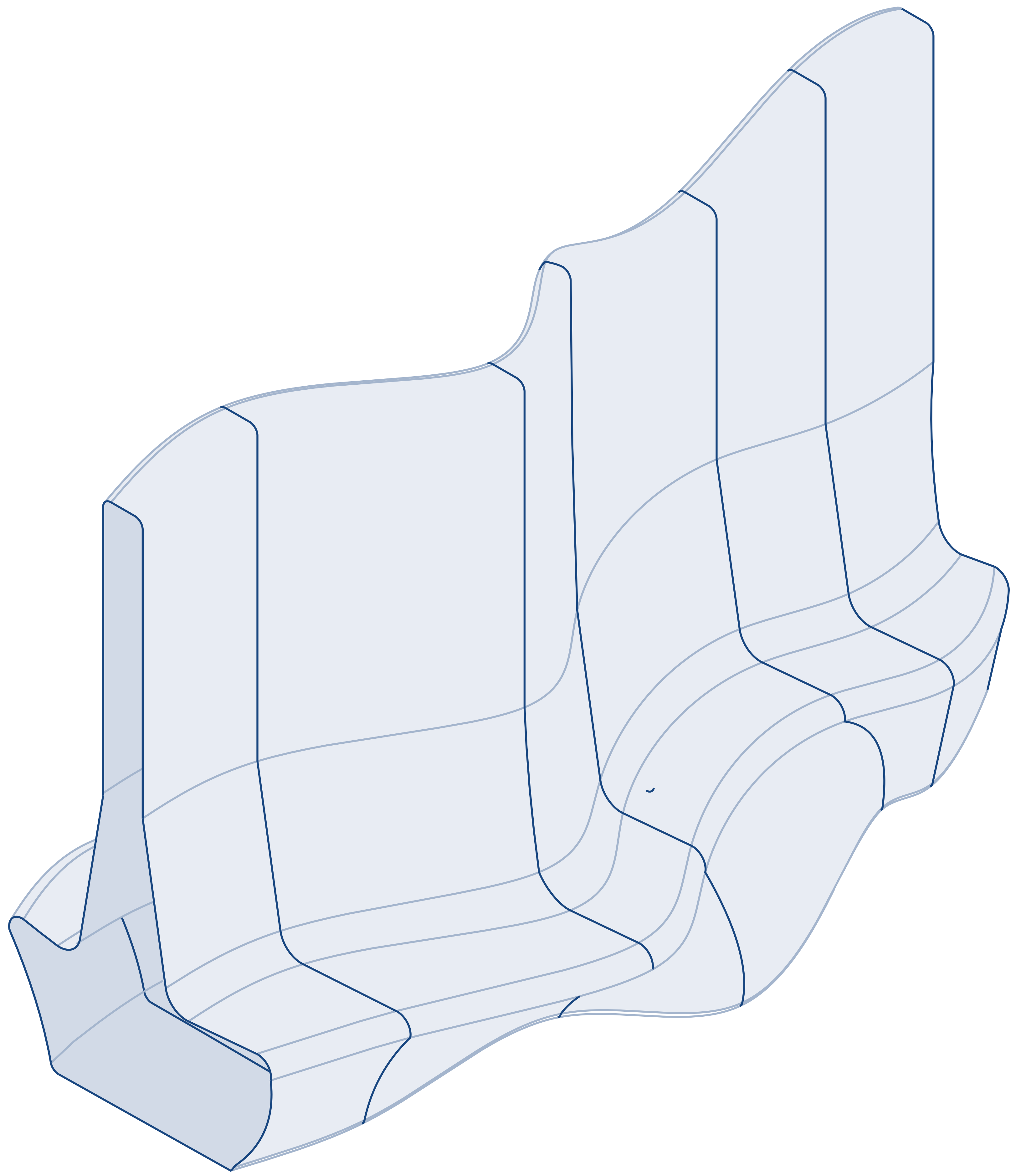
DESIGN OBJECTIVE

design a building **component** created with
additive manufacturing by using bamboo **dust** and **fibers**
as a **proof** of concept

DESIGN CRITERIA

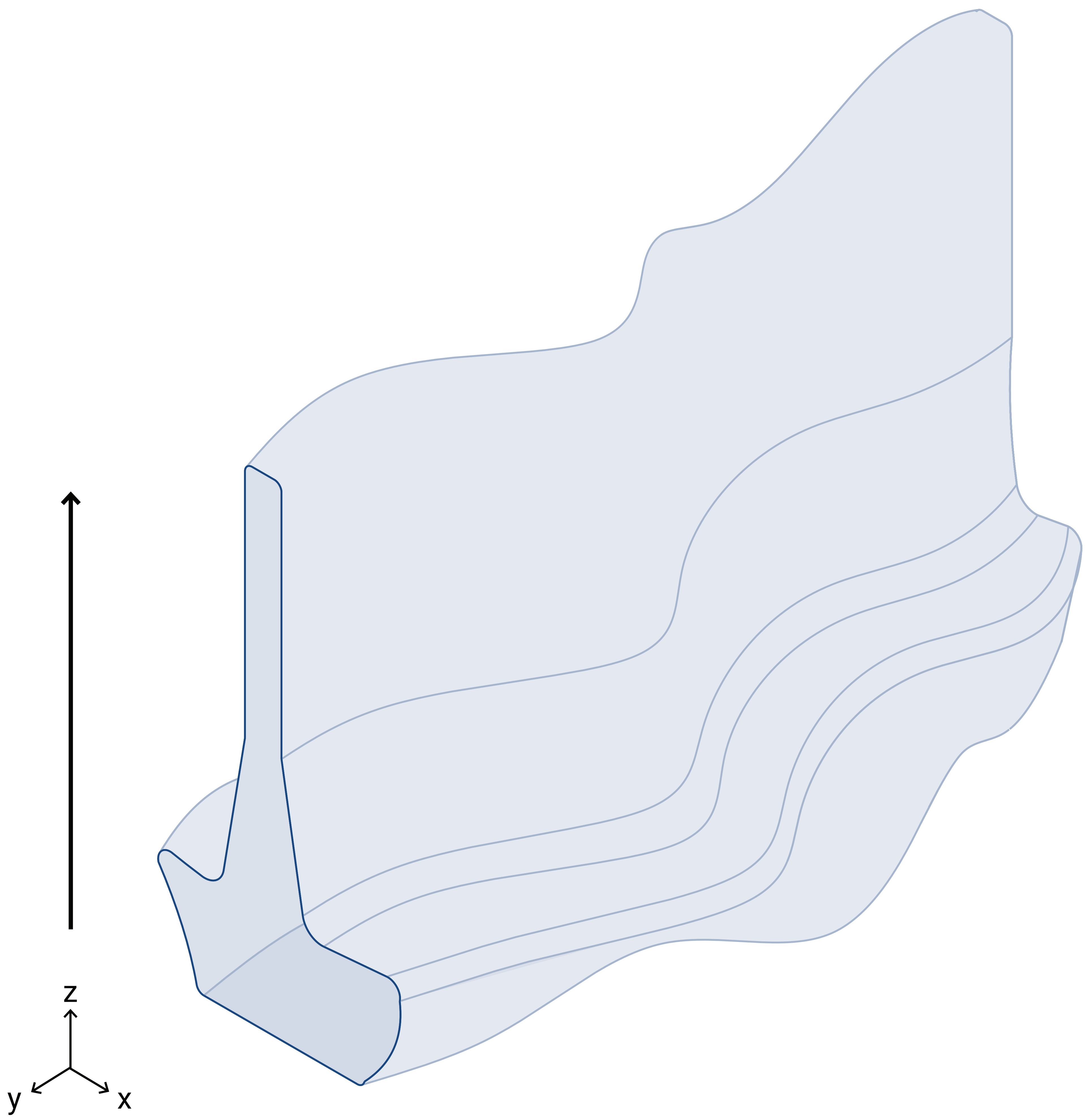


DESIGN



gif

PRINTING DIRECTION



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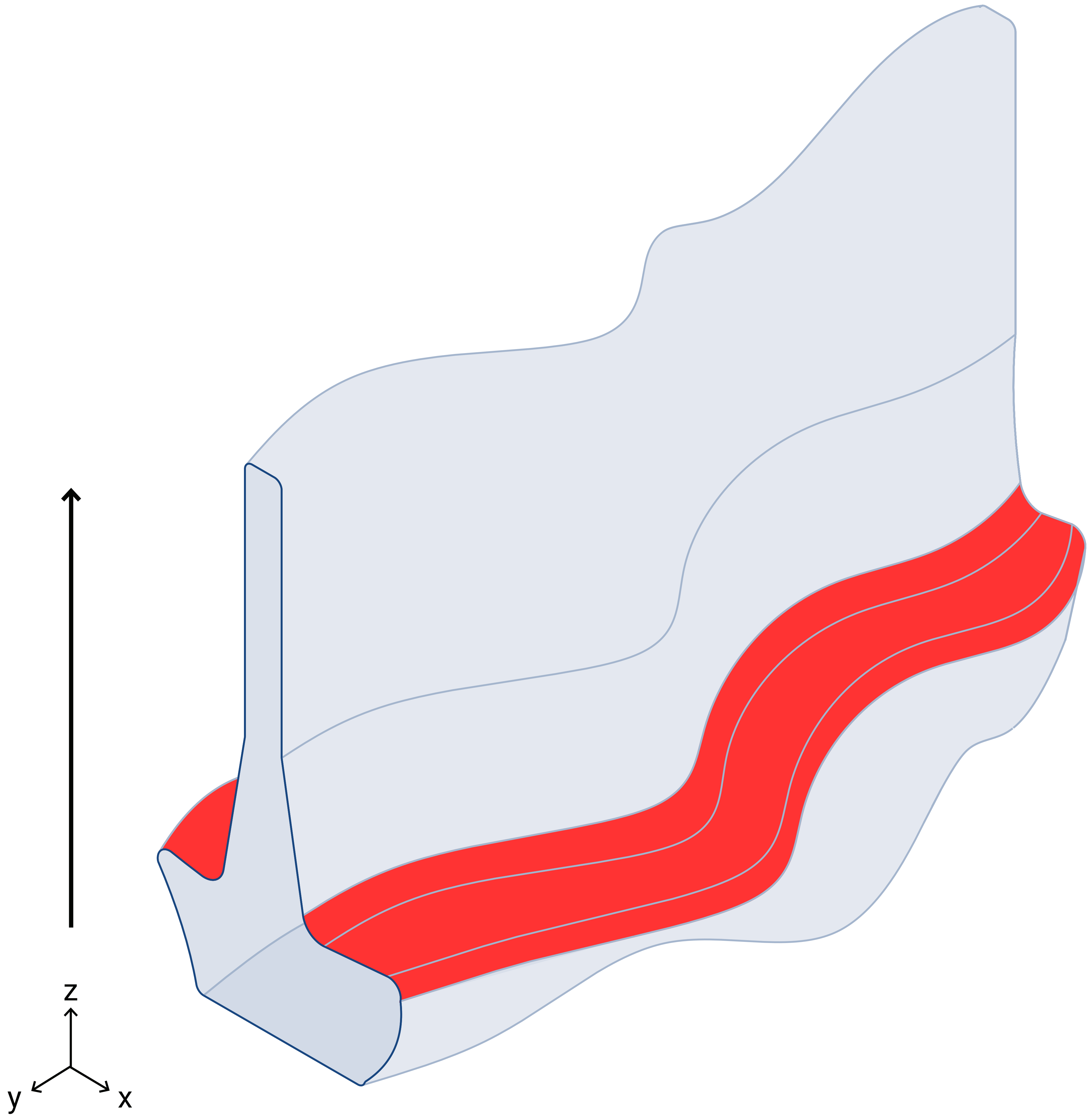

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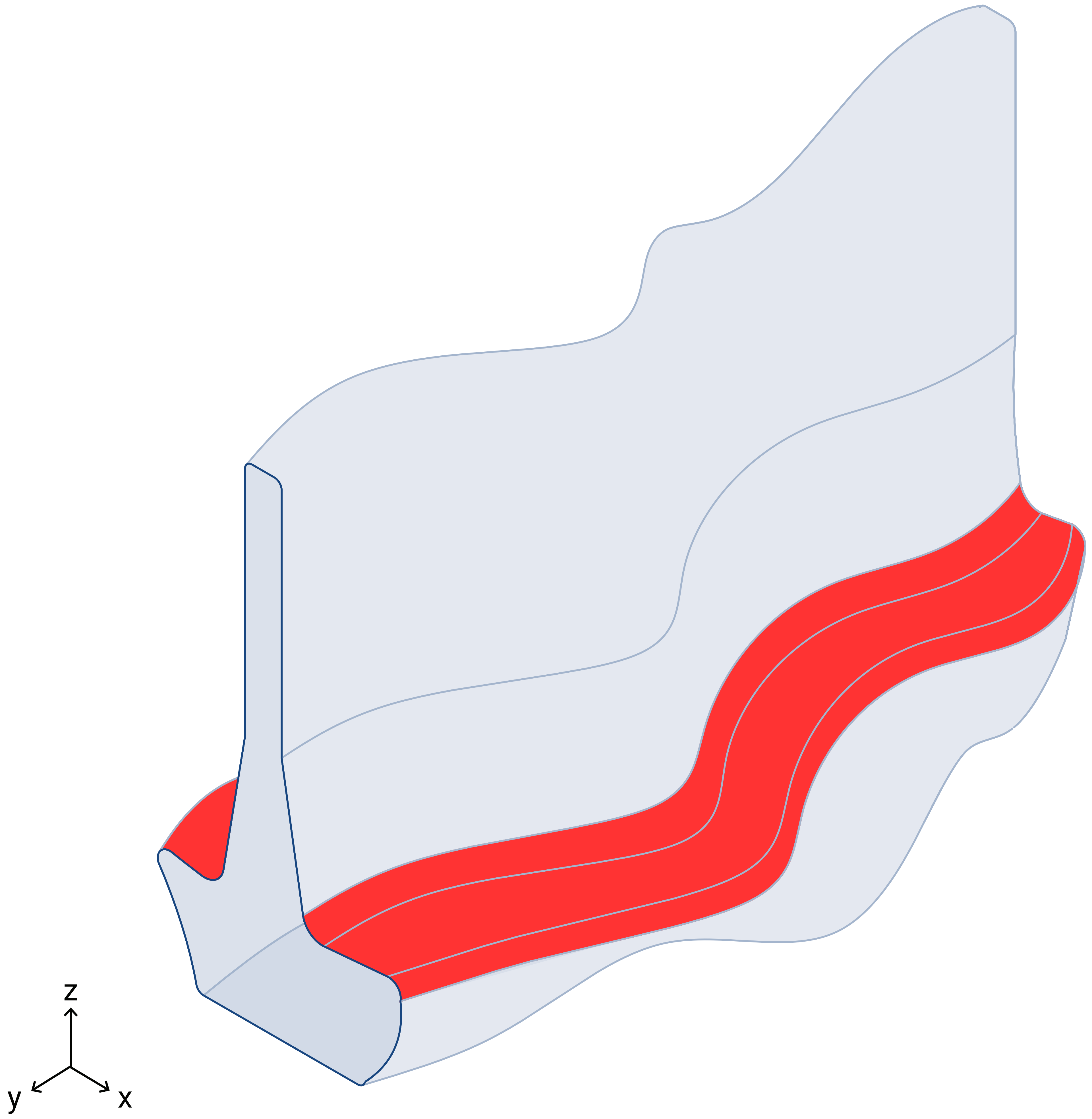
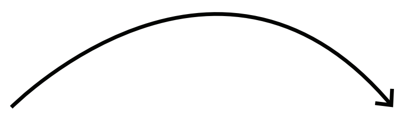
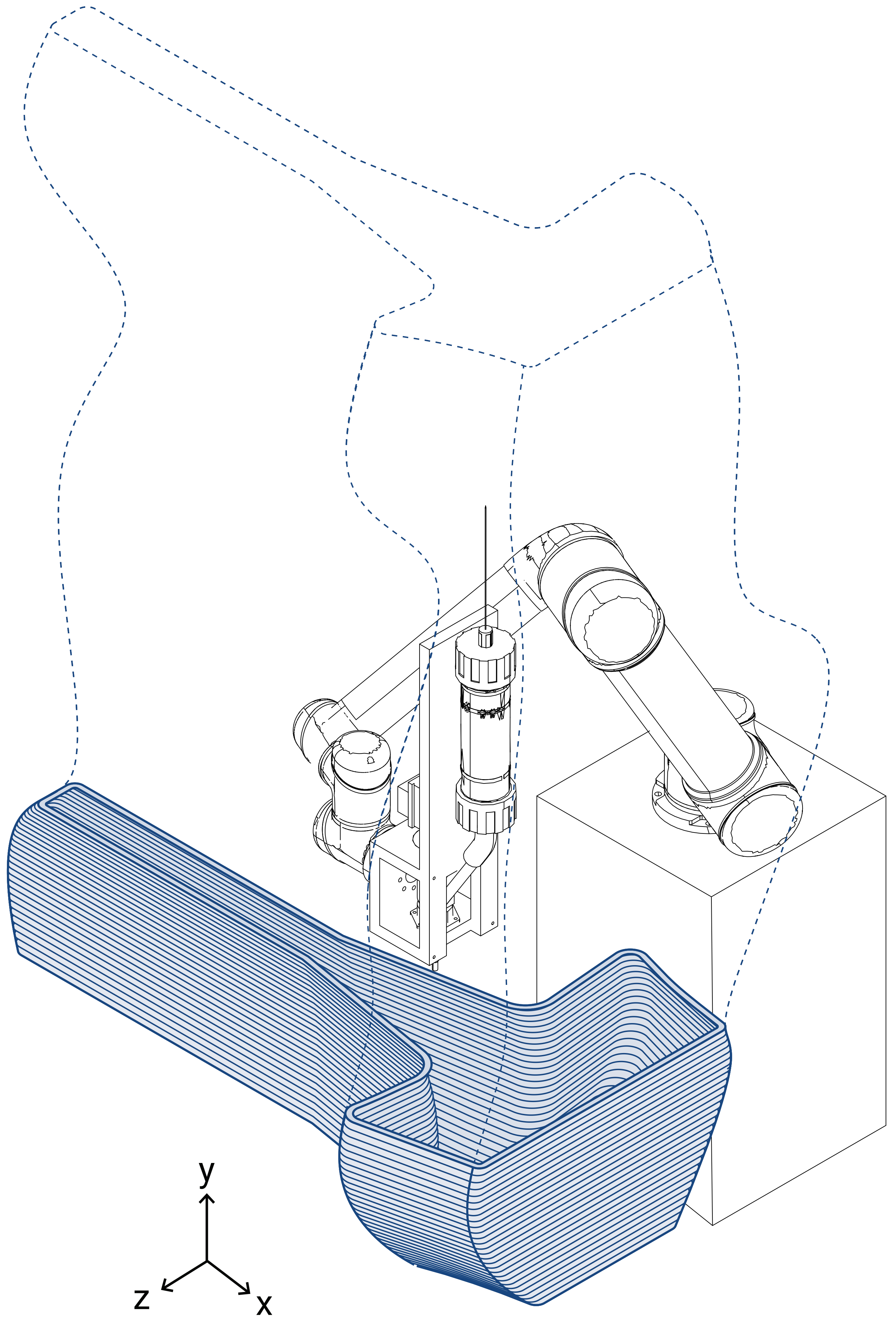
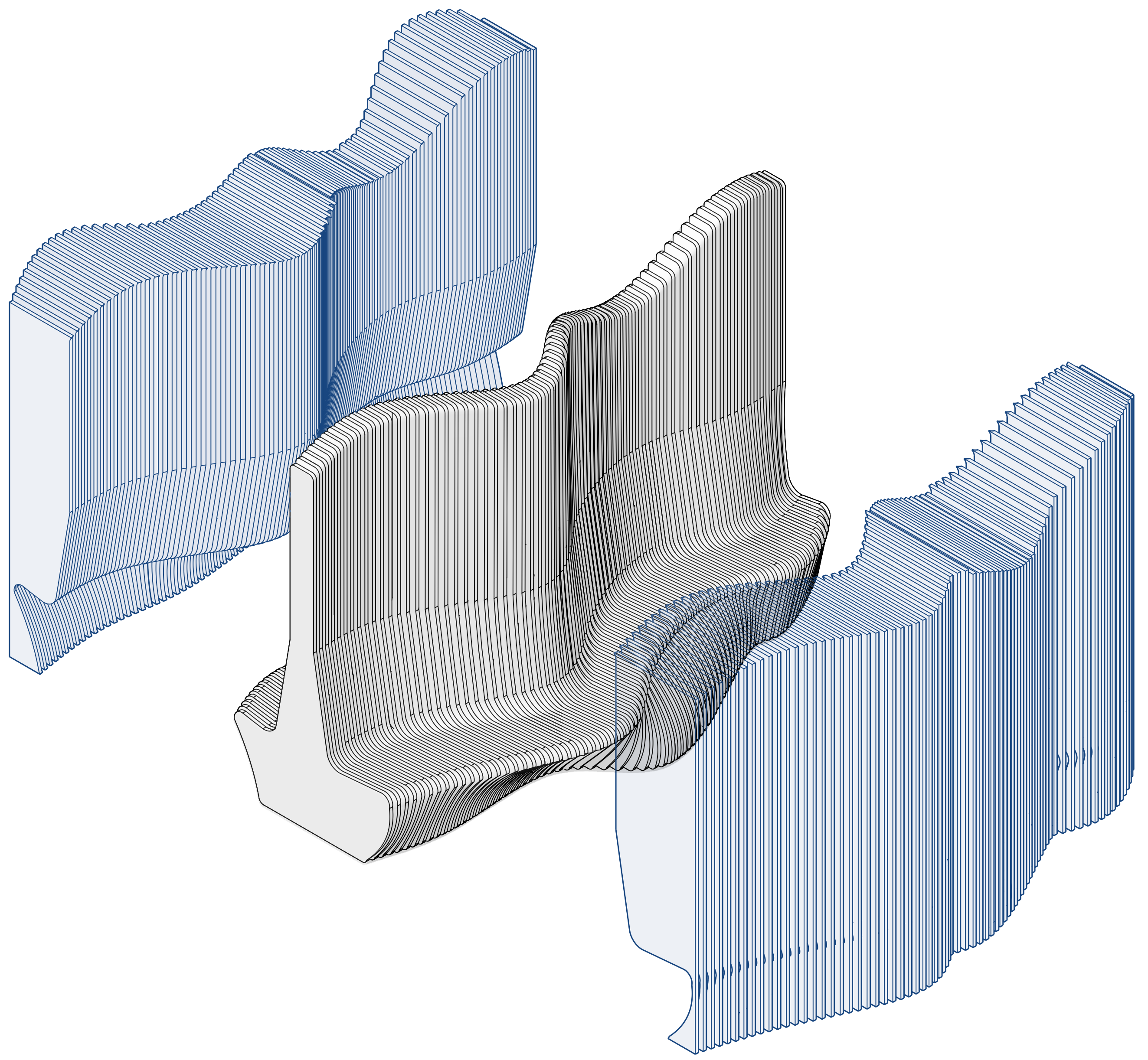






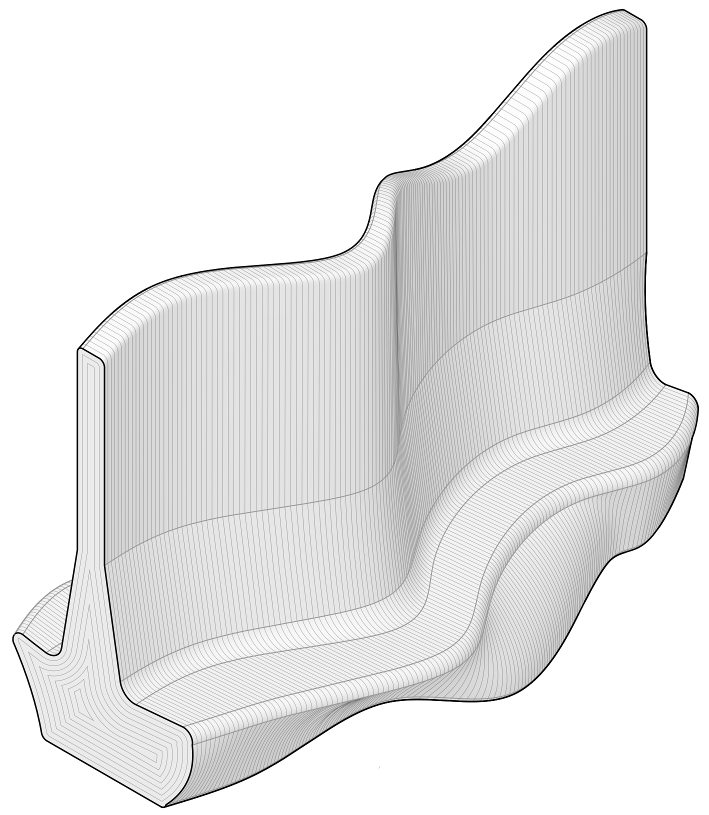
TRADITIONAL PROCESSES COMPARISON

CNC milling



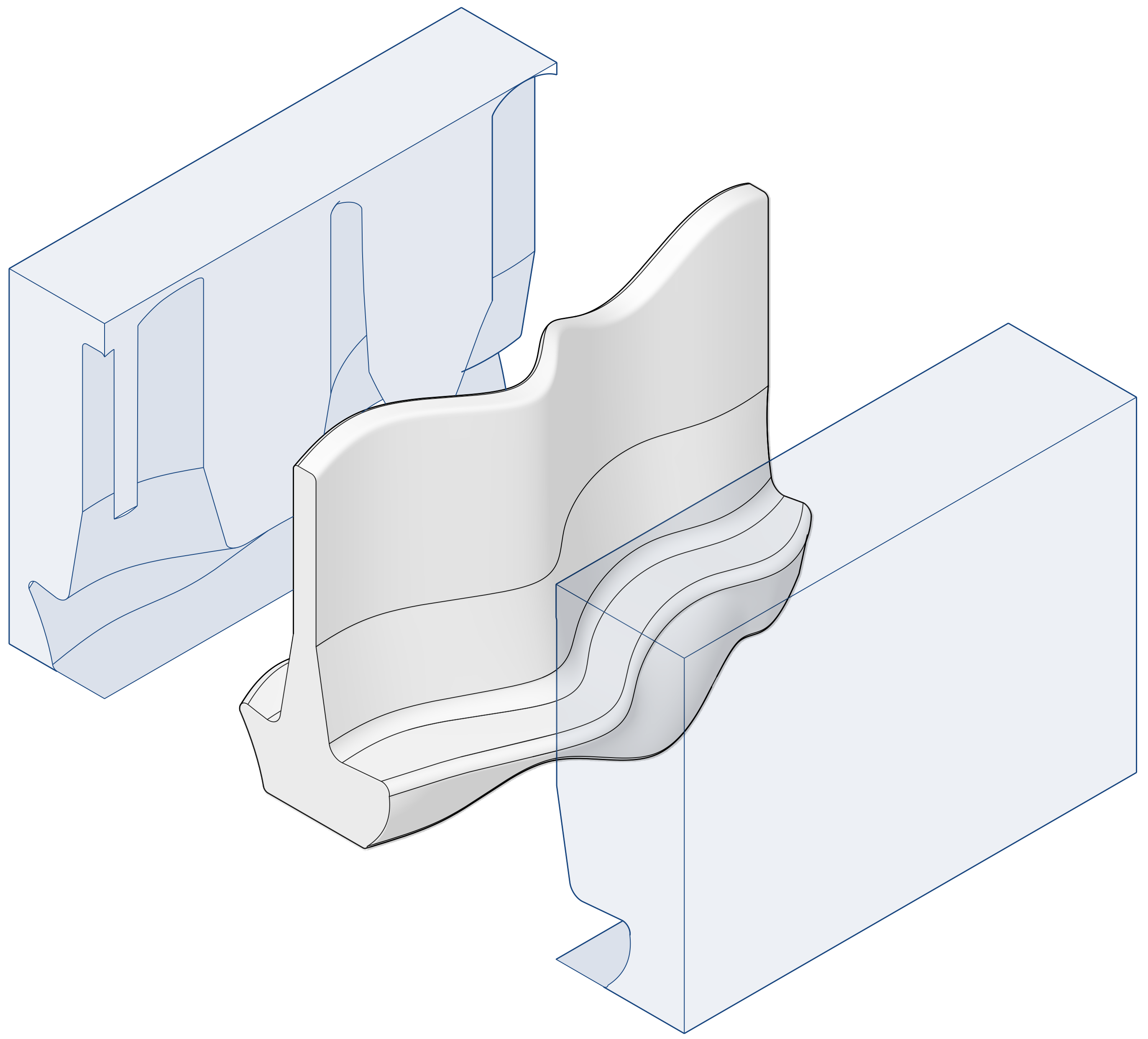
3,48 m³

additive manufacturing



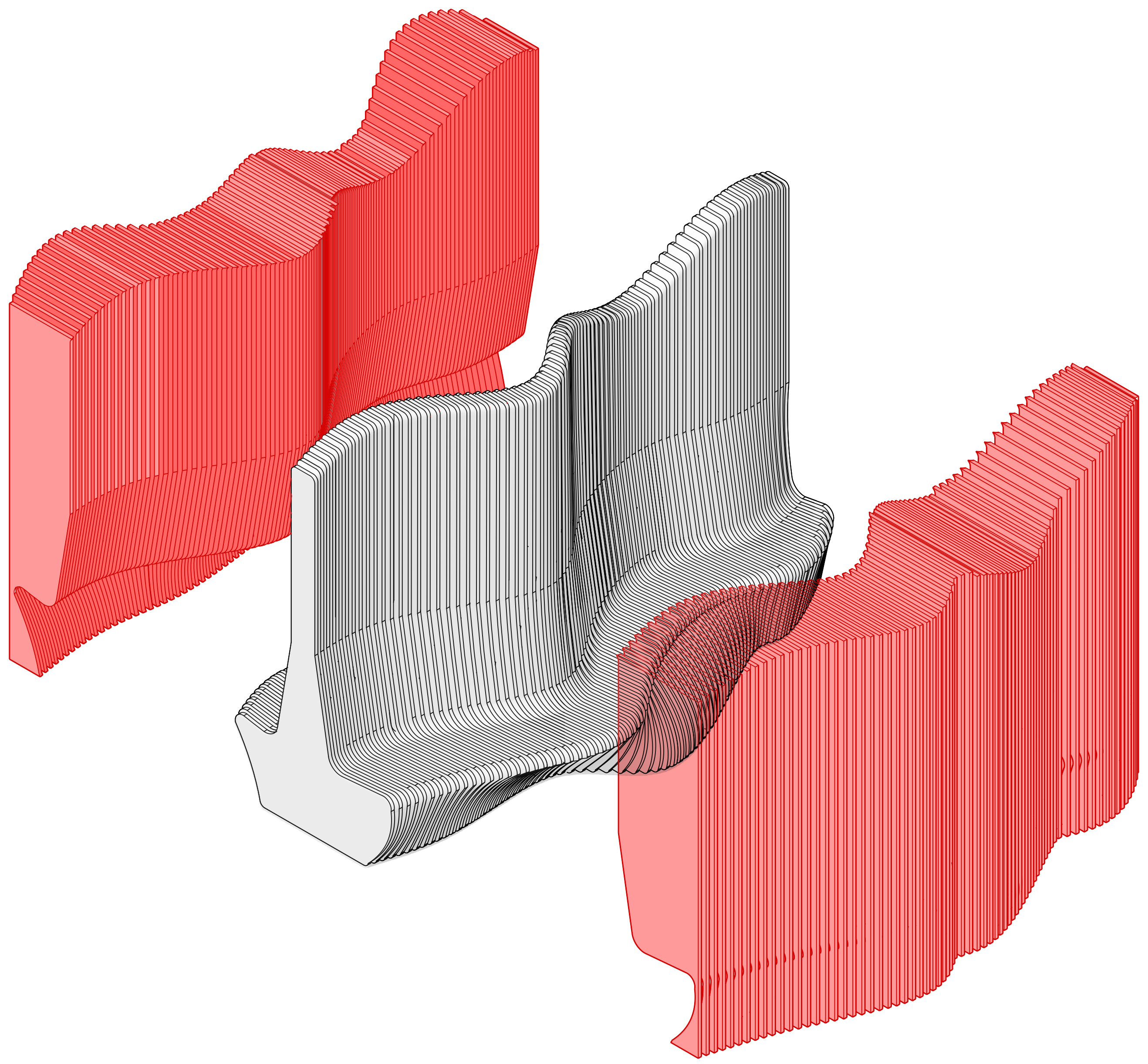
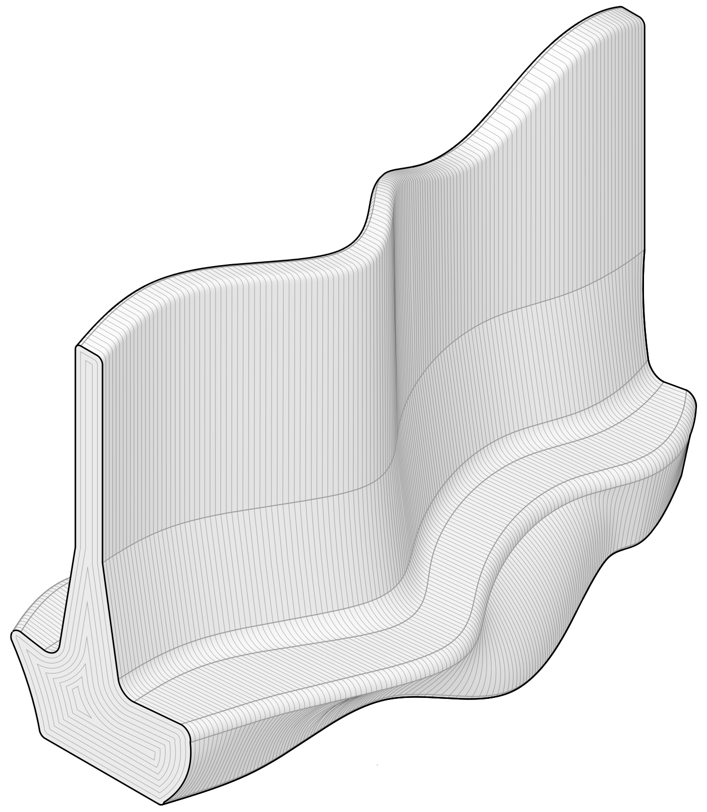
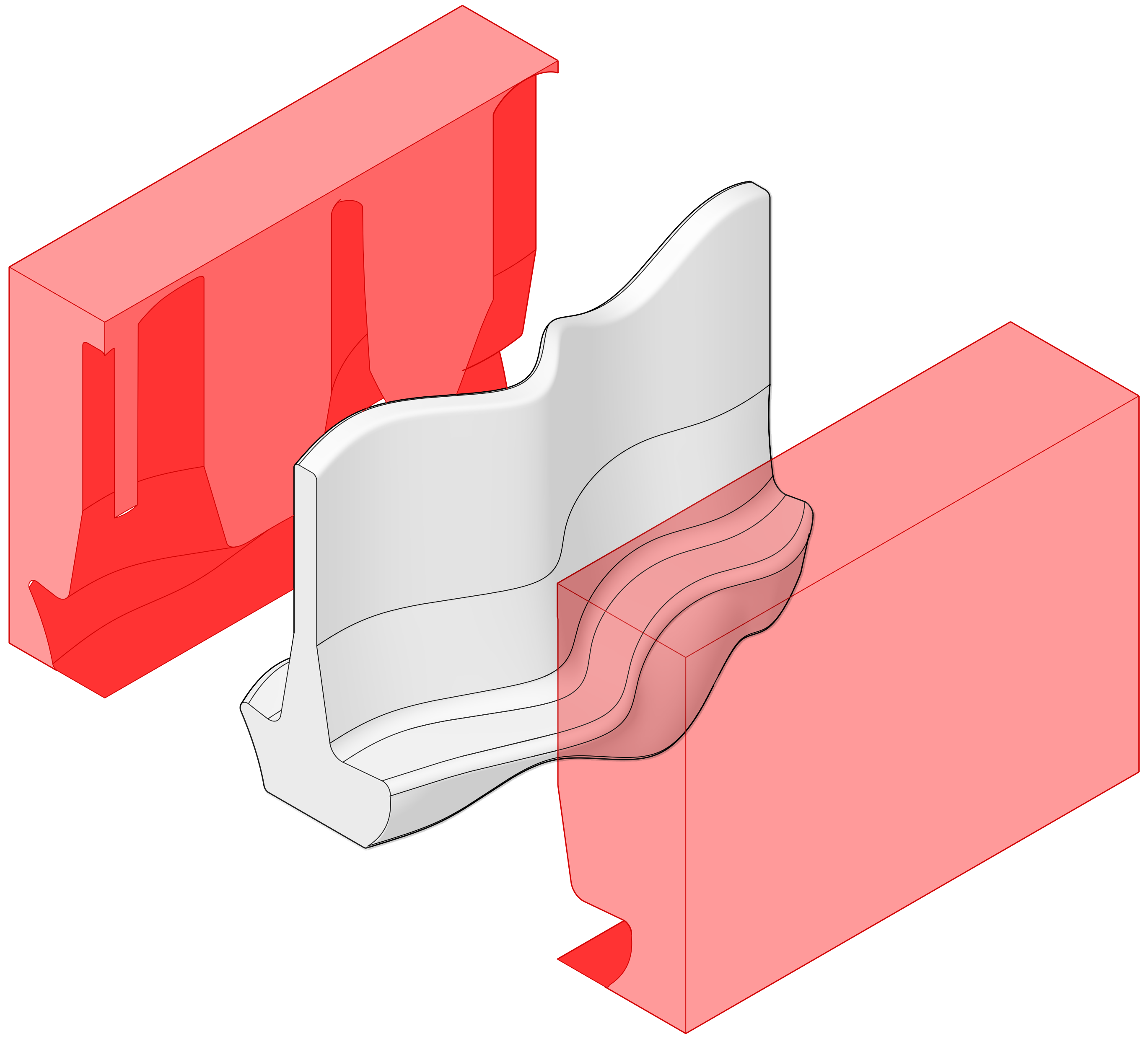
2,14 m³

molding

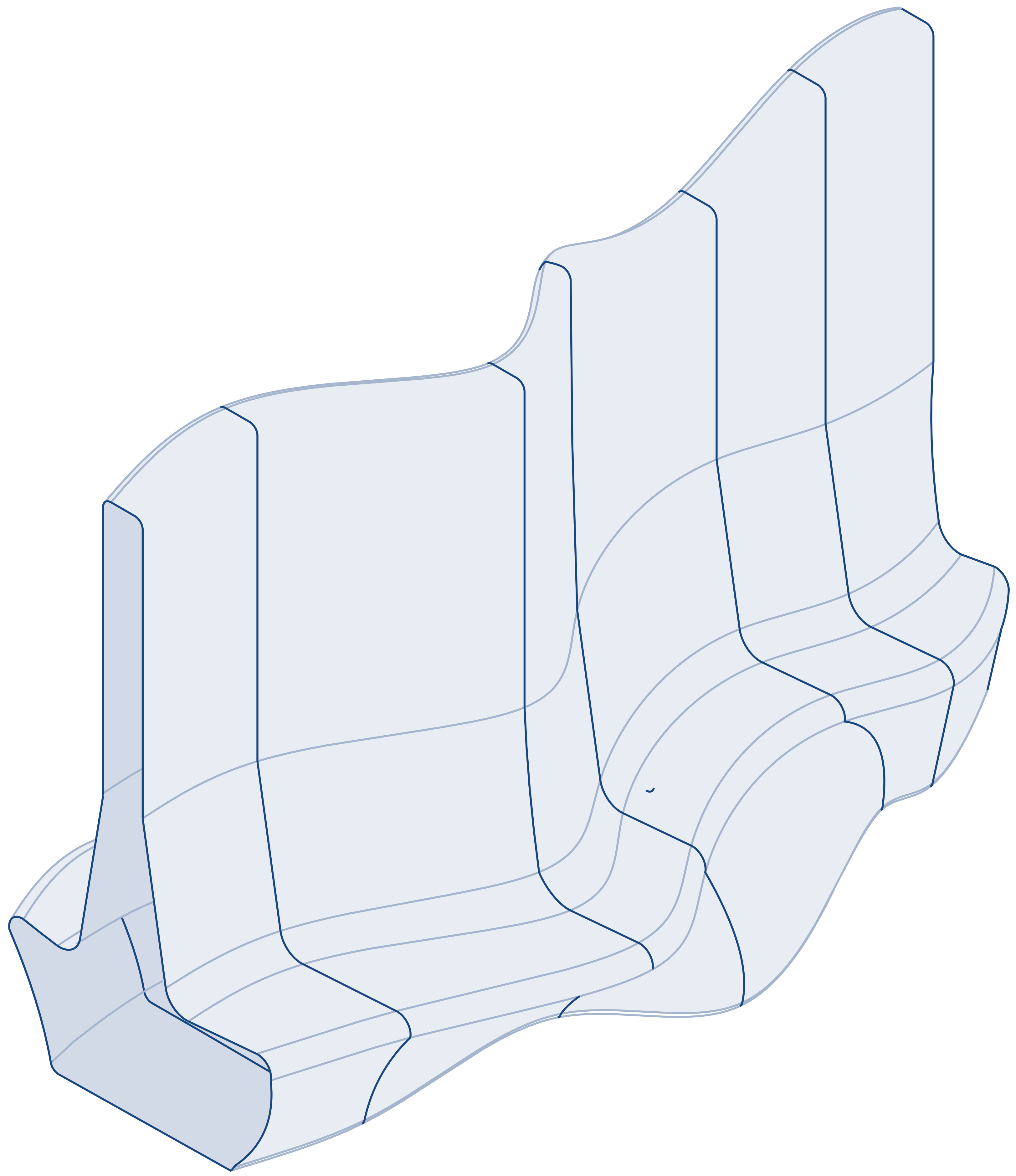


10,58 m³

TRADITIONAL PROCESSES COMPARISON

CNC milling	additive manufacturing	molding
		
3,48 m³	2,14 m³	10,58 m³
+ 48% material compared to AM		**+ 132%** material compared to AM

FLEXIBILITY




MONET


Impressionism
Monet, along with his friends Cezanne, Degas and Renoir, was one of the founders of the
Impressionist art movement, a style of painting that caused a stir in the late 19th century.
Today, its difficult to see why the Impressionists were so rebellious, but at the time,
it was a departure away from the religious, mythological and highly realistic style of
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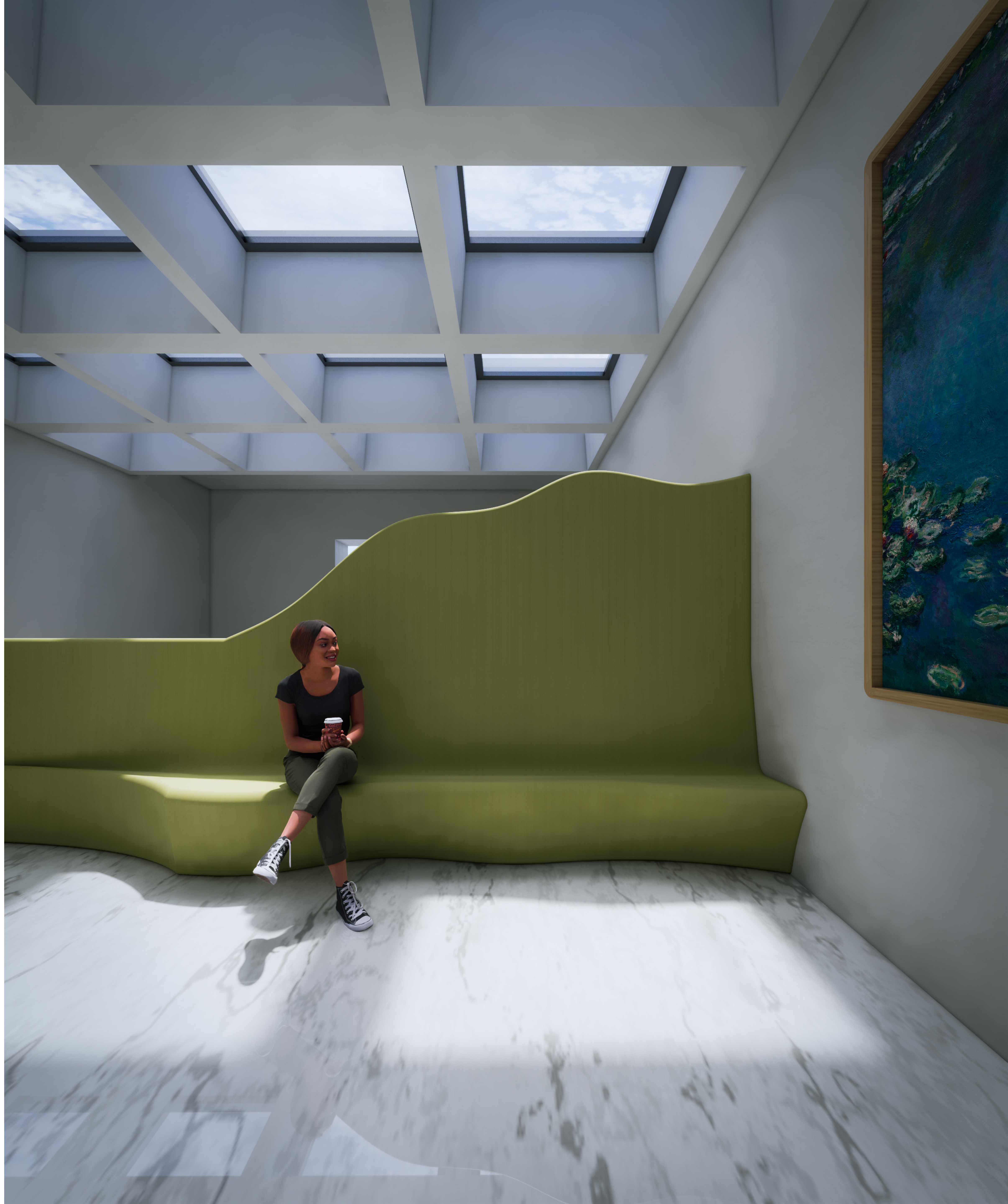
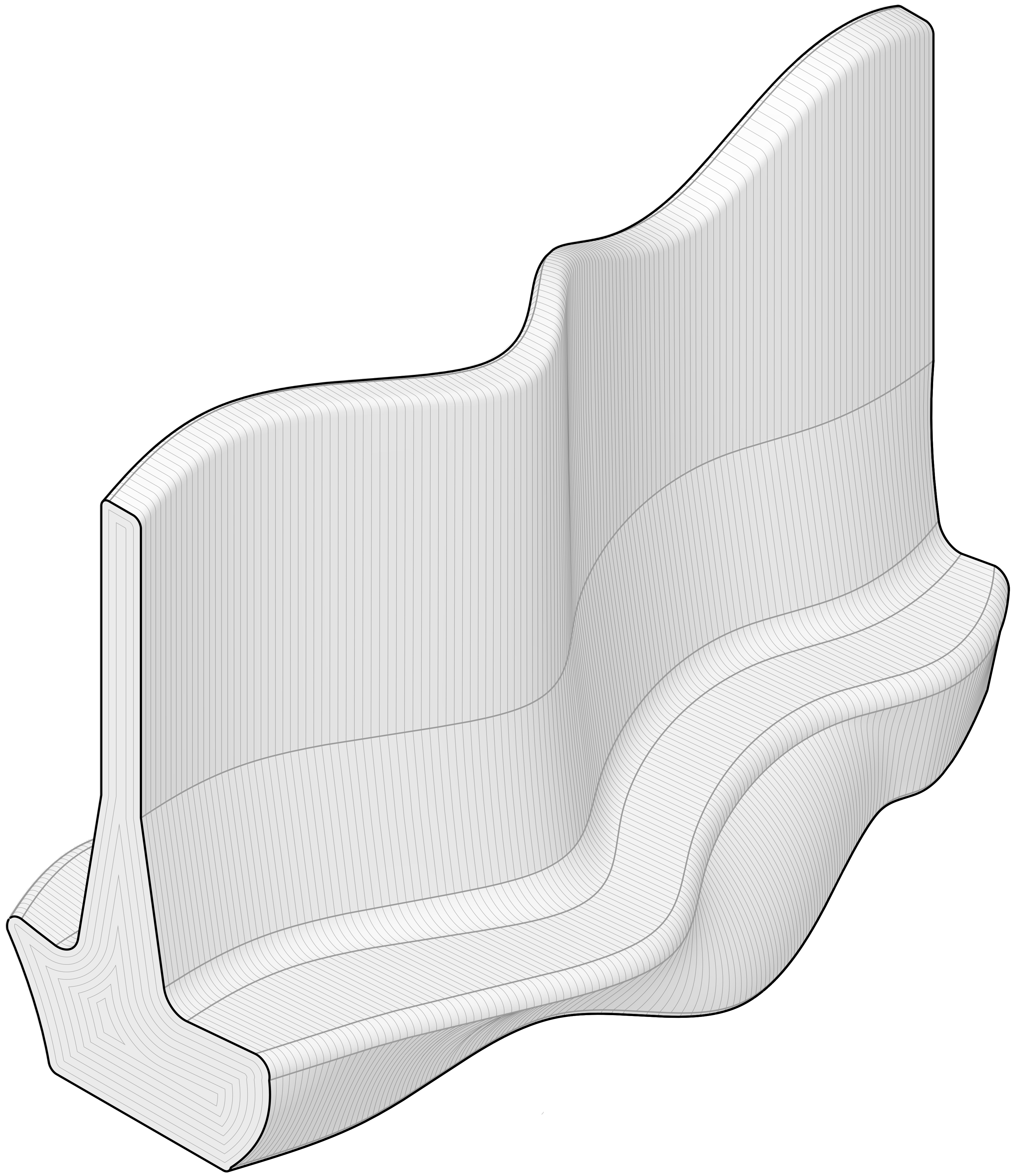
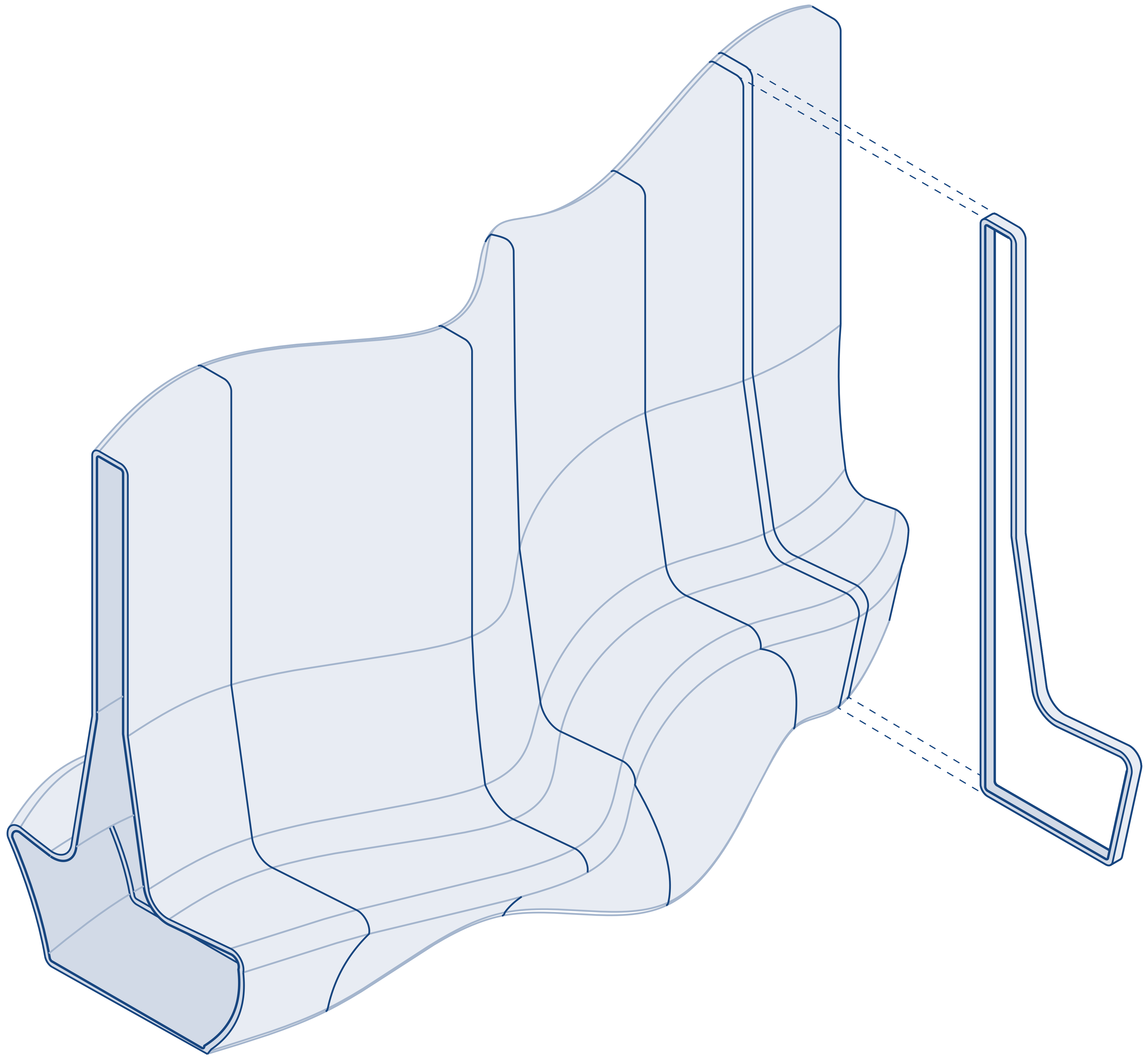
Impressionist art movement, a style of painting that caused a stir in the late 19th centu


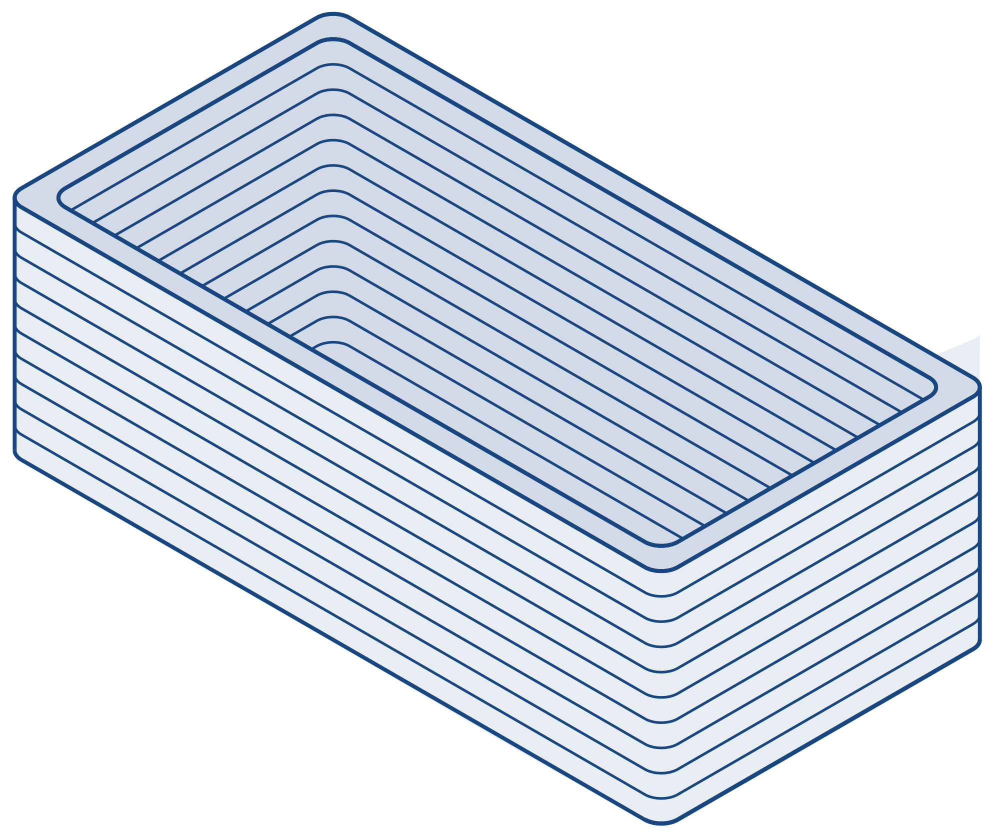
ONE OF THE MANY



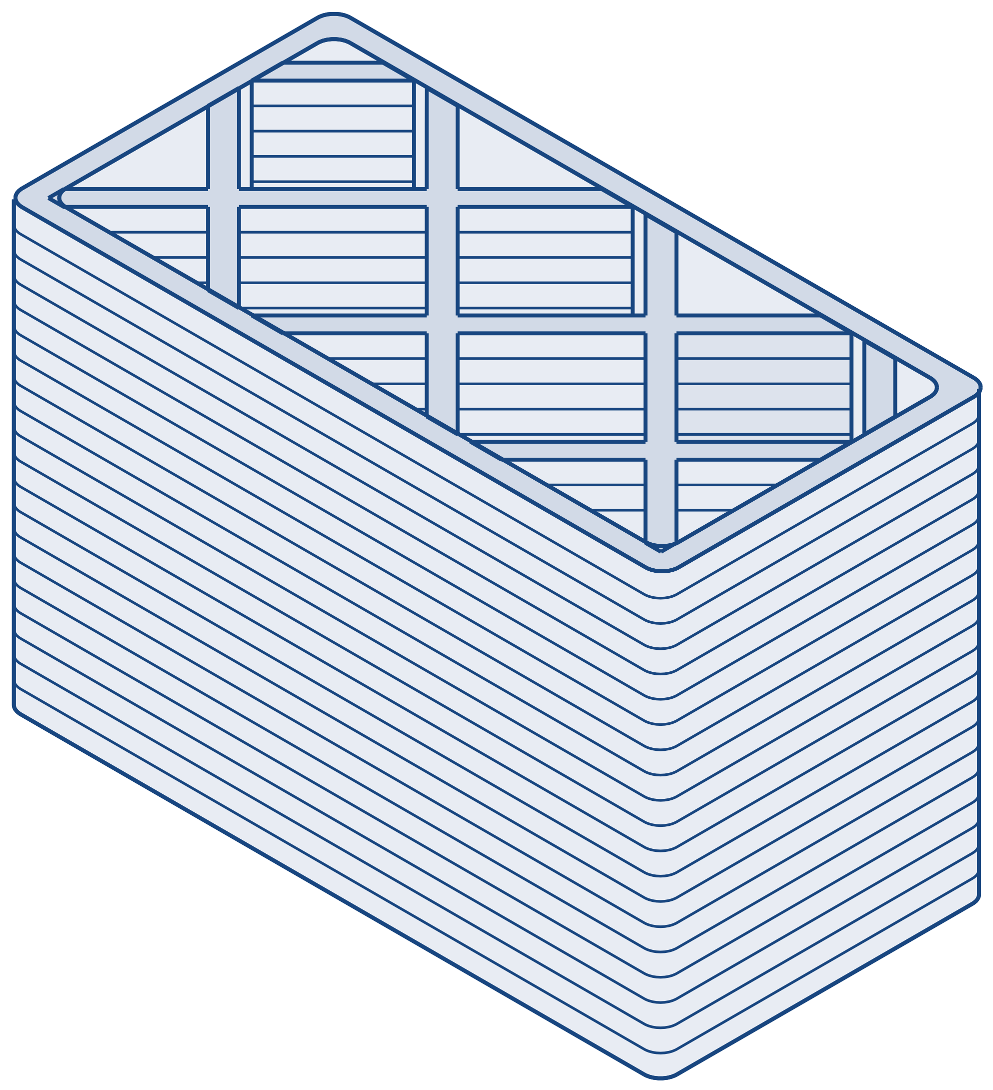
FOCUSED AREA



STABILITY

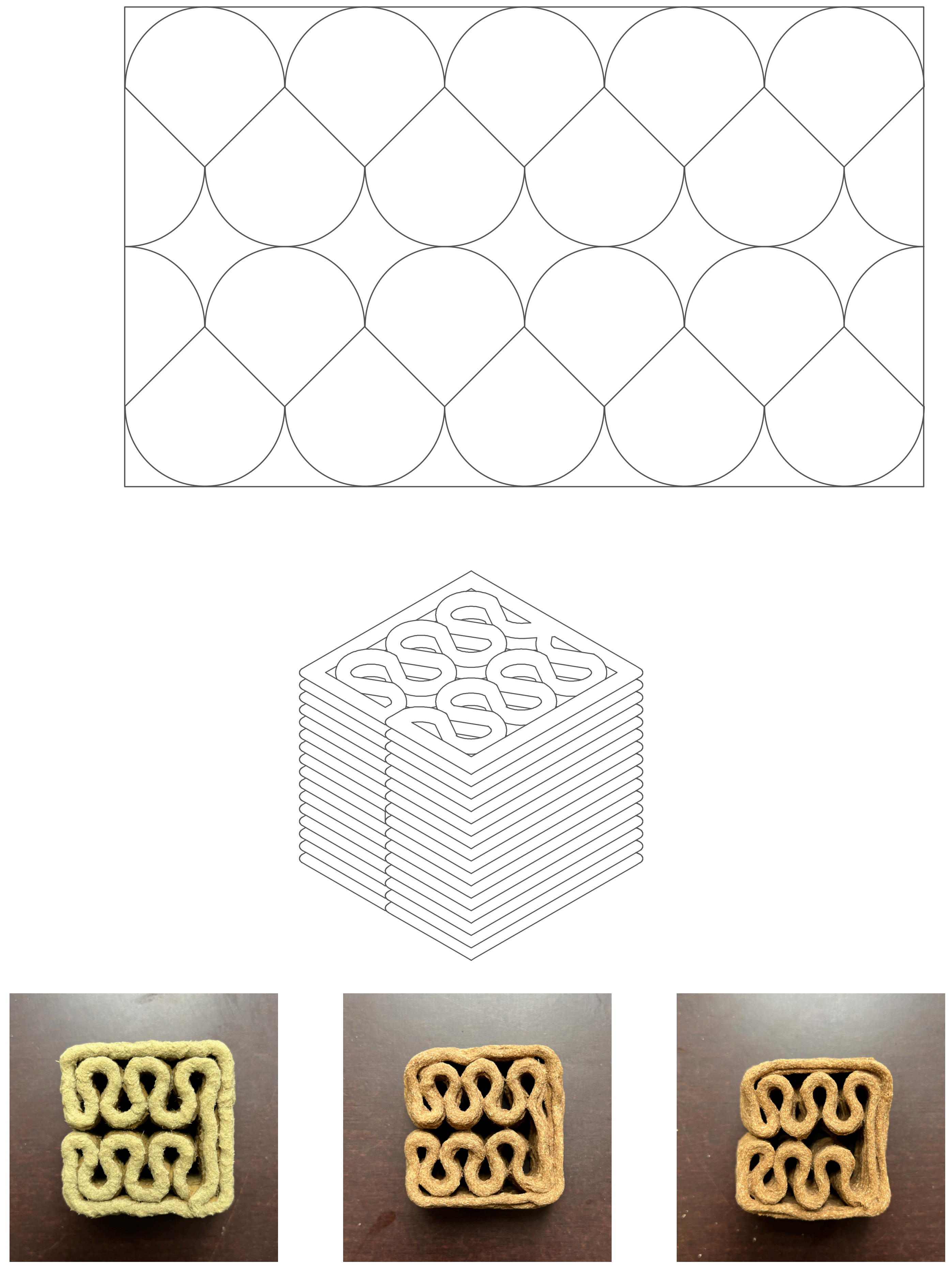


without infill

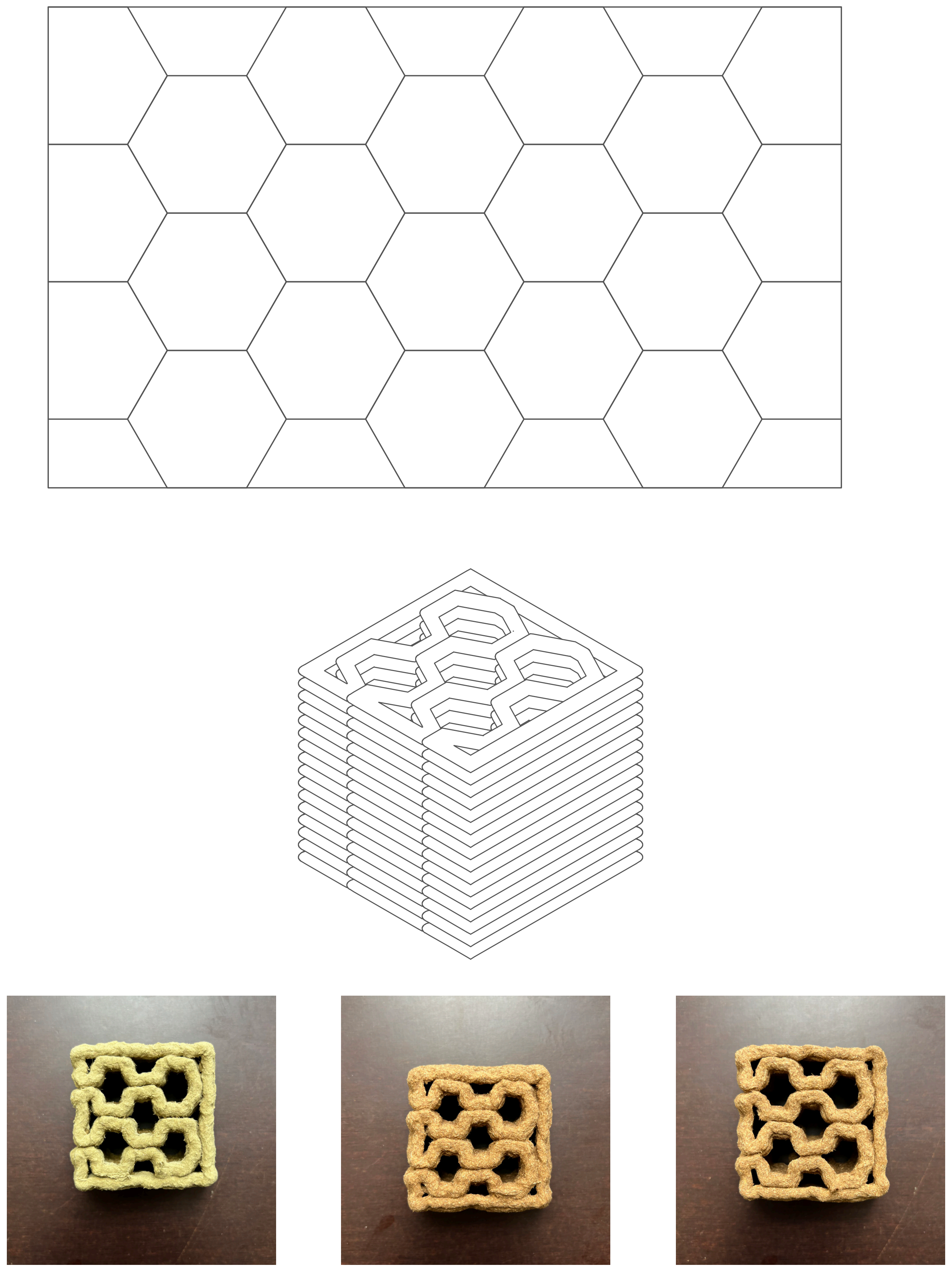


with infill

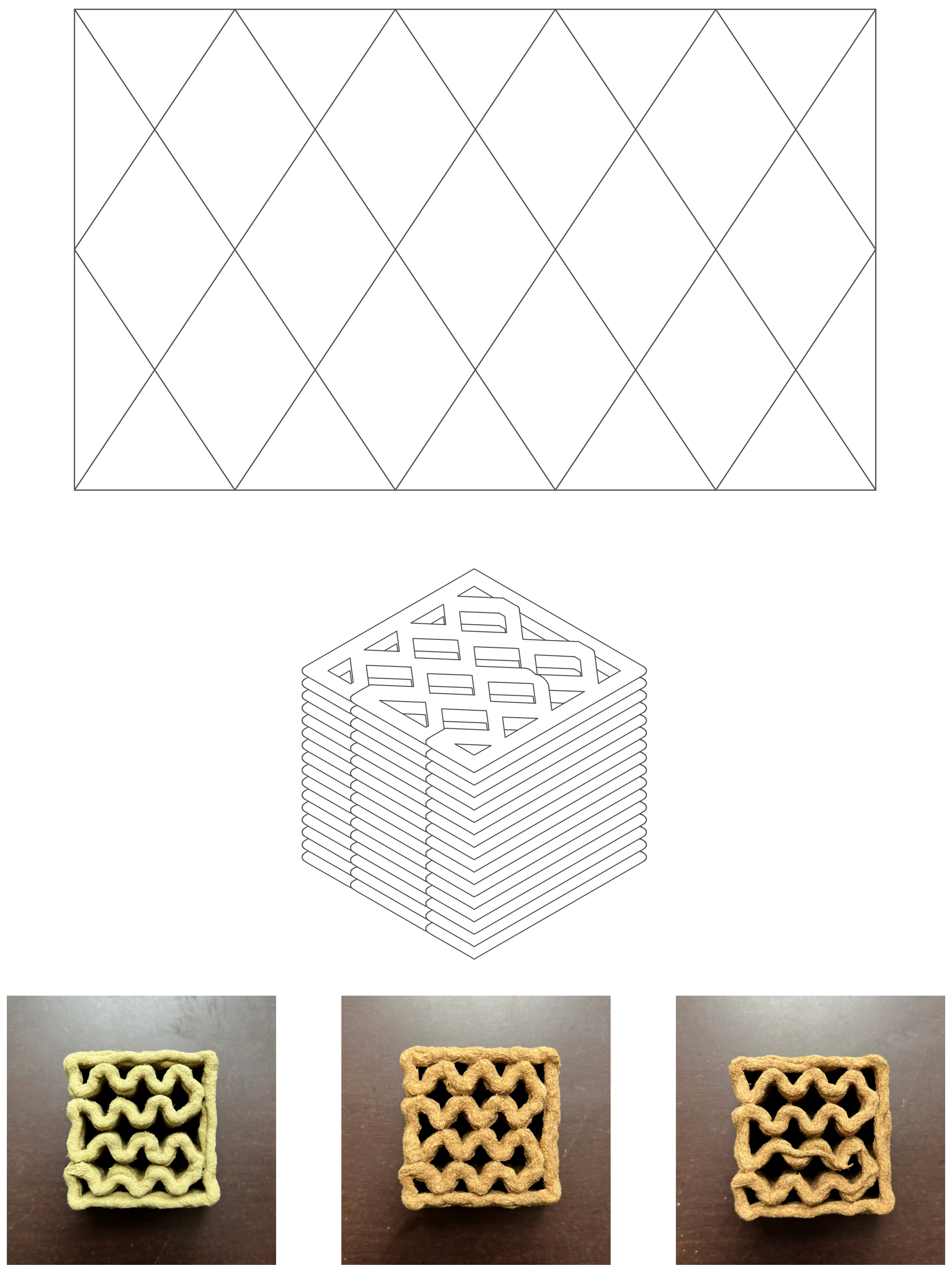
SPECIMENS



curved

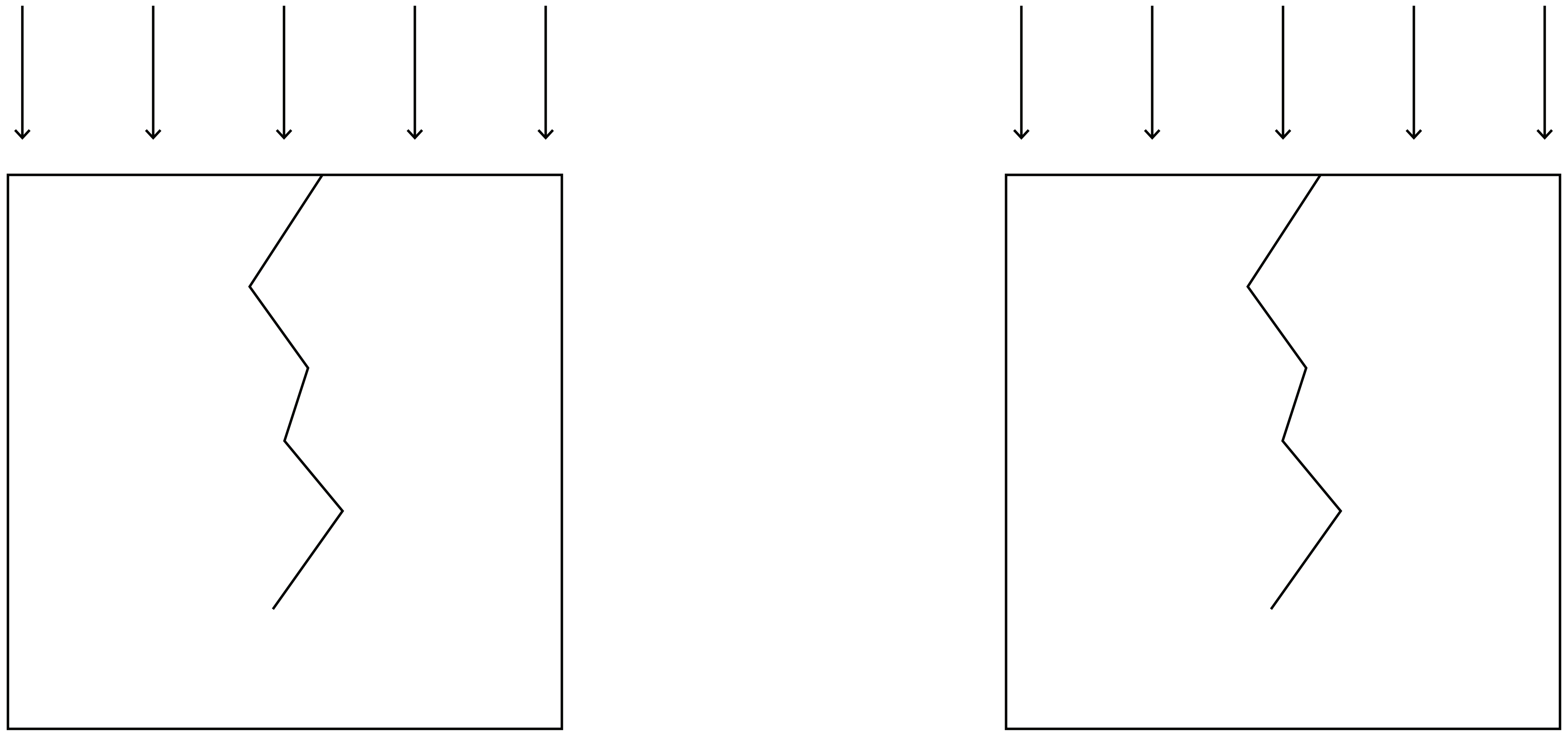


honeycomb



rhombic

MECHANICAL TEST



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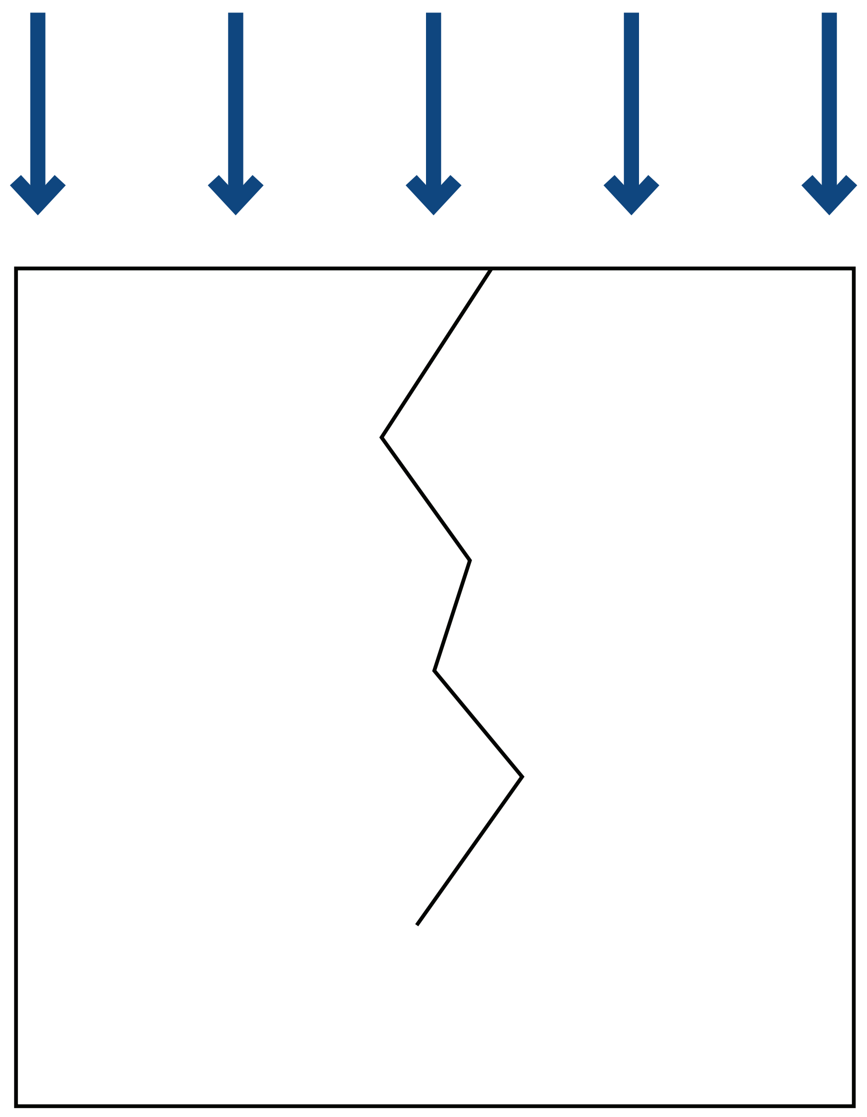
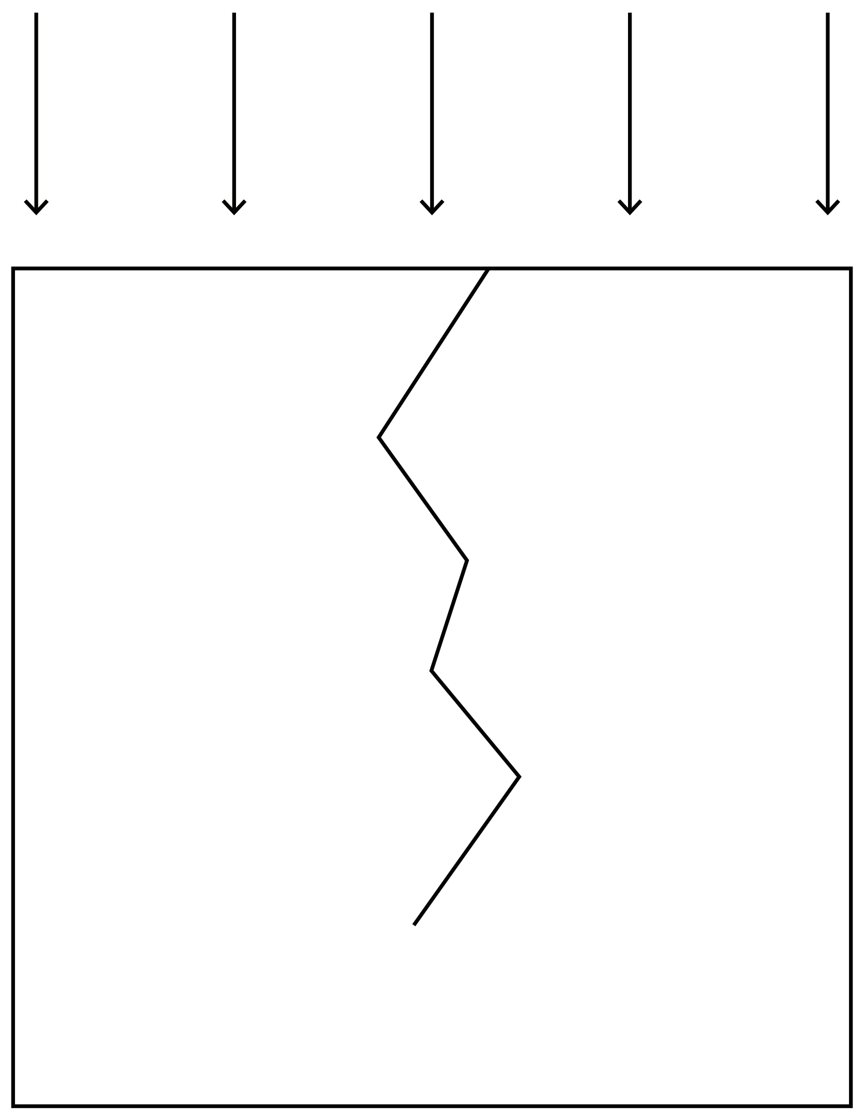
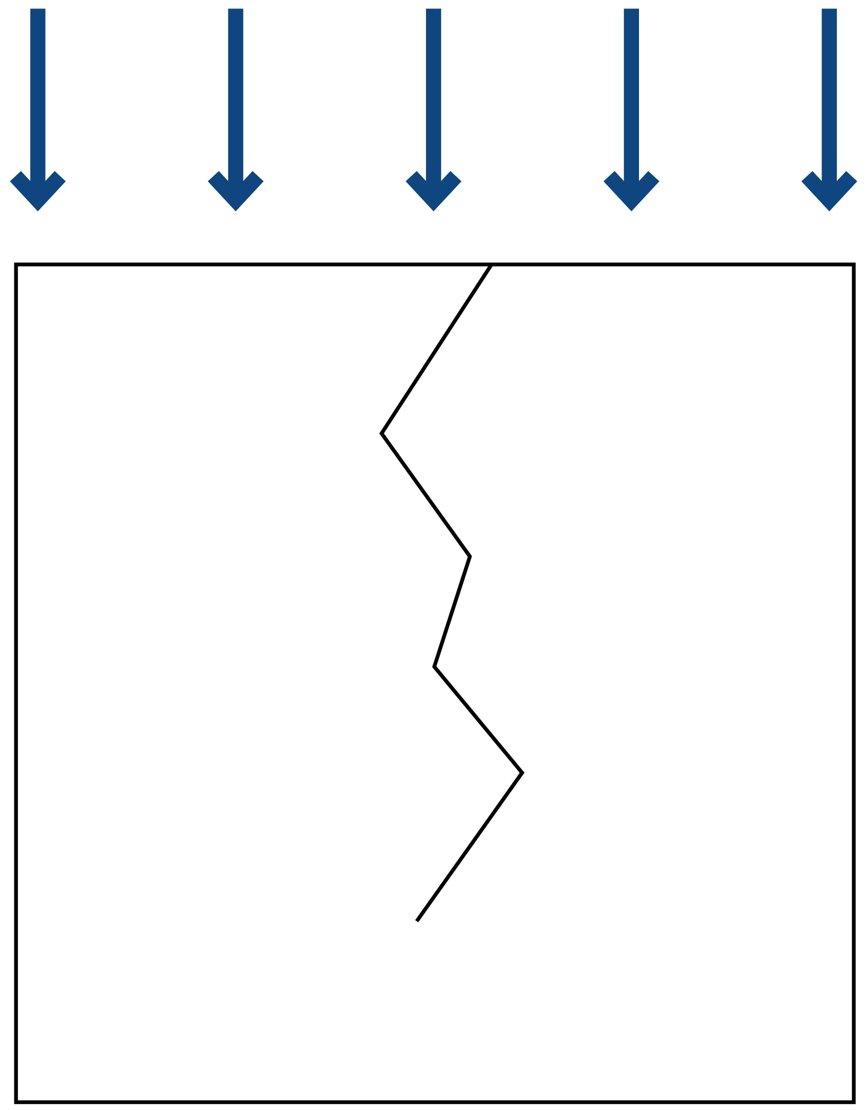


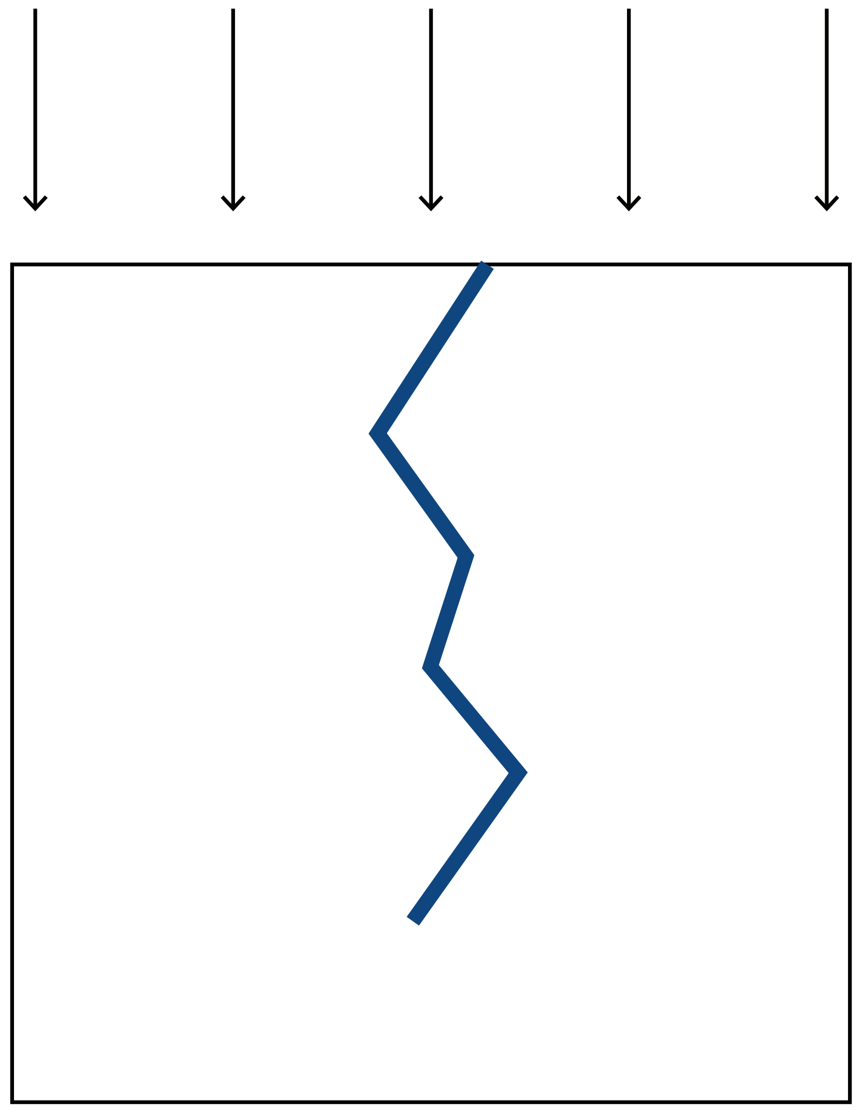
load capacity



MECHANICAL TEST



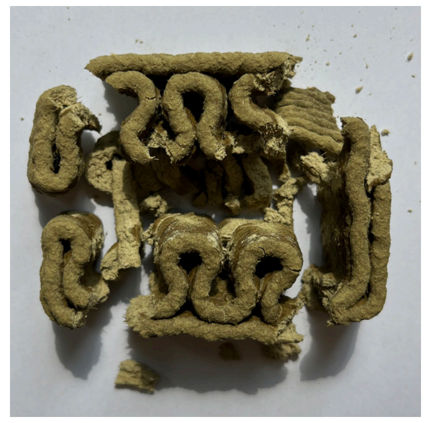
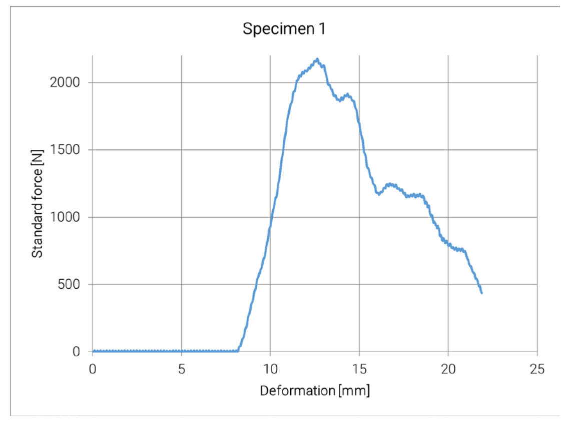
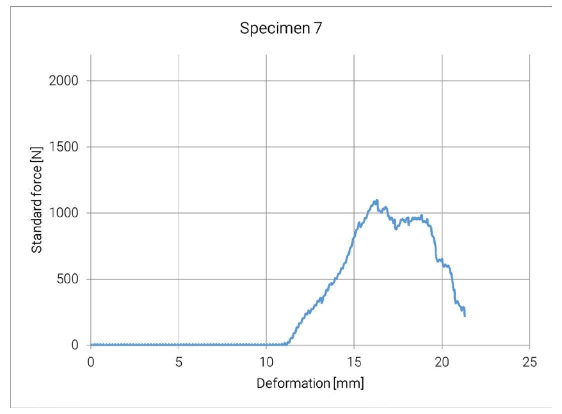
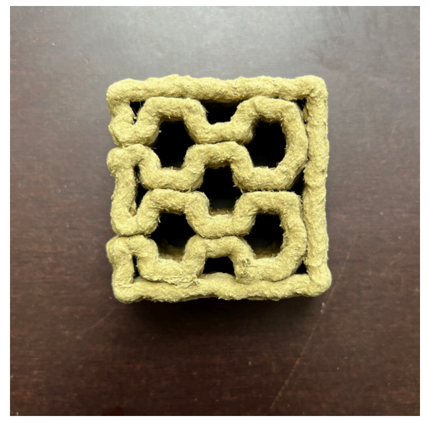
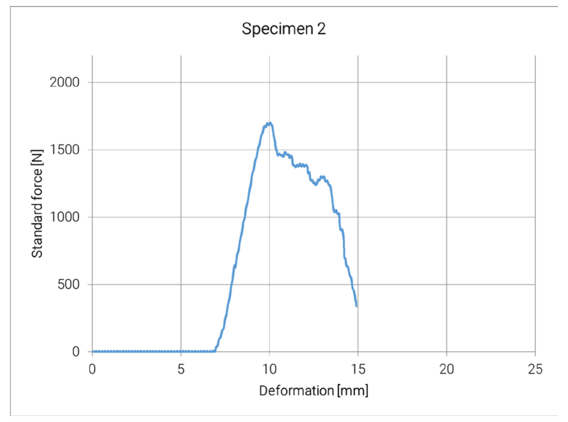
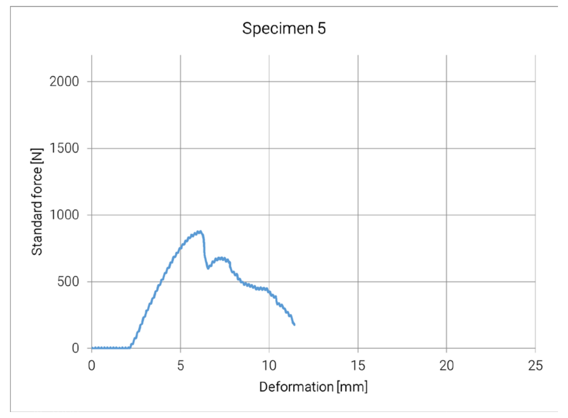
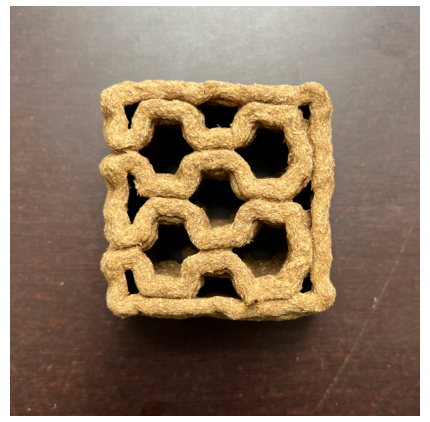
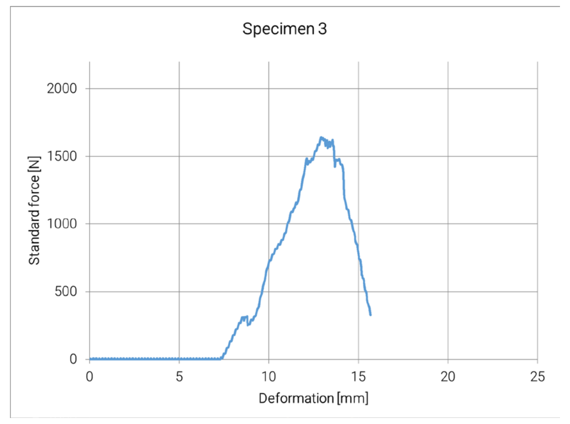
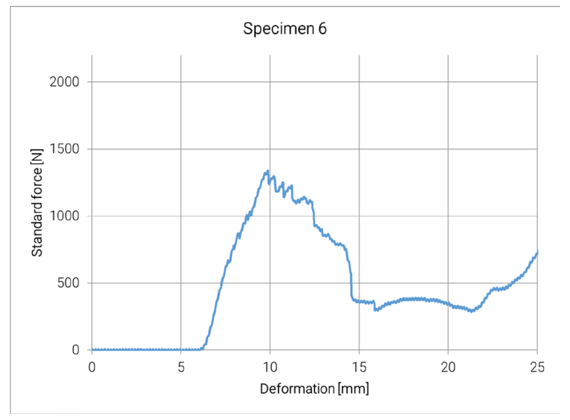
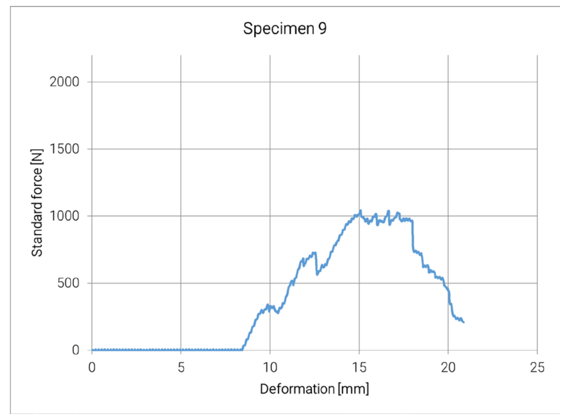
load capacity



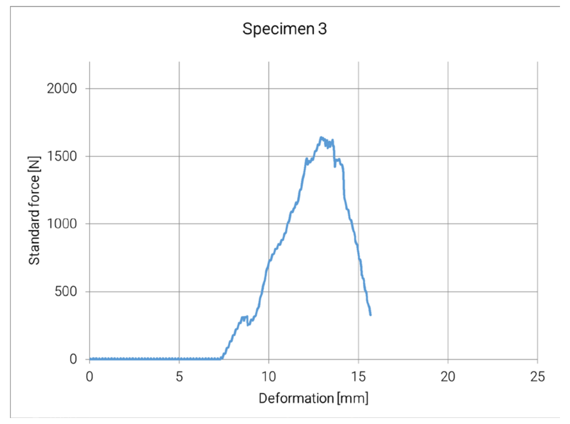
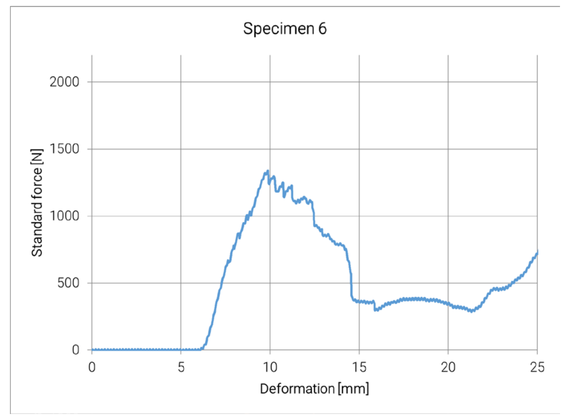
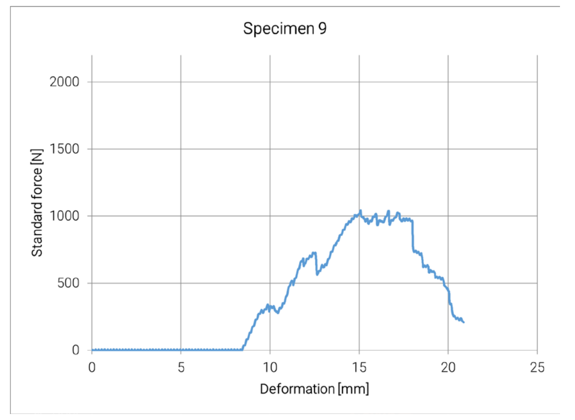
geometry behaviour

COMPRESSION TEST

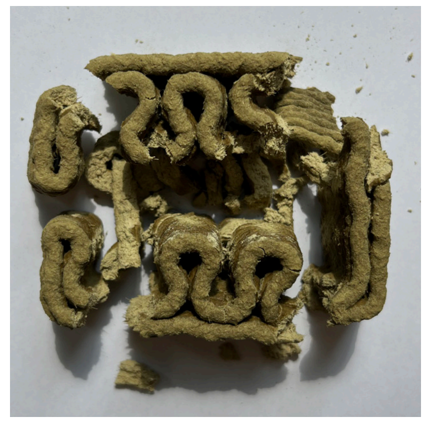
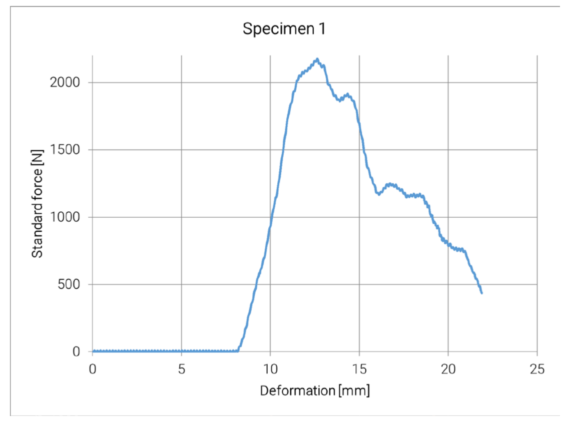
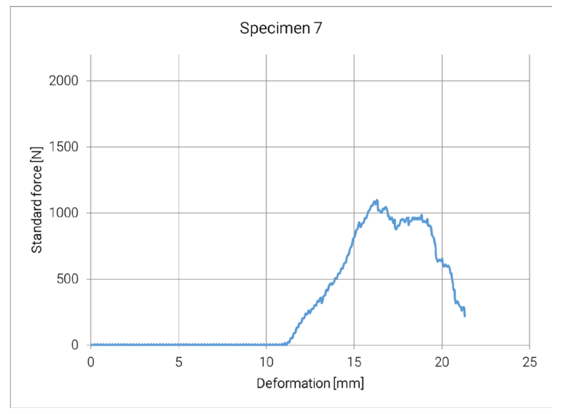
RESULTS

Mixture / Geometry	Dust + Fibers	Green Dust + Fibers	
Curved	  	  	  
Honeycomb	  	  	  
Rhombic	  	  	  

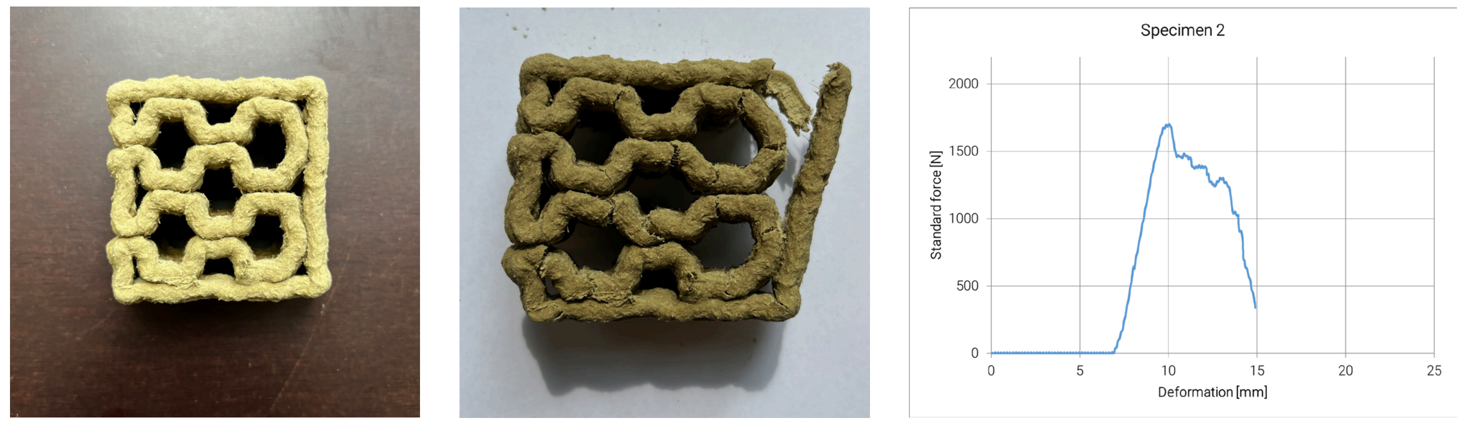
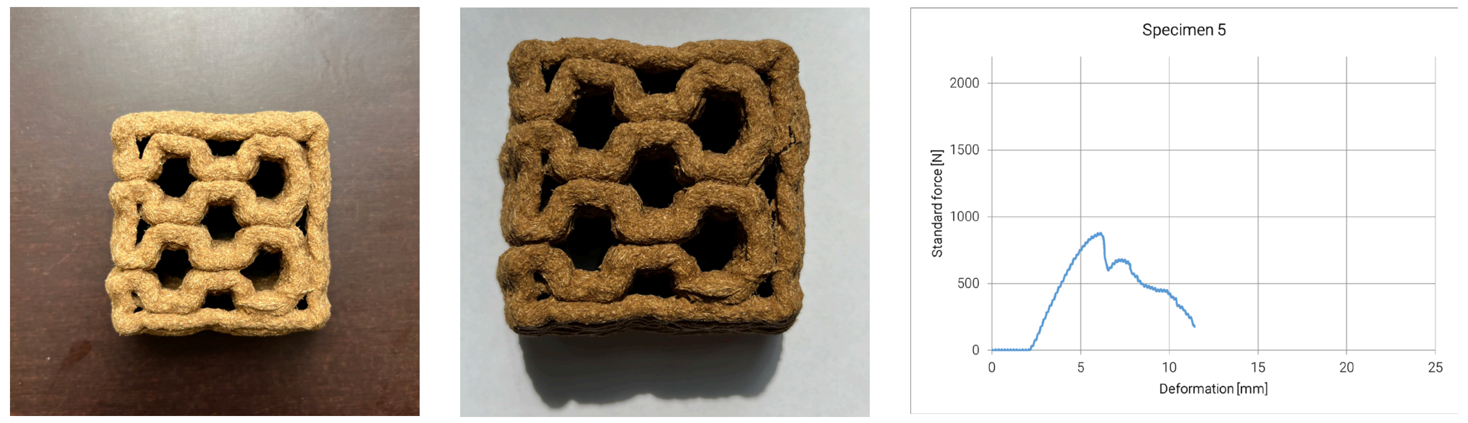
RHOMBIC

Mixture / Geometry	Dust + Fibers	Green Dust + Fibers	
Curved			
Honeycomb			
Rhombic	  	  	  

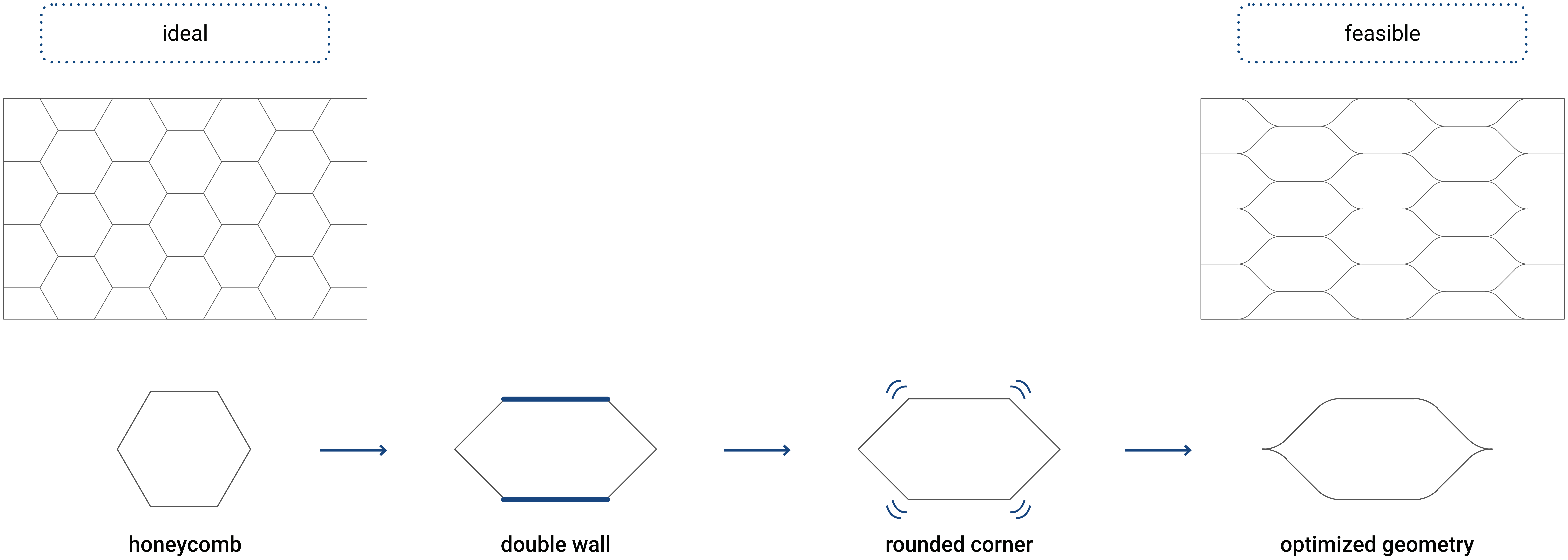
CURVED

Mixture / Geometry	Dust + Fibers	Green Dust + Fibers	
Curved	  	  	  
Honeycomb			
Rhombic			

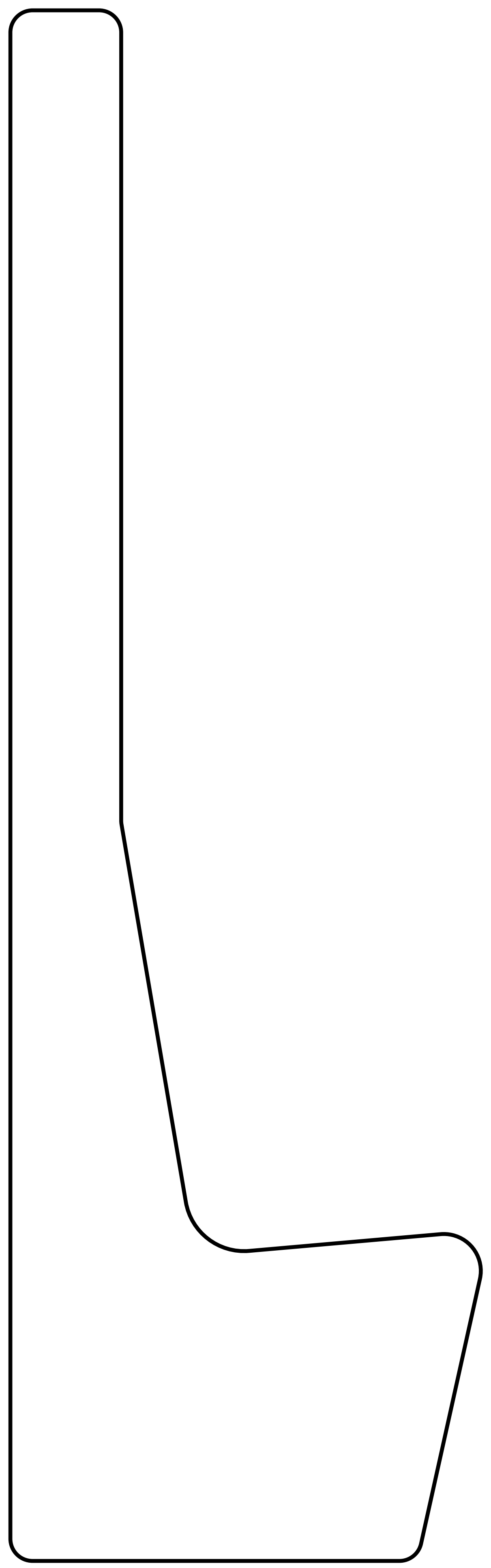
HONEYCOMB

Mixture / Geometry	Dust + Fibers	Green Dust + Fibers	
Curved			
Honeycomb			
Rhombic			

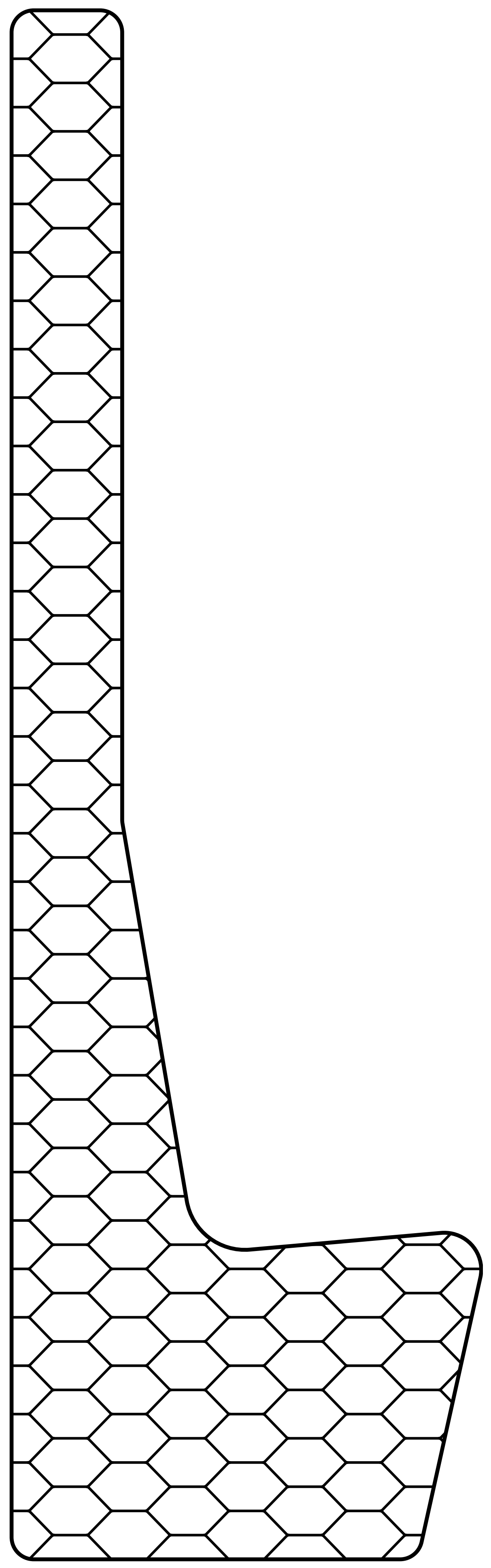
OPTIMIZED GEOMETRY



DESIGN

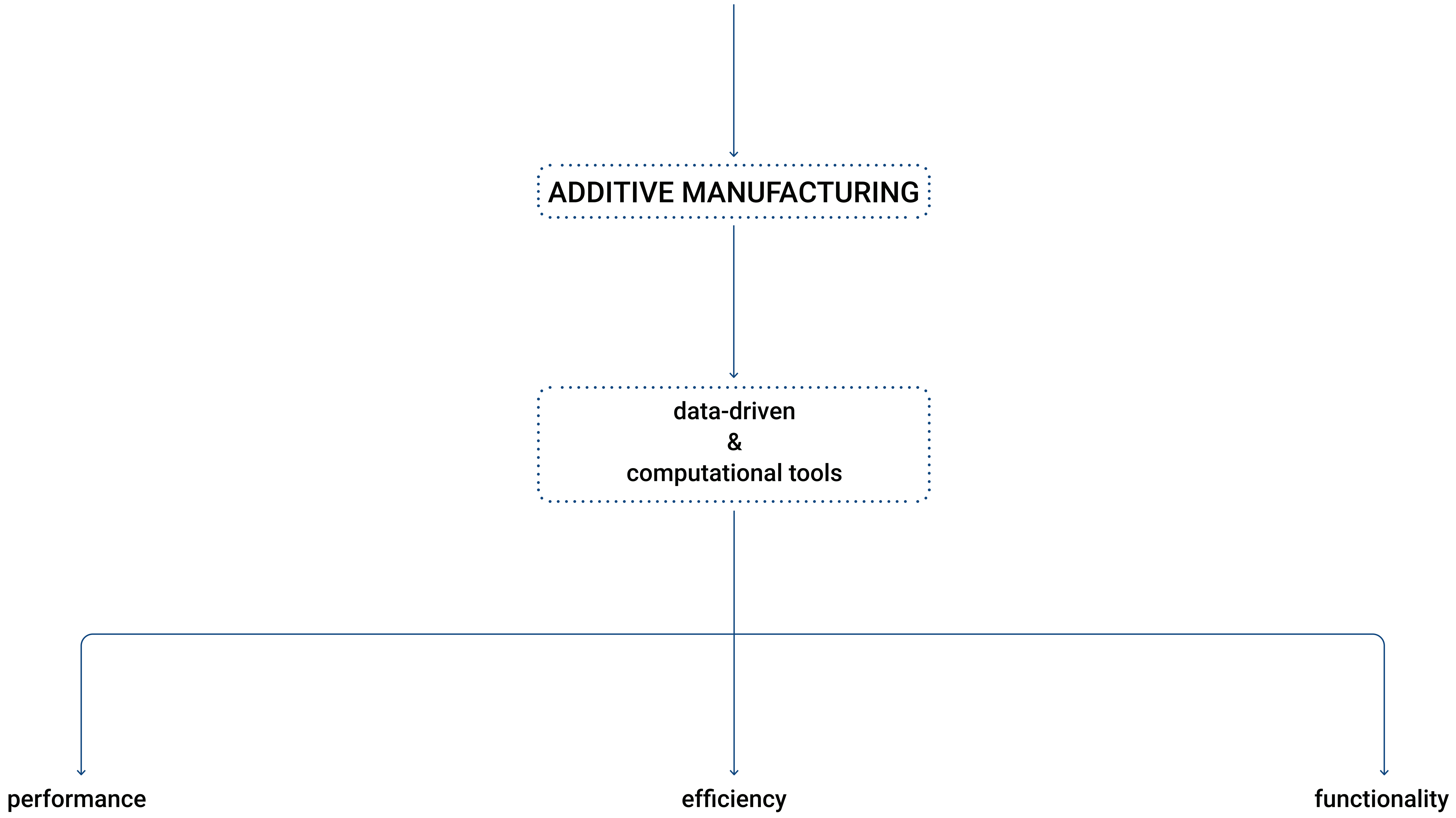


DESIGN

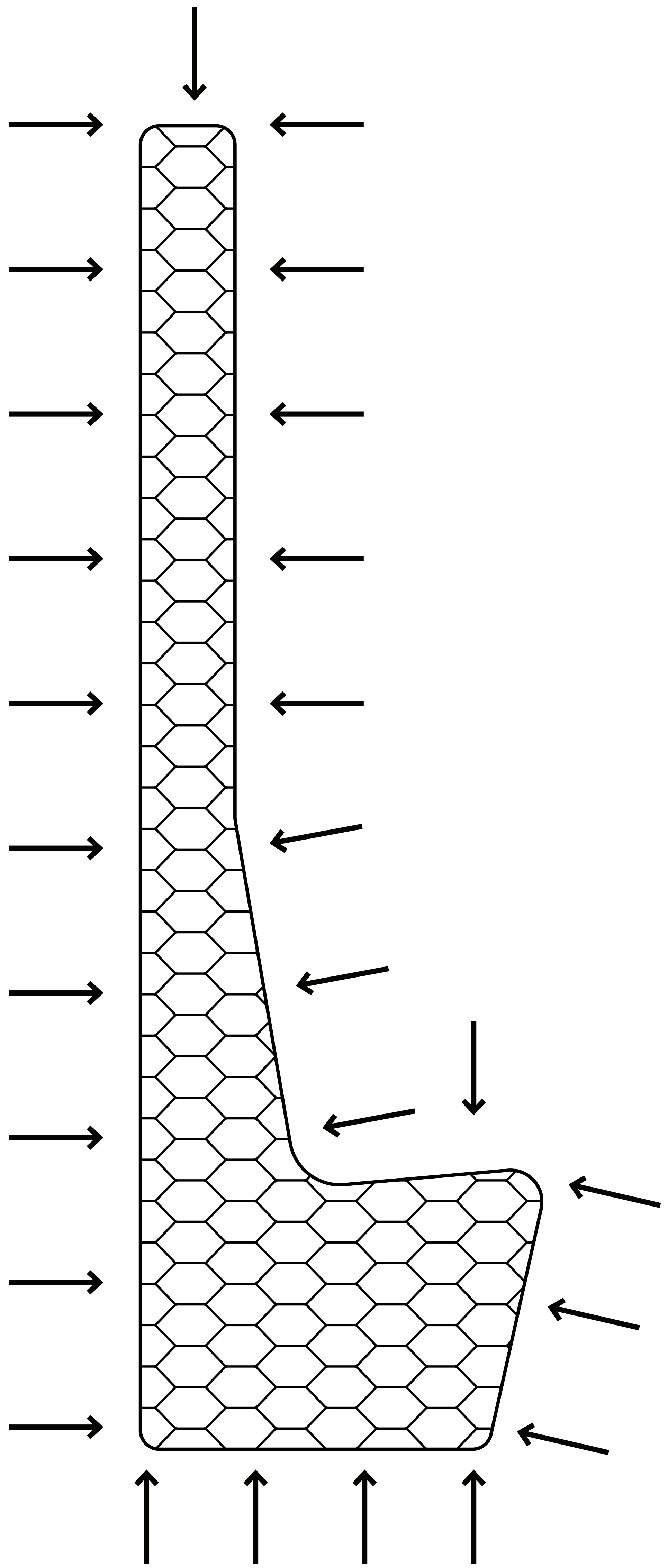


CONTENT

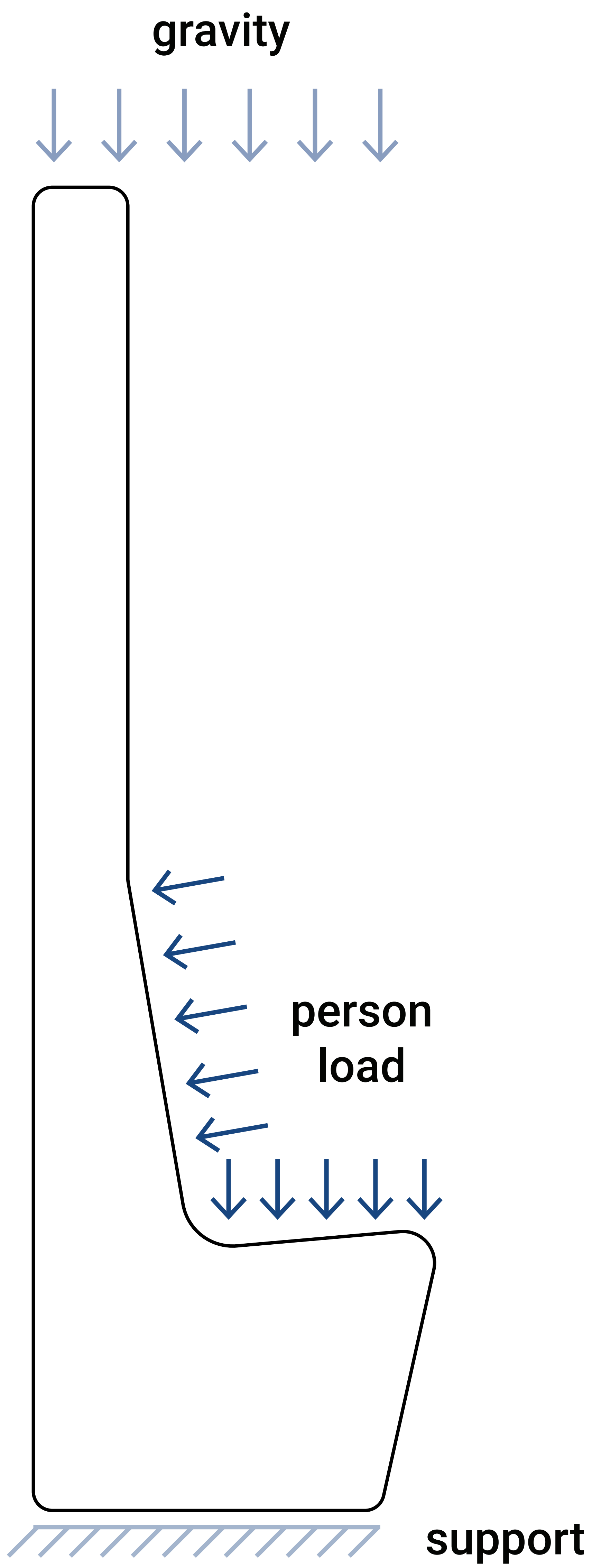
DESIGN OPTIMIZATION



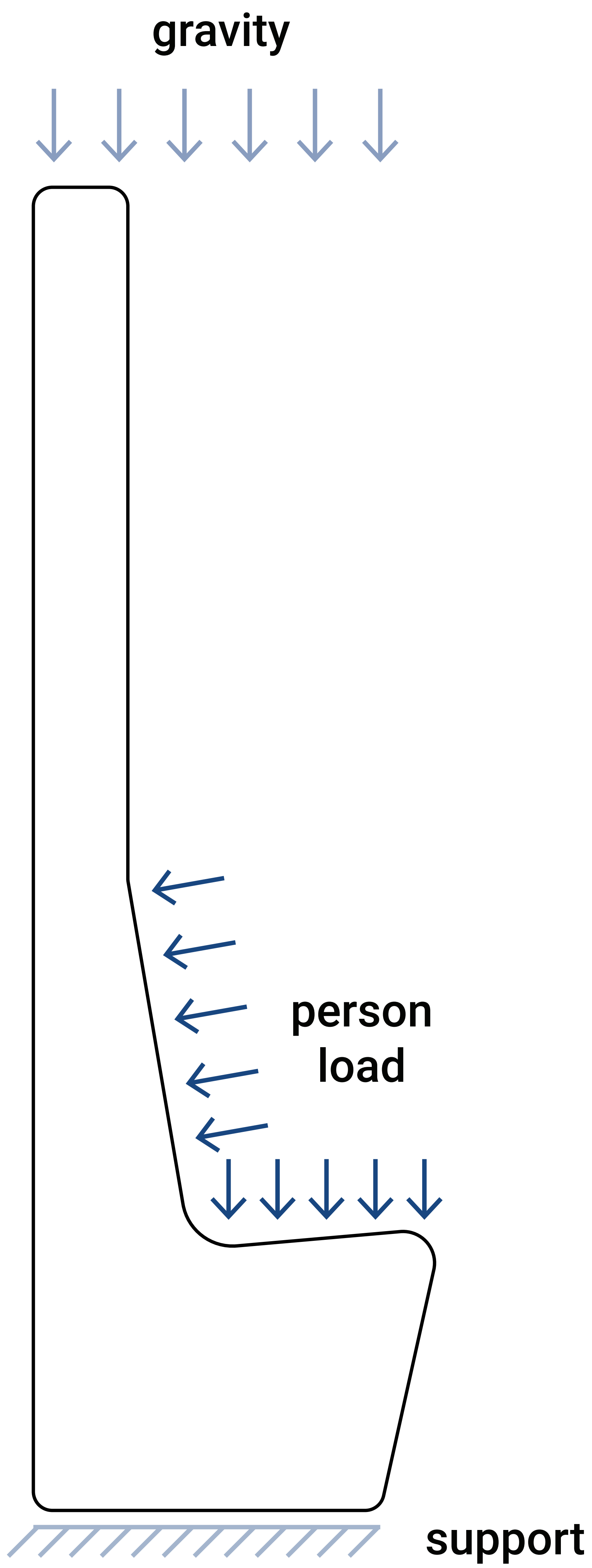
UNIFORMLY DISTRIBUTED LOADS

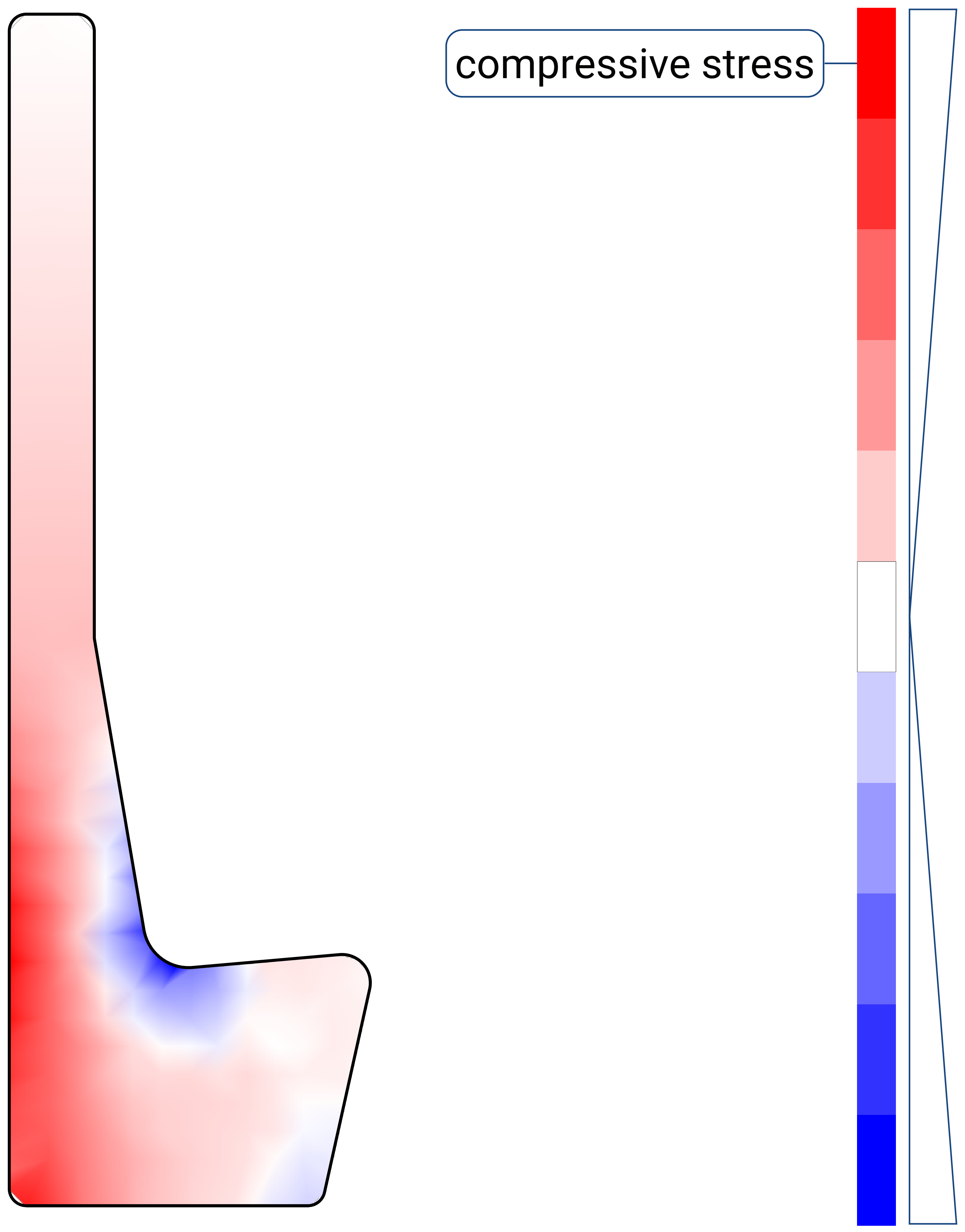


LOAD CASE



LOAD CASE





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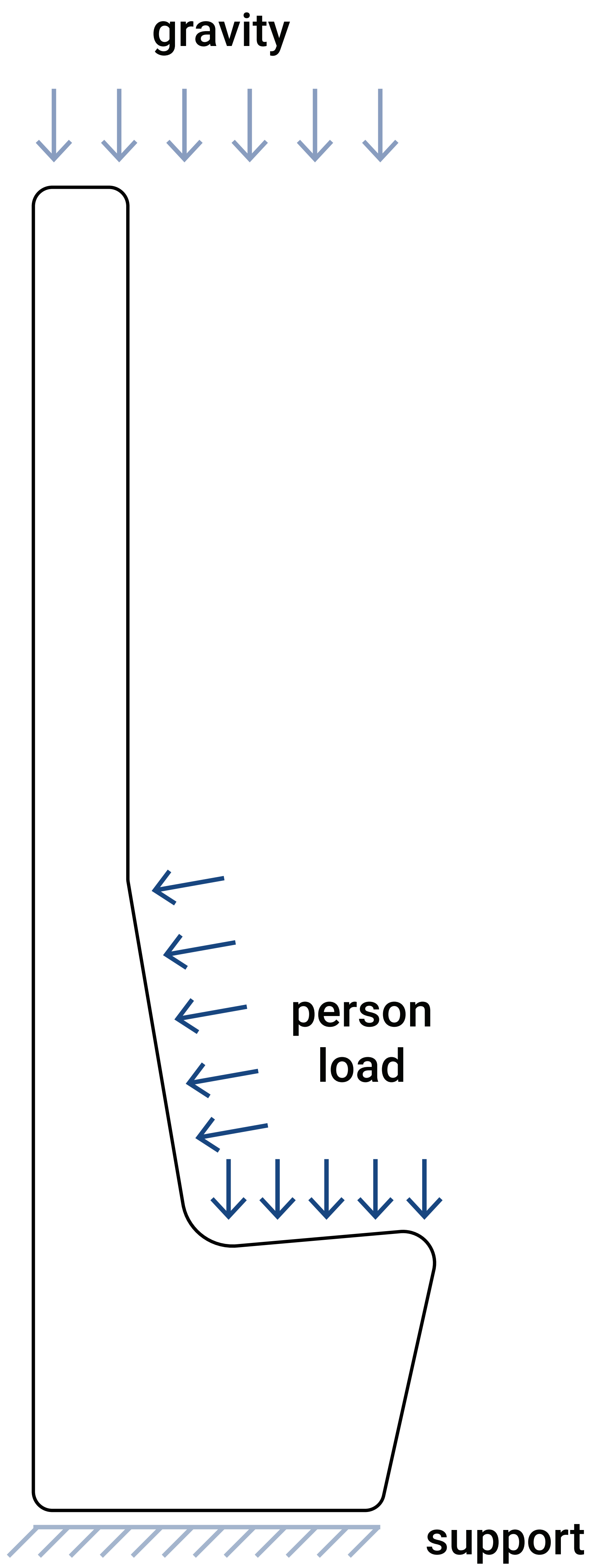
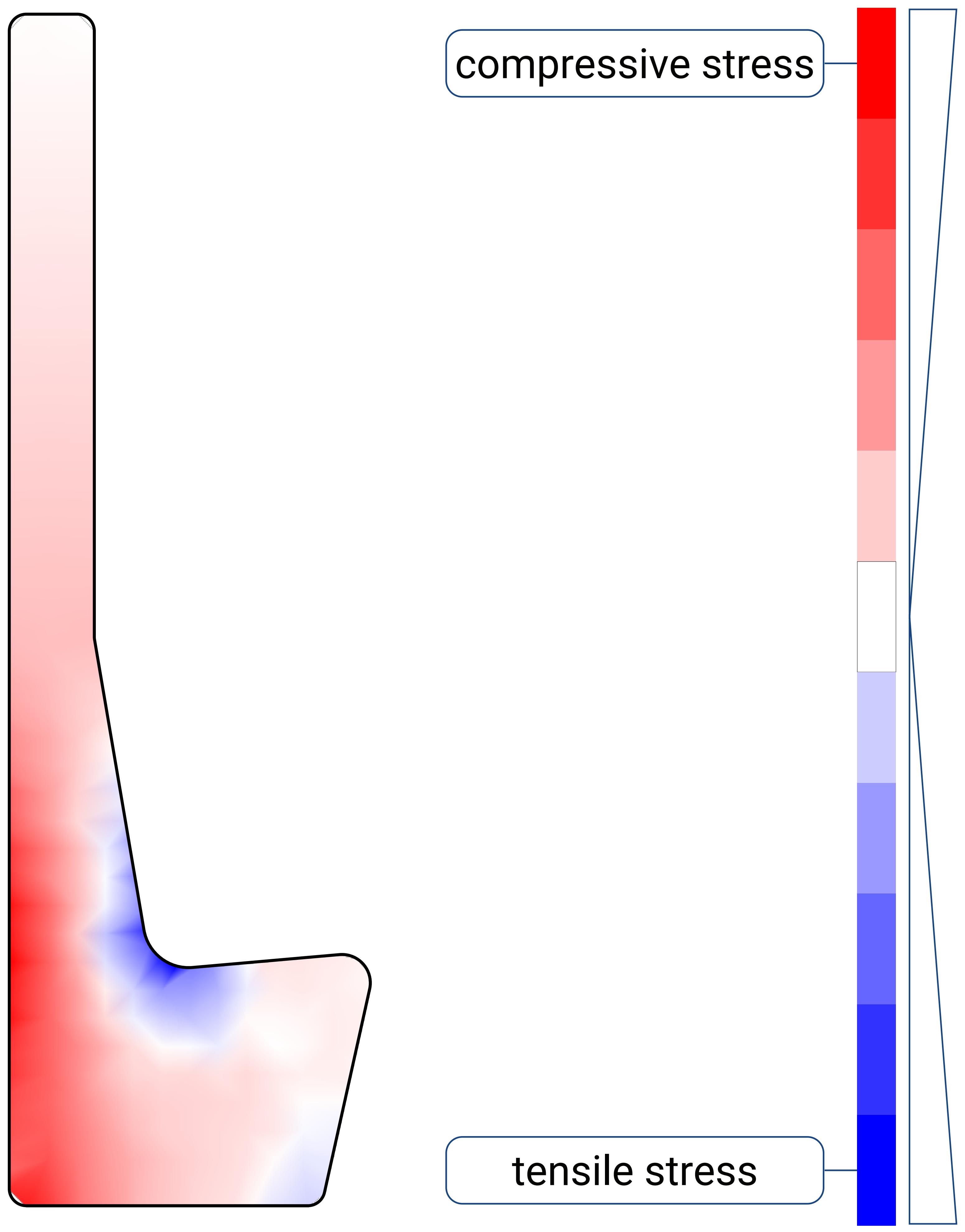
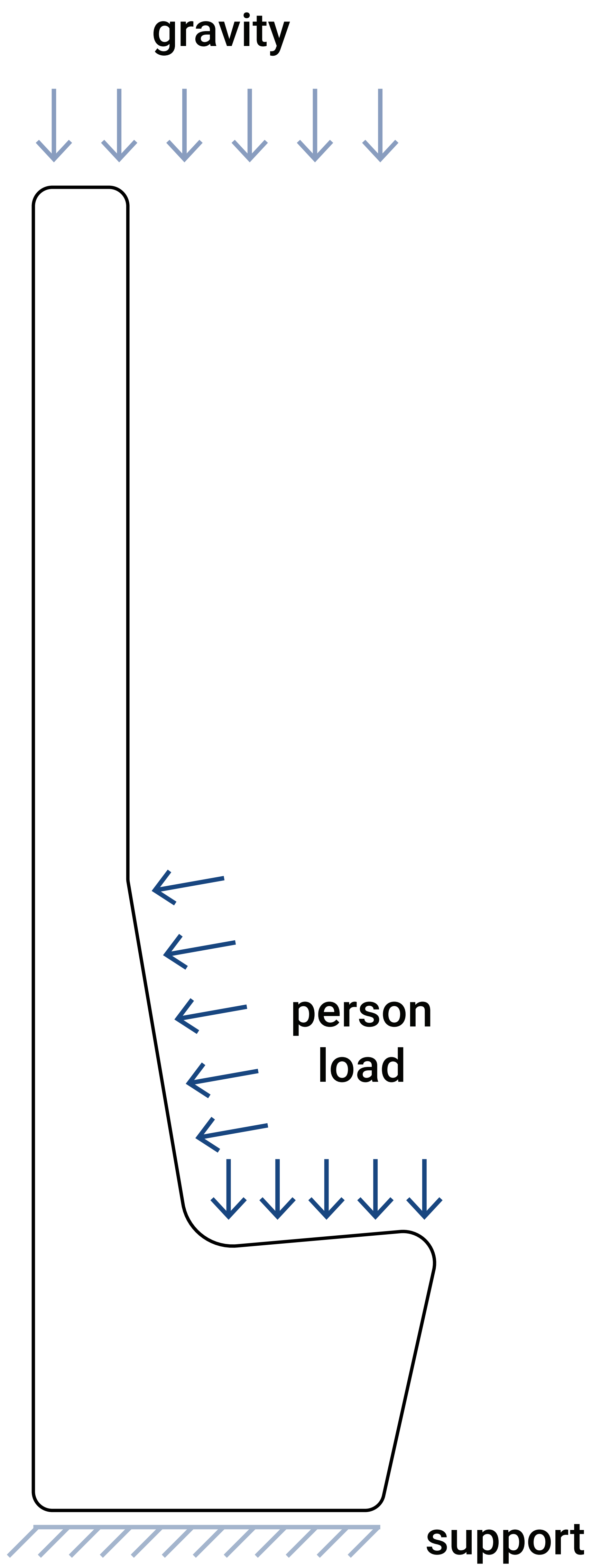
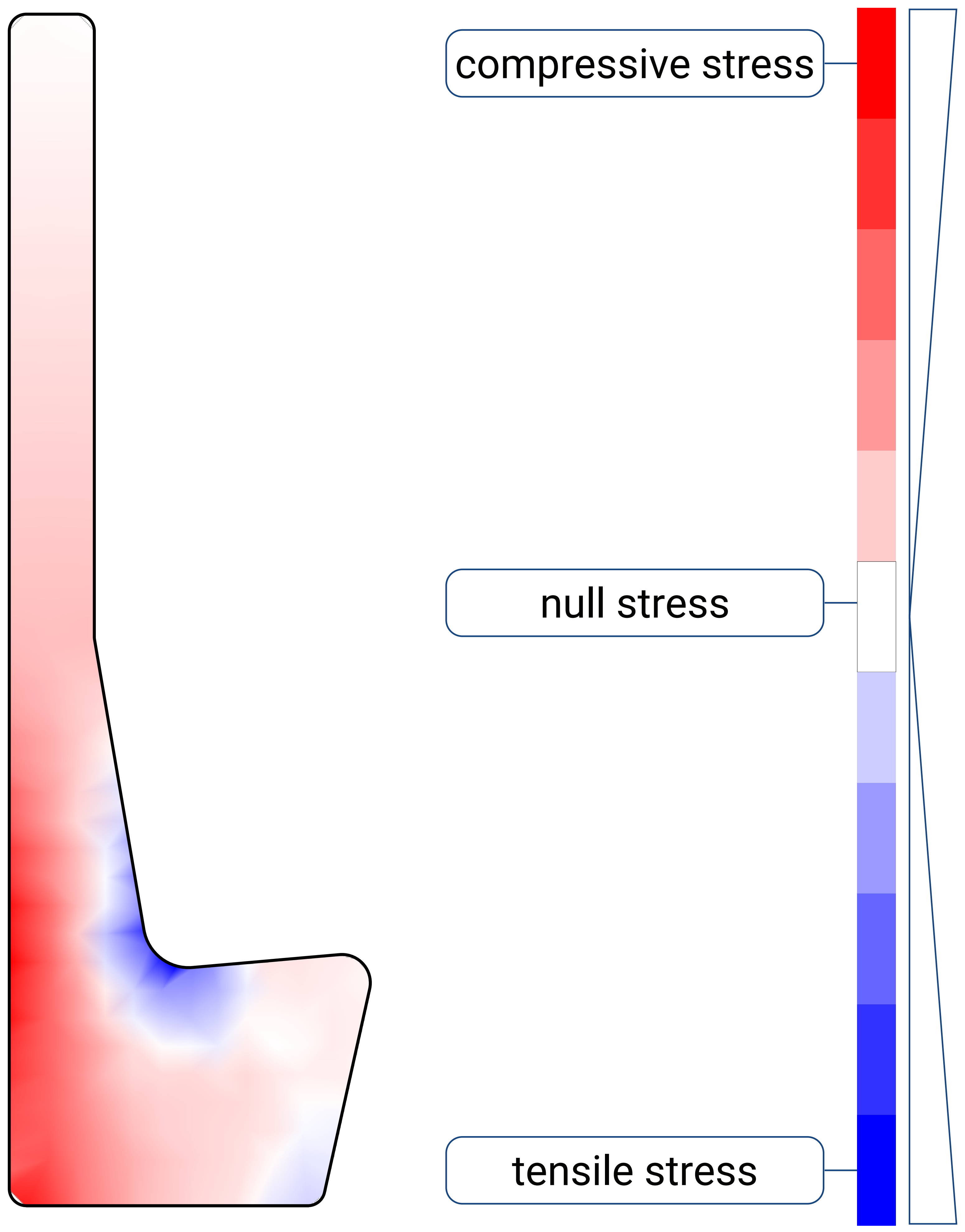

gravity
person
load
support


compressive stress
tensile stress

LOAD CASE

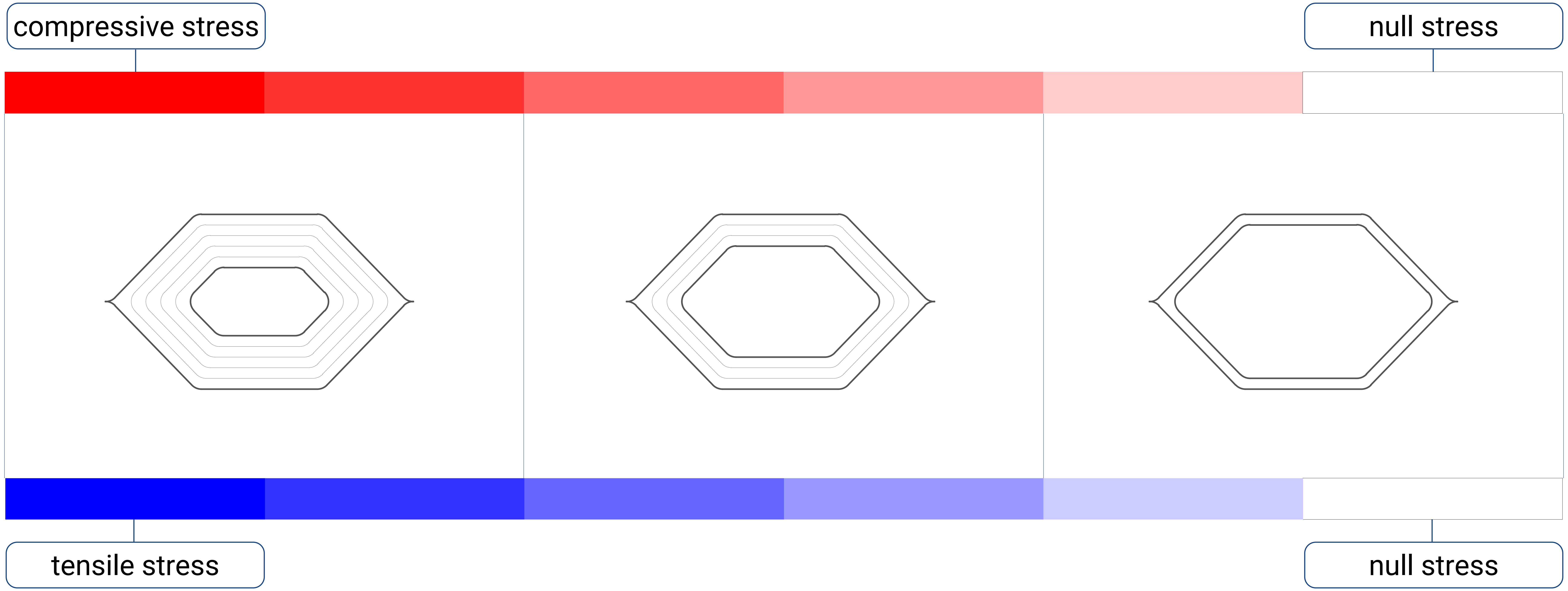

gravity
person
load
support


compressive stress
null stress
tensile stress

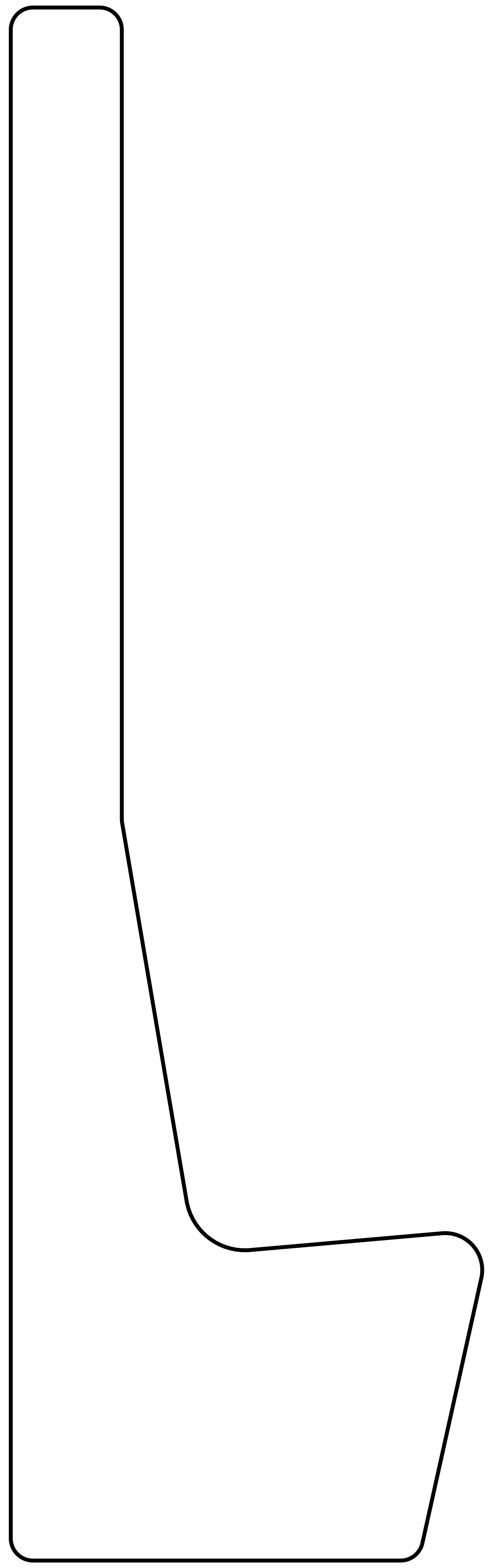
DESIGN GOAL

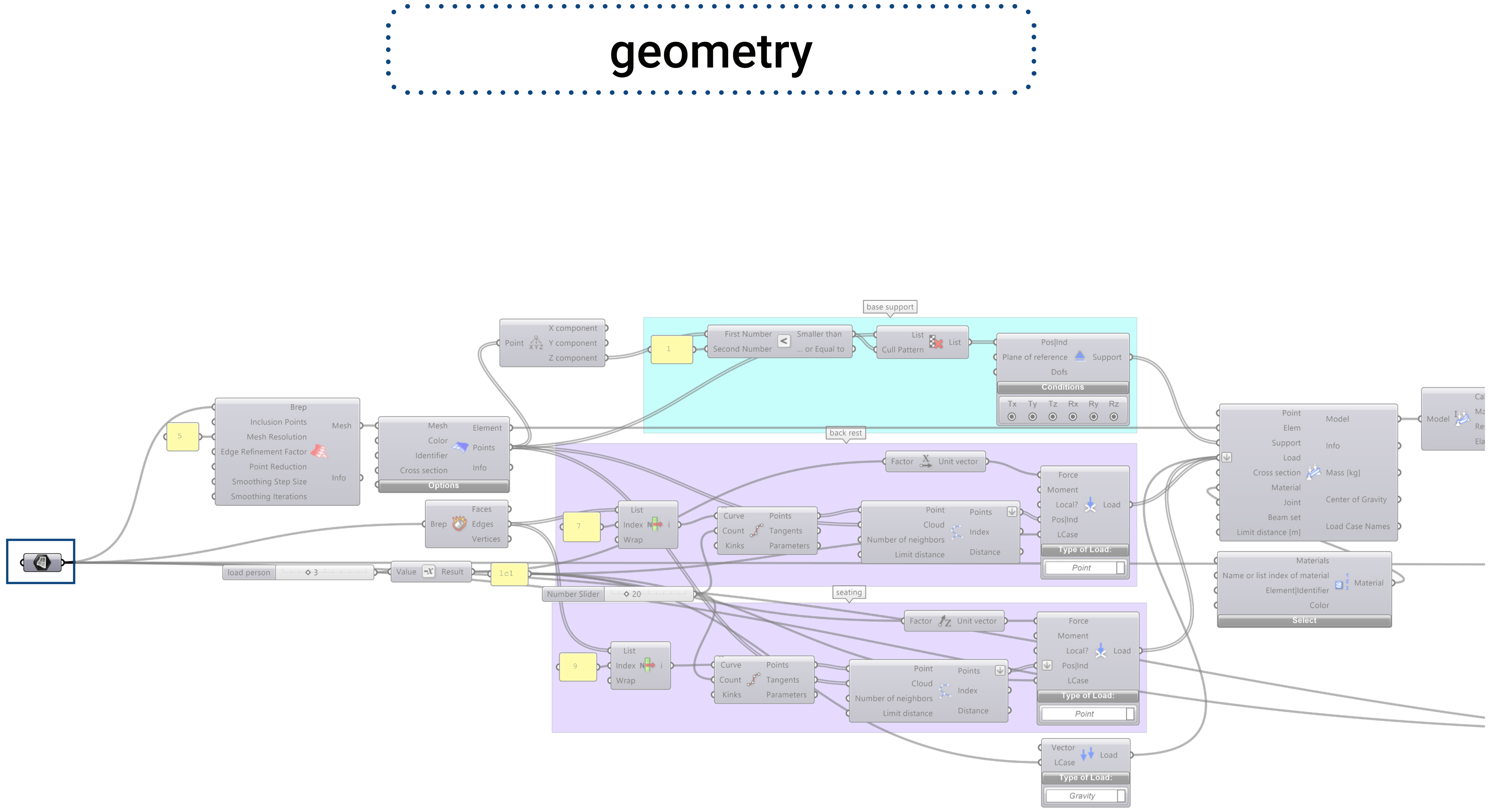
optimize the **use** of the **material** by
creating a **mechanically informed infill** tailored to the
loads on **specific parts** of component

VARIABLE THICKNESS



AUTOMATED MECHANICALLY INFORMED INFILL





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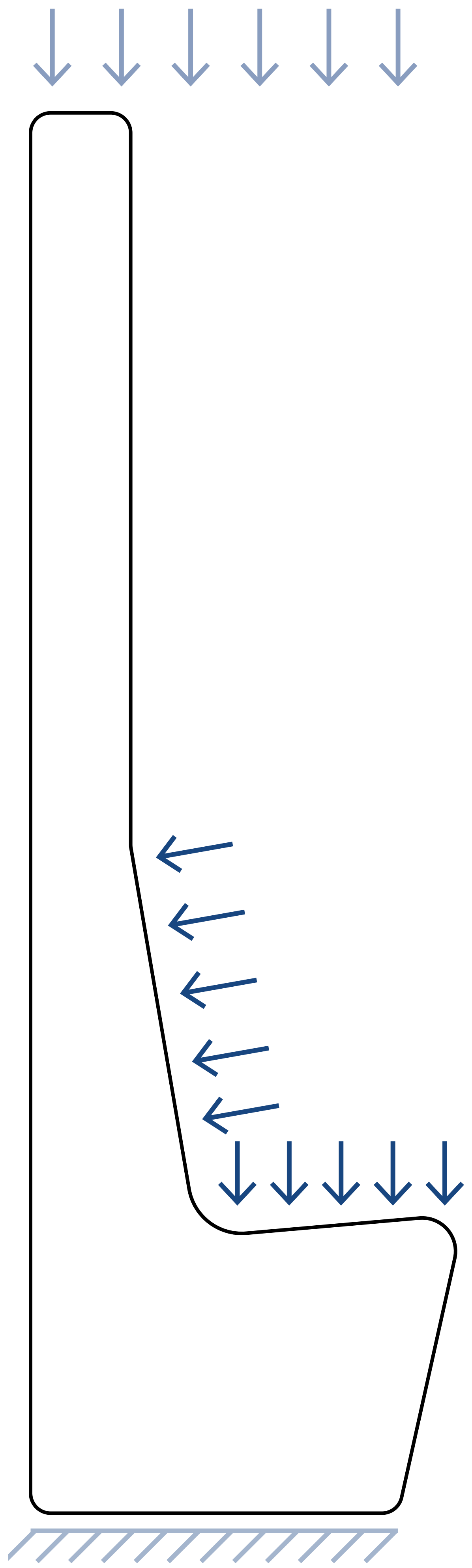
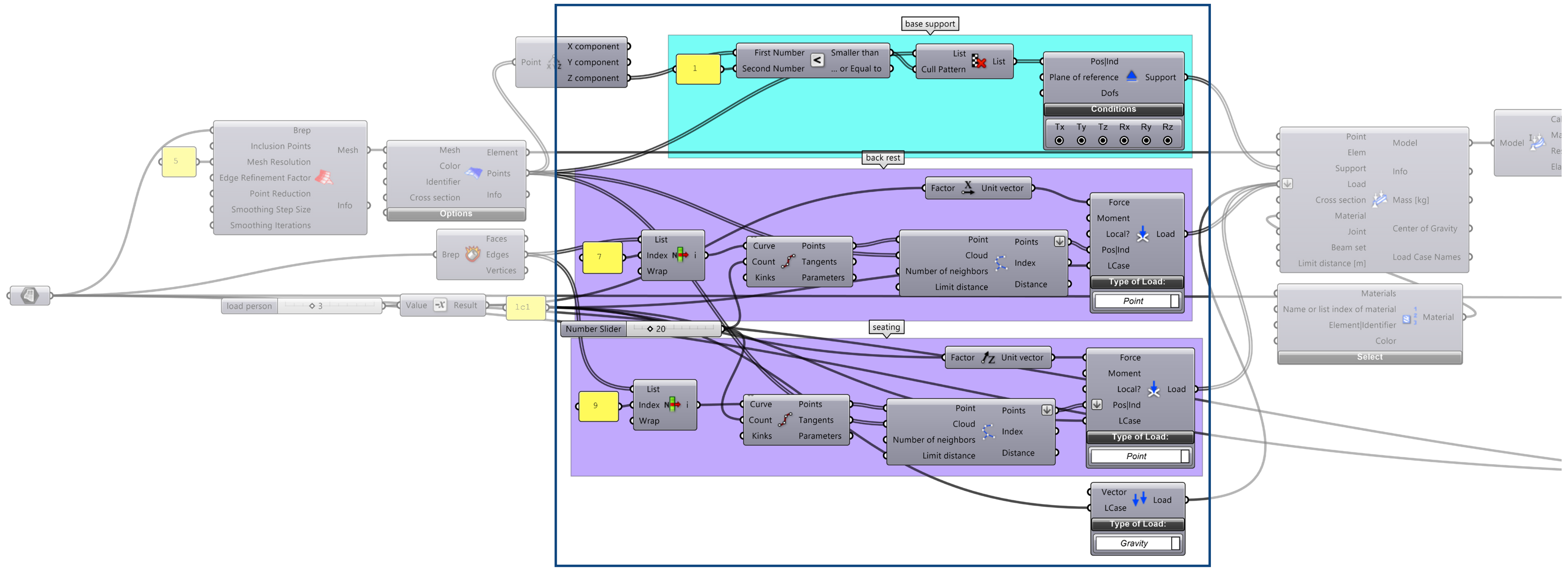


support and loads



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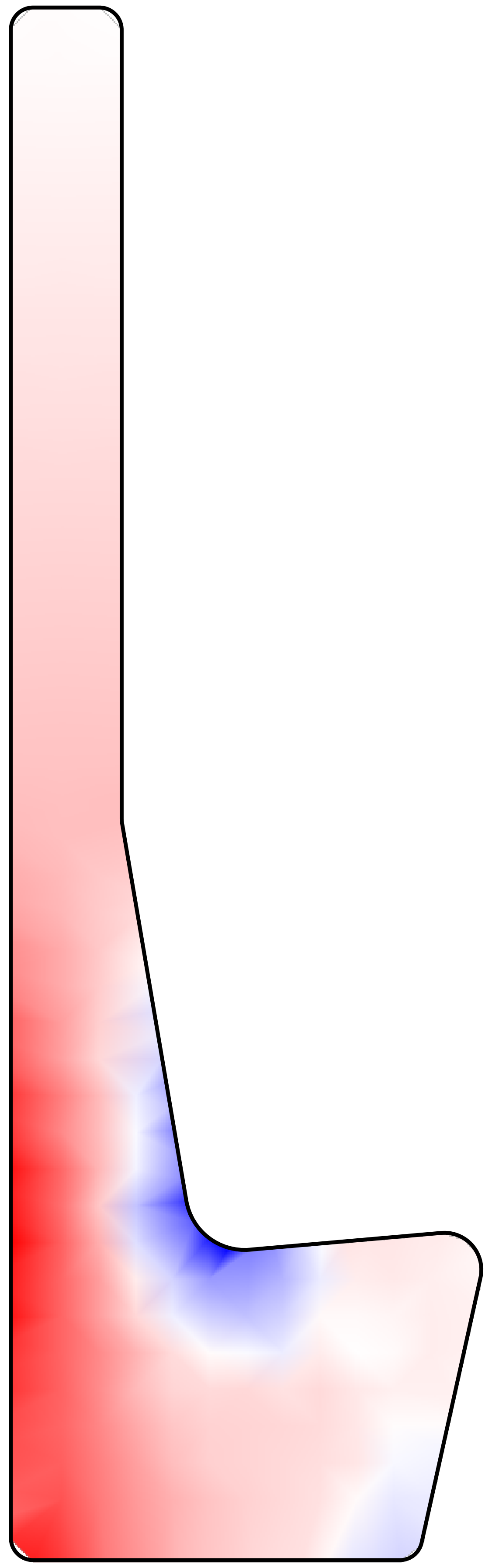
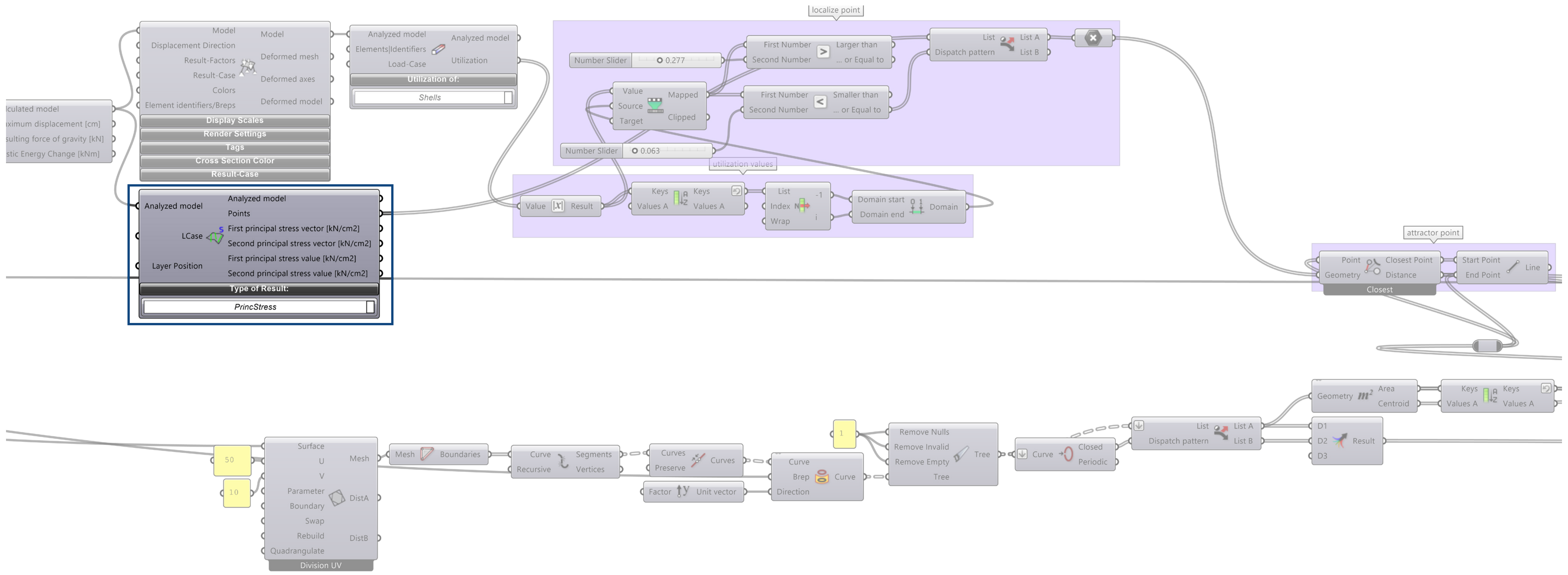
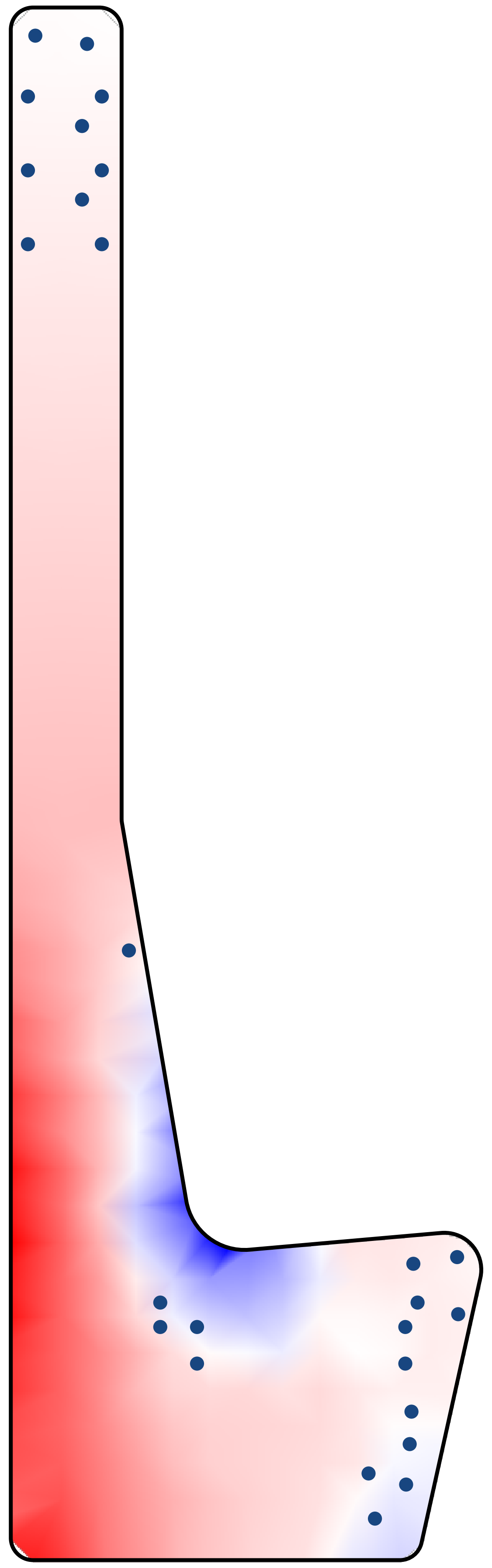


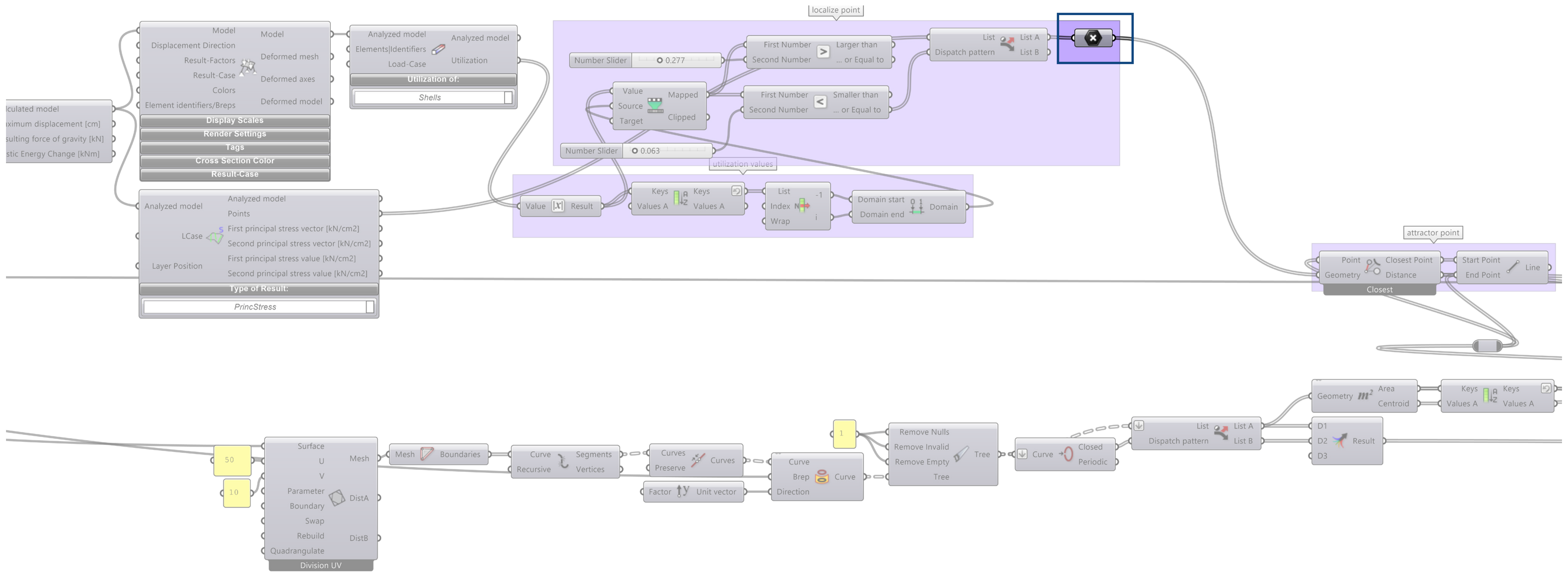
utilization



AUTOMATED MECHANICALLY INFORMED INFILL

attractor point





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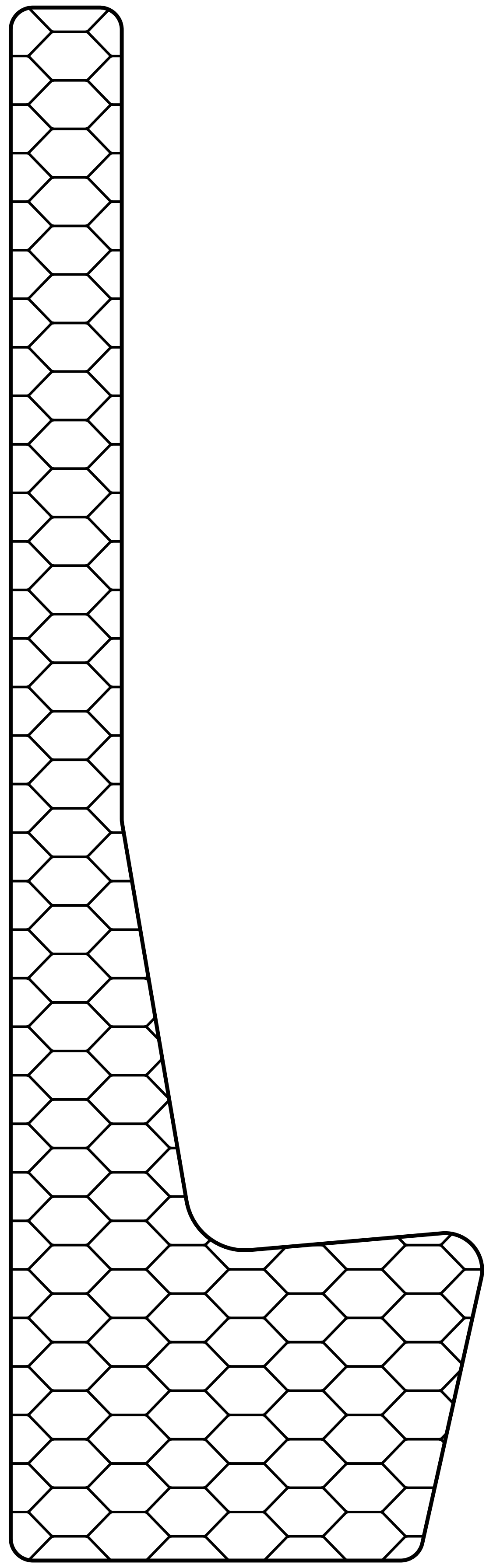
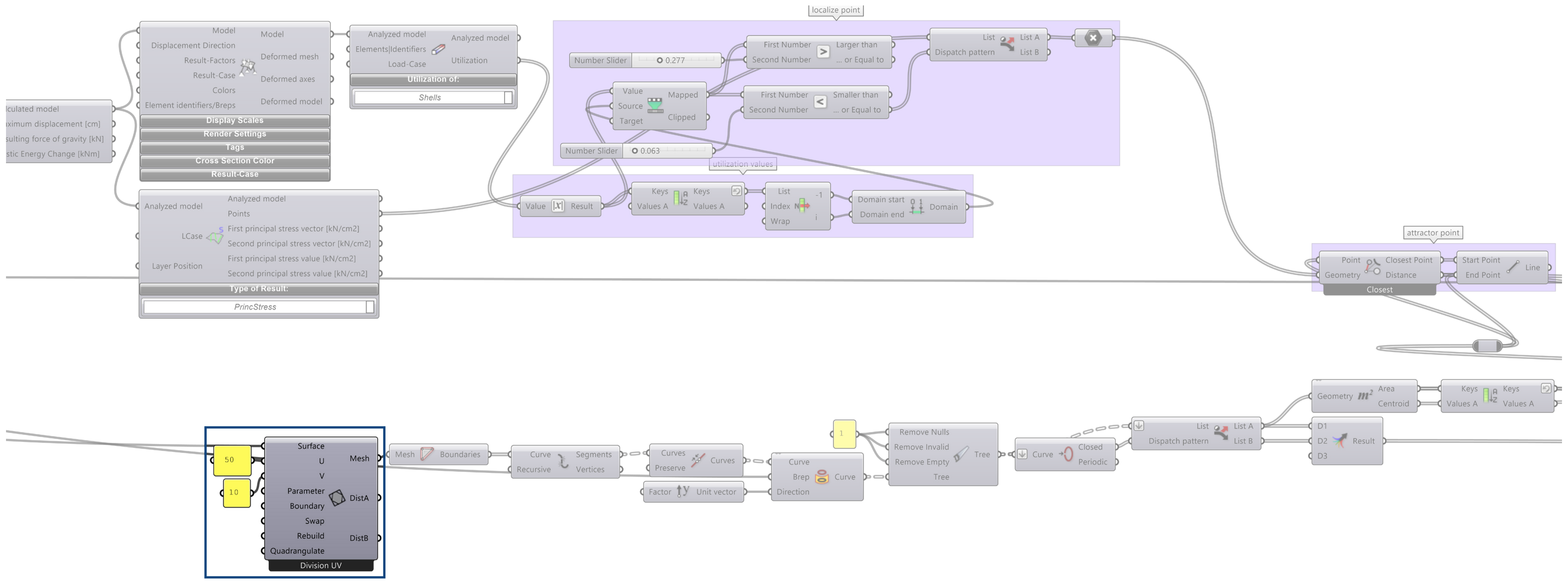
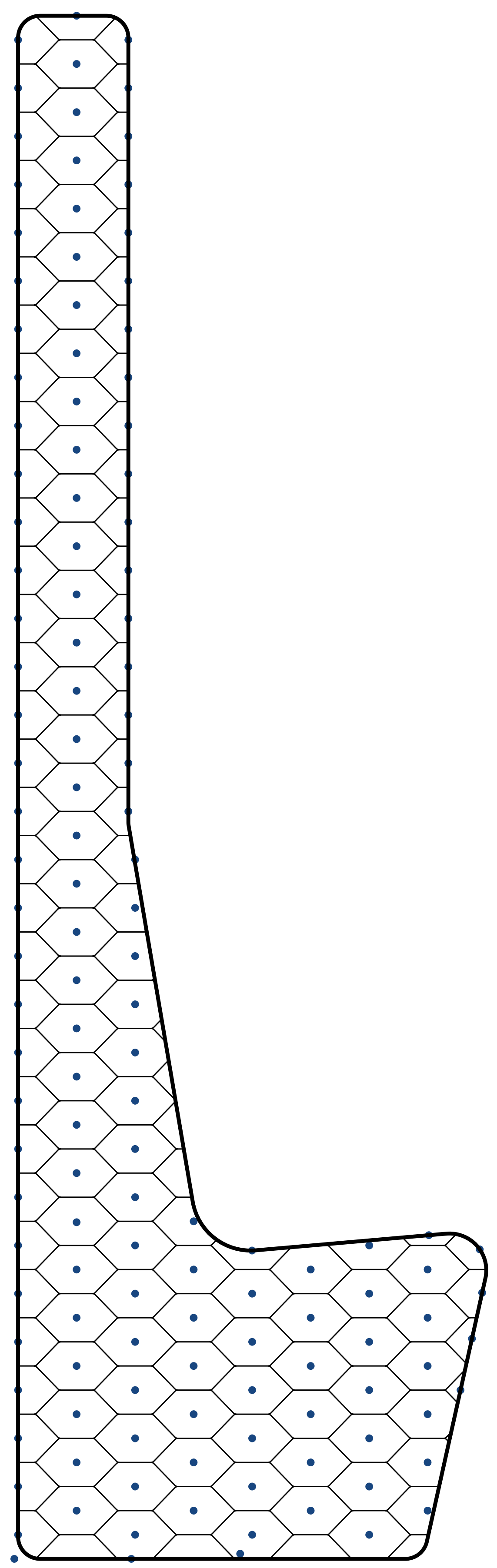


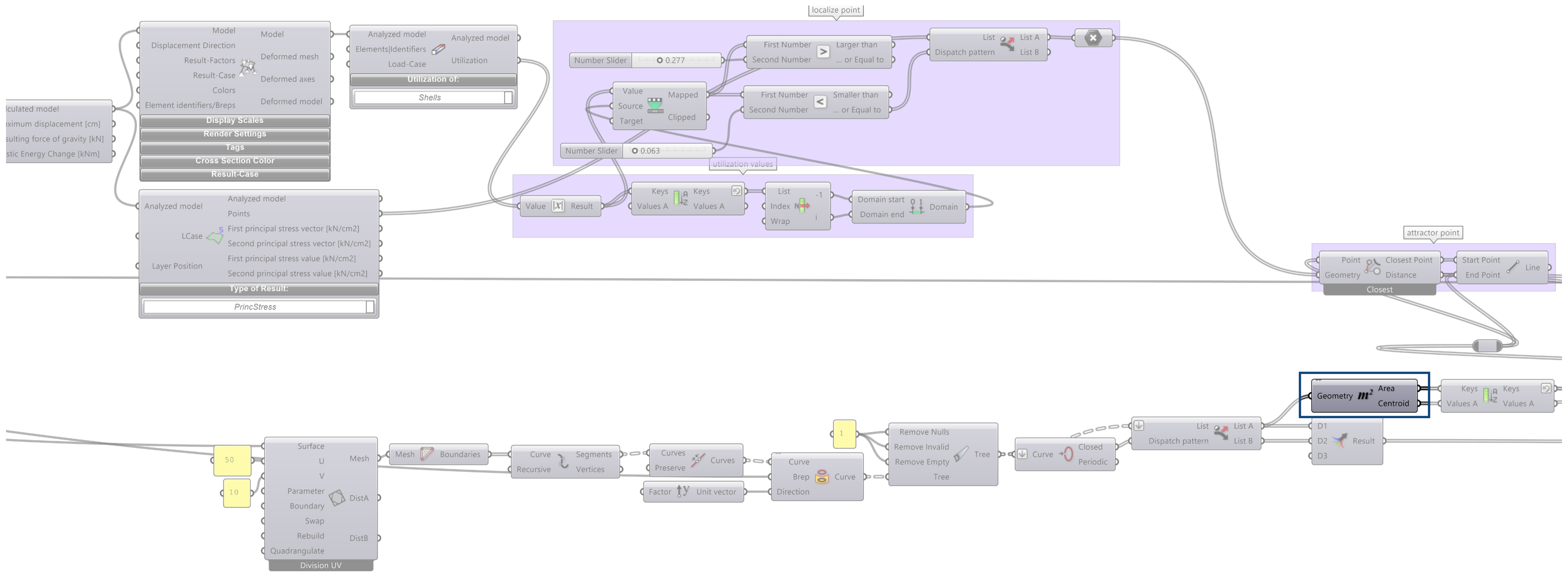
infill



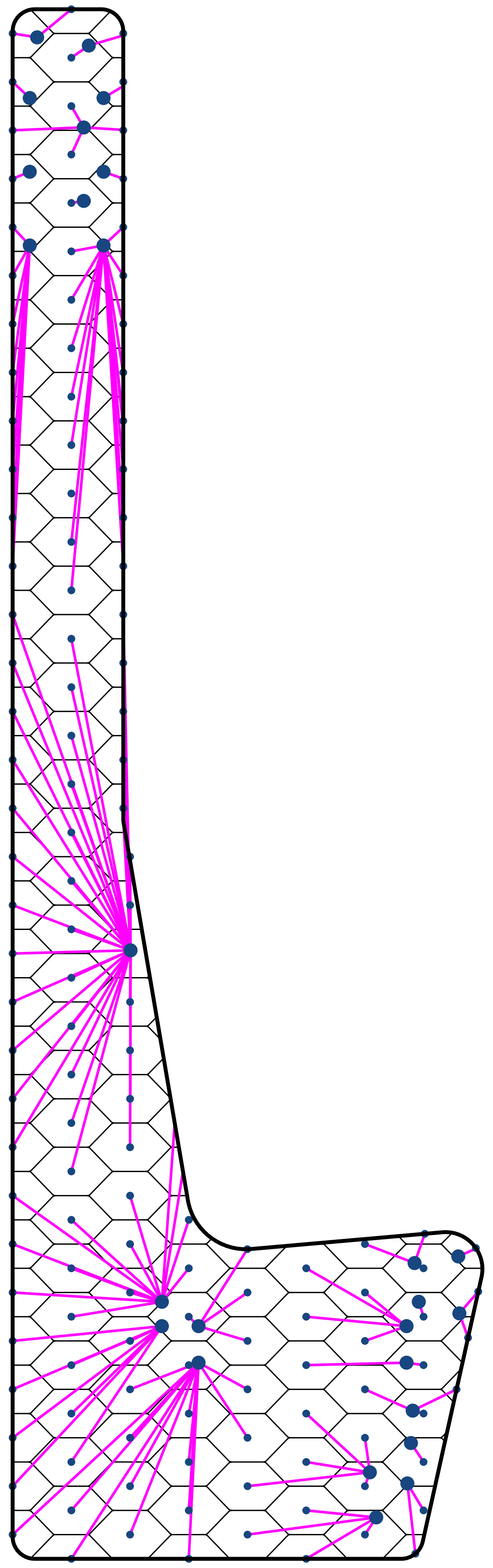
AUTOMATED MECHANICALLY INFORMED INFILL



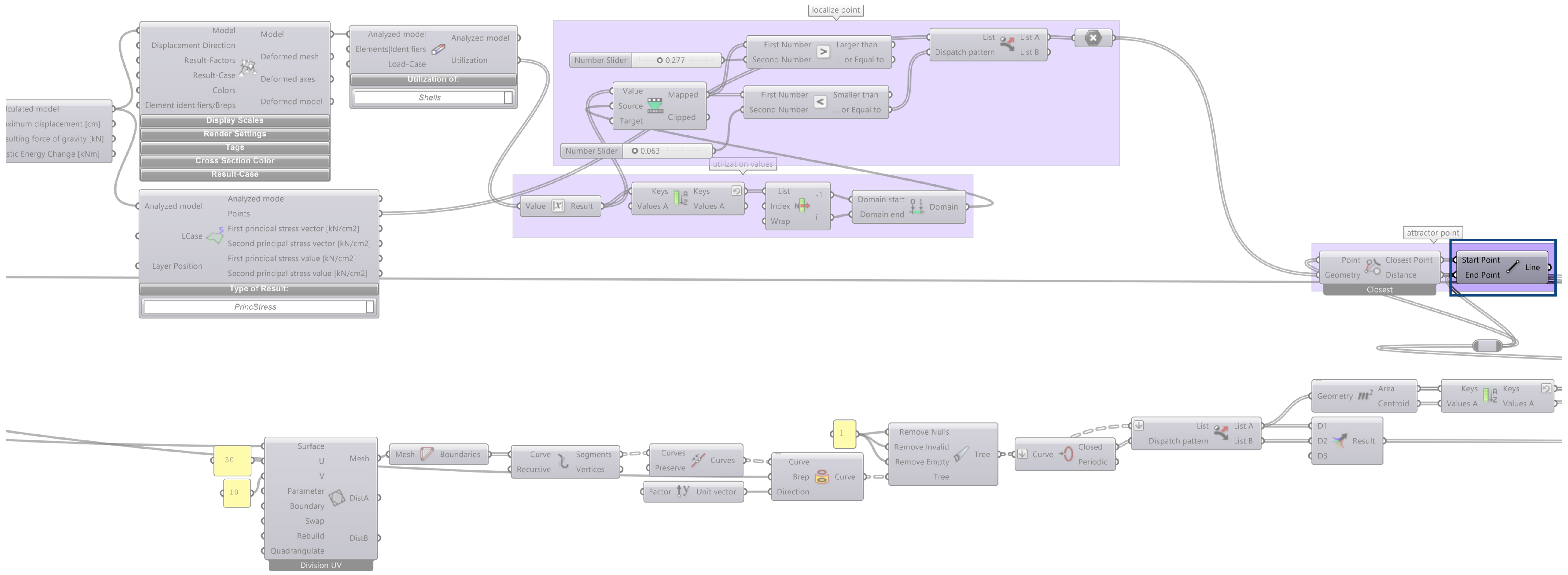
centroid



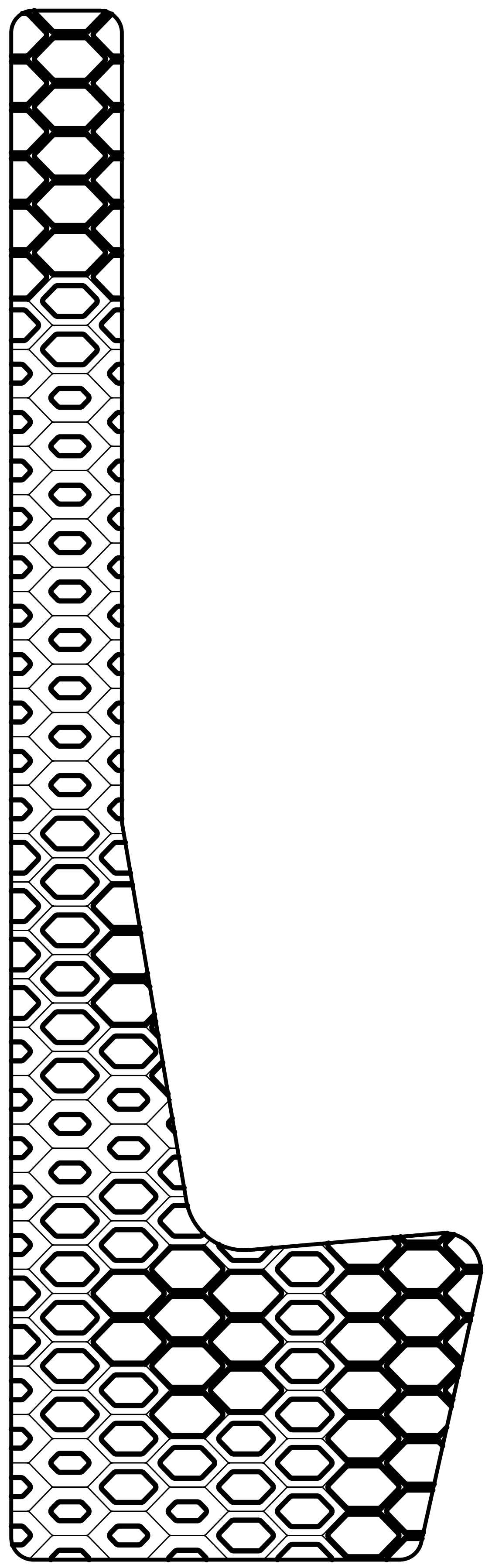
AUTOMATED MECHANICALLY INFORMED INFILL



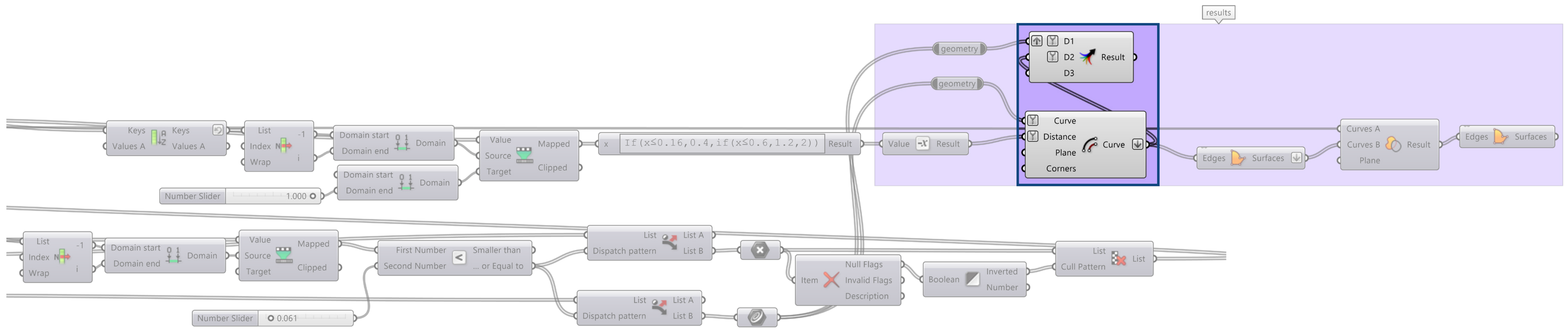
distance



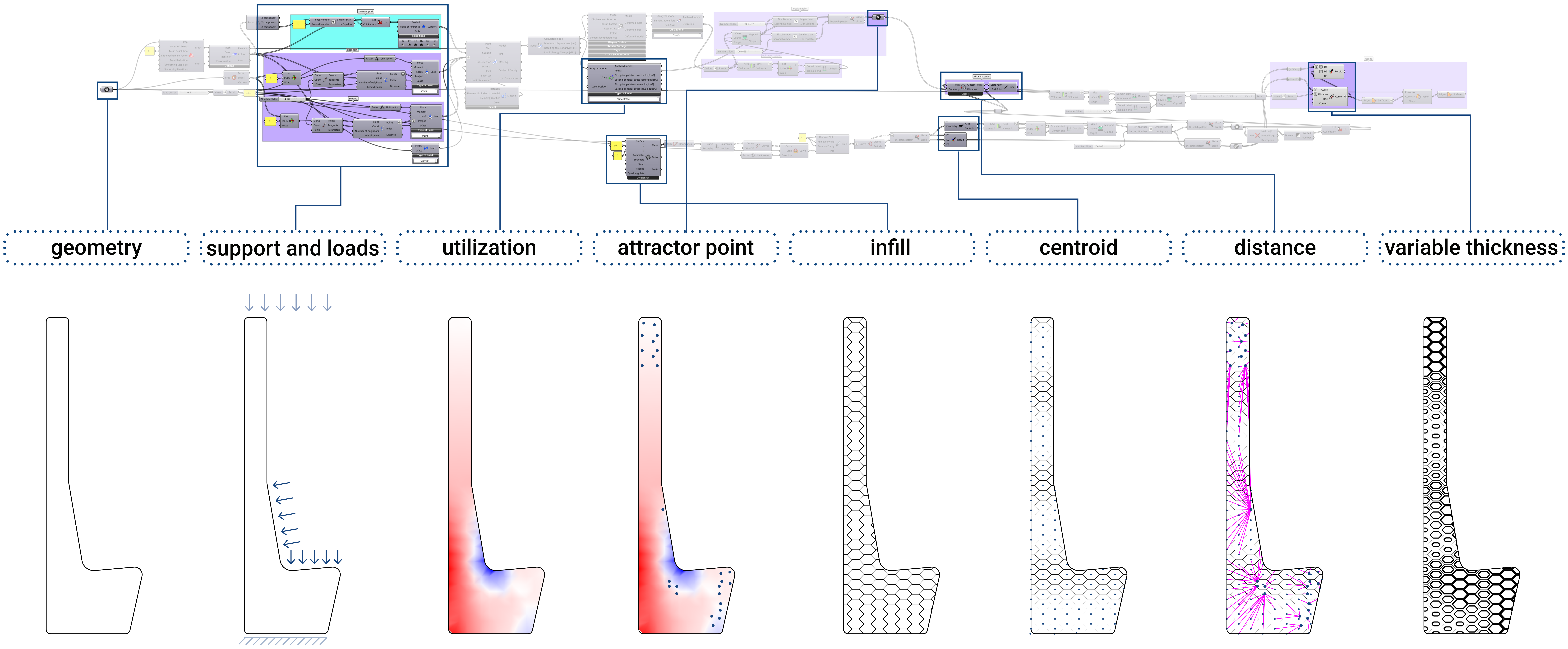
AUTOMATED MECHANICALLY INFORMED INFILL



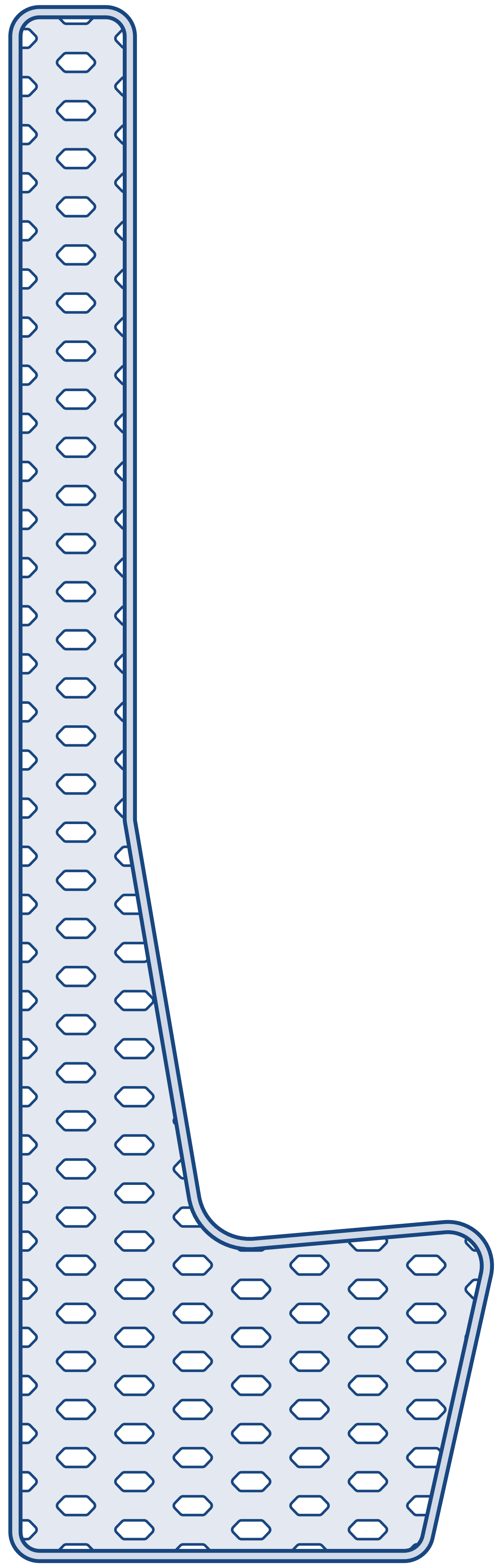
variable thickness



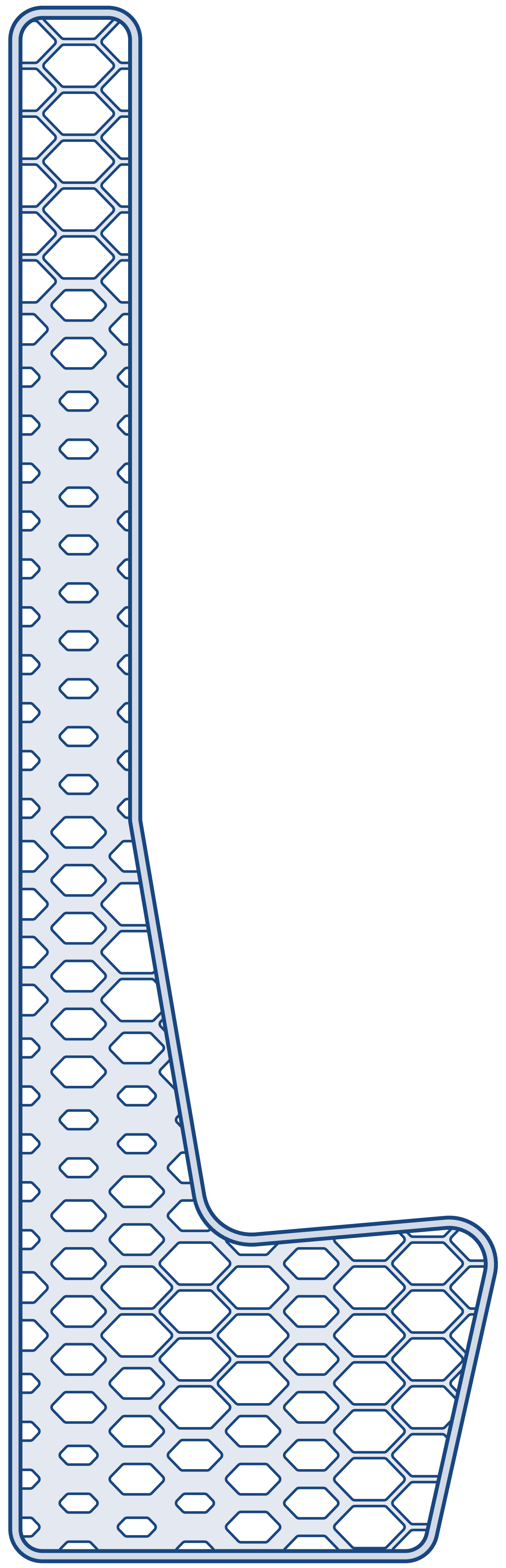
SCRIPT VERSATILITY



HOMOGENEOUS INFILL



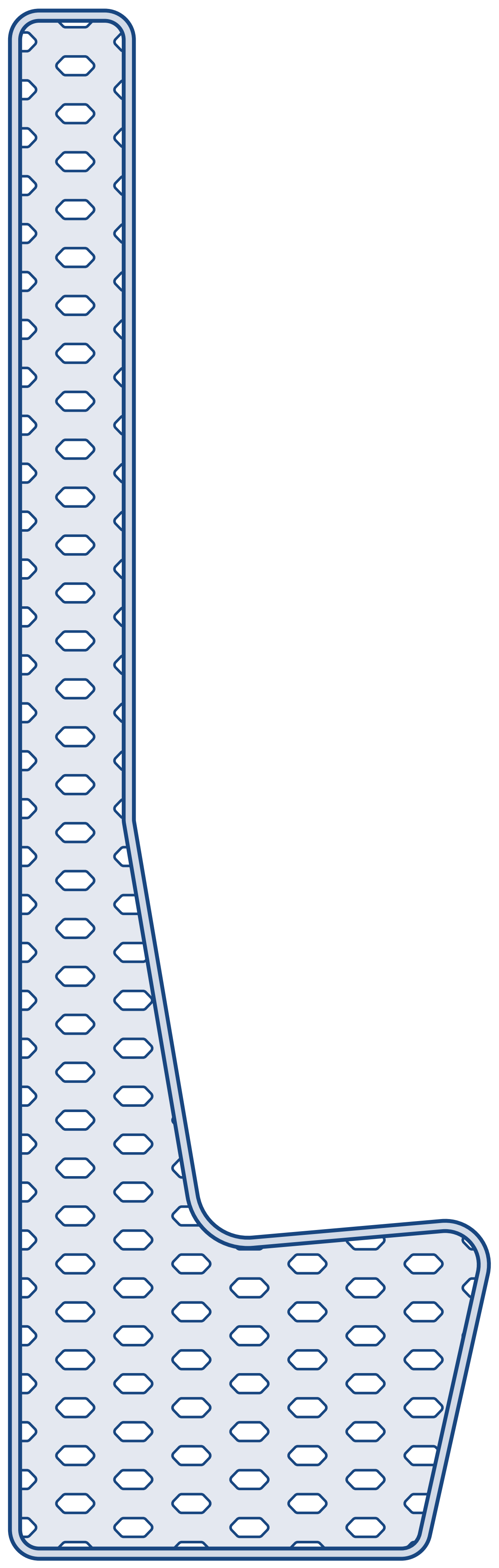
MECHANICALLY INFORMED INFILL

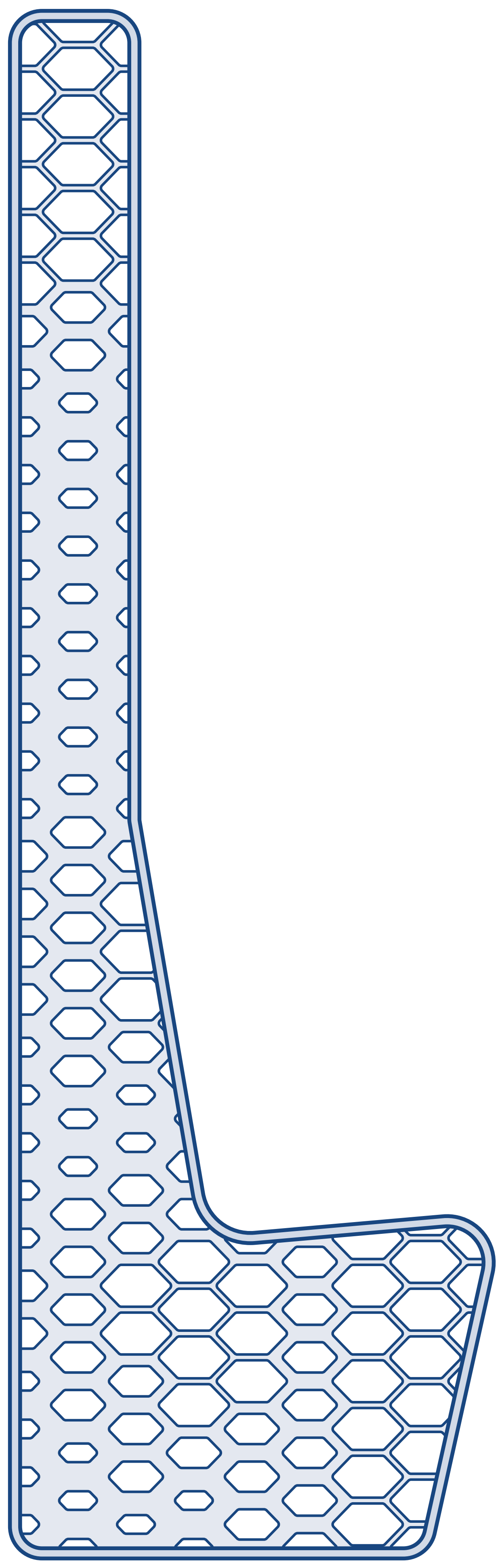


MATERIAL OPTIMIZATION

homogeneous infill

0,47 m²





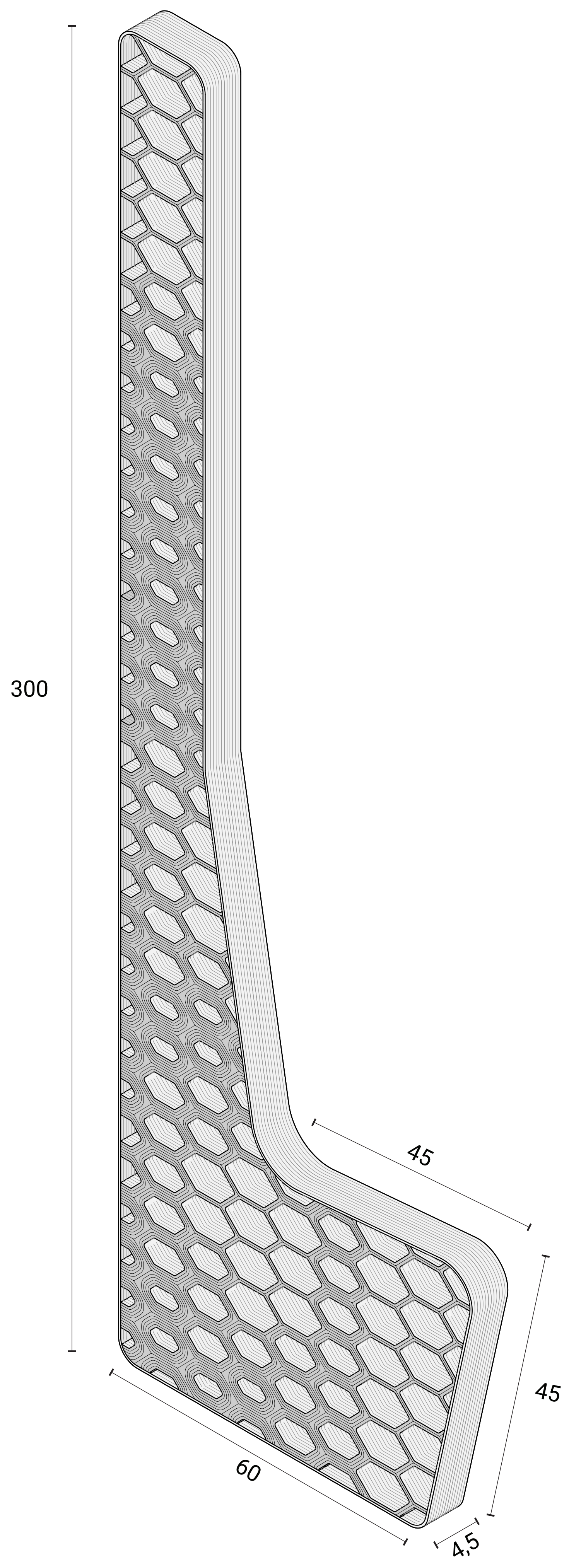
mechanically informed infill

0,34 m²

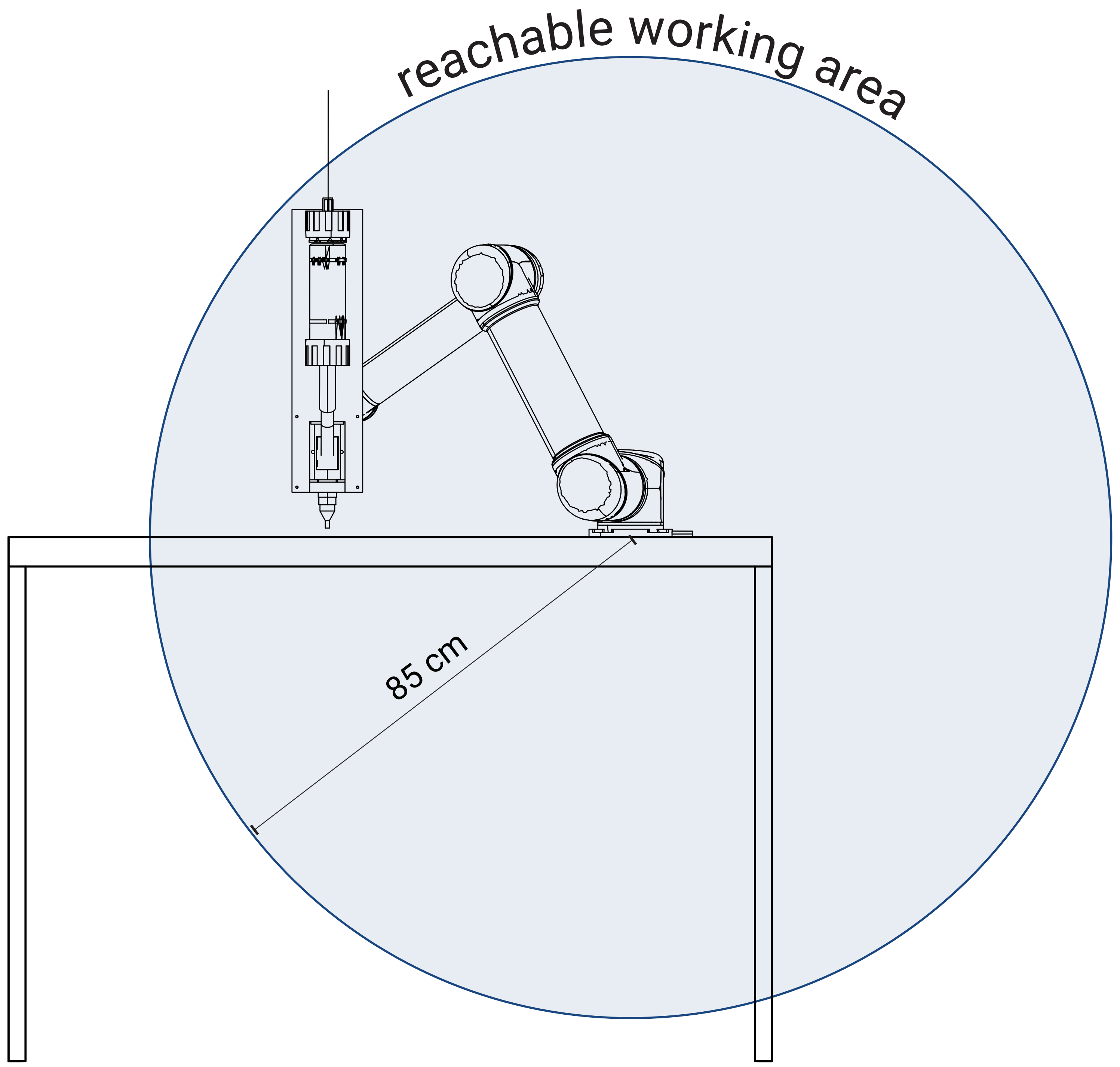
**- 32%
material used**

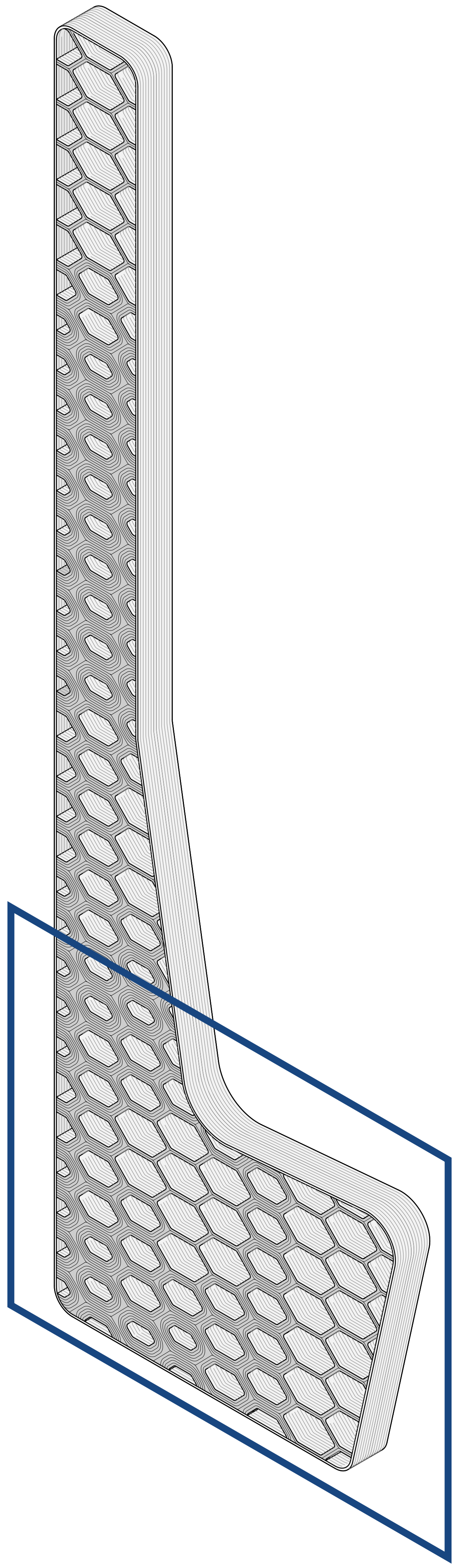
CONTENT

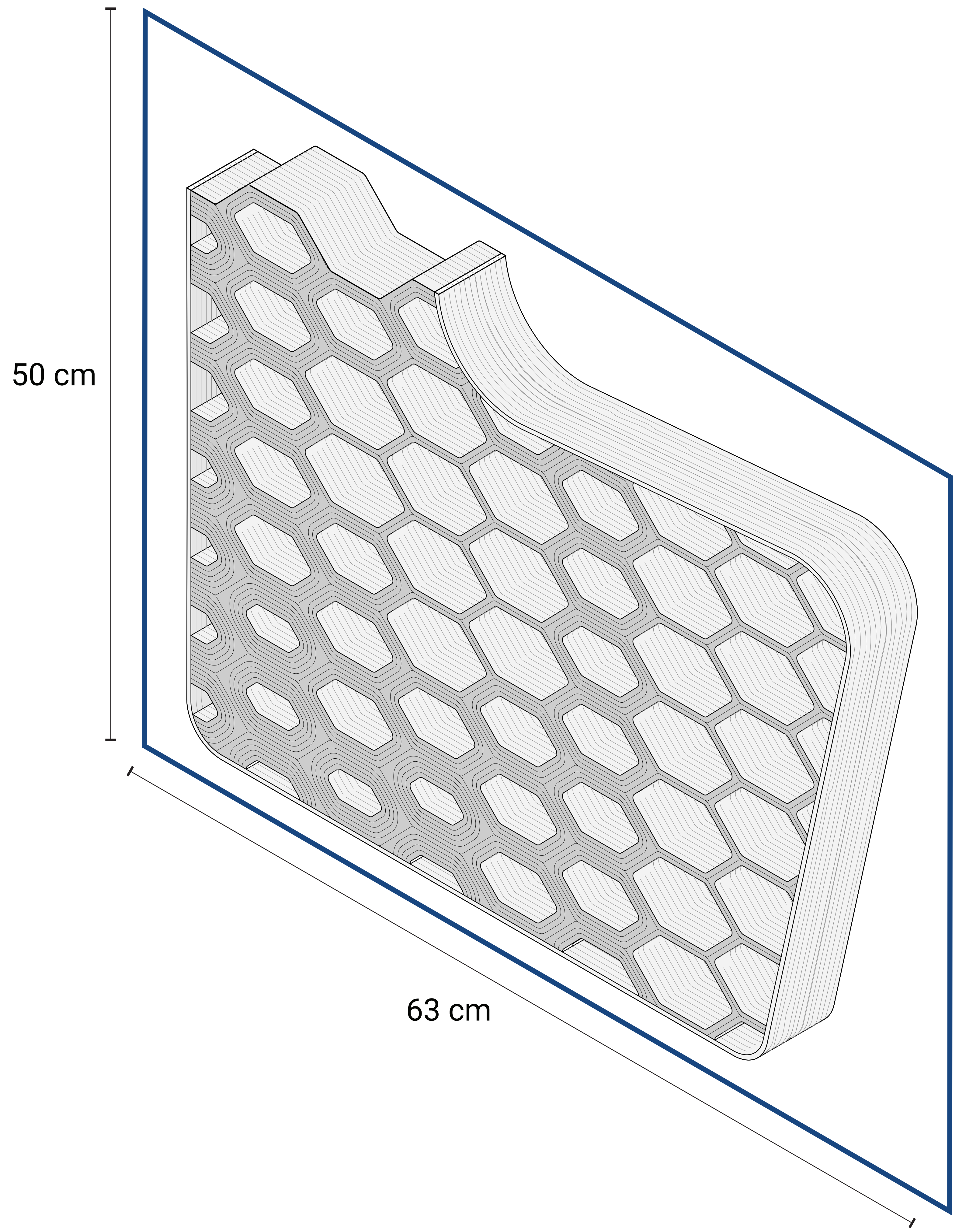
PROTOTYPE



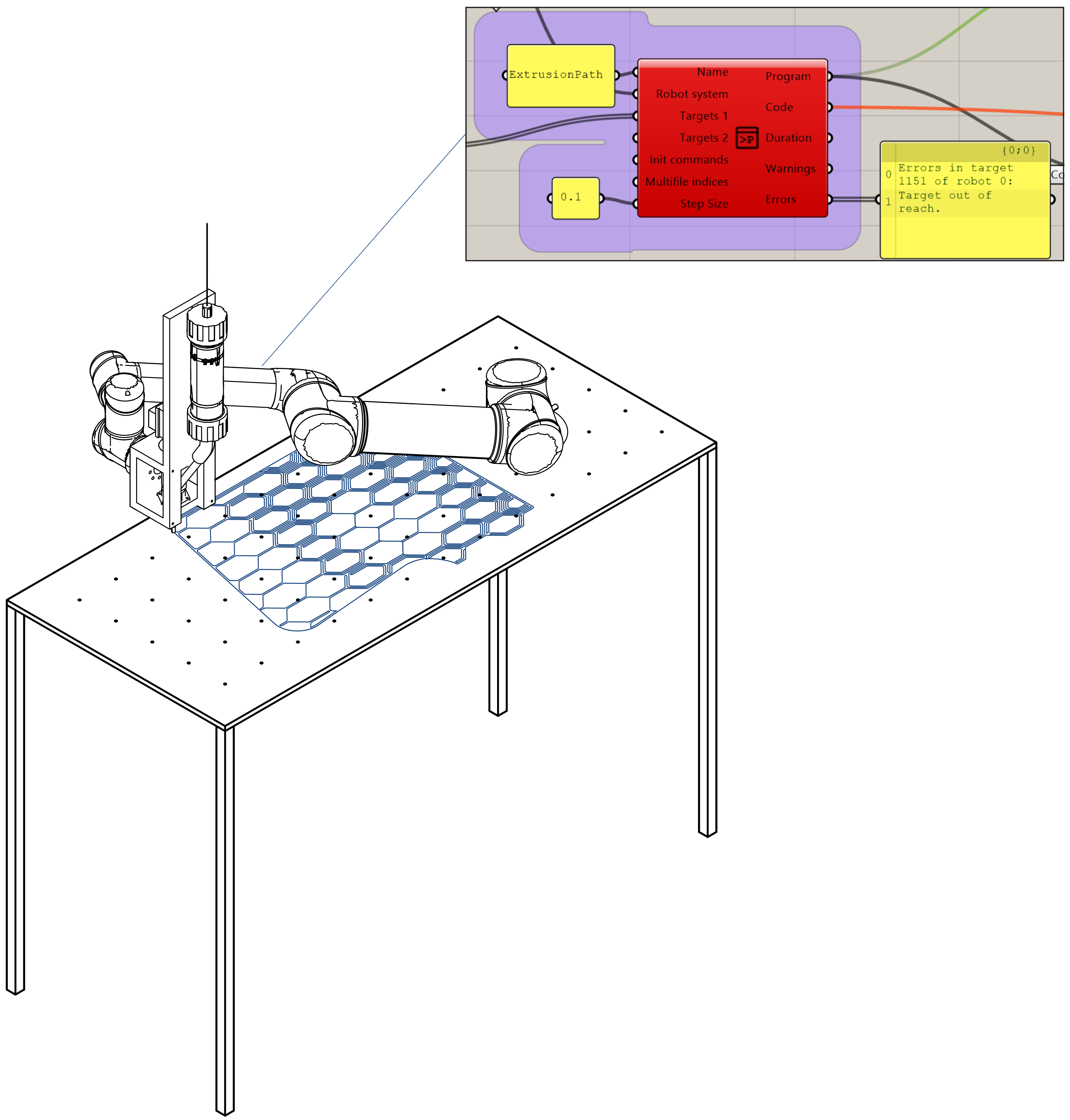
PROTOTYPE LIMITATIONS

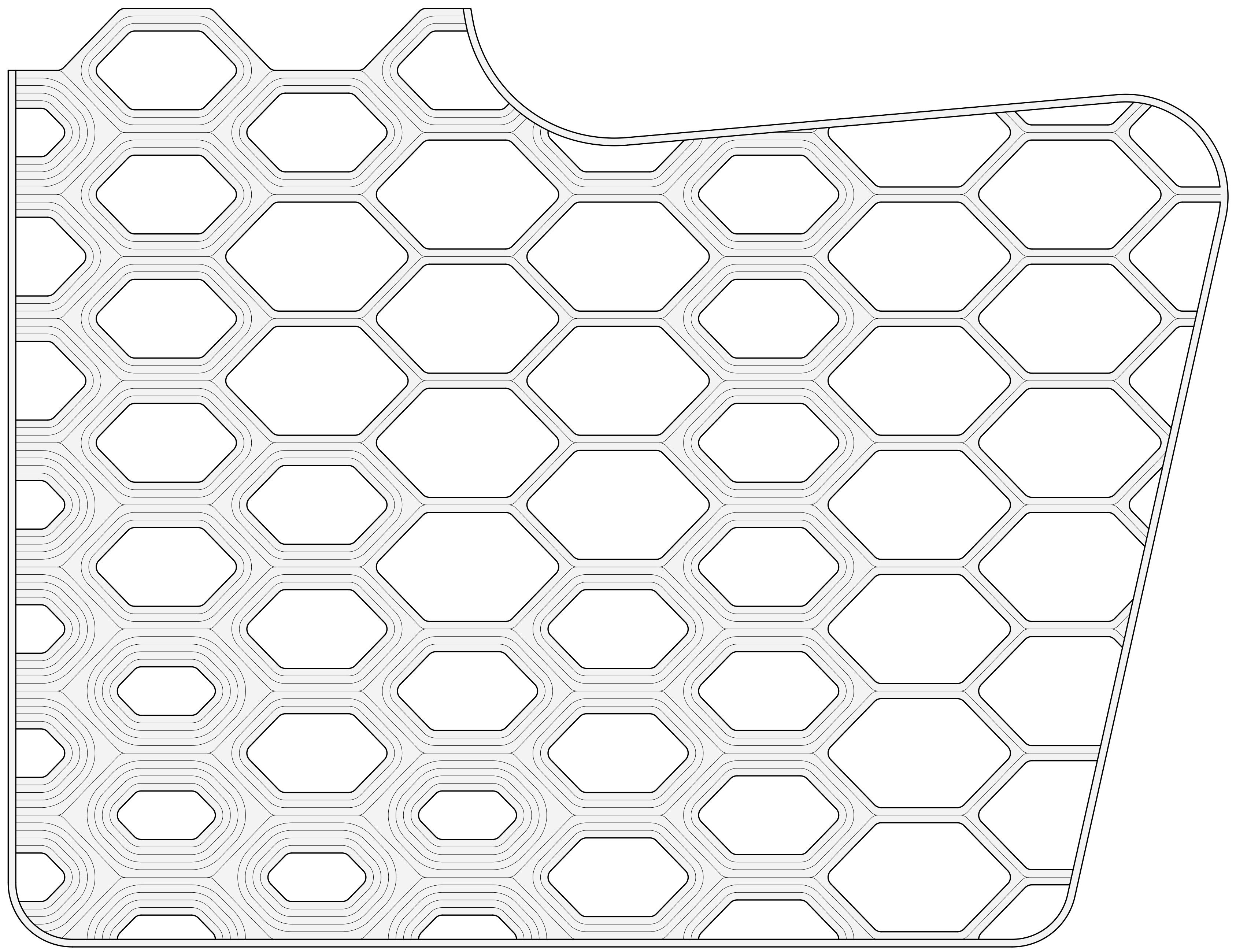




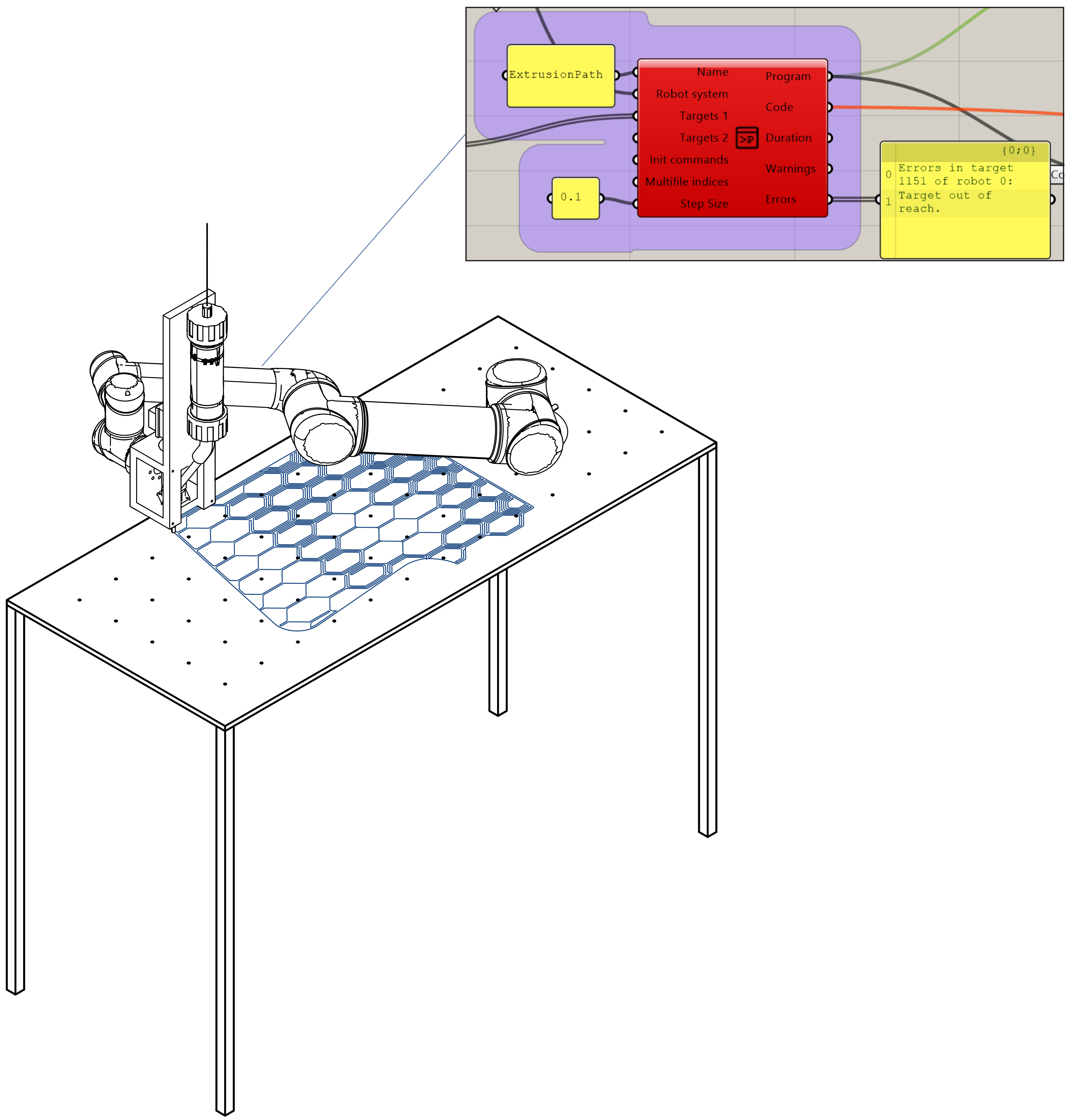


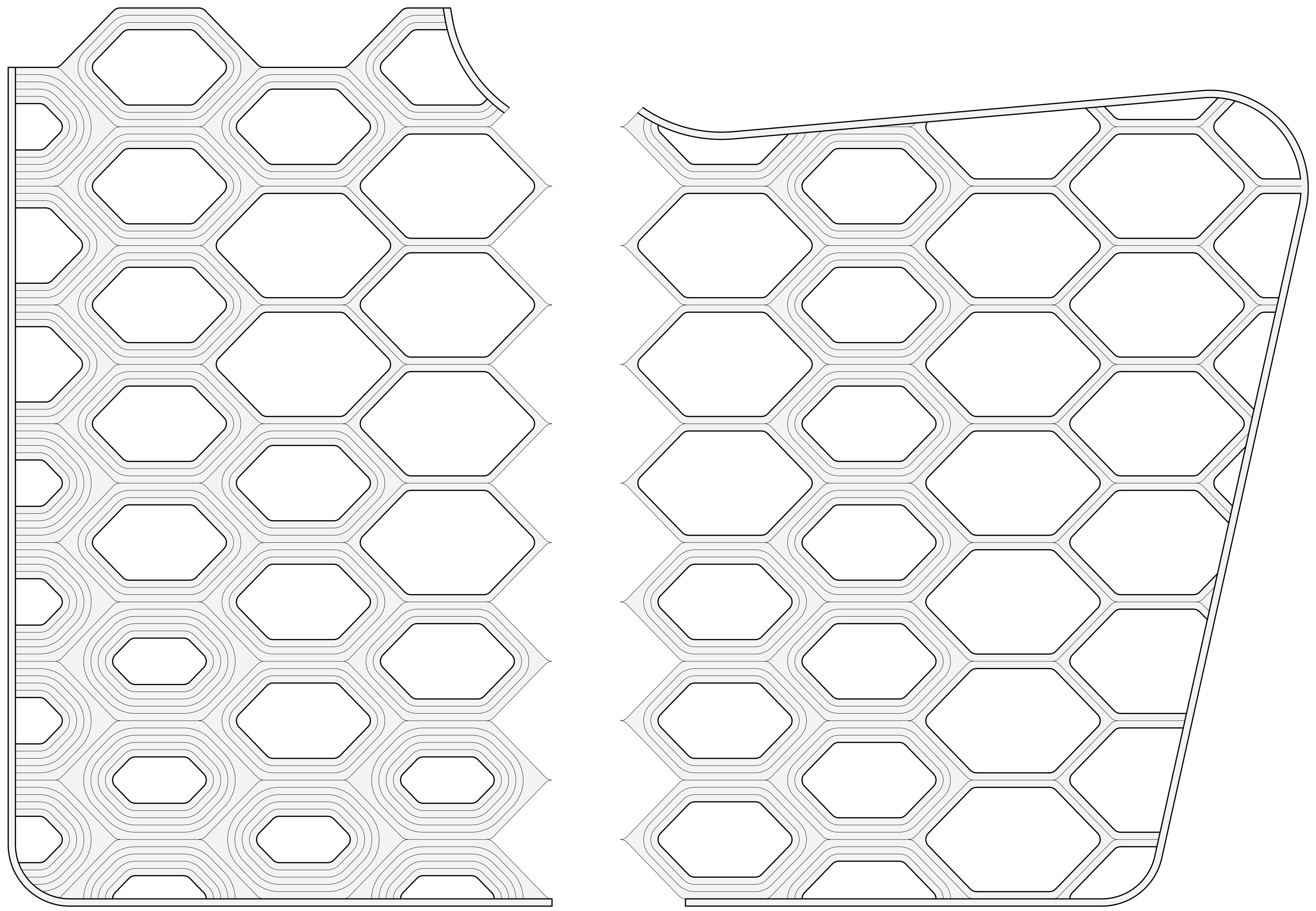
FRAGMENT 1:1 SCALE



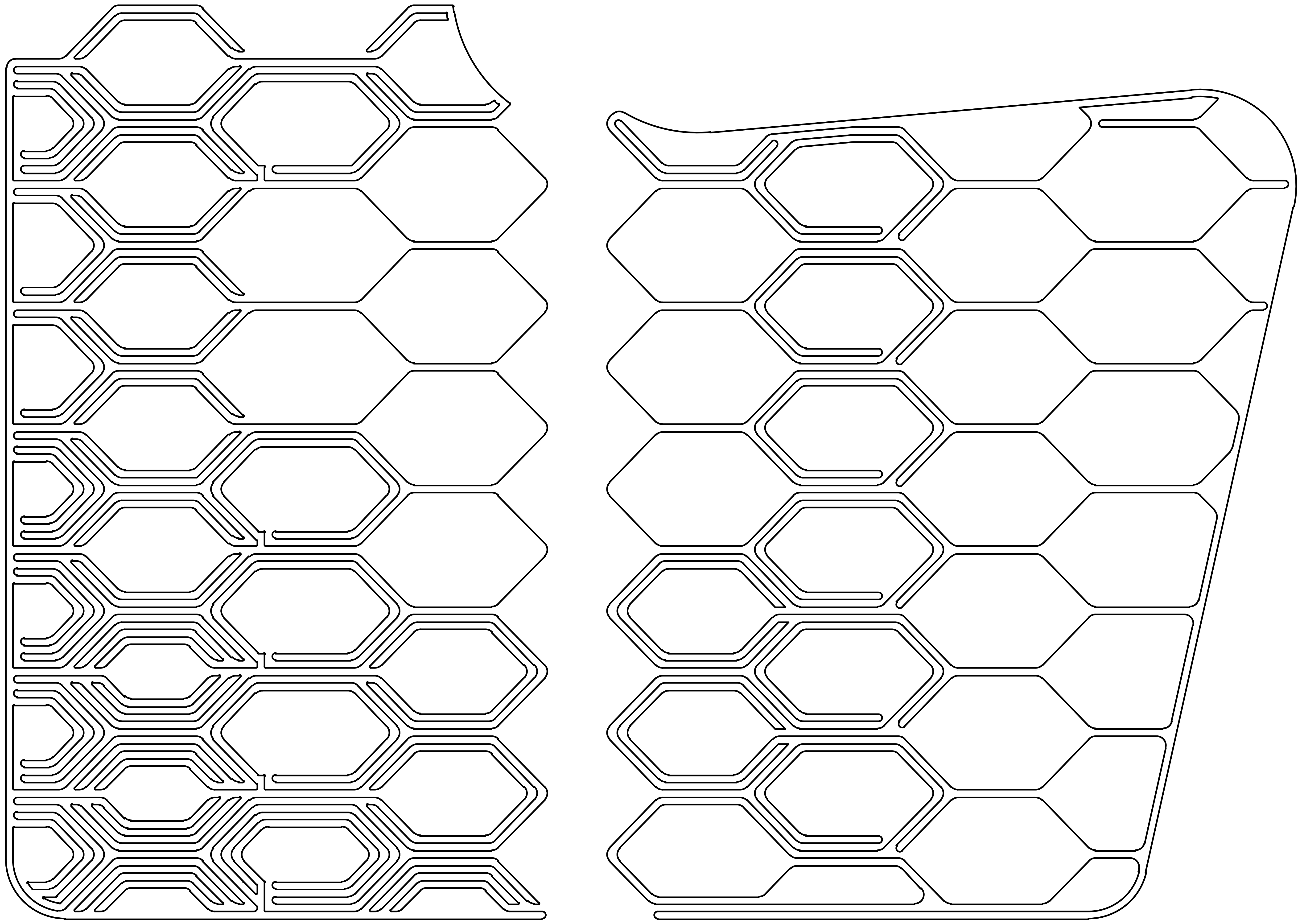


FRAGMENT 1:1 SCALE



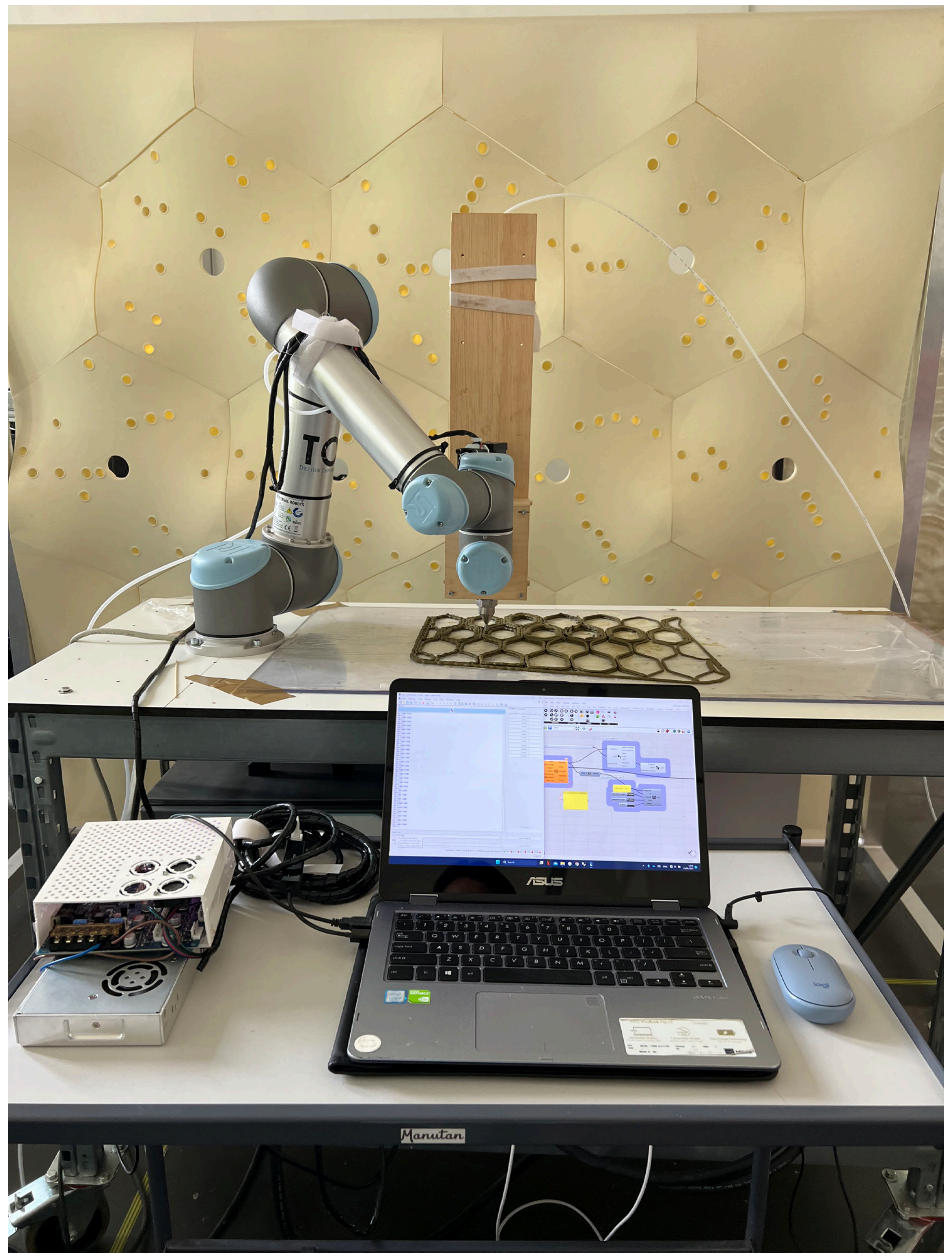


TOOLPATH



TIME FRAME

material



tool

printing

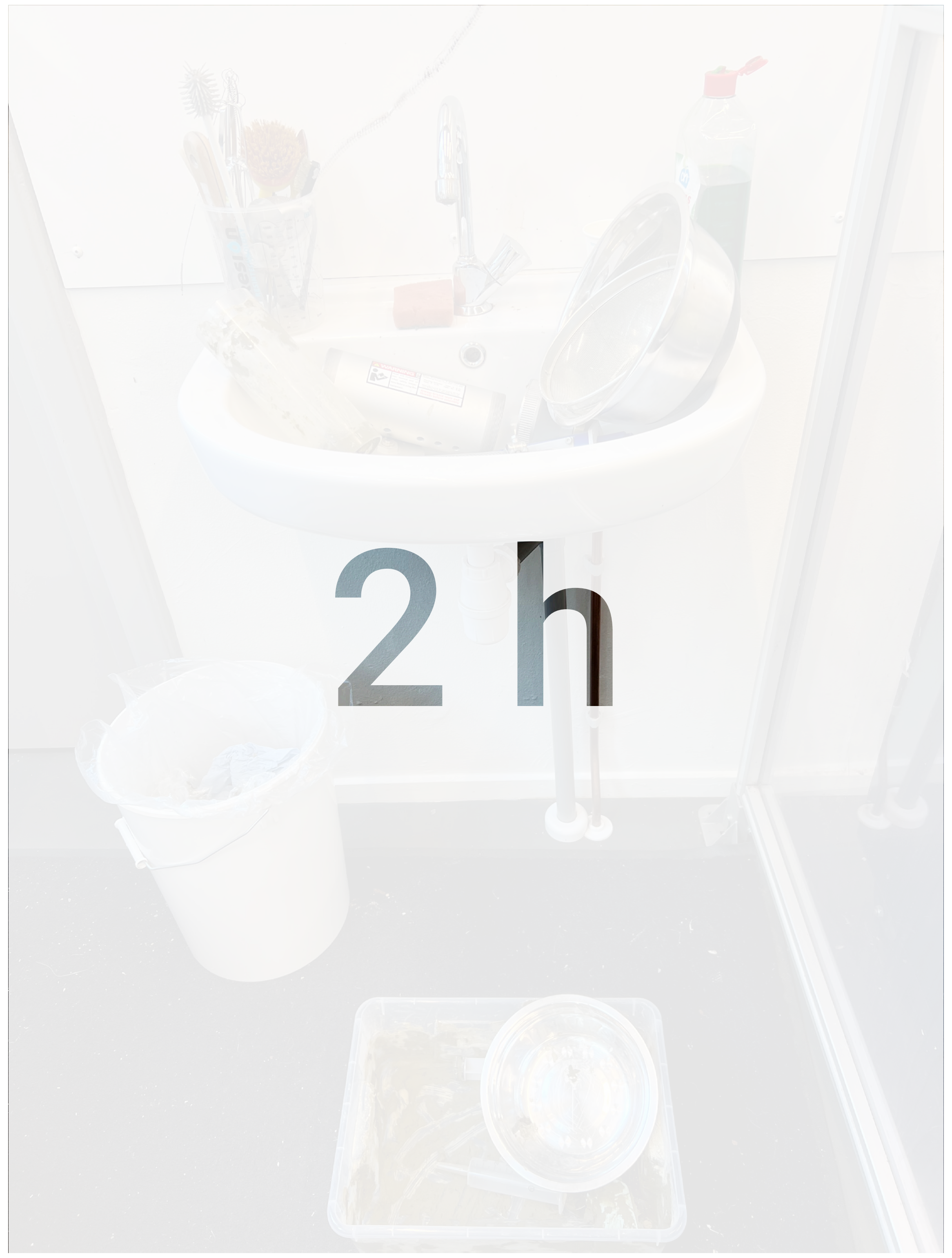
cleaning

TIME FRAME

material

tool

printing



cleaning

two working days

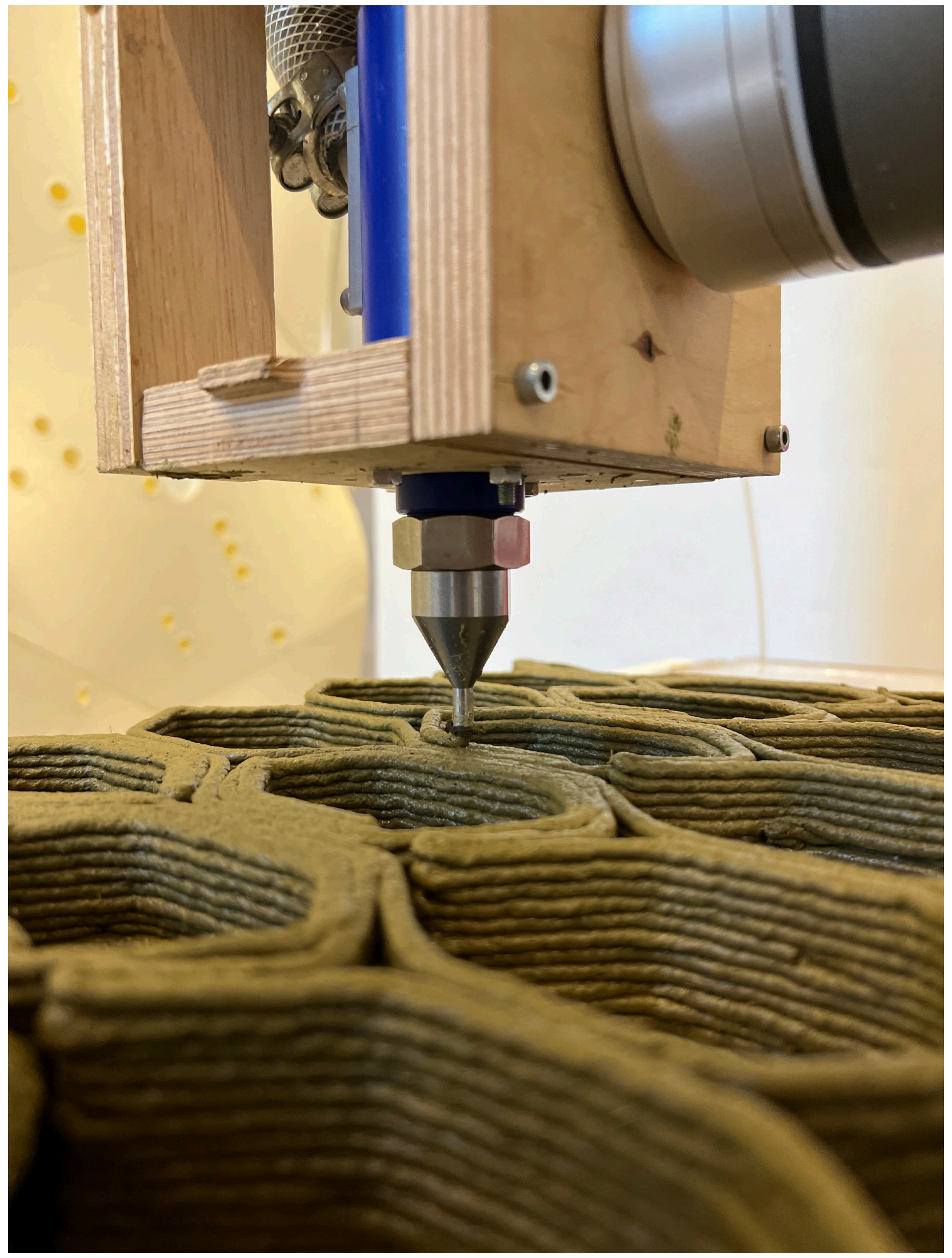
PROTOTYPE PRINTING PROCESS

LAYER - REFILL - LAYER - REFILL

over extrusion

1 layer

cartridge refill

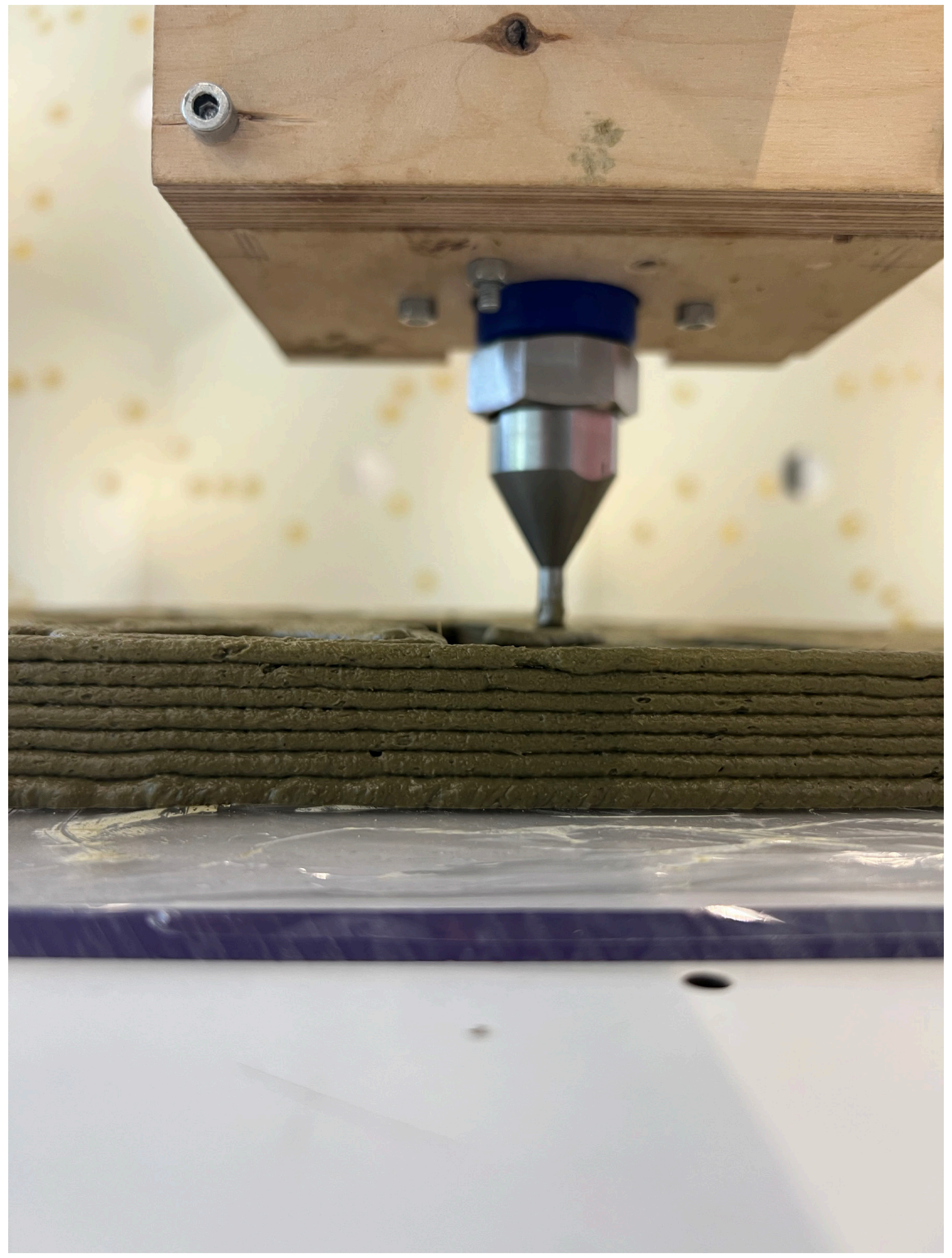


1 layer

CONTROLLED PRINTING PROCESS

HEIGHT ACHIEVED

1 layer

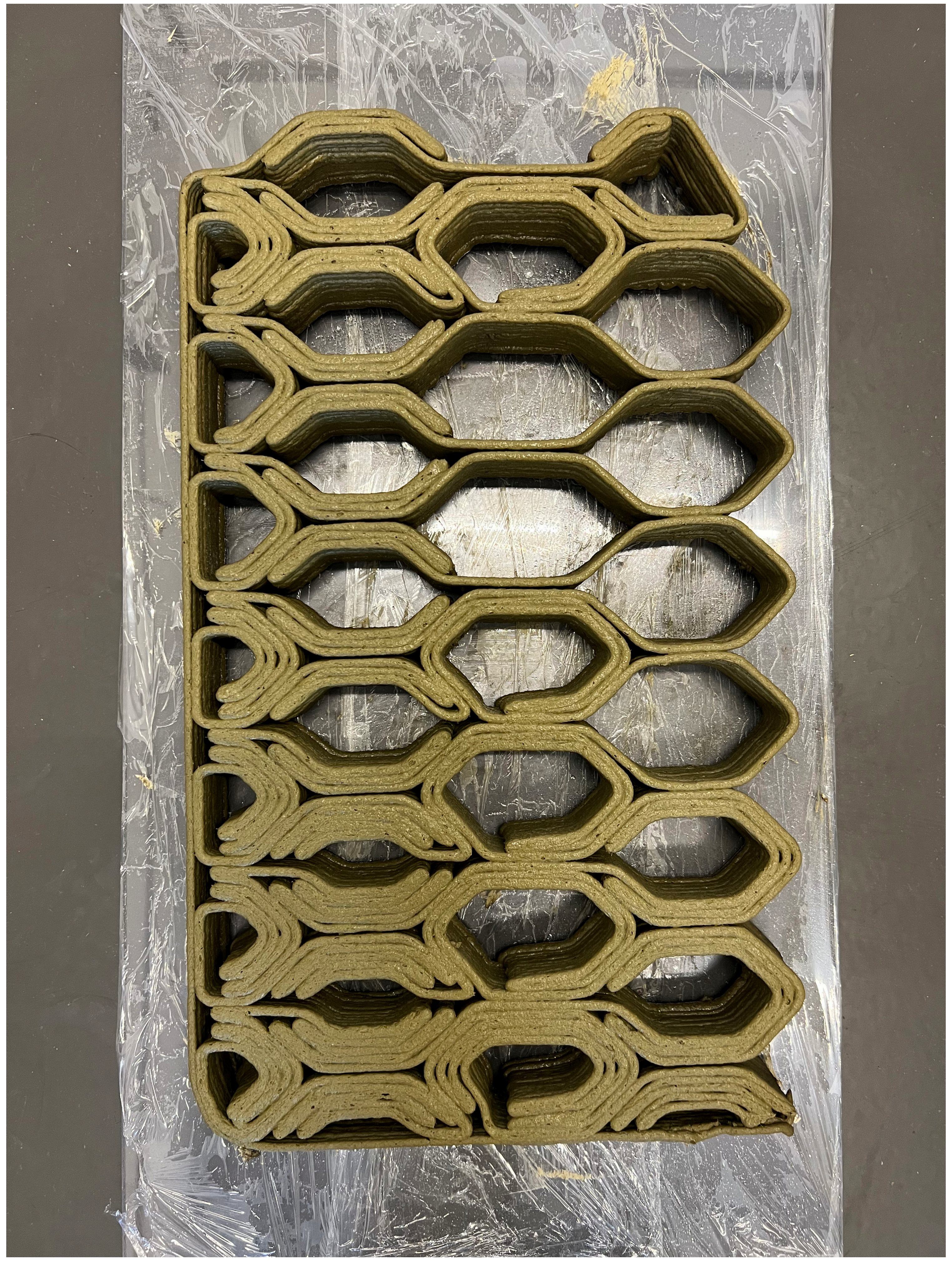


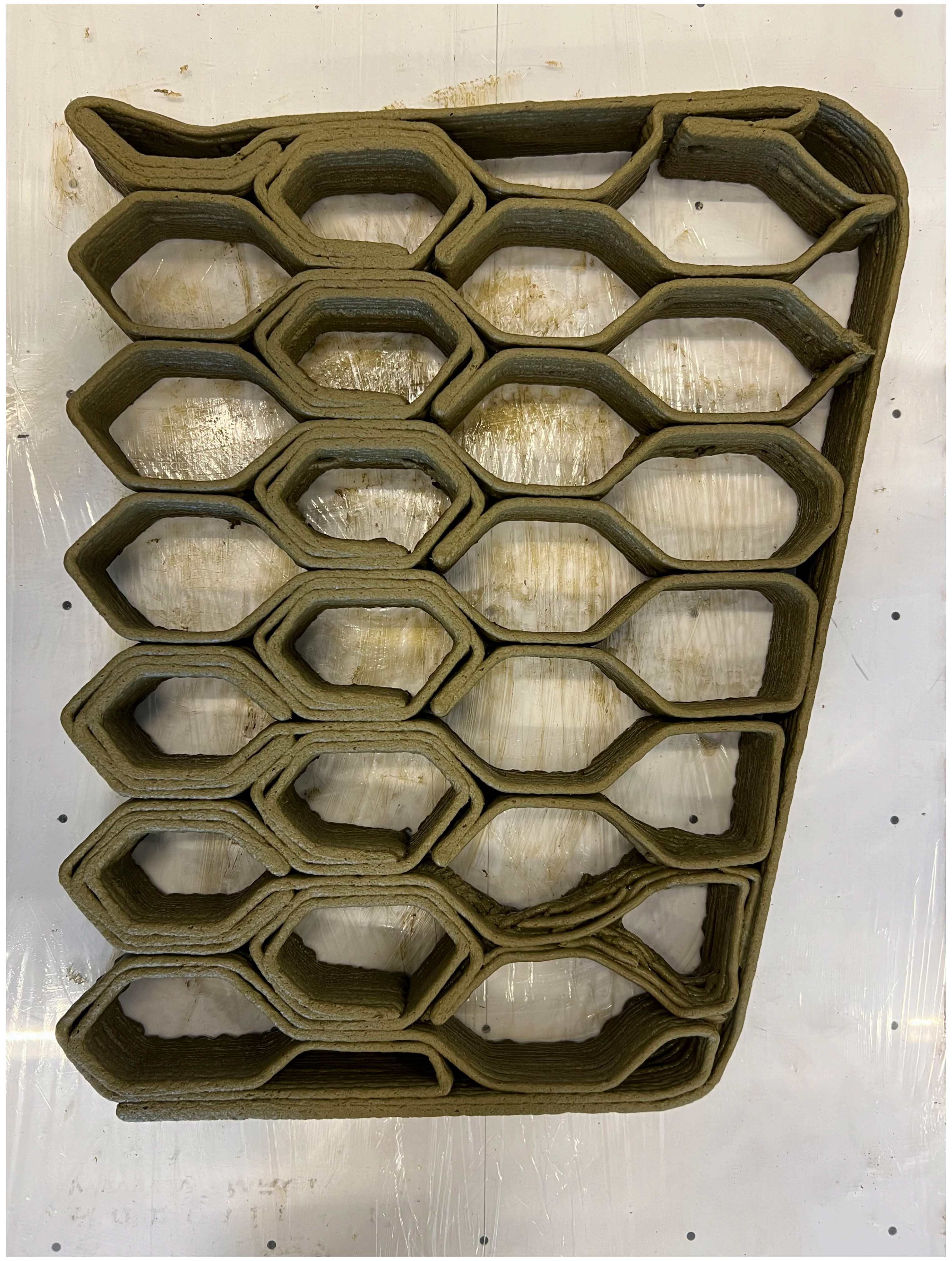
7 layers

12 layers

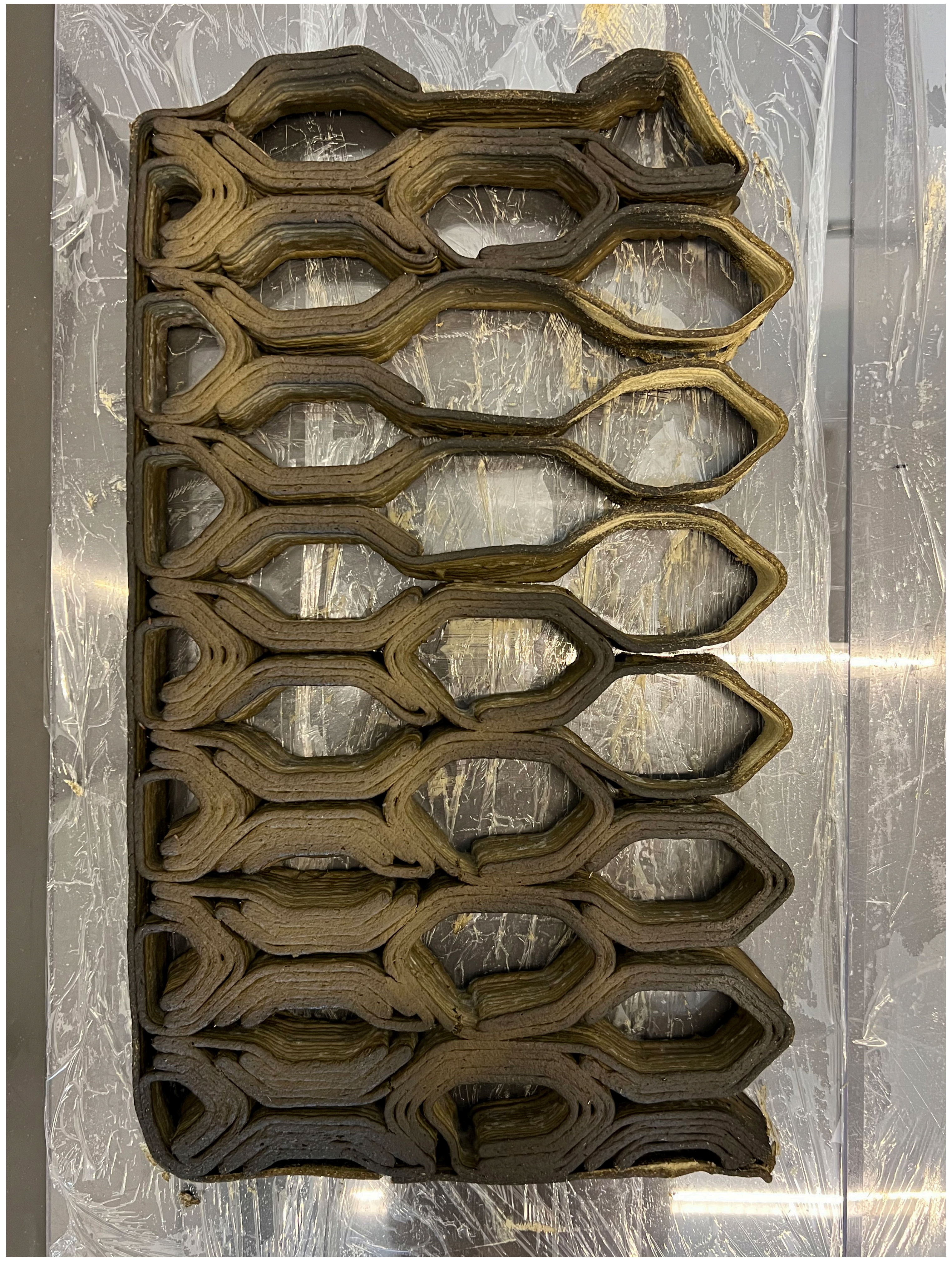
16 layers

PRINTED PROTOTYPE





DRIED PROTOTYPE



CONTENT

WORKFLOW

material

fabrication

design

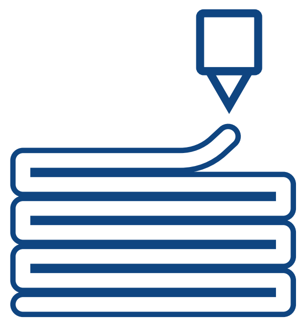
component

SCIENTIFIC RELEVANCE

material

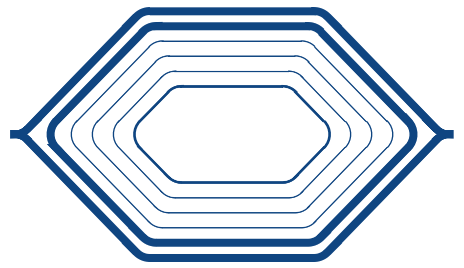
fully bio-based material

fabrication



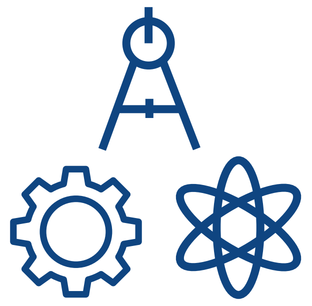
additive manufacturing prominence in the built environment

design



optimized material usage

component



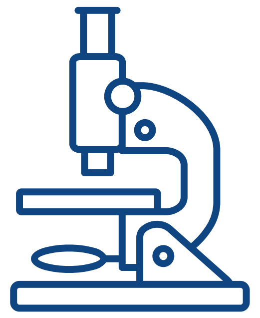
advancement in interdisciplinary research

SOCIAL RELEVANCE

material	fabrication	design	component
efficient utilization of waste streams	construction safety and minimized transportation	design customization flexibility	fully reusable material

FUTURE RESEARCH

material



deeper investigation of the properties

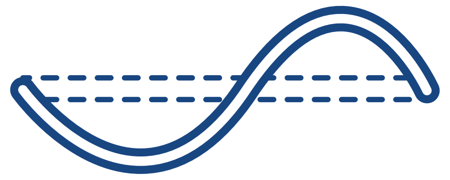
fabrication

geometry exploration and integration with other fabrication methods

design

interior and weather resistant exterior applications

component



4D printing

THANK YOU

FILLERS

green bamboo dust

dust 0100

fiber 200400 SF

fiber 4001000

CORN STARCH LONG FIBERS

dust 0100+ fiber 200400 SF

fiber 200400 SF

green dust + fiber 200400 SF

fiber 4001000

WHY NOT DUST 0100

dust 0100

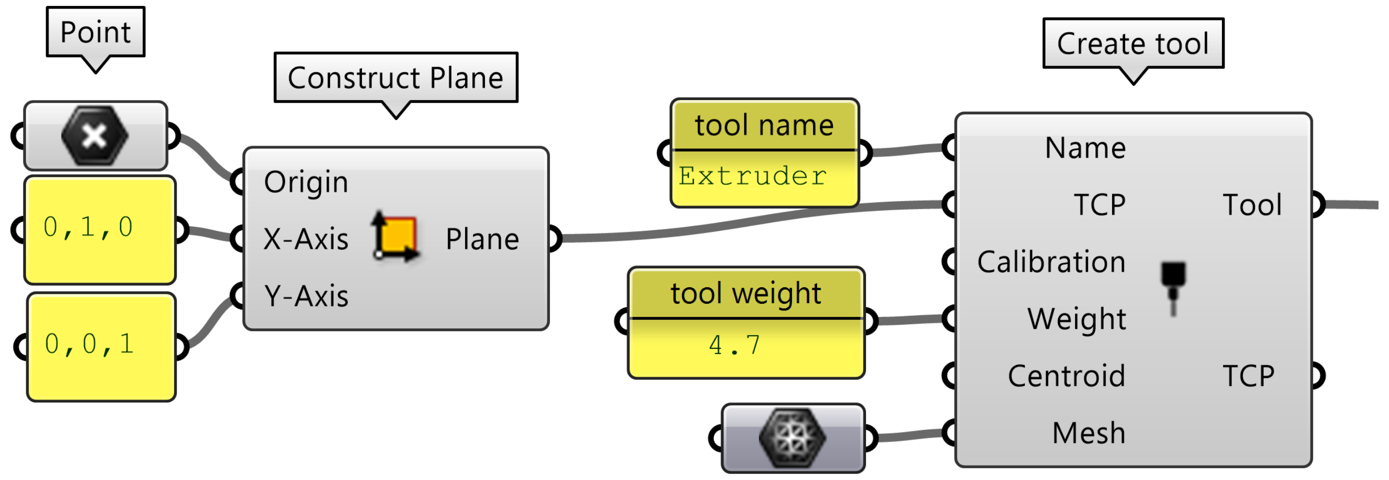
less adhesion

REUSABLE PRINTED COMPONENT

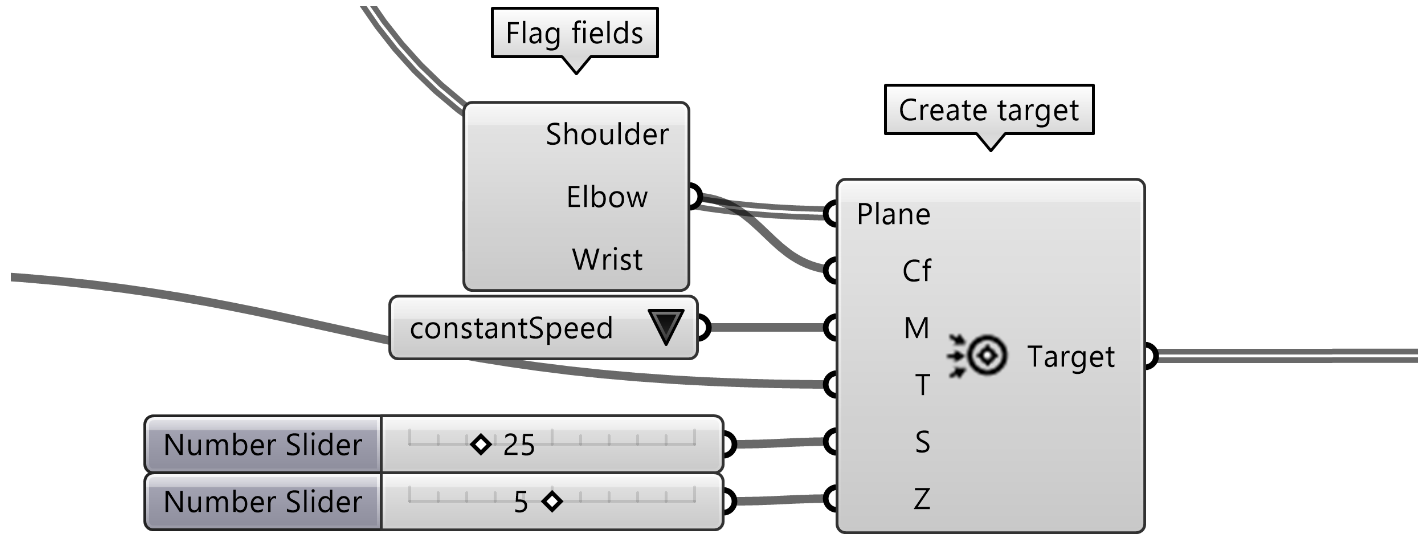
soaked

dissolved

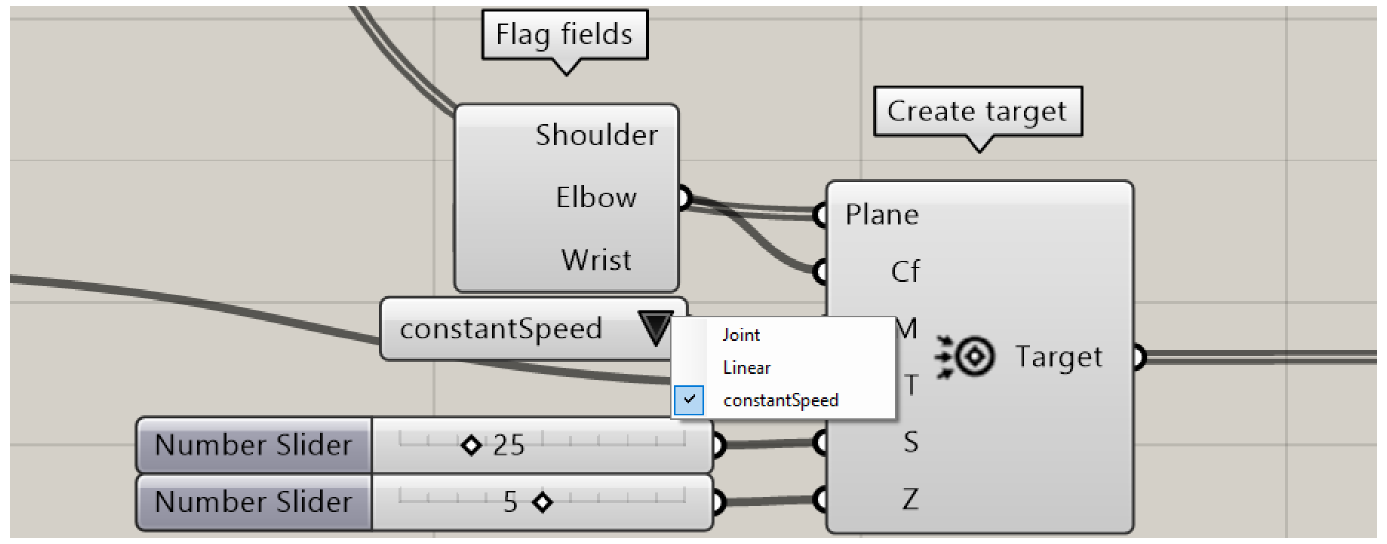
COMPUTATIONAL WORKFLOW



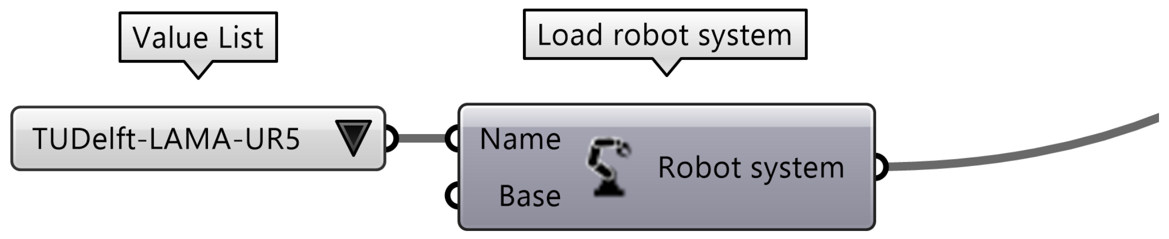
create tool



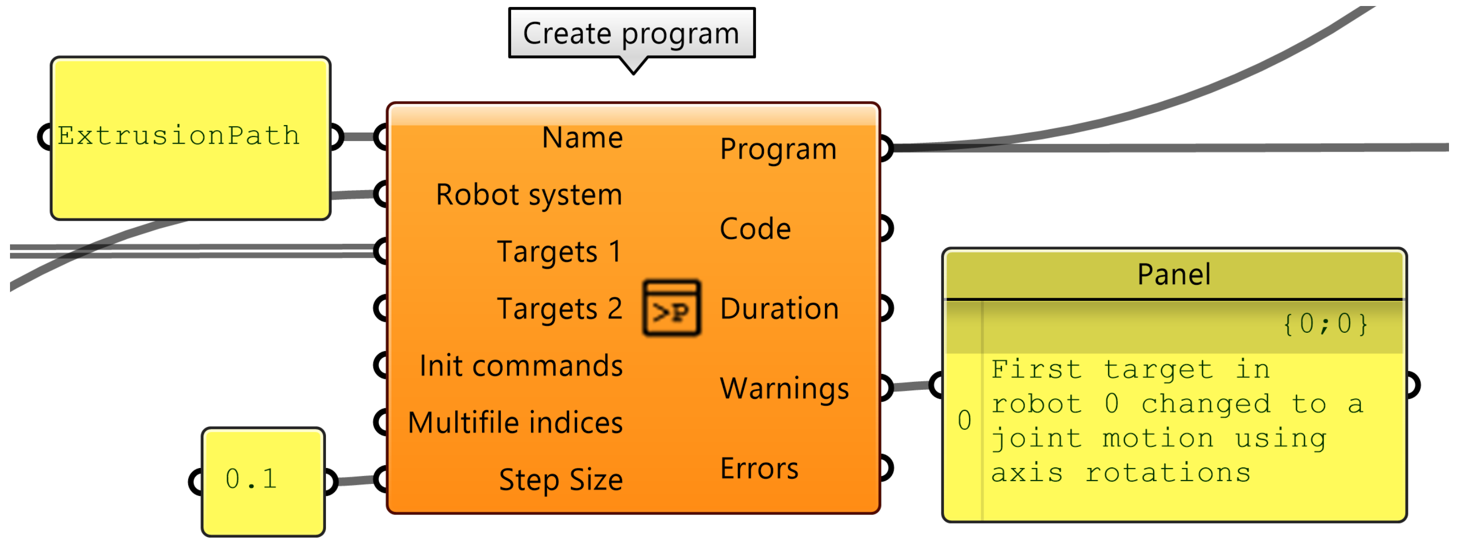
create target



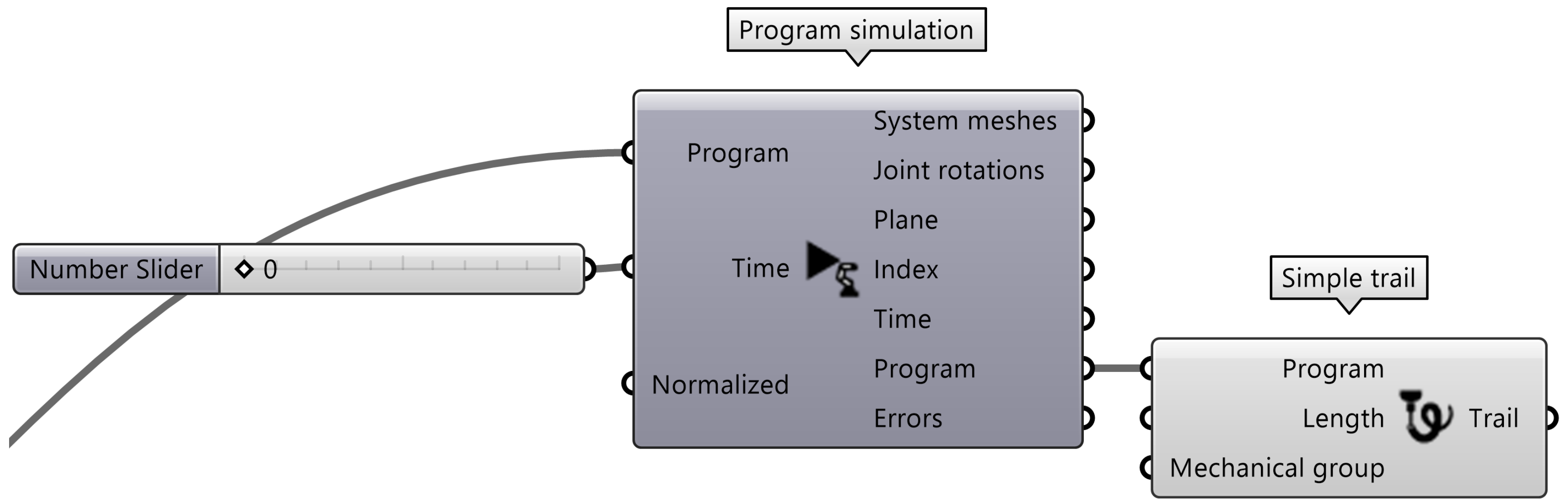
motion parameter



library input

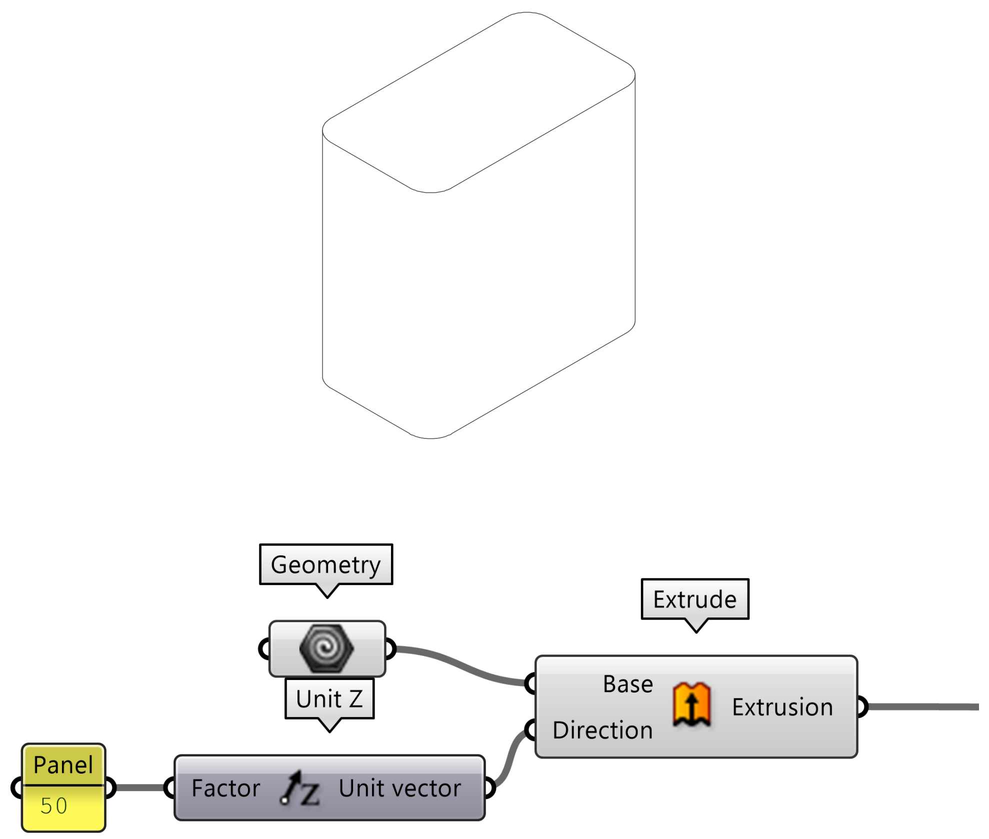


create program

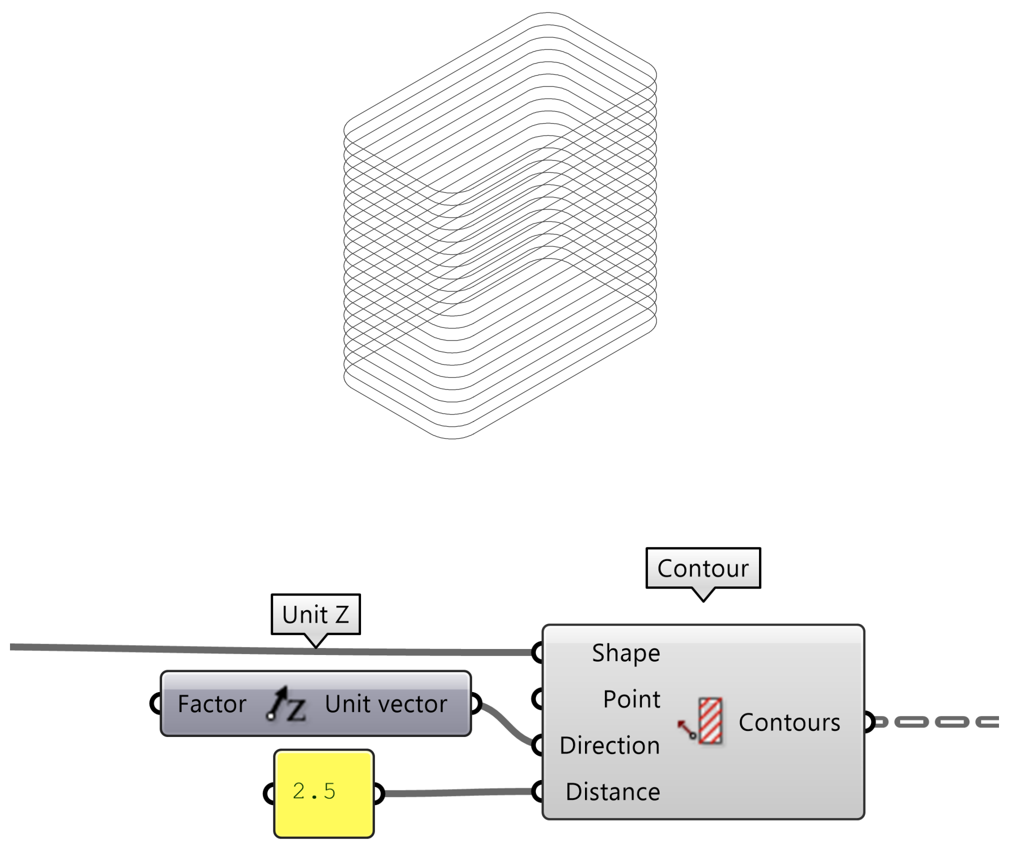


program simulation

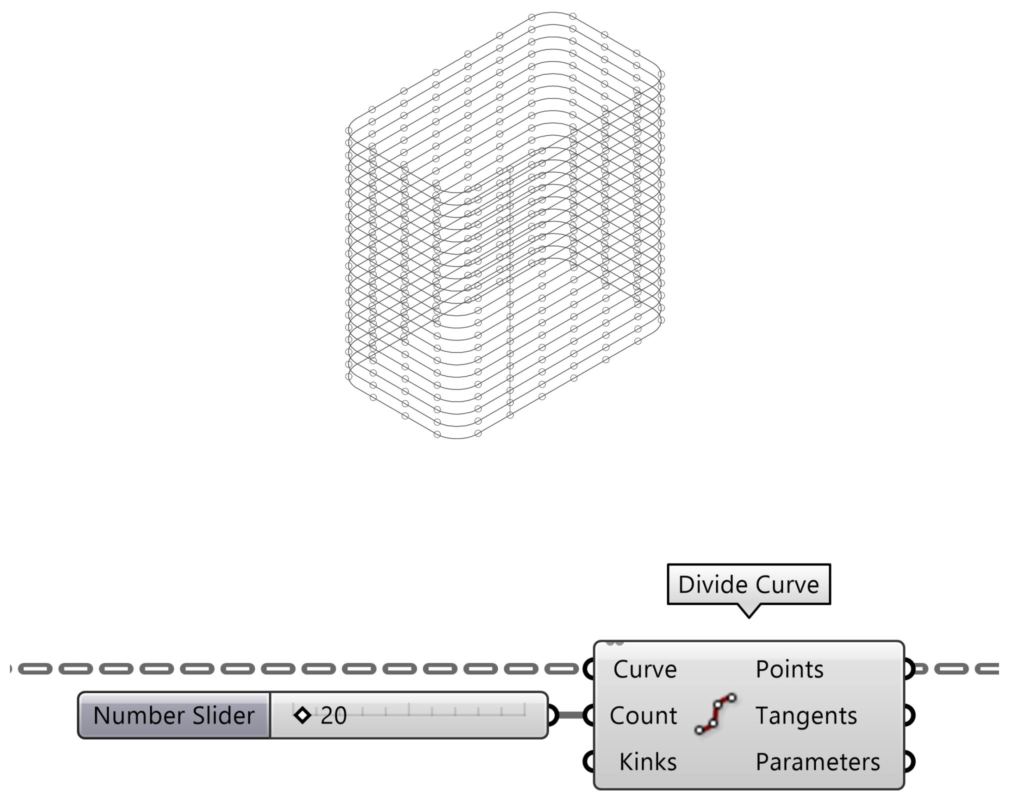
DIGITAL GEOMETRY



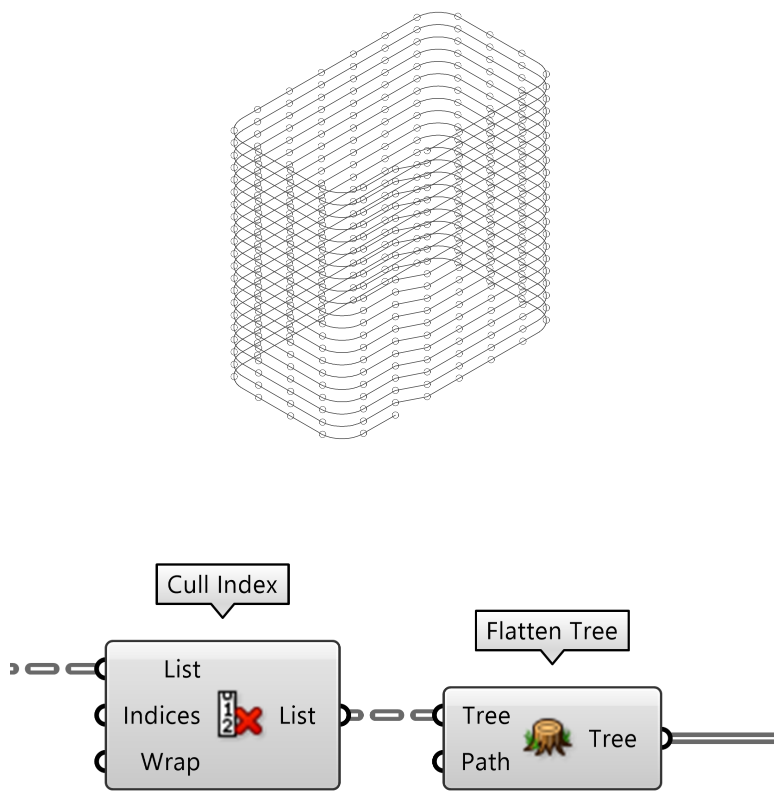
geometry



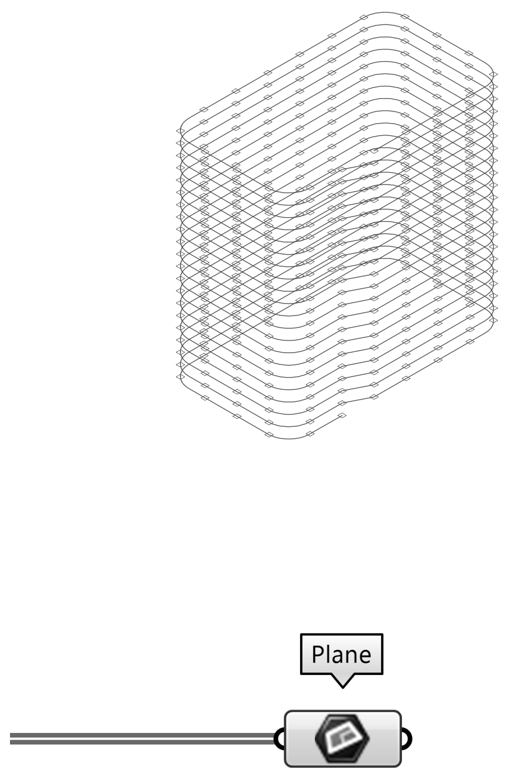
contour



curve



flatten tree



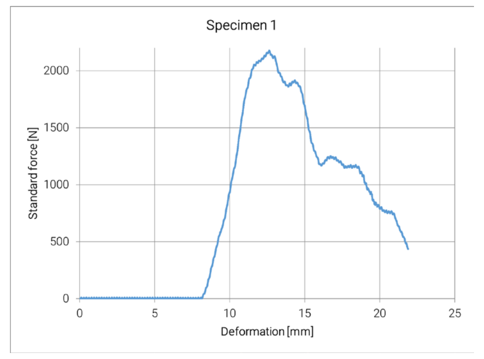
plane conversion

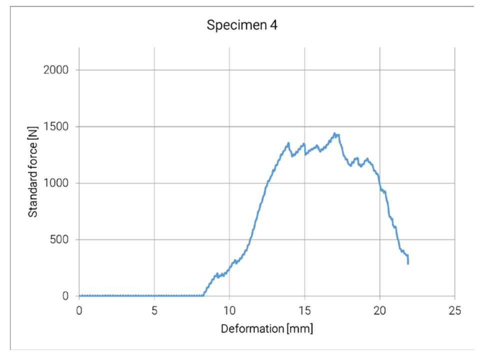
MECHANICAL TEST

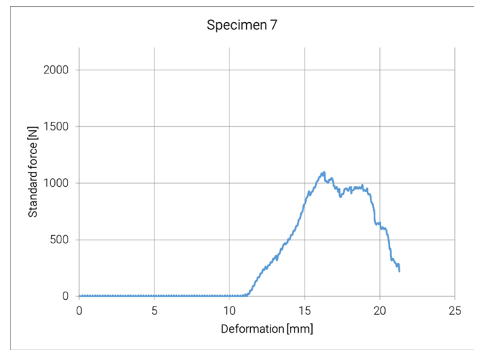
Geometry \ Mixture	Dust + Fibers *Sasa tsuboiana* + 200400 SF	Dust + Fibers 0100 + 200400 SF	

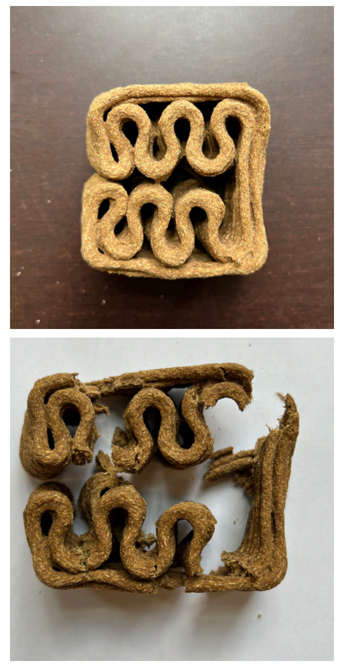
Curved

	Weight	F max	dL at F max	F break	dL at F break
1A	72 g	2177 N	12,6 mm	435 N	21,8 mm
2A	43,6 g	1443 N	16,9 mm	283N	21,8 mm
3A	34,9 g	1099 N	16,3 mm	219 N	21,3 mm



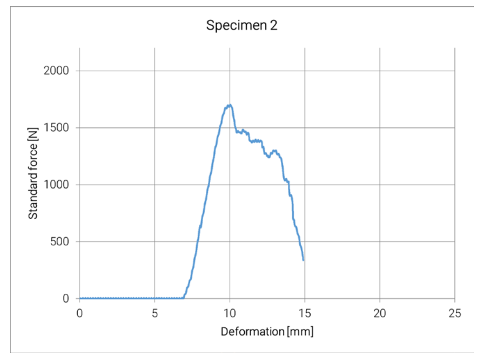



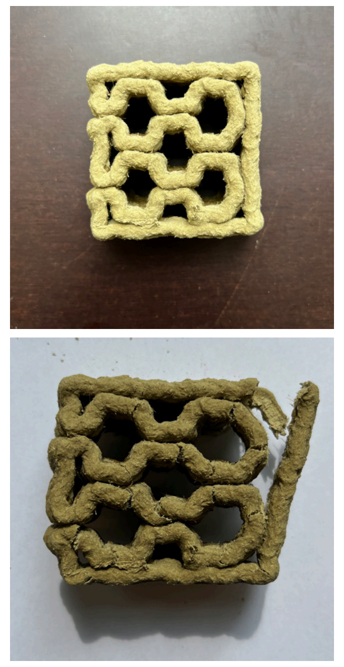
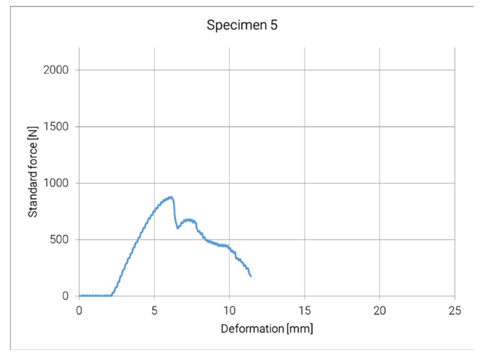



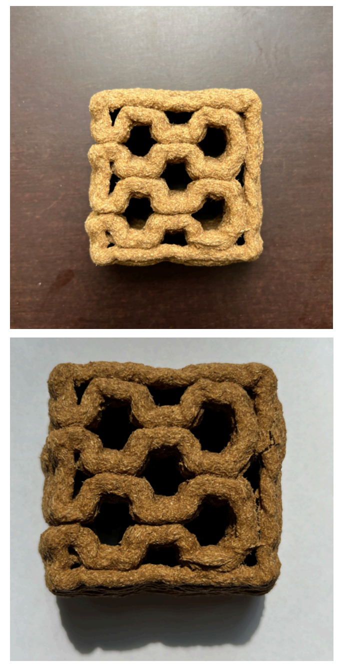
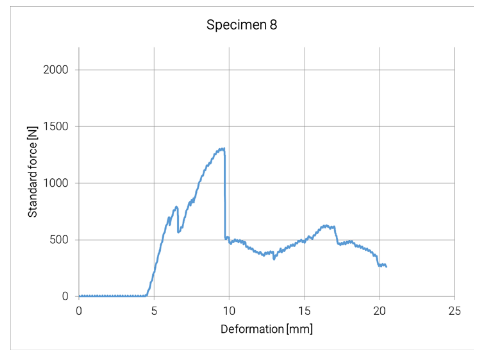


Honeycomb

	Weight	F max	dL at F max	F break	dL at F break
1B	66,8 g	1702 N	10 mm	337 N	14,9 mm
2B	68,5 g	879 N	6,13 mm	175,5 N	11,4 mm
3B	45,7 g	1308 N	9,6 mm	261,7 N	20,4 mm

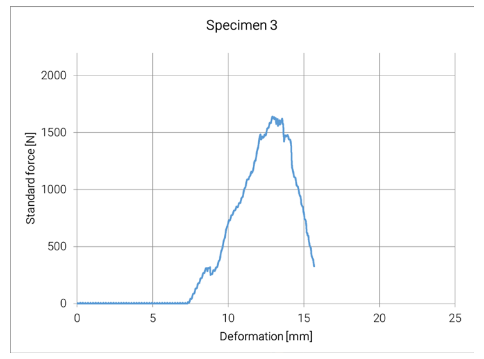


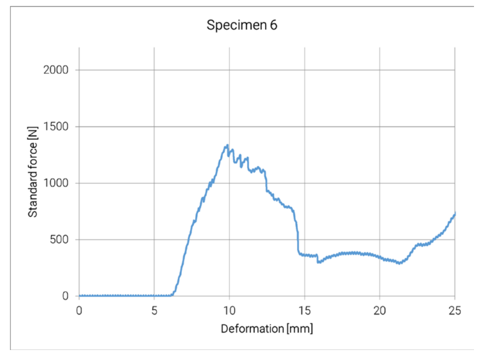



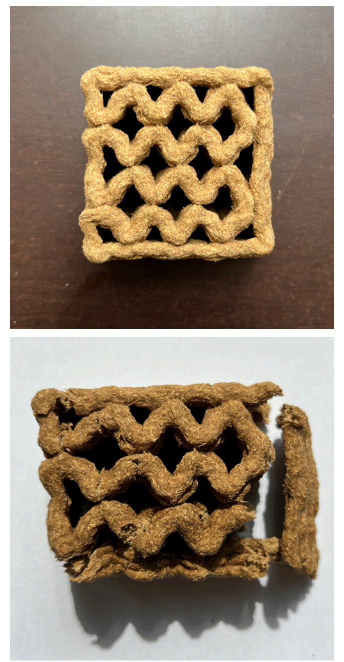
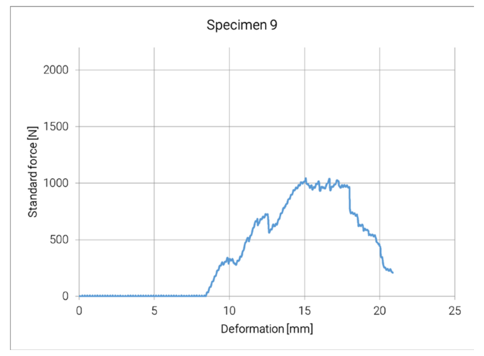



Rhombic

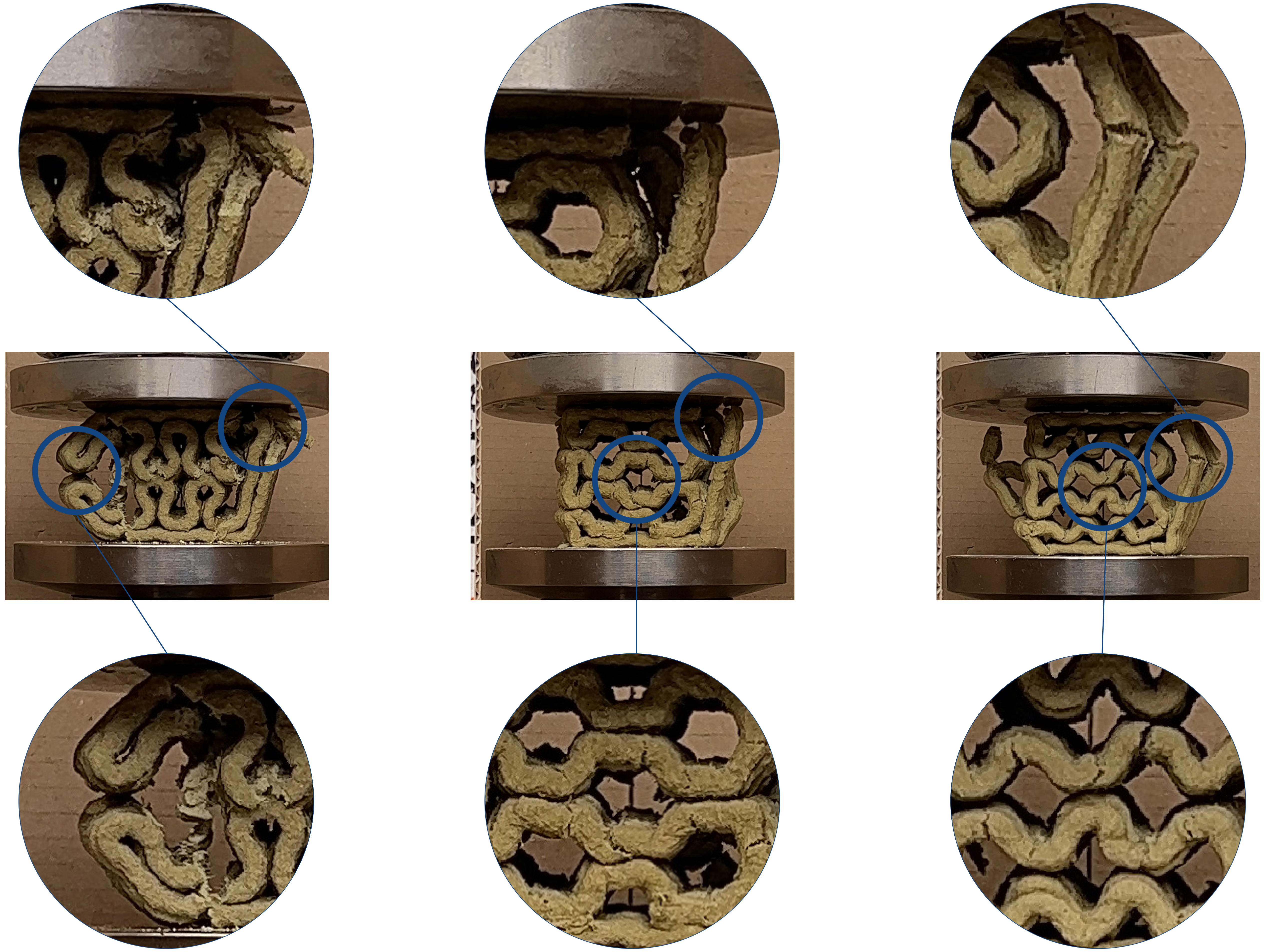
	Weight	F max	dL at F max	F break	dL at F break
1C	62,2 g	1641 N	12,9 mm	327 N	15,6 mm
2C	53,6 g	1339 N	9,87 mm	265 N	28,8 mm
3C	40,1 g	1043 N	15,1 mm	208 N	20,8 mm



MECHANICAL TEST INSIGHTS



curved honeycomb rhombic

MIXTURE LUMPS