3D PRINTING
CLAY FACADE WALLS

Integrating Ventilation systems into printing process

P5 Presentation

Student | Ammar Taher Ibrahim
Tutors | Dr. S. Asut
| Dr.ir. WH van der Spoel

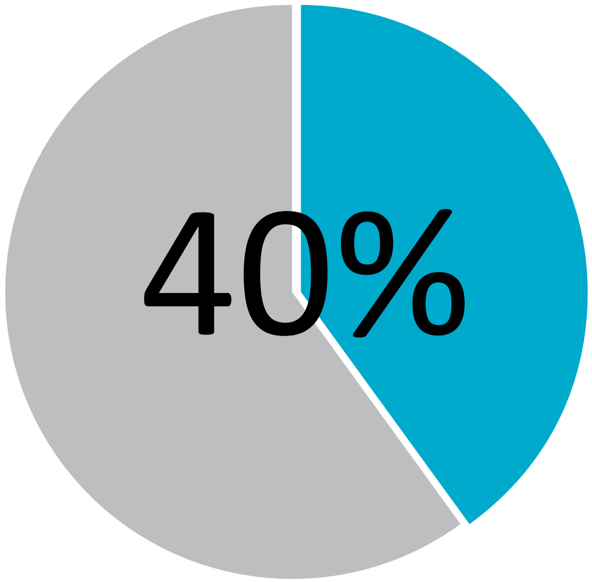
Delegate examiner | Dr.ir. G. Bracken

TU Delft
MSc Architecture, Urbanism & Building Sciences
Building Technology Track

SUSTAINABLE
ARCHITECTURE

Research context

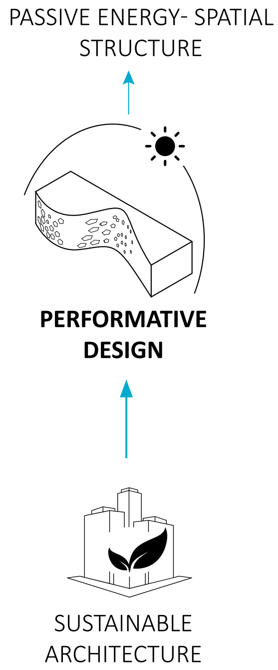
Sustainability for building industry



US Energy Information Administration annual report. 2012, P. 106

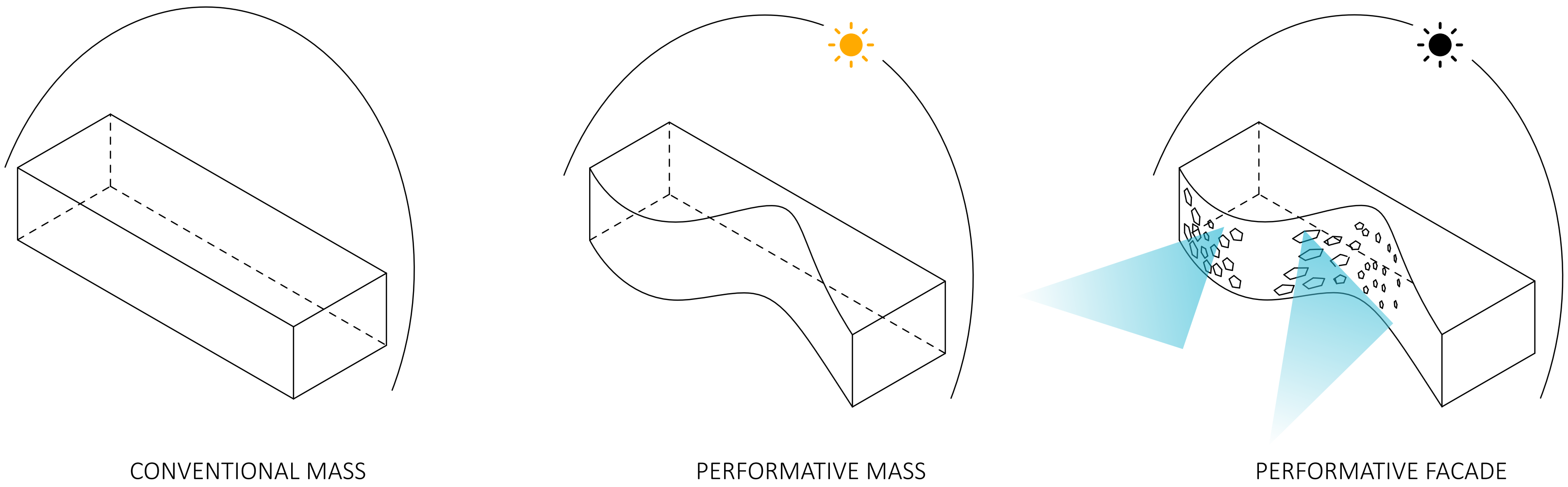
Building industry energy consumption

out of the total consumbtion



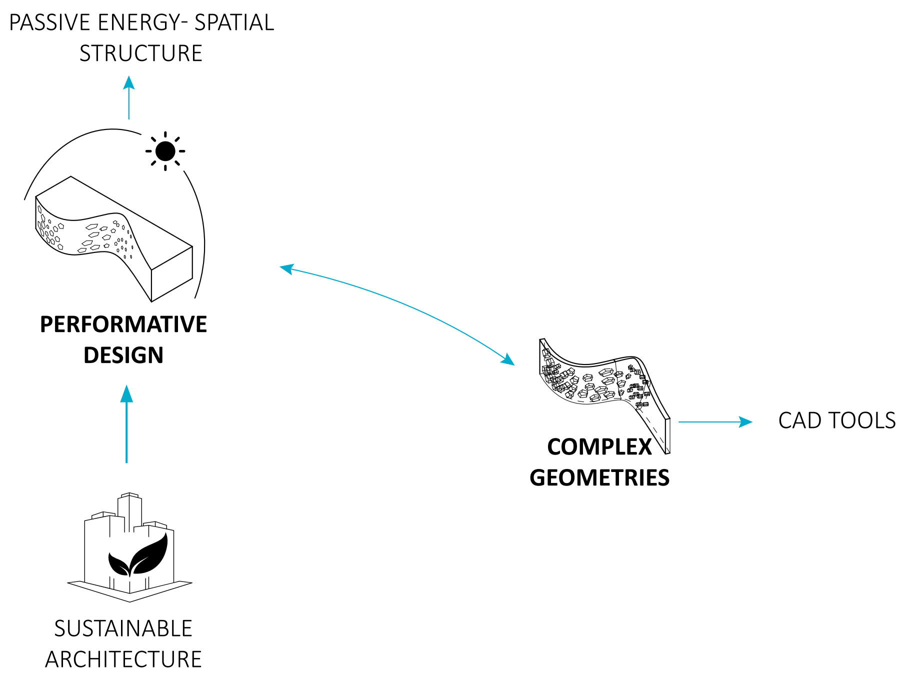
Research context

Performative Architecture materialization process.



Performative design

Energy consumption - Acoustical - Spatial.



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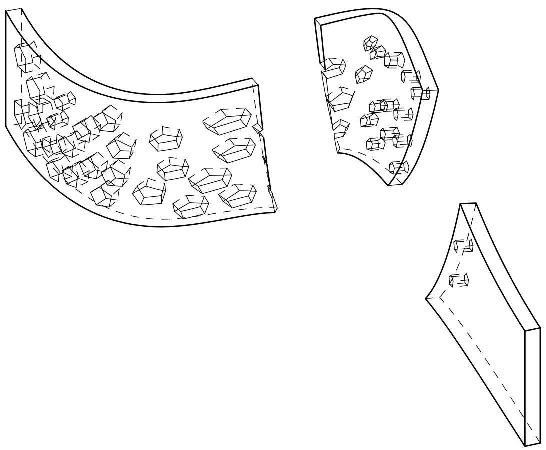
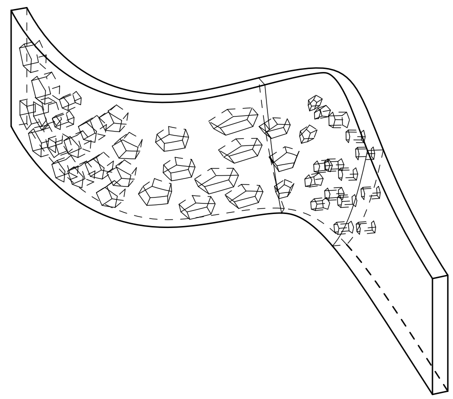


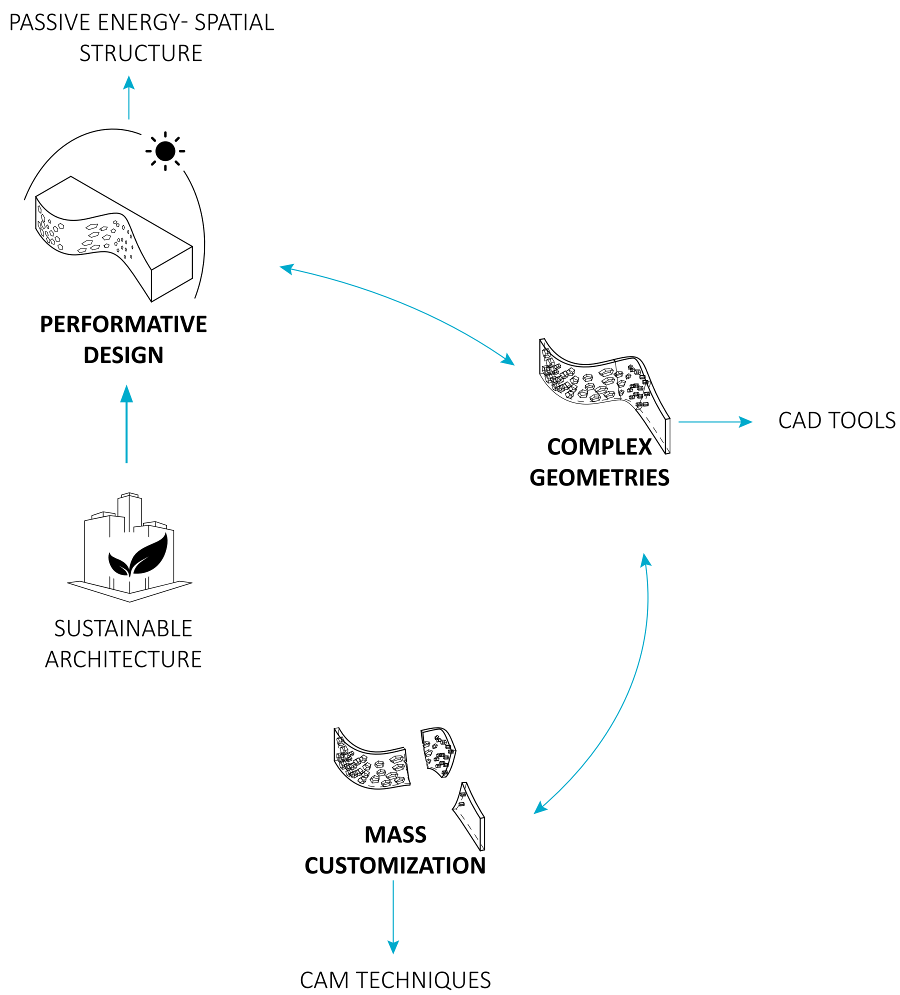
PRODUCTION TECHNIQUES



ASSEMBLY SYSTEMS

Complex geometries

Perfromative - Architectural



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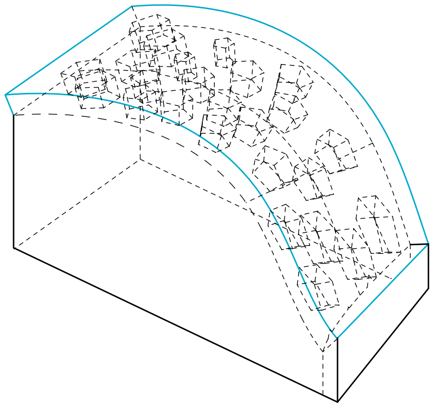
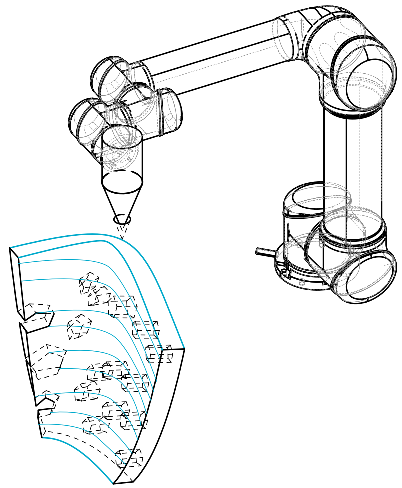
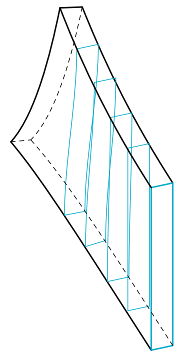


MOLDING



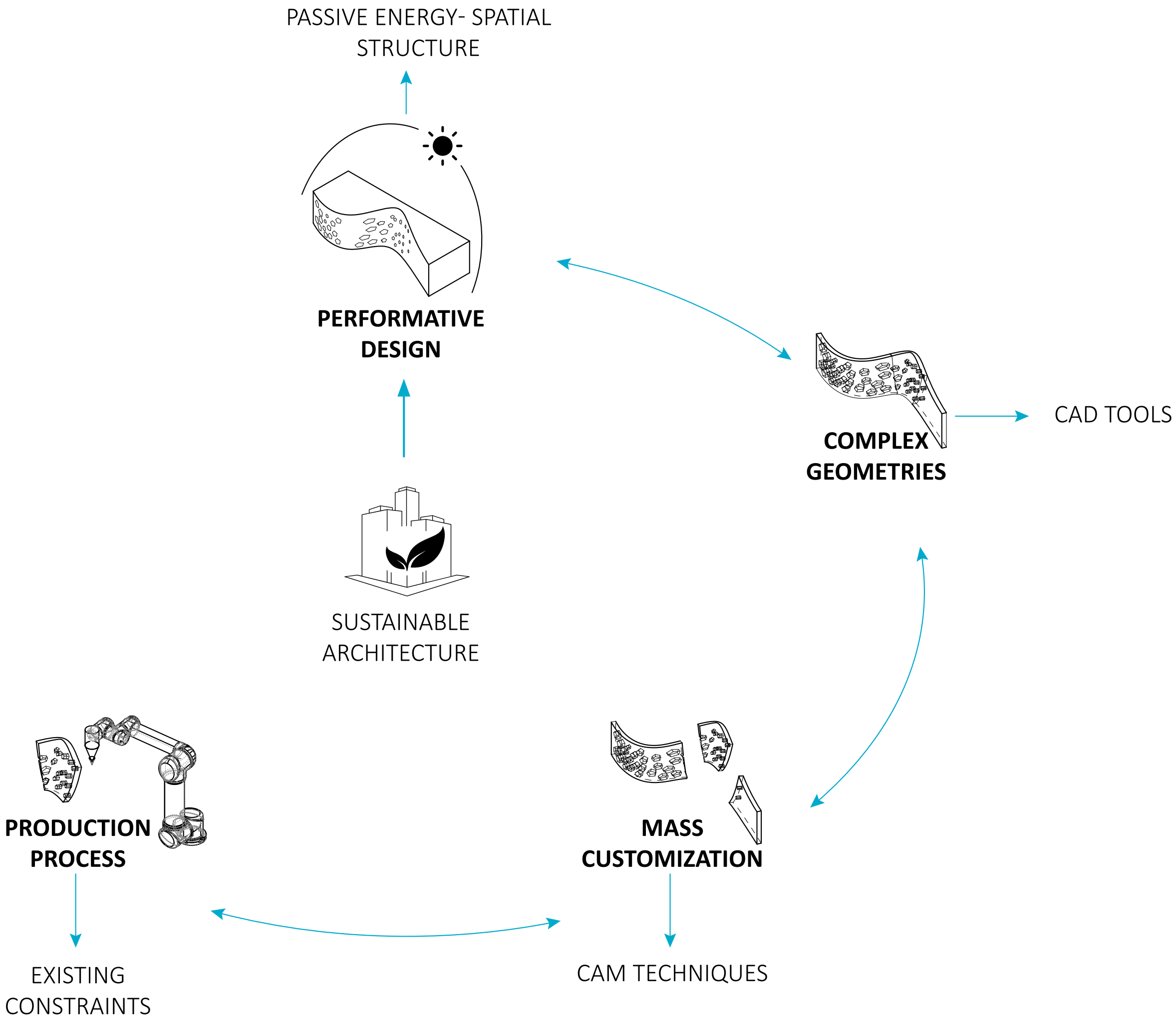
3D PRINTING



CNC MILLING

Mass customization

CAM manufacturing techniques



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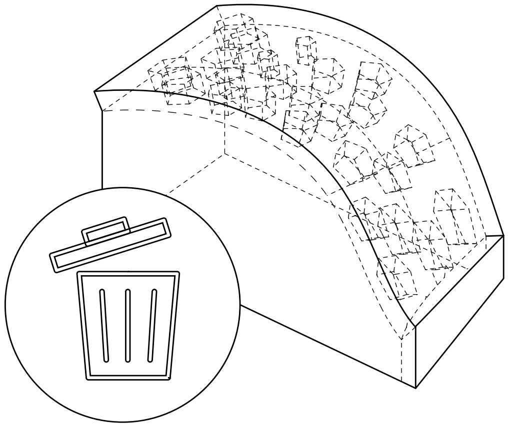
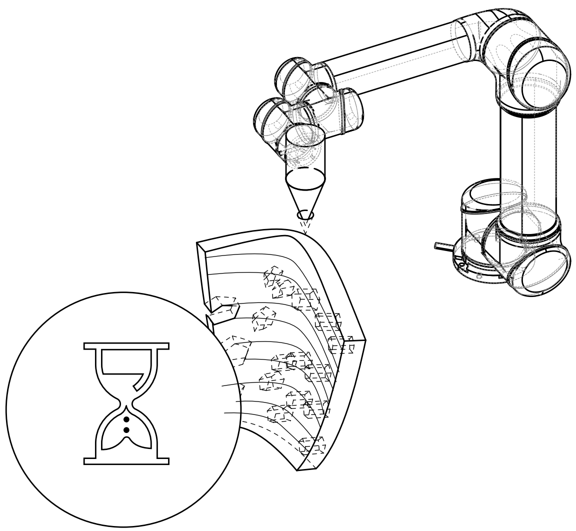
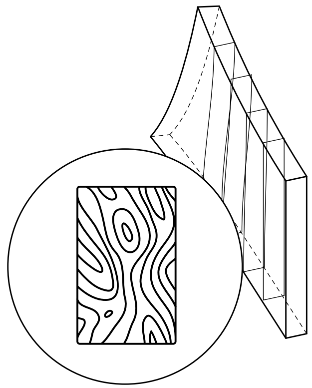


WASTE MOLDS



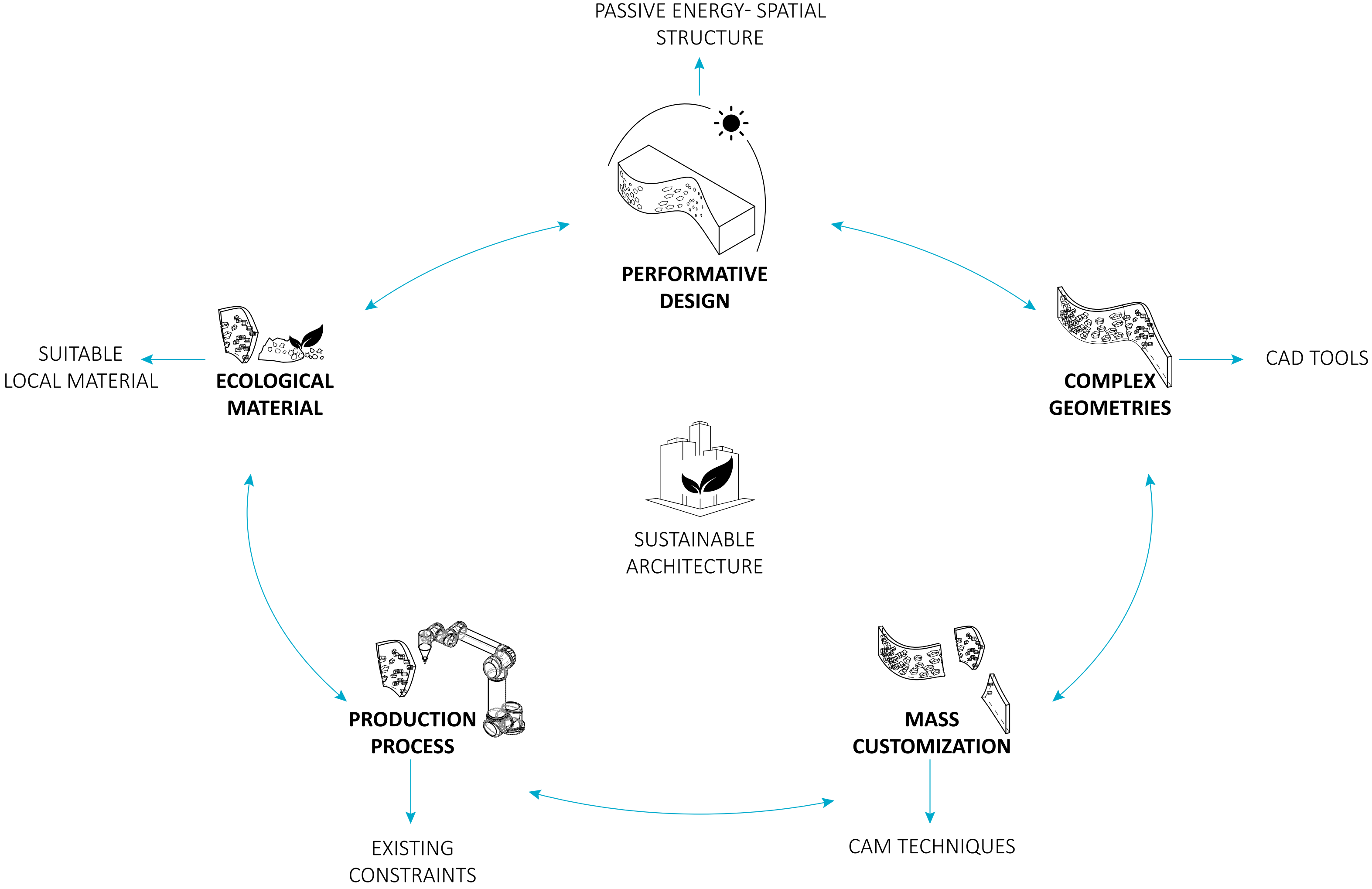
TIME



LIMITED MATERIALS

Production process

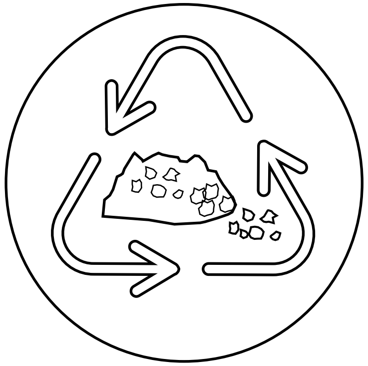
Integrative process overcoming the constraints for better results



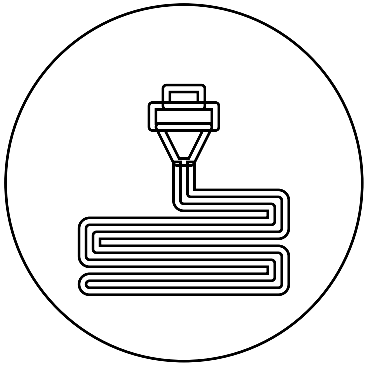
Research context

Performative Architecture materialization process.

Affordable



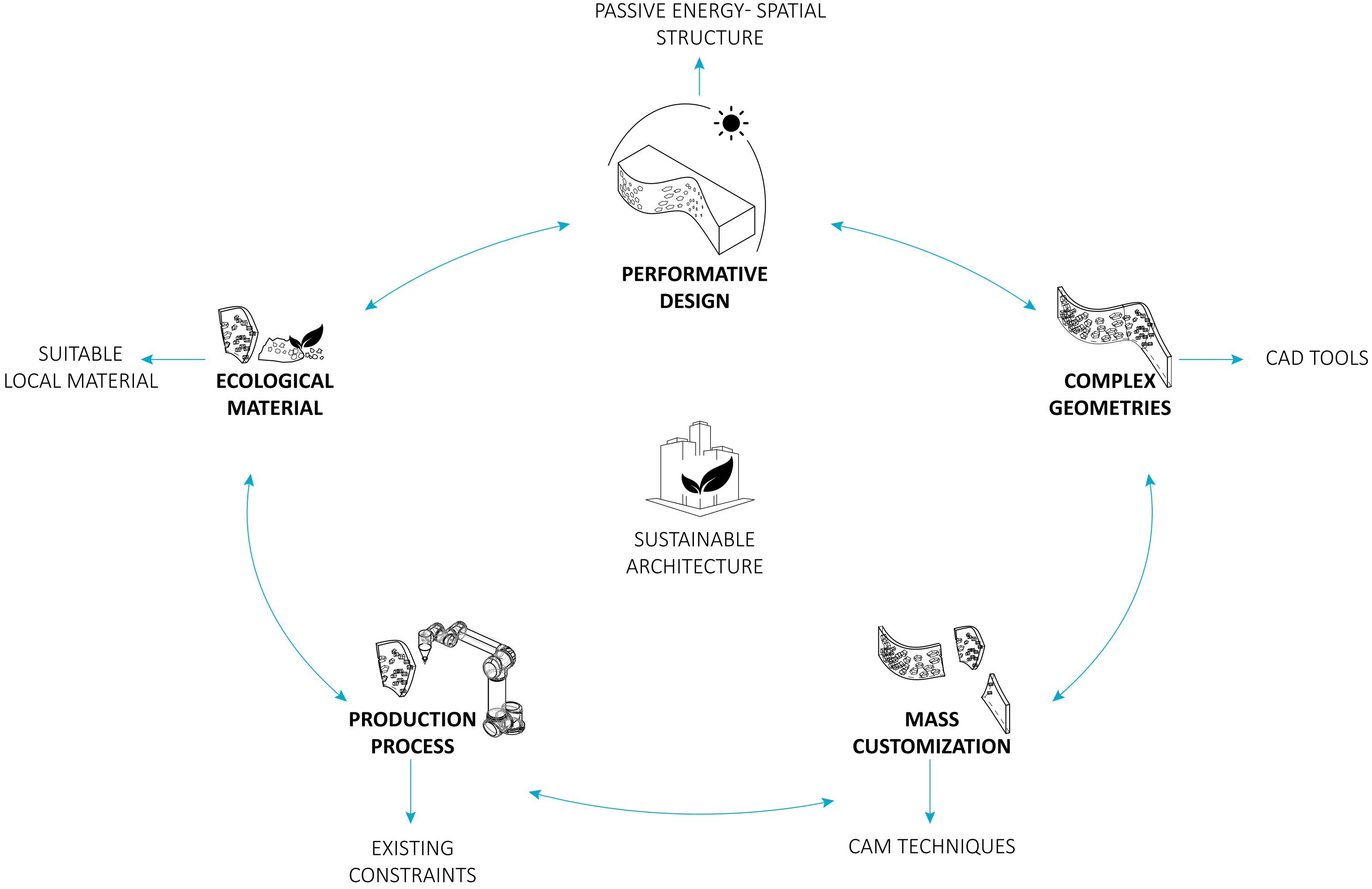
Environmental



Printable

Material Exploration

Behaviour in large scale, and the suitable bio-degradable mixture.



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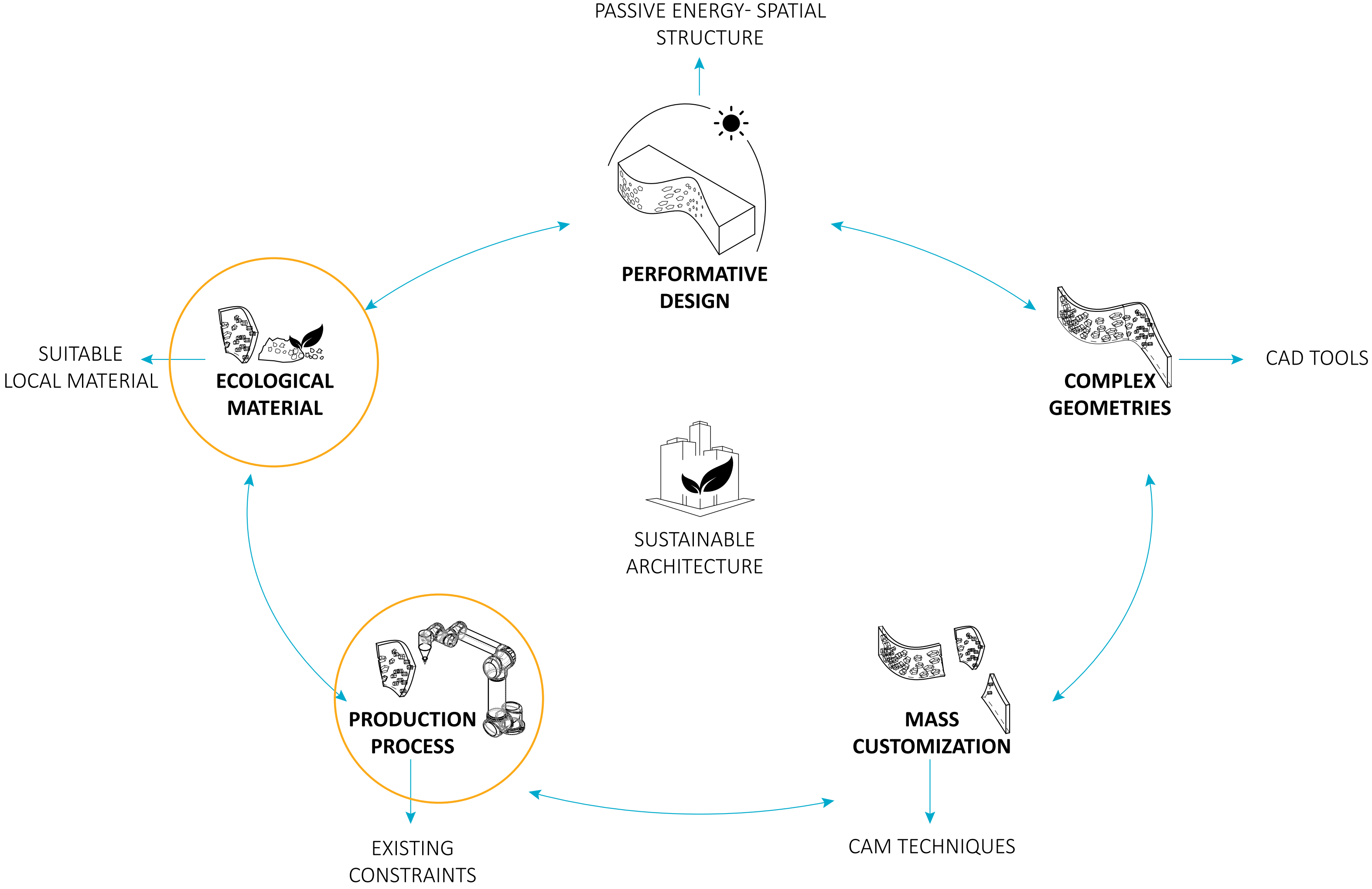

Problem statment

The need for an ecological material, within the 3d printing constraints.

An environment-friendly material is demanded,

Problem statment

An environment-friendly material is demanded, which has to be affordable,

Problem statment

An environment-friendly material is demanded, which has to be affordable, suitable for extrudability -printability-

Problem statment

An environment-friendly material is demanded, which has to be affordable, suitable for extrudability -printability- and performative in architectural and building components.

Problem statment

Concrete industry deploying resources

Cement production will double by 2050


Bekkering Adams concrete fire wall


Wasp 3d printed house

Non-Structural
Concrete

Structural
Clay

Confused exisiting materialisation

Designers & Researchers need to reconsider their approaches


Bekkering Adams concrete fire wall


Wasp 3d printed house

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Non-Structural
Clay

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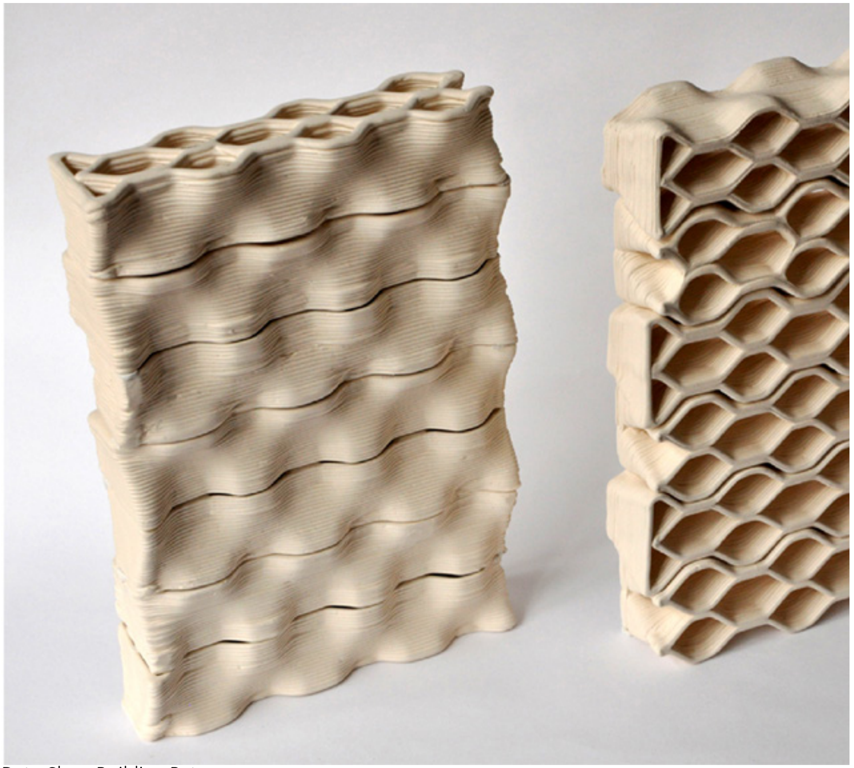
Designers & researchers need to reconsider their approaches


Data Clay: GCODE.Clay


Data Clay : Building Bytes

Clay exploration

3d printed clay objects are for art or small scale architecture bricks.

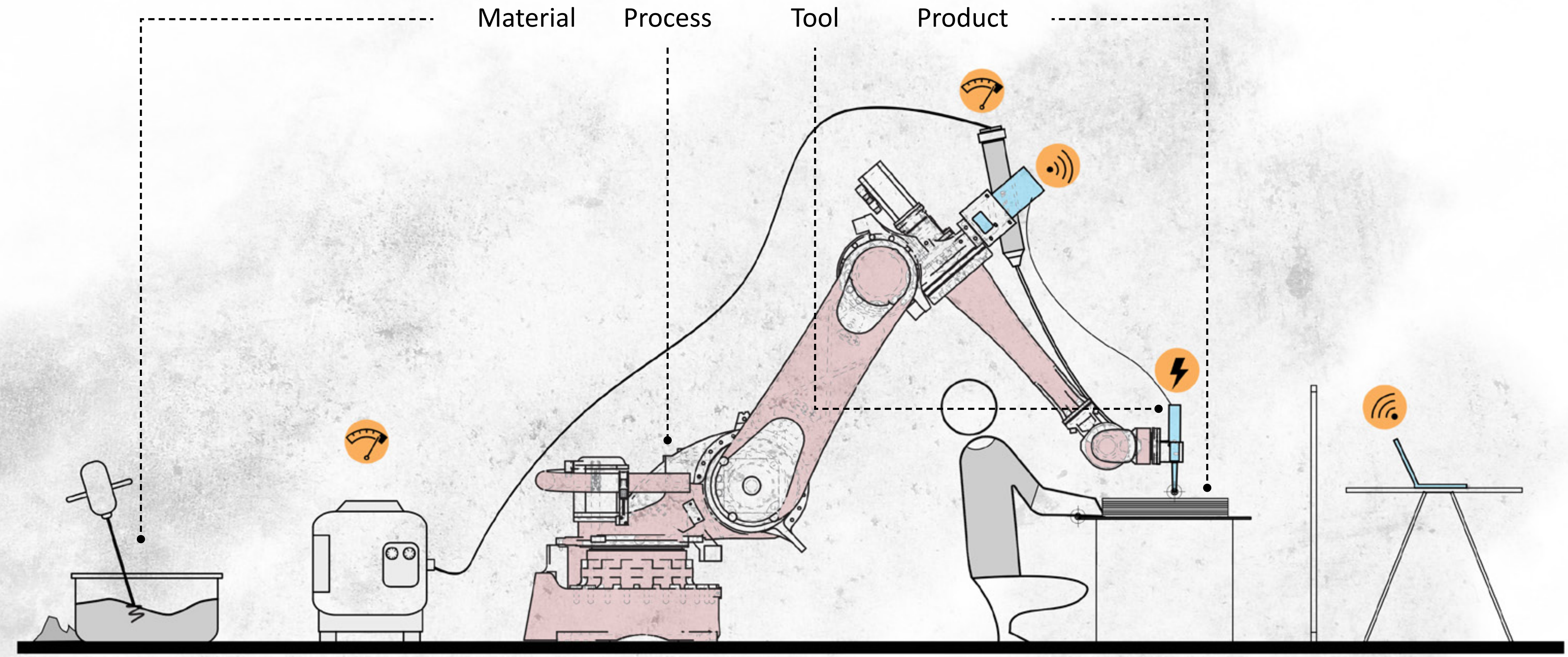
What are the printing techniques and tools that can help integrate the clay as an environmentally friendly material, into the 3d printing of building components,

while maintaining the required indoor and outdoor performance quality?

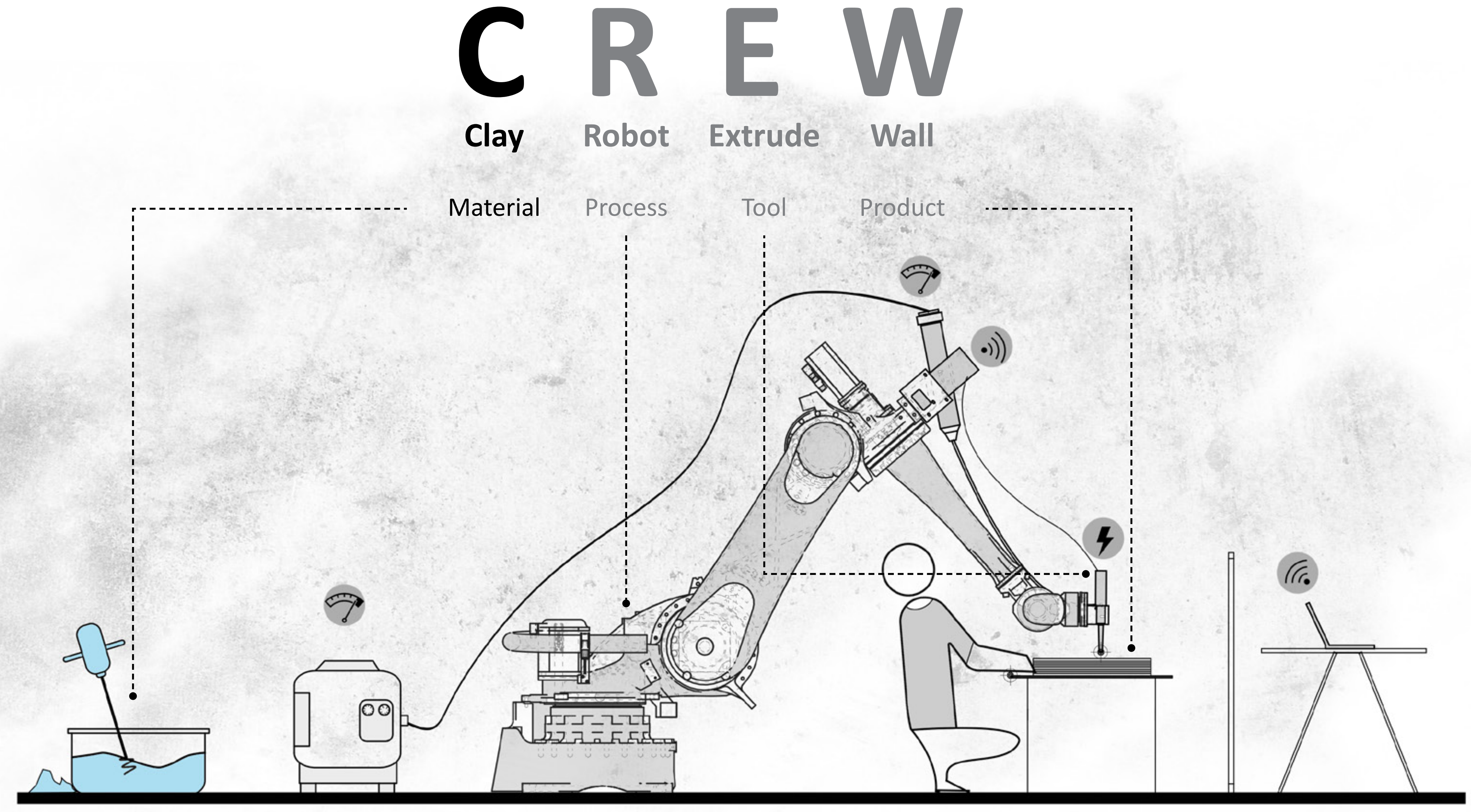
Research Question

C R E W

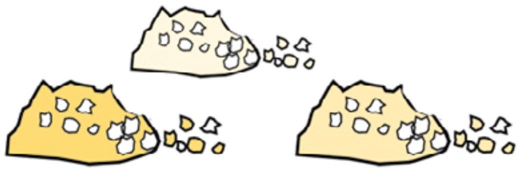
Clay Robot Extrude Wall



Research Sub-Questions



C R E W
Clay Robot Extrude Wall
Material Process Tool Product



Clay Type

Clay Mixture

Exploration objectives

Finding the best clay type for architectural components,
and preparing the mixture for printablity

Earthenware

Stoneware

Kaoline

Clay types

Literature review for material type decision

Earthenware

Stoneware

Kaoline

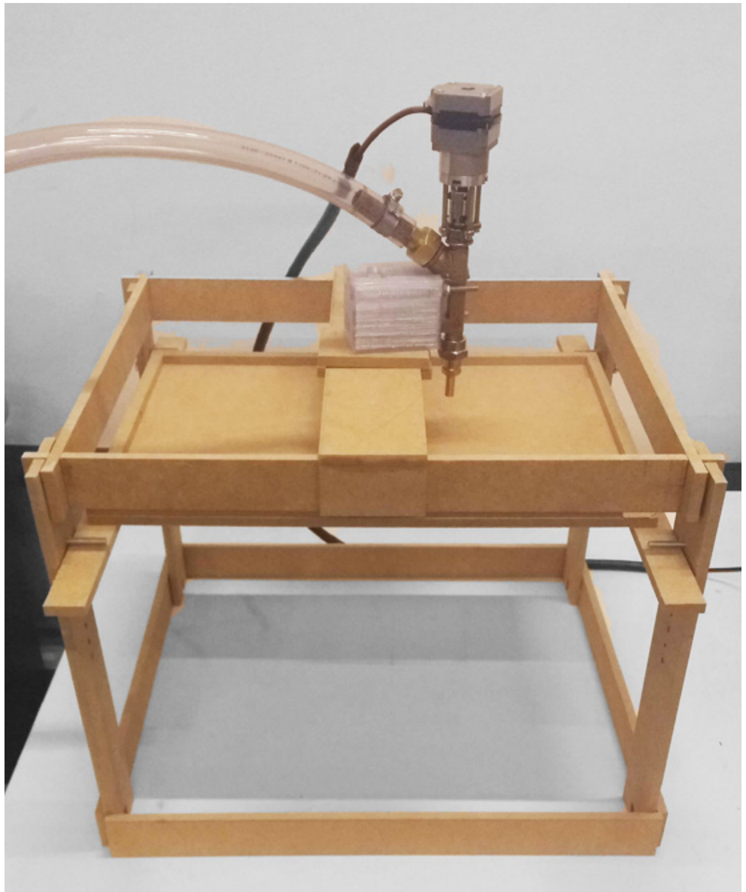
Stoneware Clay

Suitble clay type for exploration

Clay type	Color	Tempera-ture	Plasticity	Availability	Shrinkage	Surface stiffness	Thermal Resistivity
Kaolin	Whites	<1800 °C	Low	Low	Low	Low	2.70 $W^{-1}mK$
Stoneware	Grays	1200 : 1300 °C	Mid : High	High	Acceptable	High	2.58 $W^{-1}mK$
Earthenware	Red-Brown-black	950 : 1000 °C	Low : High	High	N/A	Medium	2.16 $W^{-1}mK$

Suitable for architectural components

Thermal properties, availability, shrinkage, palsticity, surface hardness and appealing color.



Material Experiments

Exploring different mixtures in an analog printing setup,
with motor wifi connection.

Clay to water

Chammote 0.2mm

Wheat flour

Gypsum

Mix1

Water Glass

Chammote 1mm

Gelatine

Saw dust

Mix2

10 clay bodies

7 organic additives and composition in 2 mixtures to choose after evaluation.

Clay to water

Chammote 0.2mm

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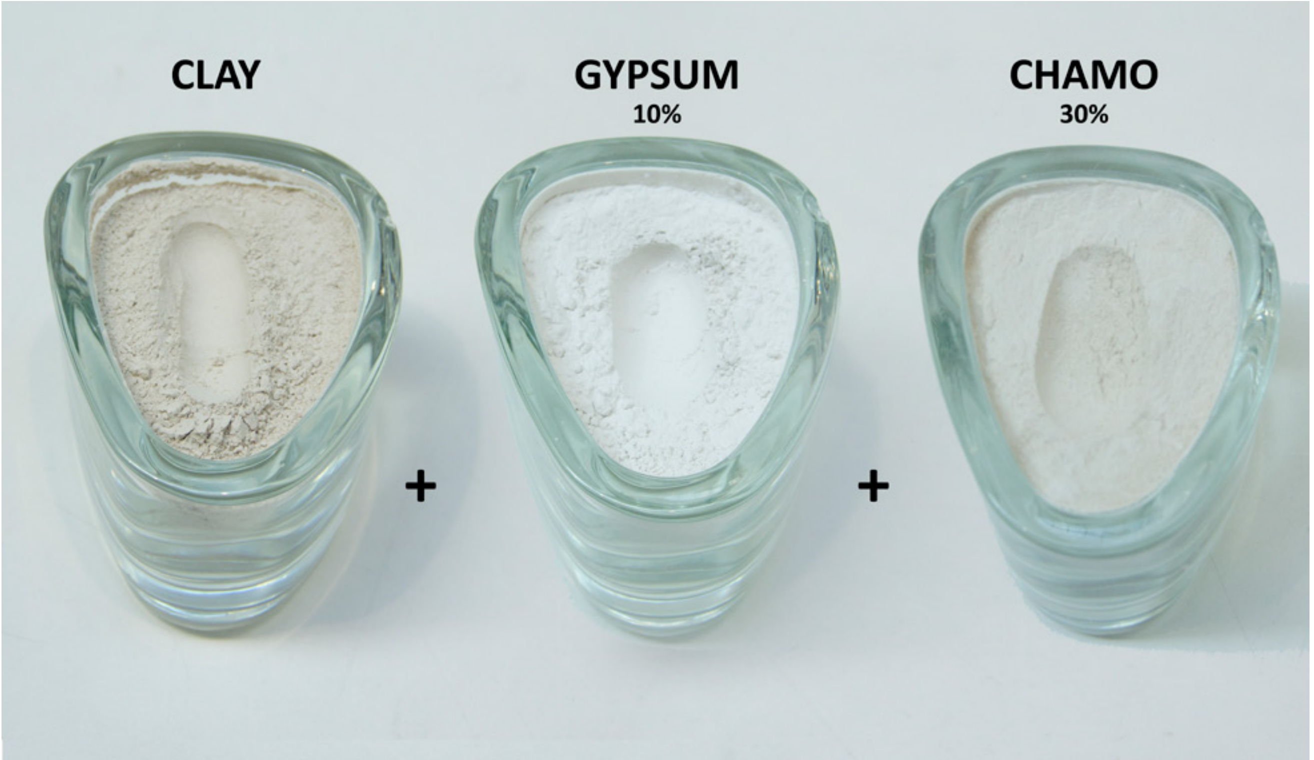
10 clay bodies

7 organic additives and composition in 2 mixtures to choose after evaluation.

Phase	Material	Function	Constants							Variables																	
										Controled						Observation											
			Layer Height mm	Nozzle size mm	Flow | Extruder speed mm/s	Observation time H	Number of layers	Air Pressure bar	Clay weight gm	Water gm	Additive	Additive %	Water % of clay	Water % of total body	Additive rec. %	before (sample + plate weight)	after (sample + plate weight)	sample weight	sample weight loss %	Ball weight loss %	average weight loss	Flow rate gm/s	Shrinkage % 24 H	Plasticity 1:5	Cracking 0-4	Line continuity 1:5	Building Speed Layer/minute
Clay Body	Stoneware - KP101	Main clay body	-	5	400	-	-	6	500	125	-	-	25%	25%	25-30%				-	-	-		-	1	-	-	-
			-	5	400	-	-	6	500	150	-	-	30%	30%	25-30%				-	-	-	-	-	1	-	-	-
			5	5	400	24 -48 H	6	6	500	175	-	-	35%	35%	25-30%				-	220	-	-	11%	3	0	4	
			-	5	400	-	-	6	500	200	-	-	40%	40%	25-30%	-	-	-	-	-	-	-	-	5	-	-	-
Solo - Additives	Chammote 0 - 0.2 mm	less shrinkage - less cracks - surface hardness	5	5	400	24 -48 H	7	5-6 bar	300	110	100	33.4	37%	27.50%	20 - 40	1000	952	270	17.8	14.3	16.05	8	4.6	4	1	4	0.21
	Gypsum	less shrinkage - less drying time	4	5	800	24 -48 H	4	5-6 bar	300	95.7	30	10	32%	29.00%	10 W	928	892	198	18.2	18.2	18.2	10.5	7.2	3	0	4	0.27
	Saw dust	Better density - less cracks	4	5	400	24 -48 H	5	5-6 bar	300	100	15	5	33%	32.00%	N/A	926	888	196	19.4	21.5	20.45	9.8	6.3	4	1	3	0.25
	Wheat	less shrinkage - less cracks - better binding	4	5	800	24 -48 H	3	5-6 bar	300	140	30	10	46.50%	42.50%	6 - 20 W	860	832	130	21.6	27.5	24.55	3.9	8.1	2	3	2	-
	Water glass(Sodium Silicate)	dispersant - less shrinkage - better viscosity	4	5	400	24 -48 H	5	5-6 bar	410	127.1	.25 cap	-	31%	31%	5%	-	-	-	-	16.7	-	-	8.4	3	0	5	0.84
	Chammote 0 - 1 mm	less shrinkage - less cracks - surface hardness	-	5	400	24 -48 H	-	5-6 bar	300	110	100	33.4	37%	27.50%	20 - 40	-	-	-	-	18.5	-	-	4.6	-	-	-	-
	Gelatin	better strength (Binding) - better viscosity	-	5	400	24 -48 H	-	5-6 bar	300	86.5	15	5	29.00%	27.50%	3 - 5	-	-	-				-	-	1	-	1	-
Mix - Additives	cham0.2+gypsum	chamotte 0.2 mm	4	5	400	24 -48 H	4	5-6 bar	250	105	75	30%	42%	30%	-	934	890	204	21.6	9.4	15.5	18.6	7.3	3	0	3	0.4
		gypsum									25	10%			-												
	cham0.2+saw dust	chamotte 0.2 mm	4	5	400	24 -48 H	7	5-6 bar	250	114	75	30%	46.50%	34%	-	1014	952	284	21.9	8.2	15.05	14.2	4.6	2	0	3	0.35
		Saw dust									12.5	5%			-												

10 clay bodies

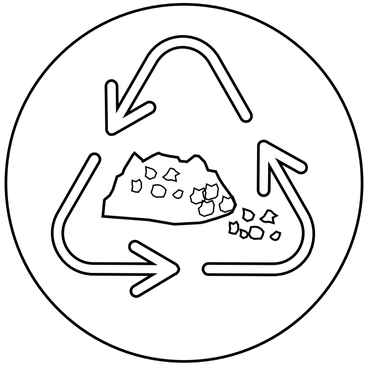
7 organic additives and composition in 2 mixtures to choose after evaluation.



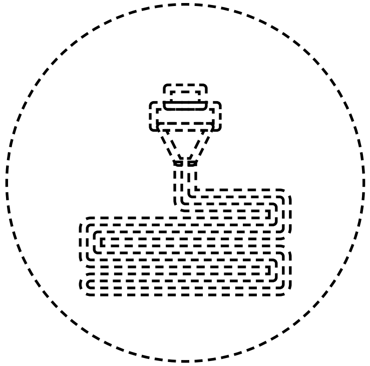
Final mixture

Recommended mixture is used for prototyping in larger scale.

Affordable



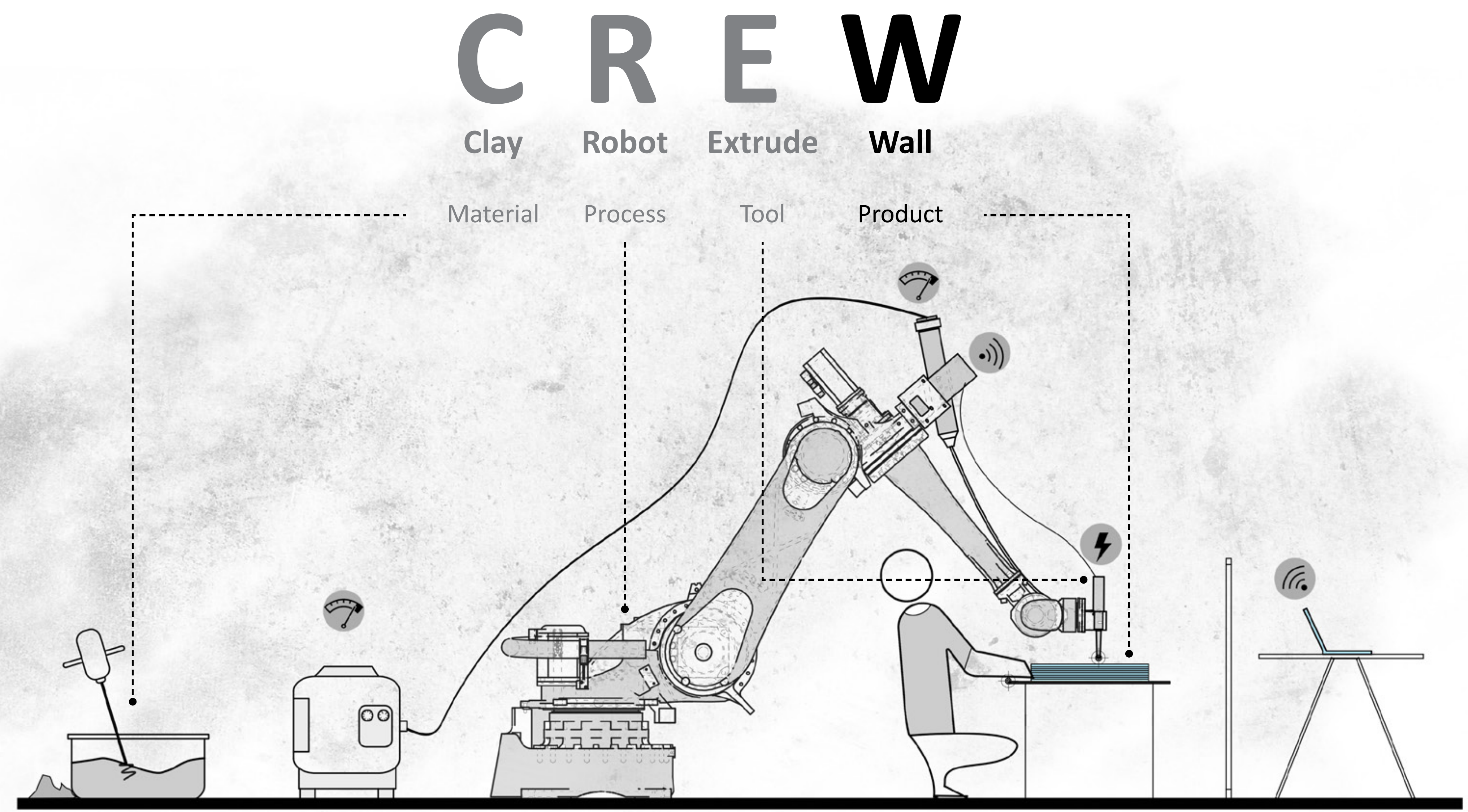
Environmental

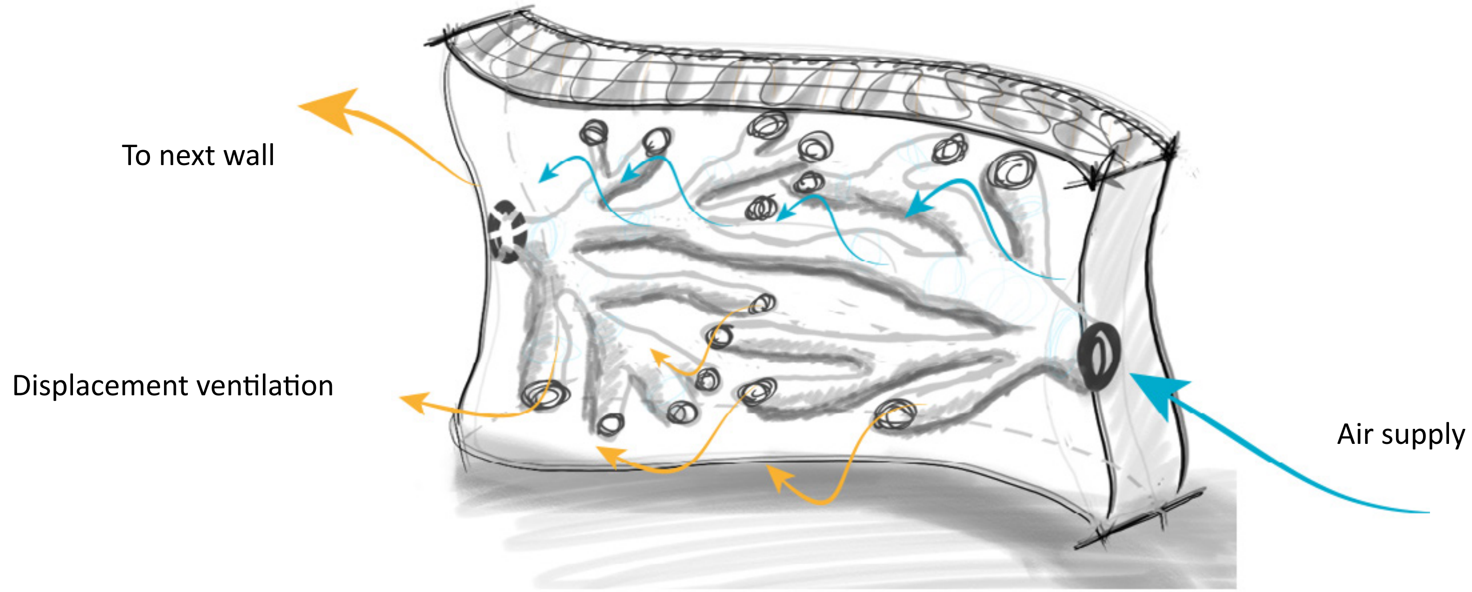


Printable

Printability behaviour in large scale

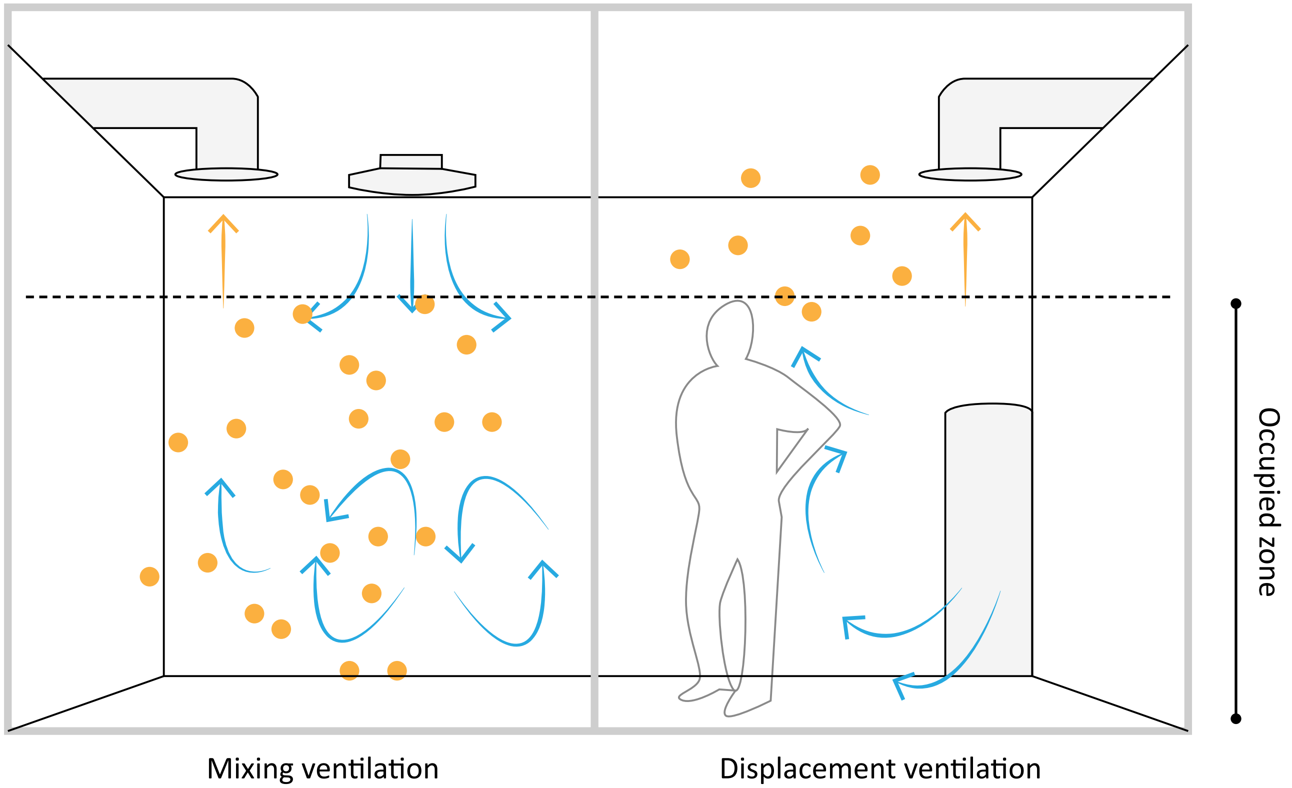
The mixture recommended is biodegradable, and affordable.


C R E W
Clay
Robot
Extrude
Wall
Material
Process
Tool
Product



Initial design concept

Inner ducts over facade walls in a continuous network



Displacement ventilation system

Better indoor air quality & more energy efficiency

Advantages

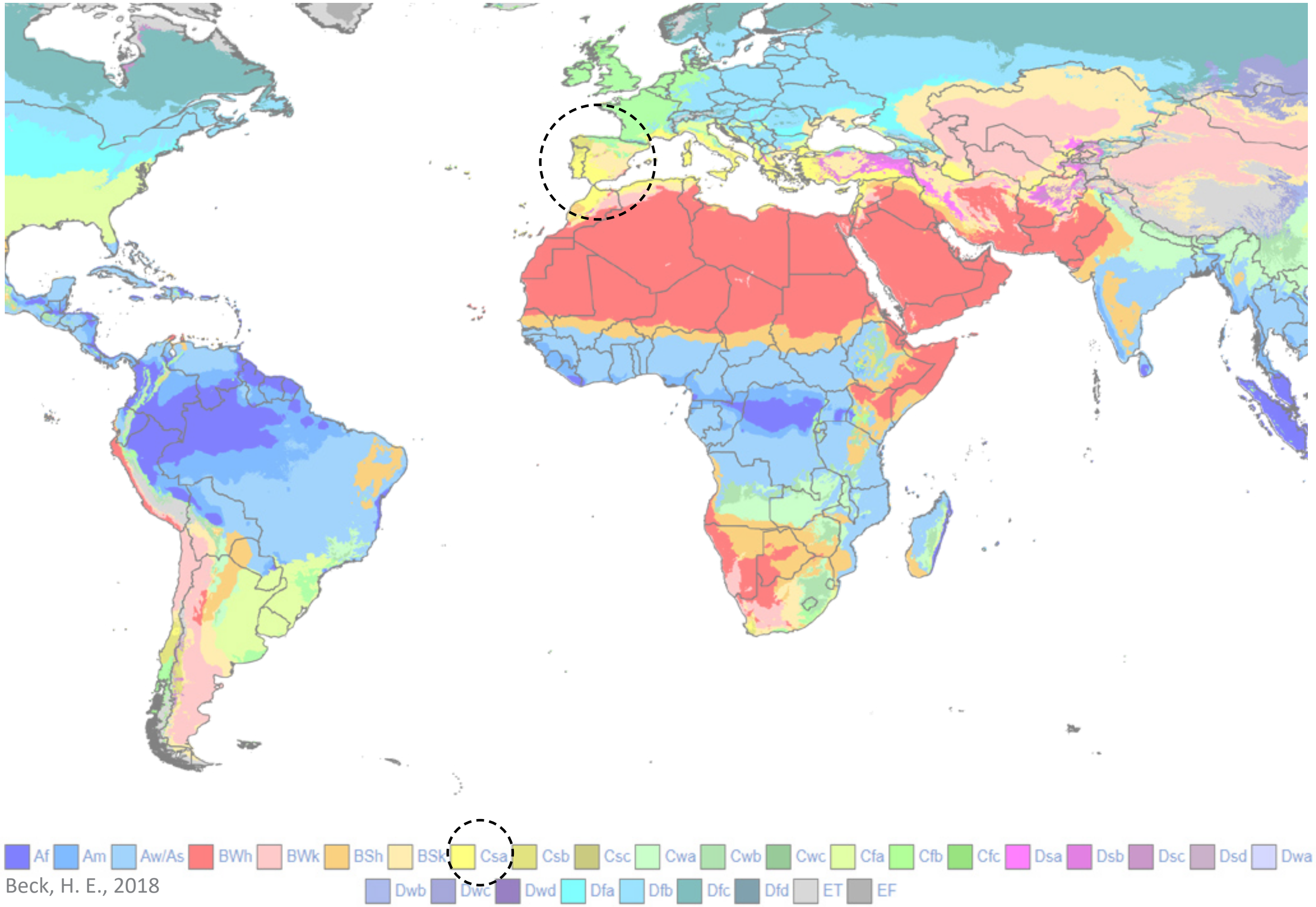
- Indoor air quality
- Low energy consump.
- More chiller efficiency
- Lower noise levels

Limitations

- Ceiling Height > 2,75m
- Room depth < 8m
- Opaque wall area
- Low velocity supply

Limitations considered for design

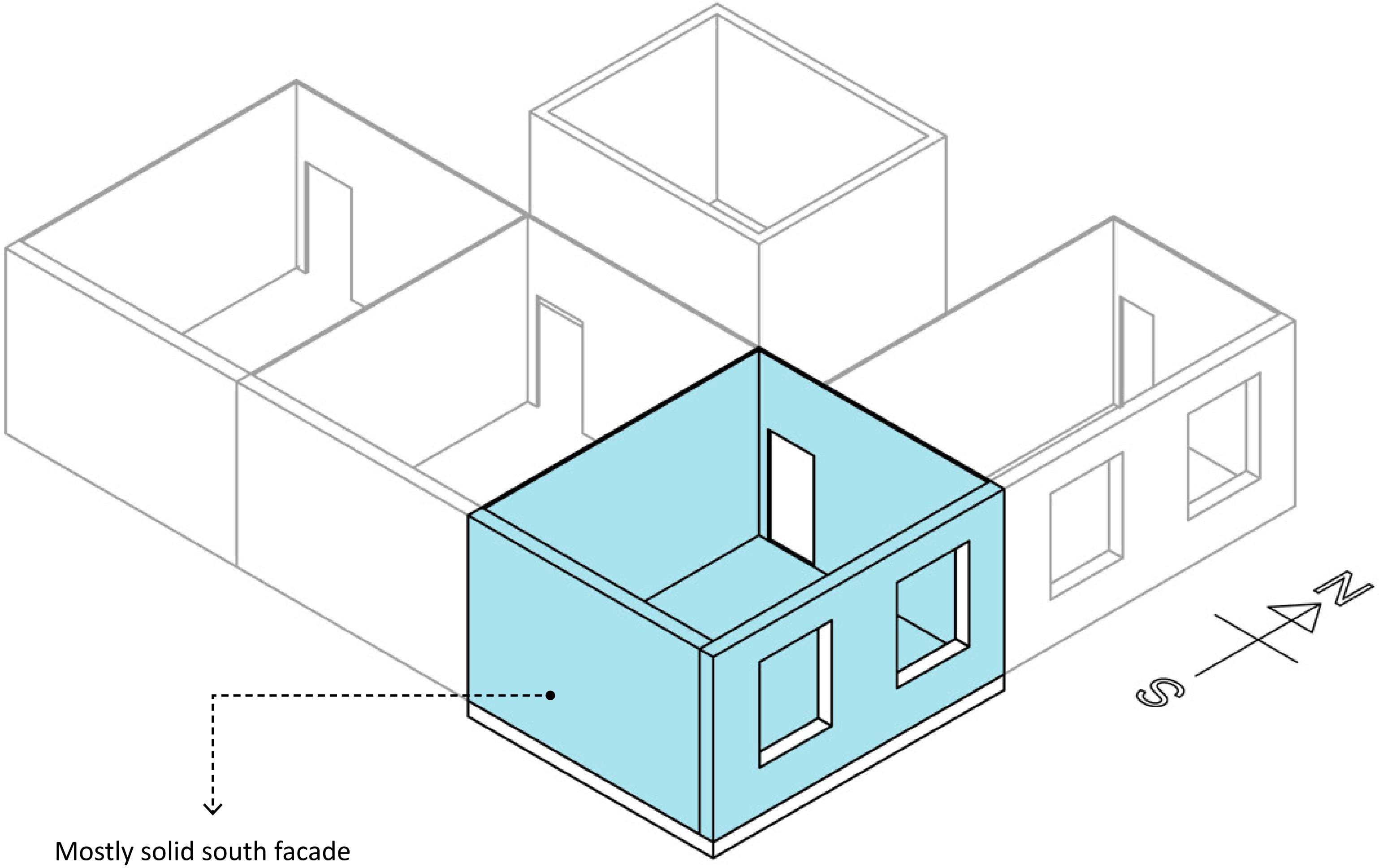
These considered in the wall & room case study design.



Beck, H. E., 2018

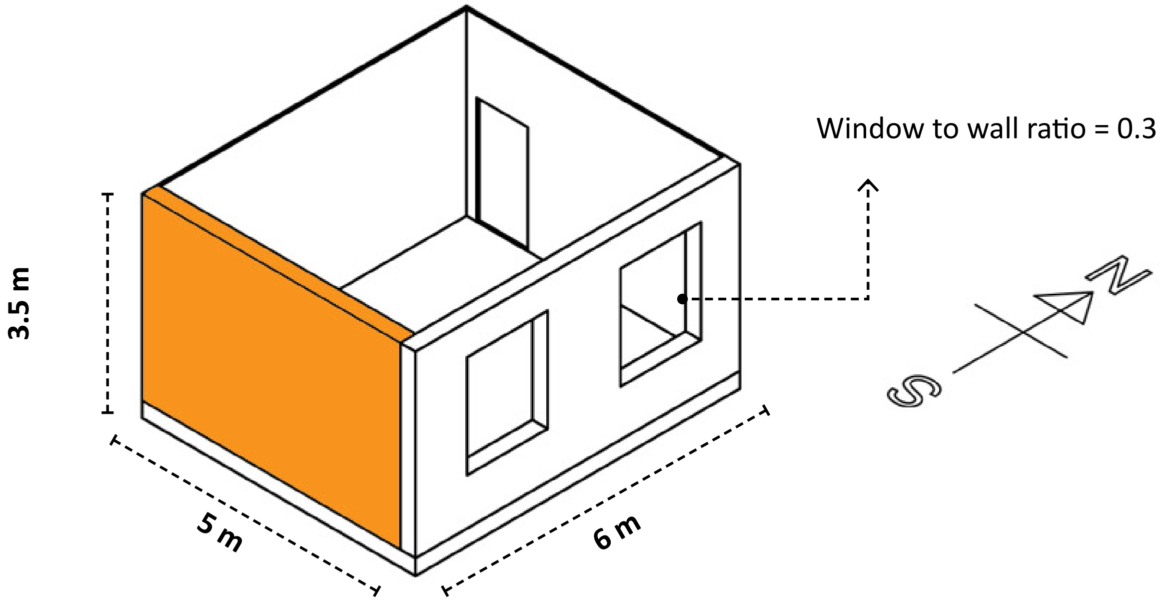
Case study location

Seville, Spain.
Mediterranean Climate Csa with hot dry summer and rainy moderate winter



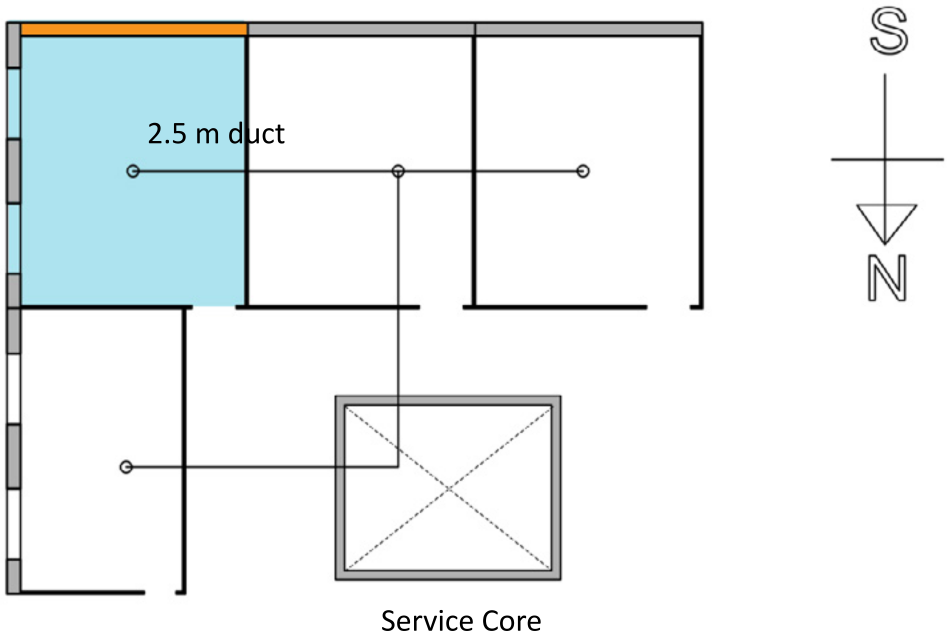
Corner room

Assuming a case of a corner office meeting room and designing its south facade.



30 m² office room

UK & US standards aim for 9 m²/person
3 persons in a group meeting room



Conventional duct design

Assuming a conventional distribution system for air into the rooms.

Function	Value	Unit
Total cooling load (Design Builder)	995.7	kWh
Total hours at or above 26	978.5	h
U-Value	0.73	$W/m^2.k$
Total cooling load	1.017577925	kW
Cp (specific heat capacity of air)	1.026	KJ/kgK
Supply air temperature	18	°C
Room air temperature	26	°C
ΔT	8	°C
m (mass flow rate)	0.1239739188	kg/s
Air dynamic Viscosity	1.83E-05	kg/m-s
Reynolds number	39,452.1	
ρ (Density of the air)	1.2	Kg/m^3
Specific Volume	0.8333333333	m^3/Kg
V (Volume flow rate)	0.103311599	m^3/s
L (length of duct)	2.5	m
Air Supply Velocity	3	m/s
P (Pressure Drop)	**0.06**	**mm water/m**
	0.6	**Pa/m**
D (Duct Diameter)	**0.2**	**m**

Design Builder analysis (Total cooling load (Design Builder) to Total cooling load)

Literature review / Calculation requirements (Cp to V (Volume flow rate))

Designed case study (L (length of duct))

Literature review (Air Supply Velocity)

Friction loss chart (P (Pressure Drop) to D (Duct Diameter))

Design & Verification criteria

Duct diameter required for the conventional design technique as a base for the wall system design.

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Total hours at or above 26	978.5	h
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L (length of duct)	2.5	m
Air Supply Velocity	3	m/s
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Literature review / Calculation requirements (Cp – V (Volume flow rate))

Designed case study (L (length of duct))

Literature review (Air Supply Velocity)

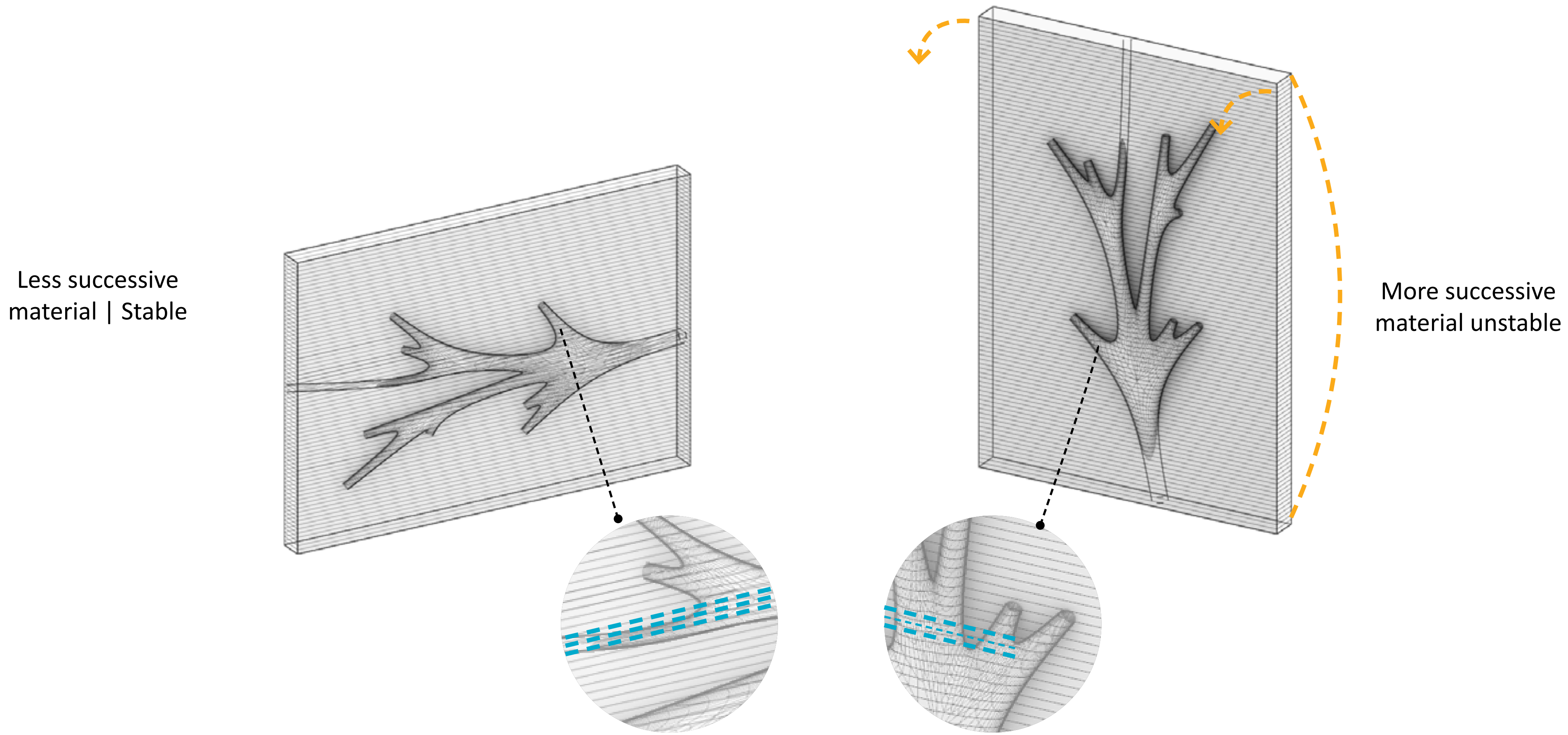
Friction loss chart (P (Pressure Drop) – D (Duct Diameter))

Design & Verification criteria

Calculated pressure drop value is used for the CFD analysis to verify the performance of the wall design.

Morphology

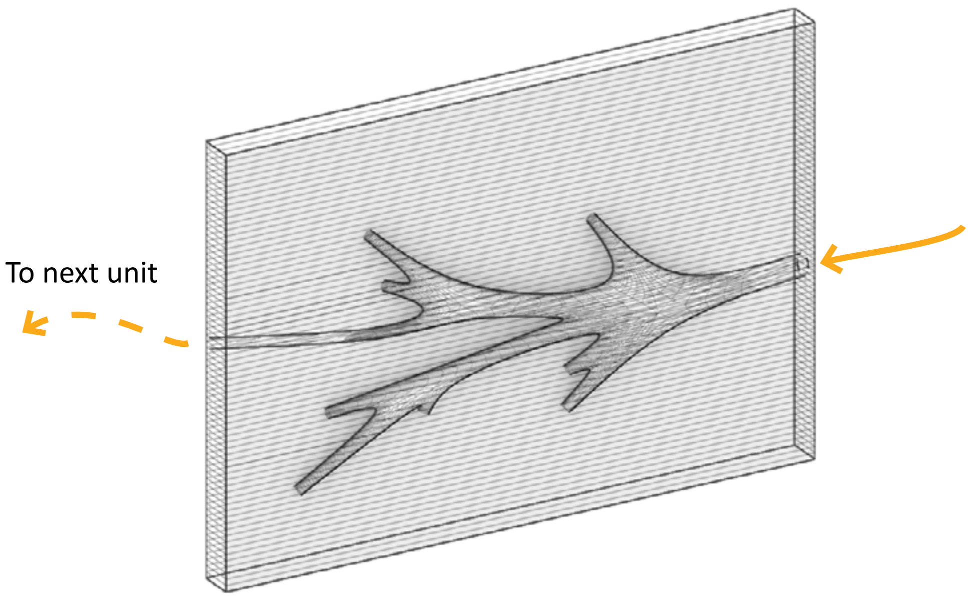
Design principles



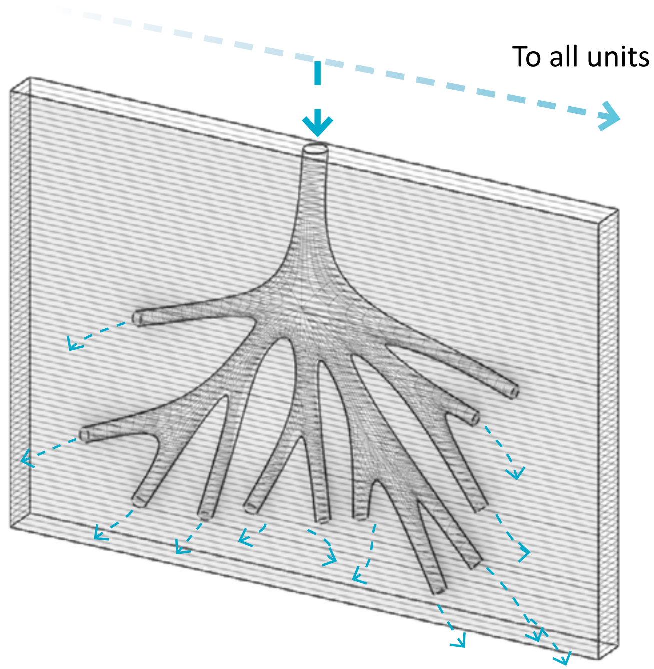
Direction of layers affecting overhangs

1. Printing orientation

Printing direction affects the stability behaviour while building up the print. it also affects the support for the overhangs to be printed.



Initial concept

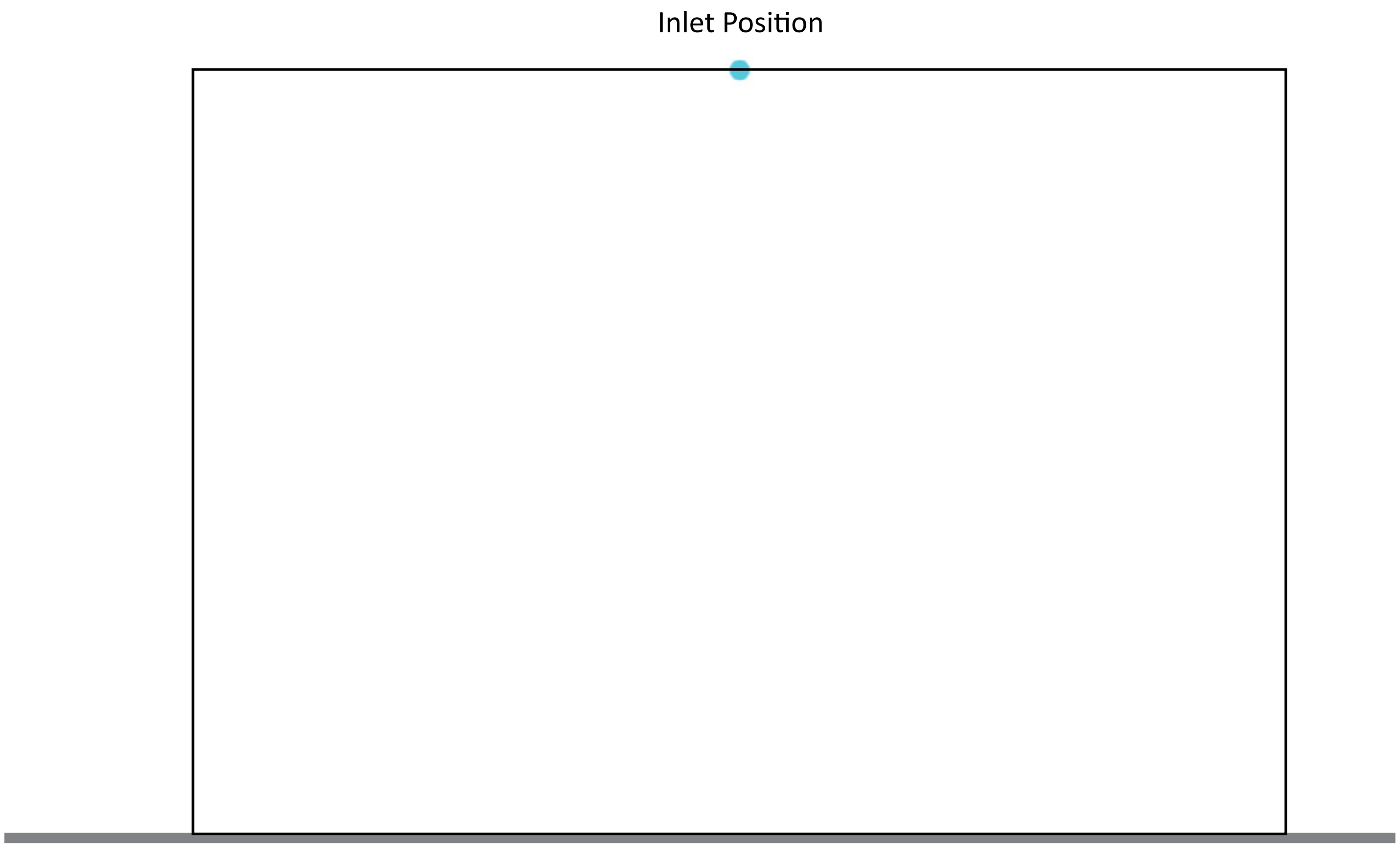


Concept developed

2. Distribution direction

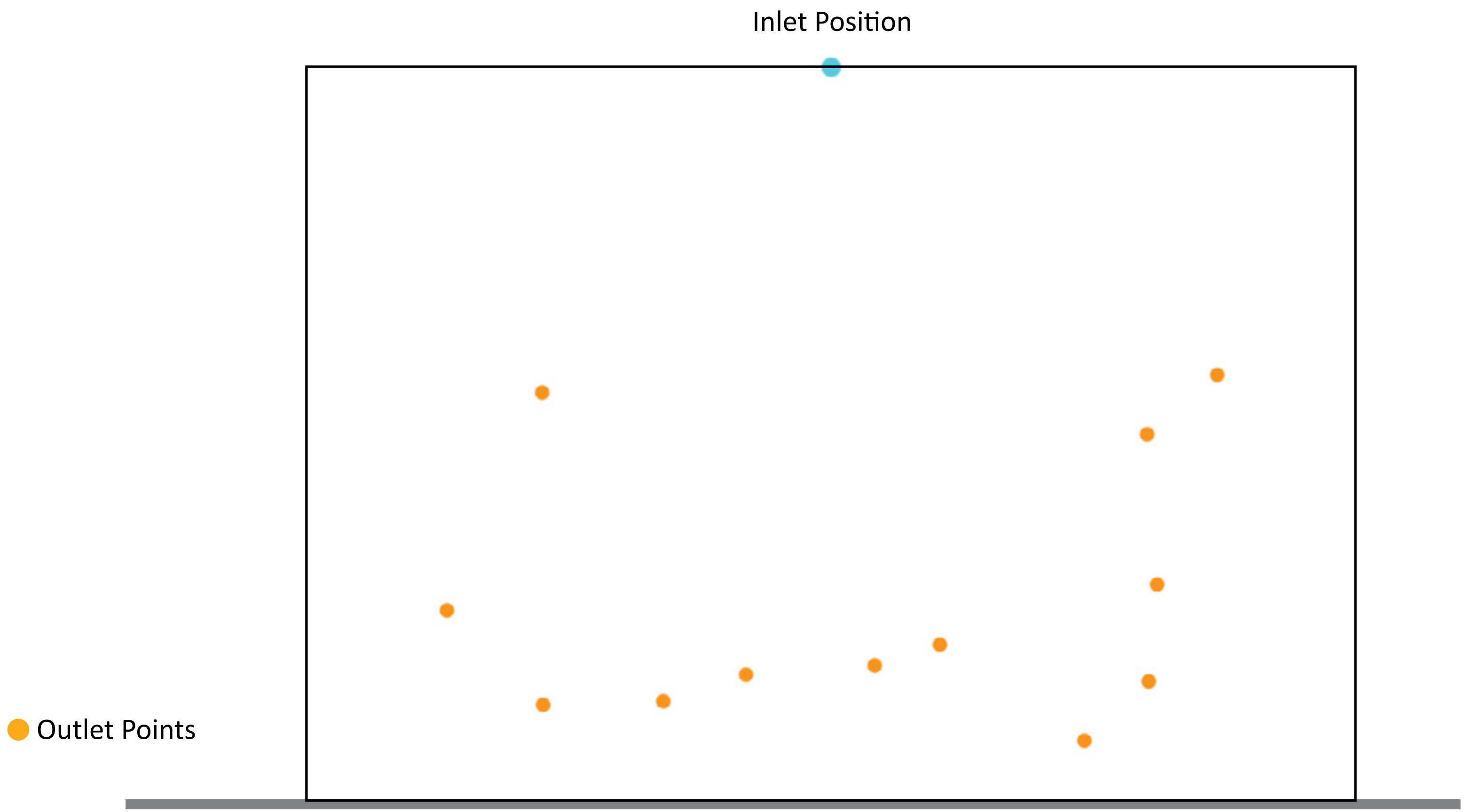
Continuous supply over the inner ducts through facade,
causes high pressure losses and different supply rates.

Principles as a generative script?



3. Shortest walk & opening height

Shortest walk among network of Proximity links between inlet and outlet points created, assure less friction losses and pressure drop.



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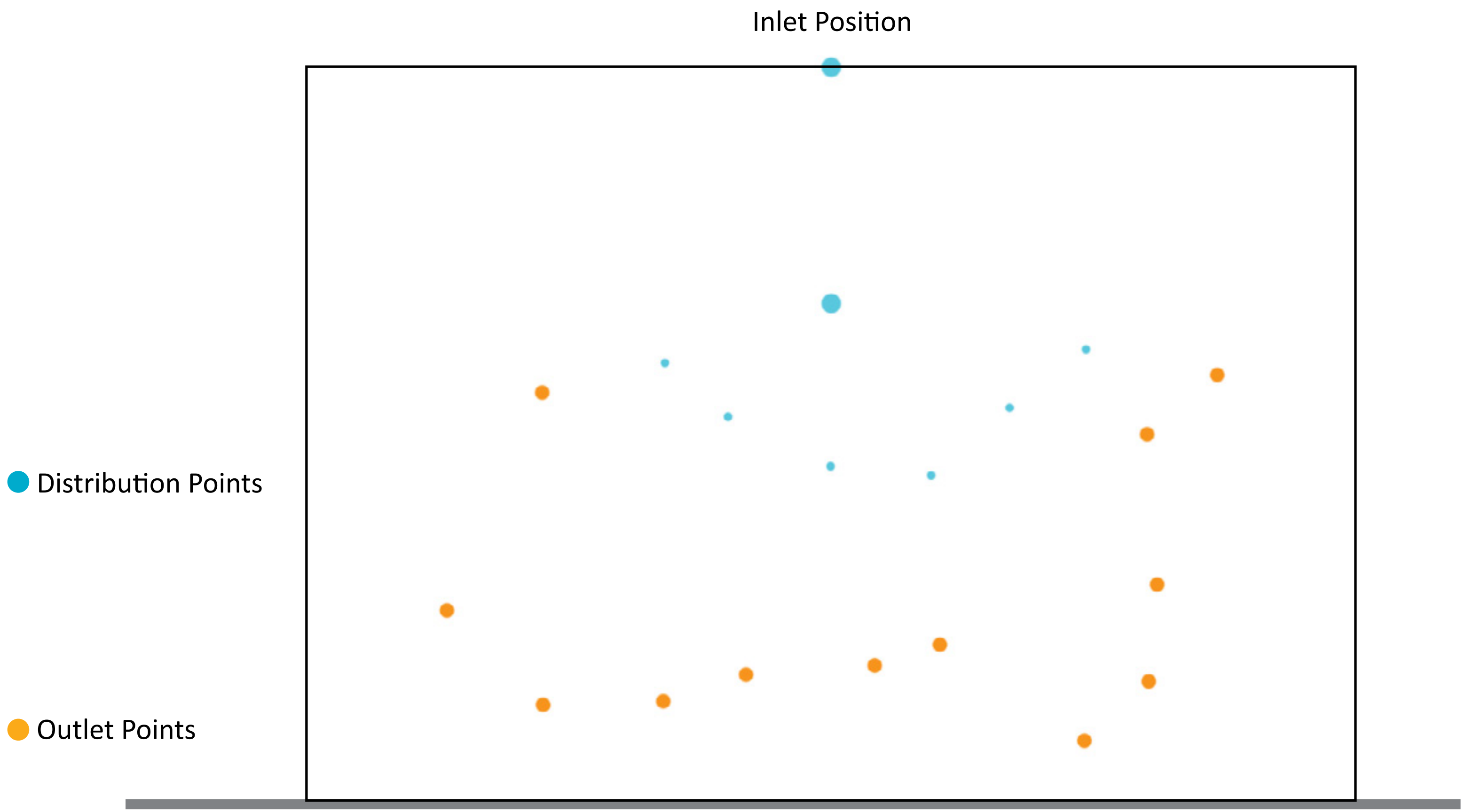

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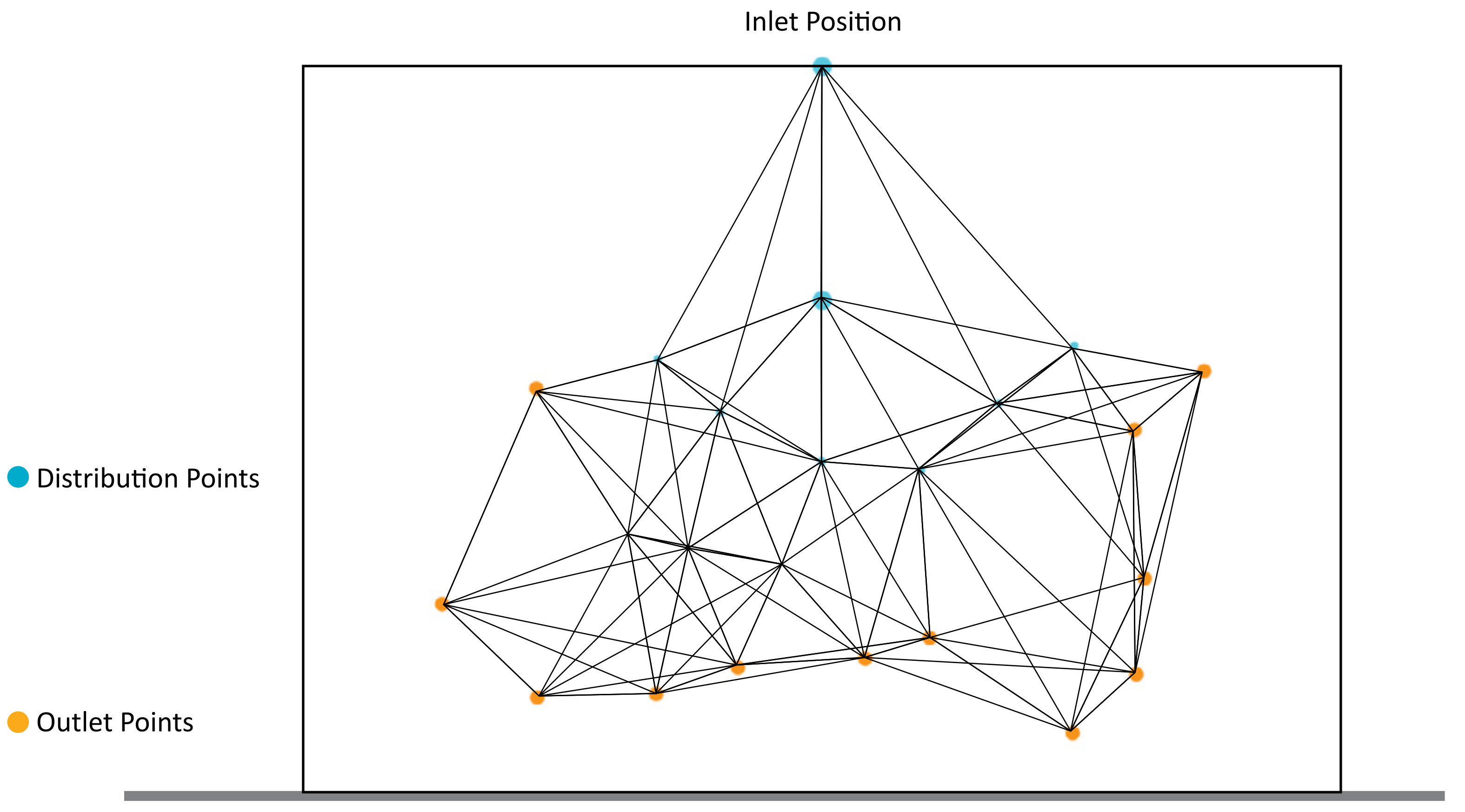
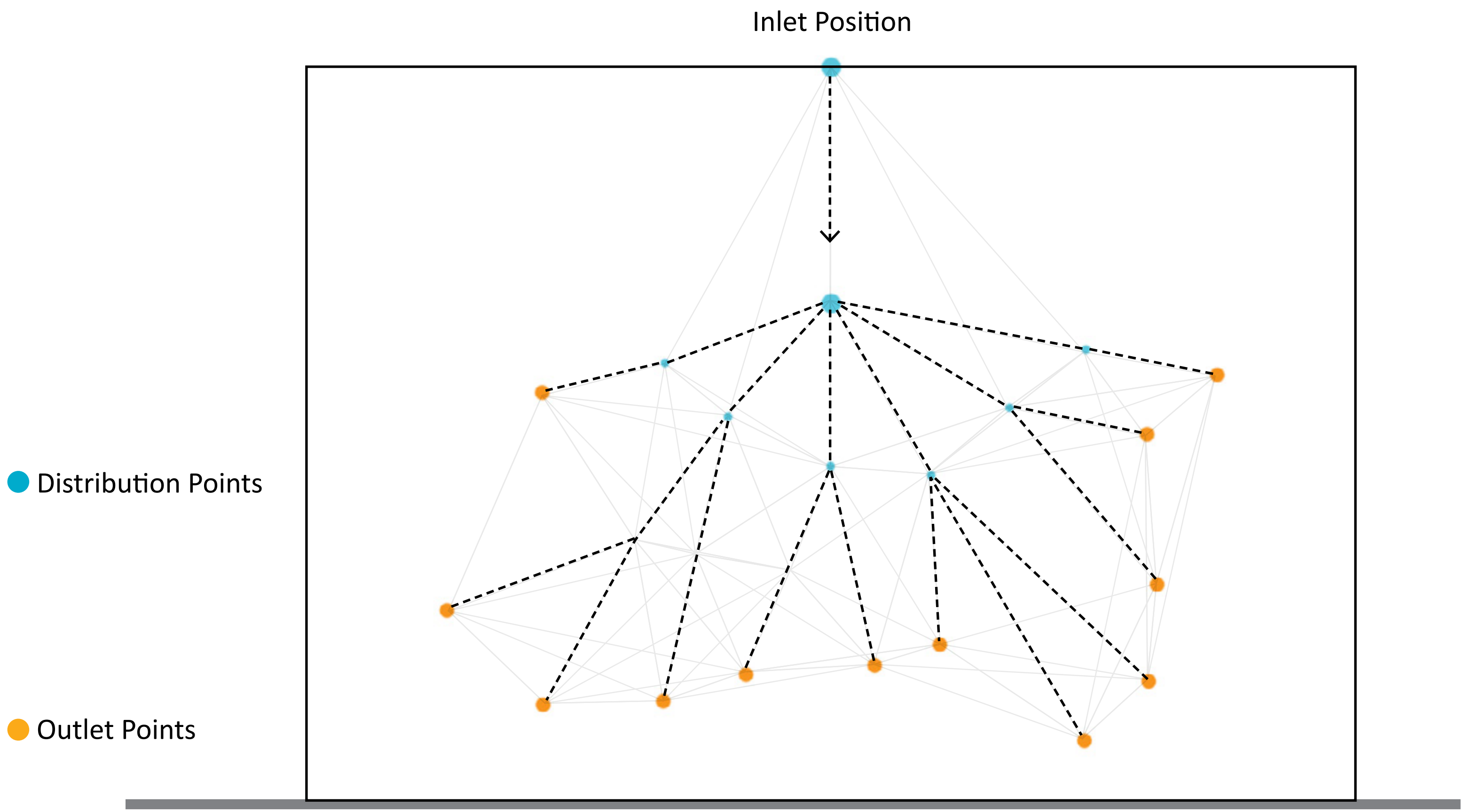


3. Shortest walk & opening height

Shortest walk among network of Proximity links between inlet and outlet points created, assure less friction losses and pressure drop.



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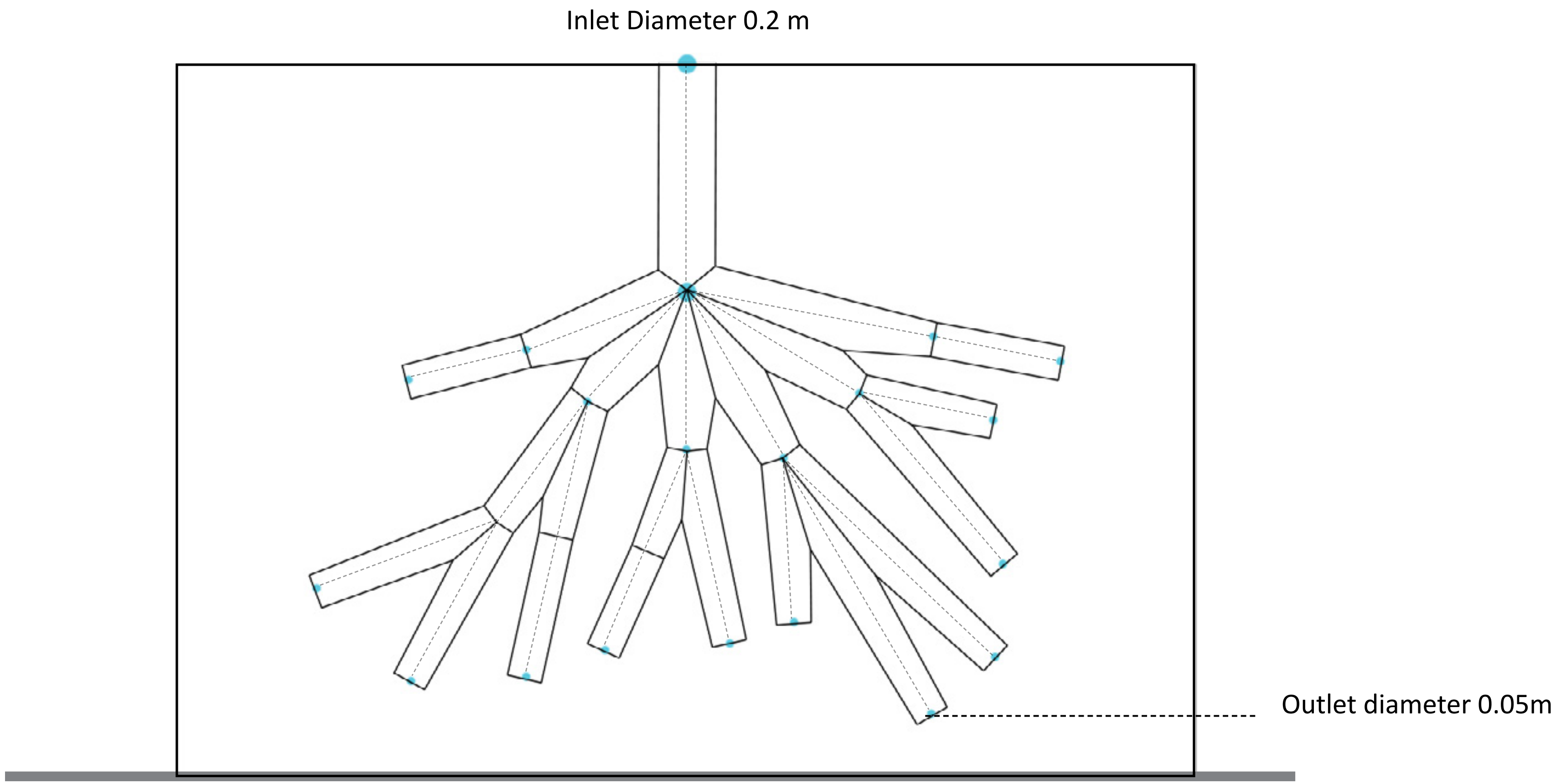
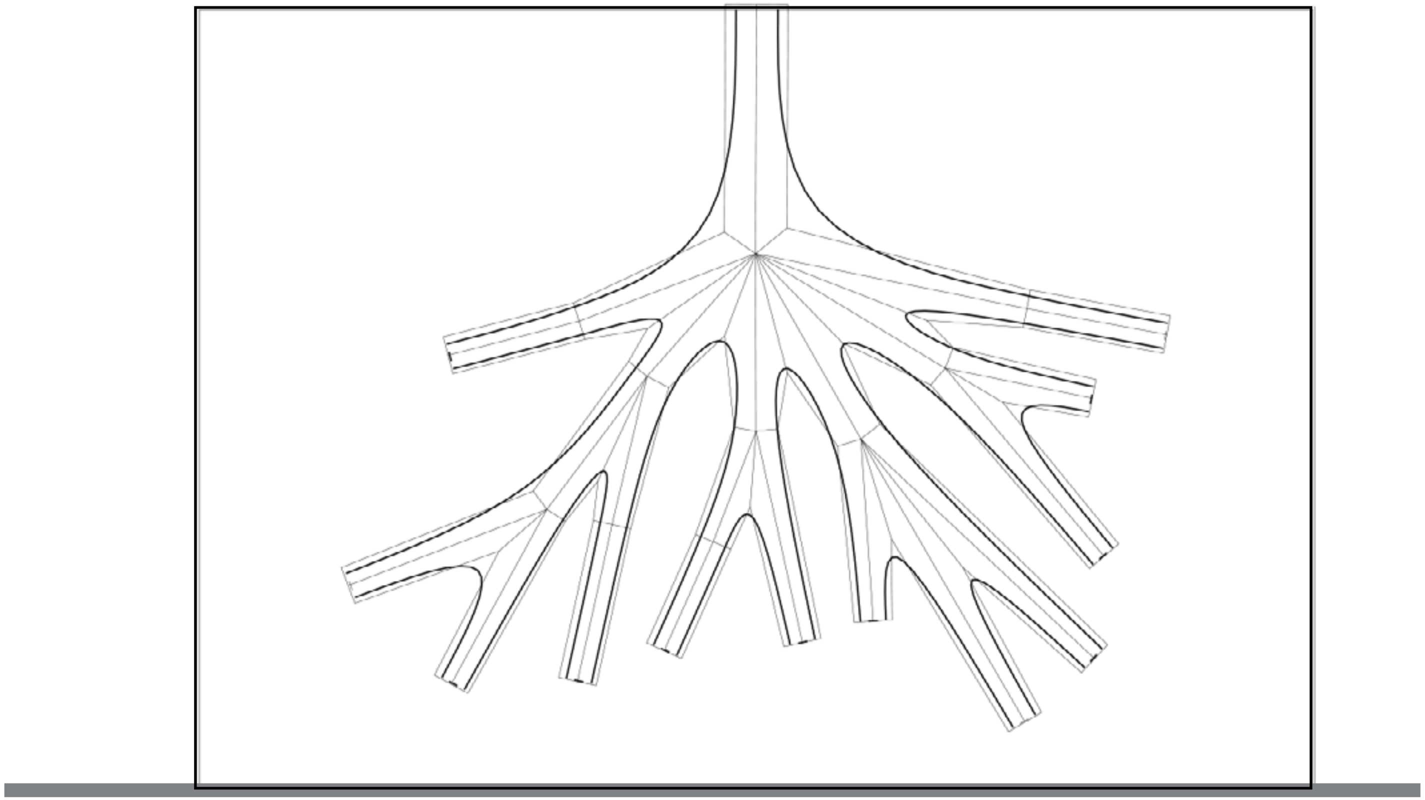


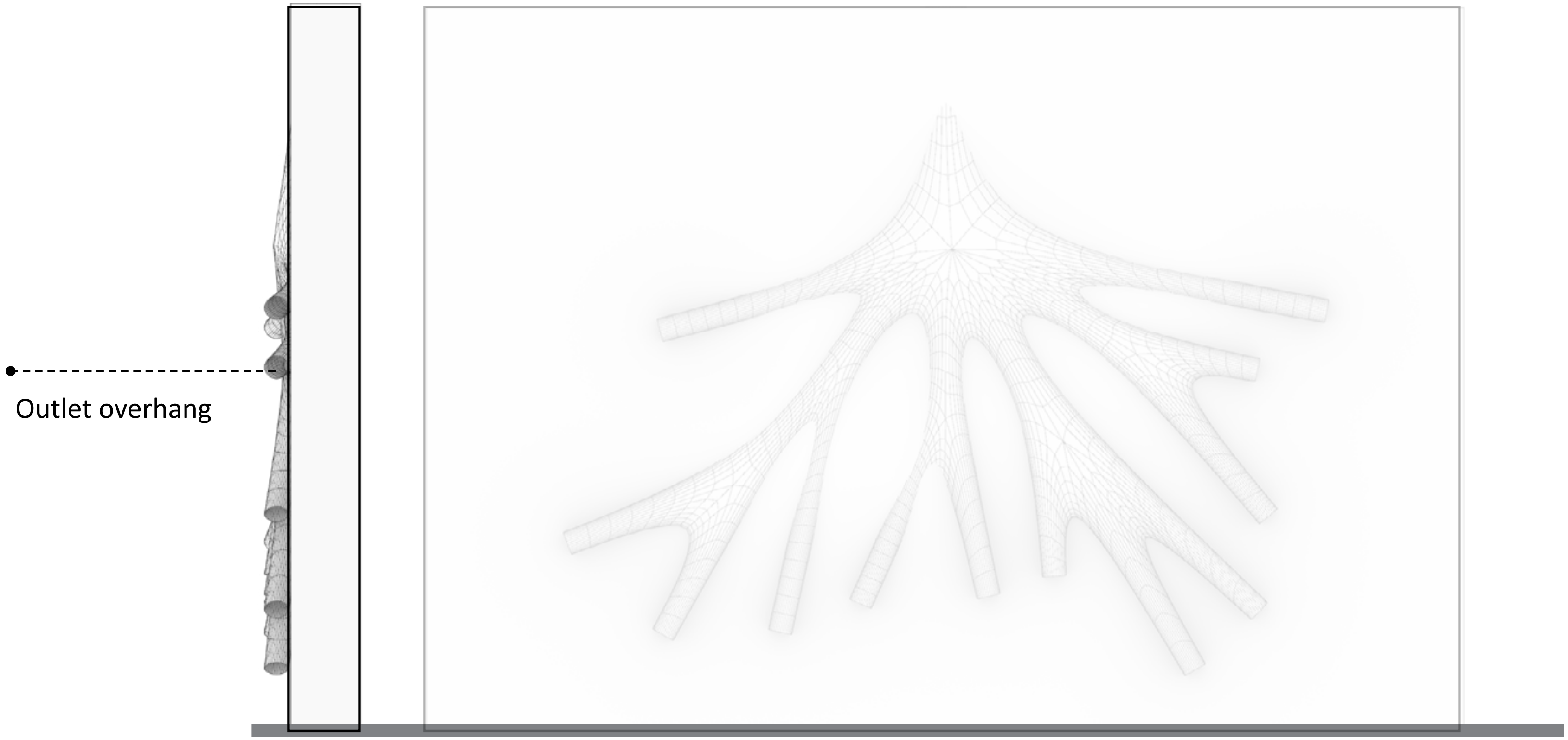
4. Inlet to outlet area ratio

Inlet diameter derived from the initial calculations for the duct design, the outlet diameters are smaller to assure better air distribution by pressure.



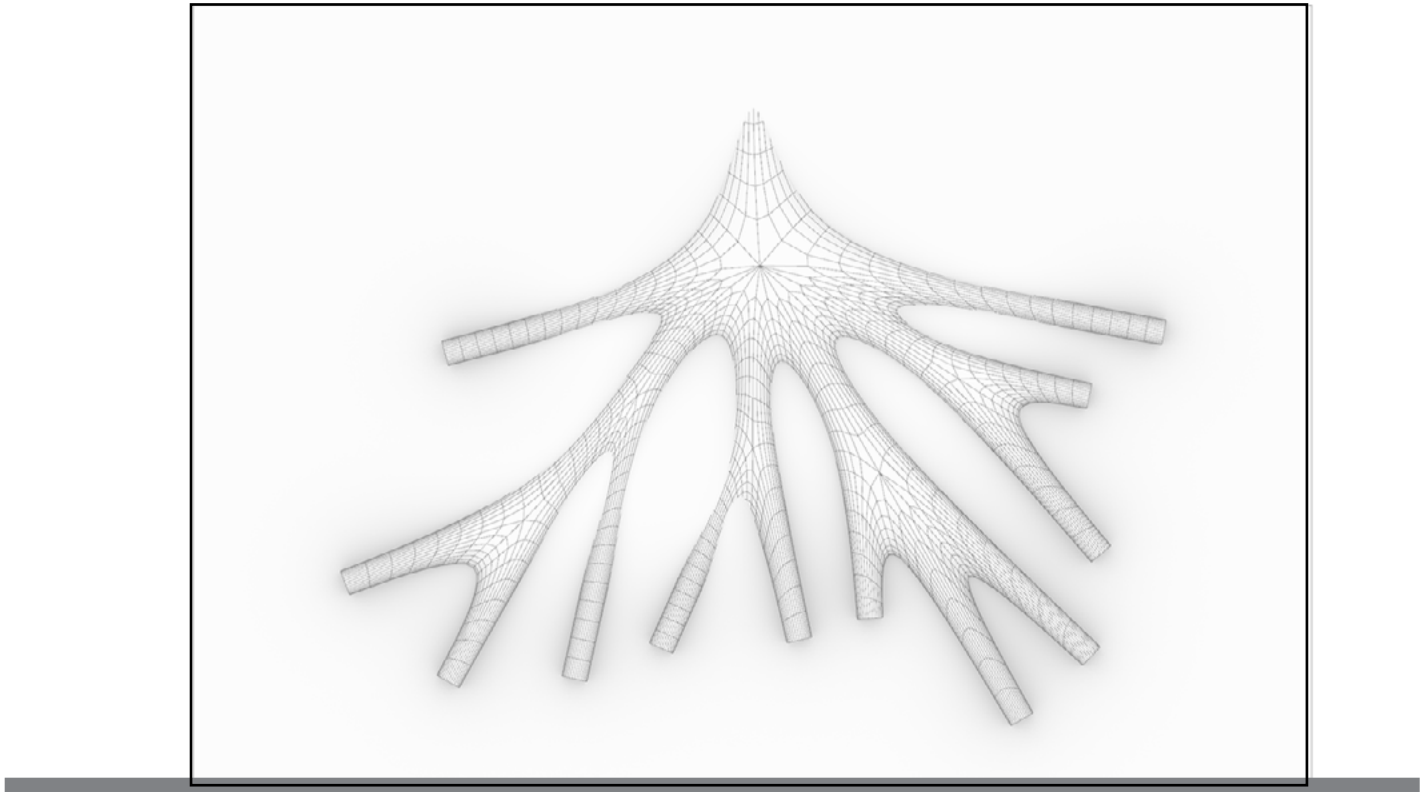
5. Smooth edges

Smooth corners and avoiding sudden corners or turns to
reduce the turbulent effect and pressure losses.

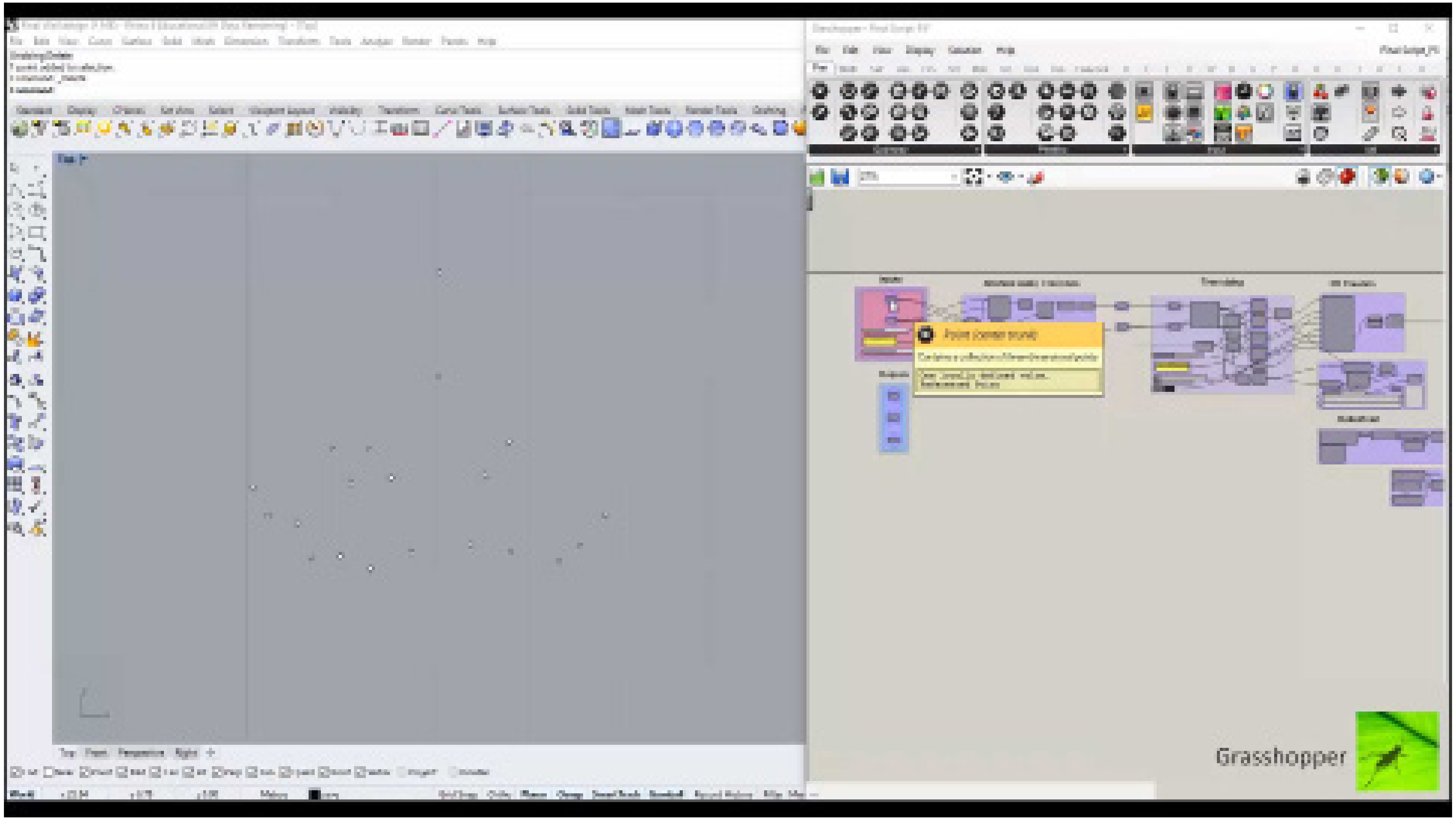


6. Outlets overhang

Overhang outlets creates bump effect over the interior surface.



Initial ventilation morphology

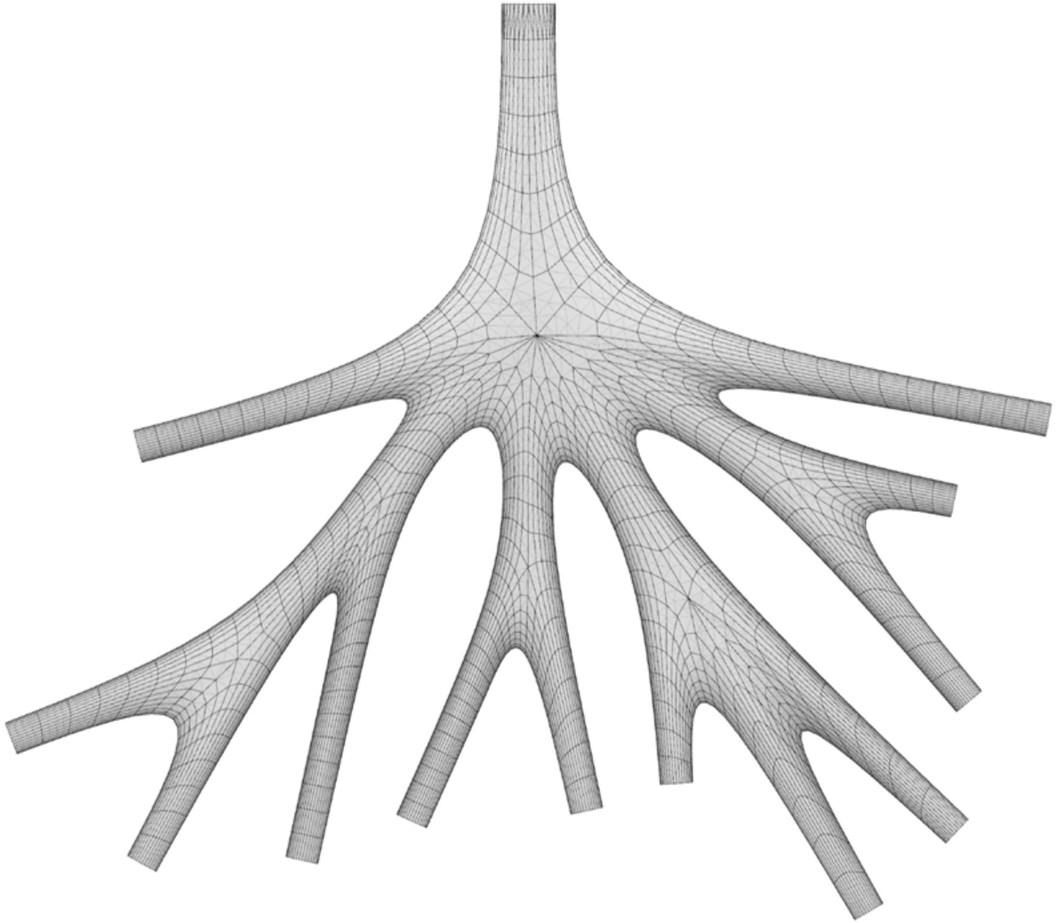


Grasshopper Morphology Generation script

Morphology

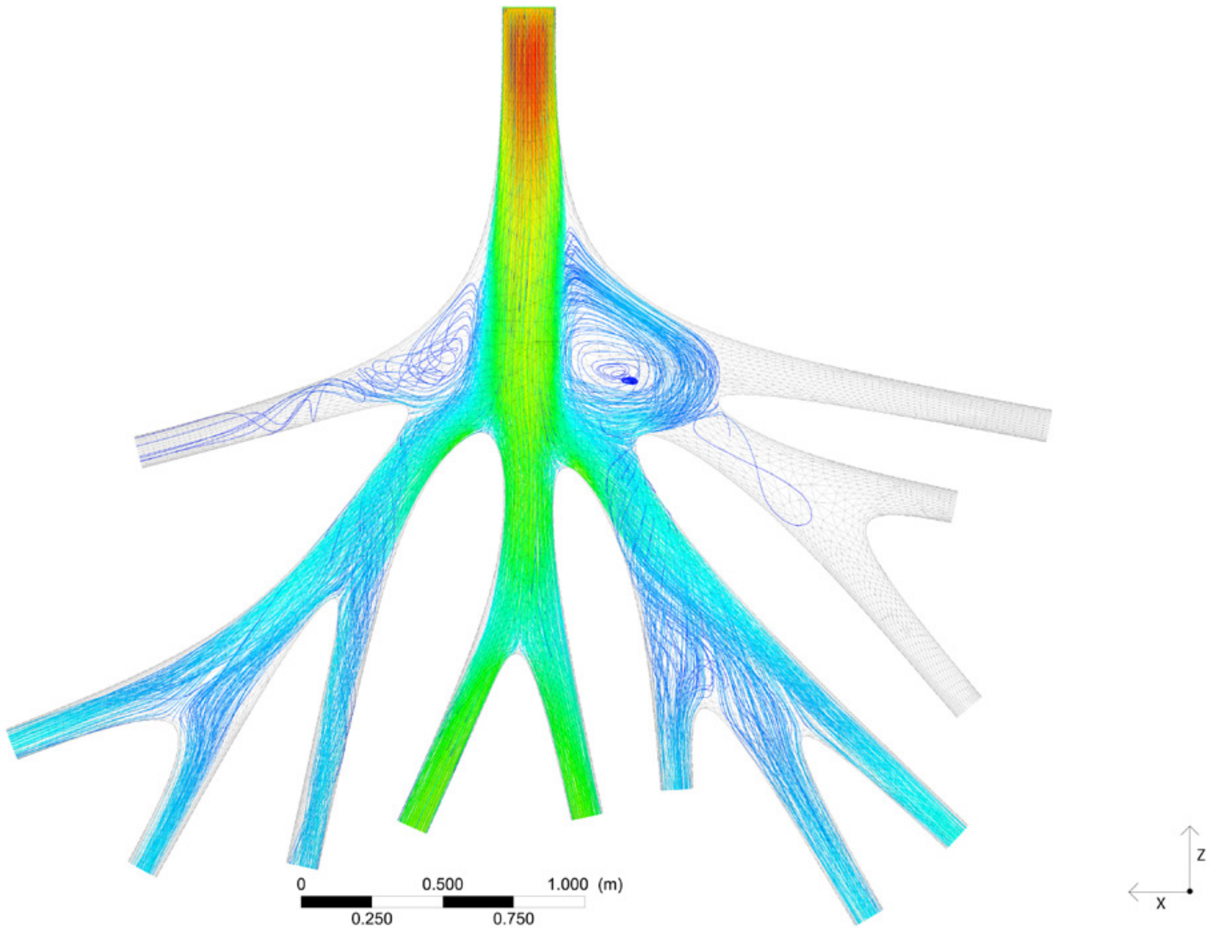
CFD Verification

ANSYS Fluent



Initial mesh analysis

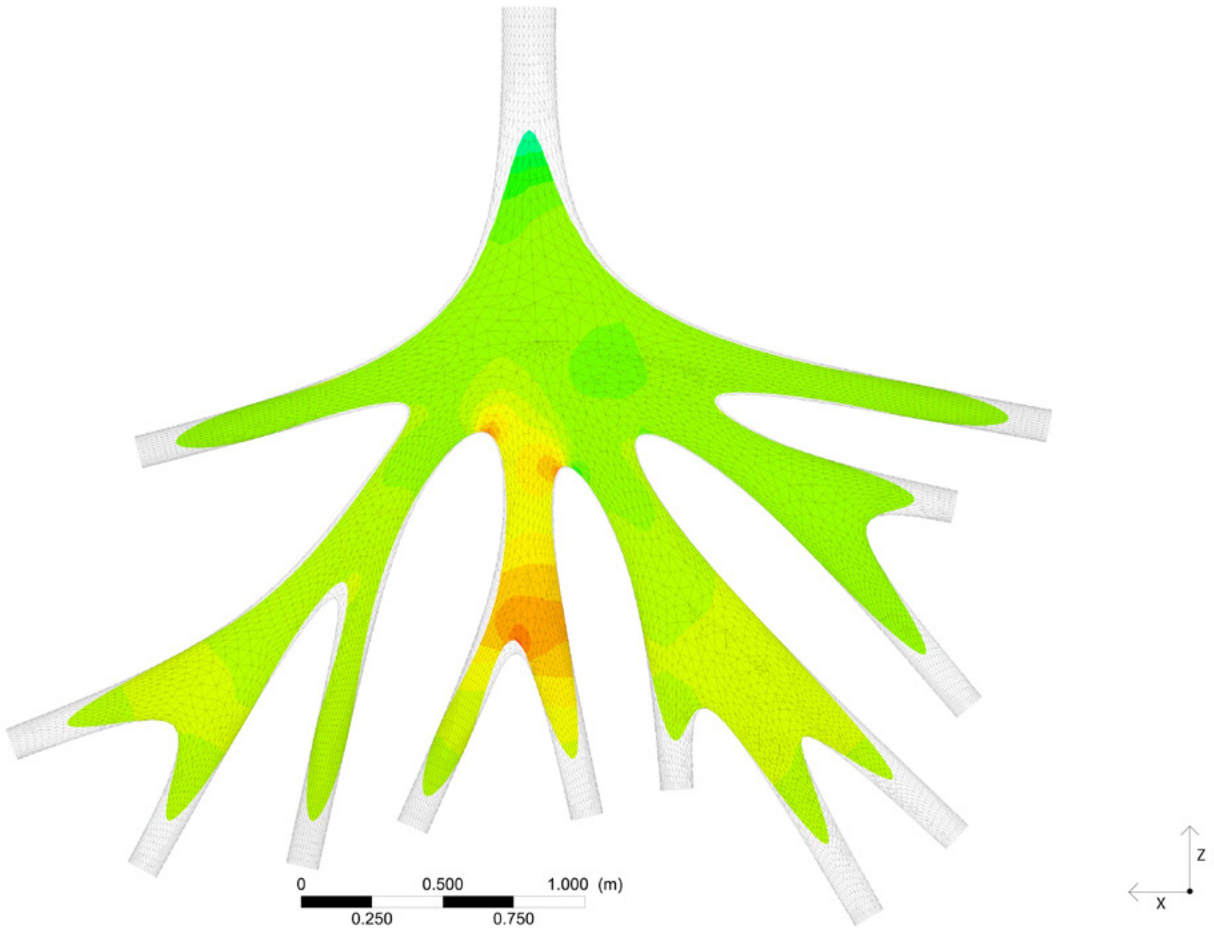
Using Ansys Fluent for CFD simulation to verify the ventilation system.



Pressure drop:
2.73 Pa

Turbulent CFD analysis

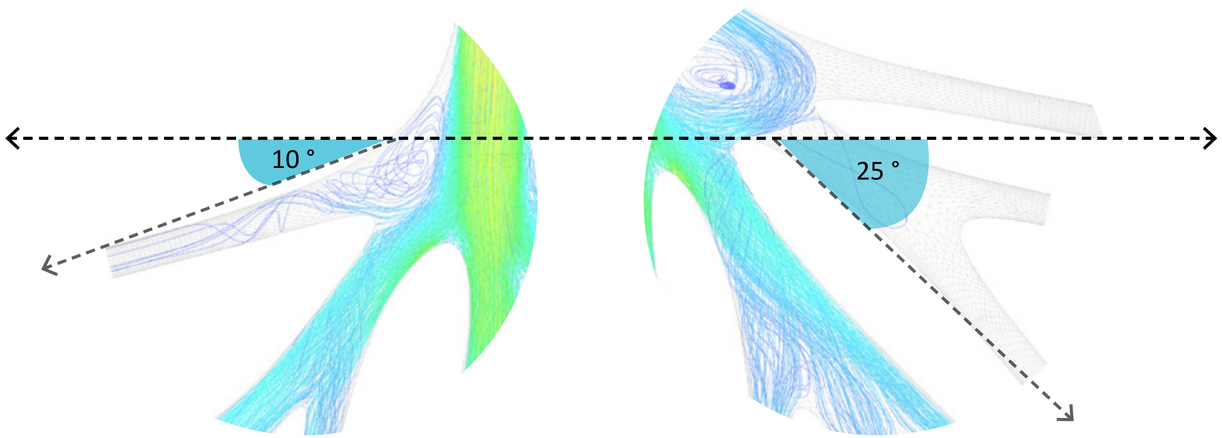
Velocity stream lines results shows the inefficient or neglectable branches in G1.



Pressure drop:
2.73 Pa

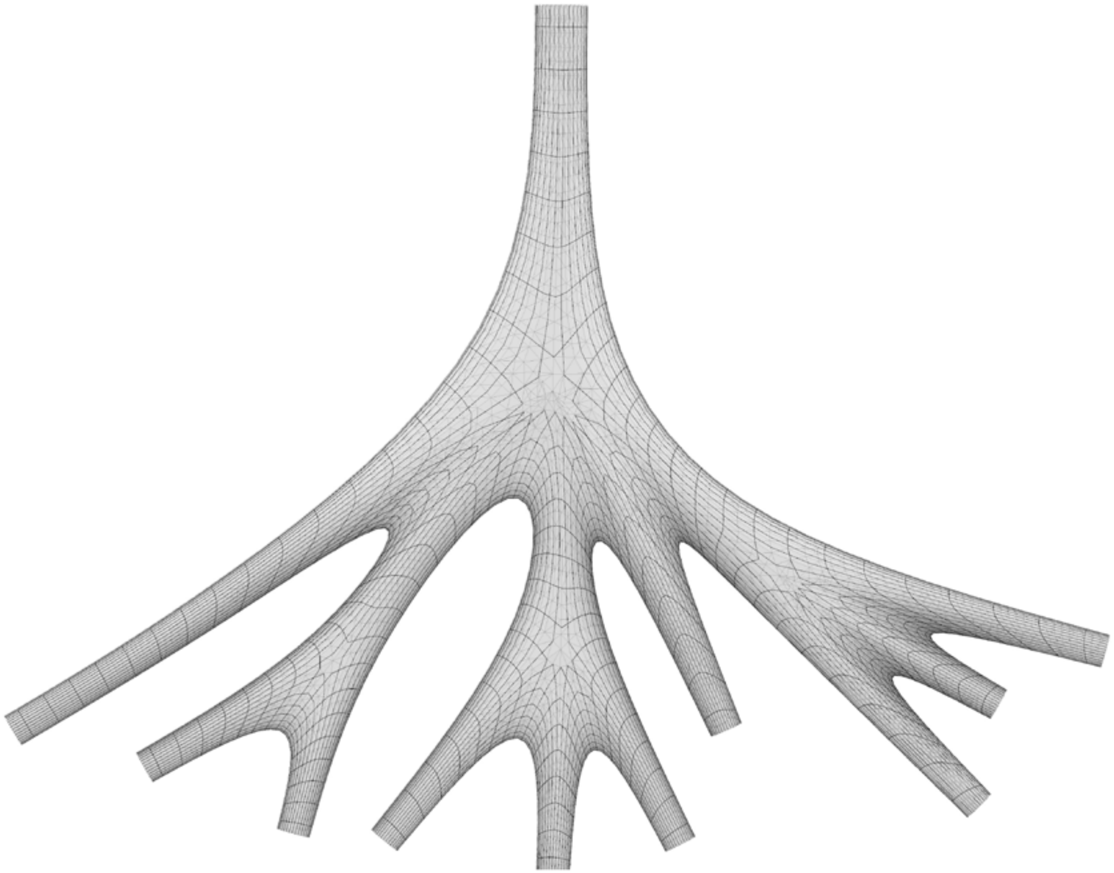
Pressure losses at the nodes

Total Pressure contour shows the velocity losses at the distribution nodes for the branches.



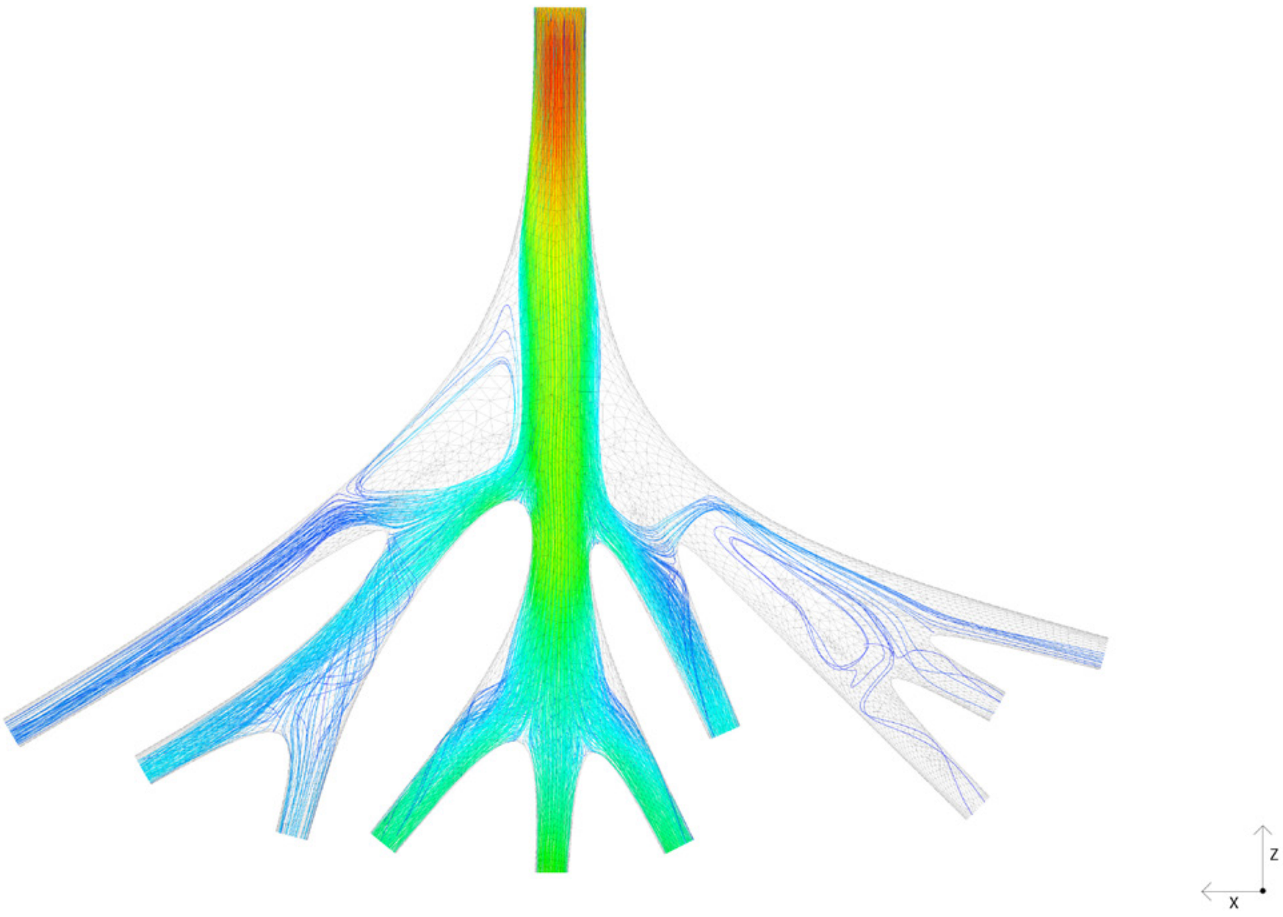
Design criteria 1

Branches that are between 10-25 degrees of inclination
are the least efficient, as the air does not flow through it.



Geometry 2

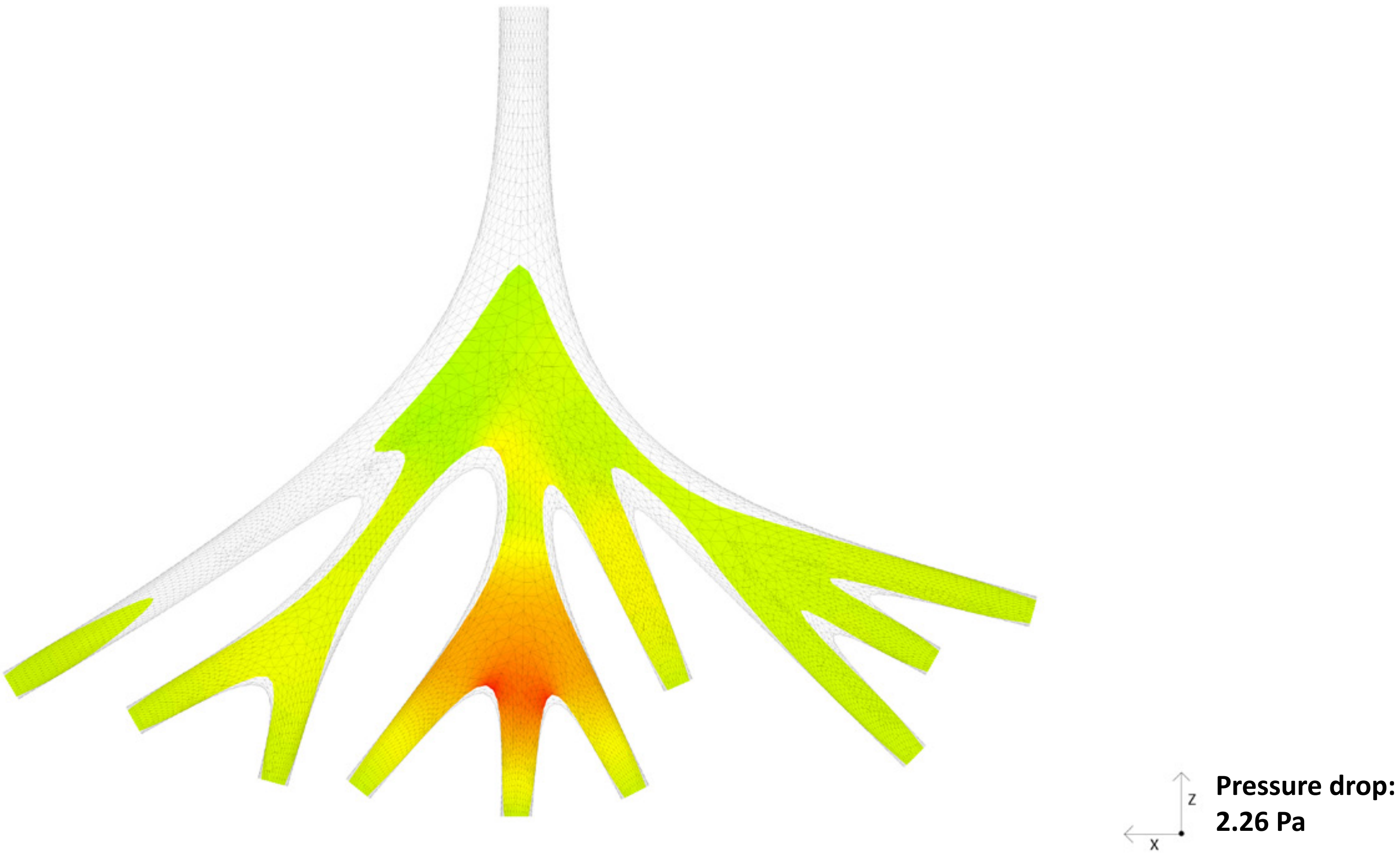
G2 second variation by culling branches of 10-25 ° inclina-
tion



Pressure drop:
2.26 Pa

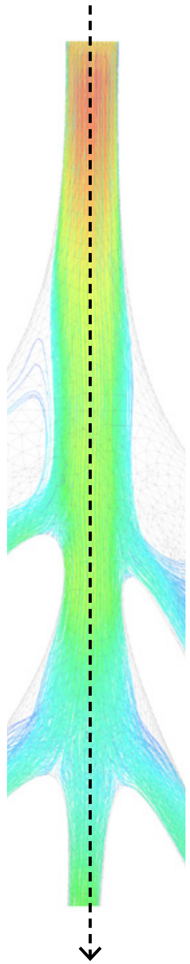
Air concentration in the middle

Unequal air distribution in the side branches from non to very low velocity.



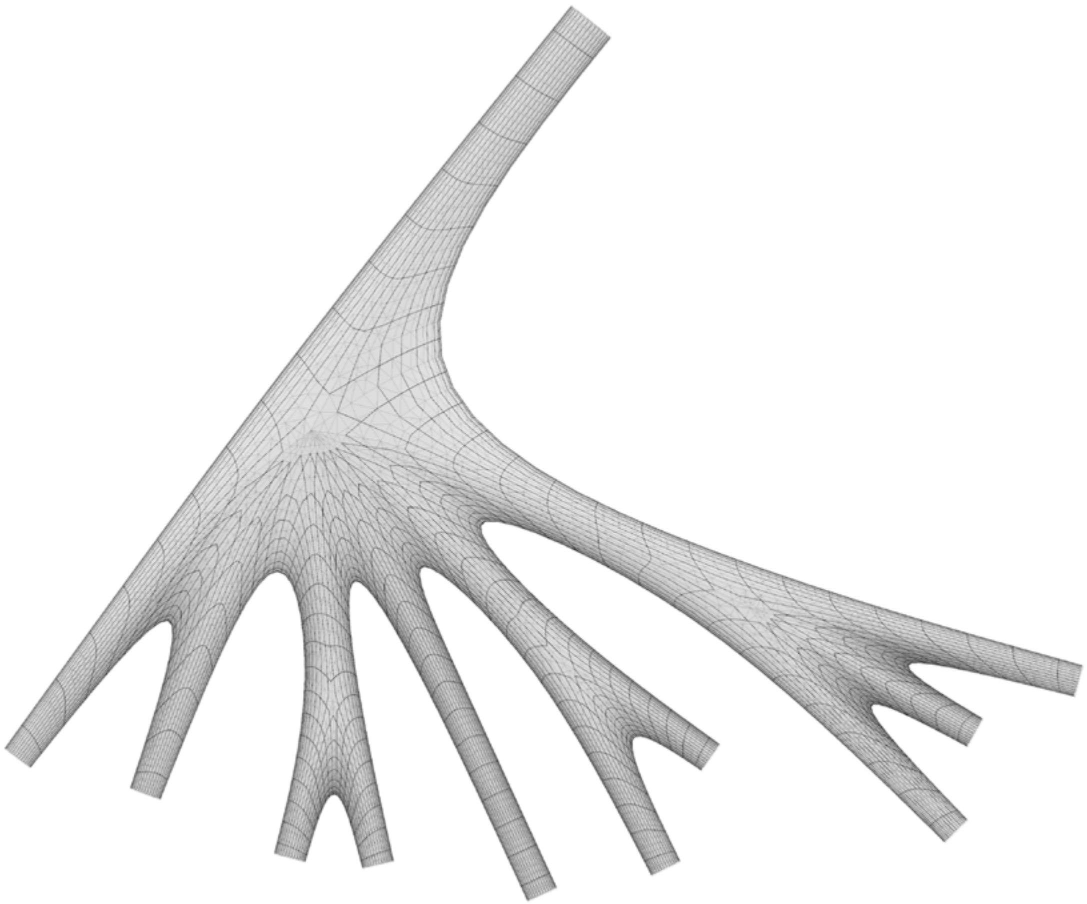
Less pressure drop

There is a need for better air distribution and less pressure losses.



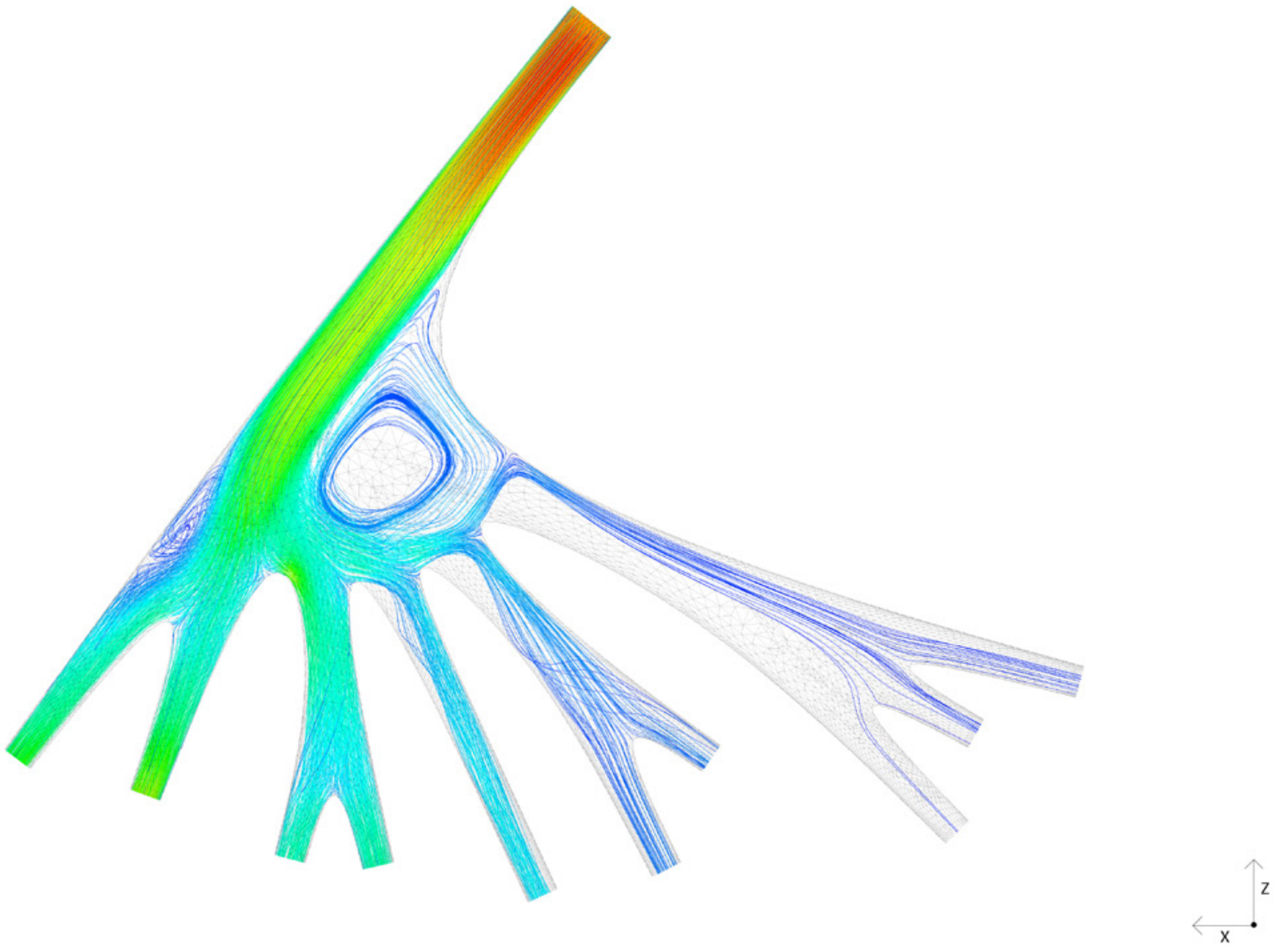
Design criteria 2

Avoid Direct inlet to outlet connections



Geometry 3

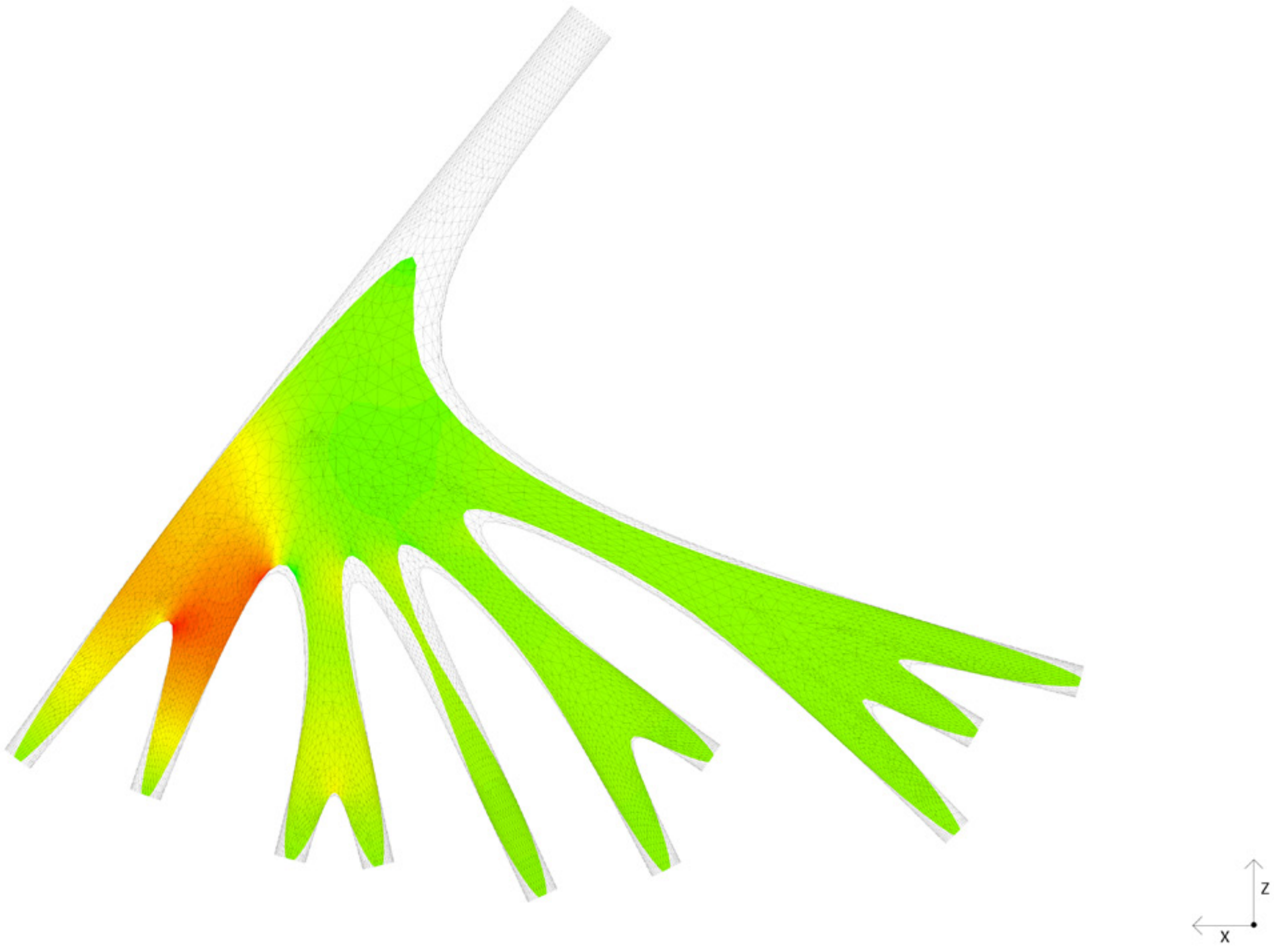
Different inlet air supply angle and maximized distribution area



Pressure drop:
2.67 Pa

Backward air movement

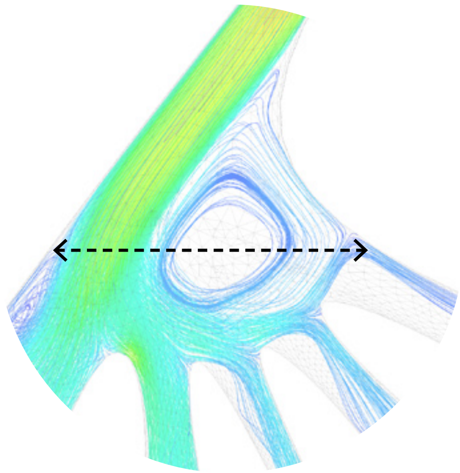
Backward movement in the huge main node cause much of the in efficient air distribution over the branches.



Pressure drop:
2.67 Pa

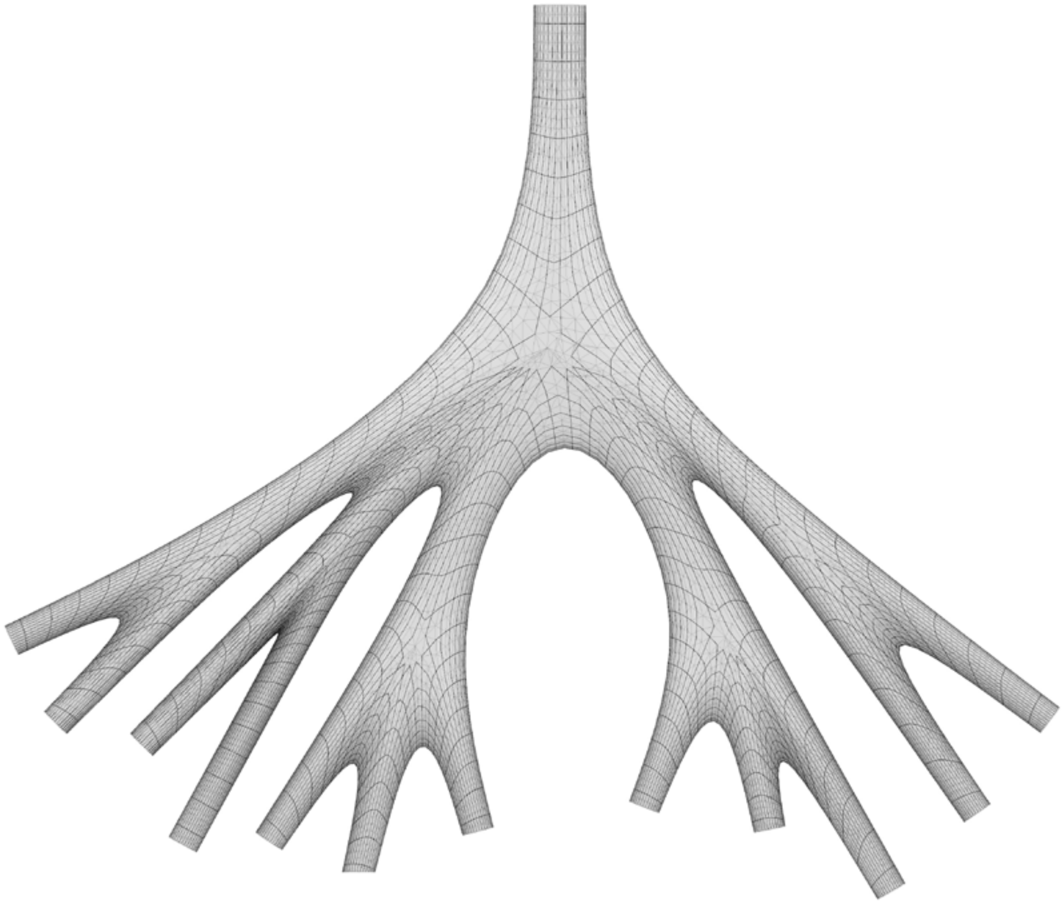
Less pressure loss at indirect supply

Total Pressure contour shows the velocity and pressure loss at the direct nodes to the inlet still as in G1.



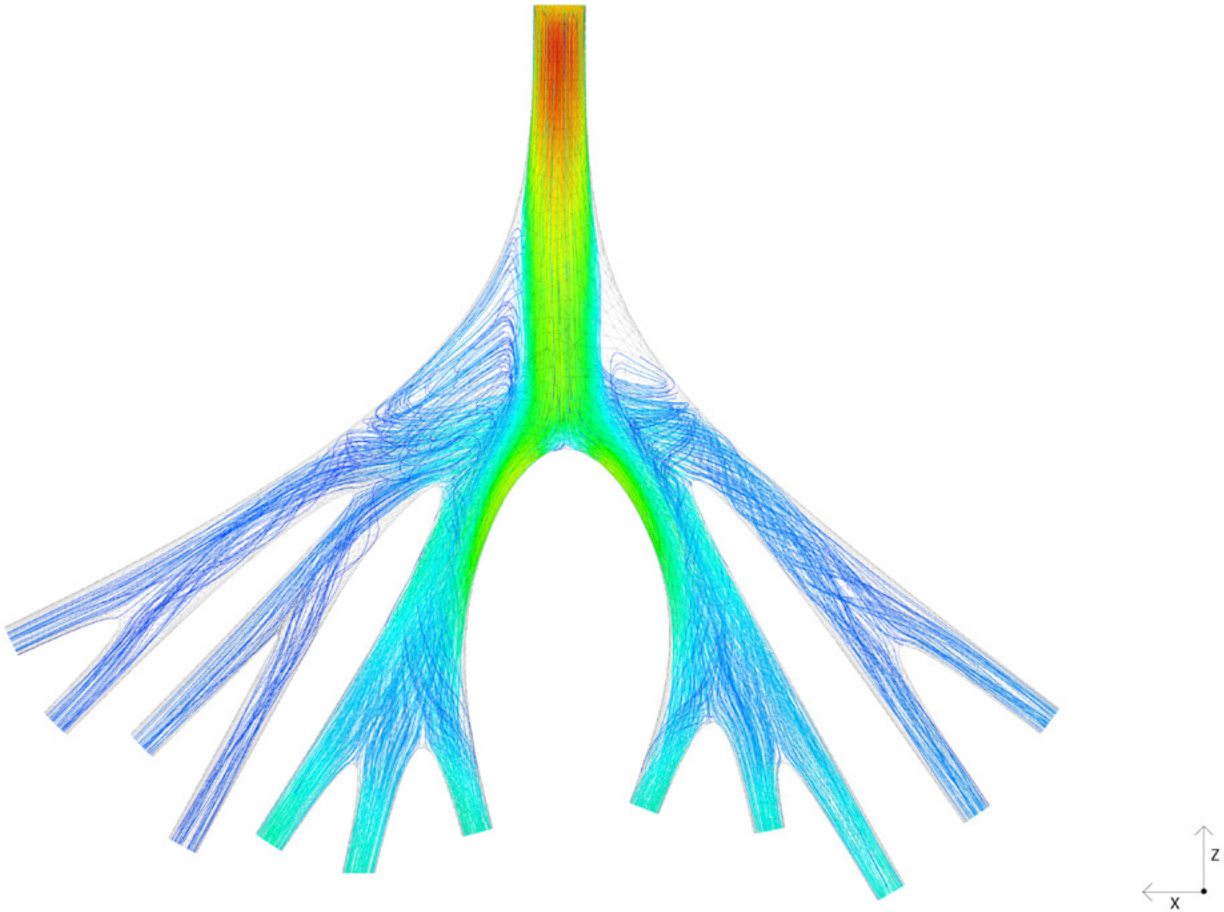
Design criteria 3

Avoid wide distribution main nodes



Geometry 4

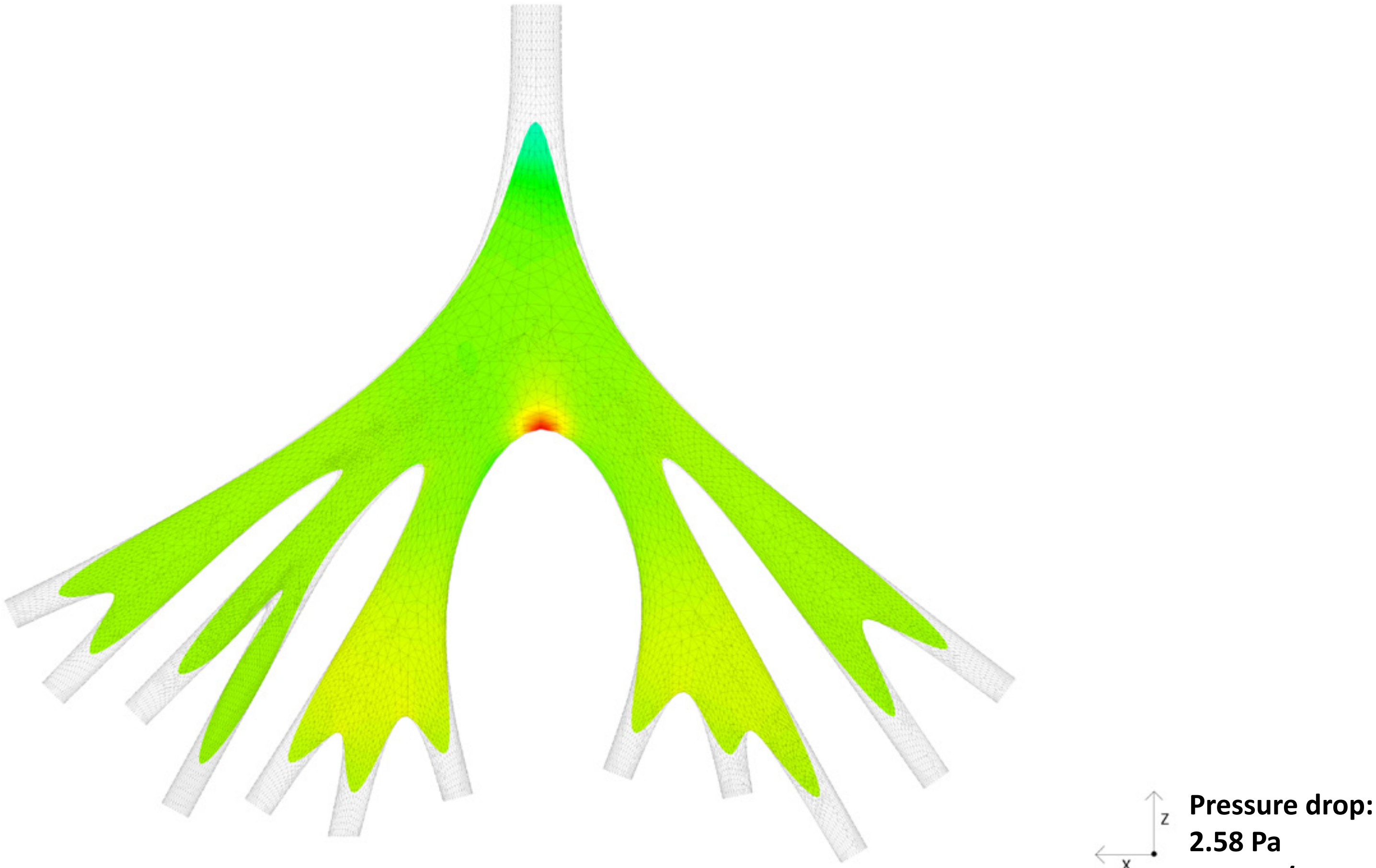
Last geometry introduced for CFD analysis includes all of the noticed considerations.



Pressure drop:
2.58 Pa
0.86 Pa/m

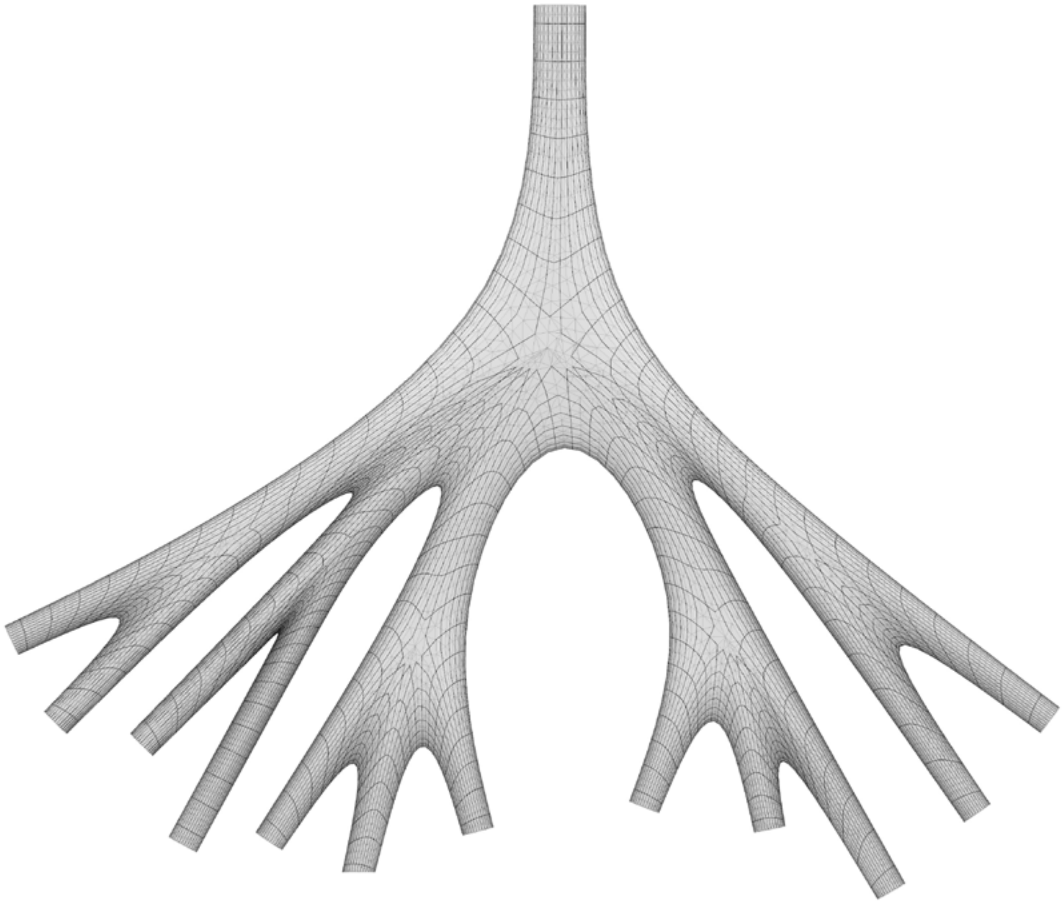
Efficient branches

Distribution over the branches is better than all of the other variations.



Less pressure losses

Least amount of pressure losses at the intersection nodes
and better pressure distribution over the geometry

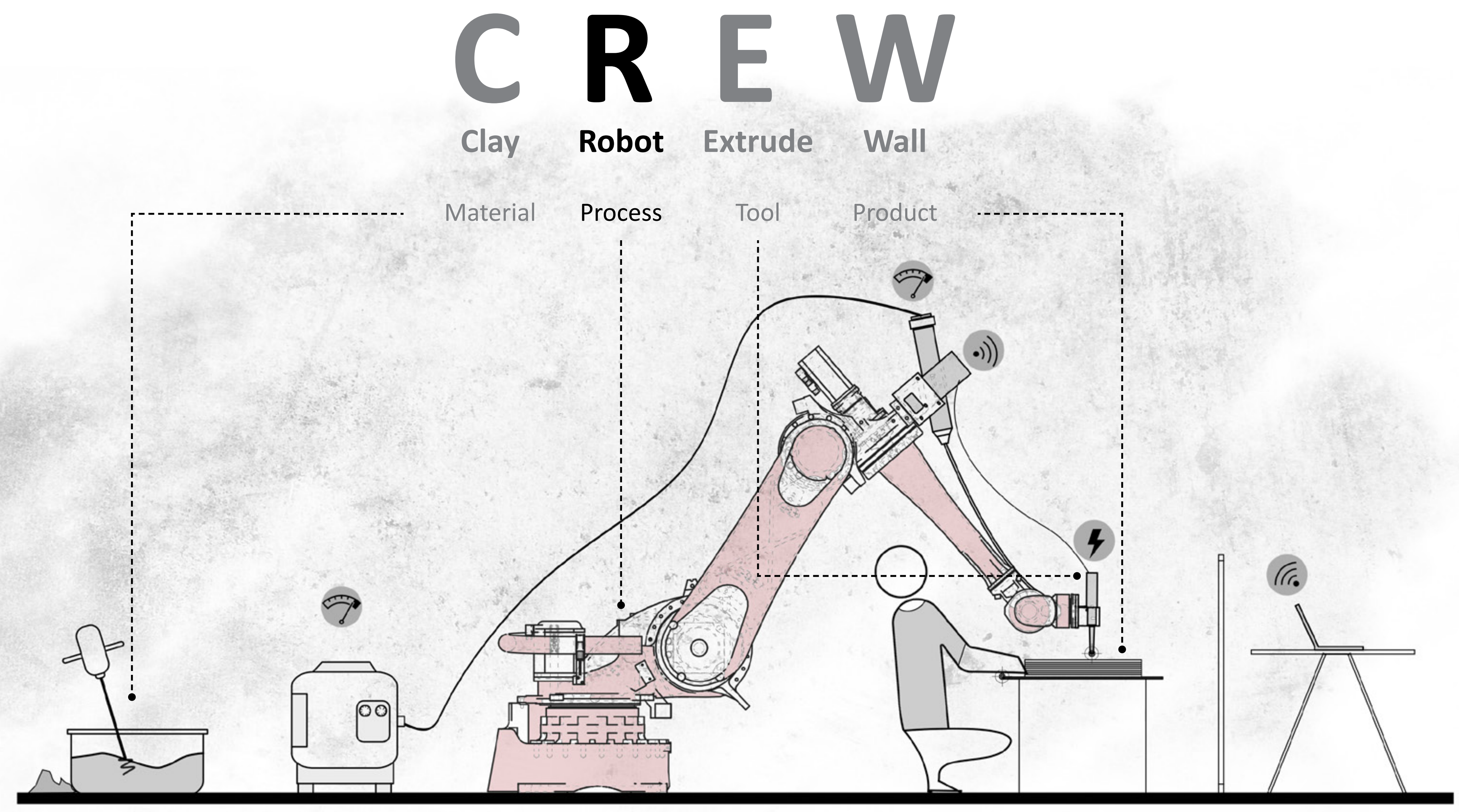


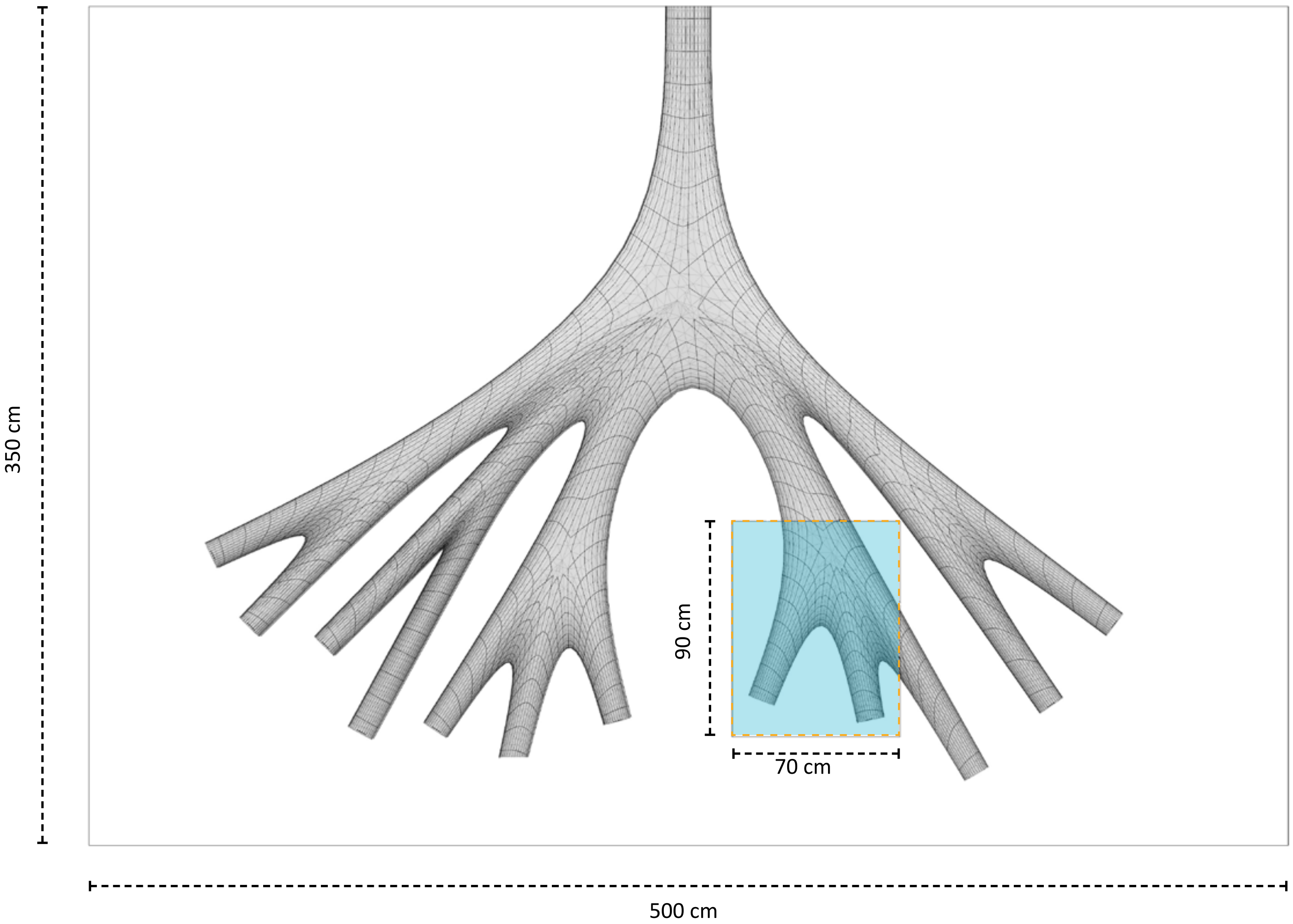
Final geometry

3D PRINTED CLAY FACADE WALLS

Integrating Ventilation system into printing process

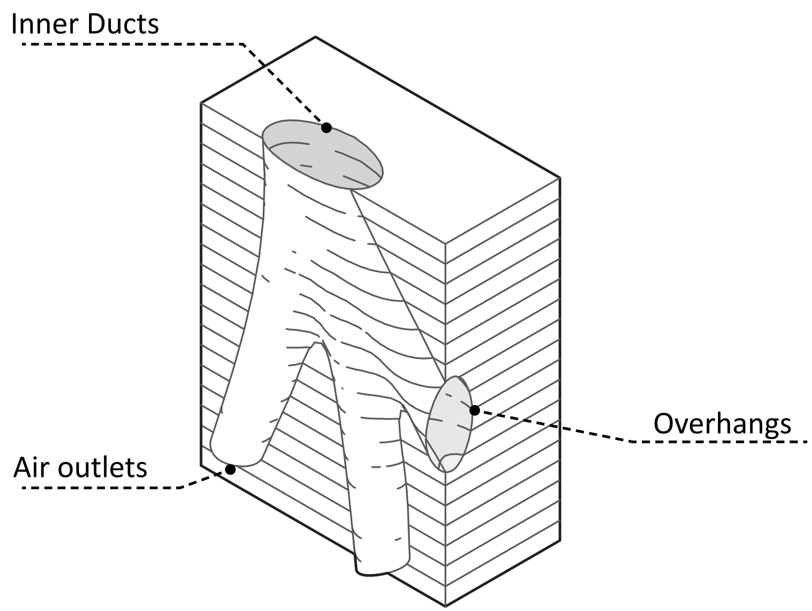

3D PRINTED CLAY FACADE WALLS
Integrating Ventilation system into printing process


C R E W
Clay
Robot
Extrude
Wall
Material
Process
Tool
Product



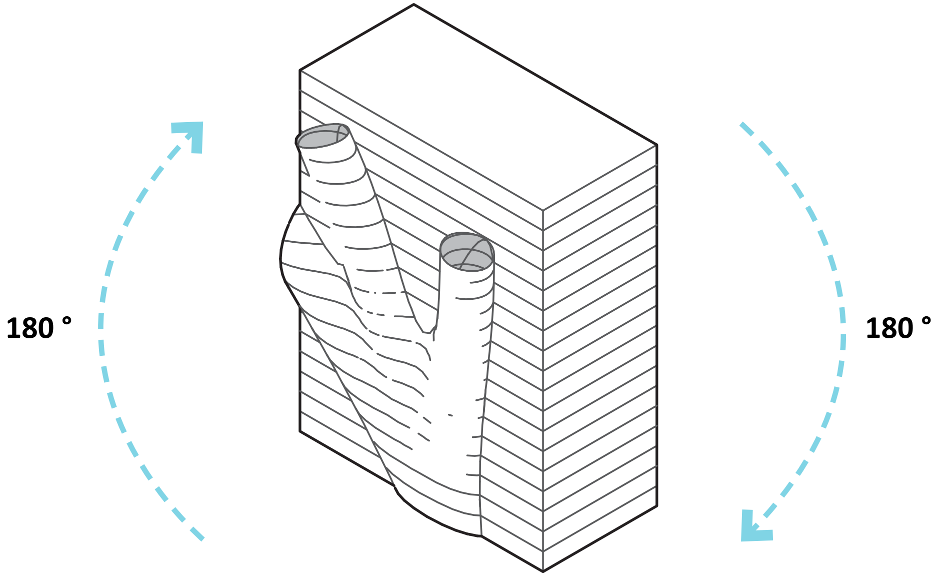
Prototype Portion

The final prototype position within the wall and its designed morphology of the ventilation system.



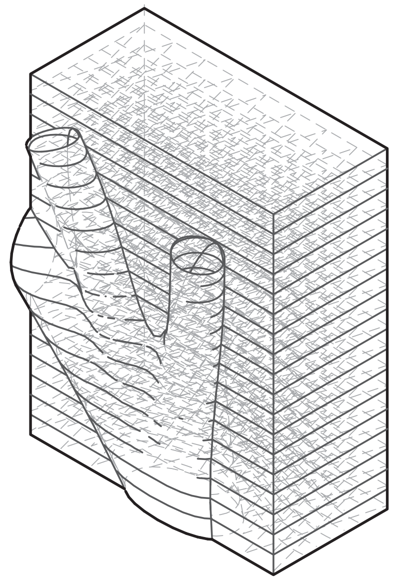
Prototype Portion

Chosen prototype exhibit the three challenging points of the printing to achieve without collapsing.



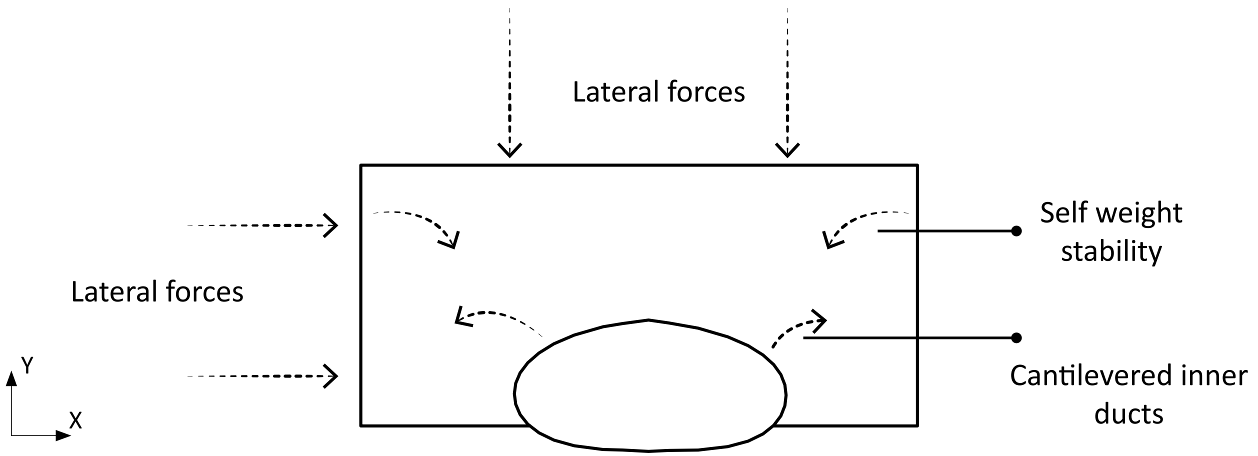
Prototype Portion

Flipping it for better printability direction.



Layers need design

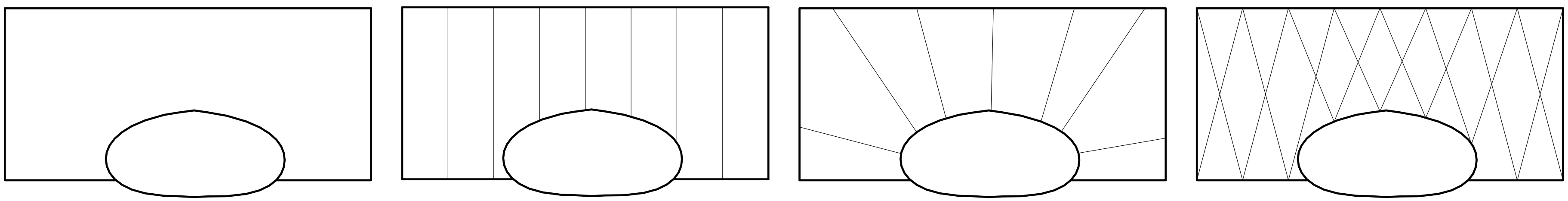
Designing the infilling of the prototype to achieve better indoor & printability performance



Principle 1 : Stability supports

Three main forces that requires support by the infilling design of the wall section.

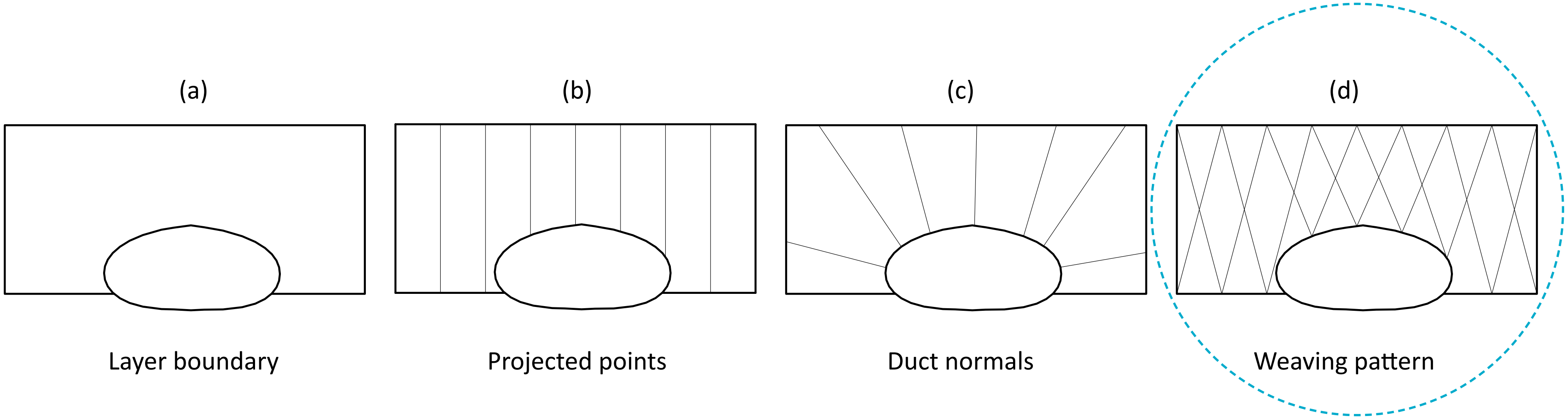
(a) (b) (c) (d)



Layer boundary — Projected points — Duct normals — Weaving pattern

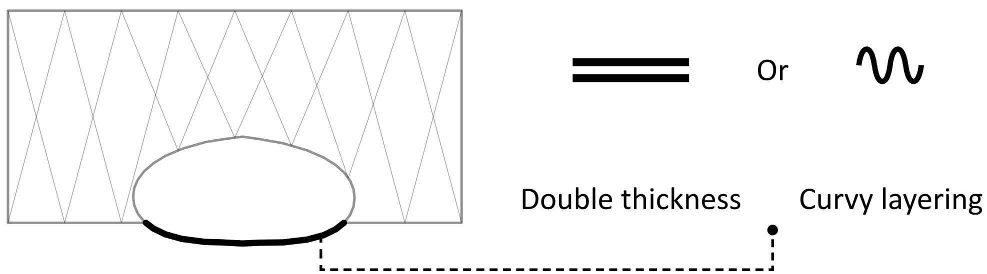
Principle 1 : Stability supports

Possible solutions for structure supports for different forces.



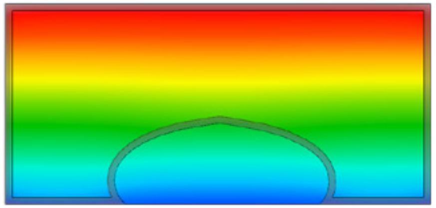
Principle 1 : Stability supports

Possible solutions for structure supports for different forces.



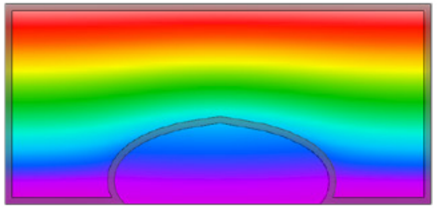
Principle 1 : Stability supports

Possible solutions for structure supports for different forces.



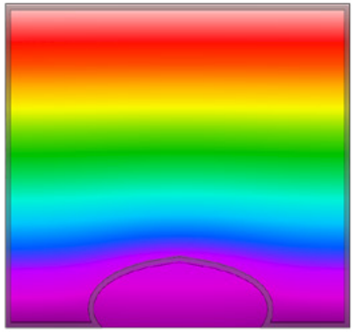
Air/ void infill

U-Value: 2.15 W/m^2K
R-Value: 0.47 m^2K/W



Solid infill

U-Value: 1.13 W/m^2K
R-Value: 0.89 m^2K/W

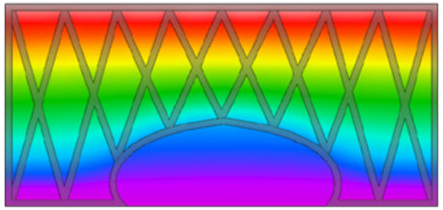


Double thickness Solid

U-Value: 0.58 W/m^2K
R-Value: 1.74 m^2K/W

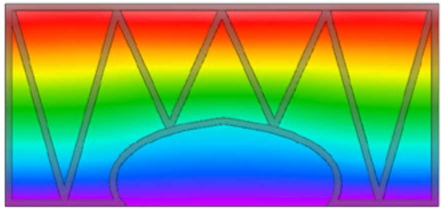
Principle 2 : Thermal performance

Solid infill tends to be more insulative than the large air cavities, while increasing the thickness takes more space.



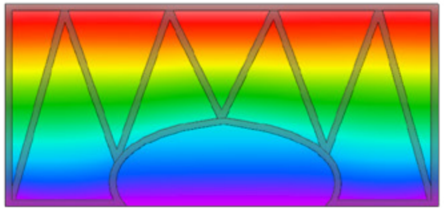
Structure support

U-Value: 1.14 W/m²K
R-Value: 0.87 m²K/W



Halved structure infill

U-Value: 1.47 W/m²K
R-Value: 0.68 m²K/W

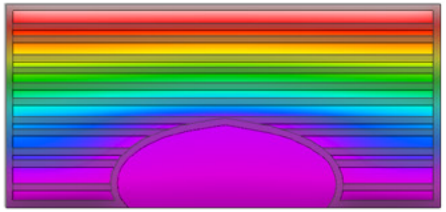


Halved structure infill 2

U-Value: 1.46 W/m²K
R-Value: 0.68 m²K/W

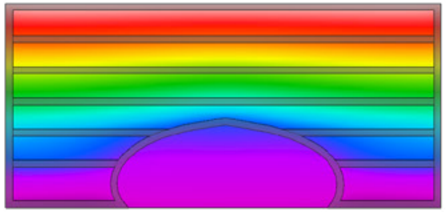
Principle 2 : Thermal performance

Designed structure support infilling already has low U-value due to the smaller cavity size created by intersections



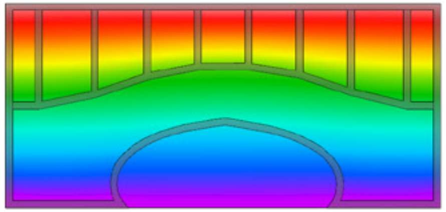
2 cm, 12 cavities

U-Value: 0.63 W/m^{2}K
R-Value: 1.59 m^{2}K/W



4 cm, 6 cavities

U-Value: 0.86 W/m^{2}K
R-Value: 1.17 m^{2}K/W

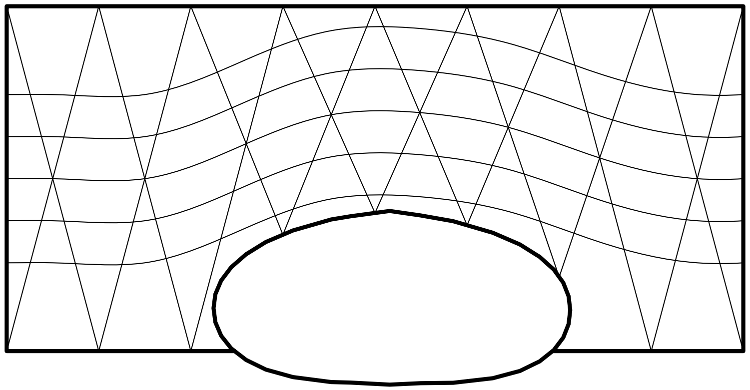


Two parallel cavities

U-Value: 1.40 W/m^{2}K
R-Value: 0.72 m^{2}K/W

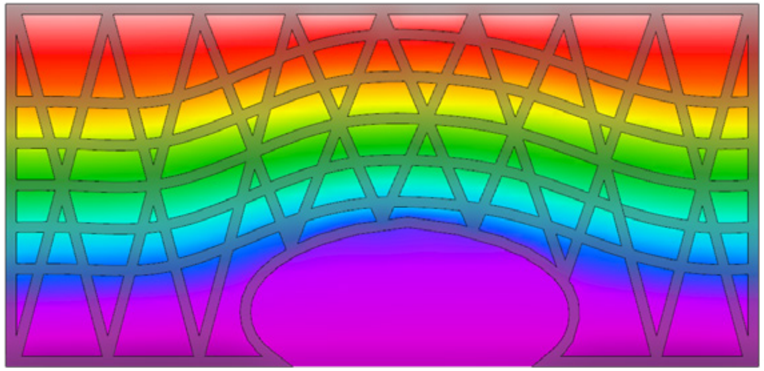
Air cavity effect

Parallel barriers with smaller and more air cavities tend to meet the design criteria for U-value.



Final infilling

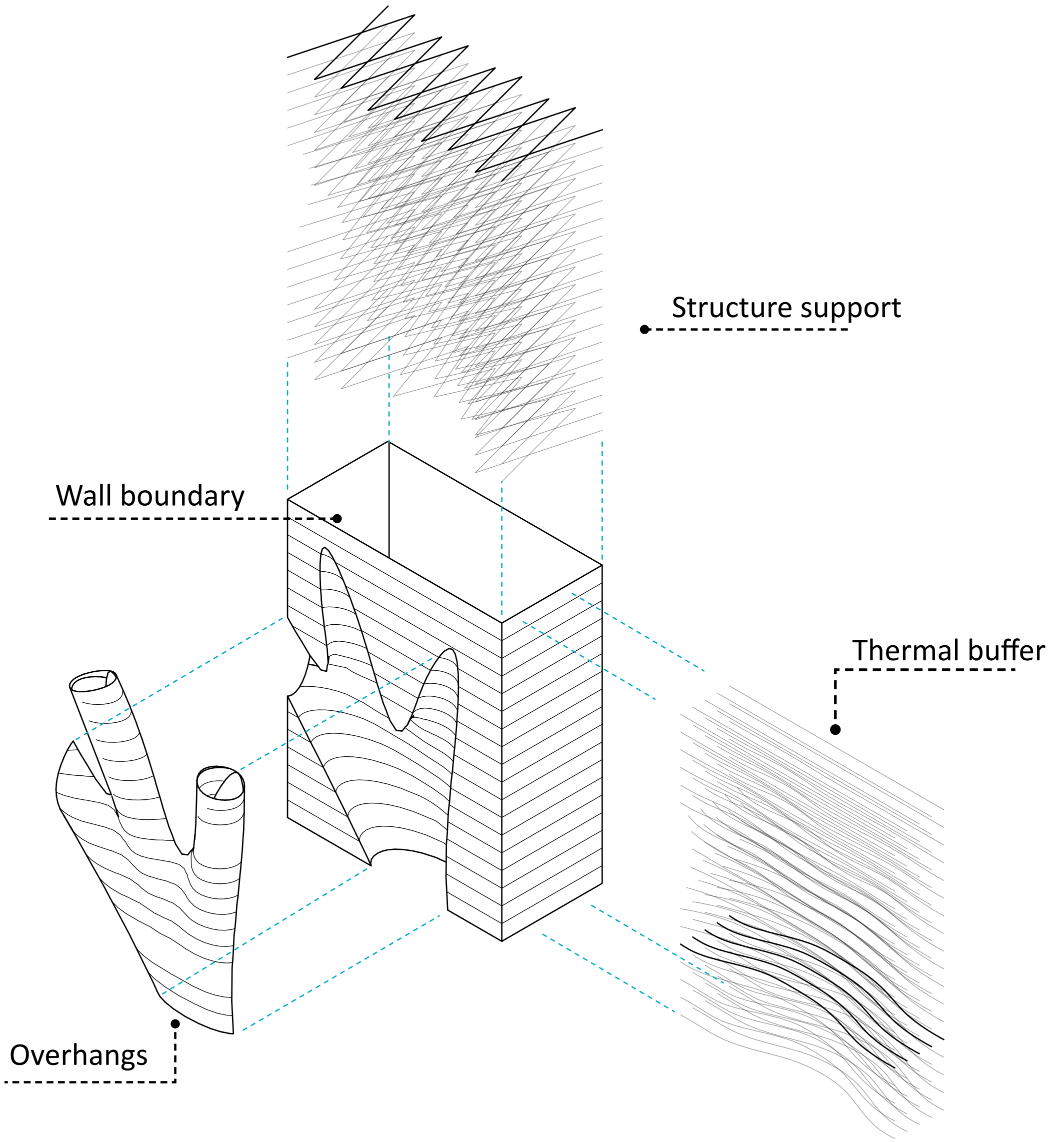
Final designed infilling to be as a starting point for proto-typing and test its build-ability.



U-Value: 0.73 W/m²K
R-Value: 1.35m²K/W

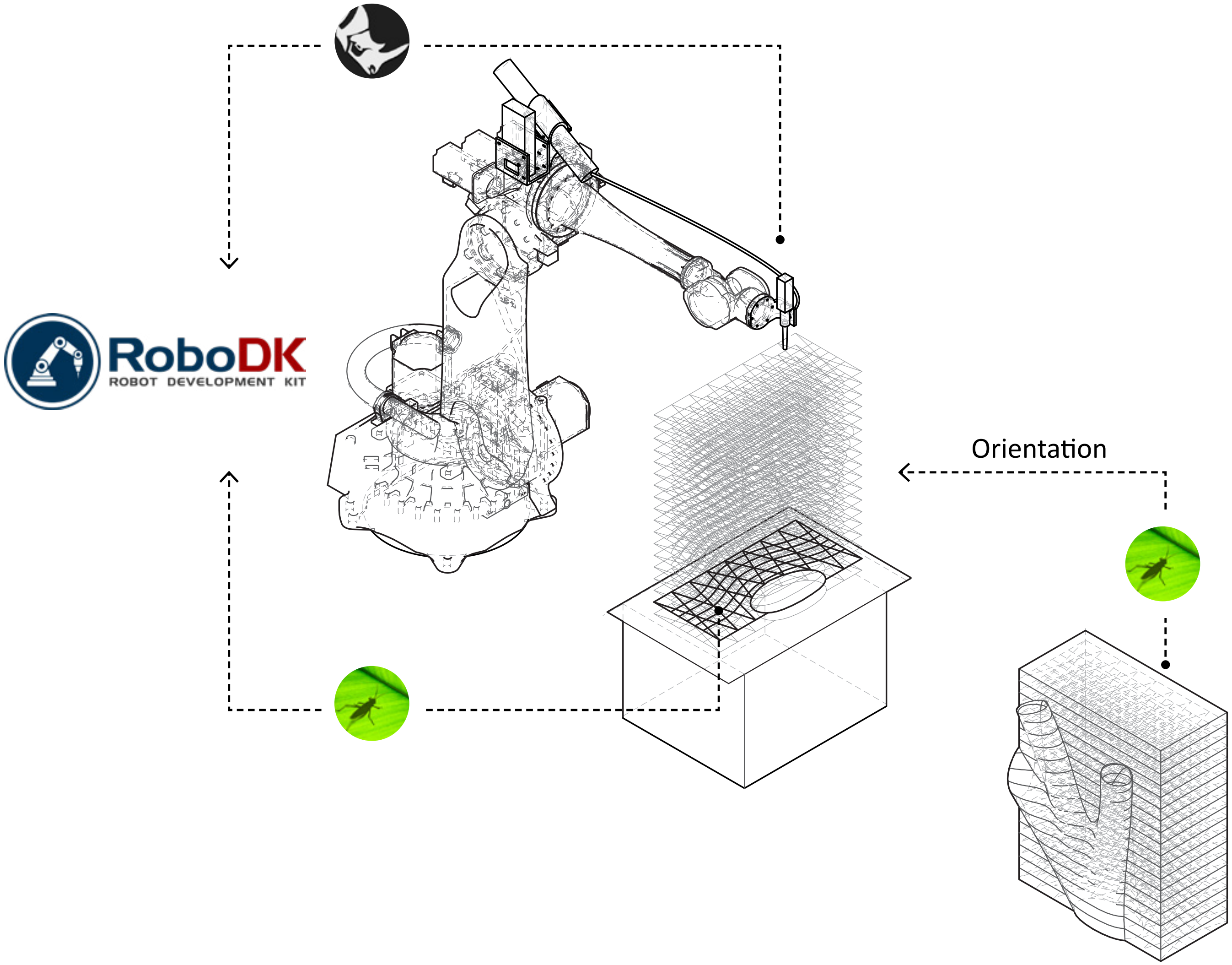
Final infilling

Achieves the required U-value.



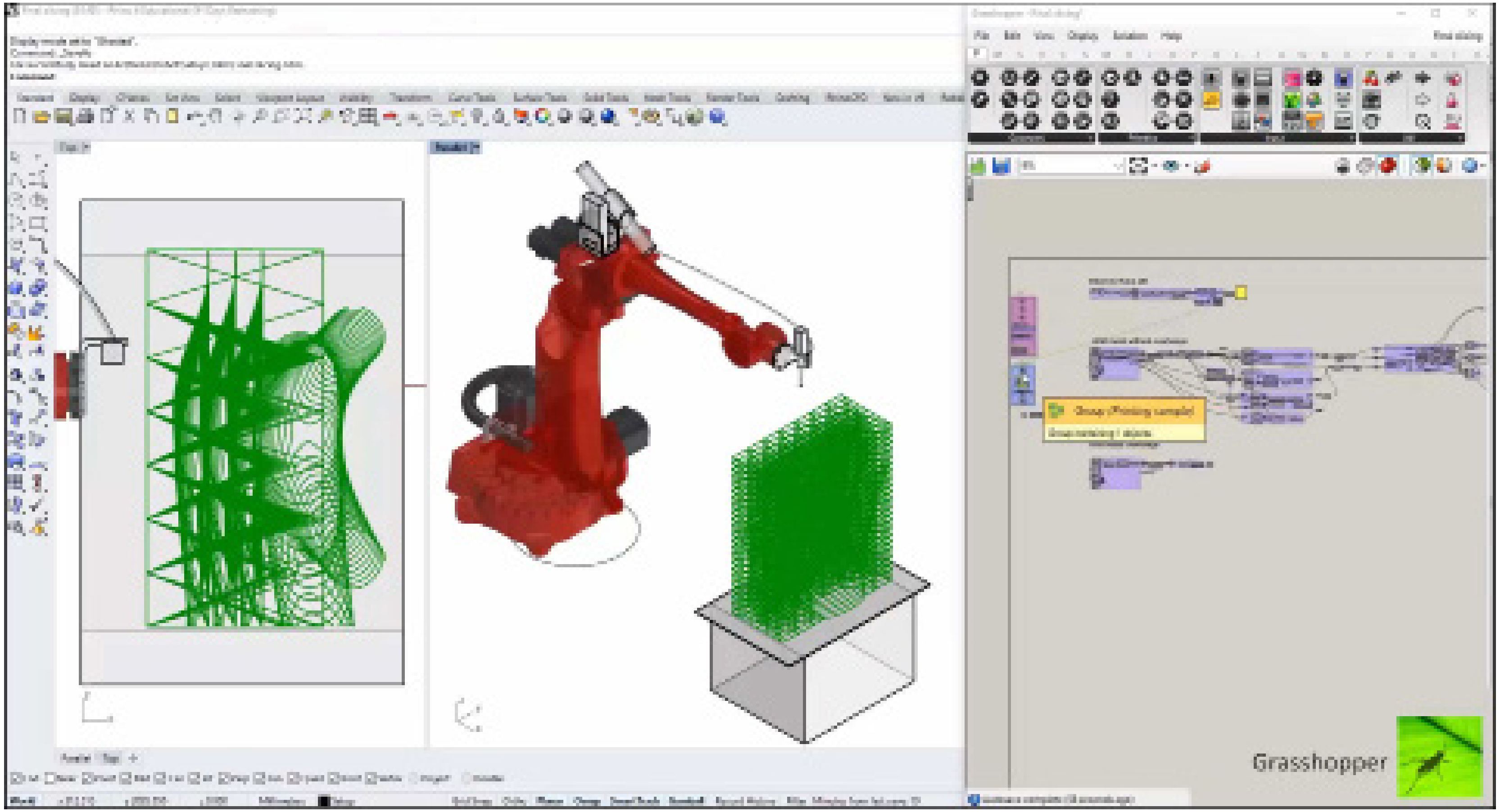
Layer components

four components that form any of the prototype layers

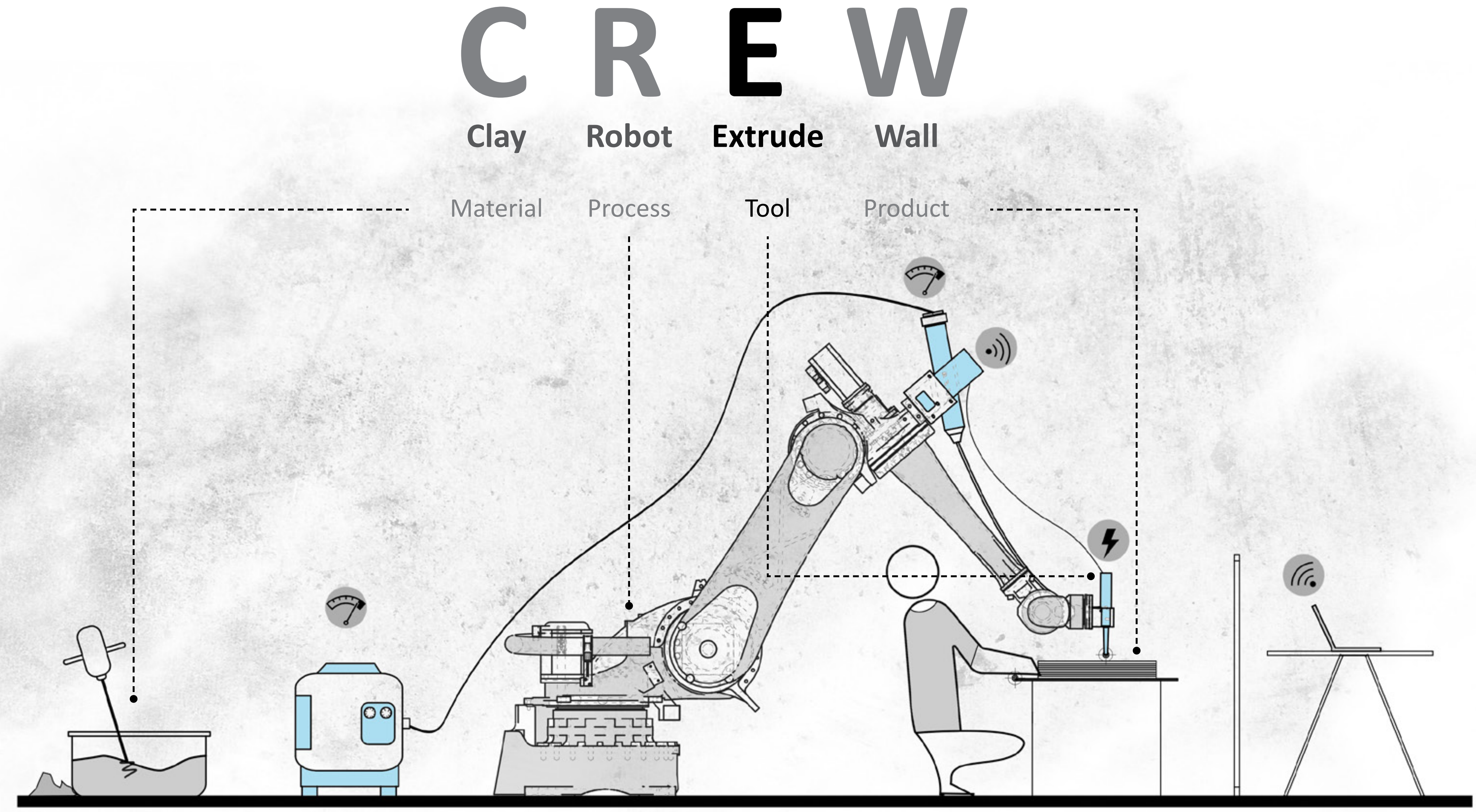


Digital work flow

Slicing layers, transferring oriented layers to RobodK by Grasshopper, and the setup from rhino, for robot code generation.

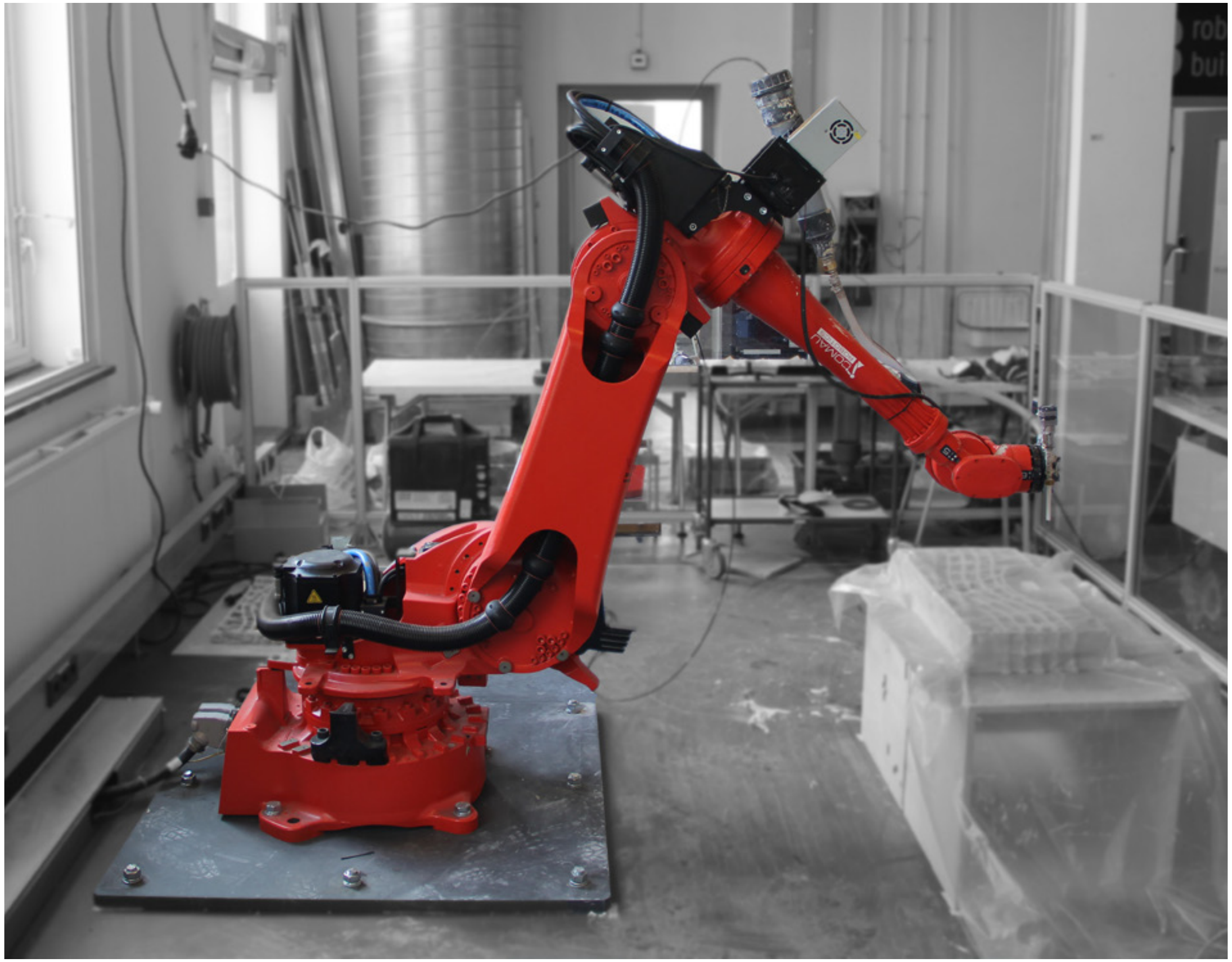


Grasshopper Slicing script


C R E W
Clay
Robot
Extrude
Wall
Material
Process
Tool
Product

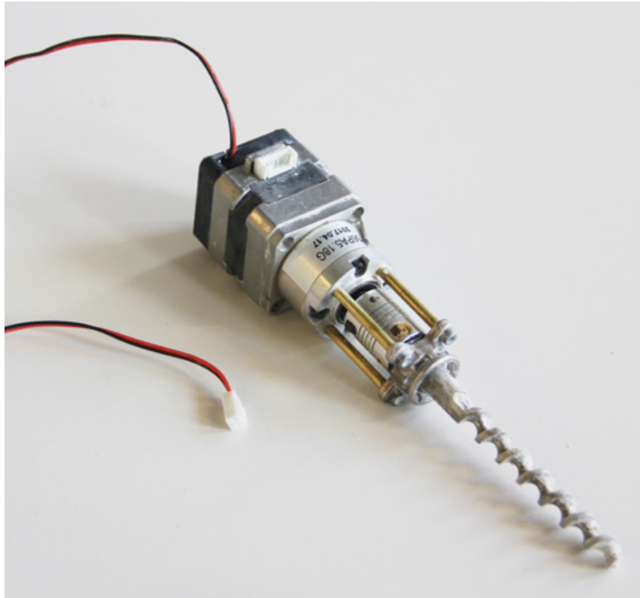
Printing

Tools & Setup



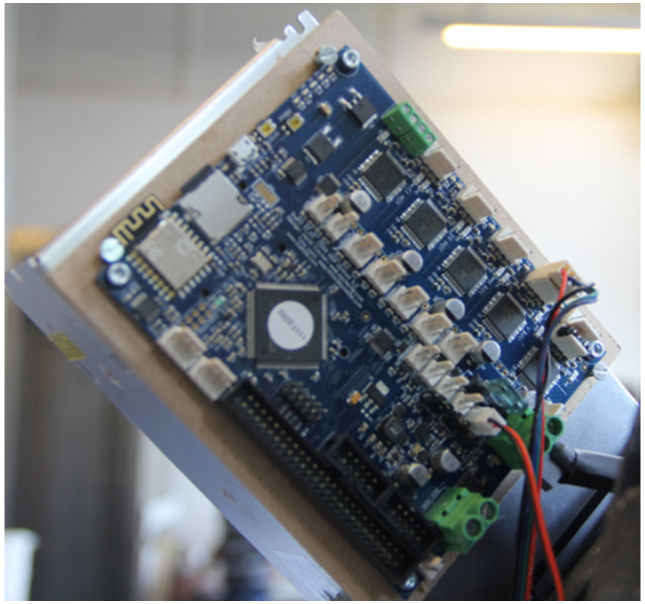
Robot Arm

6 Axis Comau NJ6022 robot as the operating machine



Motor & drill bit

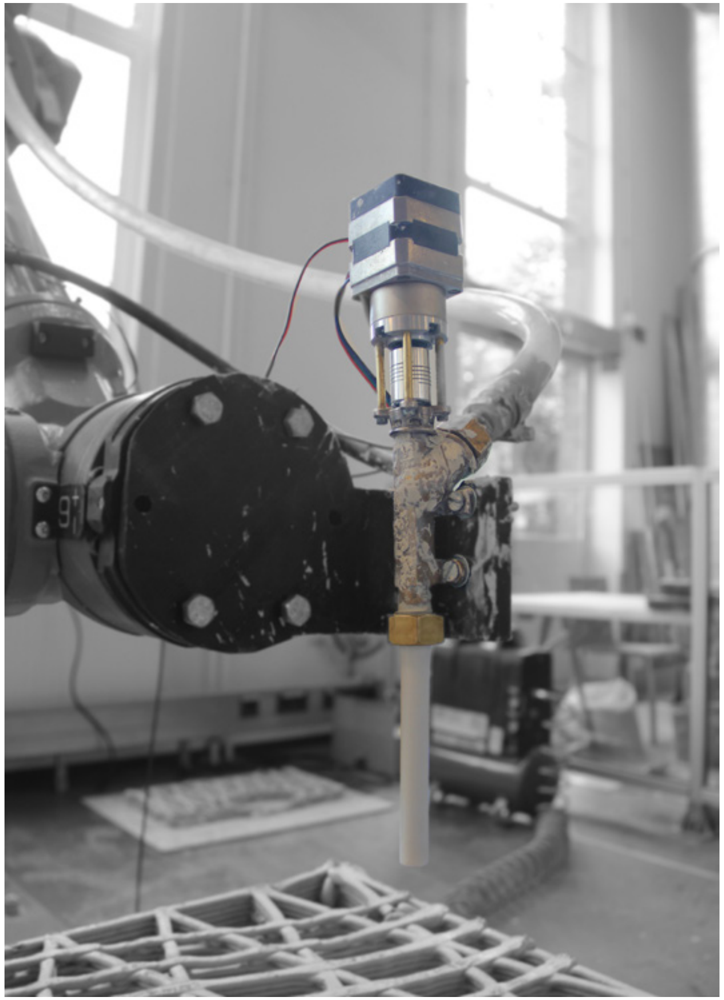
Customized Nozzle



Control board

Extruder system

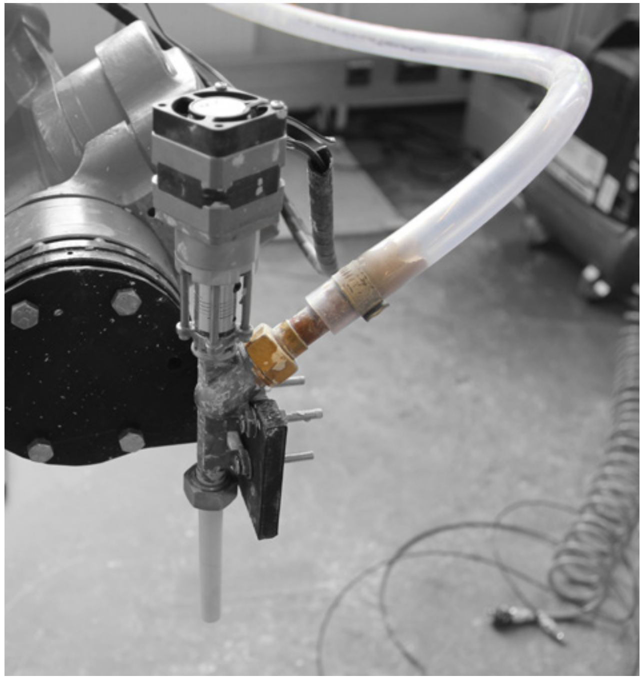
G-code Controlled motor, controls the extrusion of the material.



Extruder system

G-code Controlled motor, controls the extrusion of the material.

Cartridges



Supplying hose

Air compressor

Cartridge system

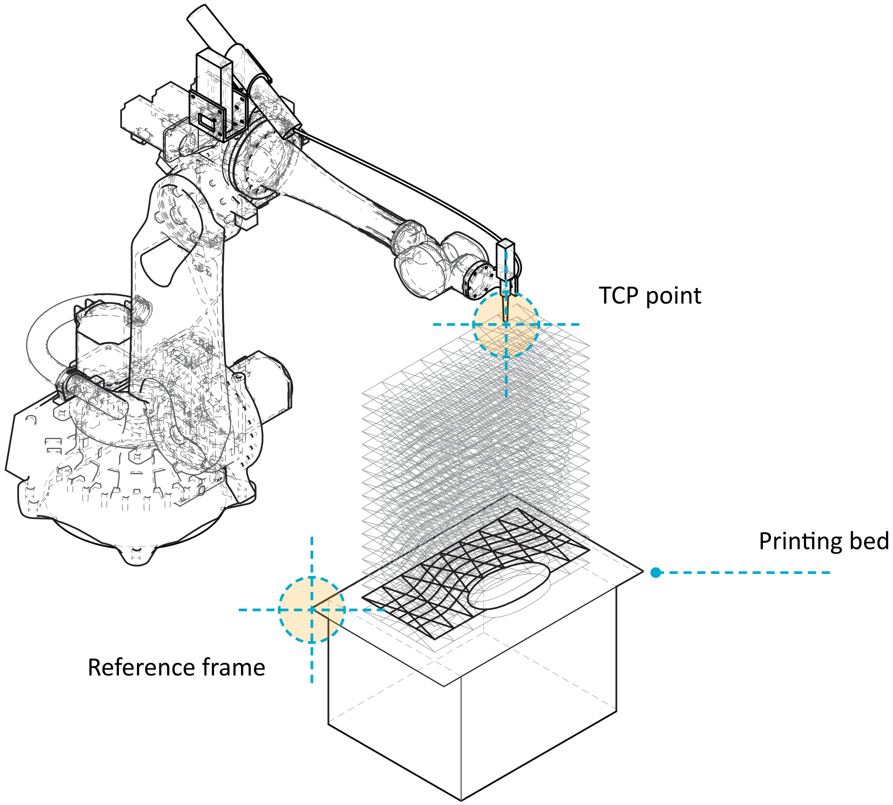
Cartridge supply material to the extruder in an air pressurised system

Mounting devices

3d Printed plastic devices were designed to mount the tools on the robot

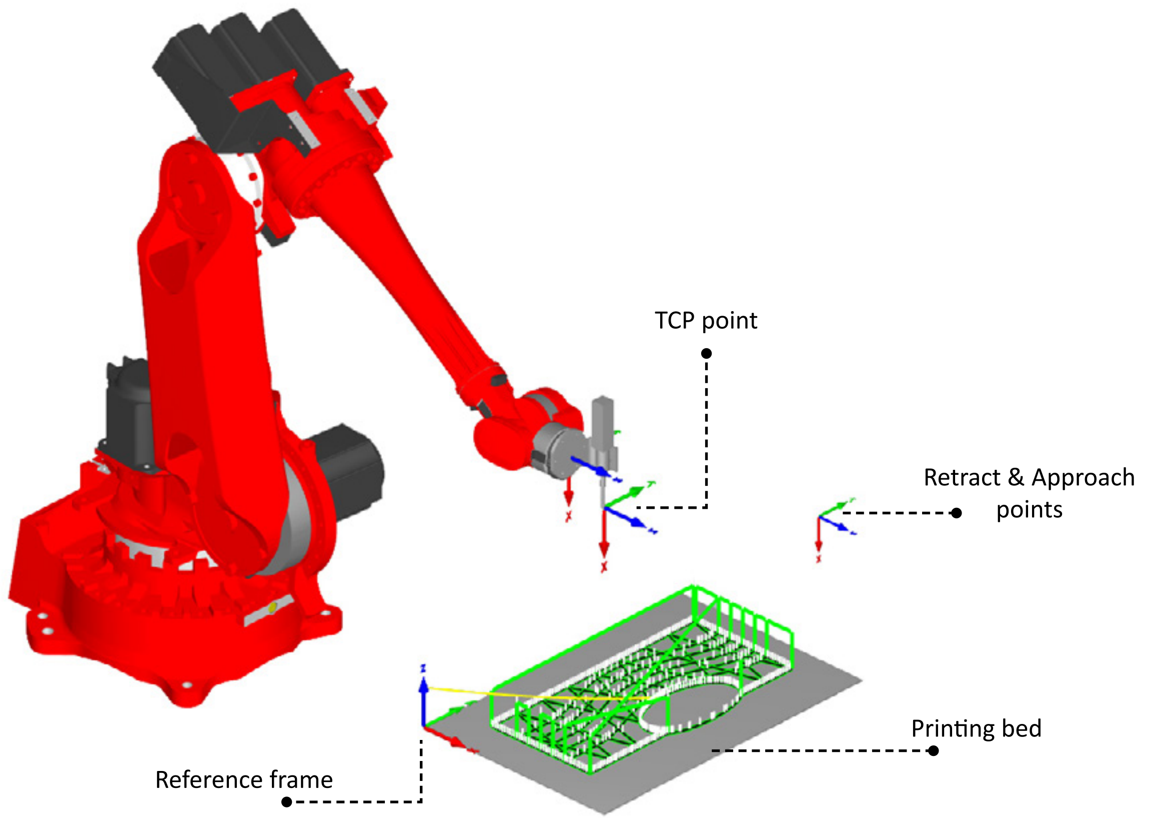
Printing

Calibration



1. Setup Calibration

Teaching robot TCP & reference frames while defining it in the digital environment.



1. Setup Calibration

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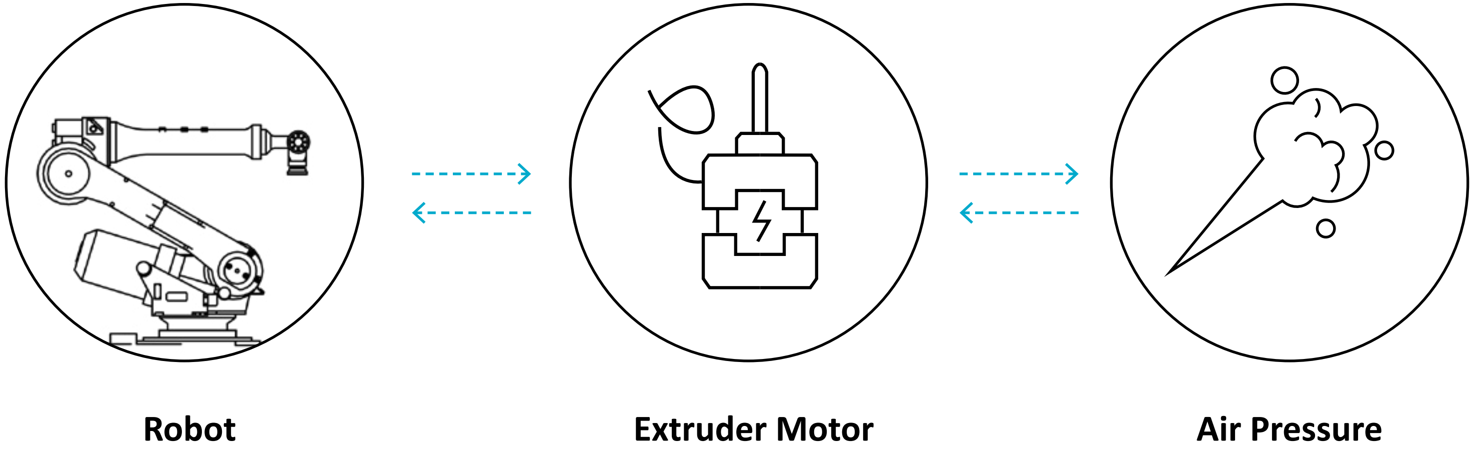


2. Speed Calibration

three rates / speeds had to be calibrated for a better flow rate.

Printing

Results

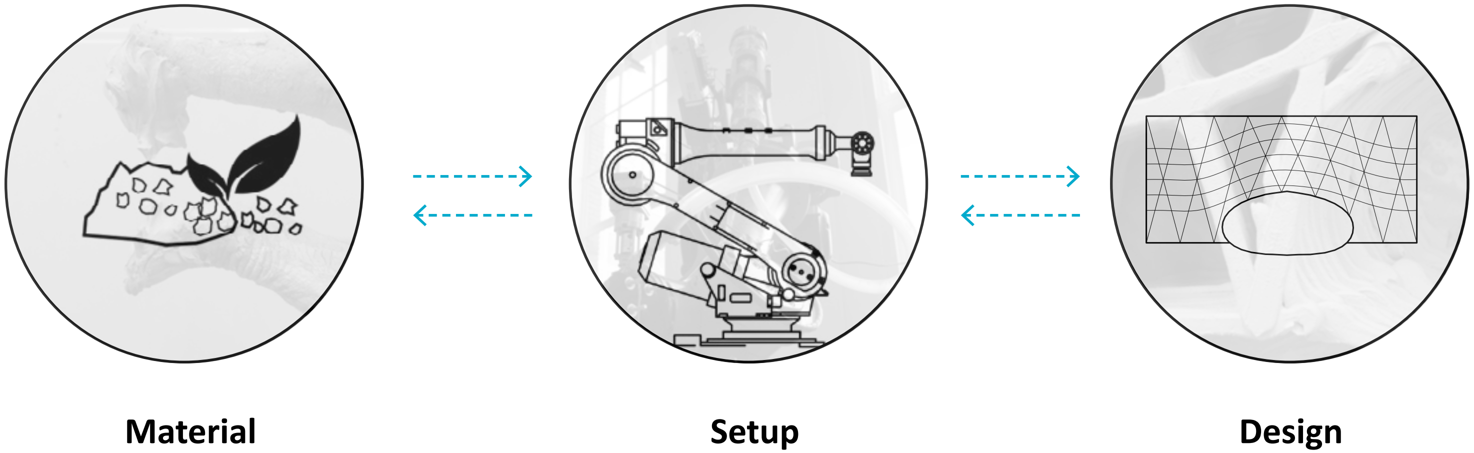
Final Print

Faster print, better material consistency and zero cracks.

Material **Setup** **Design**

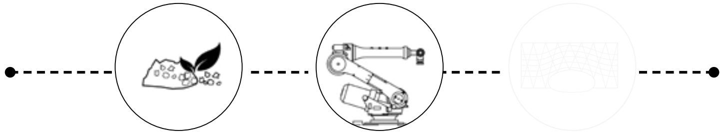
3 Aspects

Results observed are interlinked but the division is for better analysis



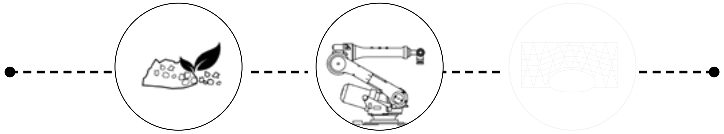
3 Aspects

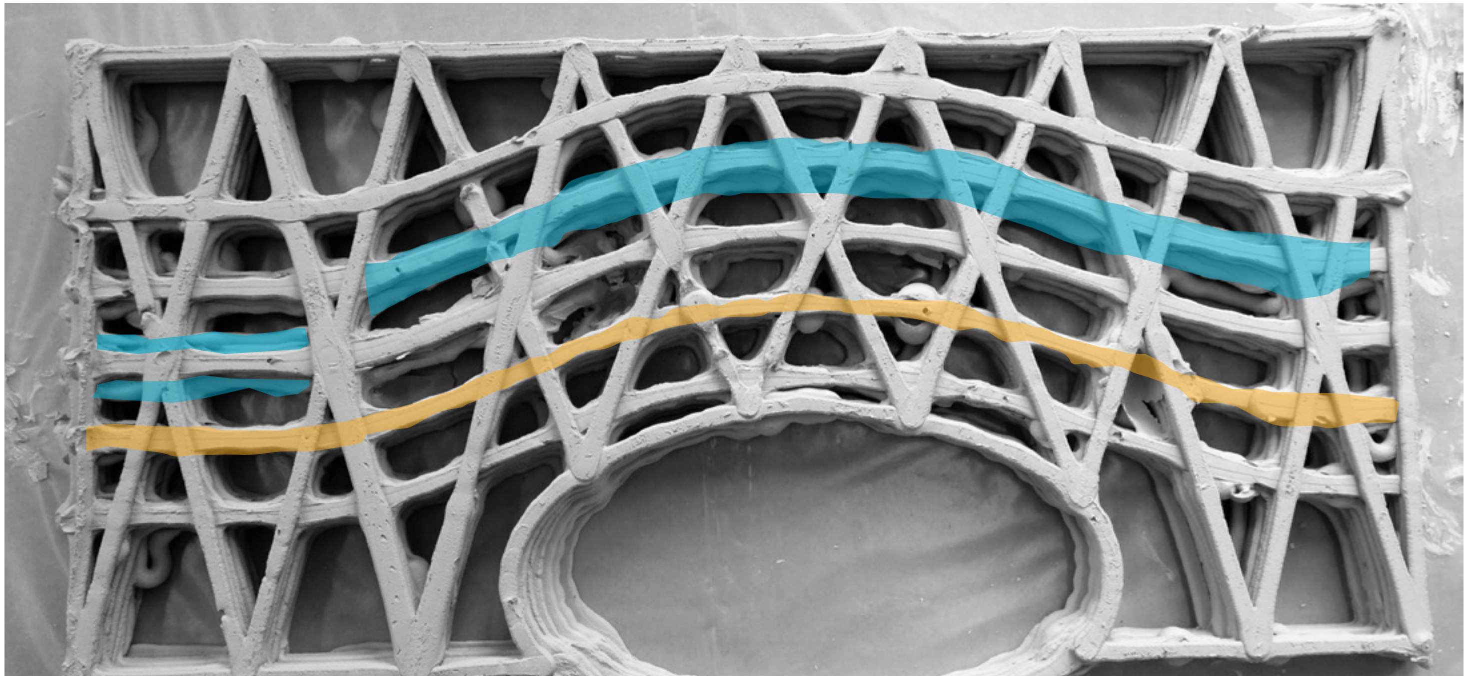
Results observed are interlinked but the division is for better analysis



1. Material Consistency

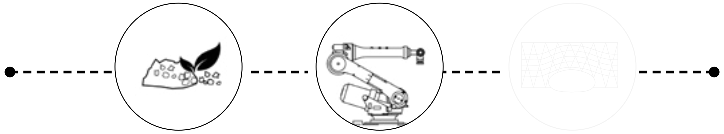
Material clogs If not mixed well, causing discontinuity.





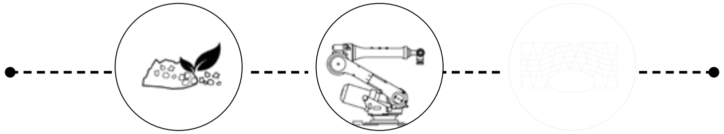
1. Material Consistency

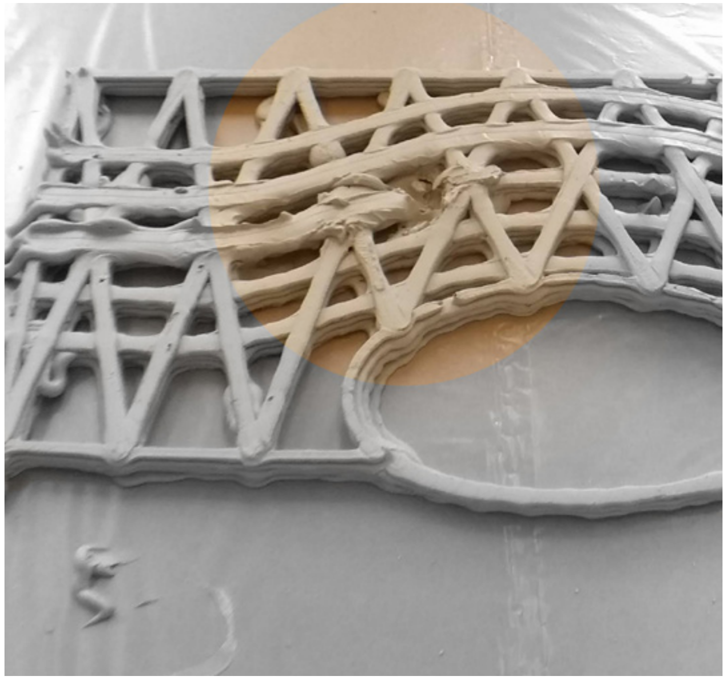
Water to Powder percentage causes unconcsistent flow
rate & unequal layer width.



1. Material Consistency

Using electric concrete mixer for bigger quantities.





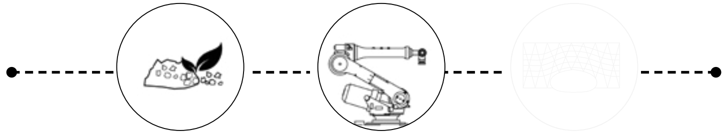
2. Material Filling

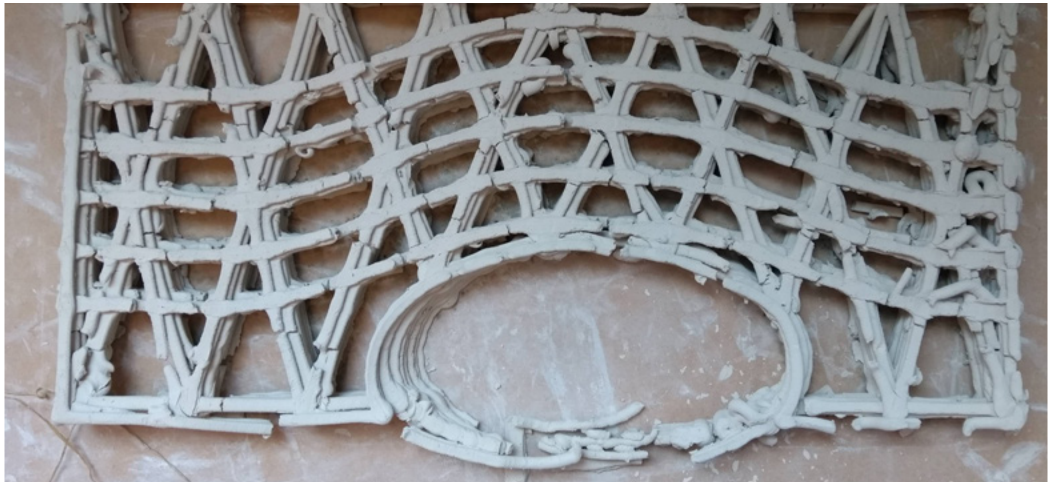
Air bubbles during filling cartridges cause
air shots & discontinuity.


Luthum: clay filling manual

2. Material Filling

Using spatula and filling in layers without any air bubbles.





3. Material Properties

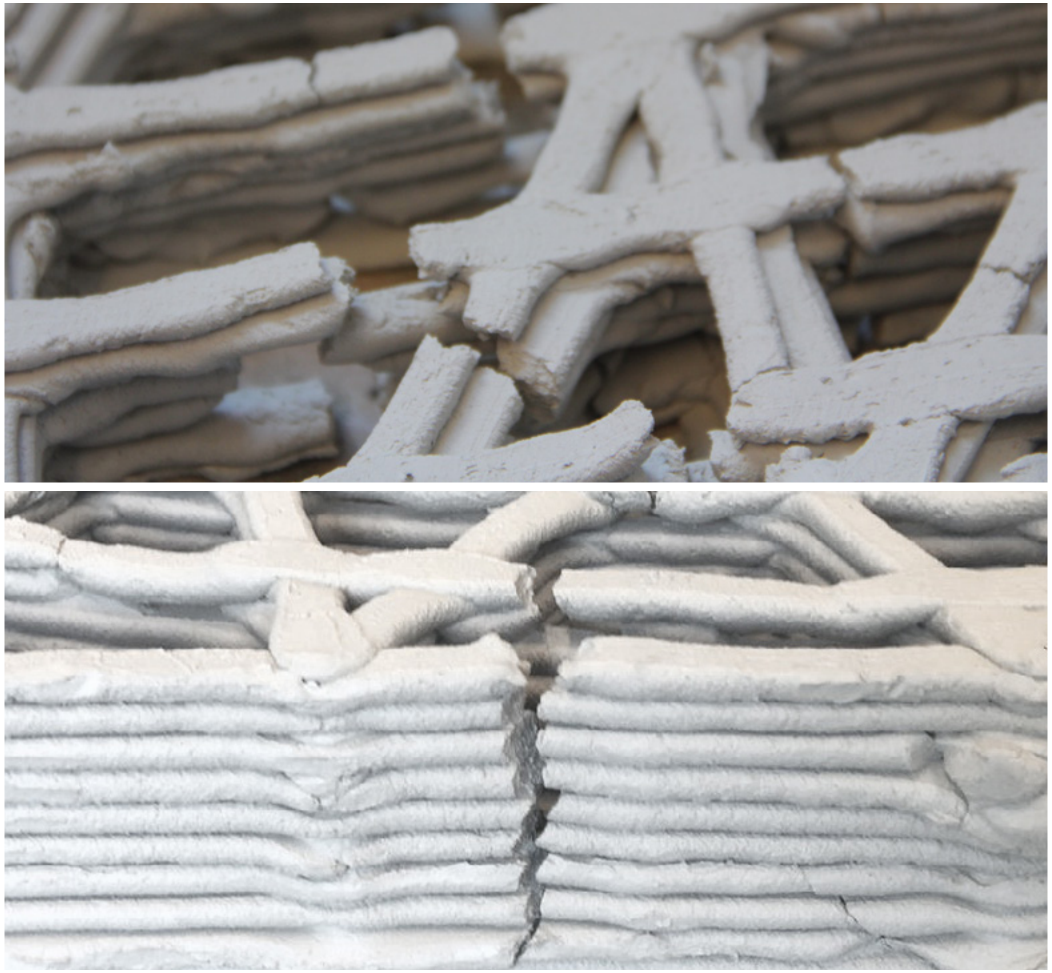
Clay shrinkage and wood water absorption properties
caused major cracks

3. Material Properties

Using plastic sheet to cover printed material avoids shock-dry.
Another sheet used as printing bed.

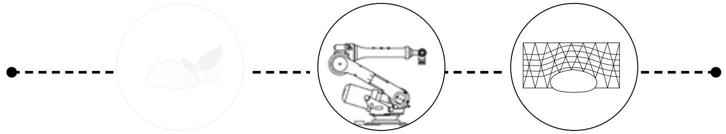
4. Layer Design

Overlaps & intersections cause material accumulation.



4. Layer Design

Accumulation of material causes cracks & higher shrinkage percentage.

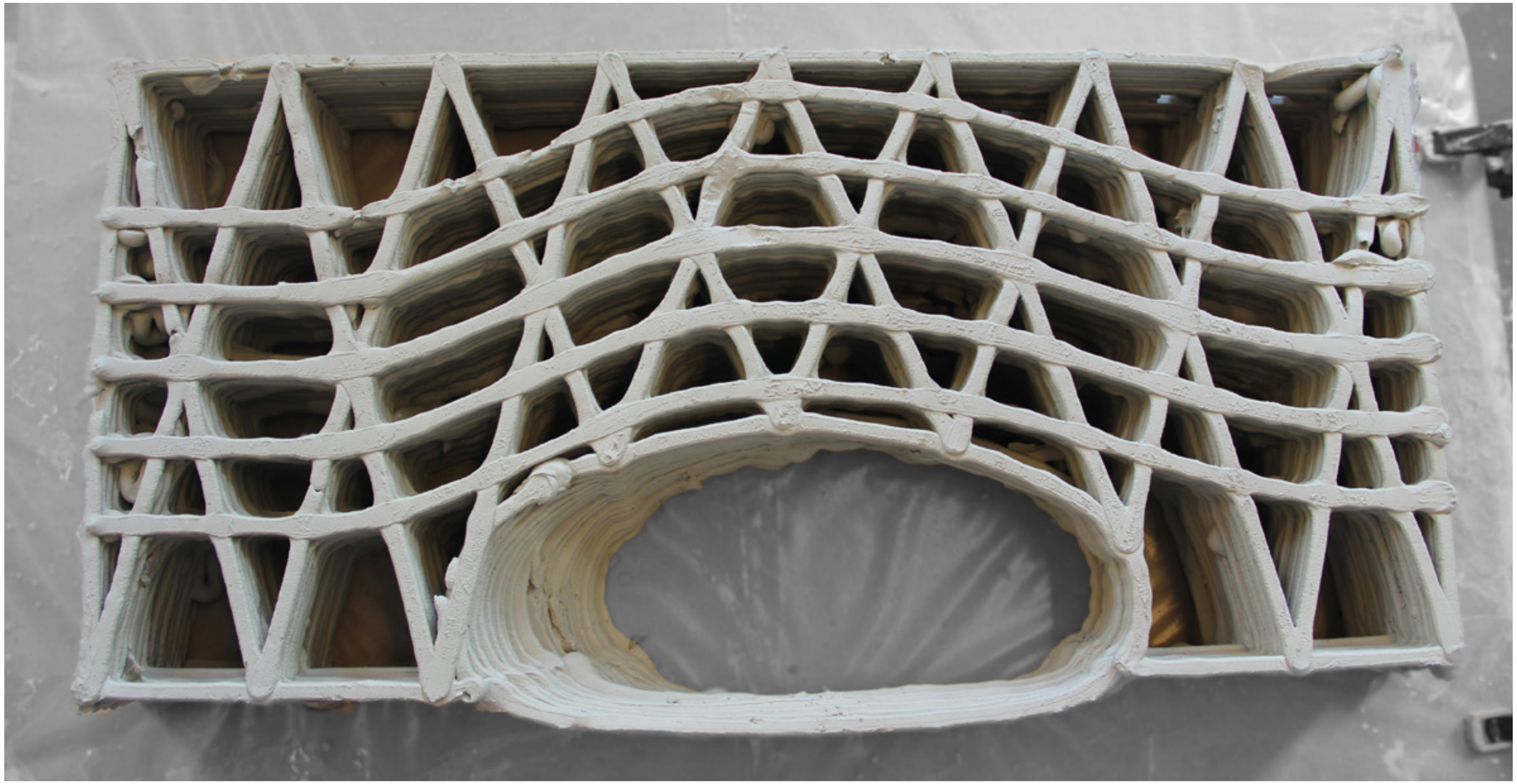


5. Motor I/O

Accumulation of material happens due to the lack of On/Off control for extruder. Affecting surface quality.

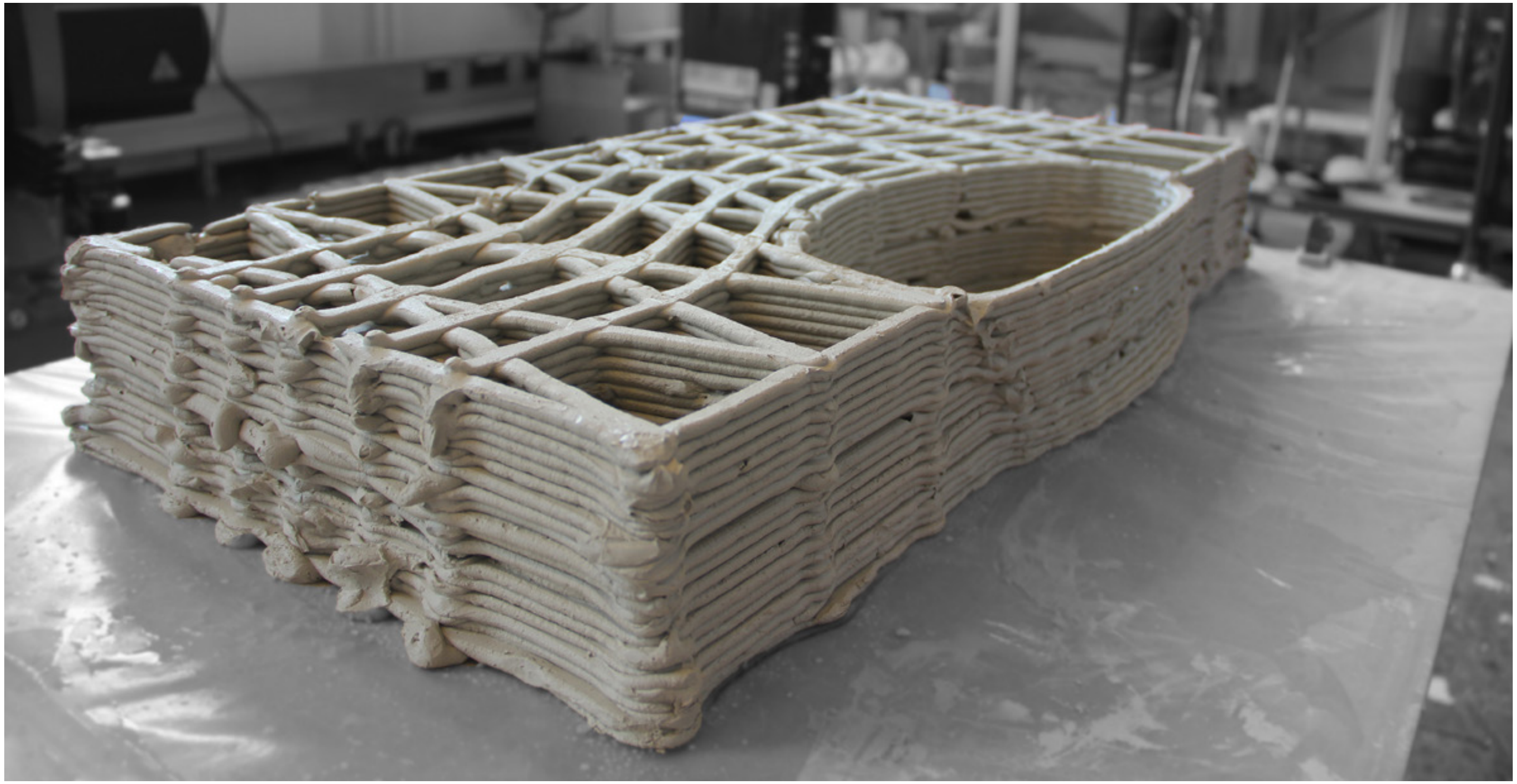
6. Overhangs

Structural supports are providing extra stability for the duct overhangs.



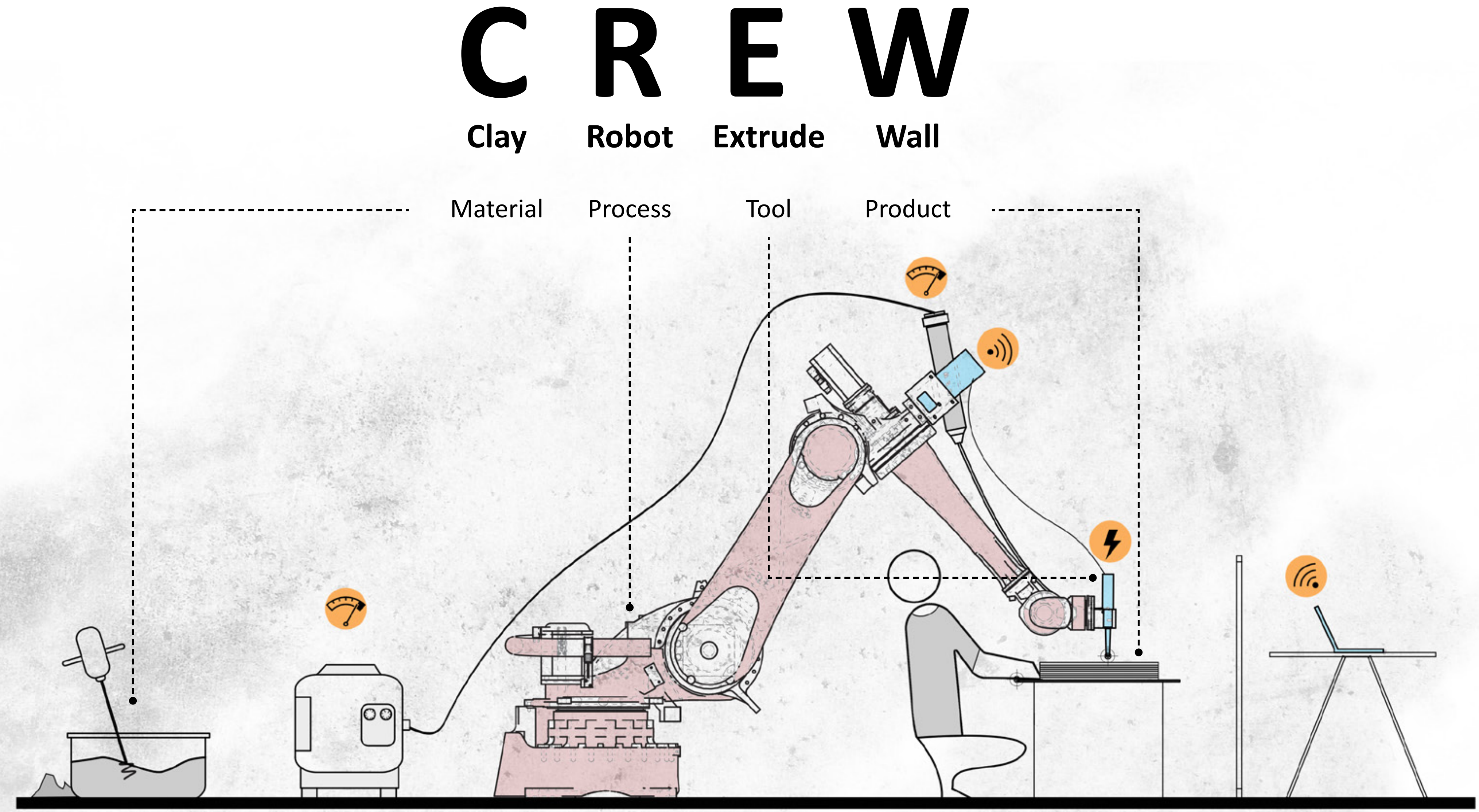
Final Print

Faster print, better material consistency and zero cracks.

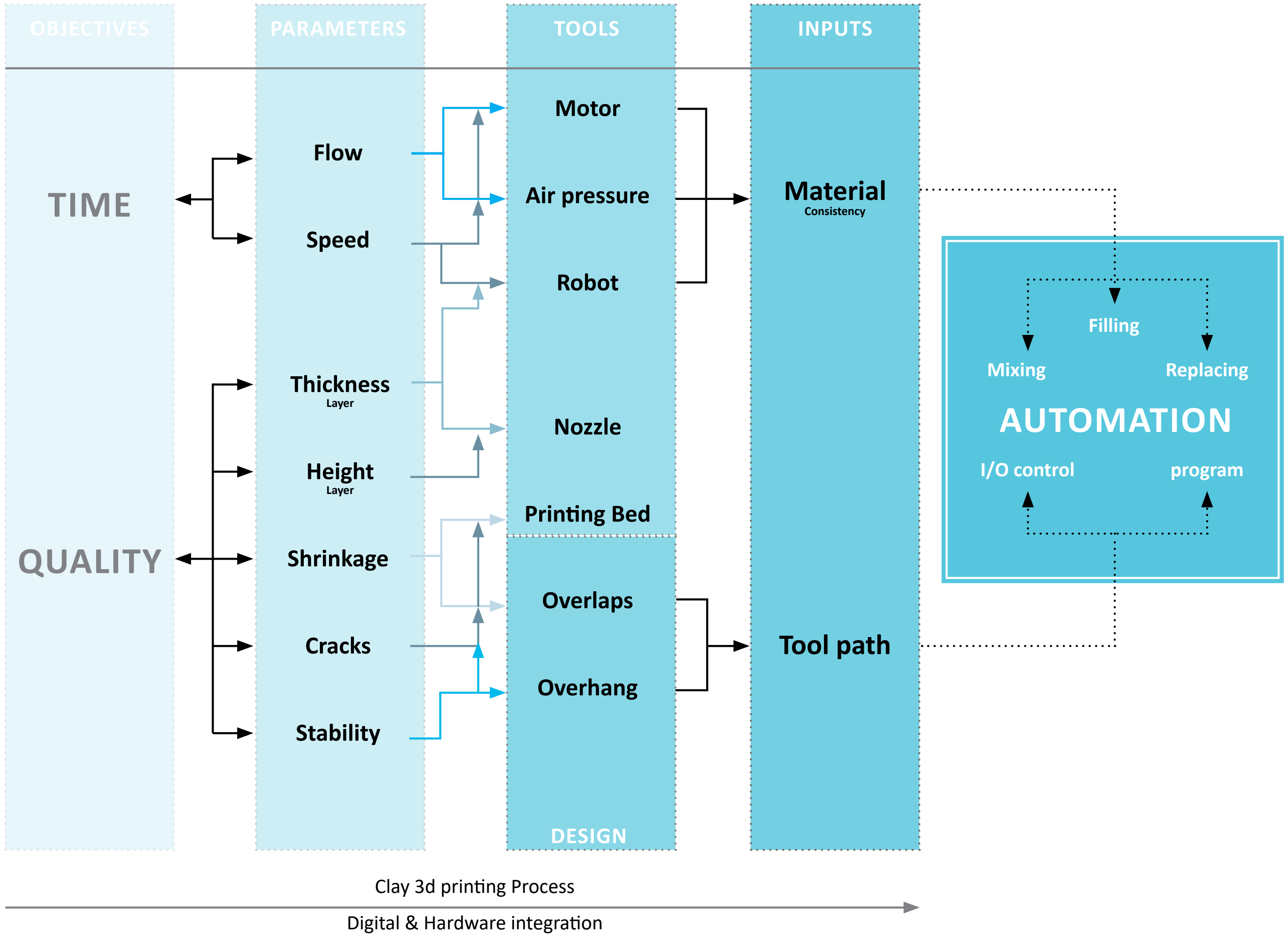


20	246 m	12 kg	30 %
Layers	Tool path length	Final model weight	Material waste

Final Print


C R E W
Clay
Robot
Extrude
Wall
Material
Process
Tool
Product

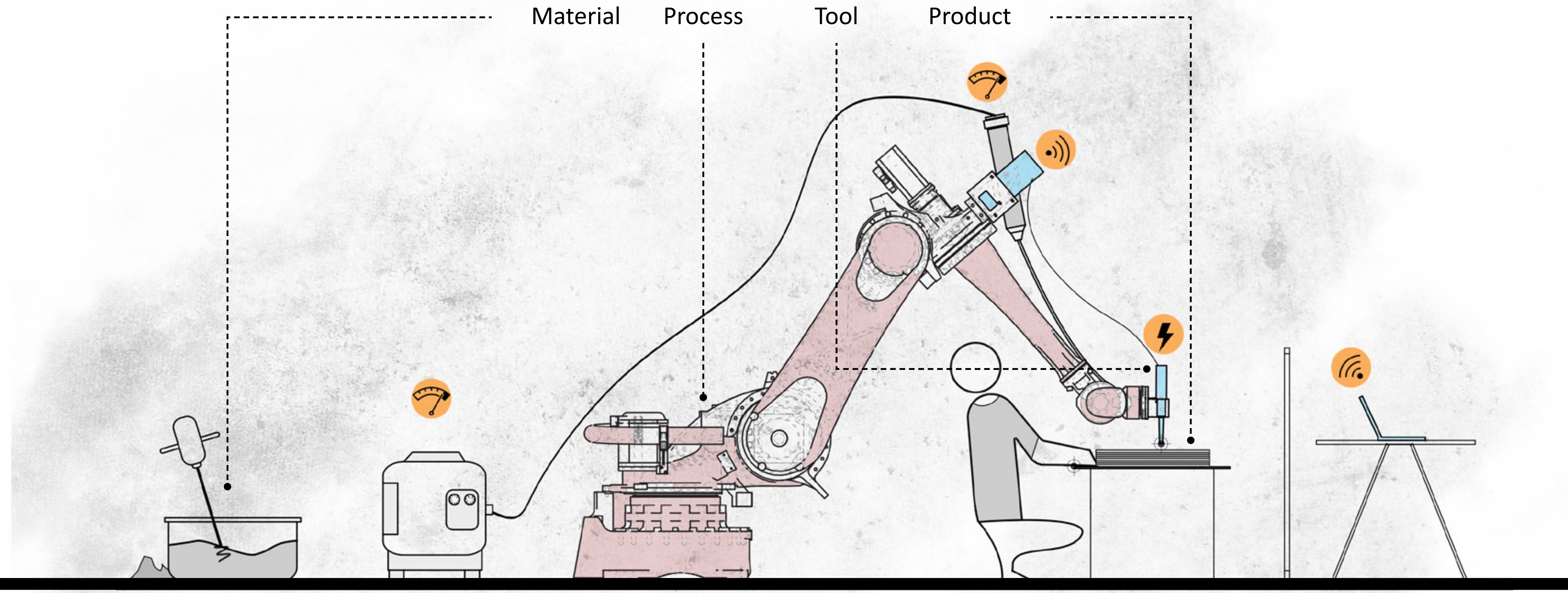
Conclusion


OBJECTIVES
PARAMETERS
TOOLS
INPUTS
TIME
QUALITY
Flow
Speed
Thickness
Layer
Height
Layer
Shrinkage
Cracks
Stability
Motor
Air pressure
Robot
Nozzle
Printing Bed
Overlaps
Overhang
DESIGN
Material
Consistency
Tool path
Filling
Mixing
Replacing
AUTOMATION
I/O control
program
Clay 3d printing Process
Digital & Hardware integration

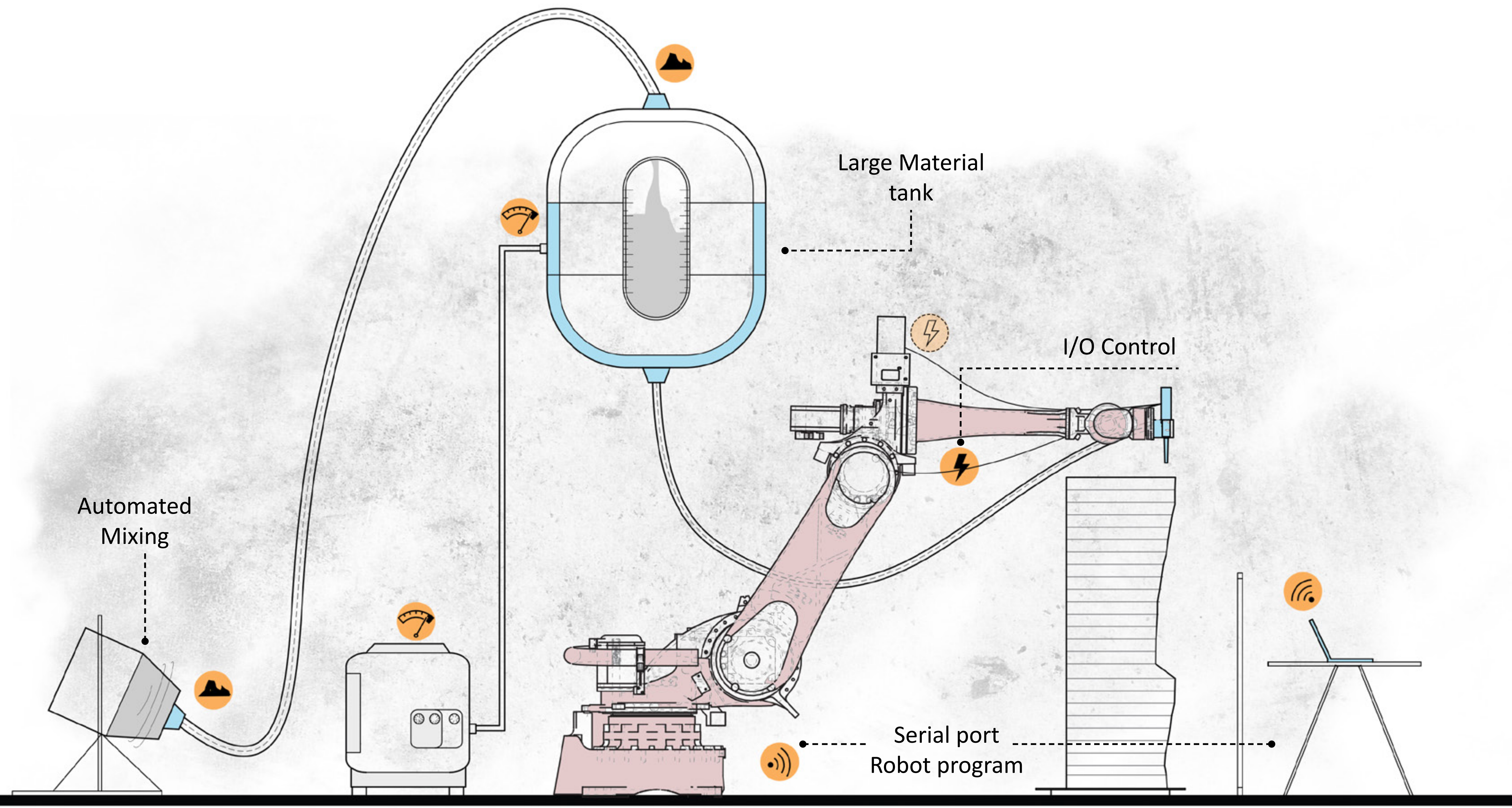
Conclusion

C R E W

Clay Robot Extrude Wall



Conclusion



Recommendation

C R E W

Material Process Tool Product

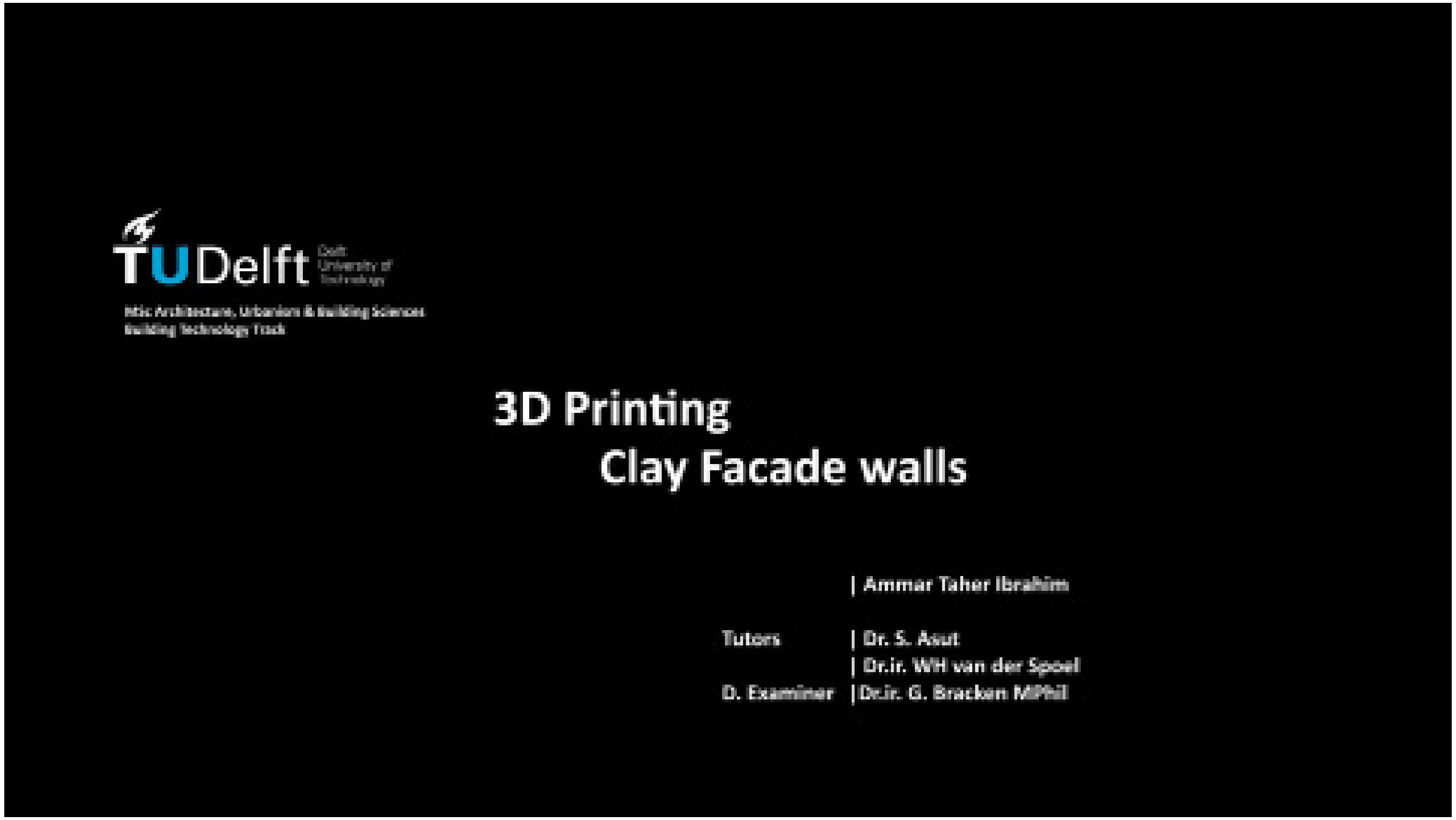
Material
- Material mixture least shrinkage
- Material mixture highest fluid rate.

Product
- Ventilation system optimization.
- Network connected facade units.

Process
- Tool Path optimization for less printing time.
- Pre-Printing Processing for clay product.

Tool
- Automating material supply for printing.
- I/O integration for extruder motor control.

Further research


TUDelft
3D Printing
Clay Facade walls
| Ammar Taher Ibrahim
Tutors | Dr. S. Asut
| Dr.ir. WH van der Spoel
D. Examiner |Dr.ir. G. Bracken MPhil

Thank you!