

THERM VENTATION

Fabricating a concrete twin-wall façade panel optimised for
integrated heat exchange system

Presented by : **Subhranshu Panda** | 4727606

Guided by : **Dr. Michela Turrin** and **Prof.de.ing Ulrich Knaack**

Delegate of the Board of Examiners : **Peter Koorstra**

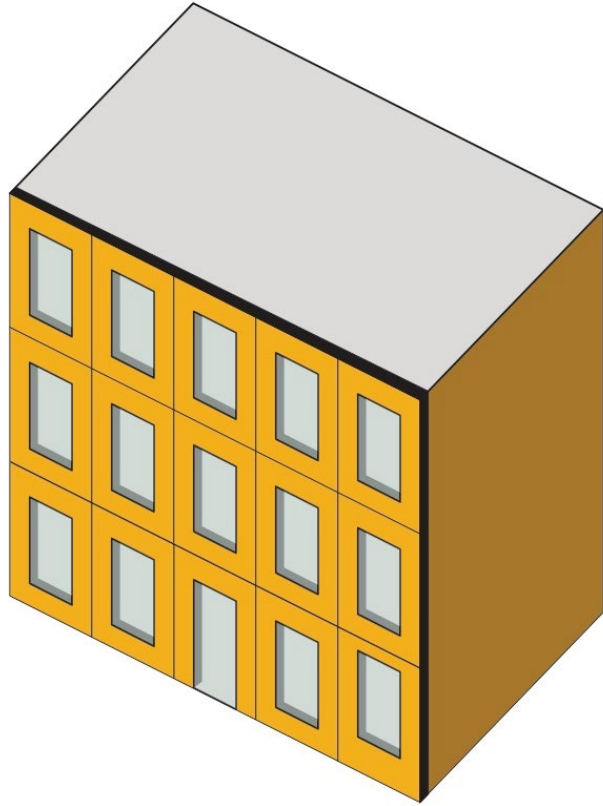
With help from :

SCHÜCO

Schöck
Dependable by design

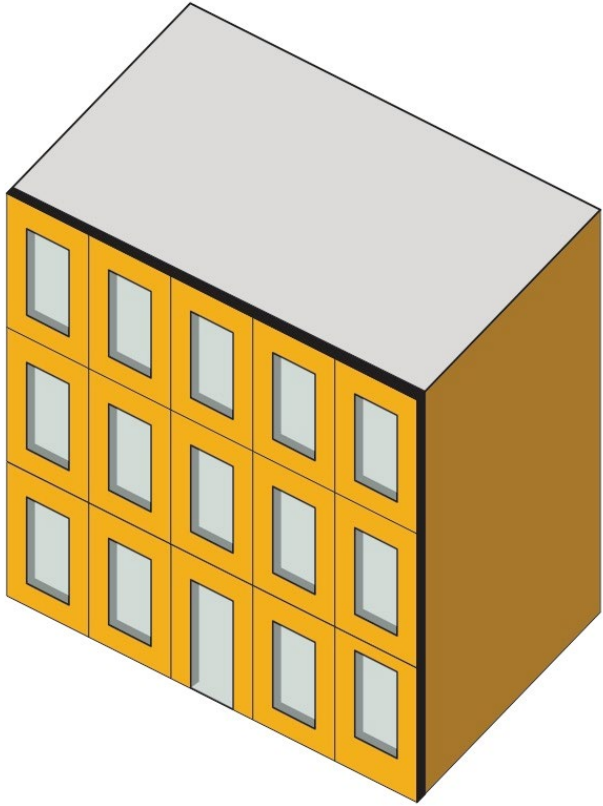
 **solidian**[®]

 **damilano**
group



India, China, US saw **70%** rise in energy demand last year

THE ECONOMIC TIMES Mar 26, 2019



SUSTAINABLE

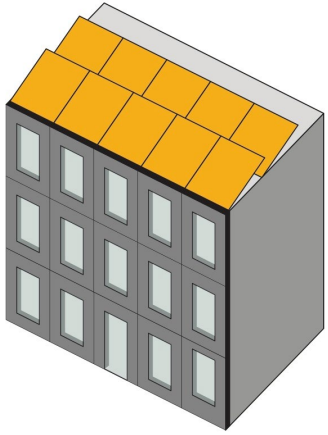
**PASSIVE
METHODS**



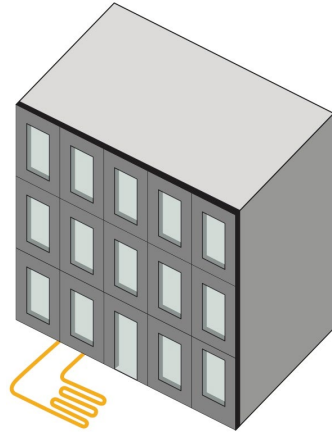
Maximise EFFICIENCY

Minimise ENERGY dependency

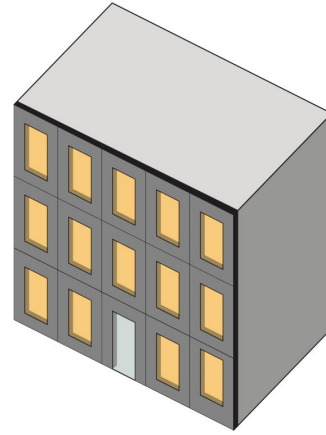
SUSTAINABLE METHODS



Solar energy

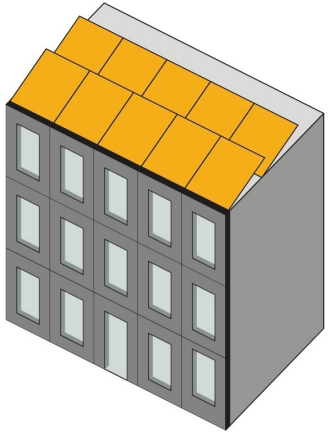


Geo-thermal energy

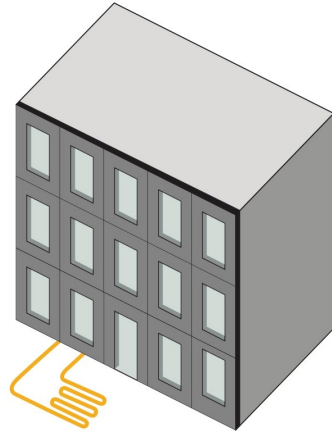


Passive systems

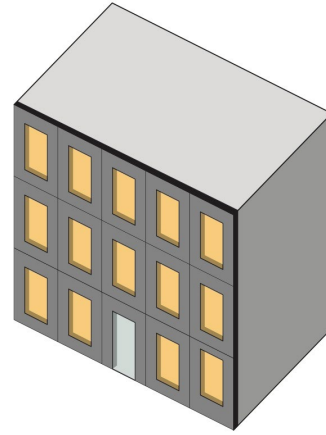
SUSTAINABLE METHODS



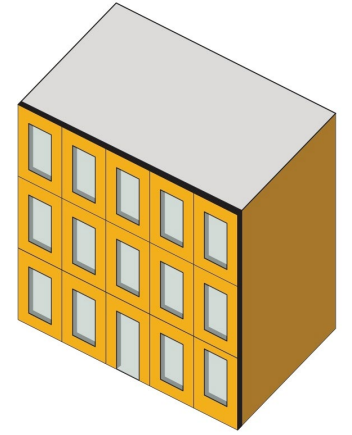
Solar energy



Geo-thermal energy



Passive systems



Opaque sections

of façade

WHY? Opaque sections



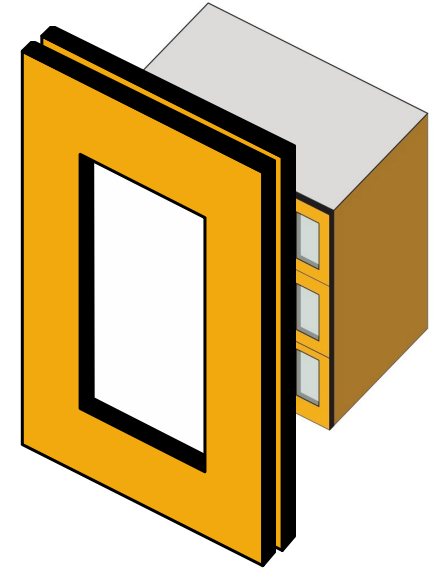
Large surface area 40-60%



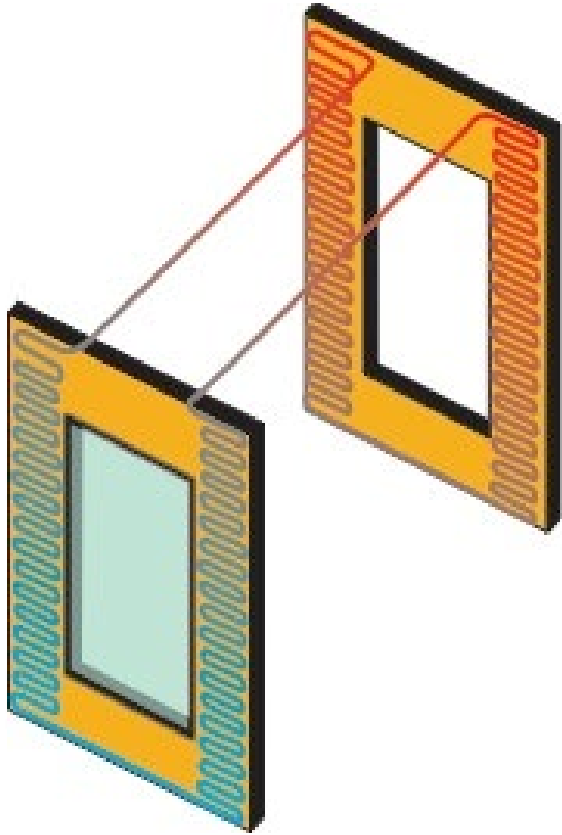
Most exposure to outdoor environment



High energy storage loss



INACTIVE FAÇADE



Heat exchange system **embed** within façade panels

DESIGN + FABRICATION

RESEARCH QUESTION

*How to **design and fabricate** a concrete façade panel with integrated heat exchange system and optimize it's geometry to ~~increase~~ efficiency ?*

maximise

LET'S DISCUSS

TYPE OF PANEL & CONTEXT

HOW IS IT **DESIGNED** ?

HOW IS IT **MODIFIED** FOR MAXIMUM EFFICIENCY ?

HOW TO **FABRICATE** IT ?

CONCRETE



Economical



Versatile

CONCRETE



Economical



Versatile



Very high specific heat capacity and thermal conductivity

	Water	Air (250K)	Concrete	Brick	Aircrete
Specific heat capacity (J/kg K)	4200	716	1000	800	1000
Thermal conductivity (W/mK)	0.60	0.024	1.13	0.73	0.15

CONCRETE



Economical



Versatile

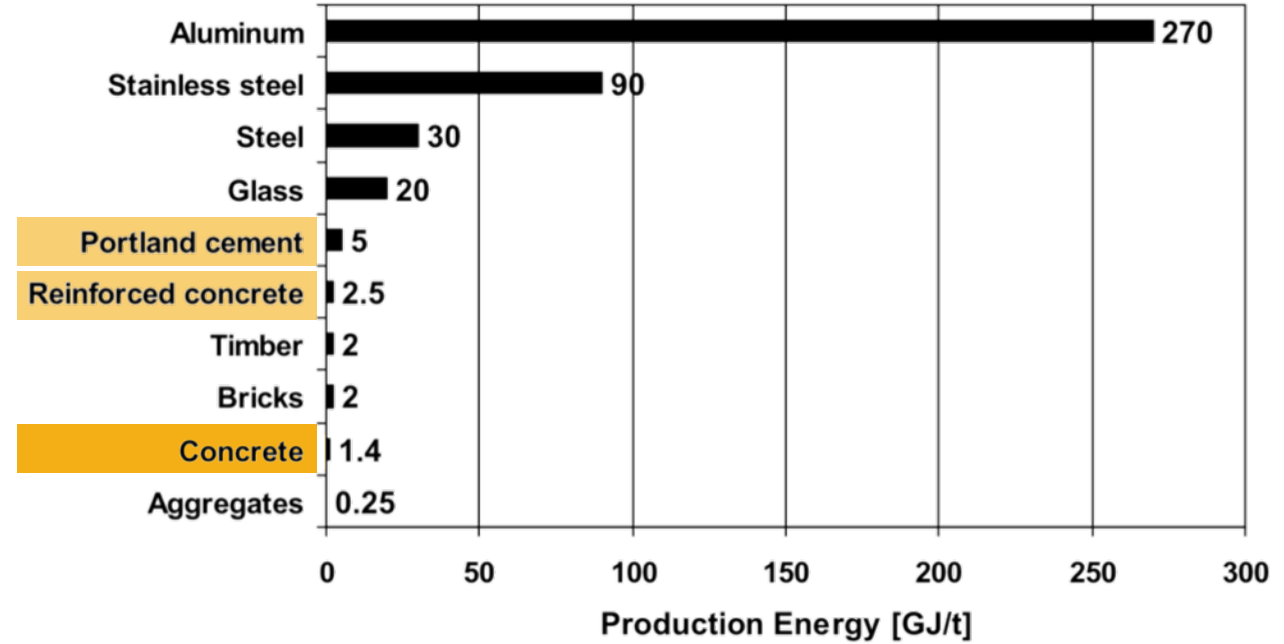


Very high specific heat capacity and thermal conductivity



Low energy for production

* LOWER IS BETTER



Inference: Eliminate metal reinforcements

CONCRETE



Economical



Versatile



Very high specific heat capacity and thermal conductivity

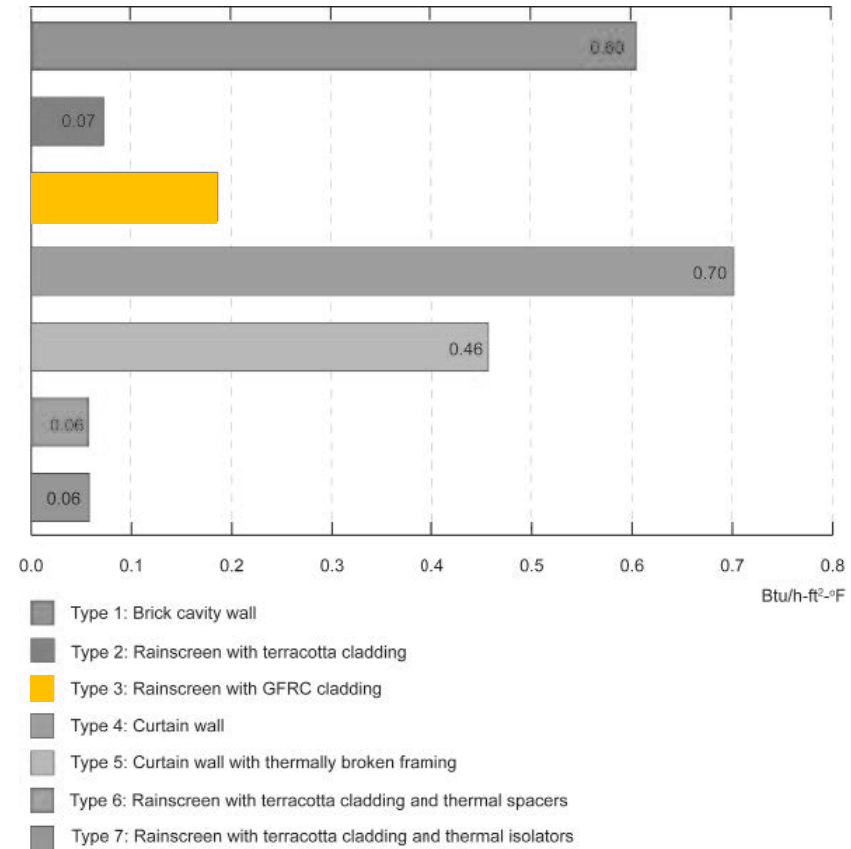


Low energy for production



High building performance

* LOWER IS BETTER



Total annual energy use for different analysed climatic zones

CONCRETE



Economical



Versatile



Very high specific heat capacity and thermal conductivity



Low energy for production

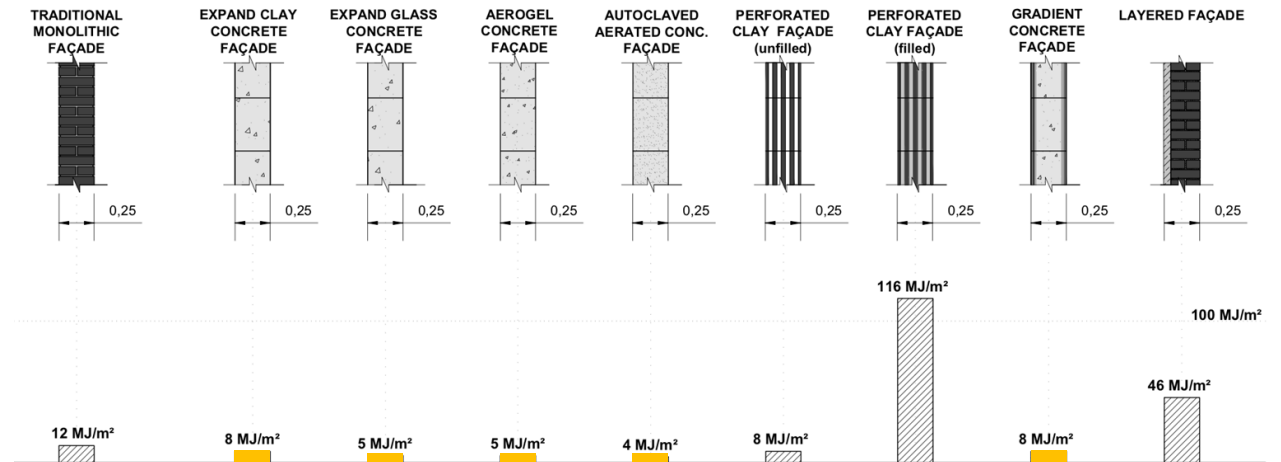


High building performance



High recyclable potential

* LOWER IS BETTER

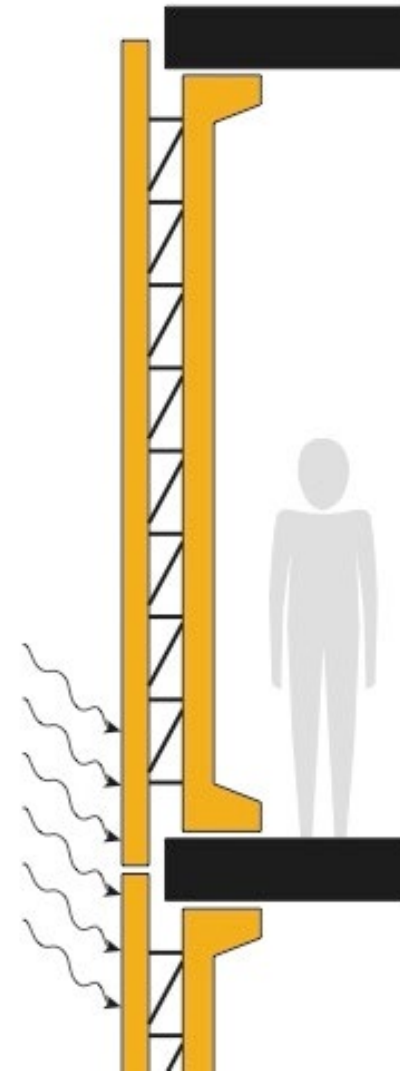


Energy for recycling for different external walls (Egypt)

FAÇADE PANEL



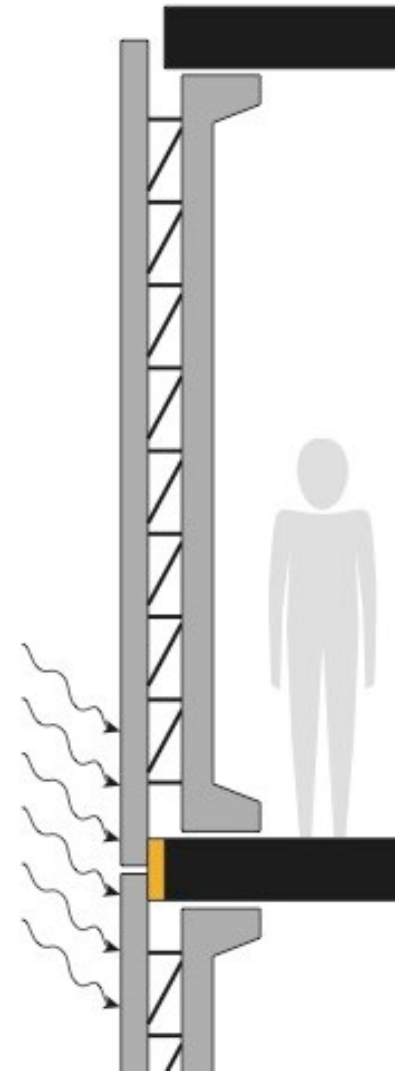
Twin wall system



FAÇADE PANEL



Twin wall system



FAÇADE PANEL

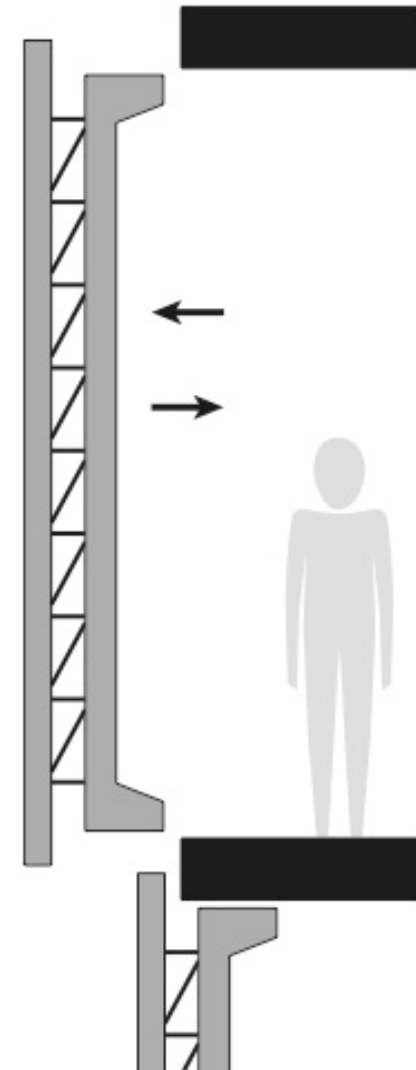


Twin wall system



Non- load bearing

- Upgradability and serviceability
- Extended service life of building



FAÇADE PANEL



Twin wall system

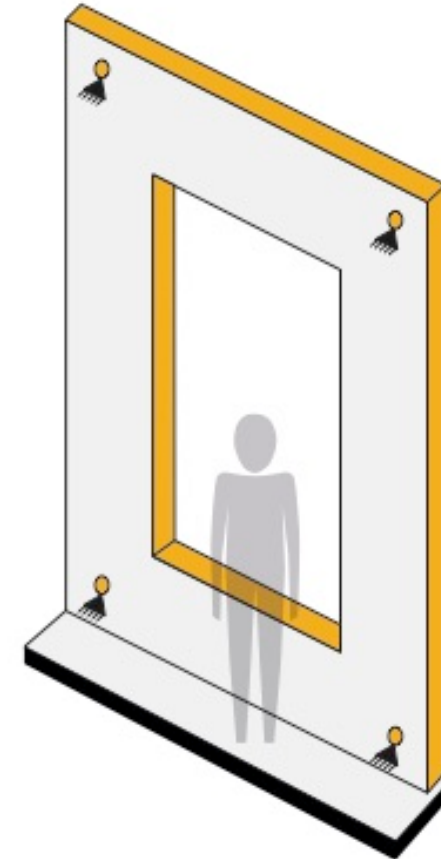


Non- load bearing

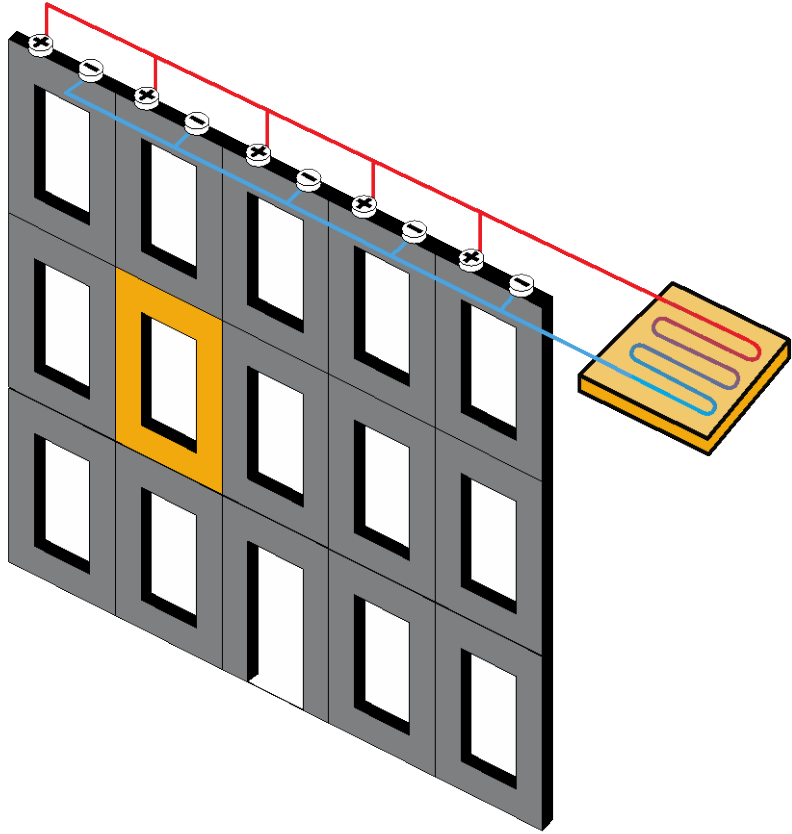
- Upgradability and serviceability
- Extended service life of building



Fixed at 4 points

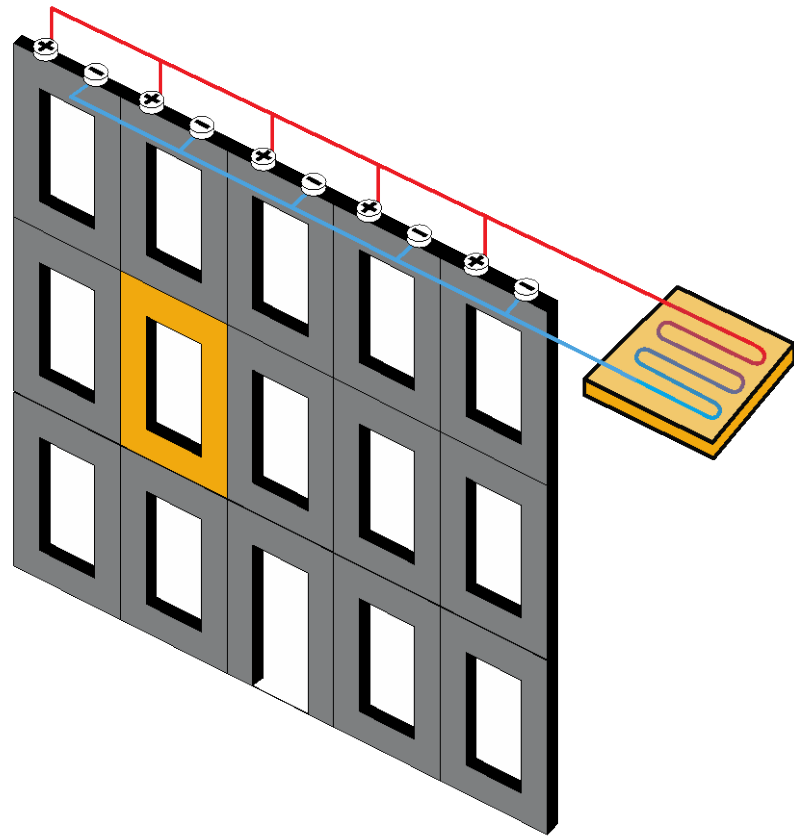


FAÇADE PANEL



Solar thermal **Collector**

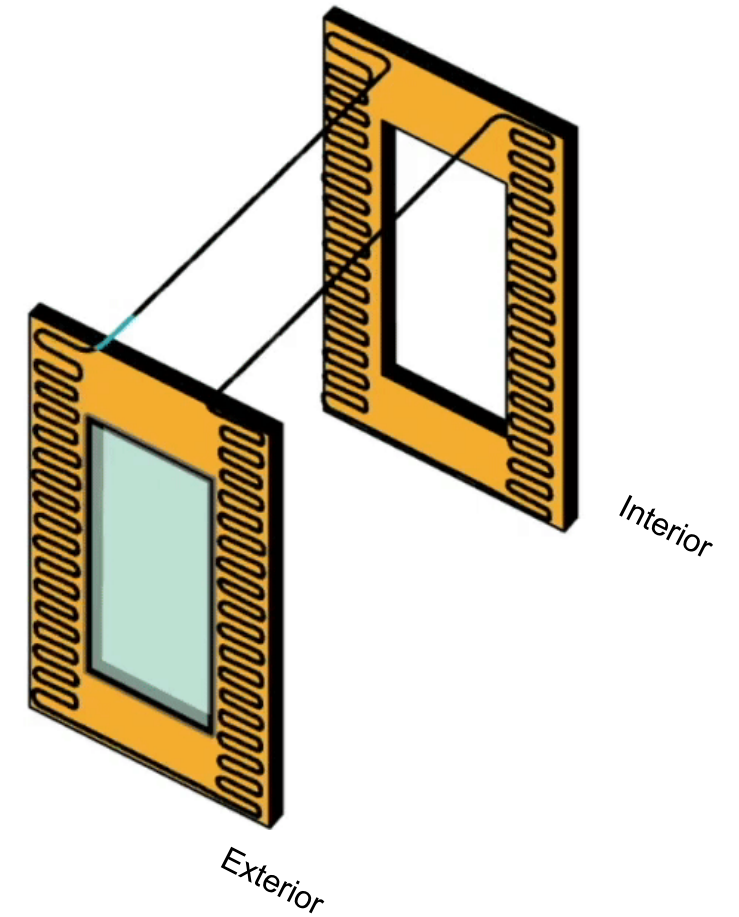
FAÇADE PANEL



Solar thermal **COLLECTOR**

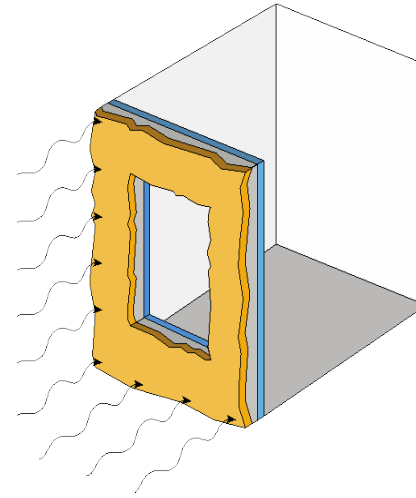
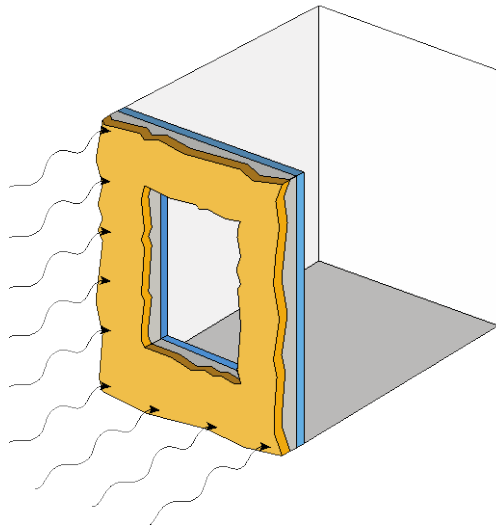


Respond to Nature



Solar thermal **EXCHANGER**

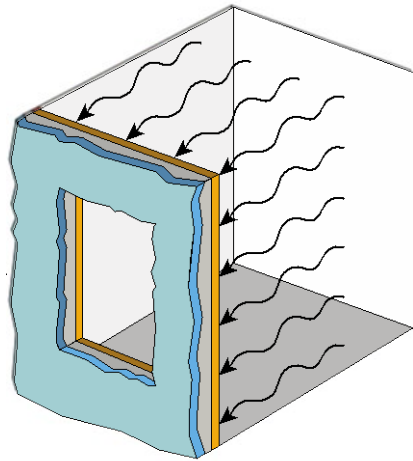
SYSTEM




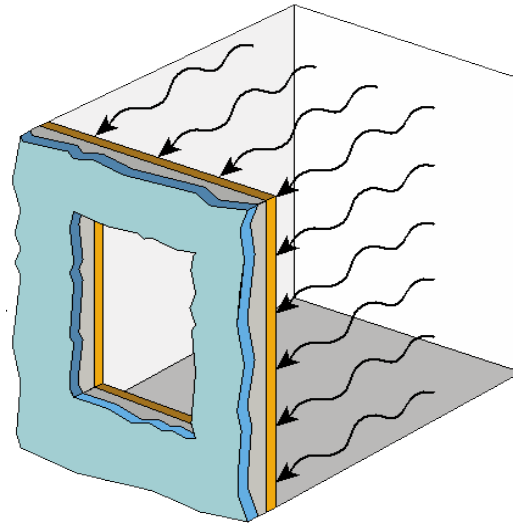
Winters with cold nights and sunny days

SYSTEM

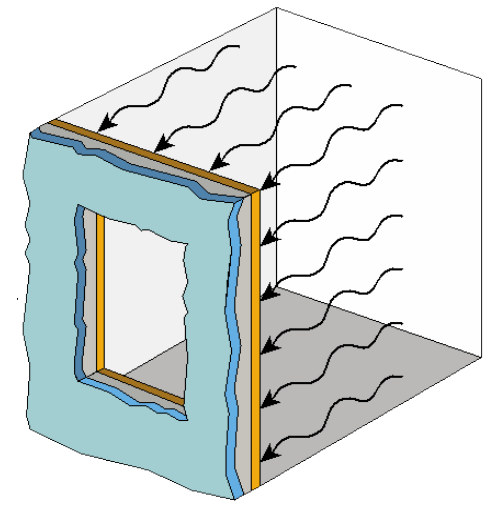
 DAY



 SUNSET



 SUNRISE



Summer with hot days and cooler nights

SYSTEM

Delhi, India

Composite climate



40 °C

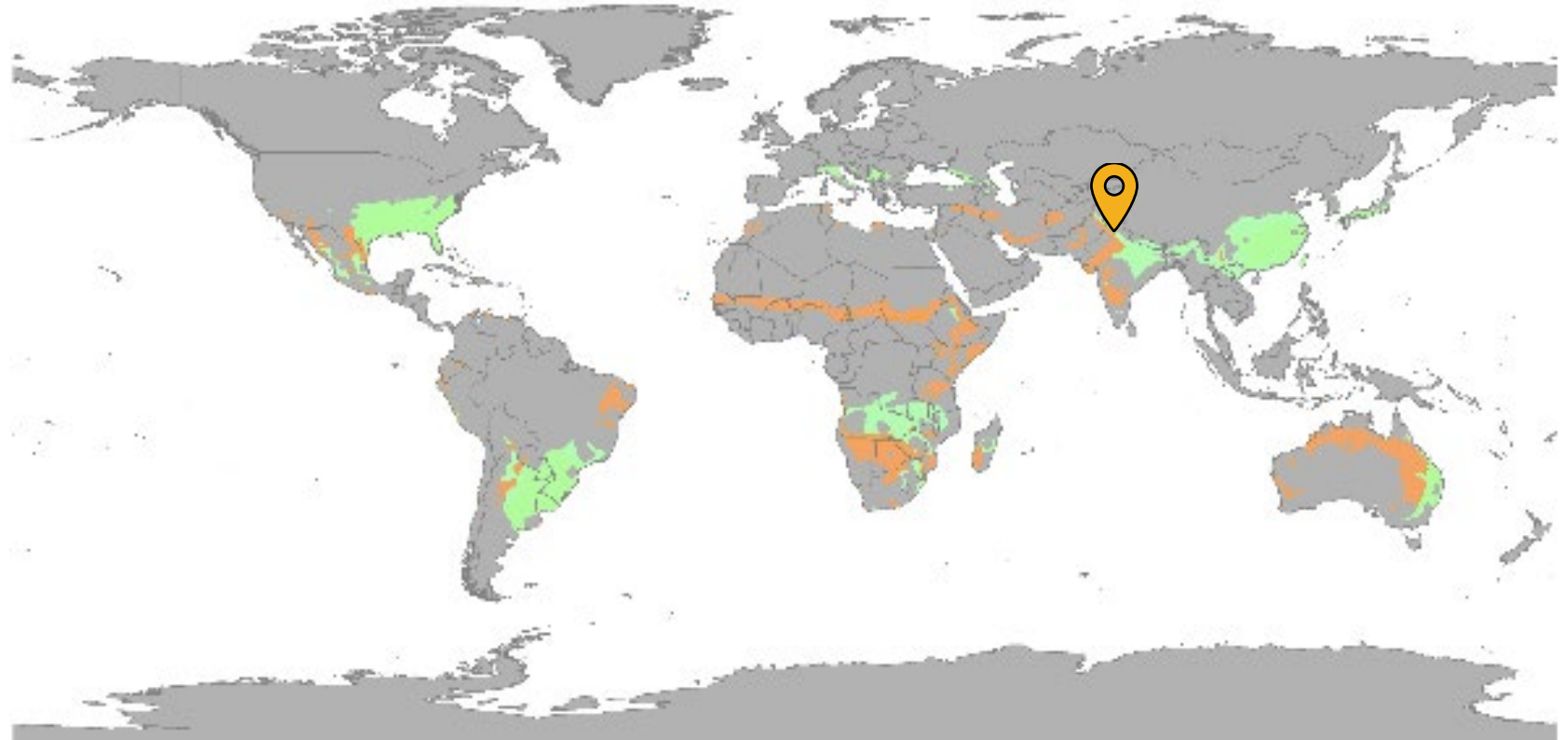


04 °C



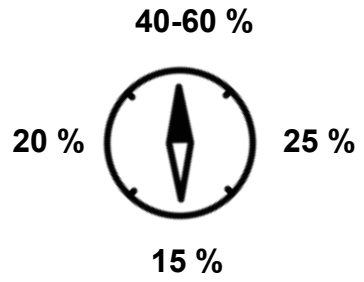
10 m/s

39 m/s (safe loading)



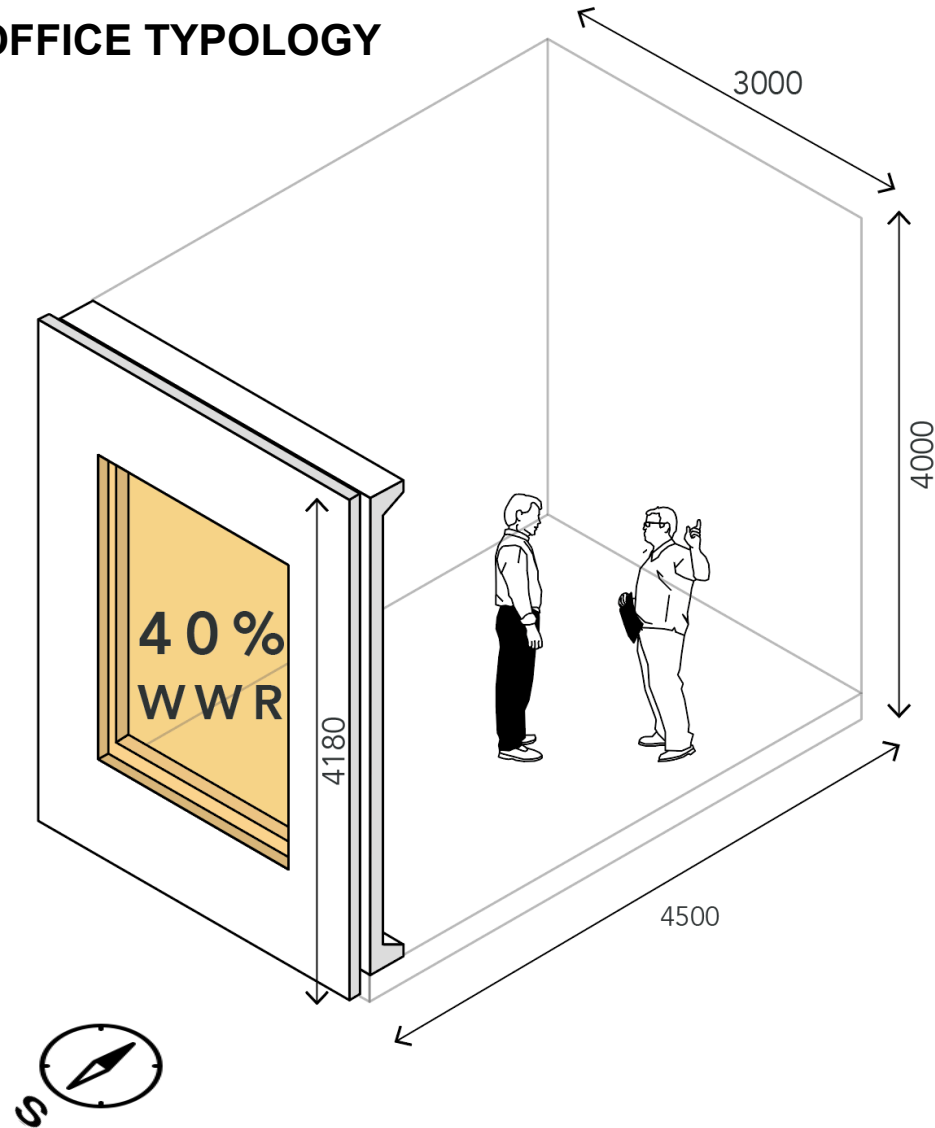
AF	BWh	Csa	Cwa	Cfb	Csa	Uwa	Ufa	Ef
Am	BWk	Csb	Cwb	Cfb	Csb	Uwb	Ufb	Ef
Aw	BSh	Cwa	Cka	Cfb	Cwa	Dwb	Dfb	
	BSk					Ucd	Uwd	Utd

SYSTEM



Double glass with an U-value of 3.3 W/m²K

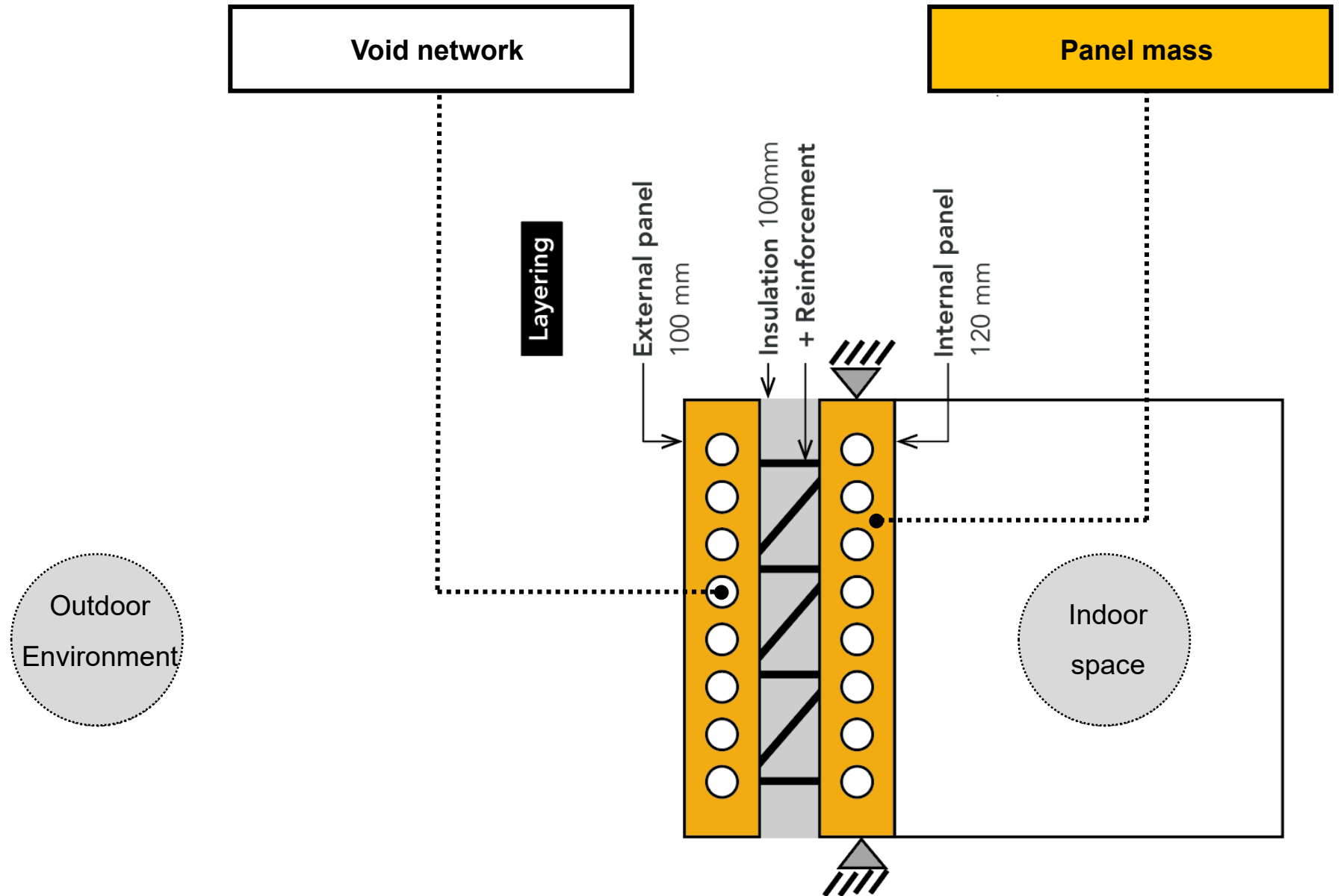
OFFICE TYPOLOGY



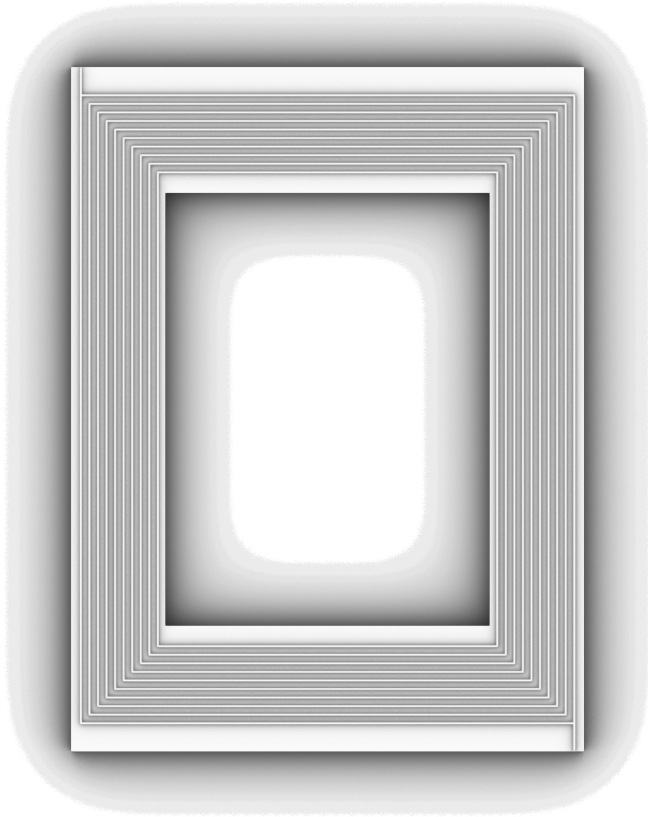
LET'S DISCUSS



SYSTEM - concept



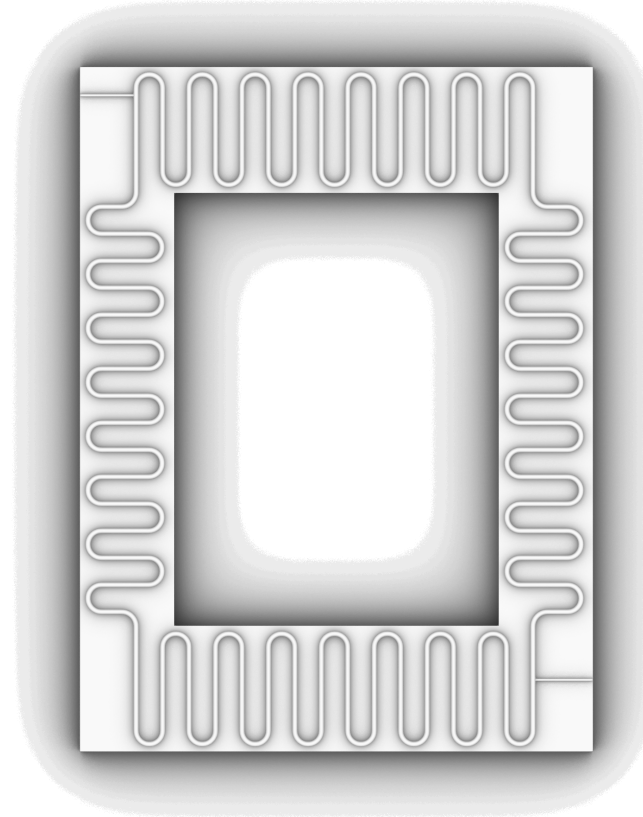
SYSTEM - concept



Multiple branching --- increasing pressure drop

Long tubes --- higher pressure drop

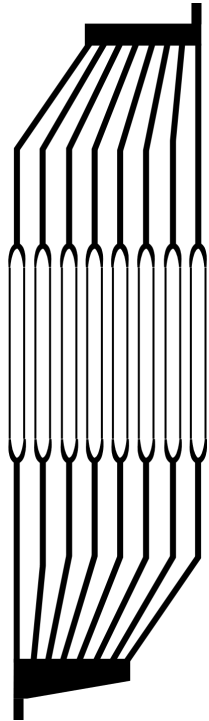
No space for fixtures



Single long tube --- prone to blockage

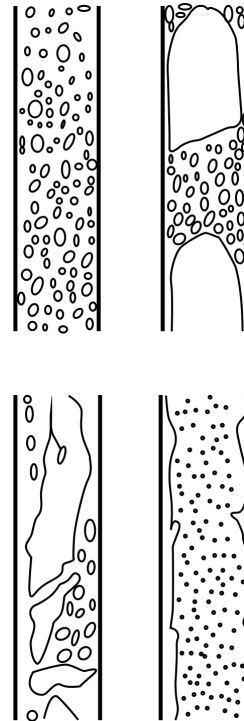
Long tubes --- higher pressure drop

Minimum service.



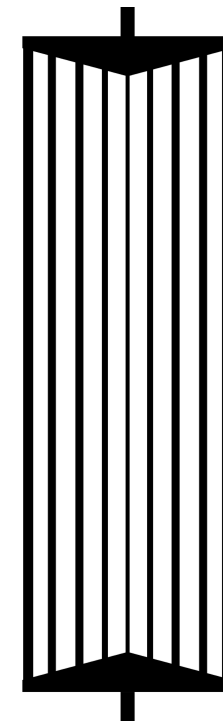
Spong3D

Heat transfer of water by convection



Flow patterns

Water flow & Pressure management

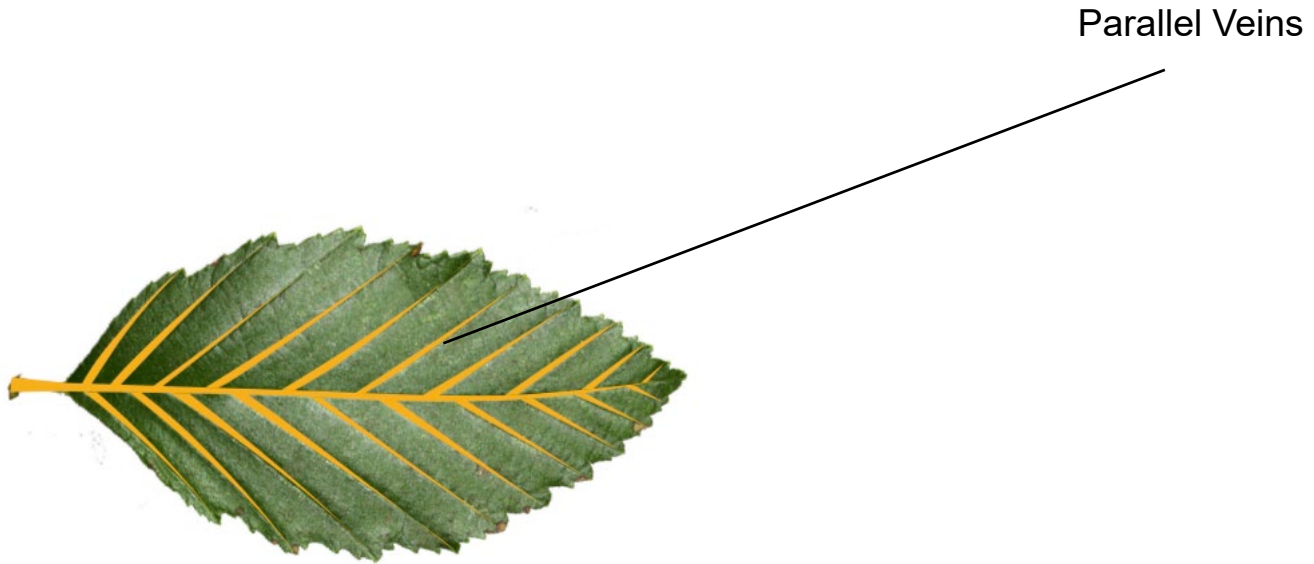


Leaf venation

Pressure mgmt.. & Geometry

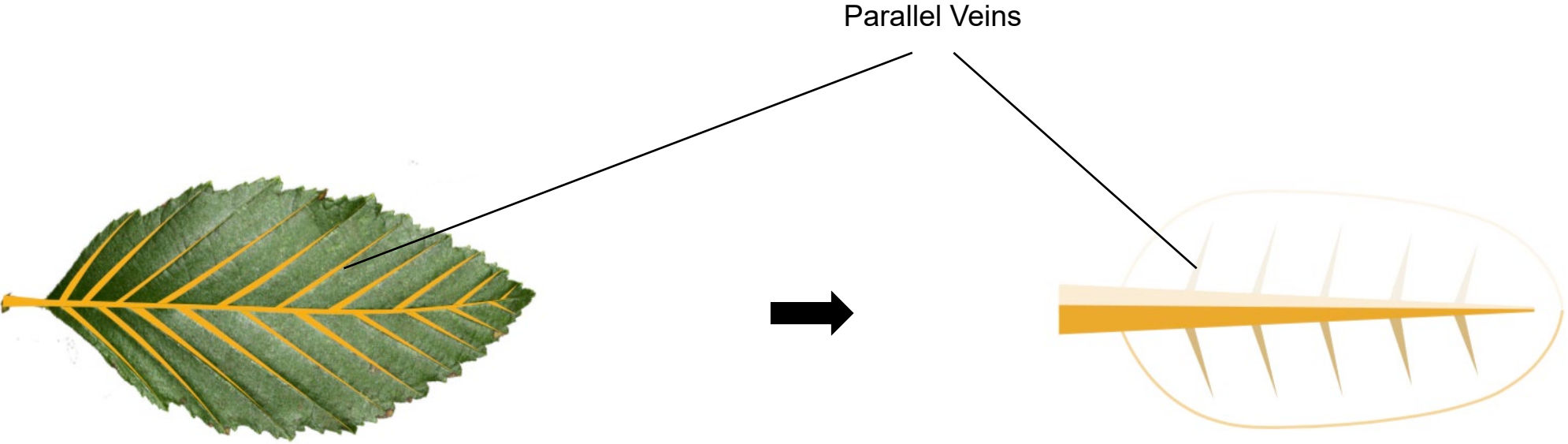
LEARN from Nature



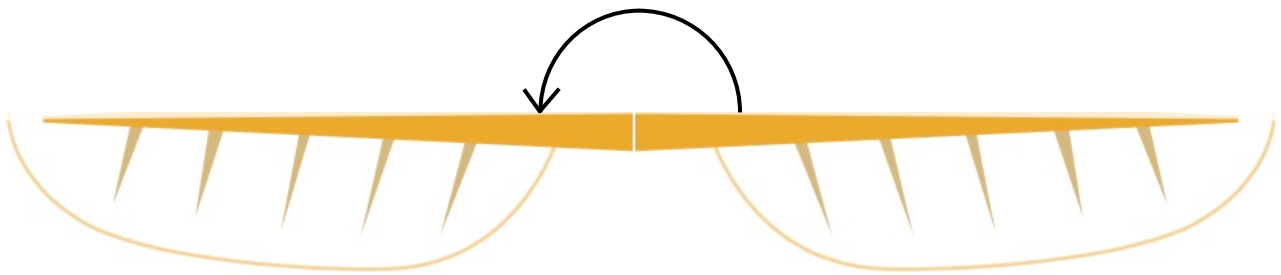


Parallel Veins

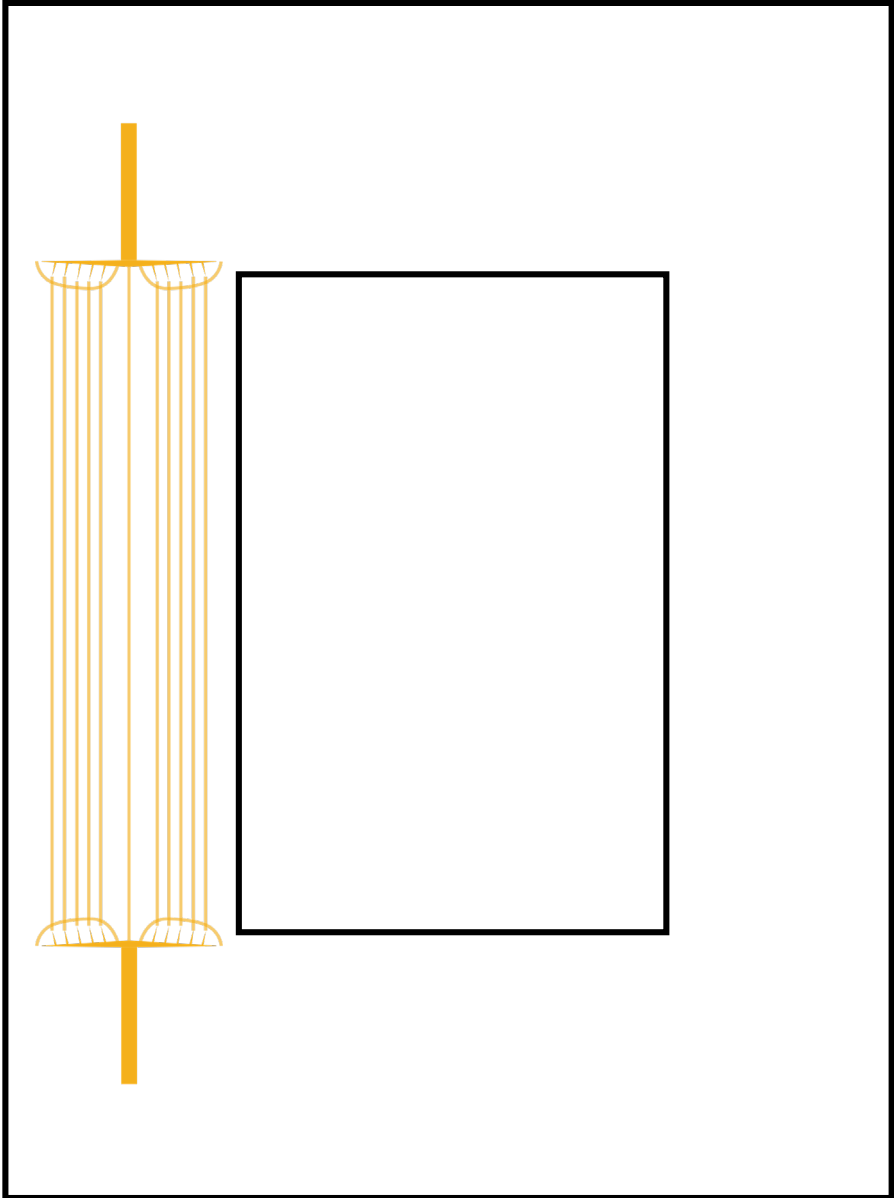
VENATION



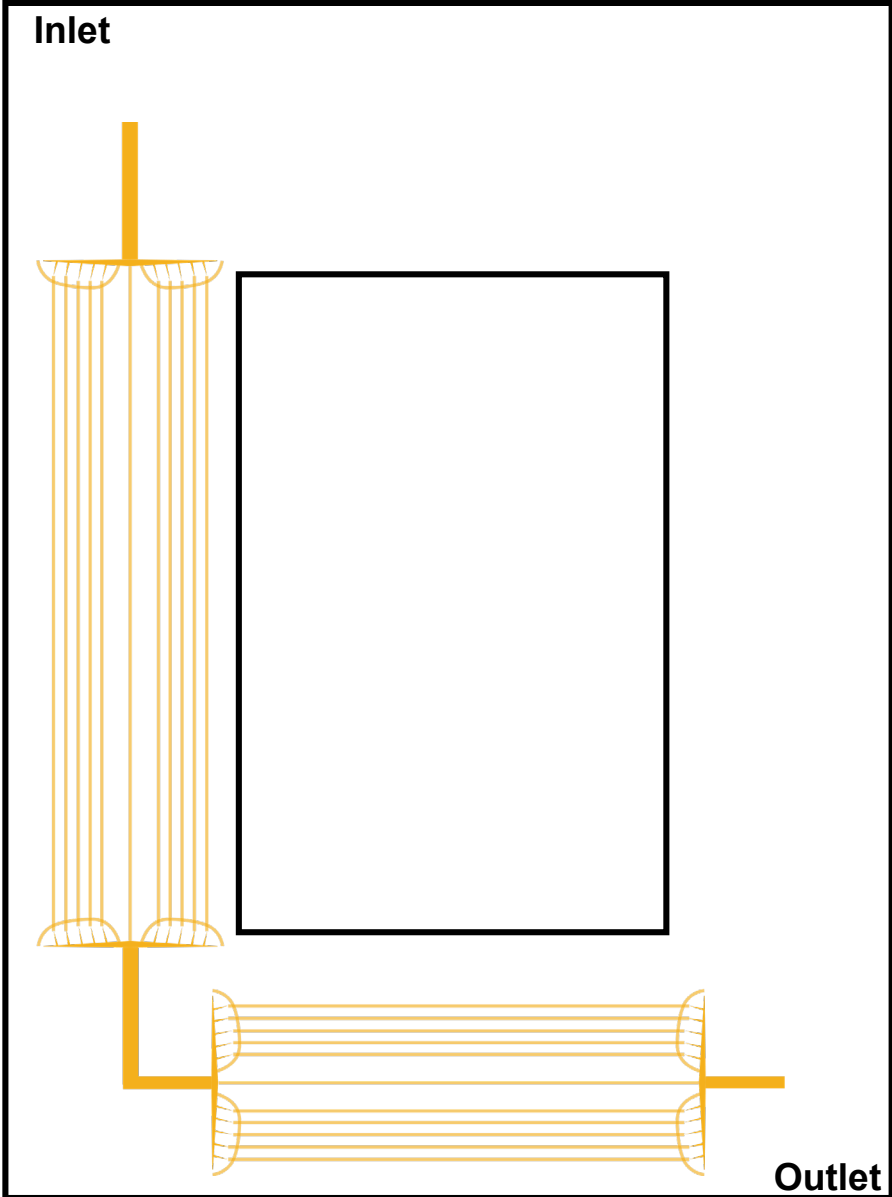
SYSTEM - concept



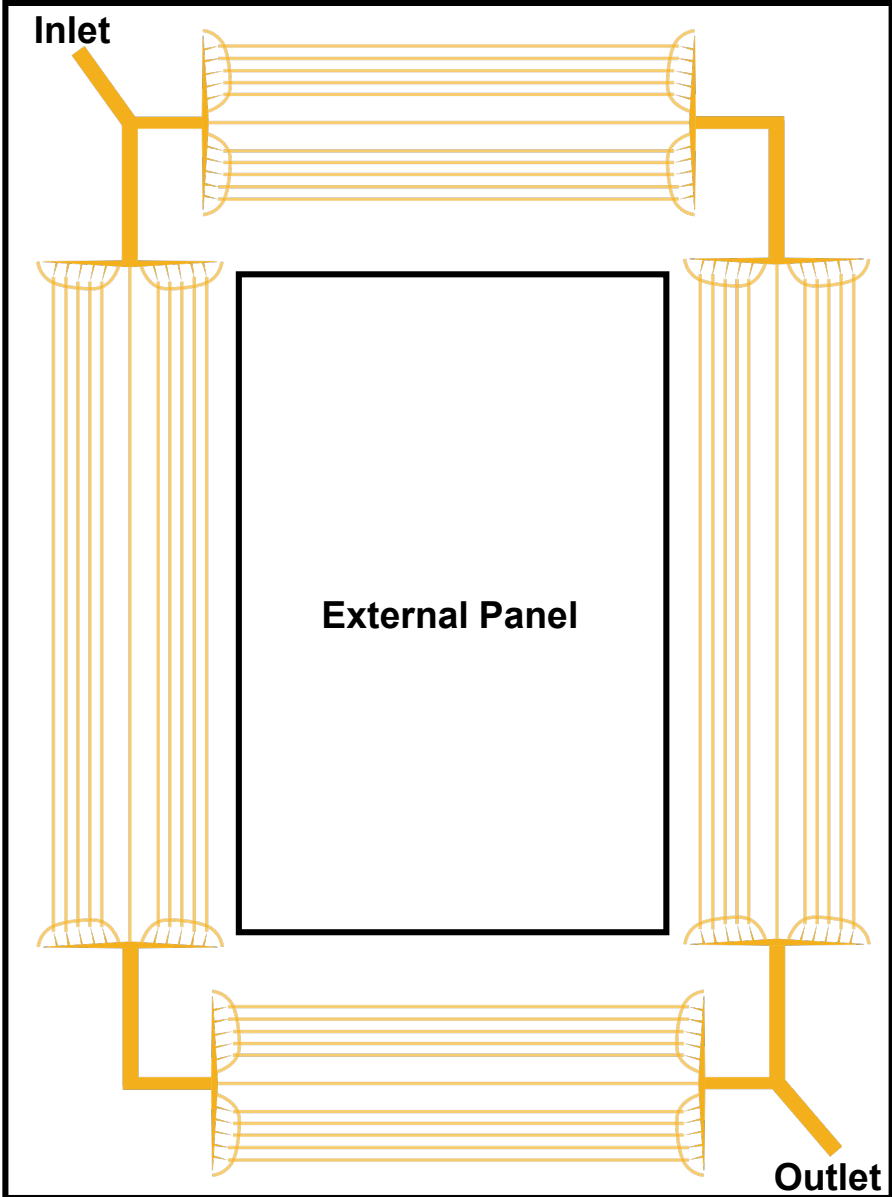
SYSTEM - concept



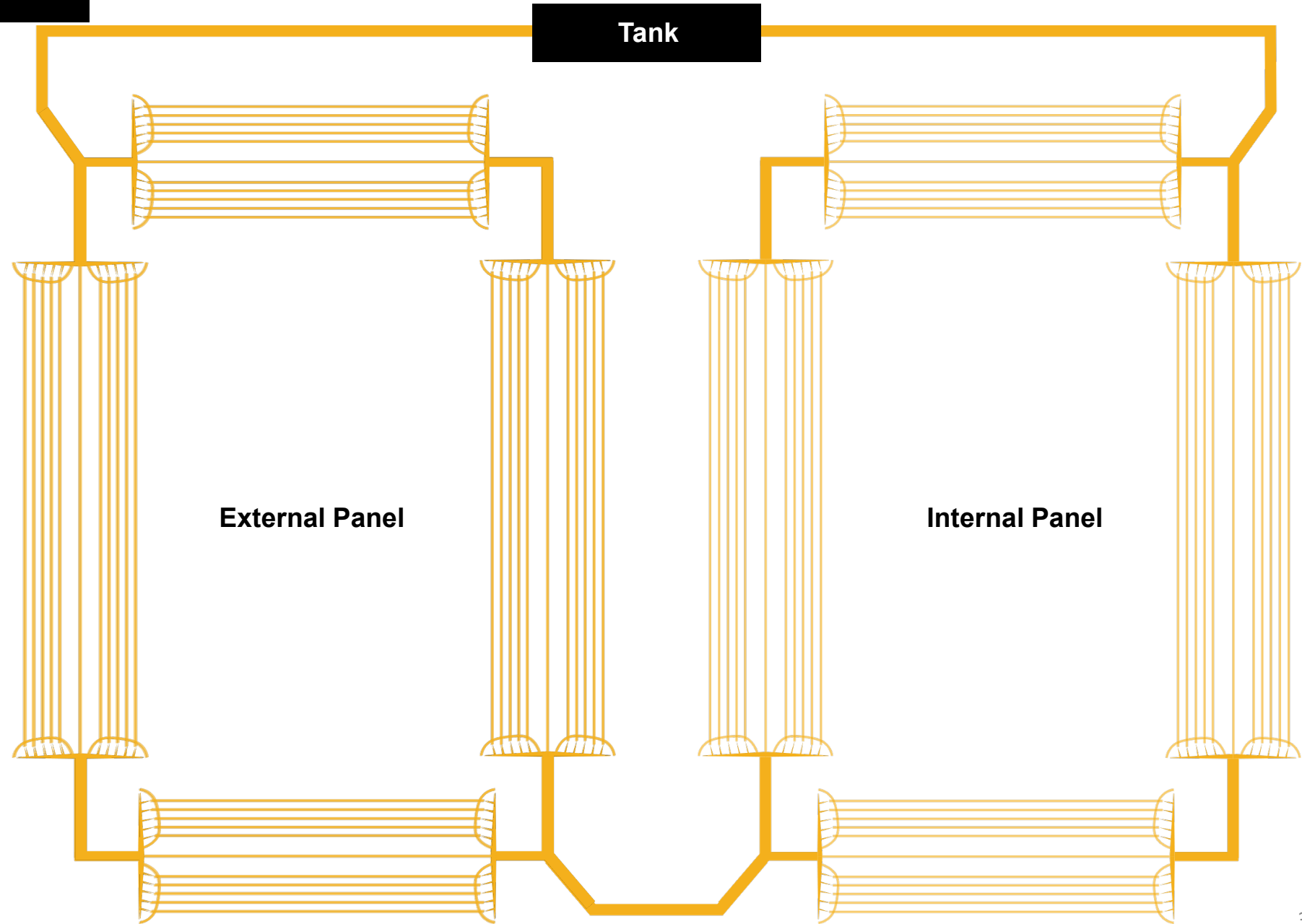
SYSTEM - concept



SYSTEM - concept



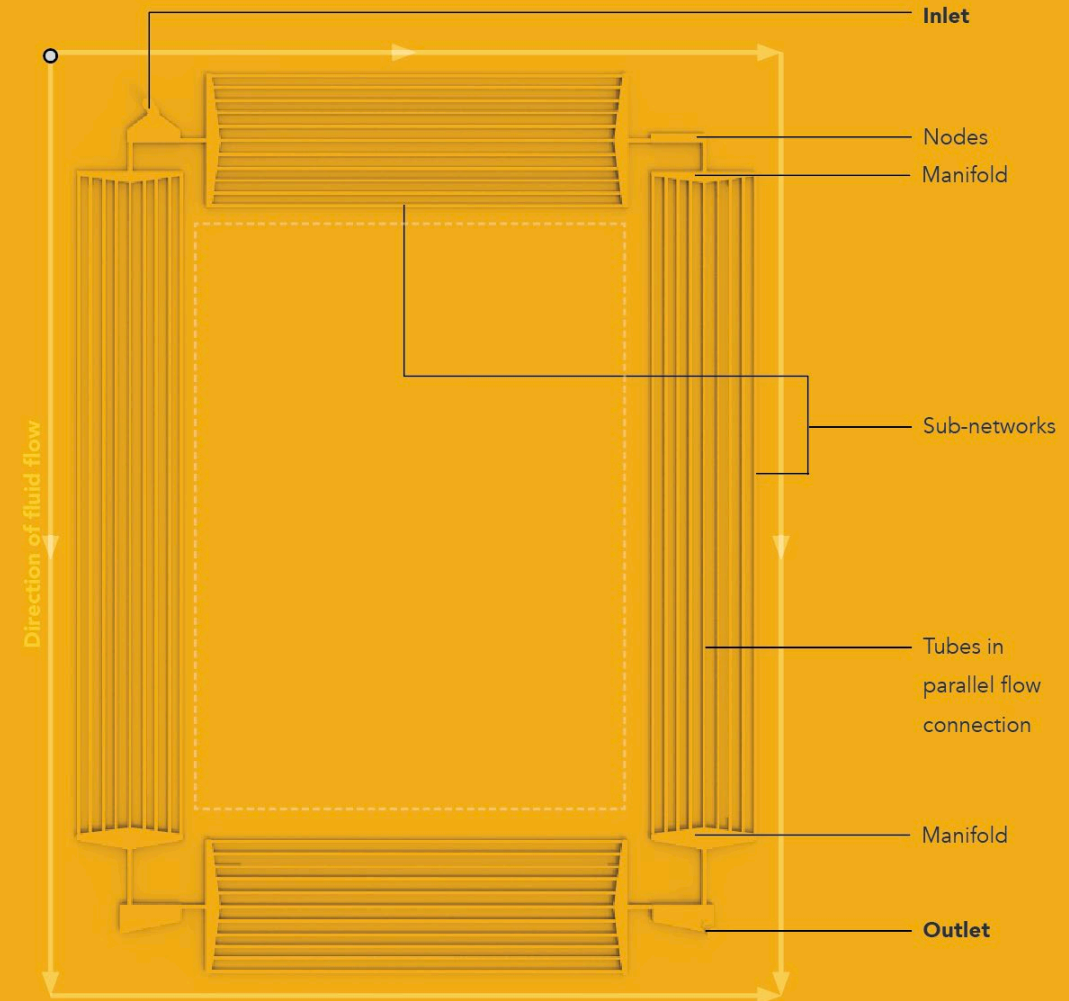
SYSTEM - concept



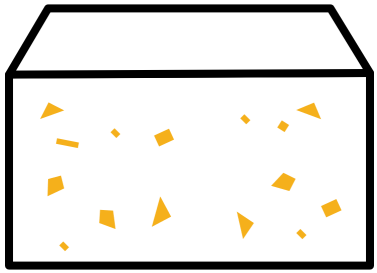
Volume of network:
26.3 litres

Constrained by Structural system

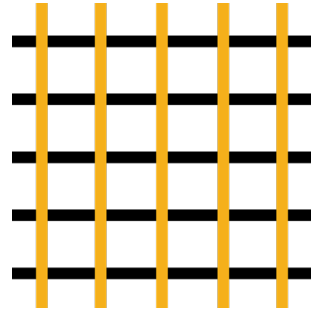
Conceptual network



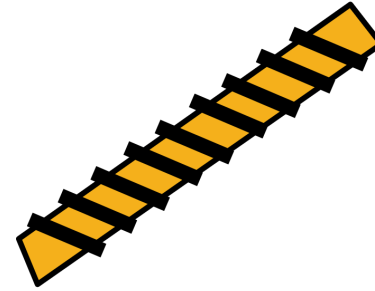
STRUCTURAL SYSTEM



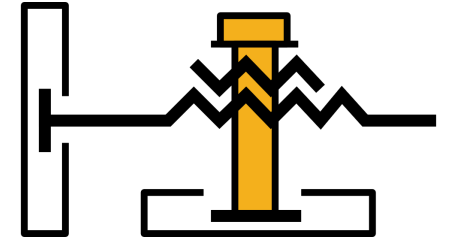
Fibre reinforced concrete



Reinforcement mesh



Reinforcement dowel



Façade bracket

STRUCTURAL SYSTEM

Grey cement : **2-5%**

Fibre type: Glass fibre, 50 microns, 6mm long

Density: 2026 kg / m³ (author, by lab test)

Compressive strength > 20 N/mm²



Fibre reinforced concrete

Weber Beamix with fibre



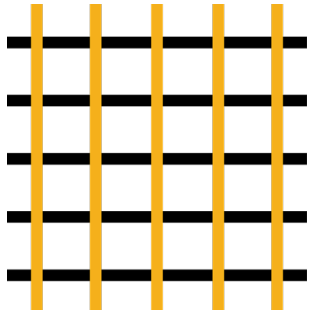
WHY?

Very high strength

Availability

Light weight

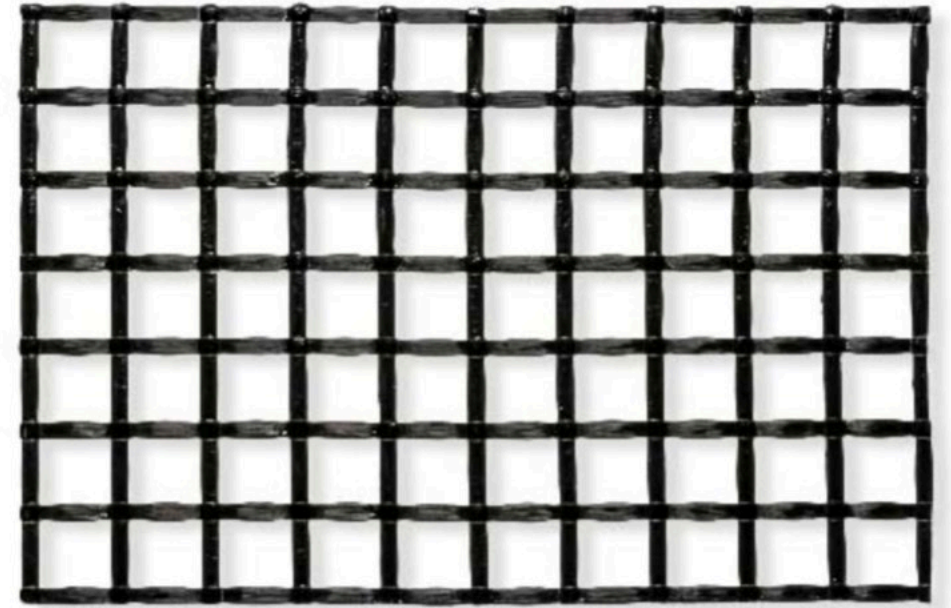
STRUCTURAL SYSTEM



Reinforcement mesh

Solidian Grid Q142/142- CCE-25

Fiber material : Carbon
Impregnation. : Epoxy Resin
Tensile strength. : 3,100 N/mm²



WHY?

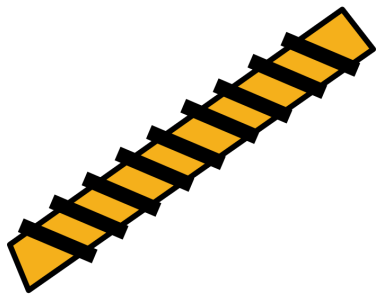
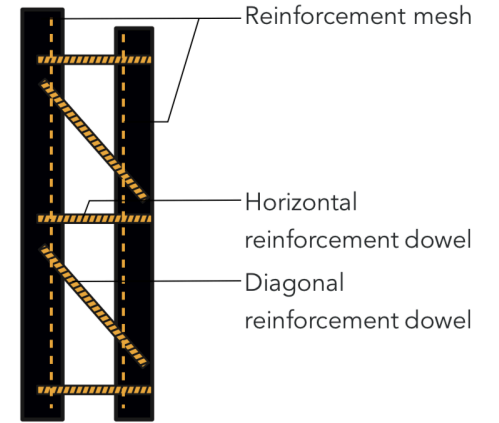
Very high strength, light-weight

Less concrete cover

Low embodied energy

STRUCTURAL SYSTEM

Material : Fiber glass
Impregnation : Resin
Diameter : 12 mm
Length : 300 mm



Reinforcement dowel

Schöck Combar Isolink TA-H



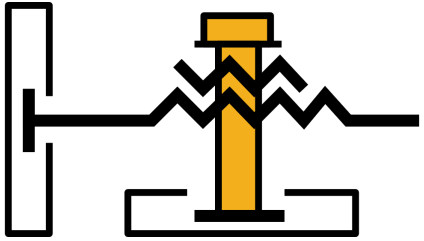
WHY?

Very high strength, light-weight

High thermal insulation

Low embodied energy

STRUCTURAL SYSTEM

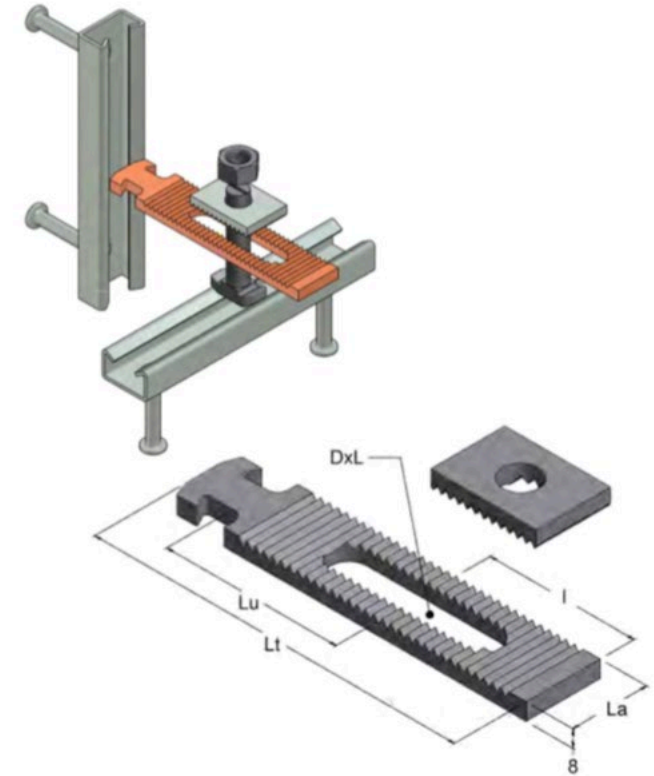


Façade bracket

Hook-head toothed straps by Technogrip

Load carrying capacity : 8.5 kN (safety factor=3)

11.5 kN (safety factor=2)

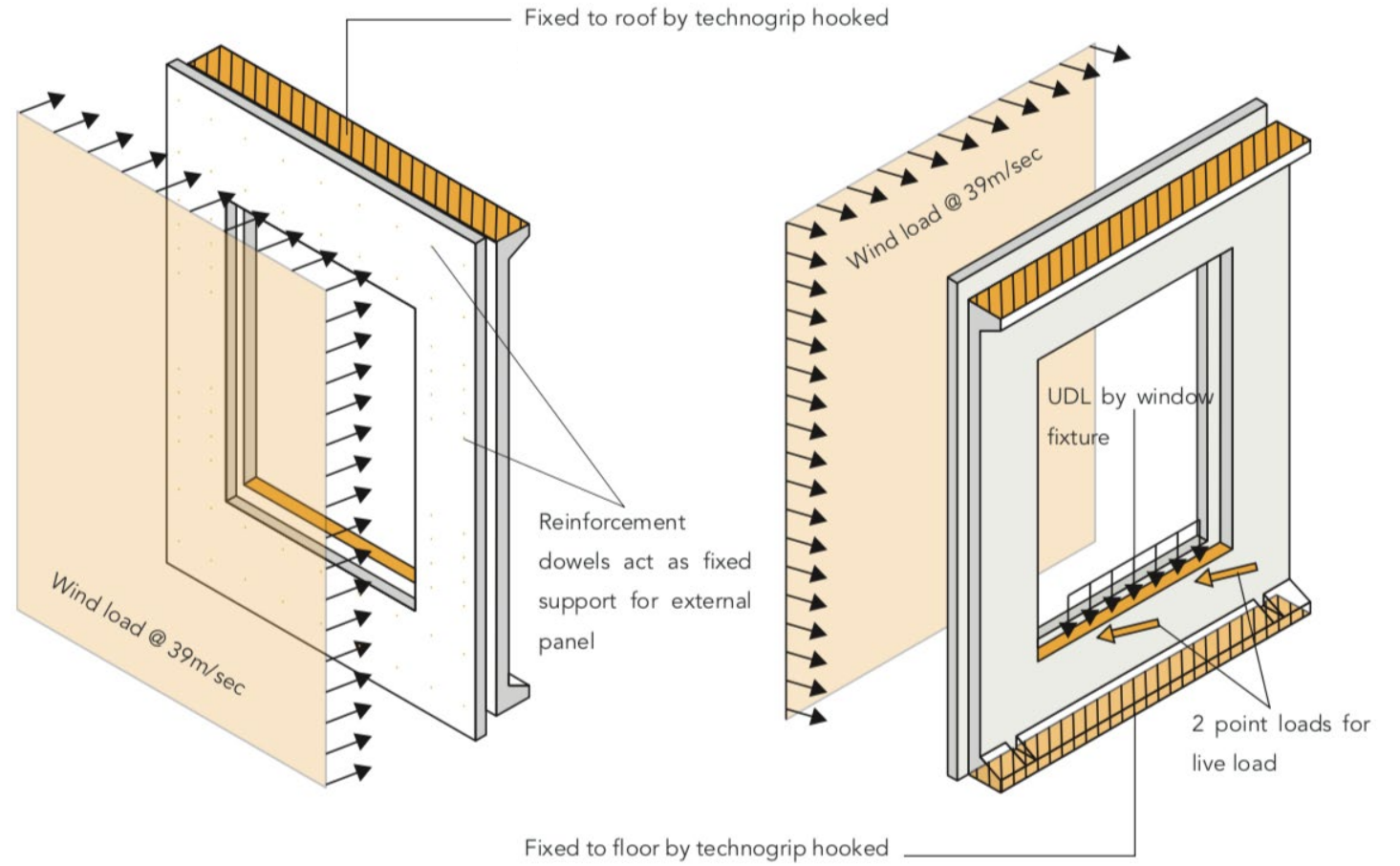


WHY?

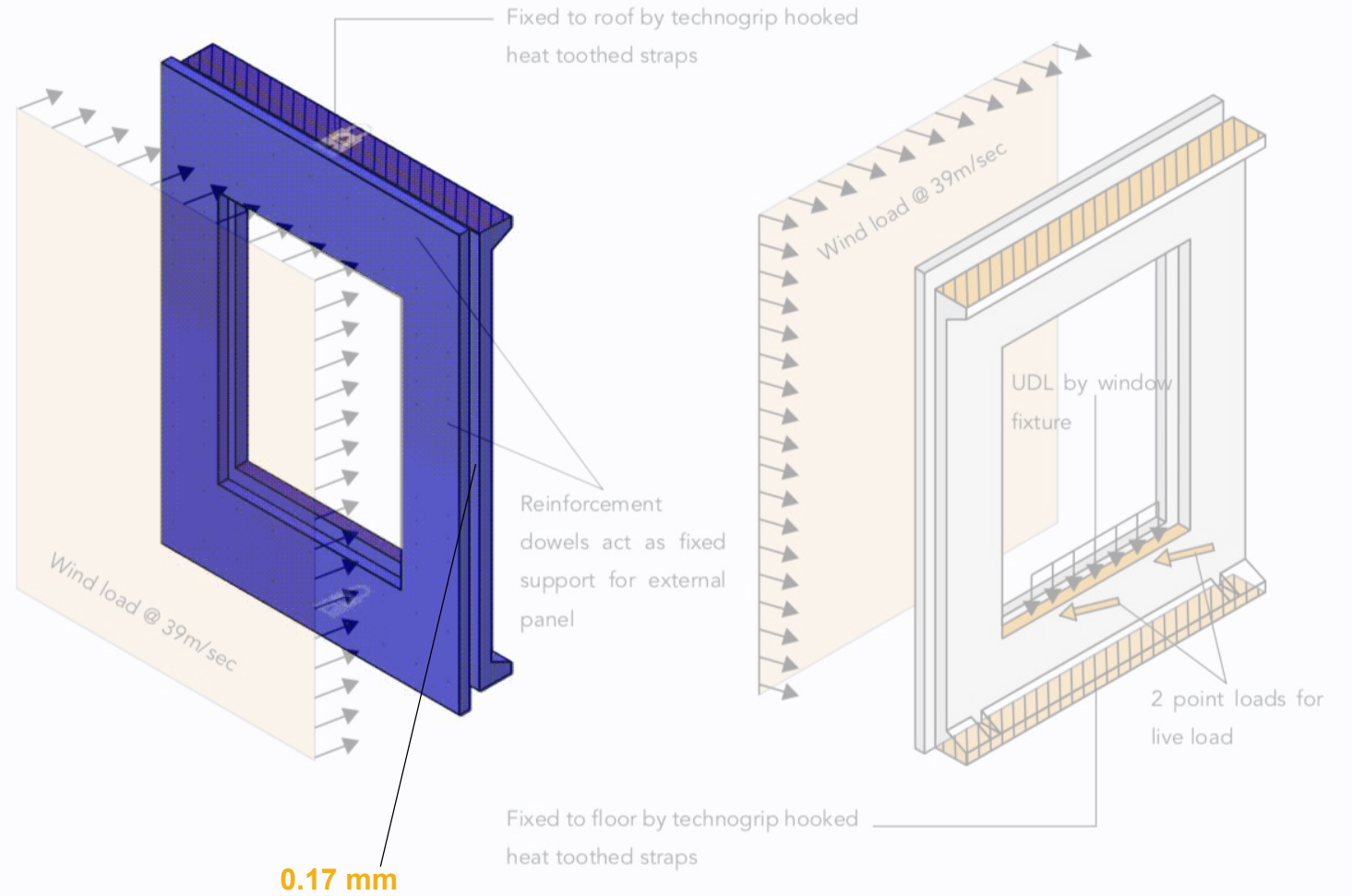
Simple fixture

High load carrying capacity

STRUCTURAL SYSTEM



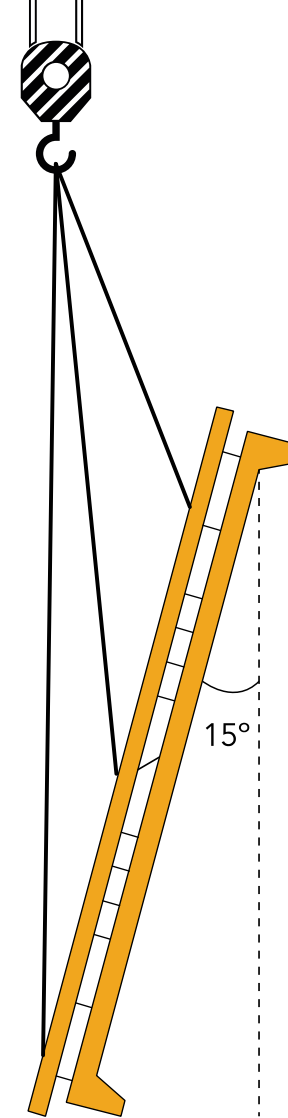
STRUCTURAL SYSTEM



* simulation does not consider reinforcement mesh

STRUCTURAL SYSTEM

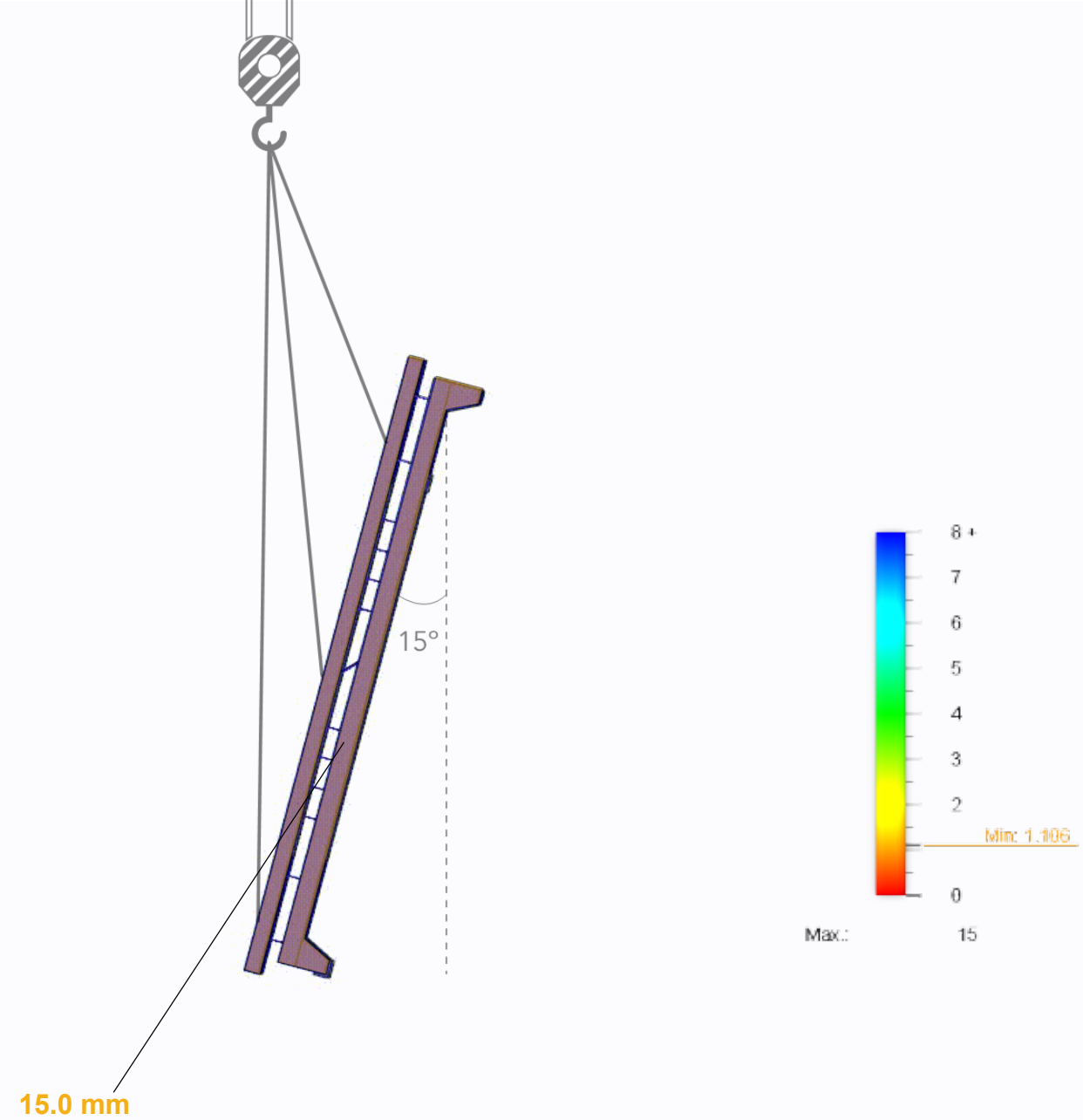
Tilt-up crane handling and installation



STRUCTURAL SYSTEM

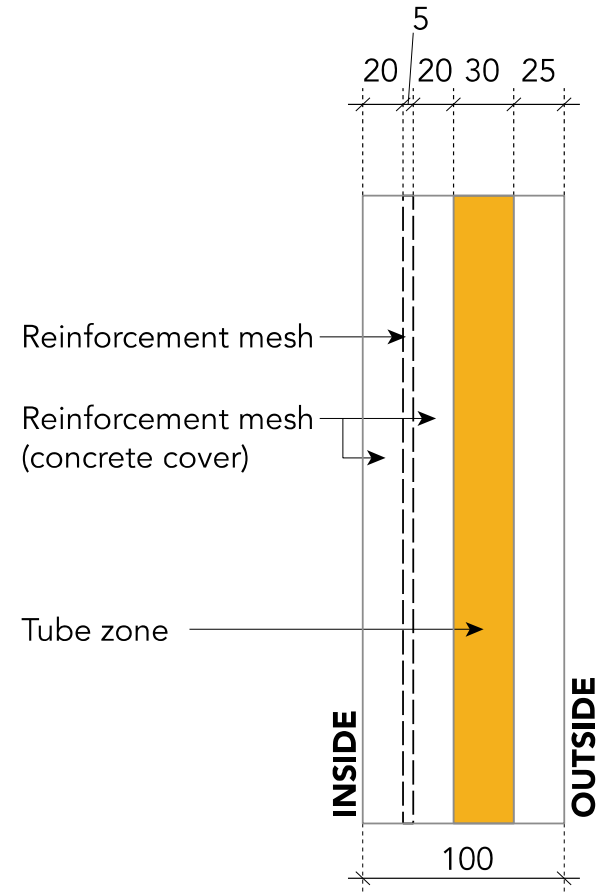
Tilt-up crane handling and installation

Solution: Reinforcement mesh added to both panels



* simulation does not consider reinforcement mesh

STRUCTURAL SYSTEM



Section of single panel

STRUCTURAL SYSTEM

Analytical

74 bars

Simulation

74 bars

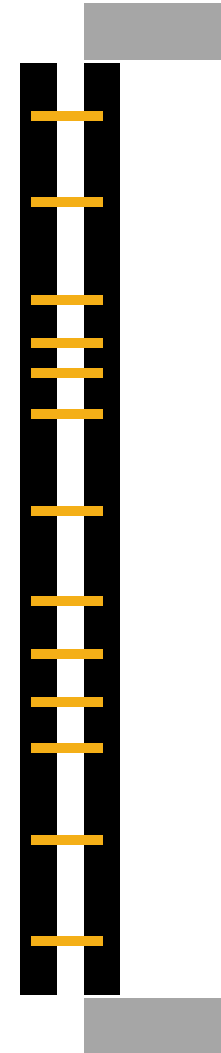
Company specifications

45 bars

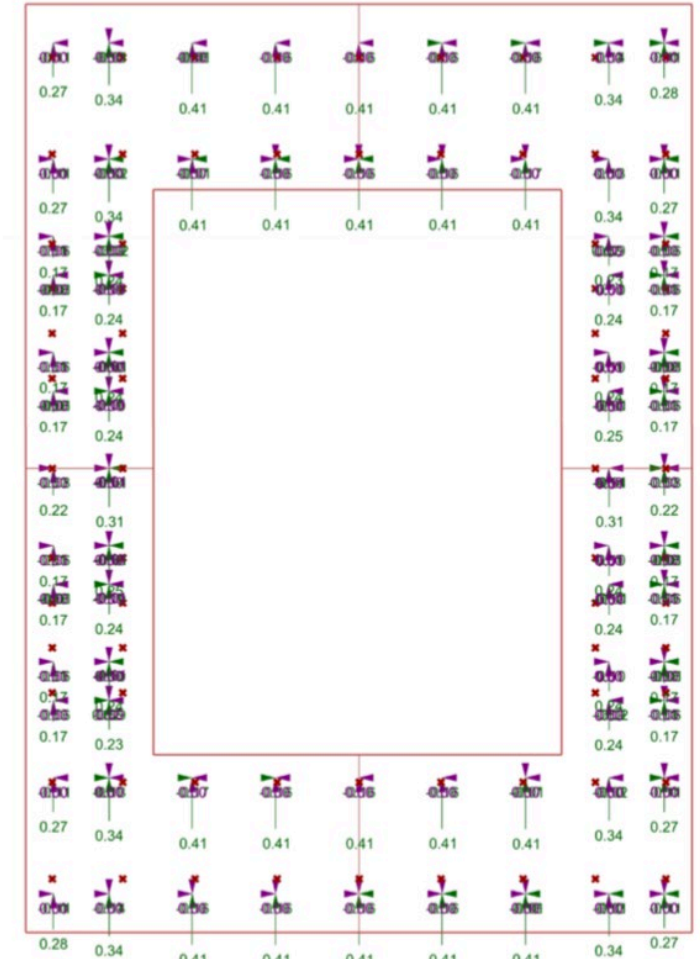
Total no of dowels: **72**

Horizontal bars: **68**

Diagonal bars: **4**

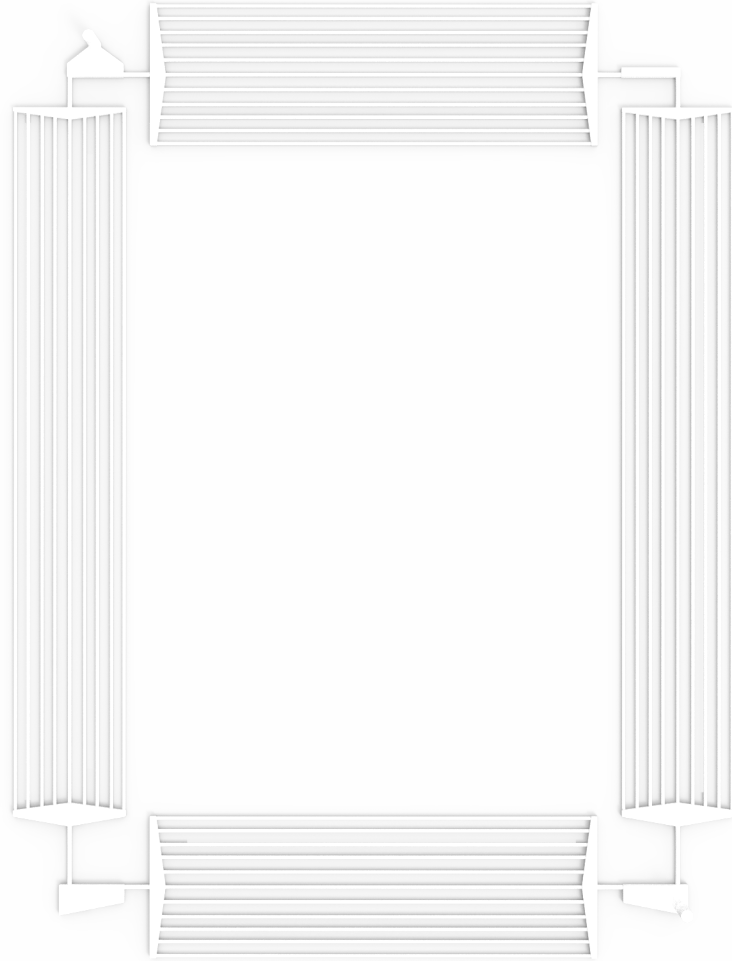


SECTION



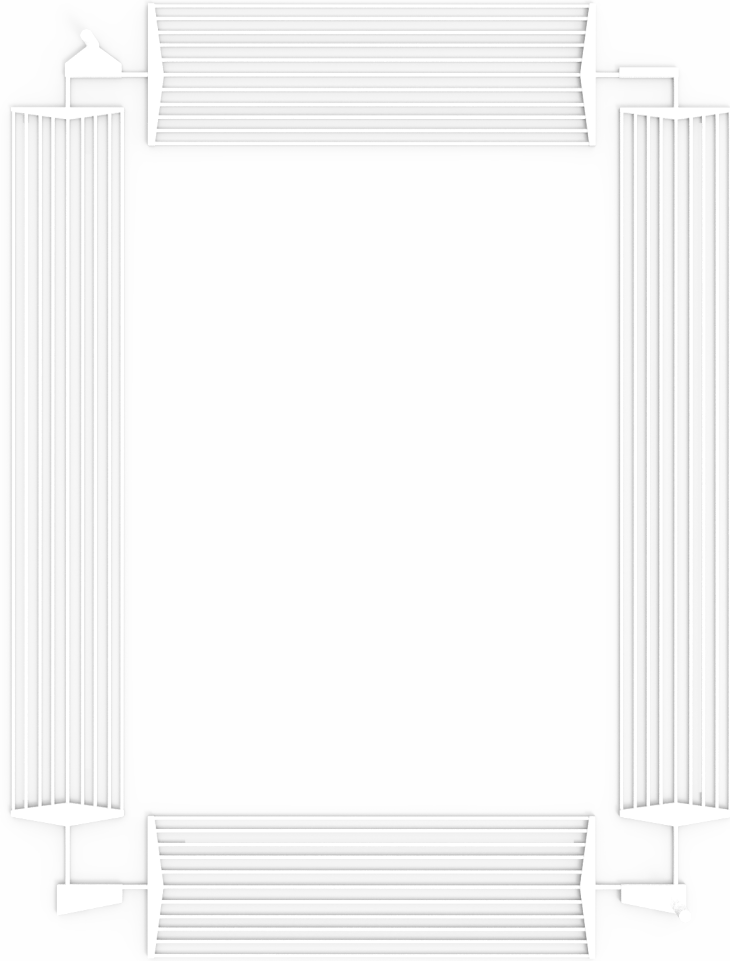
ELEVATION

STRUCTURAL SYSTEM

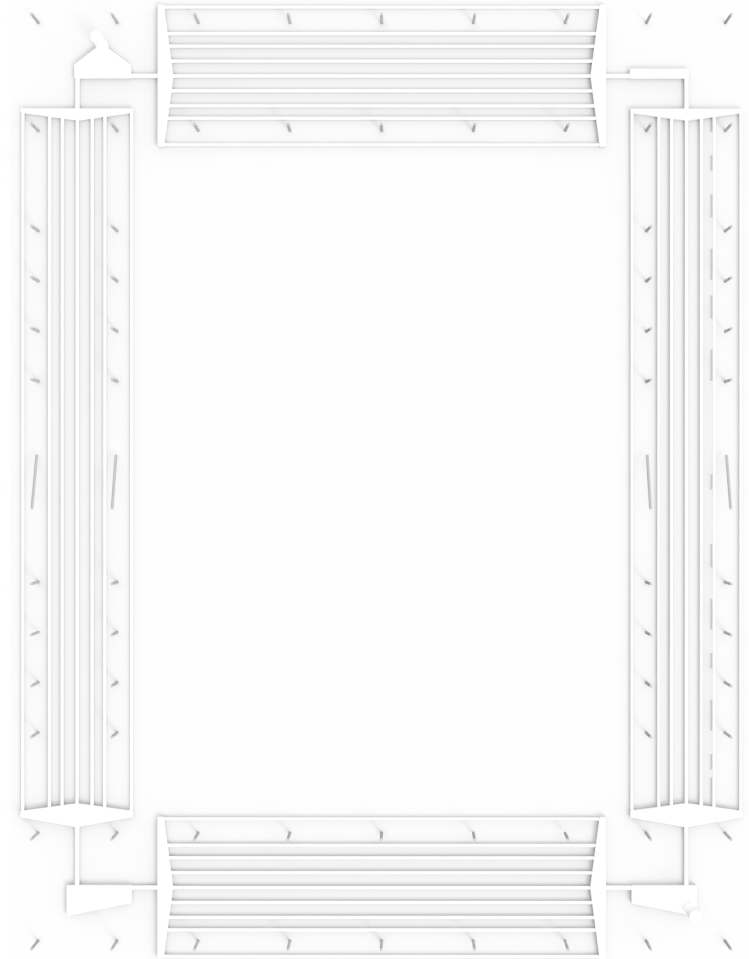


Before introducing reinforcement dowels

STRUCTURAL SYSTEM

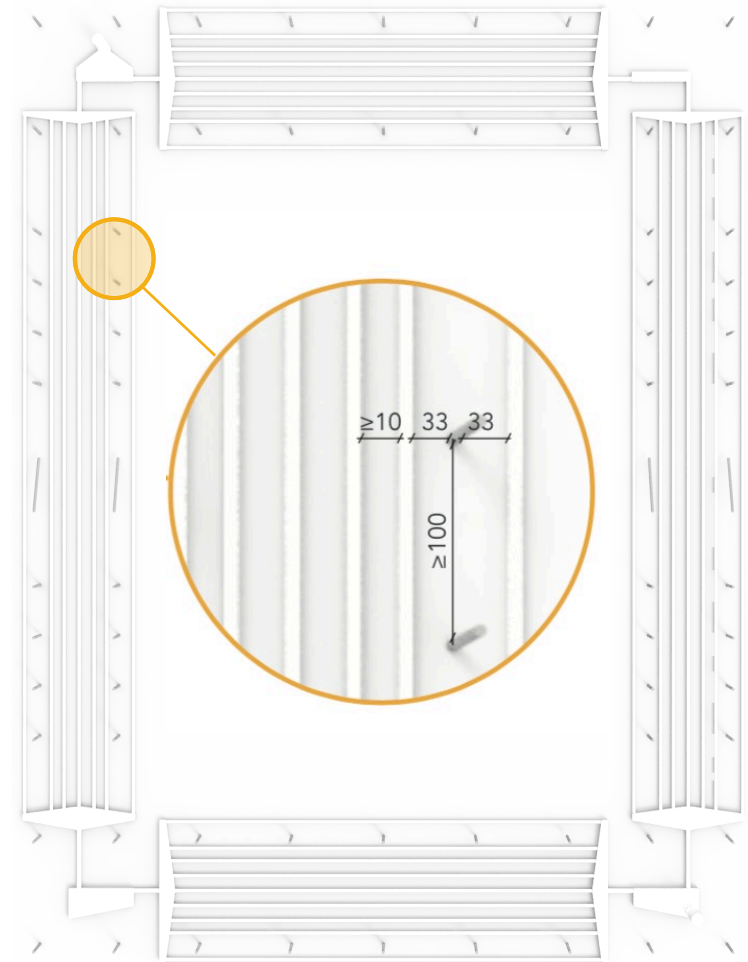


Before introducing reinforcement dowels



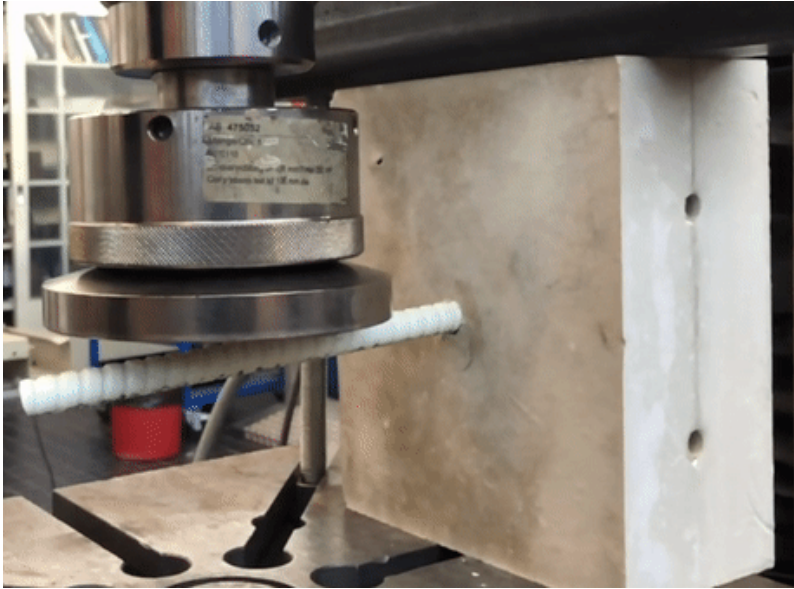
After introducing reinforcement dowels

STRUCTURAL SYSTEM



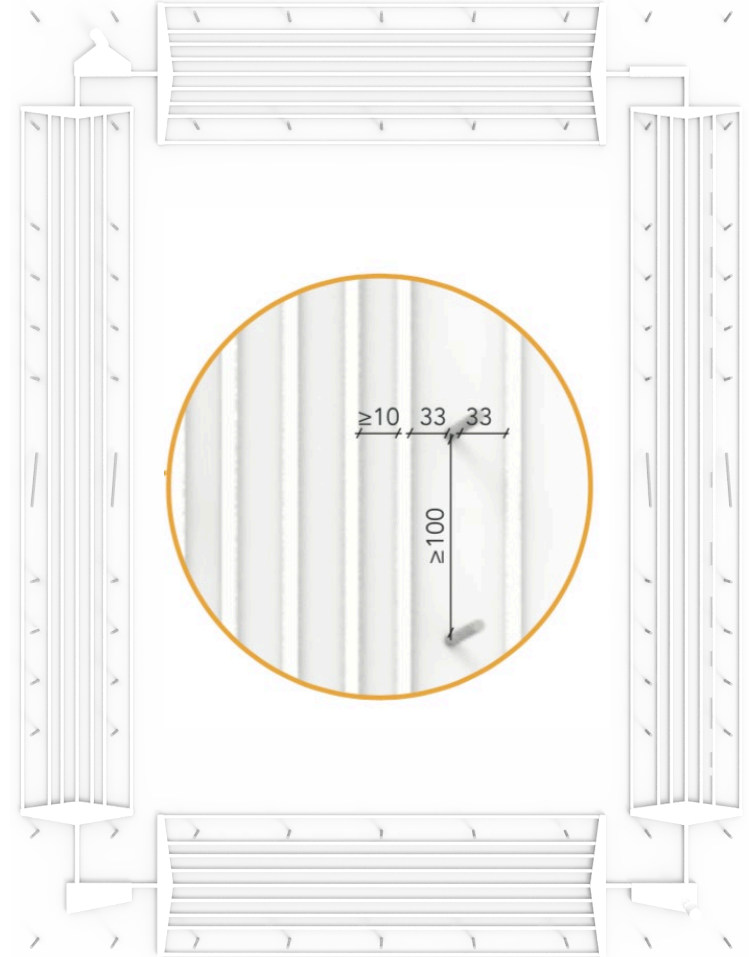
After introducing reinforcement dowels

STRUCTURAL SYSTEM



Design load = **670 N**

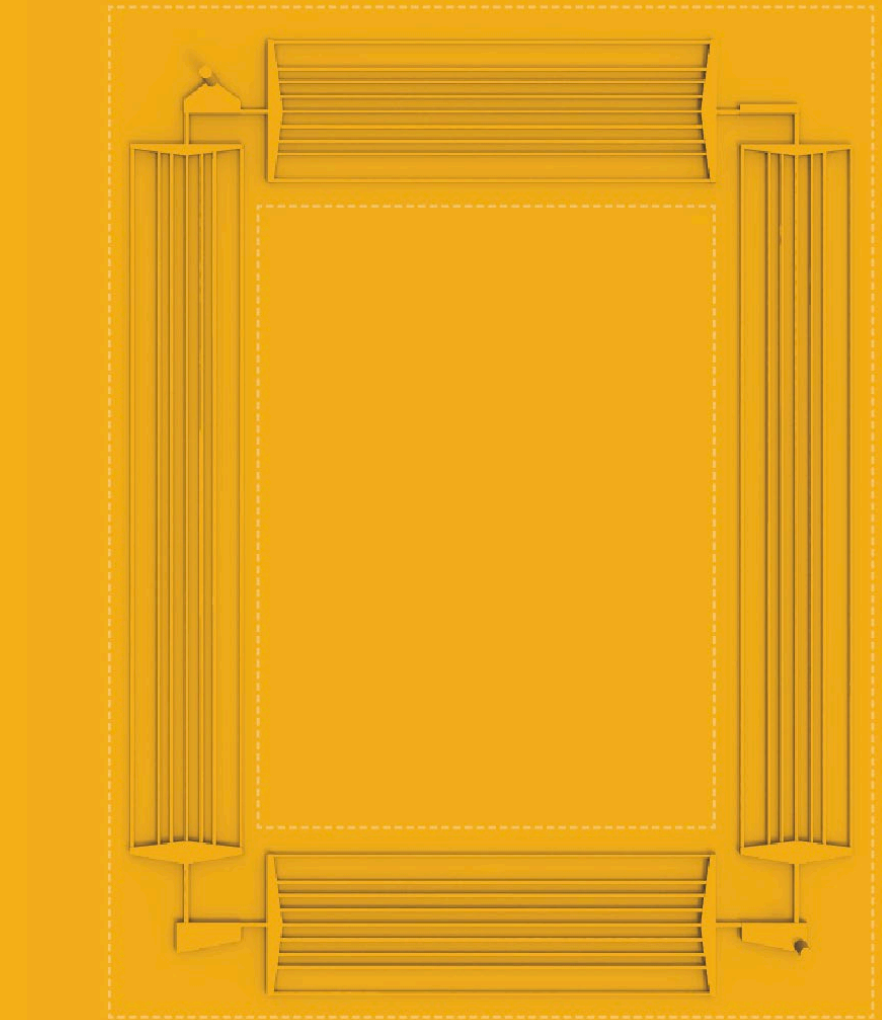
Actual load = **4900 N**



Volume of network:
20.63 litres

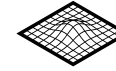
Constrained by Fabrication method

Pressure drop:
1167.96 Pa



LET'S DISCUSS



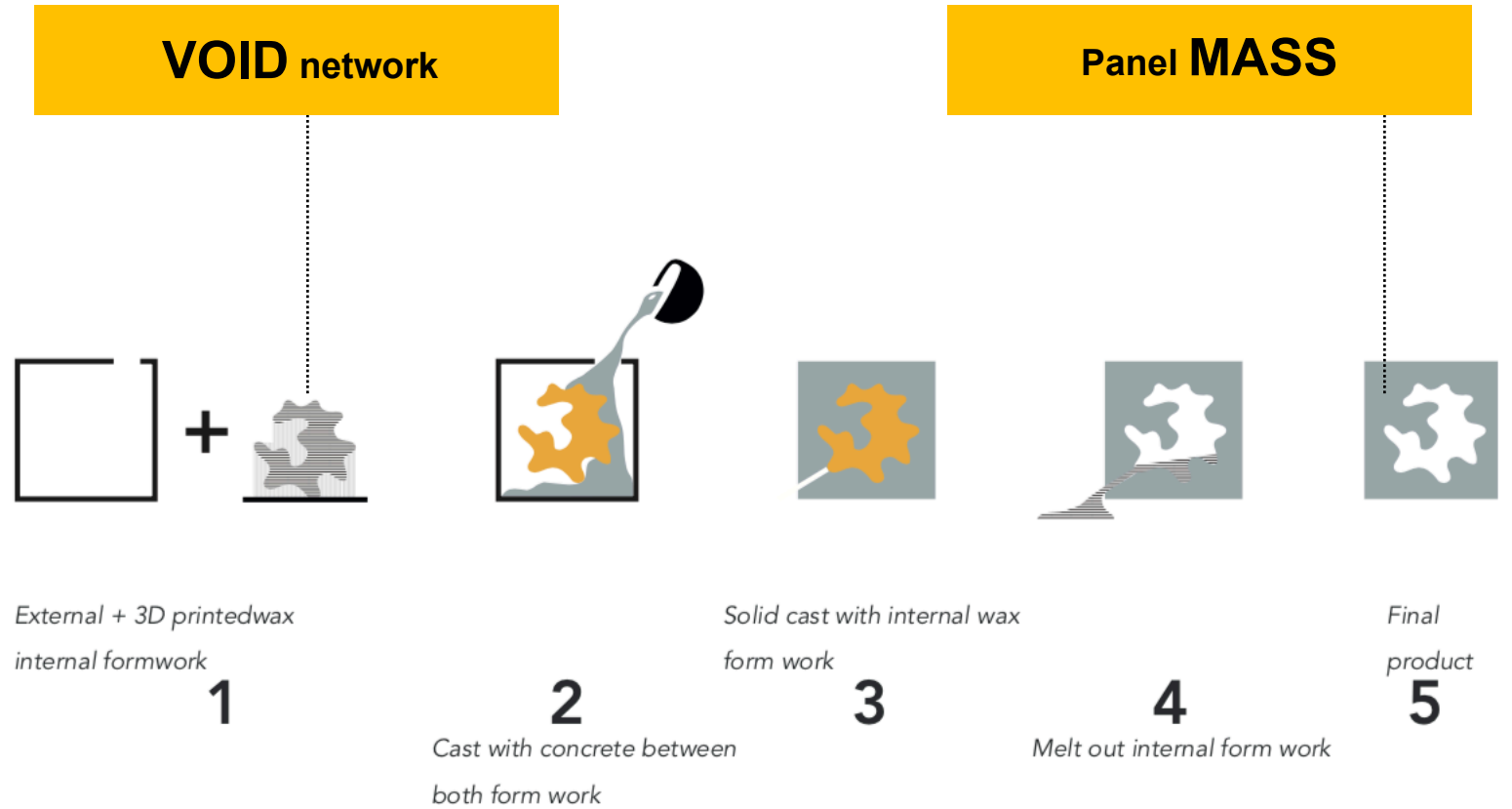


Investment Casting



FABRICATION METHOD

Inverse Investment Casting



FABRICATION METHOD

VOID network

3D printing **Wax**



LET'S DISCUSS



Focus: **VOID** network

Medium of fluid: **Water**

GOALS



Maximise volume

of fluid / tube

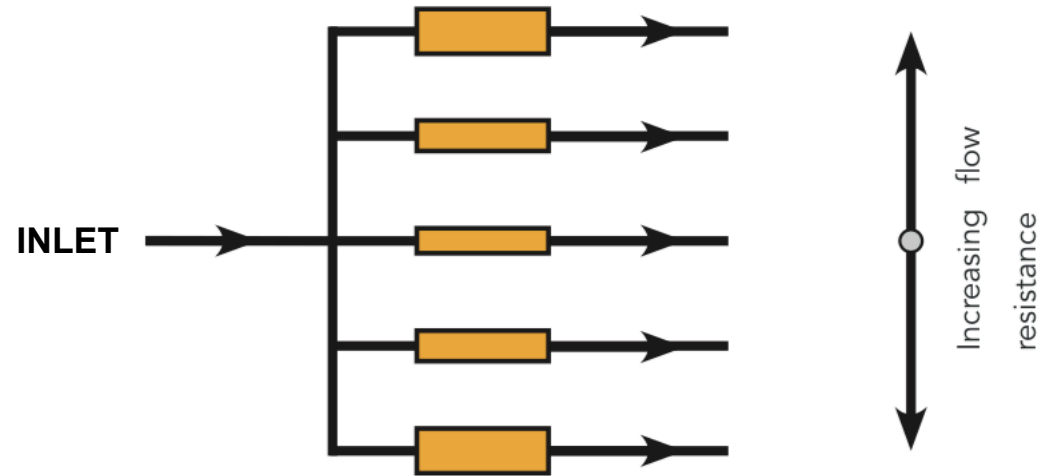
- Maximised **efficiency**
- Maximum **heat exchange** between panels

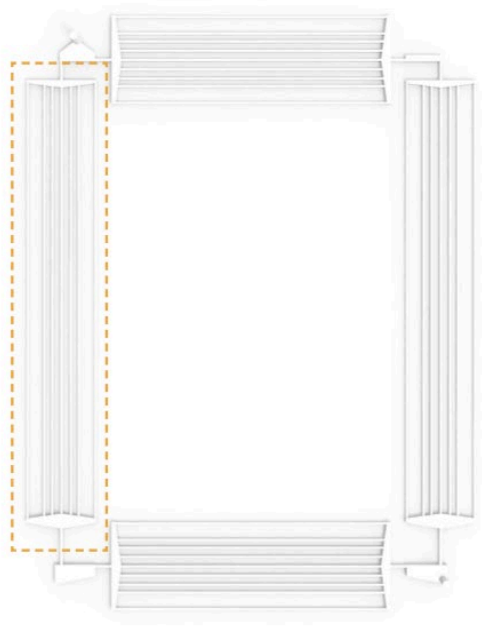


Minimise pressure drop

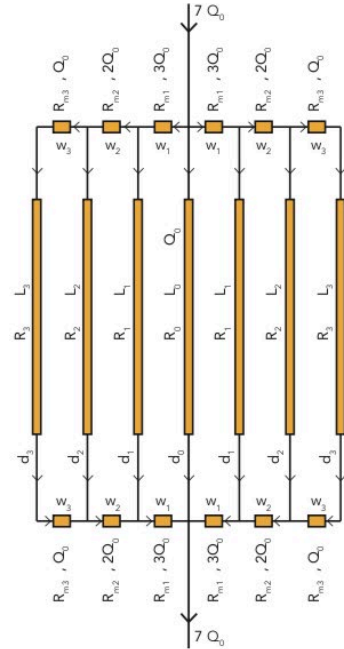
across inlet and outlet

- Avoid **blockage** and maintenance
- Minimise **energy to pump** fluid
- Maximise number of **exchange cycles**



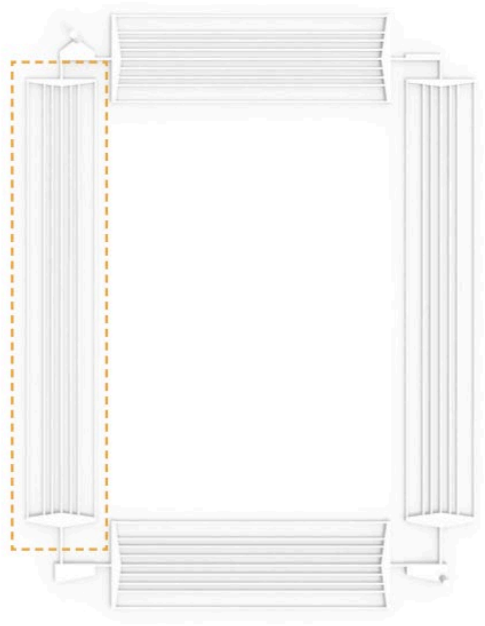


WATER FLOW

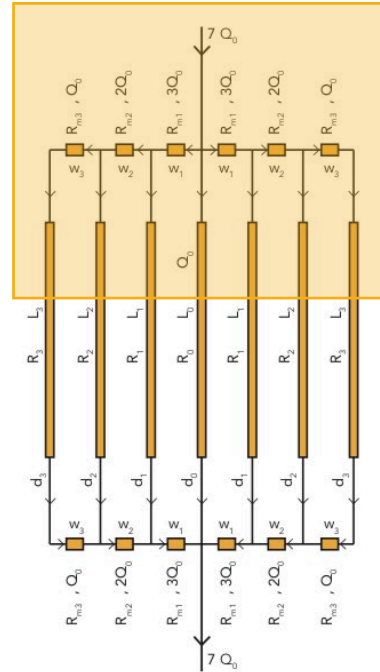


ELECTRICITY FLOW

Step 01 Unify flow resistance of tubes

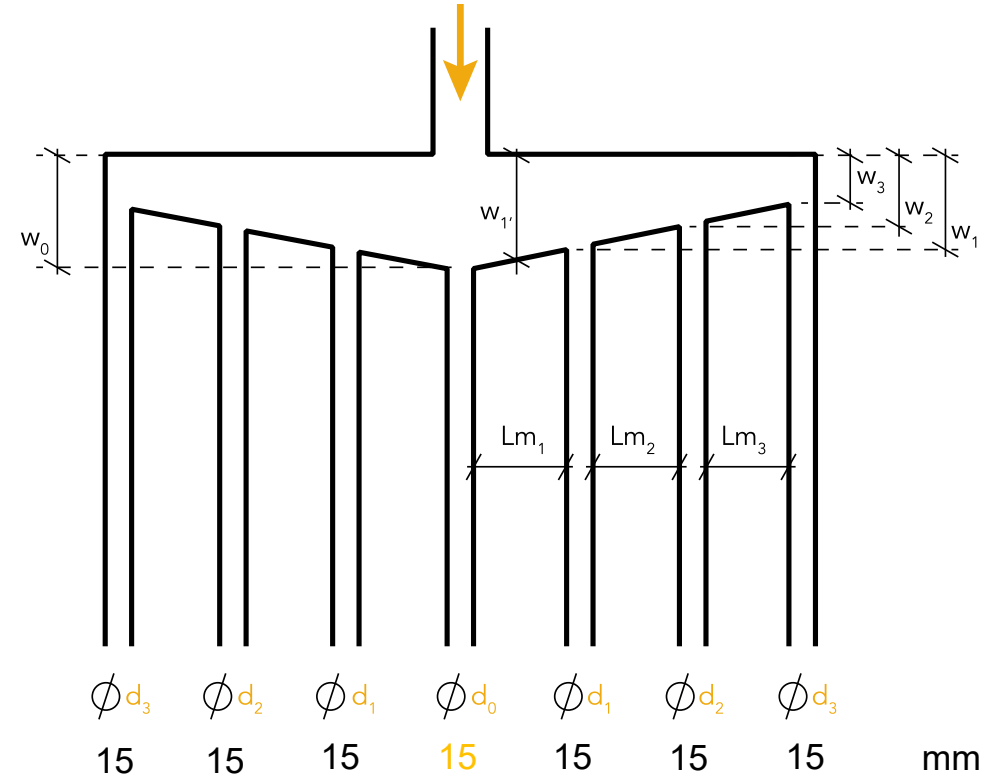


WATER FLOW



FLOW RESISTANCE

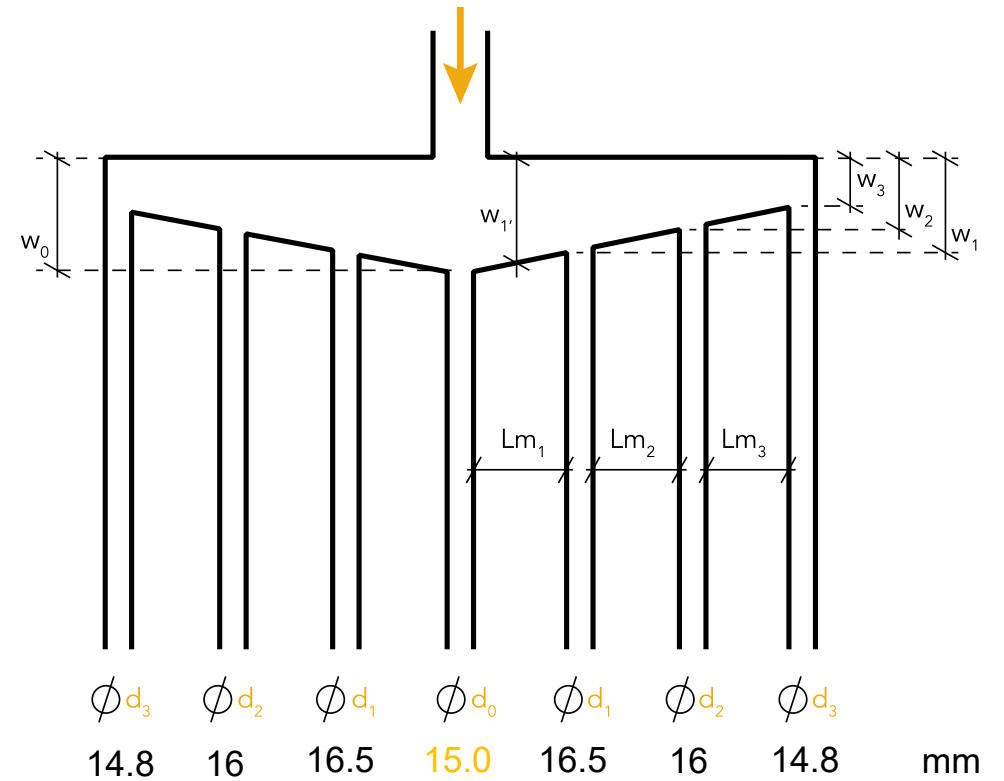
W, Lm – derived by design

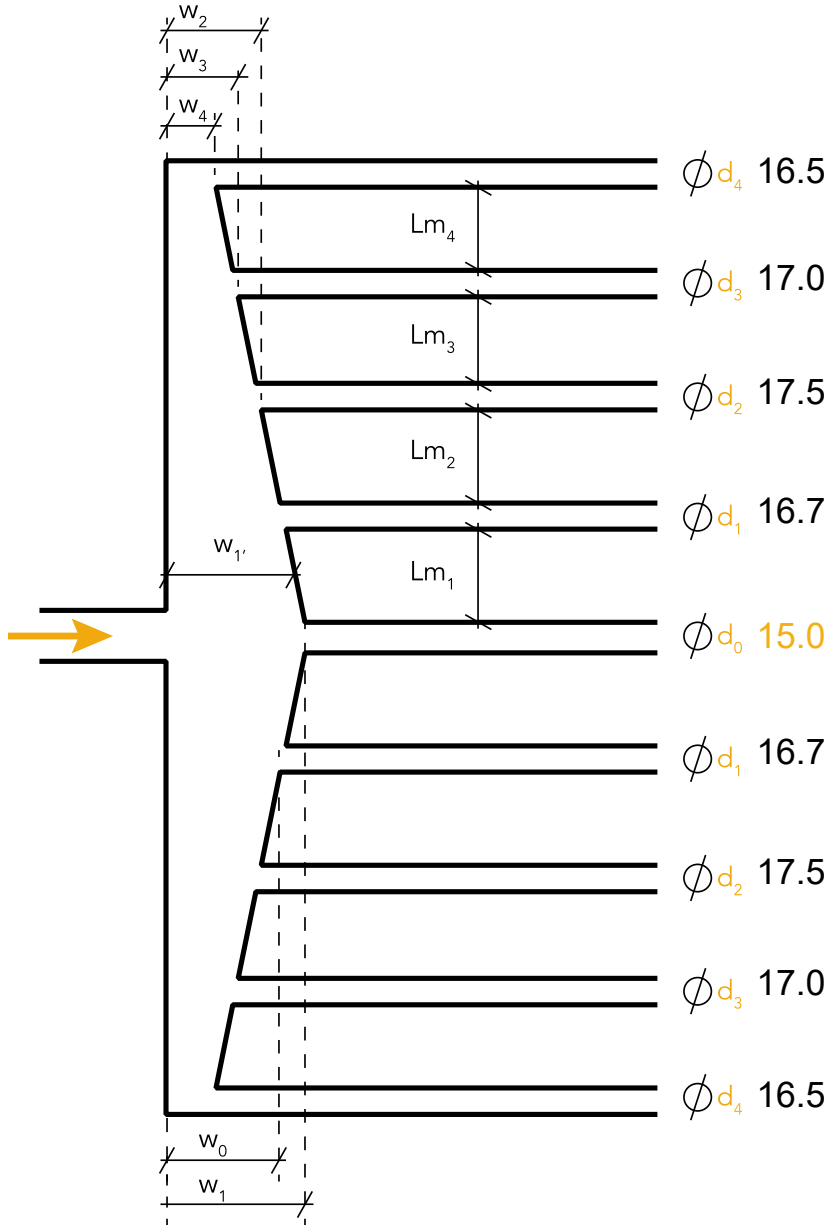


15 15 15 15 15 15 15 mm

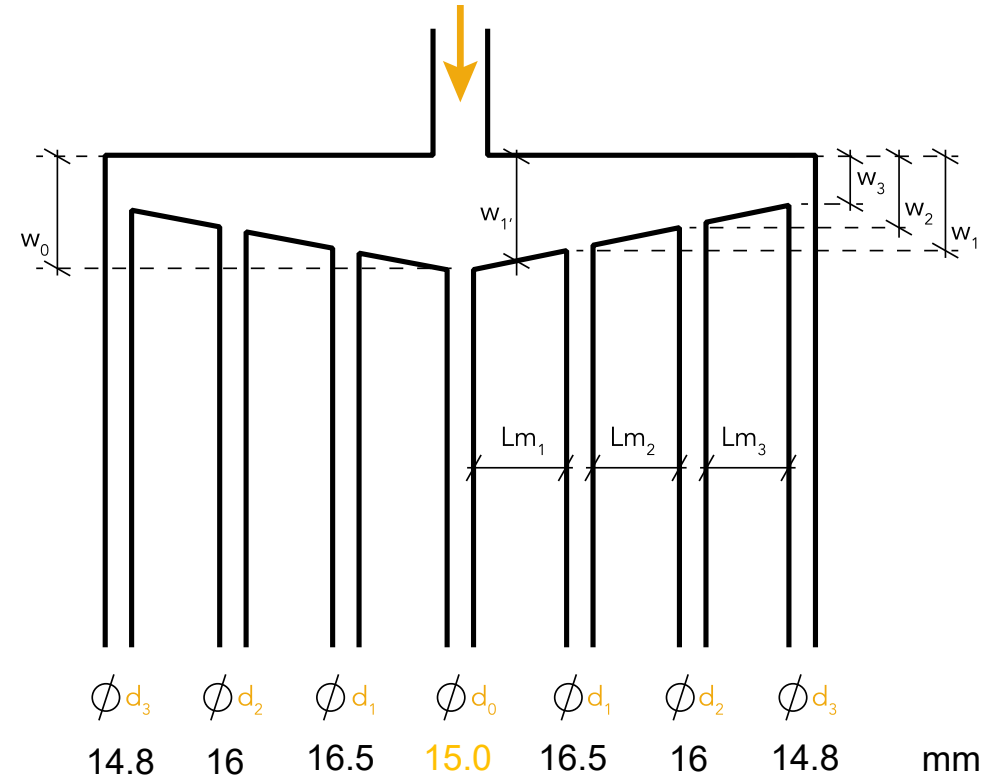
Step 01 Unify flow resistance of tubes

W, Lm – derived by design





W, Lm – derived by design

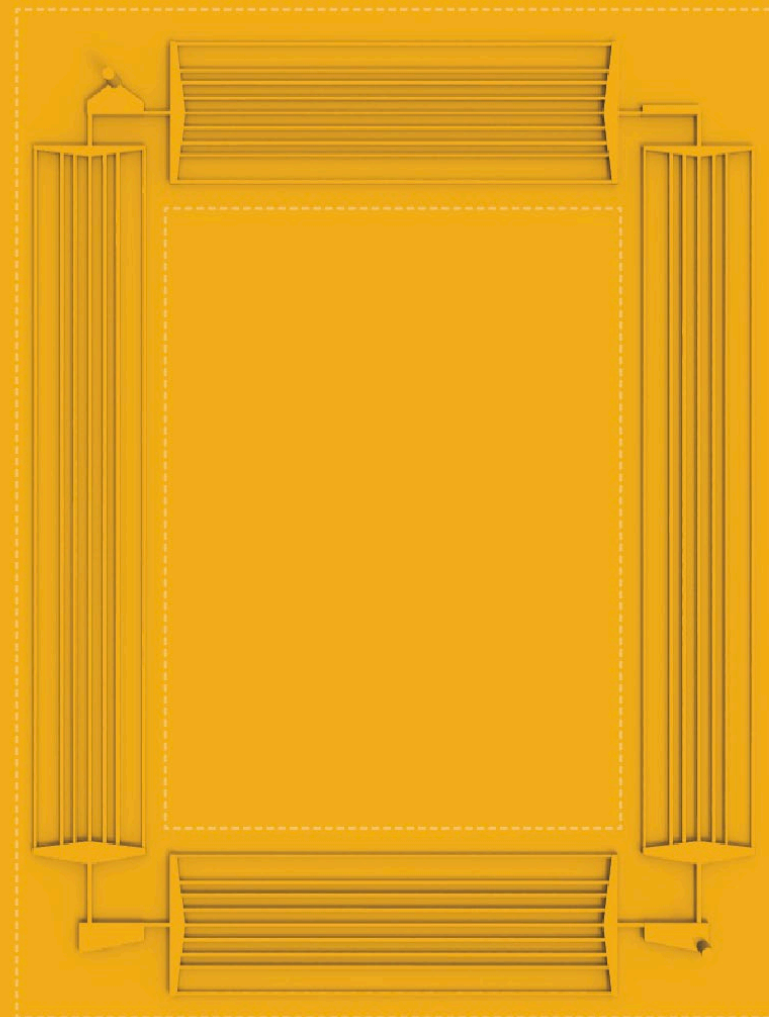


Volume of network:
22.53 litres

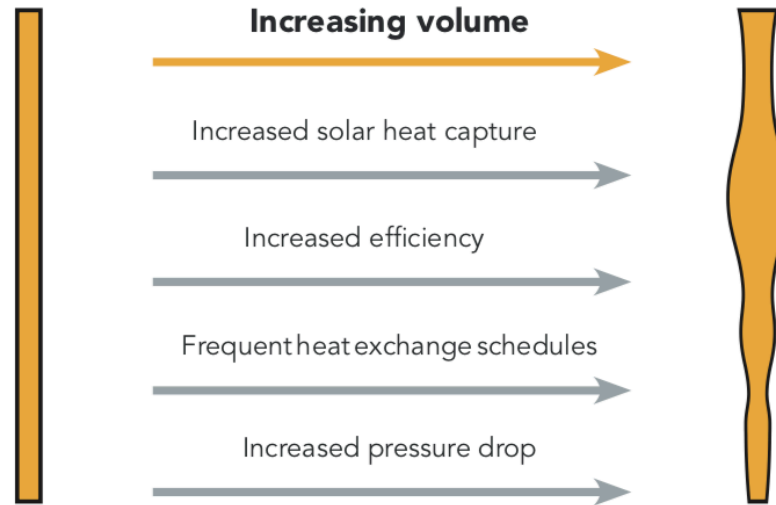
+ 9.2 %

Pressure drop:
1167.96 Pa

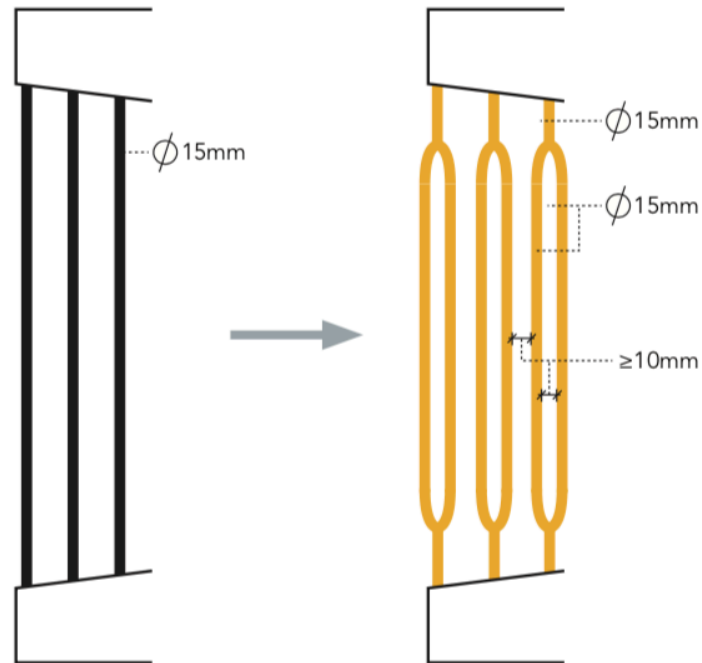
-5 %



Step 02 Increase volume of tubes



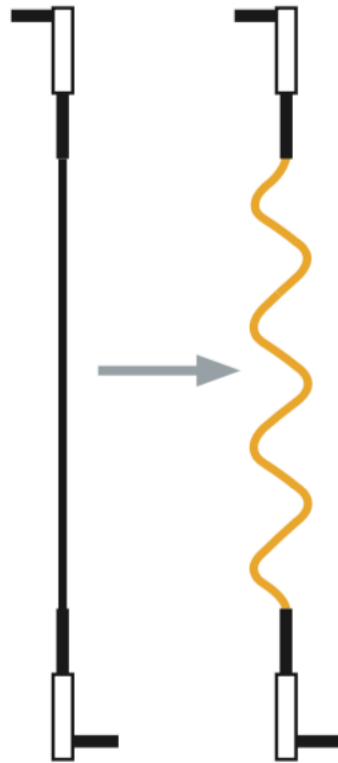
Method 01



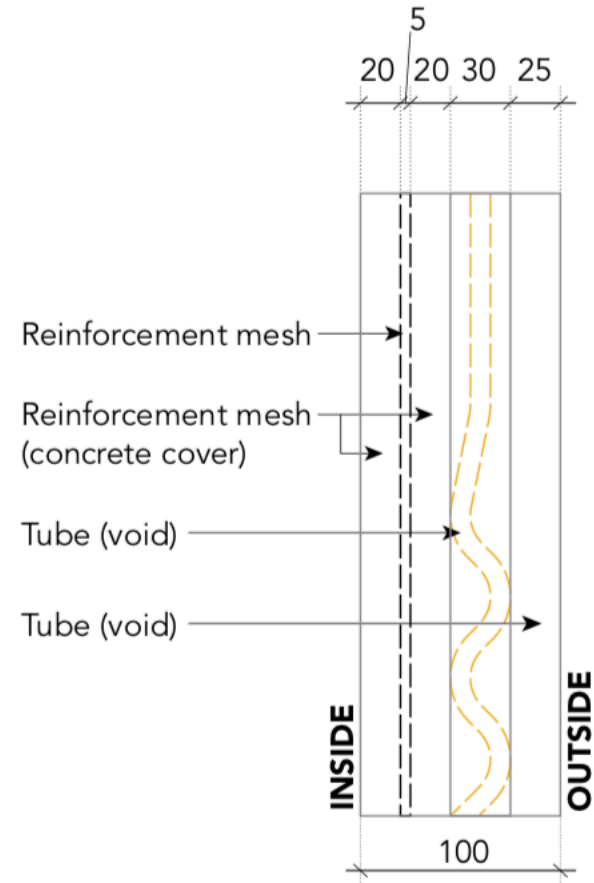
Elevation

+85.5 %
increase in volume per tube

Method 02

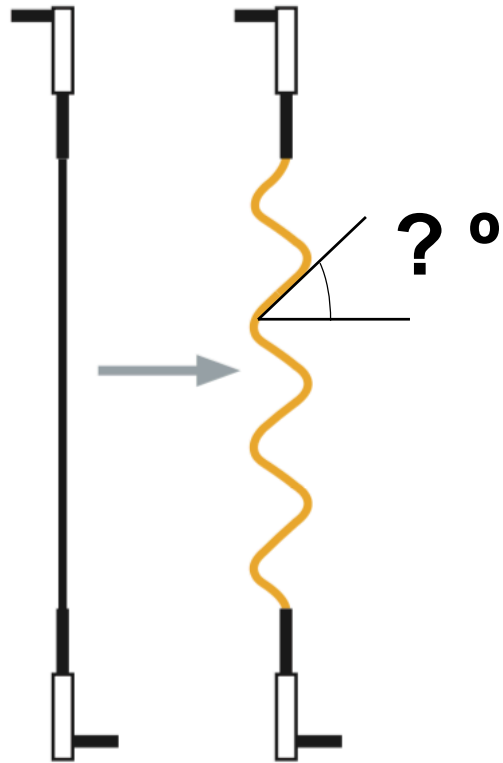


Section

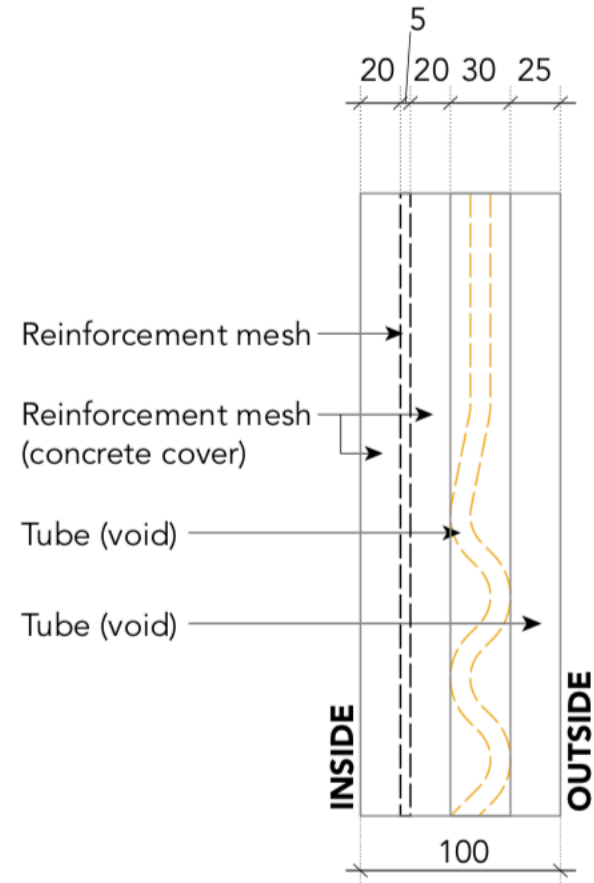


Section

Method 02

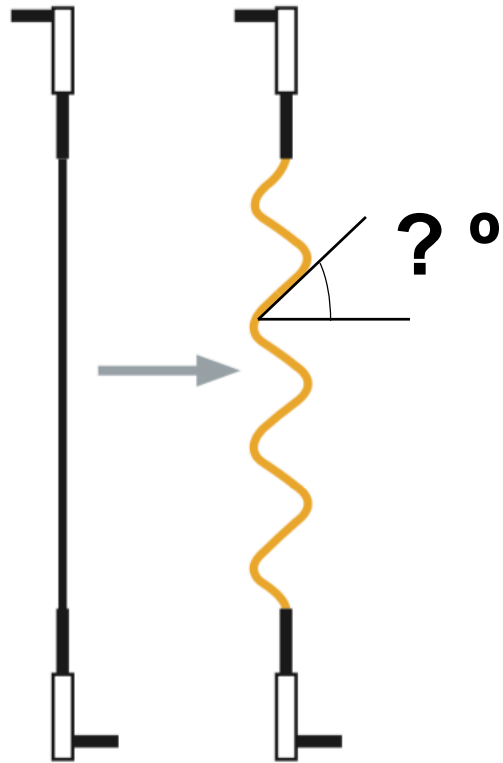


Section

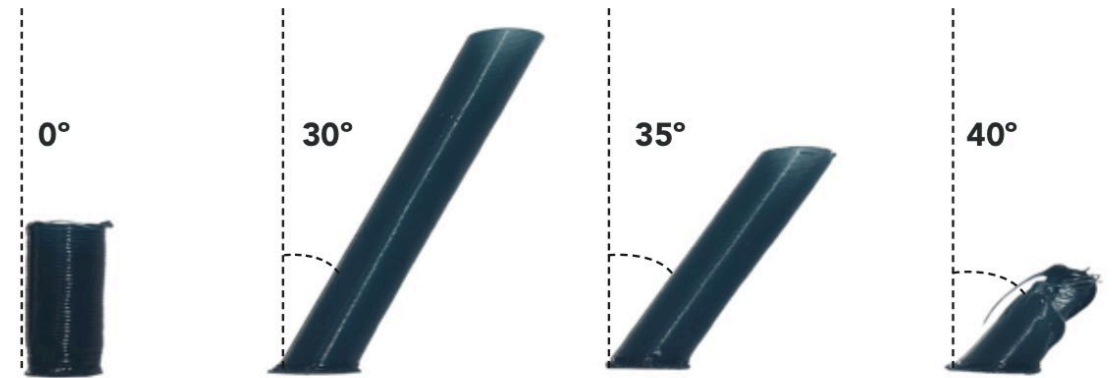


Section

Method 02

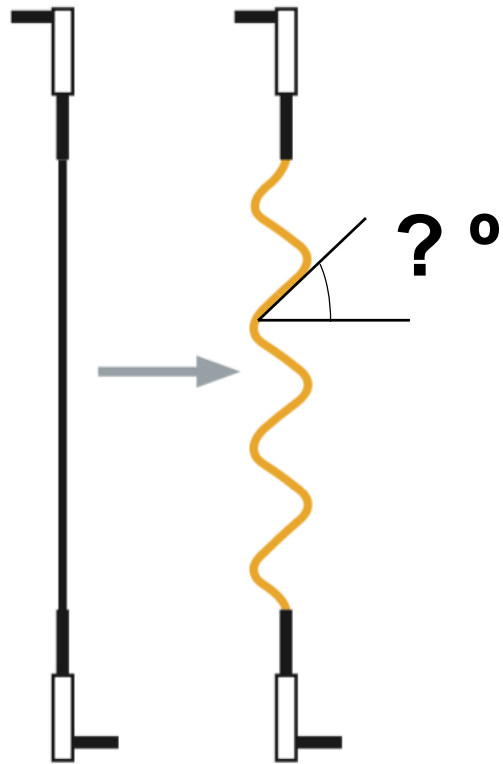


Section

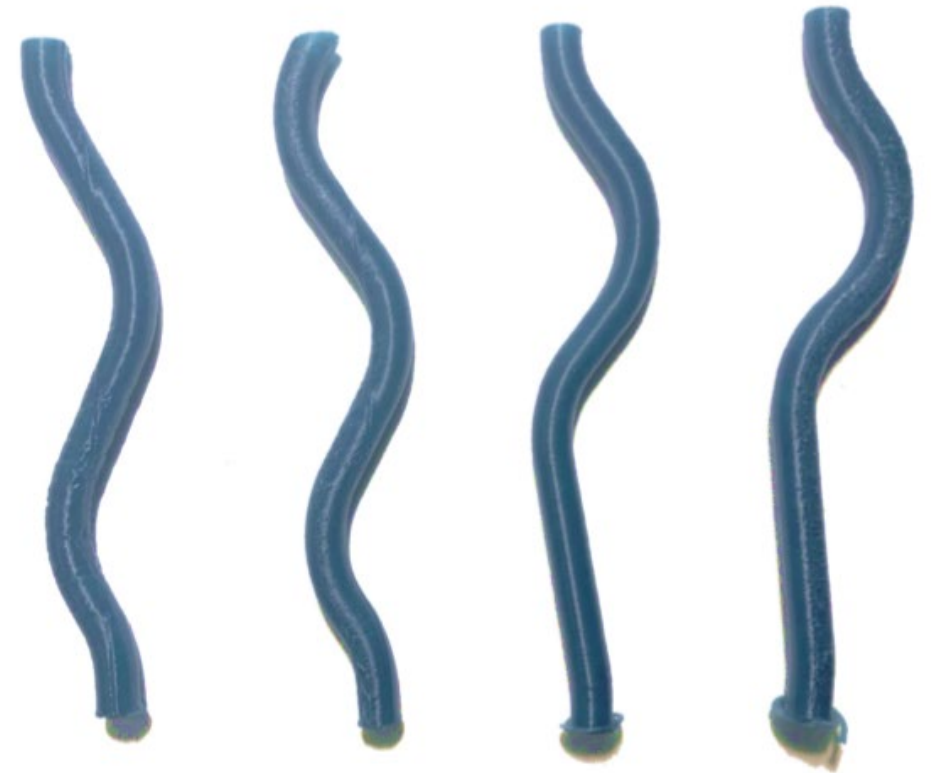


Without INFILL

Method 02



Section



30°

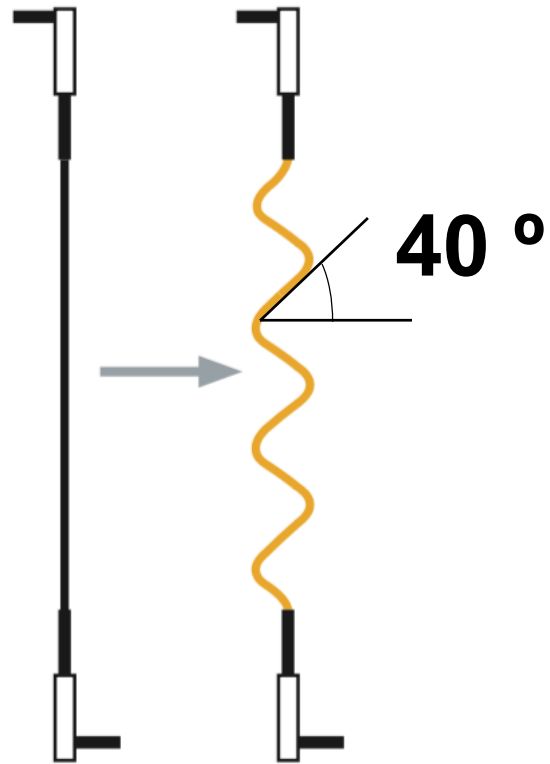
35°

40°

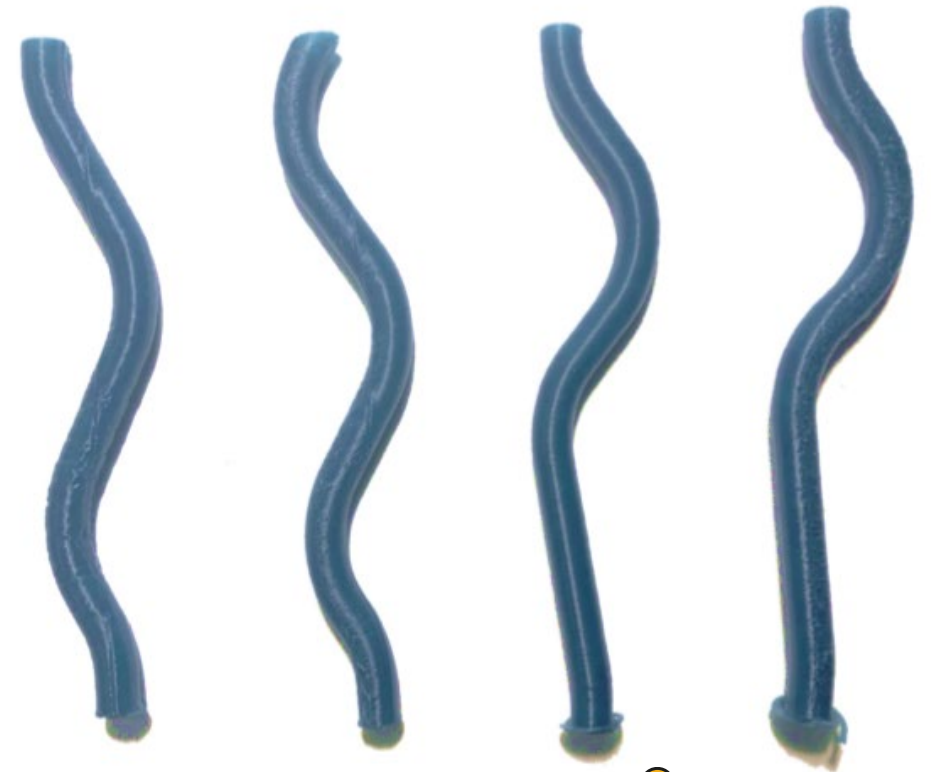
45°

With INFILL

Method 02



Section



30°

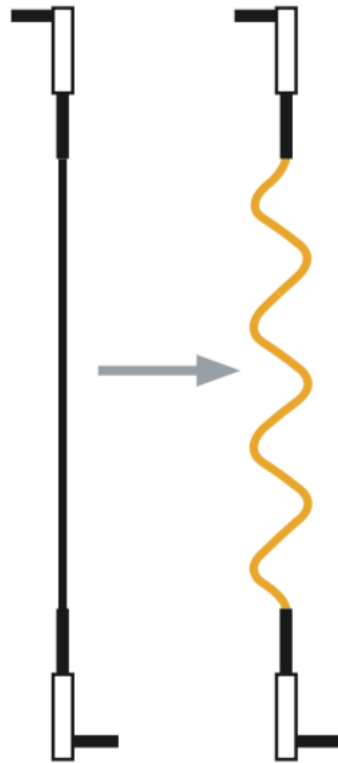
35°

40°

45°

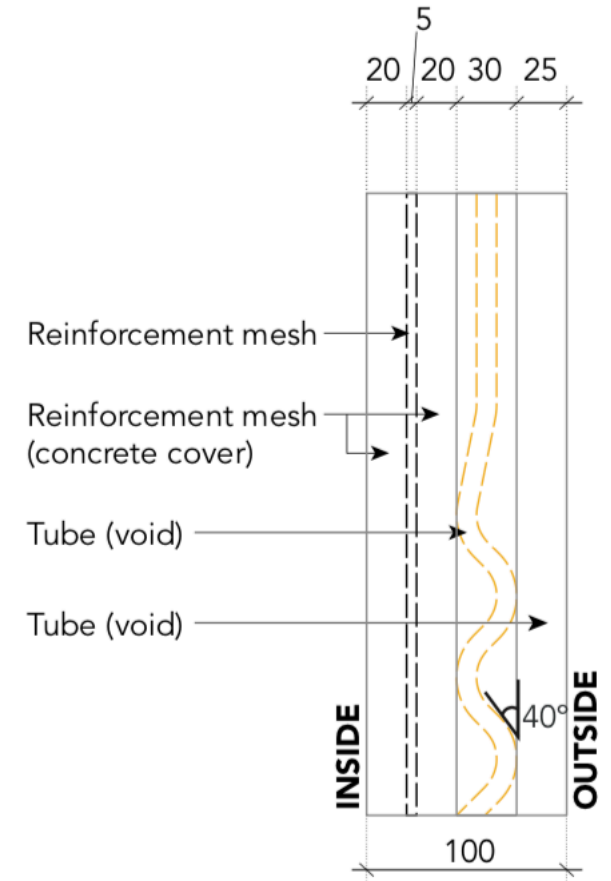
With INFILL

Method 02



Section

+105.8 %
increase in volume / per tube

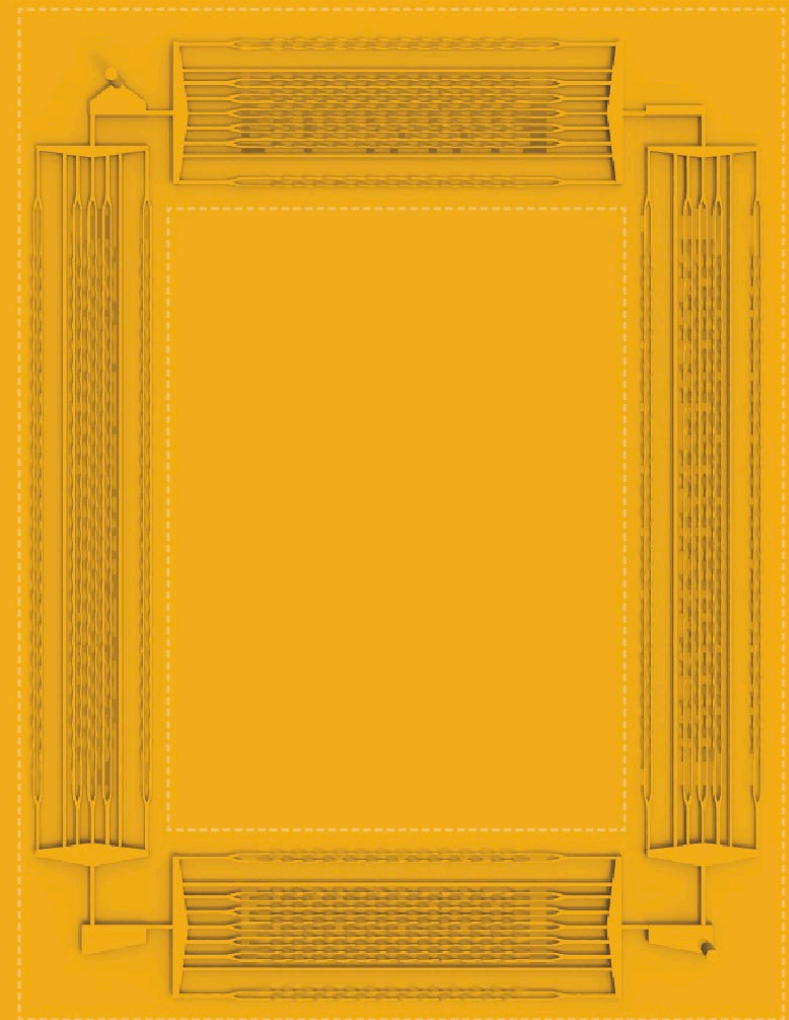


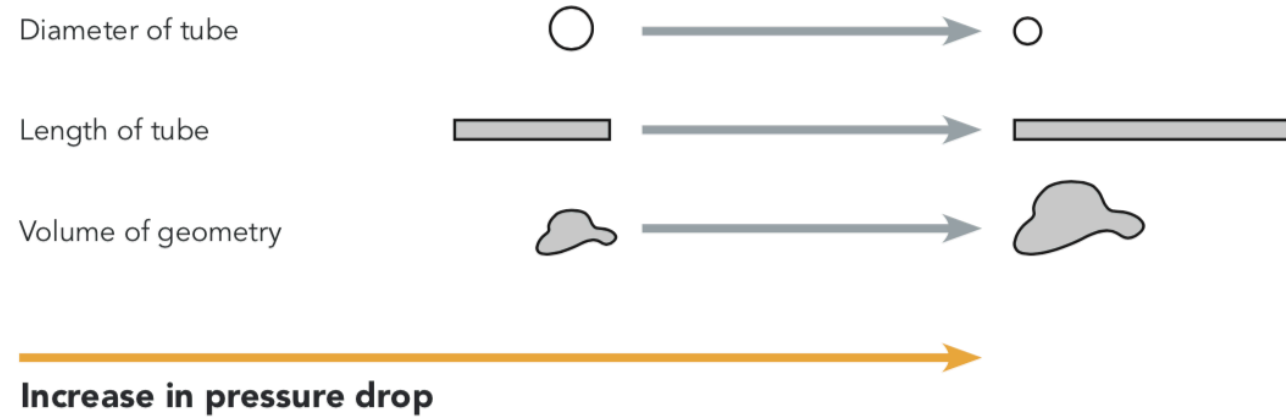
Volume of network:
31.2 litres

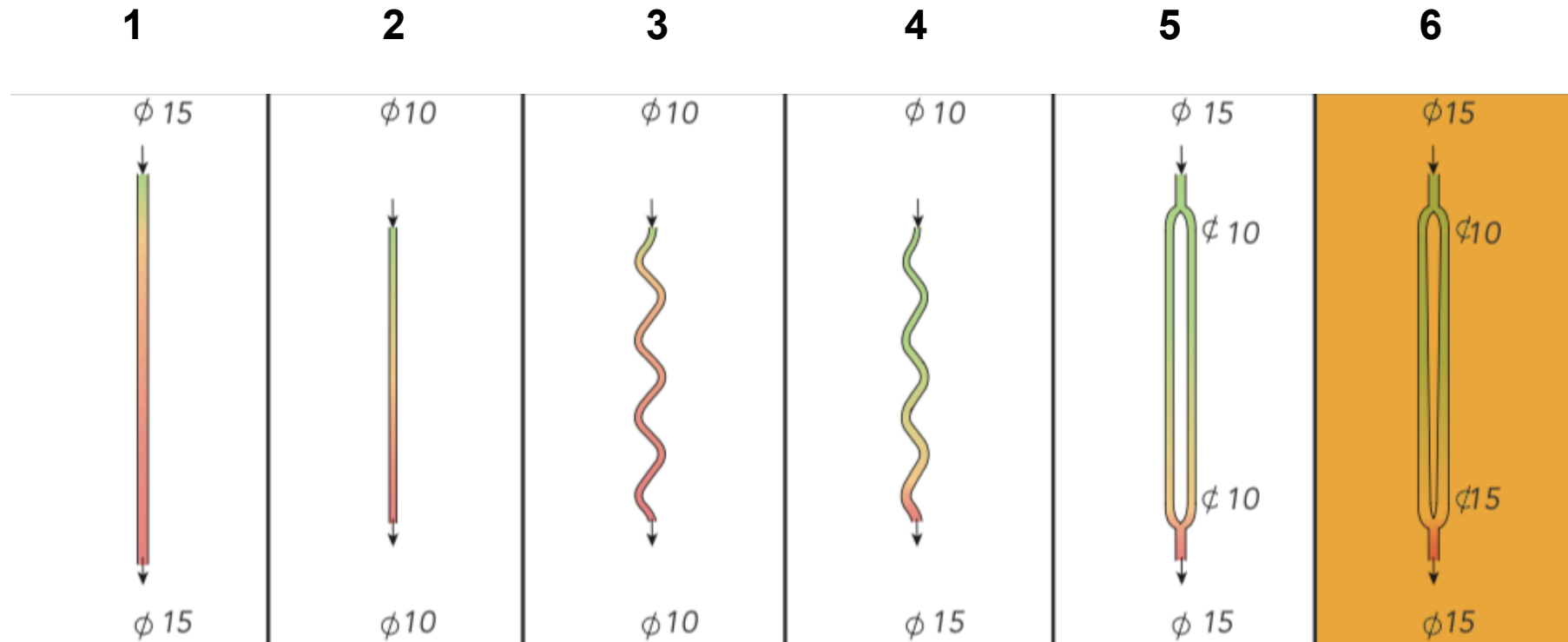
+ 51.4 %

Pressure drop:
1463.10 Pa

+18.4 %







change in pressure drop

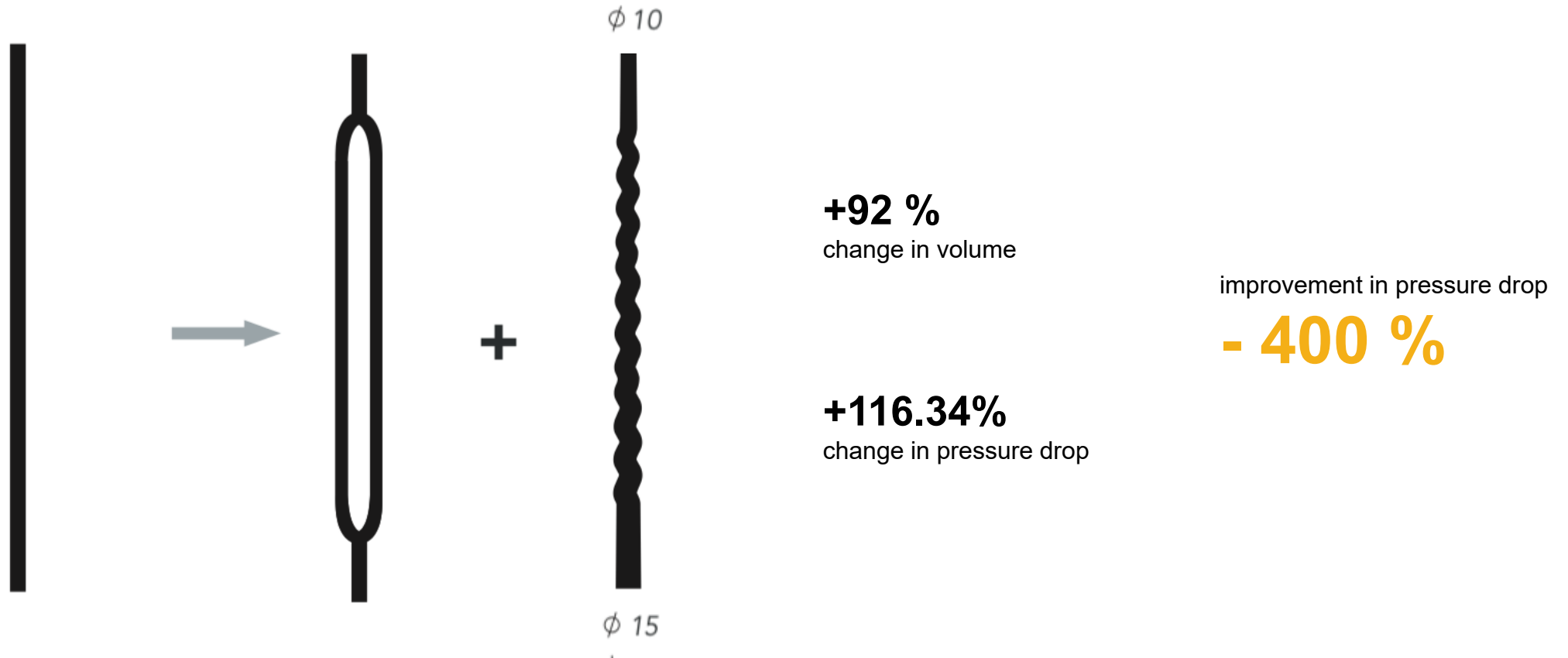
+ 75.6 %

+ 288.9 %

- 9.33 %

+ 465.1 %

+ 66.6 %

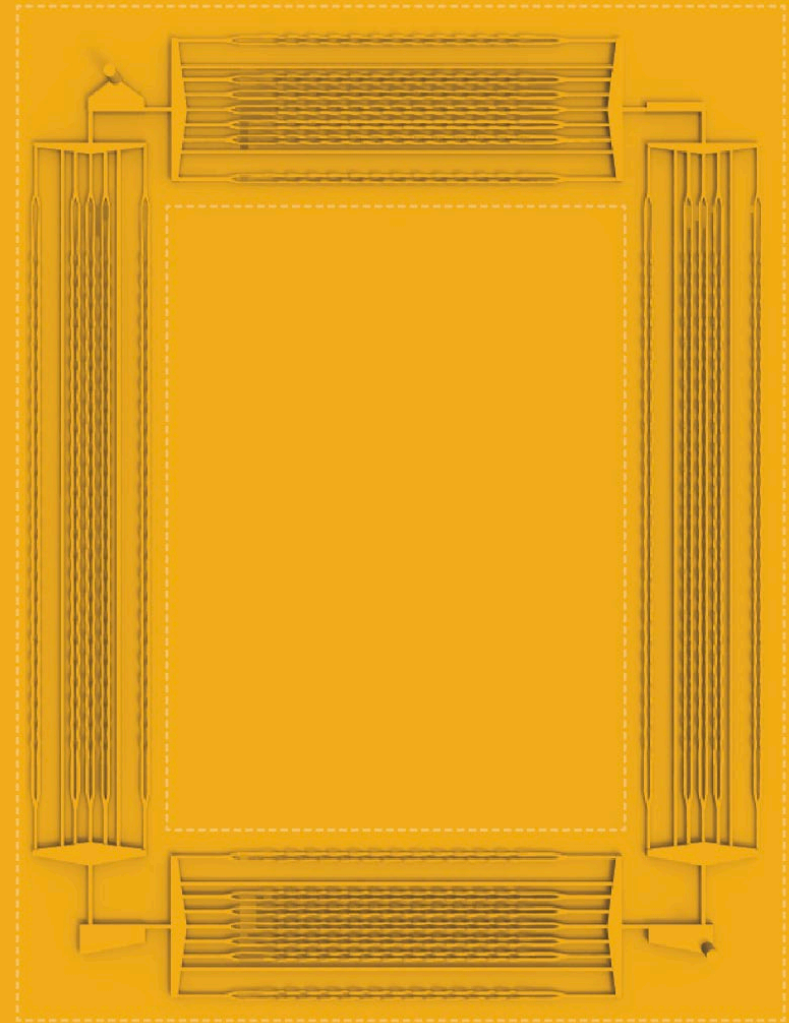


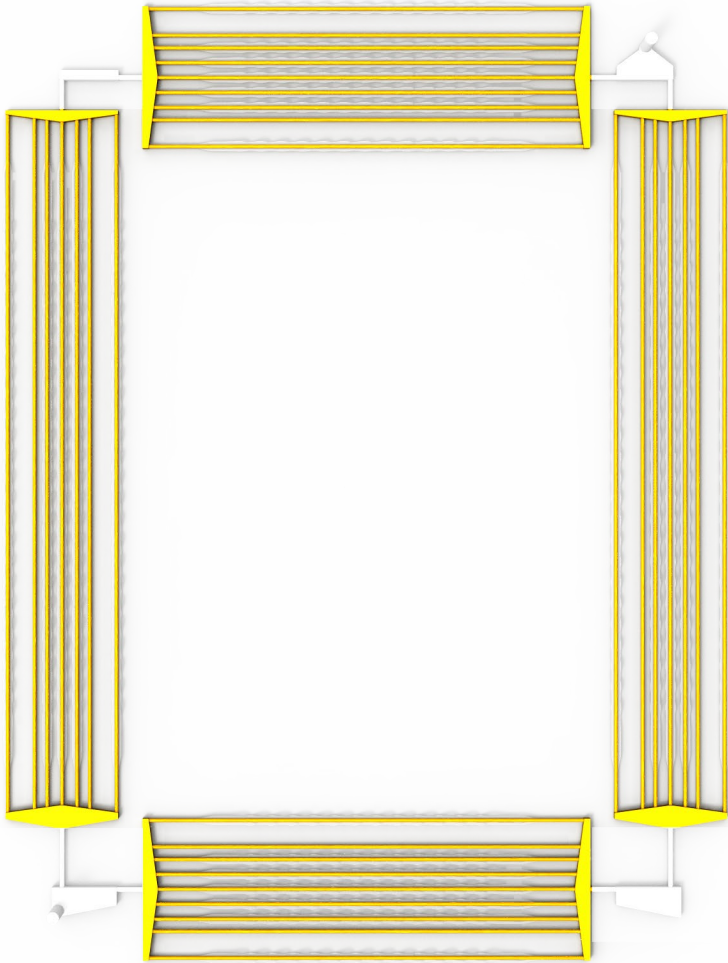
Volume of network:
29.41 litres

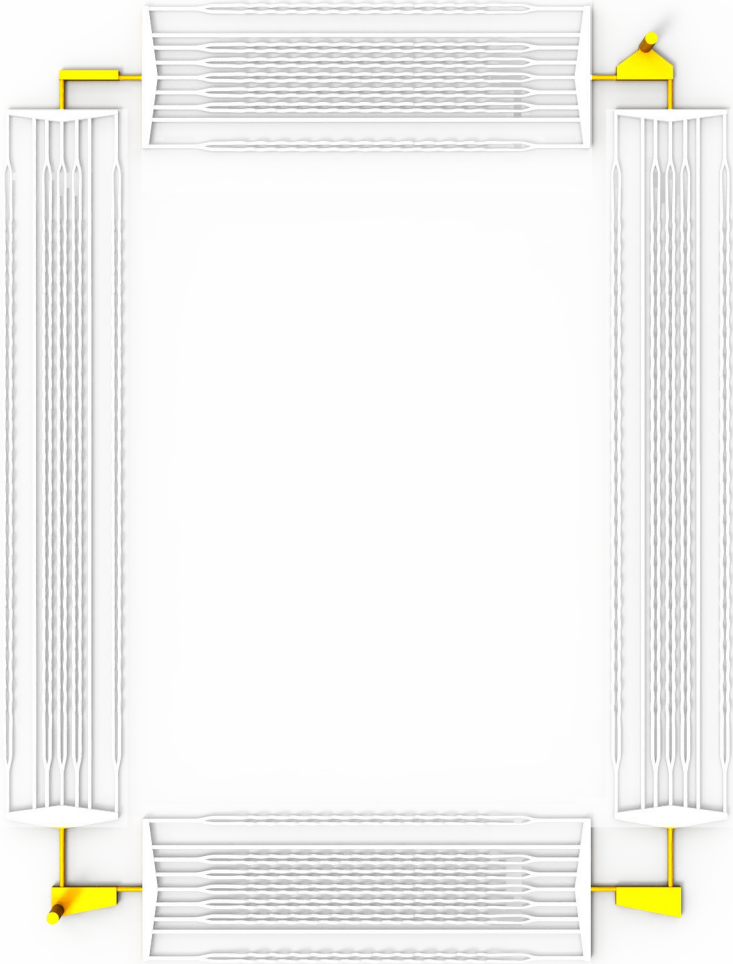
+ 42.7 %

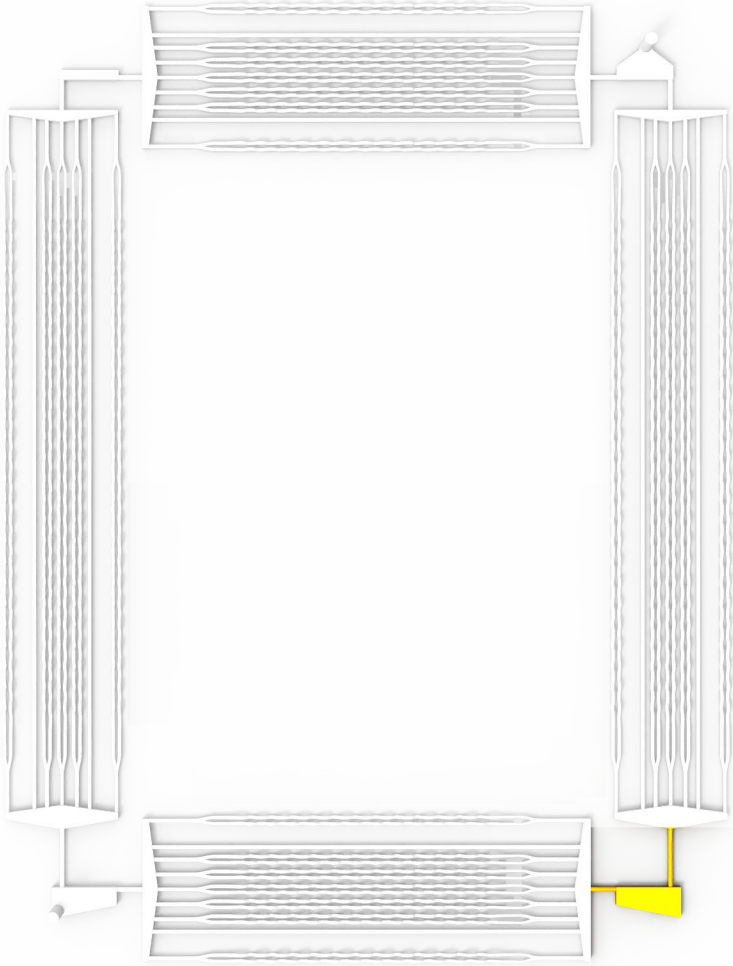
Pressure drop:
1319.67 Pa

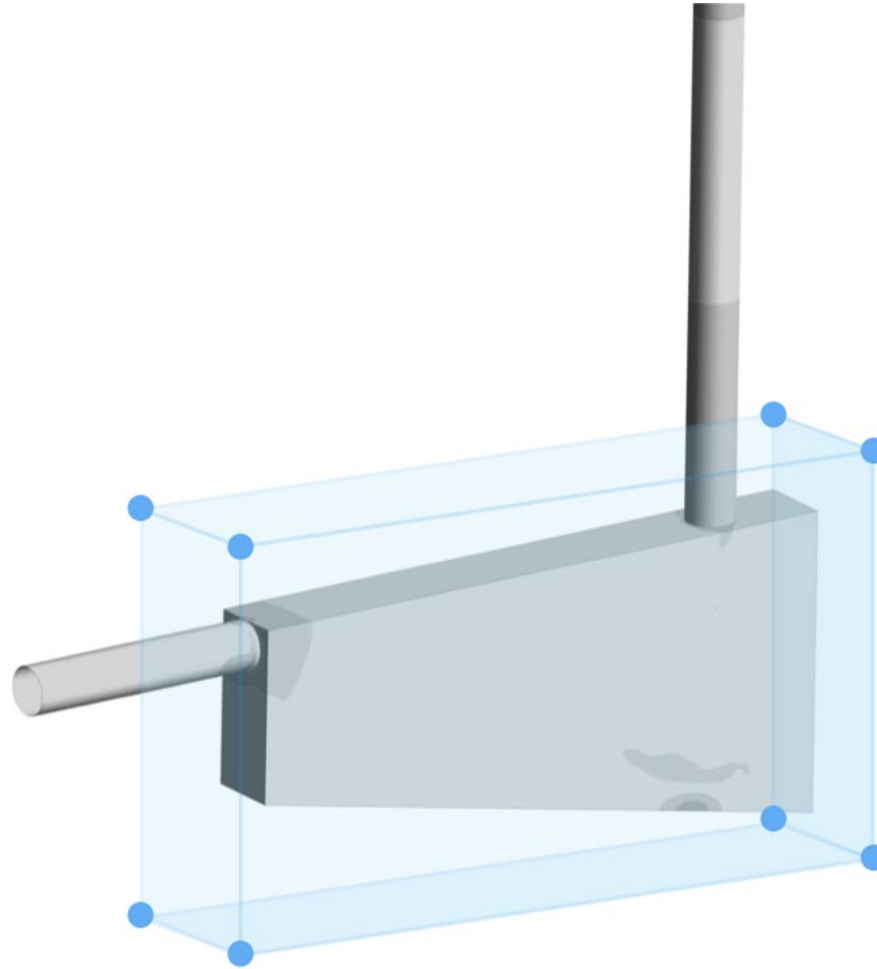
+ 6.8 %



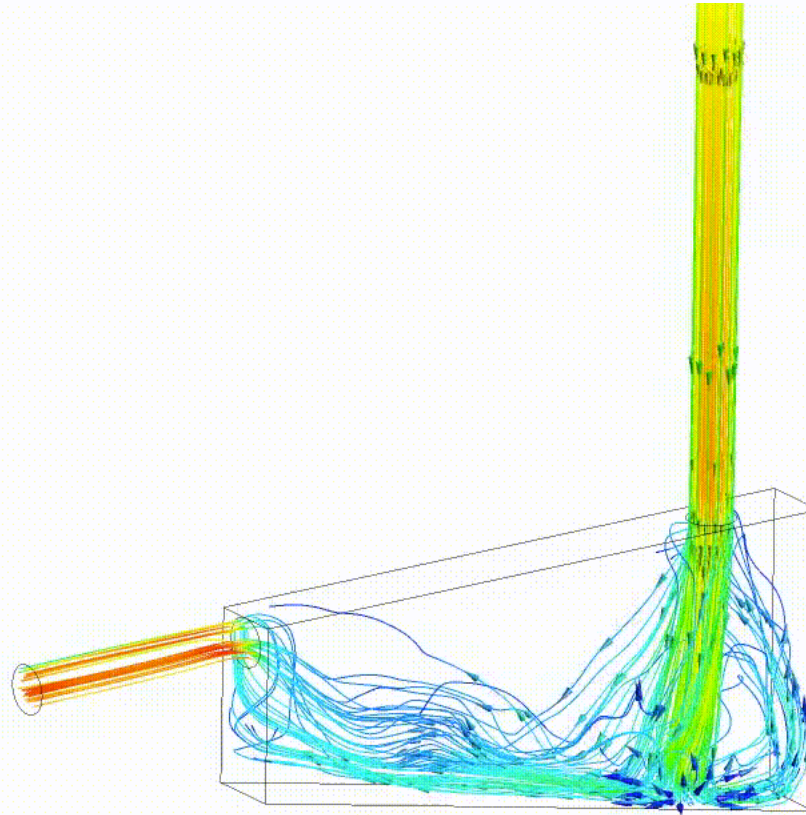


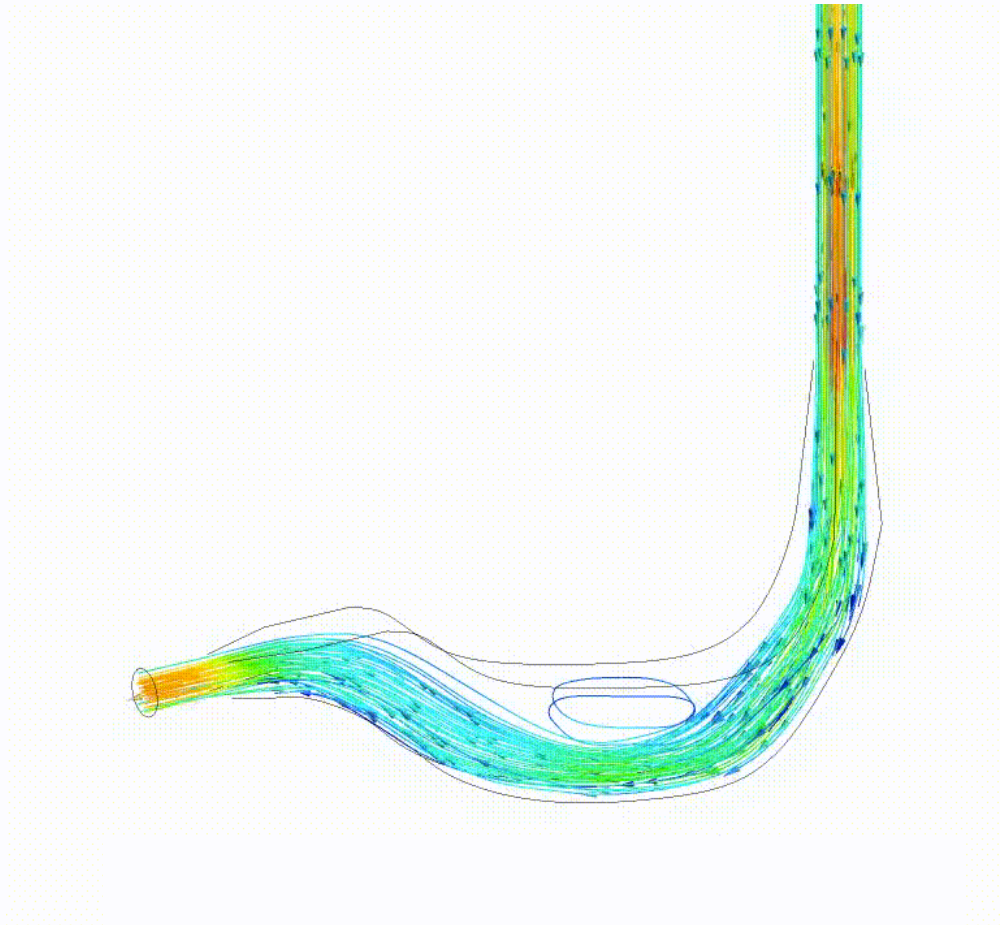






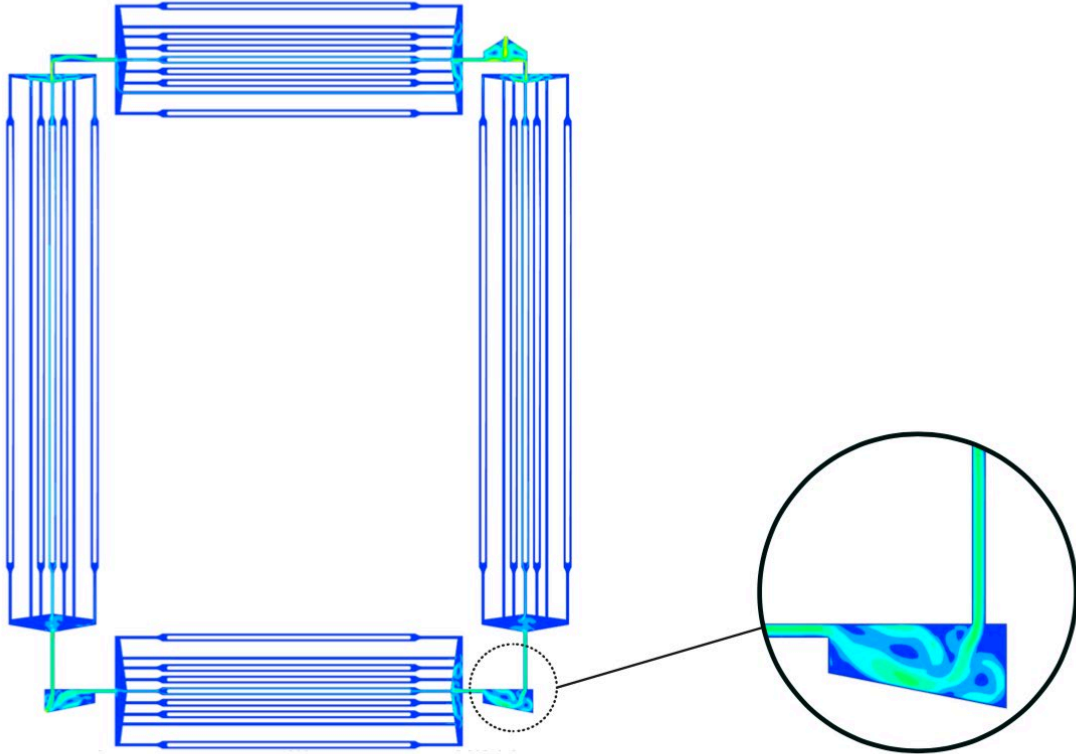
GOAL: Minimise Pressure drop



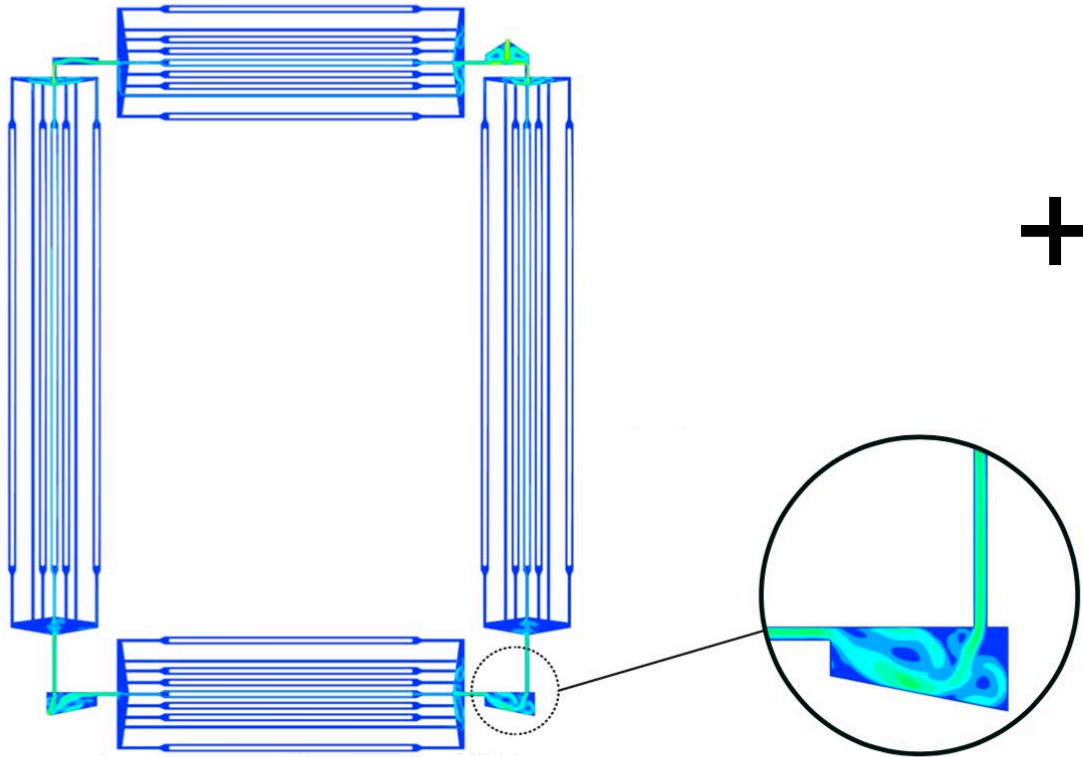


- 57 %
change in pressure drop

- 44 %
change in volume

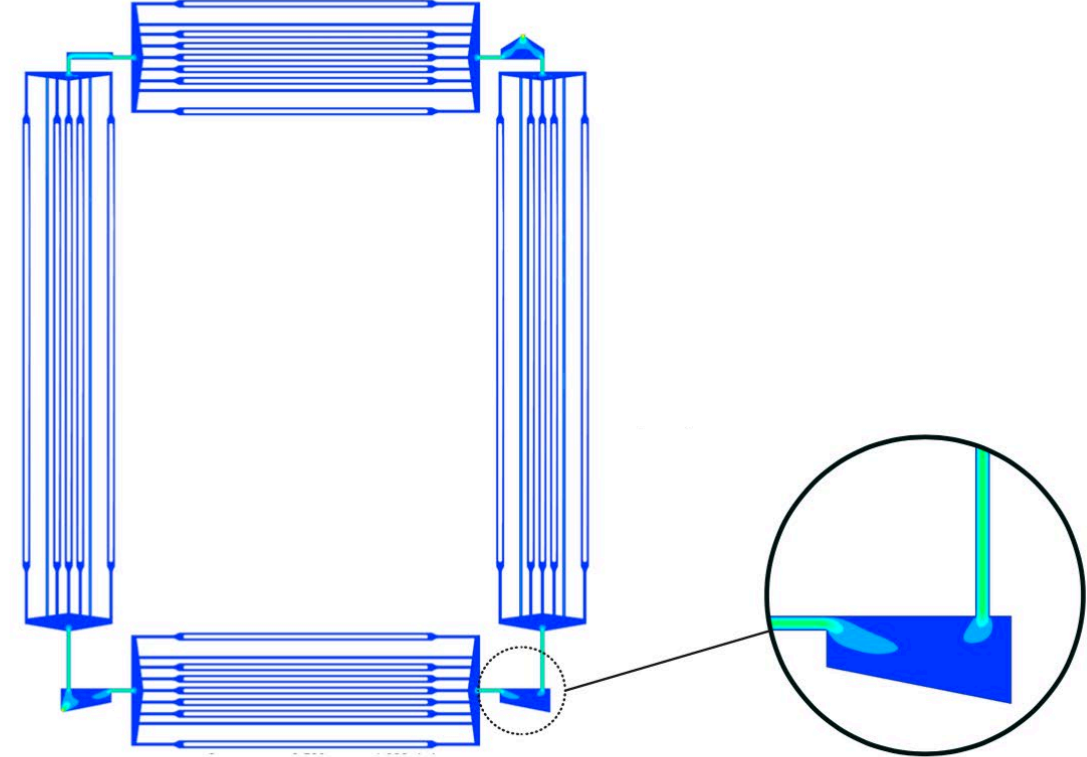


Fluid: Water @ 20°C

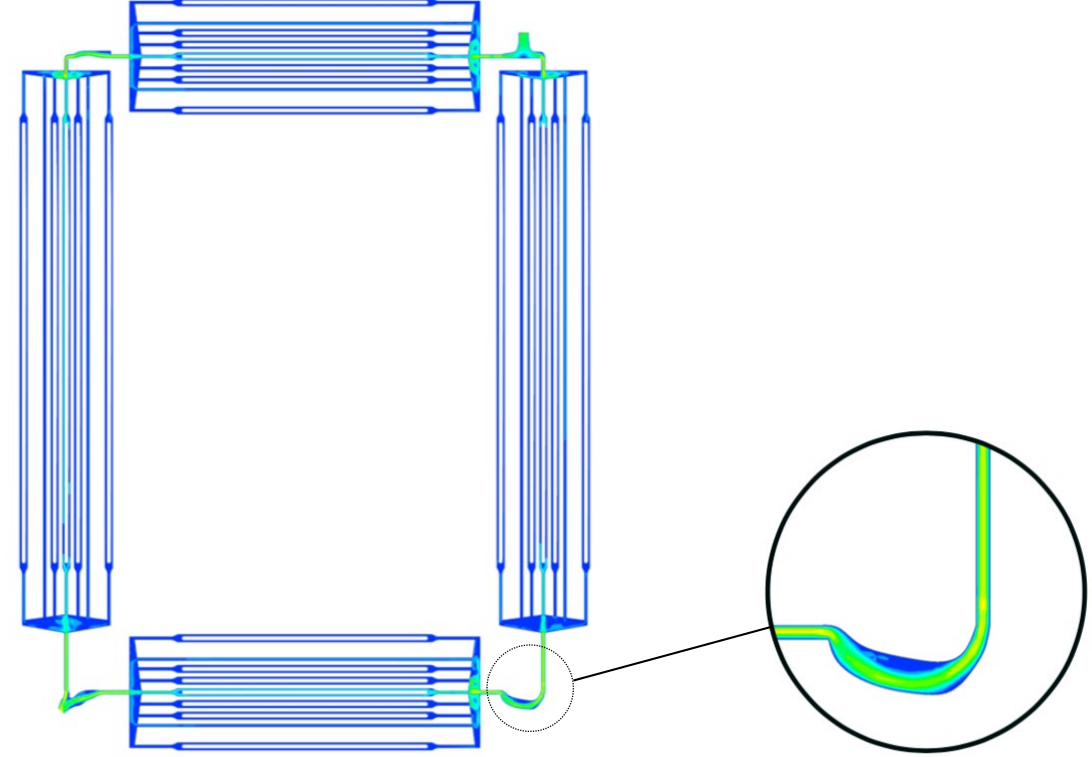
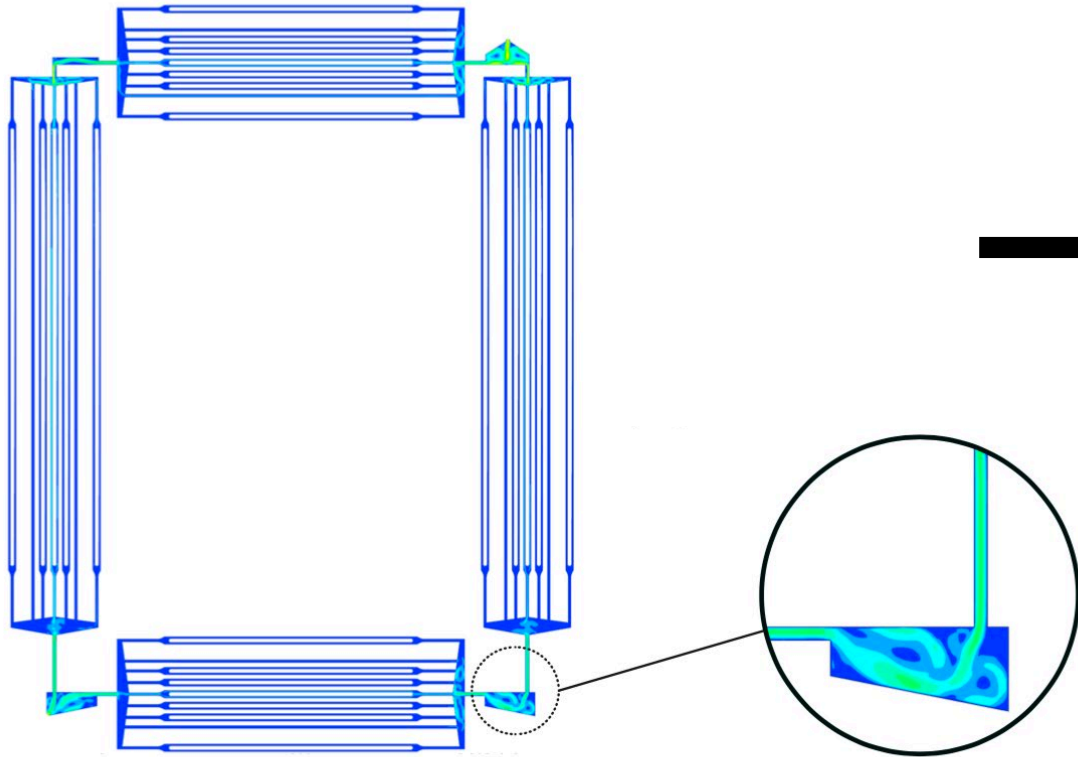


Fluid: **Water @ 20°C**

+



Fluid: **Molten wax @ 117°C**



Fluid: **Water + Wax**

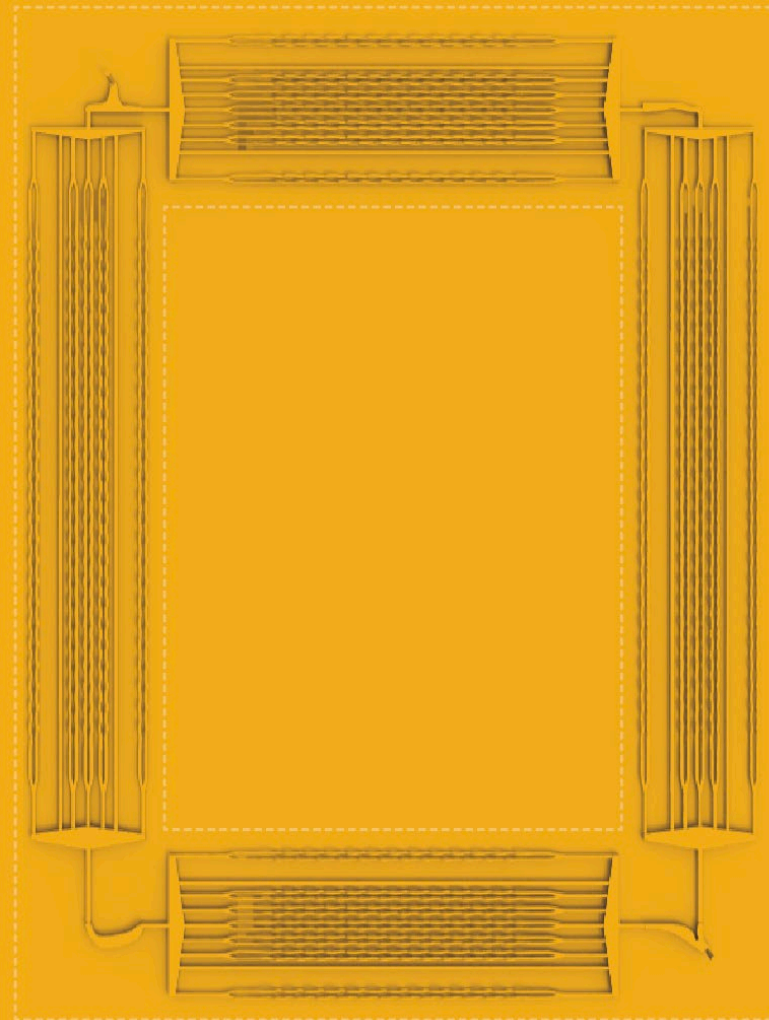
Fluid: **Water + Wax**

Volume of network:
28.11 litres

+ 36.4 %

Pressure drop:
62.51 Pa

- 94.9 %



Focus: Façade panel **MASS**

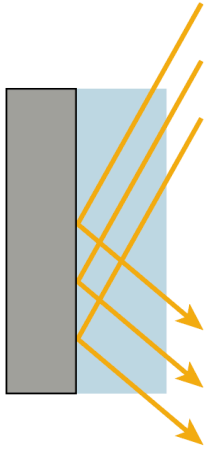
Material: **Concrete**

GOAL

1

Maximise thermal entrapment

- Maximised heat-exchange efficiency of system
- Faster exchange cycle



Flat surface

Low surface area

Direct radiation on surface

$$\frac{Q}{t} = \frac{kA(T_2 - T_1)}{d}$$

where,

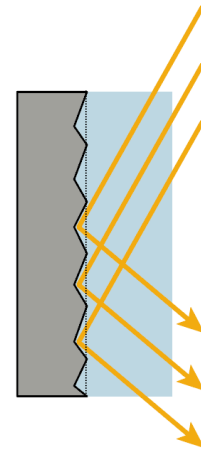
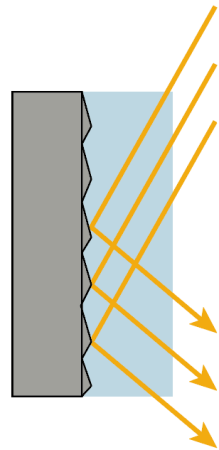
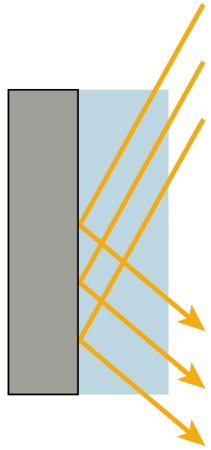
Q/t = rate of heat transfer

k = thermal conductivity of the material

$T_2 - T_1$ = temperature difference between the two materials

d = thickness of the material

A = surface area



Flat surface

Geometry Addition

Geometry Subtraction

Low surface area

Added mass

Structurally unstable

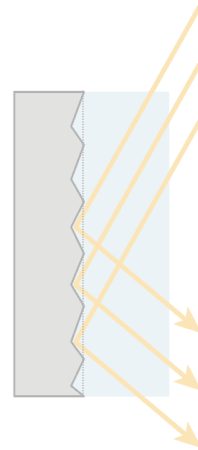
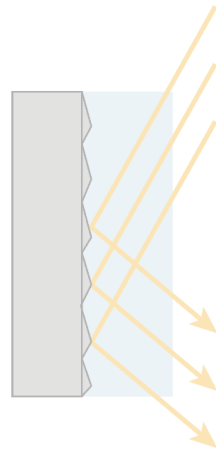
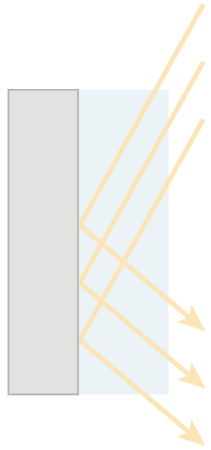
Direct radiation on surface

Increased surface area

Increased surface area

Self shaded to radiation

Self shaded to radiation



Flat surface

Low surface area

Direct radiation on surface

Geometry Addition

Added mass

Increased surface area

Self shaded to radiation

Geometry Subtraction

Structurally instable

Increased surface area

Self shaded to radiation

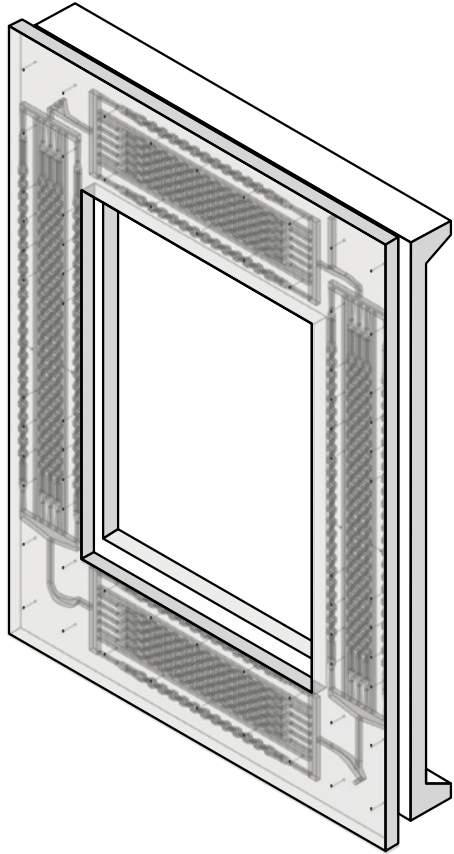
Topology optimisation

Increased Surface area

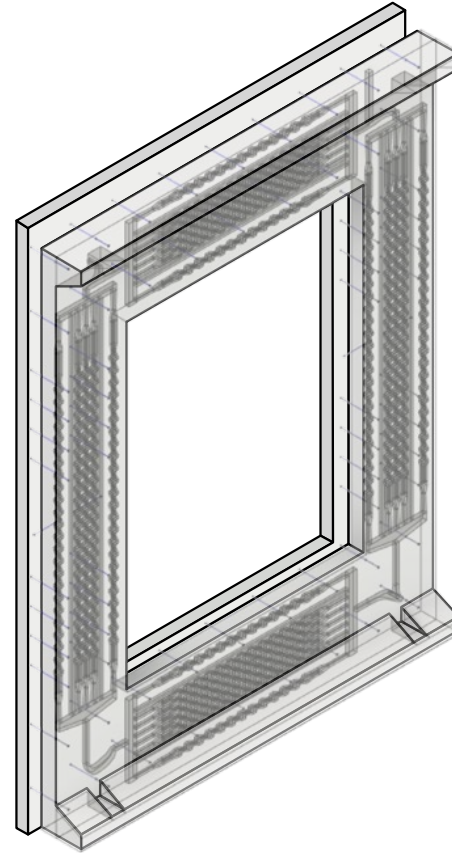
Reduce mass

Structurally stable

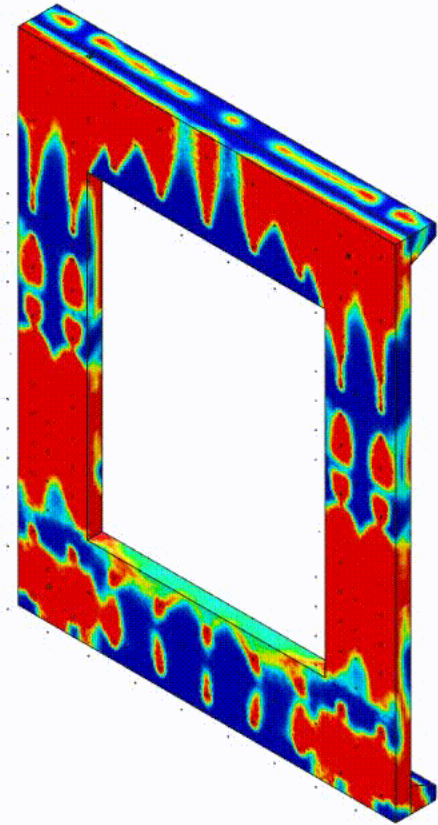
Self shaded to radiation



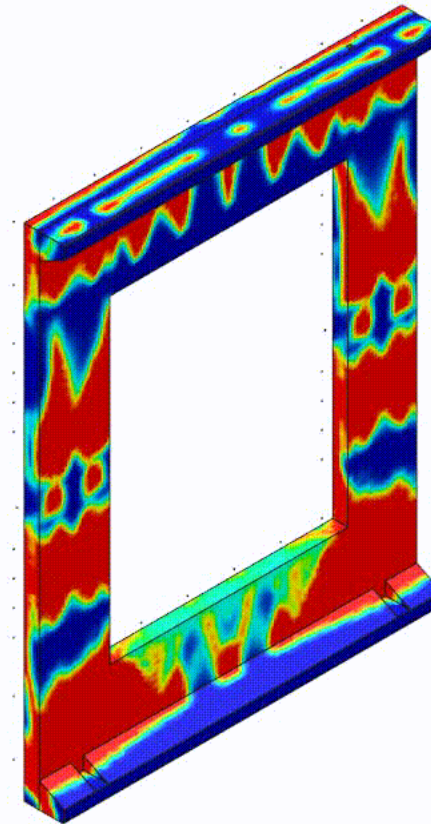
External panel



Internal panel



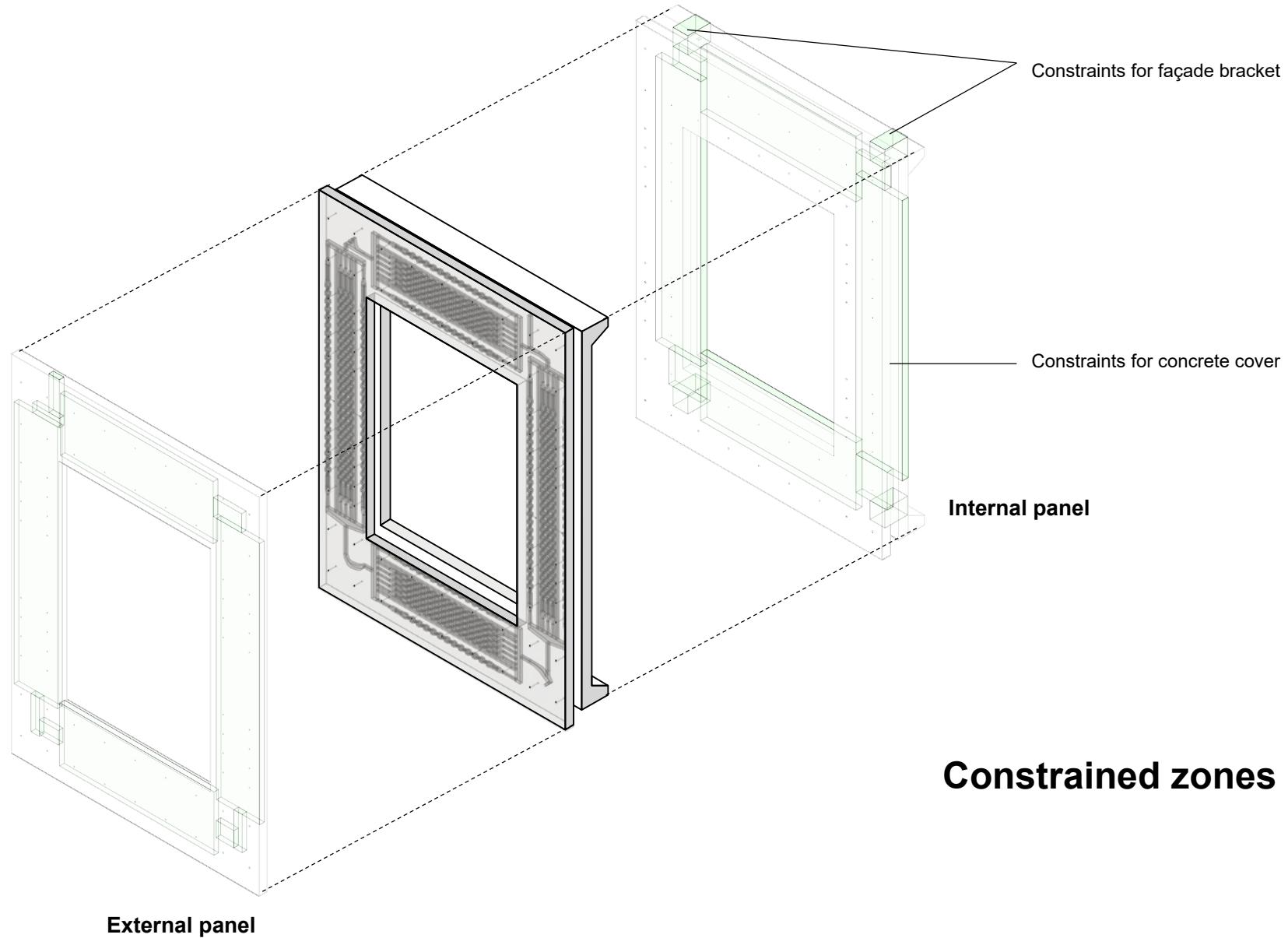
Internal panel- **Front view**

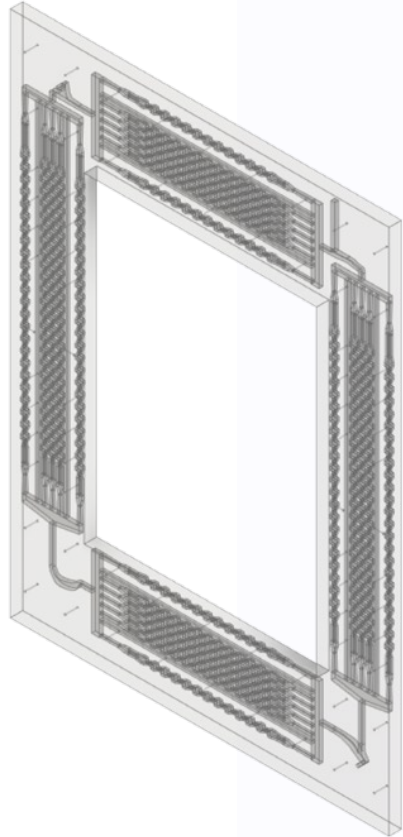


Internal panel- **Back view**

Non- constrained

Topology optimisation

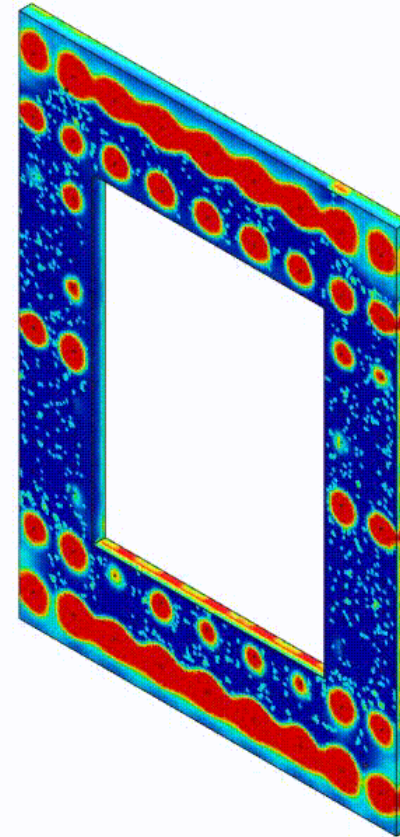




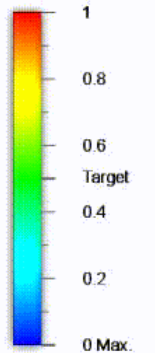
11.5 %
Increase in surface area
+
thermal exchange



12.5 %
Volume reduction



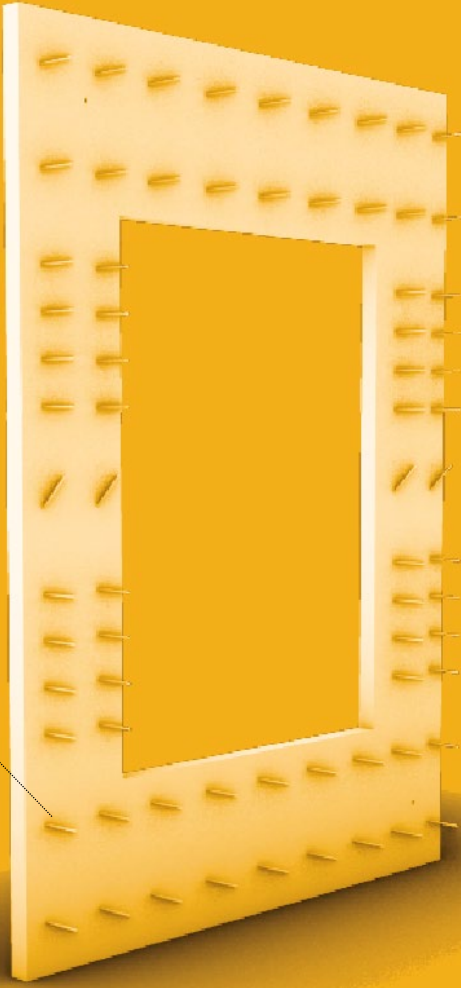
Load Path Criticality

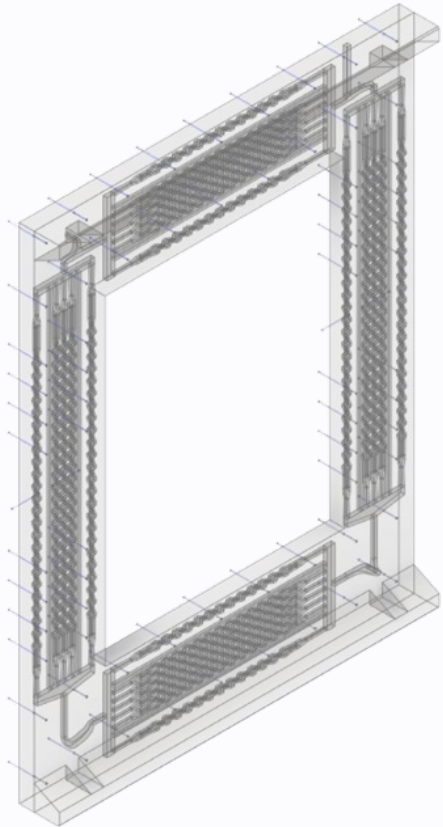


Mass Ratio: 100.00%
Approx. Mass: 1257.457 kg

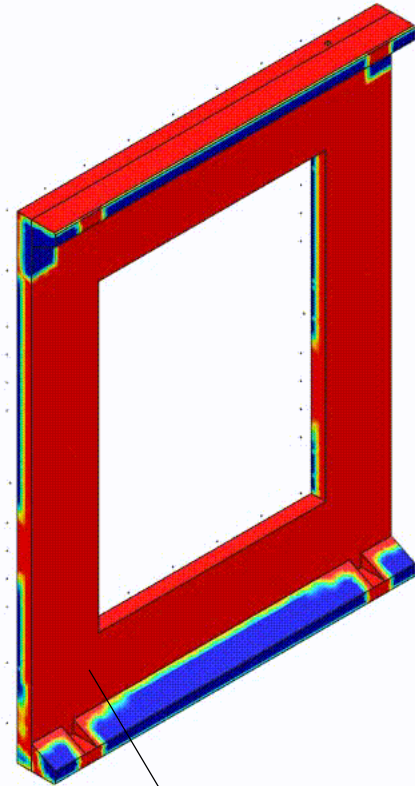


Zones of reinforcement dowels

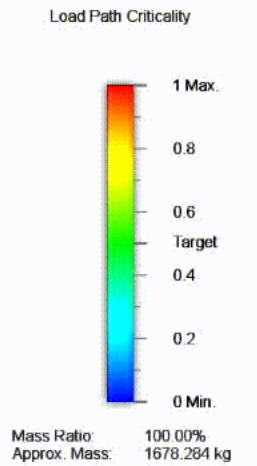
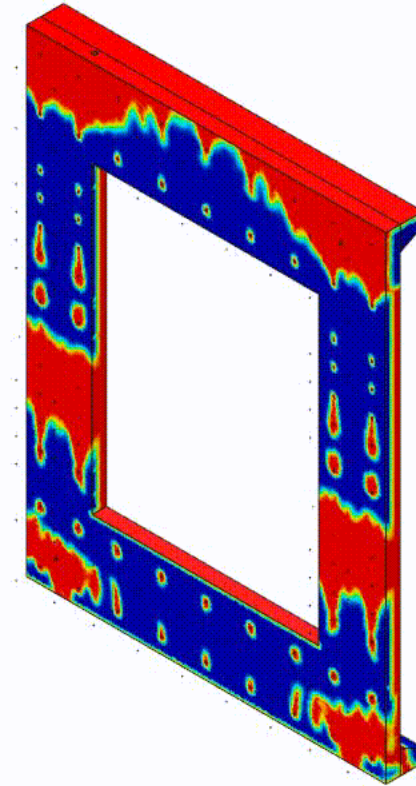




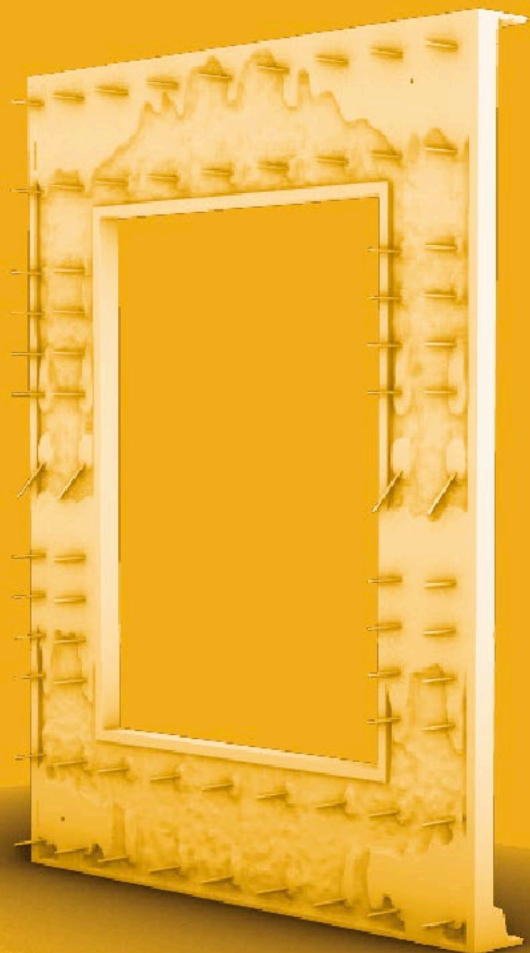
20.7 %
Volume reduction



Constrained to flat inner surface



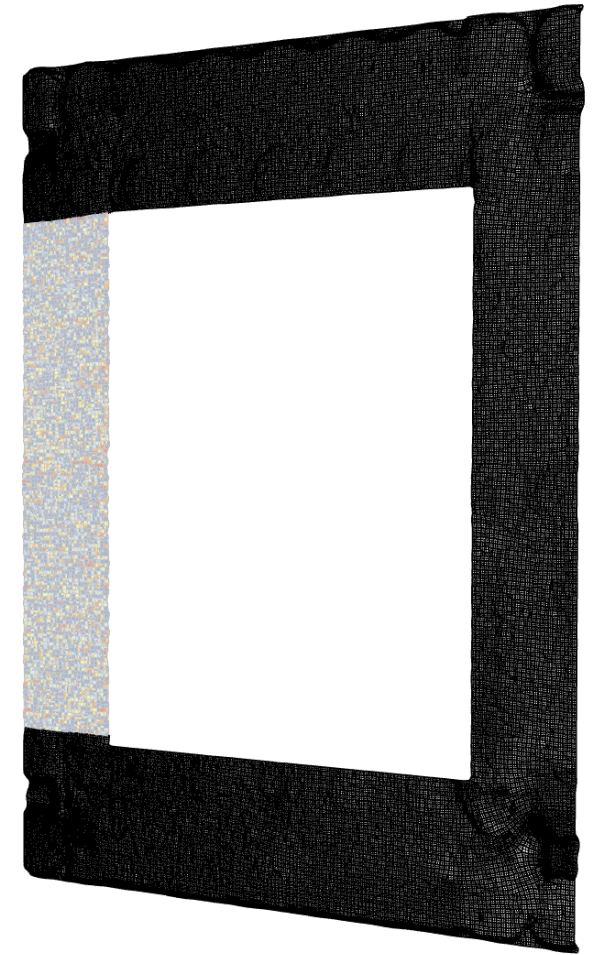
Internal panel



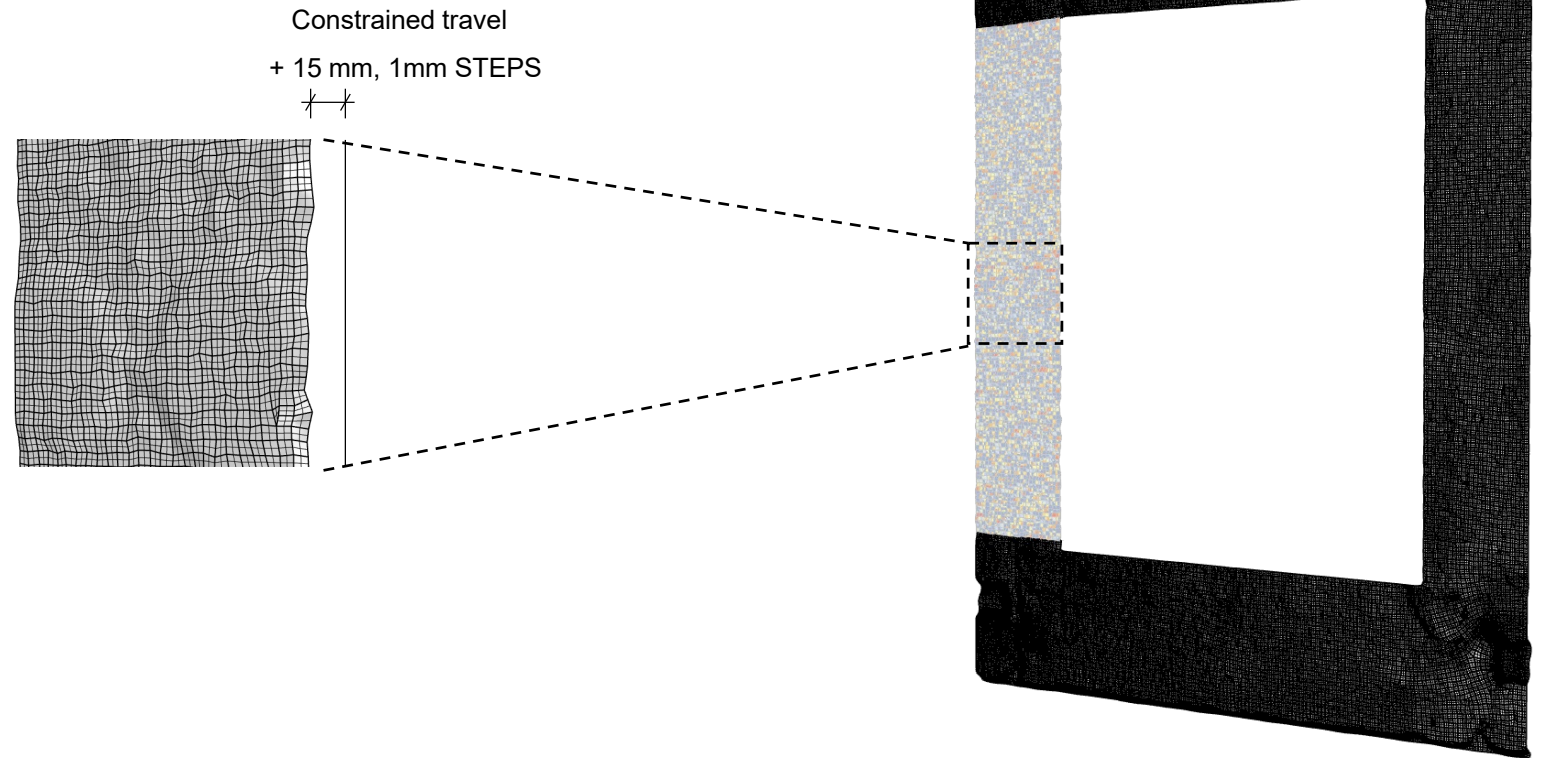
Constrained to
flat inner surface

Façade brackets



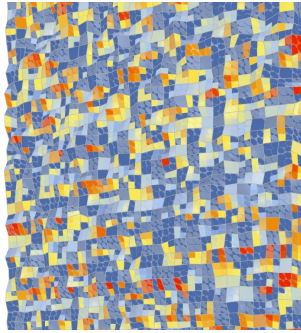
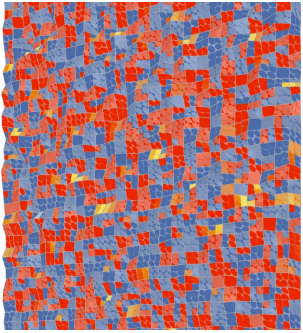


Step 02 Surface Modification

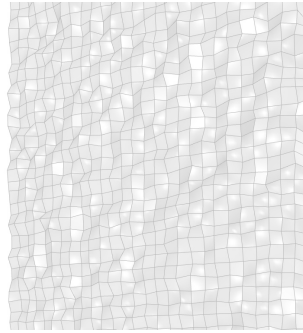


WINTER RAD.

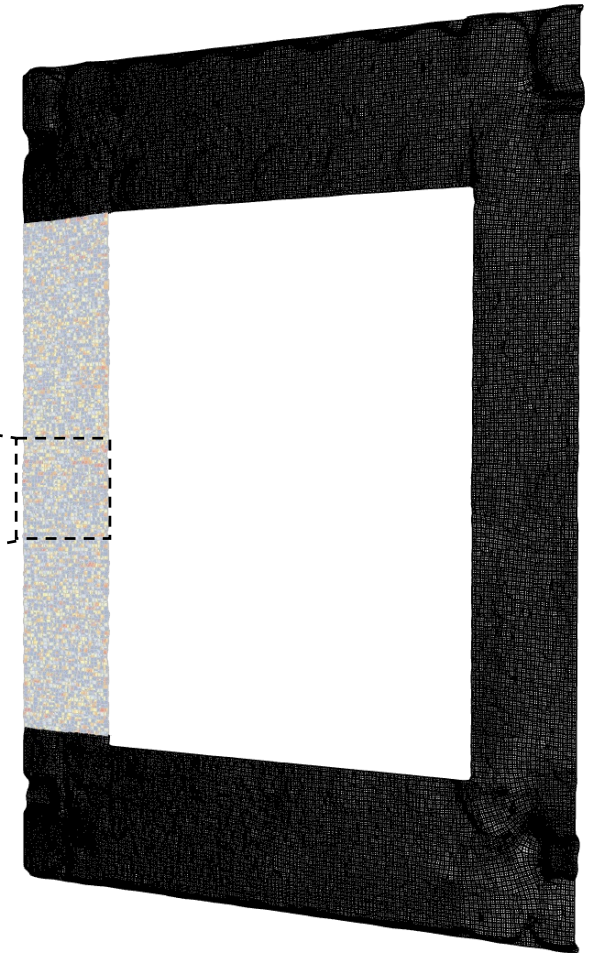
SUMMER RAD.



SURFACE AREA

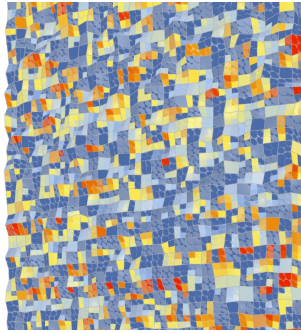
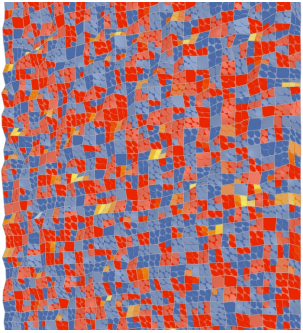


MAXIMISE

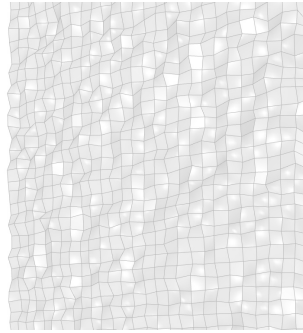


WINTER RAD.

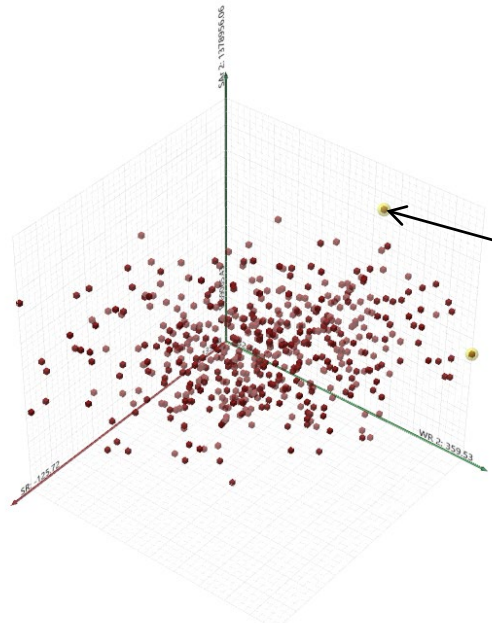
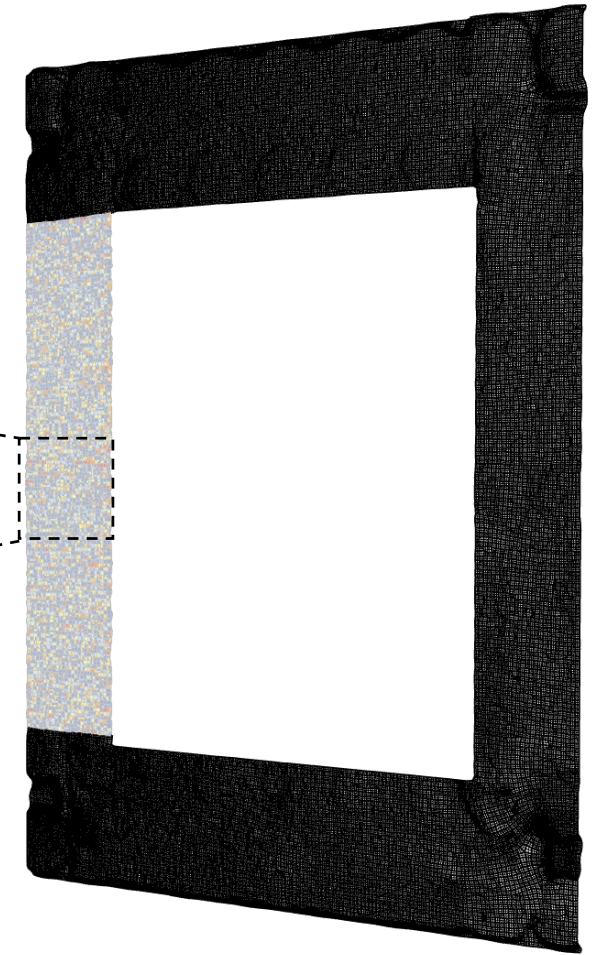
SUMMER RAD.



SURFACE AREA



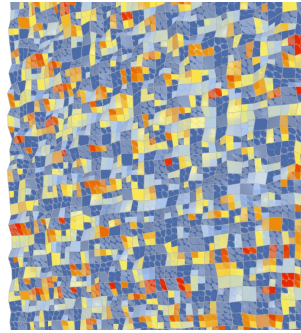
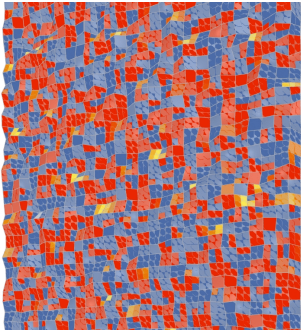
MAXIMISE



5-7 % increase in surface area
with similar radiation performance

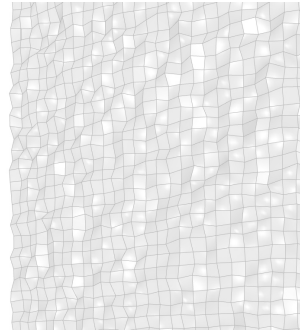
WINTER RAD.

SUMMER RAD.

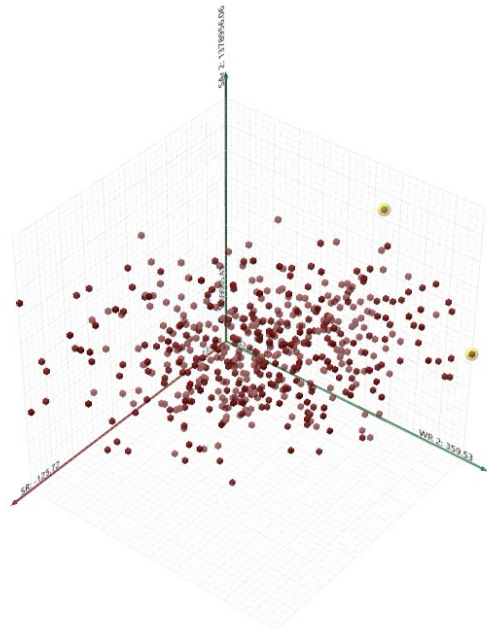
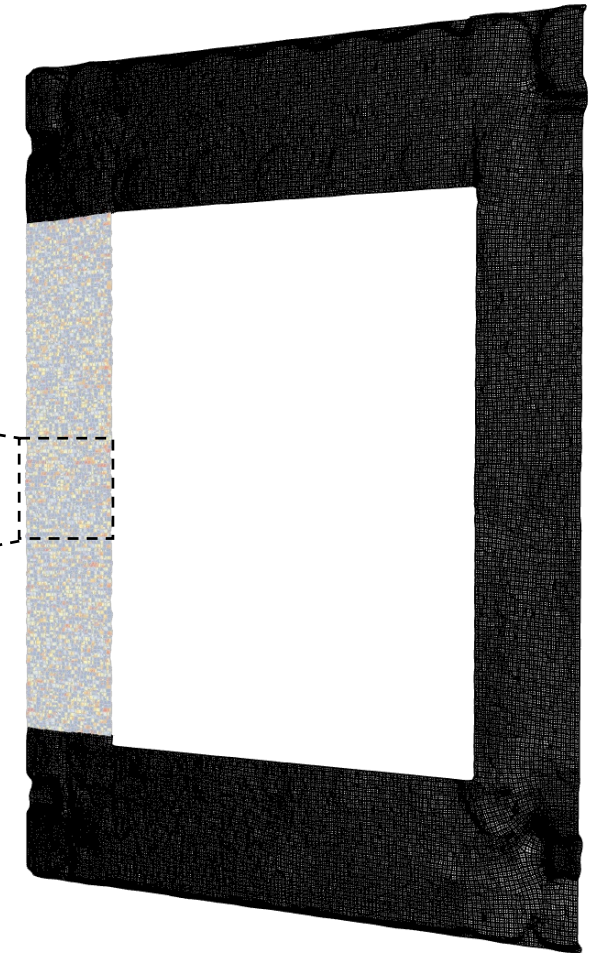


CONSTANT

SURFACE AREA



MAXIMISE



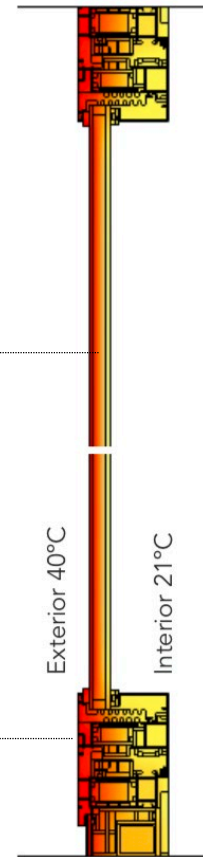
5-7 % increase in surface area
with similar radiation performance

18.2 % increase in surface area
Topology Opt. + Surface modification

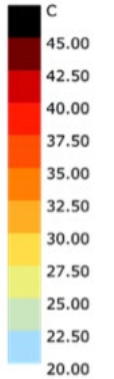
Fenestration

Glass panel : Saint Gobain Planitherm
PLT T- Argon / 6-12-6
U = 1.5 W/m²K

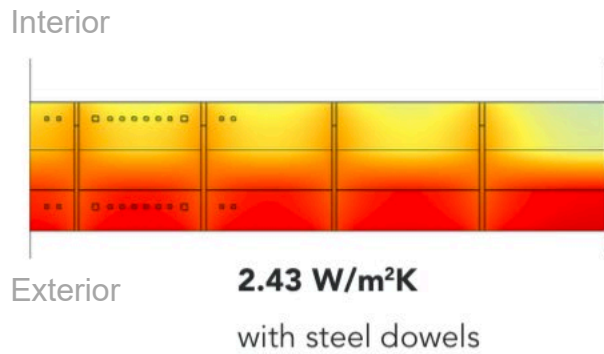
Window section : Schüco AWS75 SI+
U = 1.2 W/m²K



**1.88 W/m²K
for fenestration**



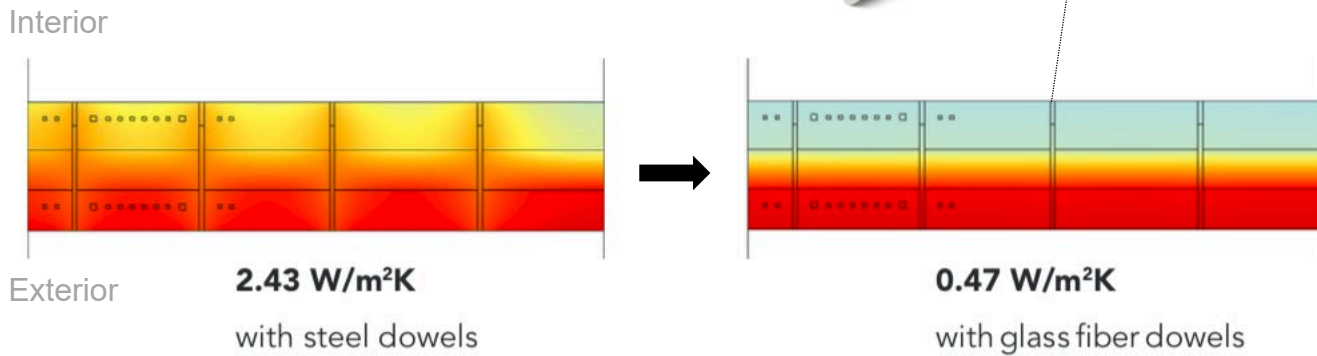
Opaque section



ECBC : **0.63 – 0.40 W/m²K**

ECBC + : **≤ 0.40 W/m²K**

Opaque section



5 times

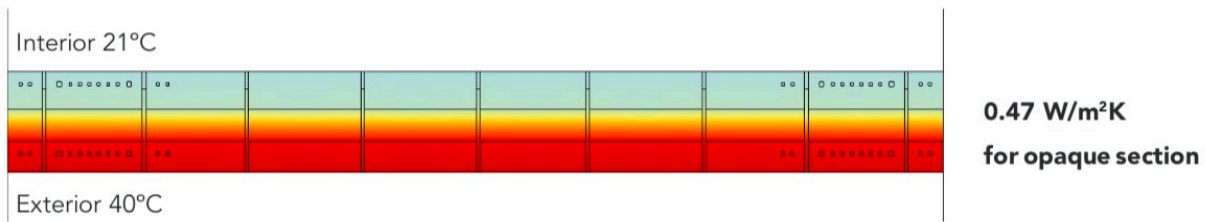
increase in insulating performance

ECBC : 0.63 – 0.40 W/m²K

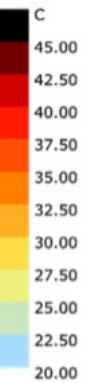
ECBC + : ≤ 0.40 W/m²K

ECBC norms compatible

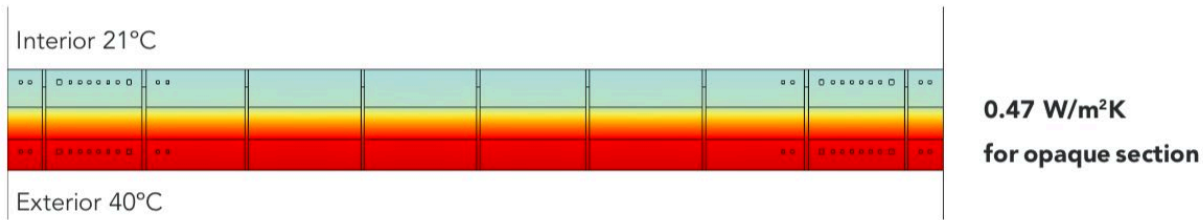
Opaque section



ECBC norms compatible



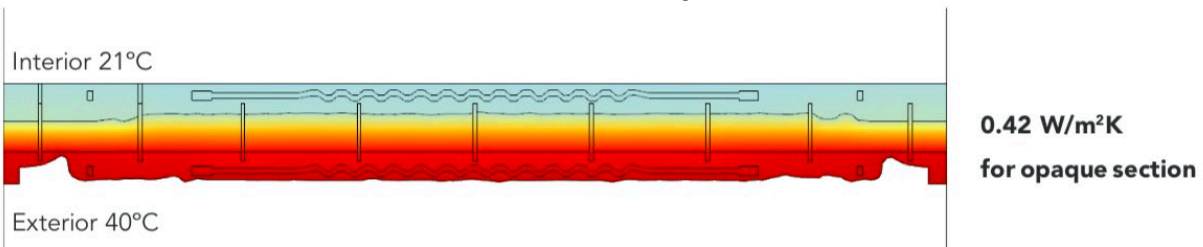
Opaque section



ECBC norms compatible

↓

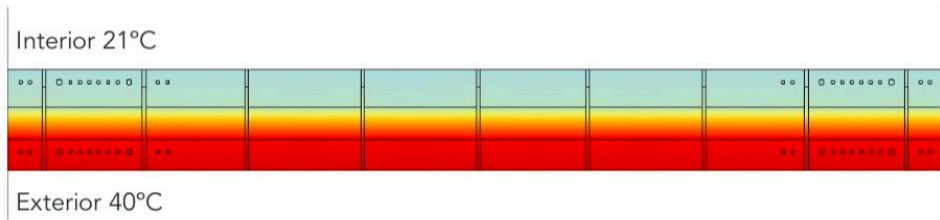
ECBC+ norms compatible



12 %
increase in insulating performance



Opaque section

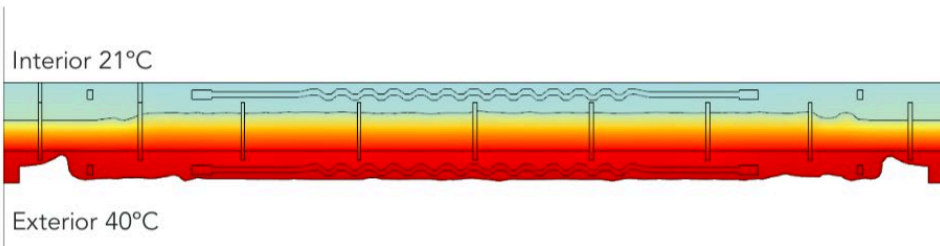


0.47 W/m²K
for opaque section

ECBC norms compatible

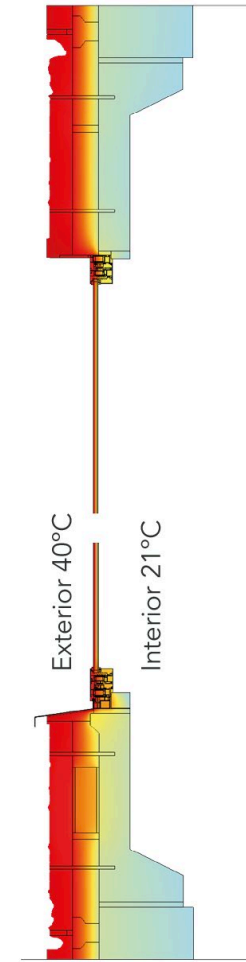
↓

ECBC+ norms compatible

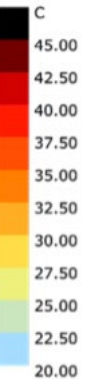


0.42 W/m²K
for opaque section

12 %
increase in insulating performance



0.95 W/m²K
for wall section

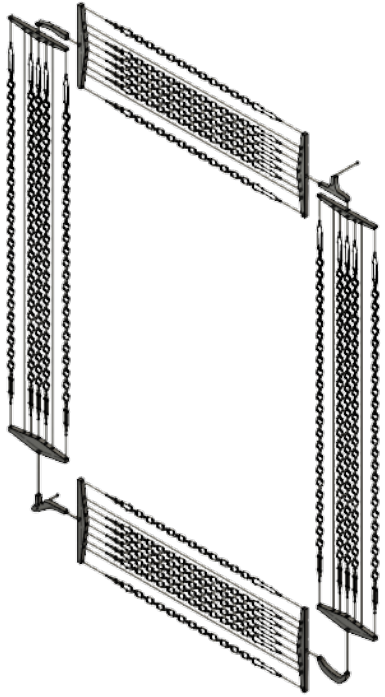


LET'S DISCUSS

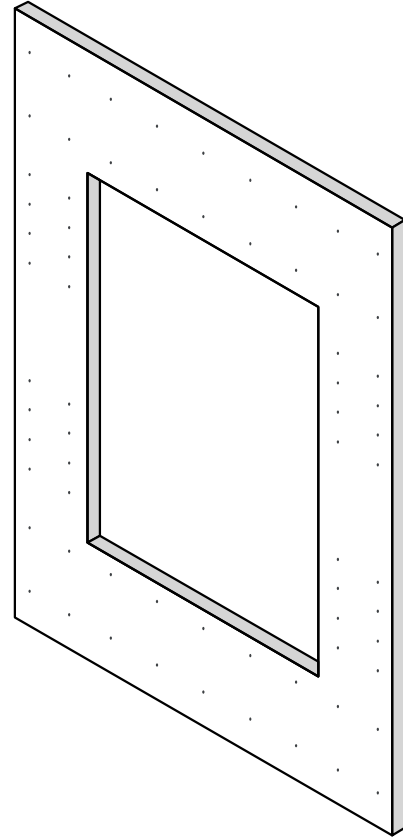


FABRICATION METHOD

Casting



+

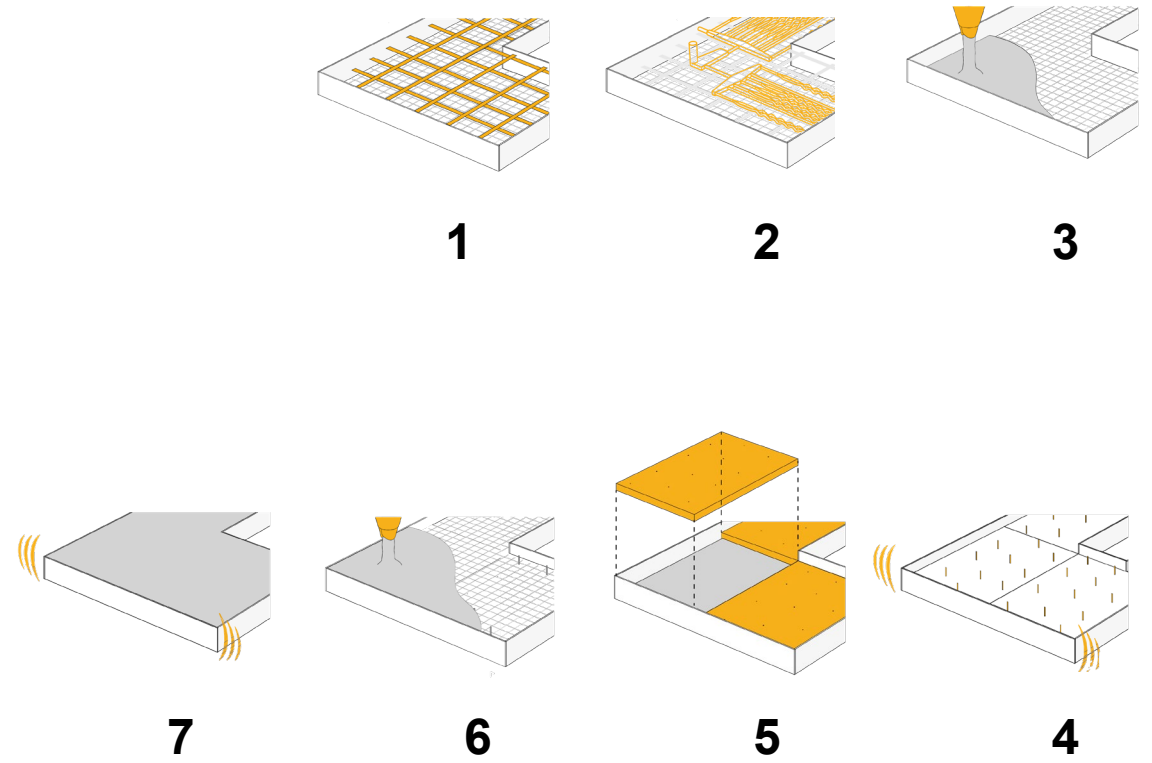
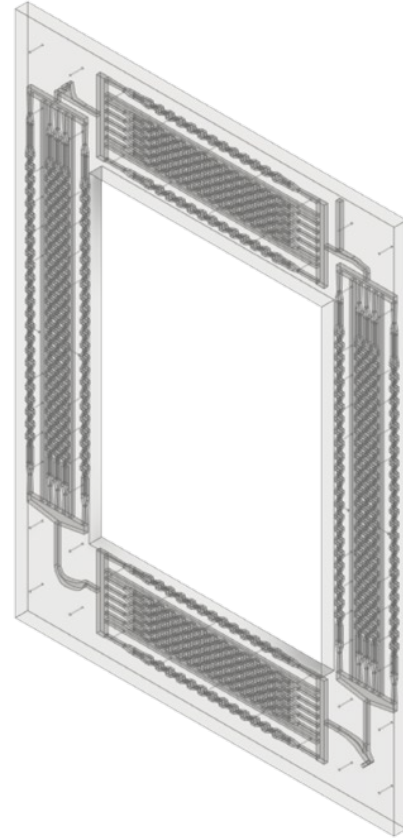


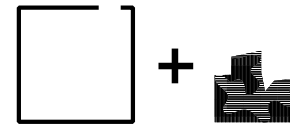
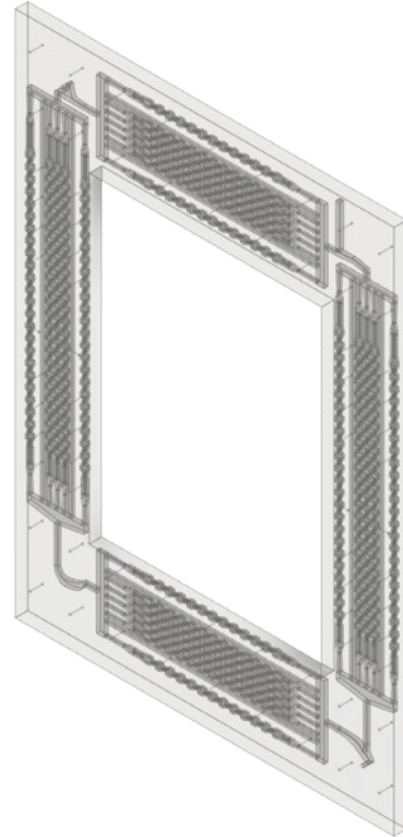
WAX 3D printed

Panel

network geometry formwork

formwork





External + 3D printed wax
internal formwork

1



Cast with concrete between
both form work

2



Solid cast with internal wax
form work

3



Melt out internal form work

4



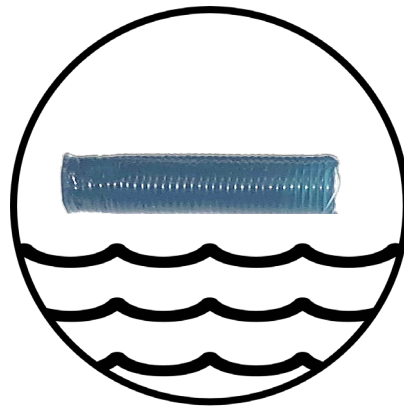
Final
product

5

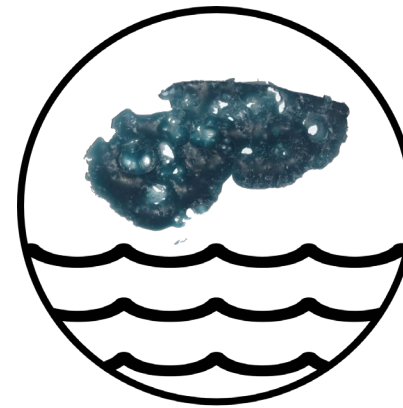


Burning temp. > 290 °C





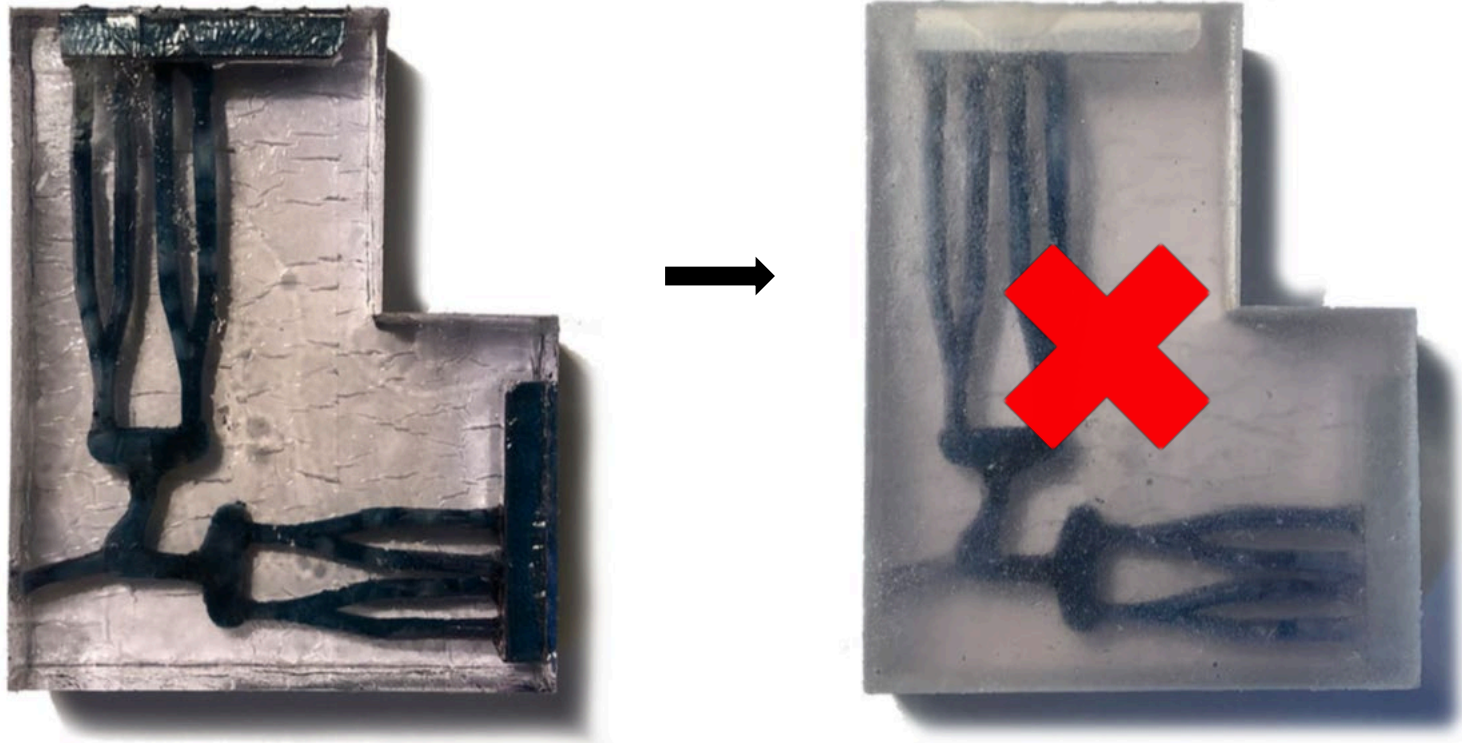
100 °C



120 °C

(pressurised)

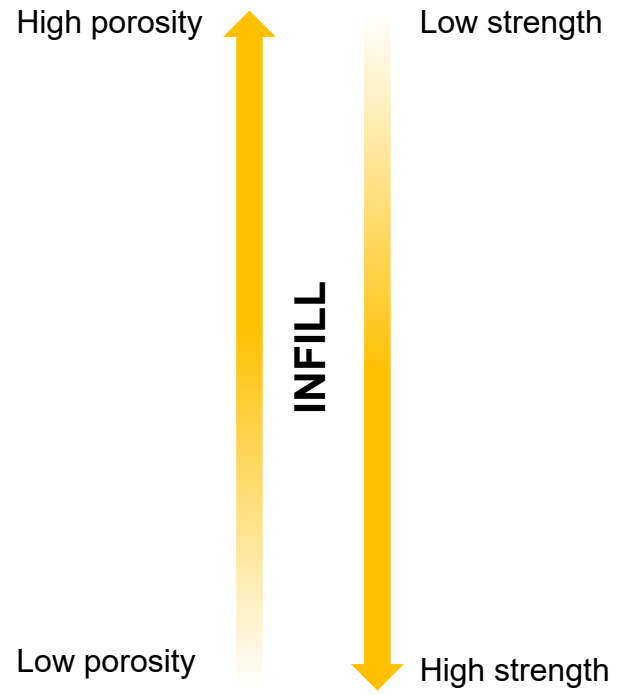
Wax filament
Melting temp: 117 °C



Inference: Infill needed for hot water to pass through

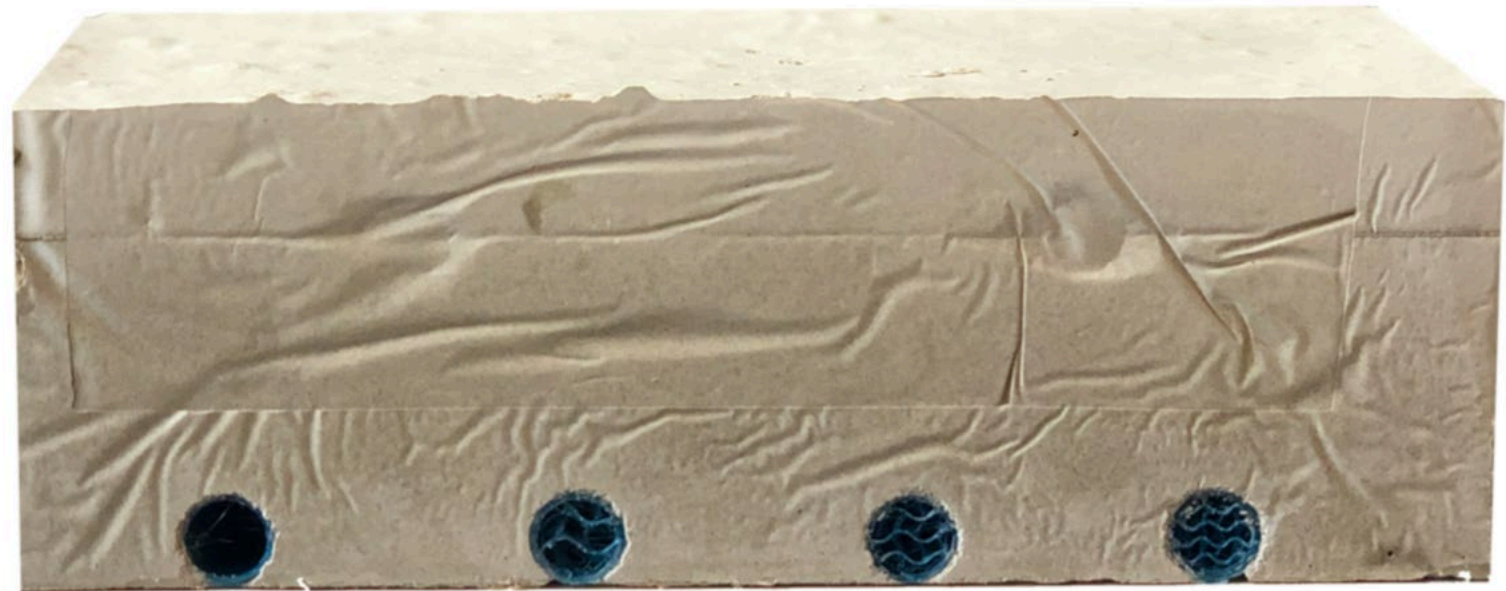
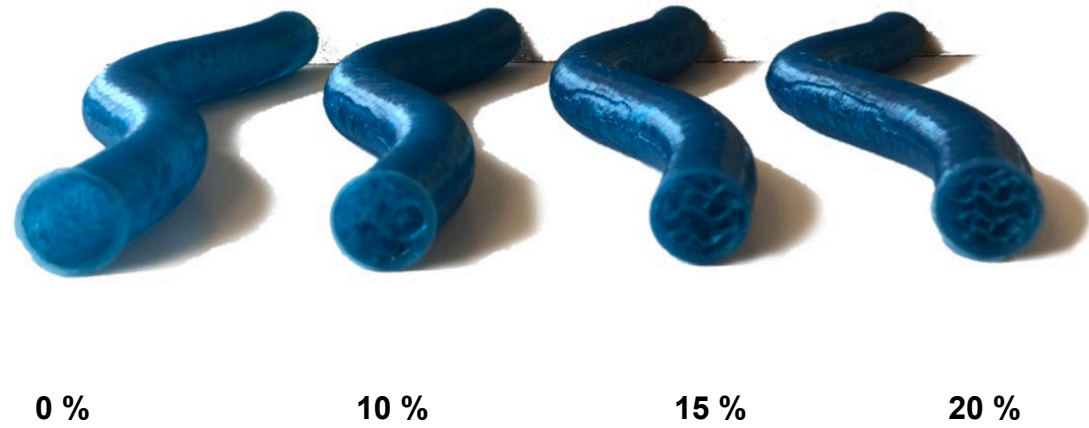
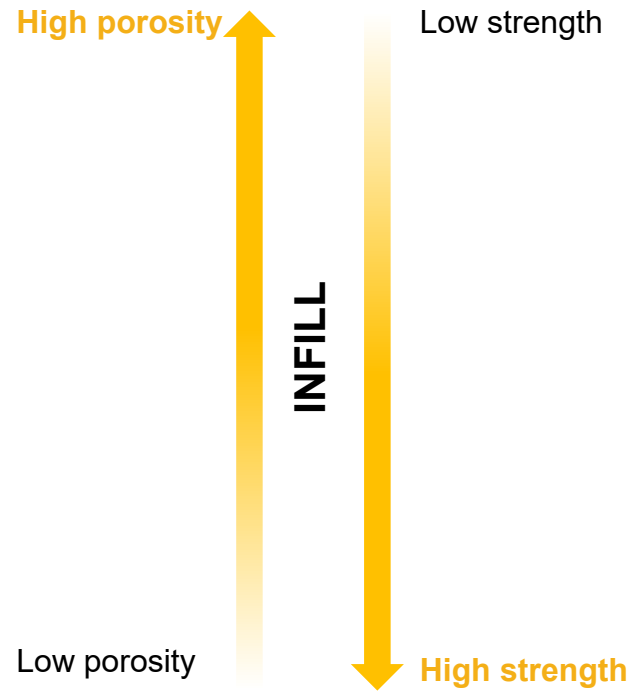
FABRICATION METHOD

Infill



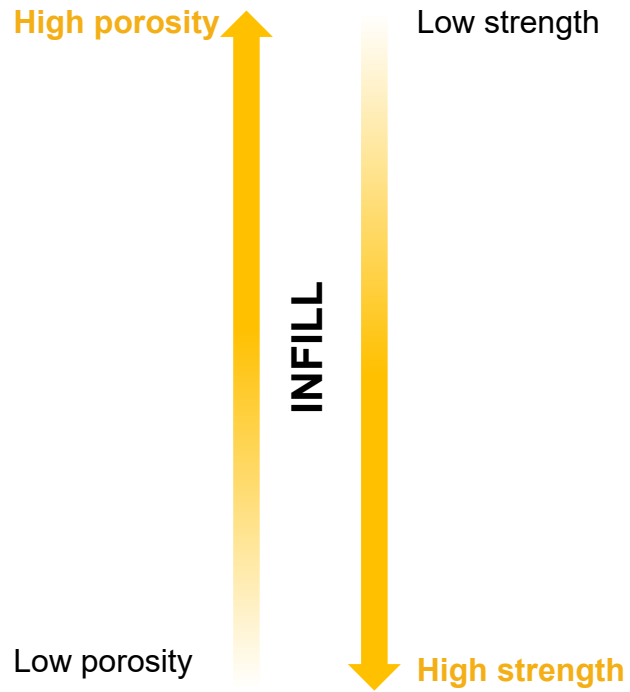
FABRICATION METHOD

Infill

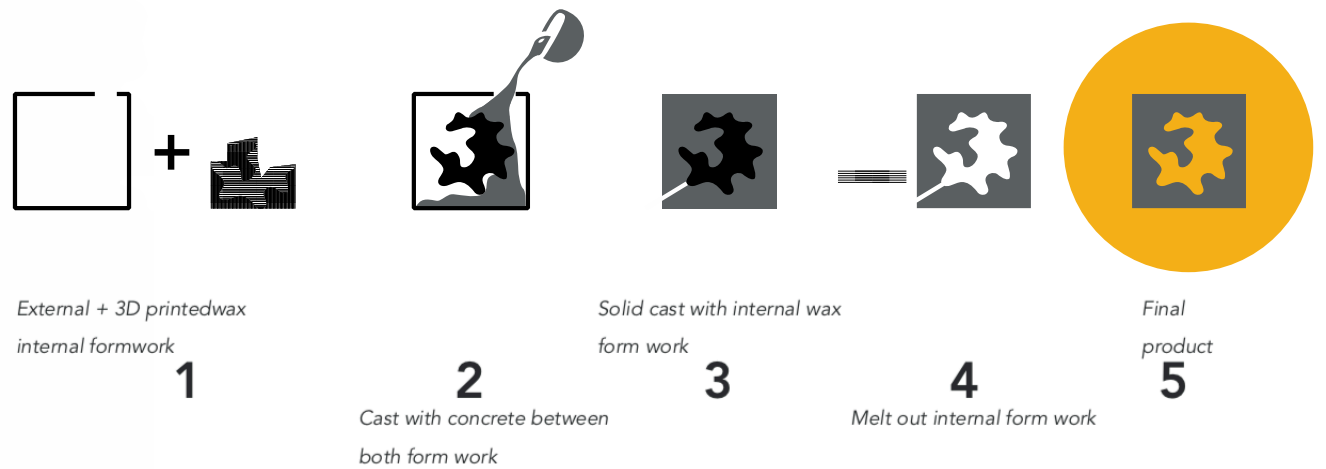
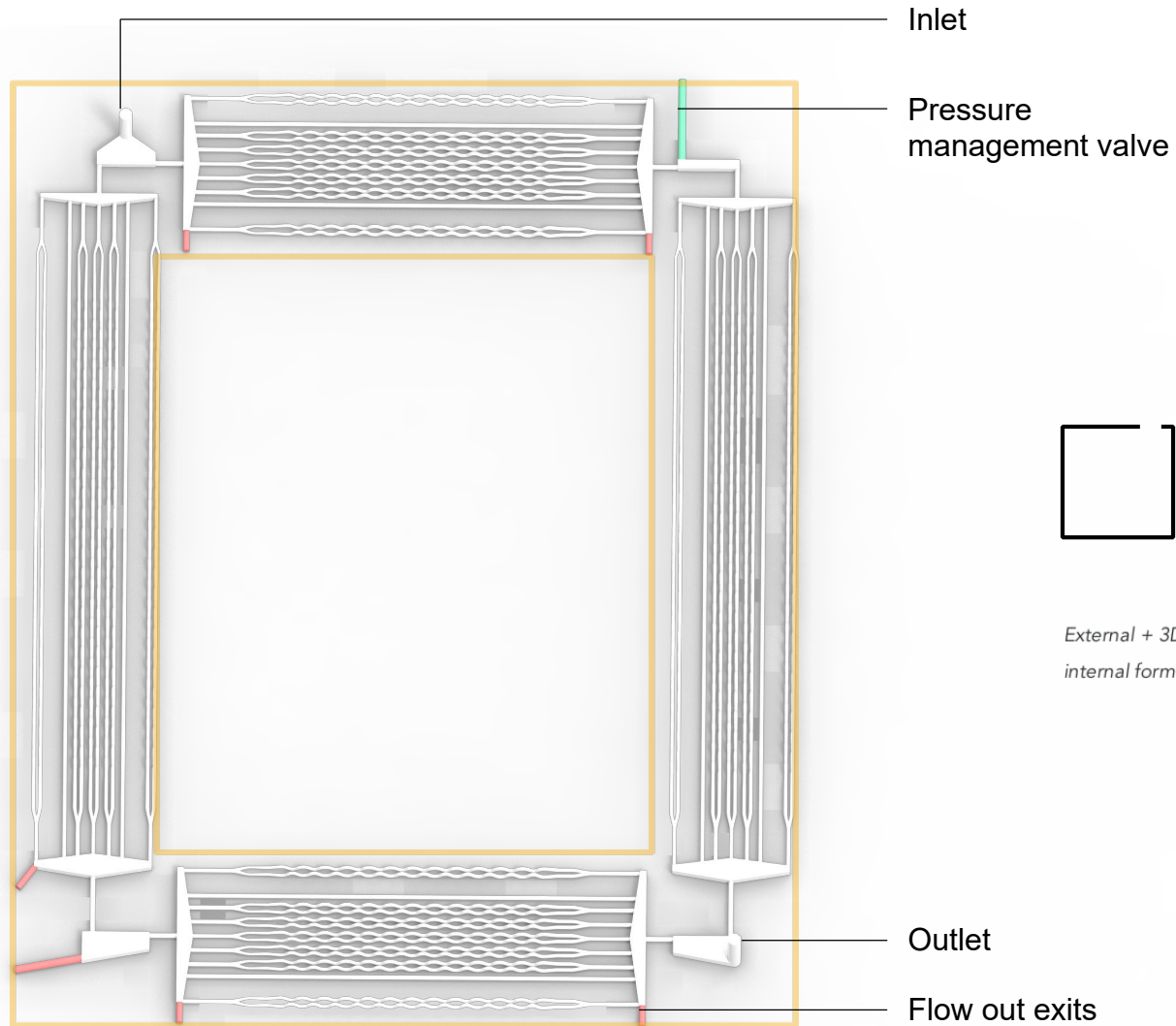


FABRICATION METHOD

Infill



FABRICATION METHOD



PERFORMANCE

MATERIALS

STRUCTURE

DESIGN

FABRICATE

MAXIMISE POTENTIAL

PERFORMANCE

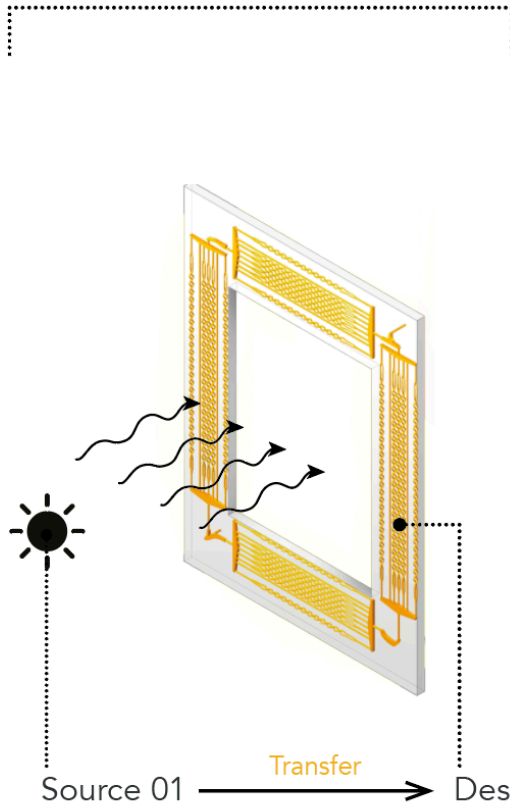
① Maximise surface area

② Maximise void volume

③ Minimise pressure drop

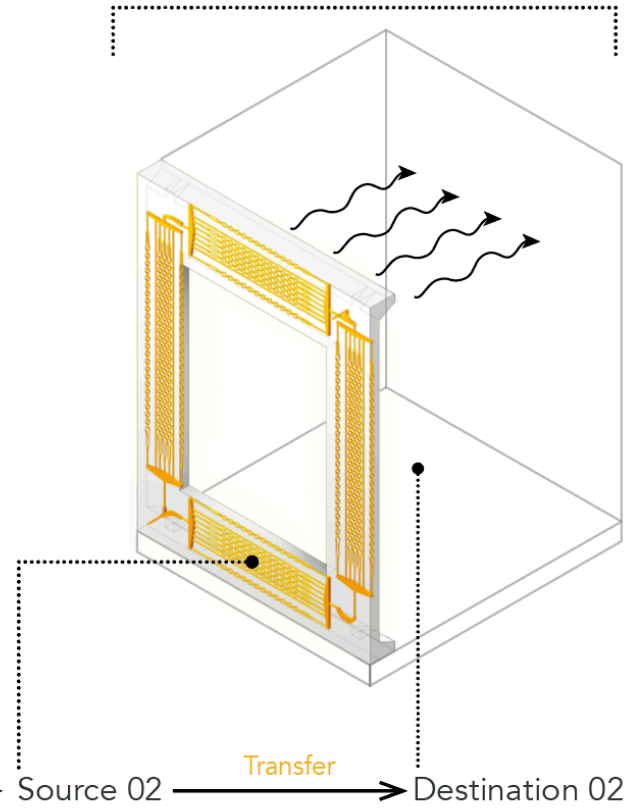
PERFORMANCE

INSTANCE 01



WINTER SOLSTICE

INSTANCE 02



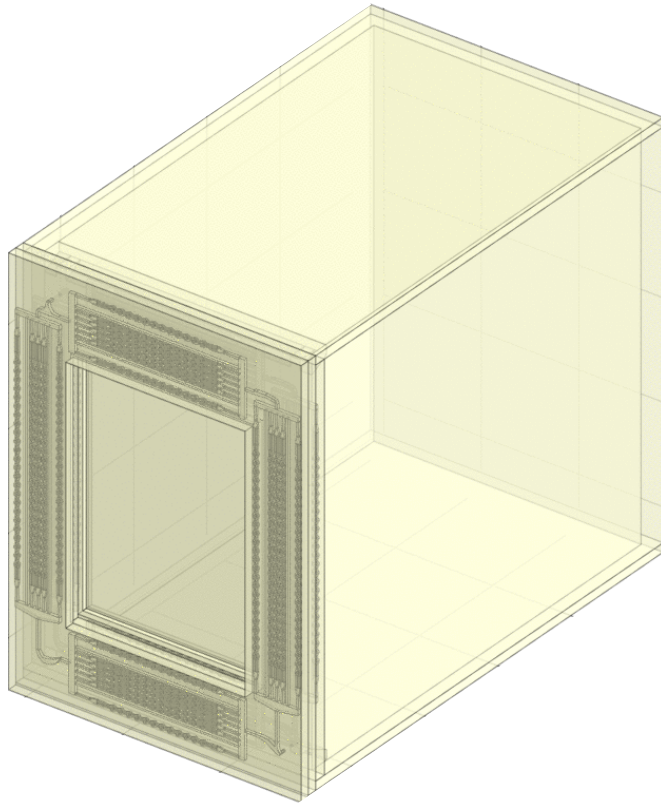
Increase surface area



Maximise void volume



Minimise pressure drop



Time=0 min

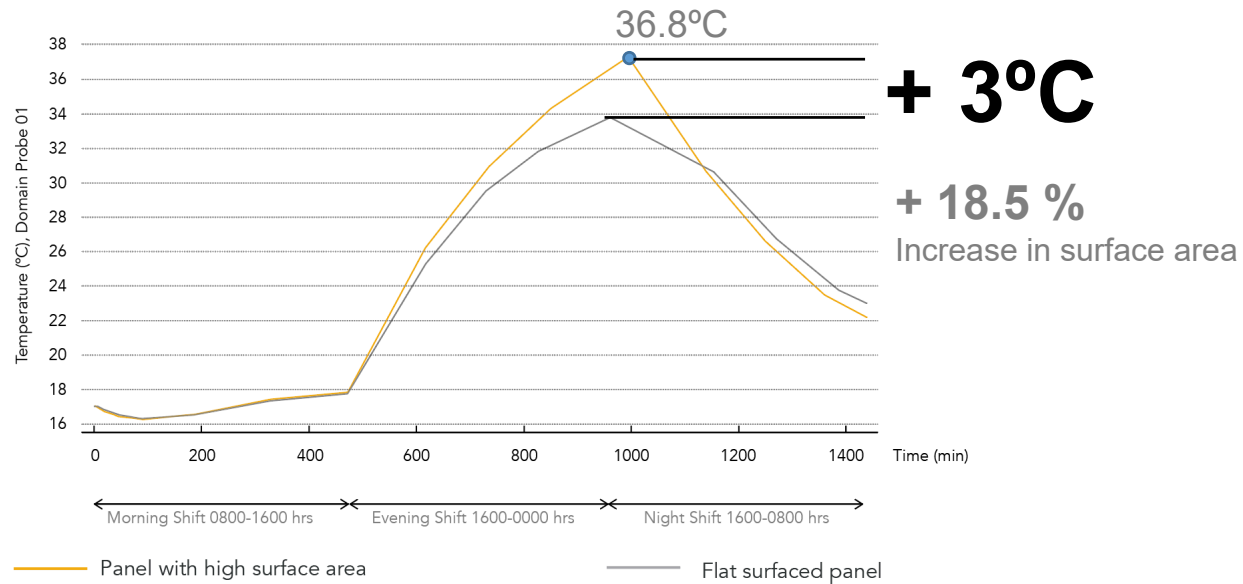


Increase surface area

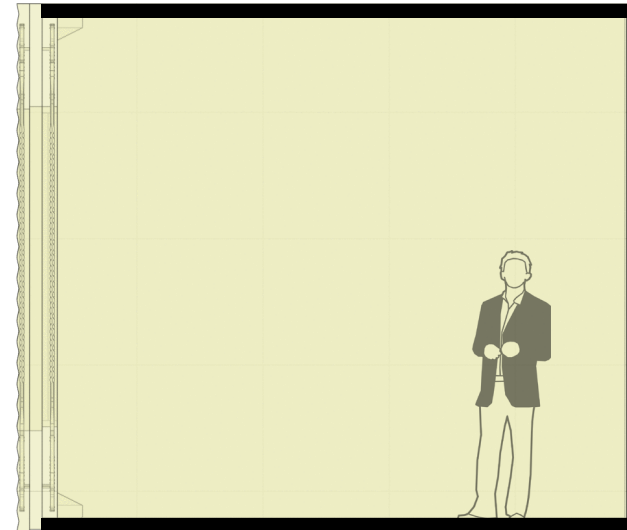
Maximise void volume

Minimise pressure drop

Time=0 min

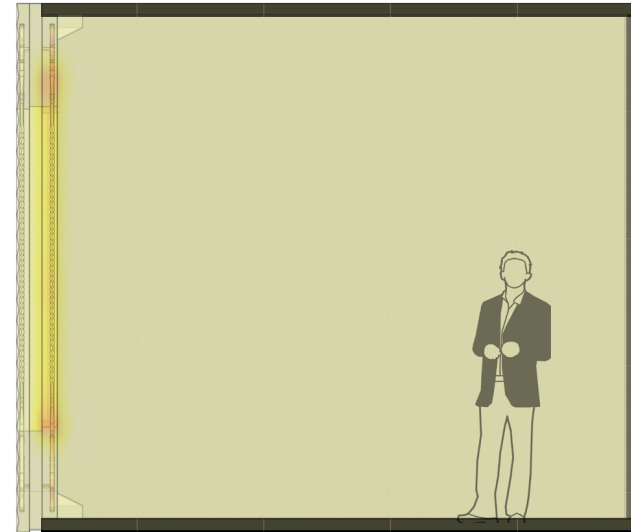


PANEL with MODIFIED SURFACE



- Increase surface area
- Maximise void volume
- Minimise pressure drop

Time=0 min



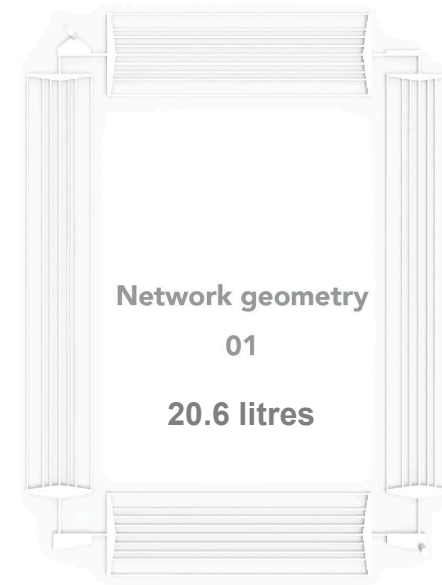
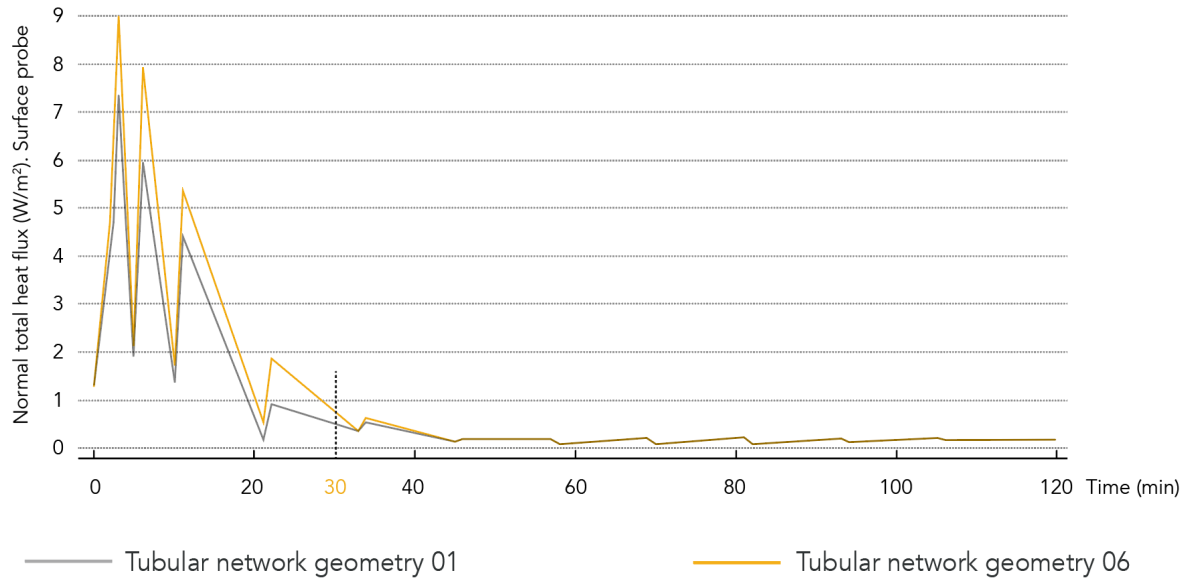
Increase surface area



Maximise void volume



Minimise pressure drop



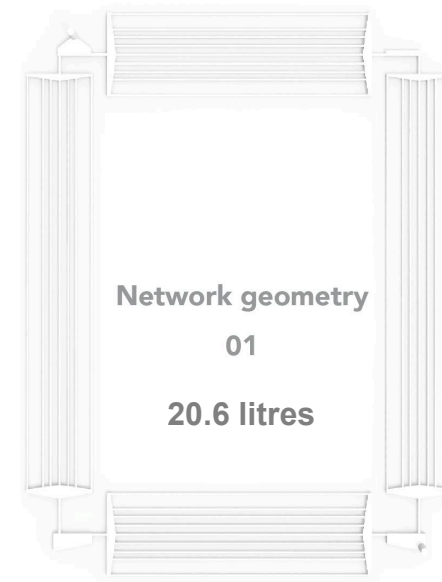
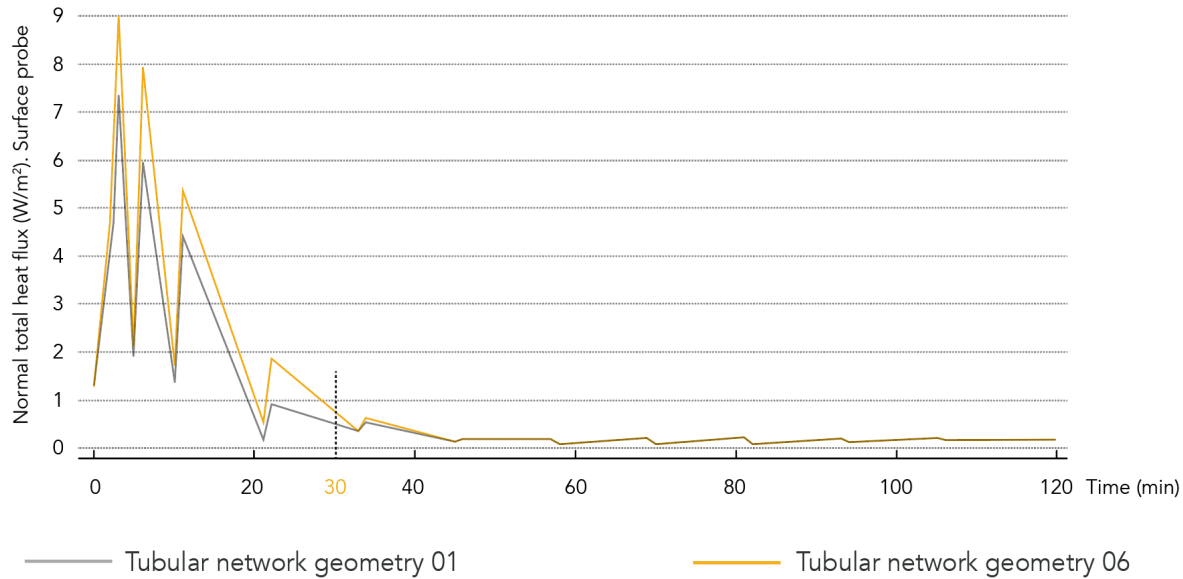
○ Increase surface area

○ Maximise void volume

○ Minimise pressure drop

PERFORMANCE

INSTANCE 02



+ 36.4 %
Increase in volume

+ 39.7 %
Increase in amount of heat transmittance

○ Increase surface area

● Maximise void volume

○ Minimise pressure drop

PERFORMANCE

96.8 W/m² per 0.5 hours

Without heat management

16.6 W/m² – 6 hours

With heat management



Increase surface area



Maximise void volume



Minimise pressure drop

PERFORMANCE


96.8 W/m² per 0.5 hours
Without heat management

Cycle – every 18 to 30 minutes

16.6 W/m² – 6 hours
With heat management

Supply – for 2 working shifts

(* Approximated)

 Increase surface area

 Maximise void volume

 Minimise pressure drop

INSTALLATION



INSTALLATION

3-point Tilt-up lifting system



INSTALLATION



INSTALLATION



INSTALLATION



INSTALLATION



INSTALLATION

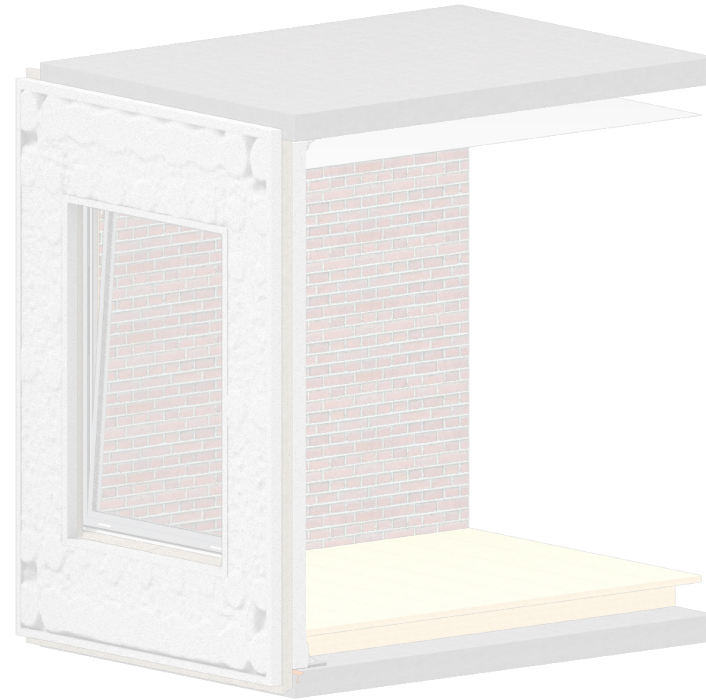


INSTALLATION

High insulated water tank + pumps

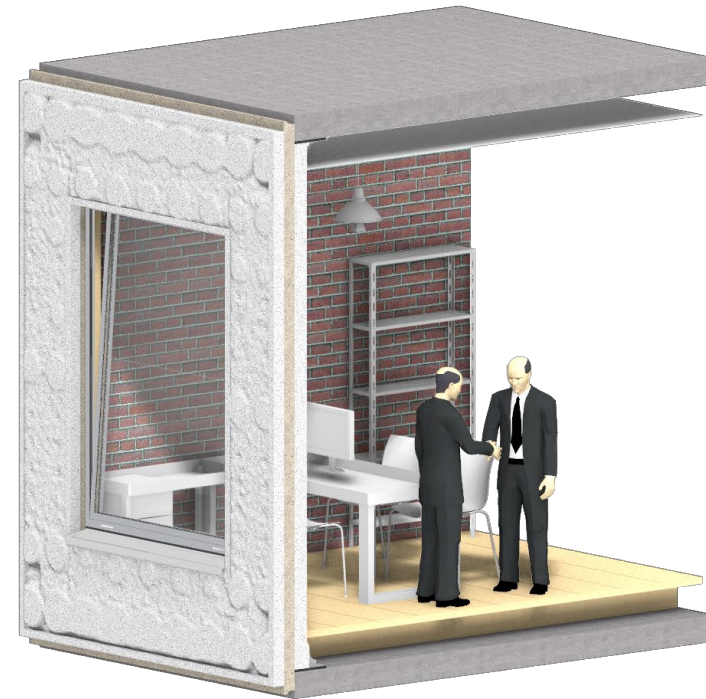


- _____ Damping butyl strip
- _____ Brackets



THERM_VENATION
PREFABRICATED FAÇADE SYSTEM

INSTALLATION



PANEL OPTION 01



PANEL OPTION 02



PANEL OPTION 03



INTERIOR OPTION 01



INTERIOR OPTION 02



CONCRETE, WATER, WAX



SUMMARY

CONCRETE, WATER, WAX



TWIN WALL SYSTEM +
STRUCTURE



SUMMARY

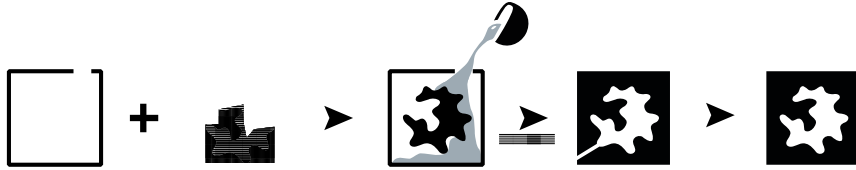
CONCRETE, WATER, WAX



TWIN WALL SYSTEM +
STRUCTURE



WAX 3D PRINTING +
INVERSE INVESTMENT CASTING



SUMMARY

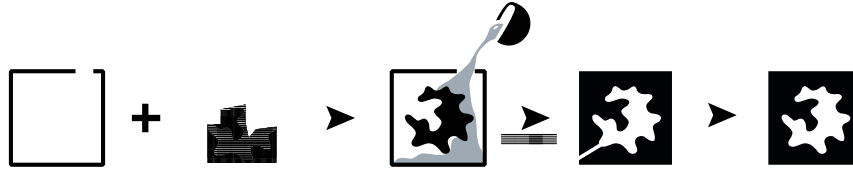
CONCRETE, WATER, WAX



TWIN WALL SYSTEM +
STRUCTURE



WAX 3D PRINTING +
INVERSE INVESTMENT CASTING



MAXIMISING VOLUME +
MINIMISING PRESSURE DROP



SUMMARY

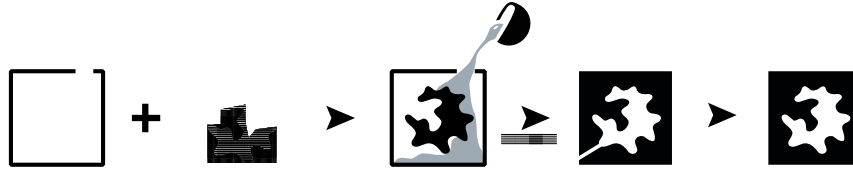
CONCRETE, WATER, WAX



TWIN WALL SYSTEM +
STRUCTURE



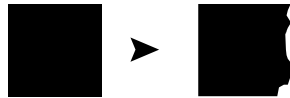
WAX 3D PRINTING +
INVERSE INVESTMENT CASTING



MAXIMISING VOLUME +
MINIMISING PRESSURE DROP



MAXIMISING SURFACE AREA



SUMMARY

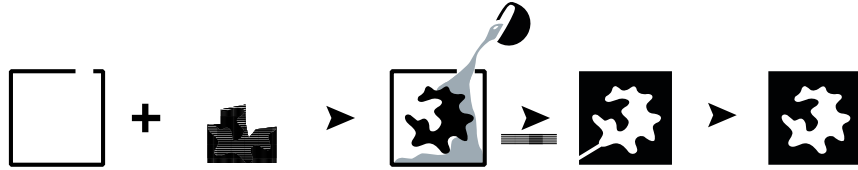
CONCRETE, WATER, WAX



TWIN WALL SYSTEM +
STRUCTURE



WAX 3D PRINTING +
INVERSE INVESTMENT CASTING



MAXIMISING VOLUME +
MINIMISING PRESSURE DROP



MAXIMISING SURFACE AREA



IMPROVING INSULATION



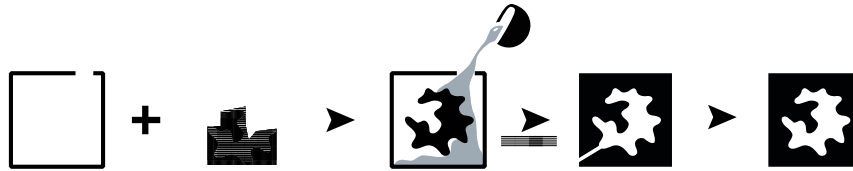
CONCRETE, WATER, WAX



TWIN WALL SYSTEM +
STRUCTURE



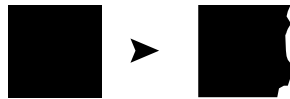
WAX 3D PRINTING +
INVERSE INVESTMENT CASTING



MAXIMISING VOLUME +
MINIMISING PRESSURE DROP



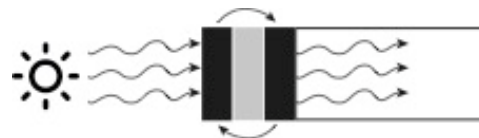
MAXIMISING SURFACE AREA



IMPROVING INSULATION

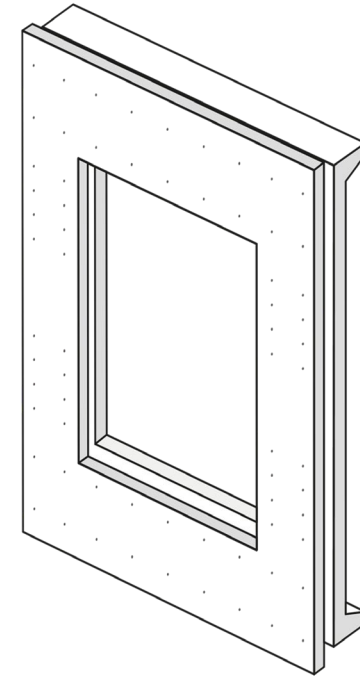


PERFORMANCE



1 Inactive façade

2 1300 kg Carbon footprint



PROPOSED

1

Active façade

with heat exchange system

Harvests solar energy

Responds to local climate

33 W/m² /hr of heating
for two working shifts

18-30 minutes exchange cycle

2

Highly insulating

0.95 W/m² , ECBC + compatible

3

Saving material use

618 kg of material reduction

4

Carbon footprint reduction

77% reduction

5

Modular

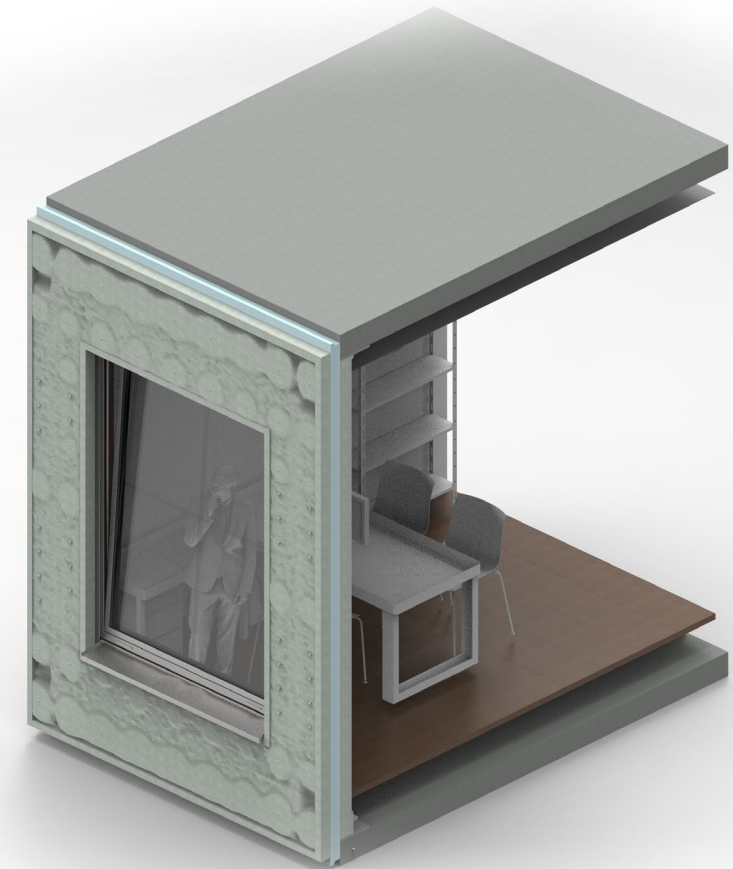
4 Point mounting

6

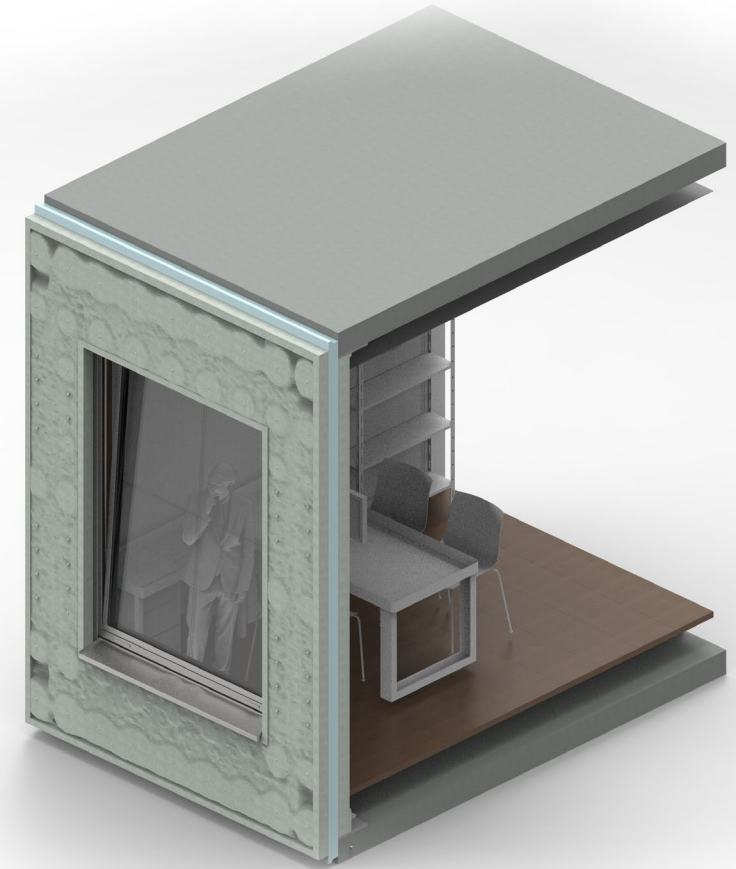
Minimising energy needs of building

Step to **save the nature**

CONCLUSION



1. Examine energy savings
2. Effect of heat on pressure drop
3. Non-planar façade panels
4. Commercial method
5. Effective valuation



The future will be green, or not at all

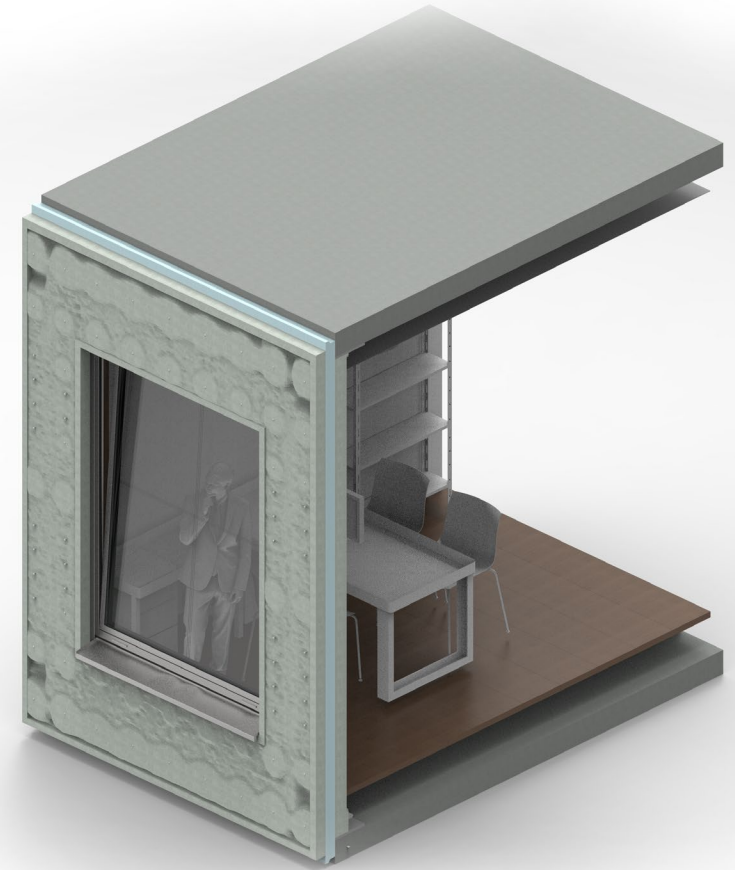
Sir Jonathon Porritt, British environmentalist

Let's

Learn from nature

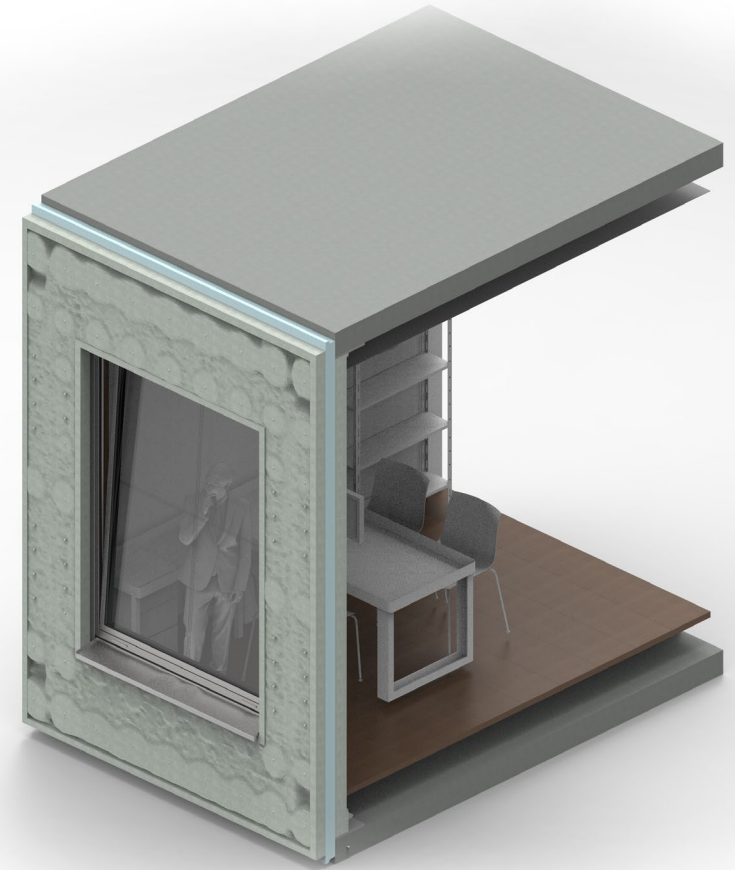
Respond to nature

Save the nature



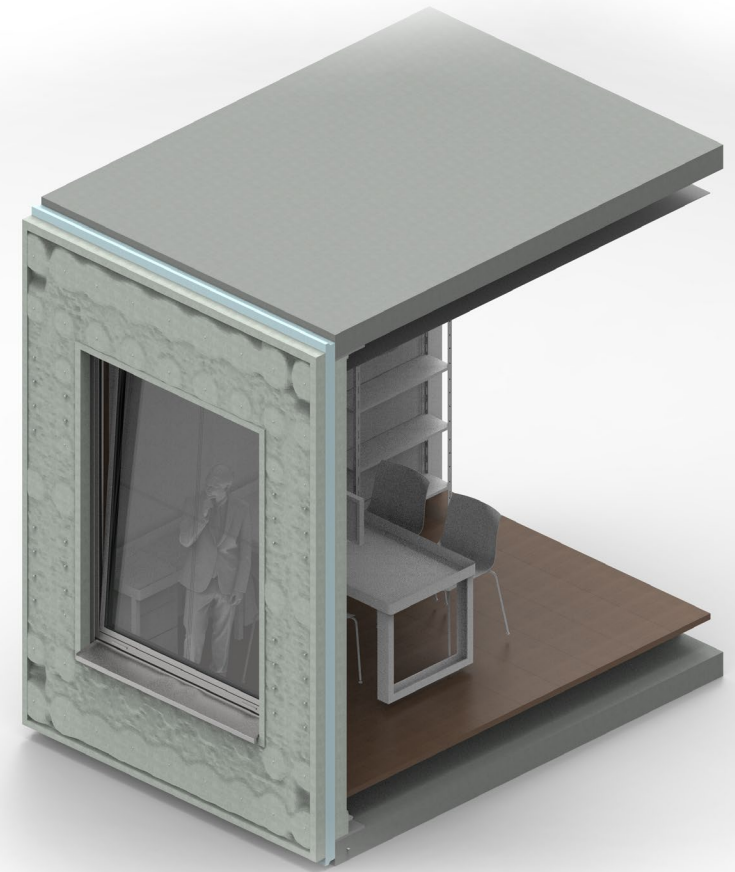
THERM VENTATION

Thank You



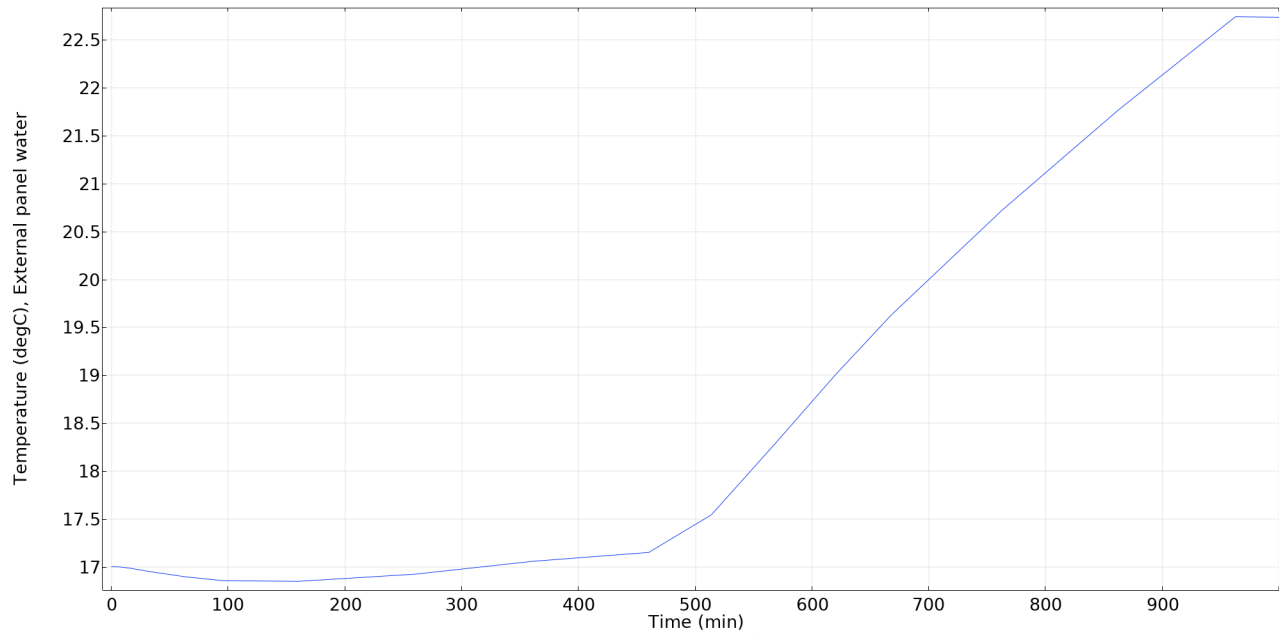
THERM VENTATION

Thank You



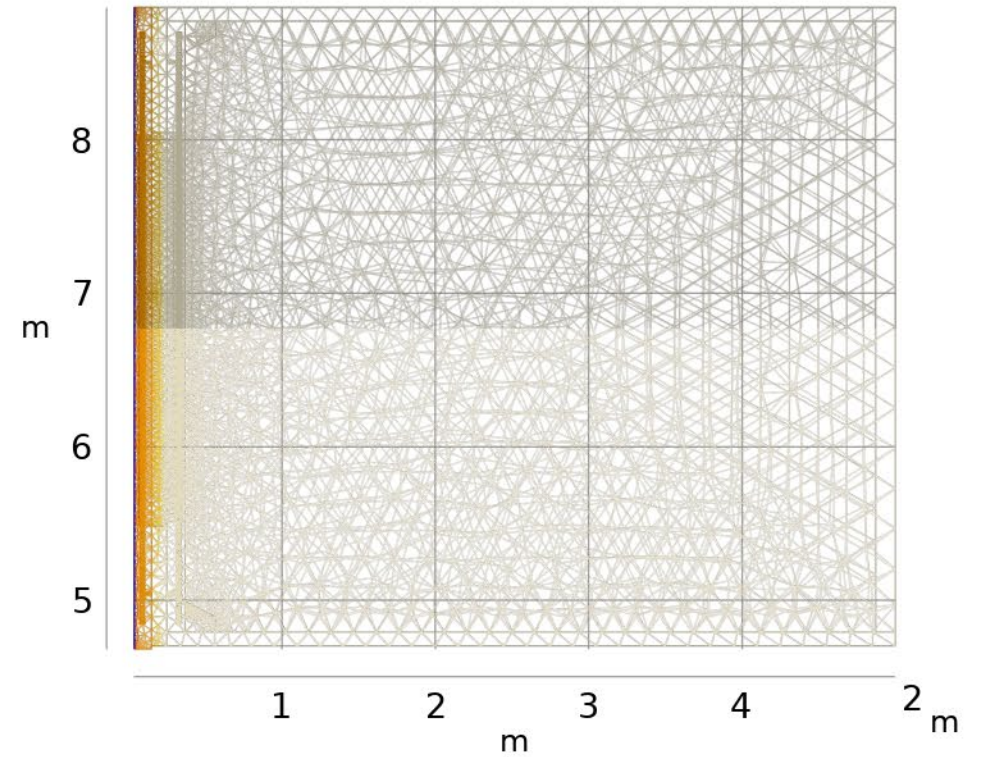
SYSTEM - concept

Time=1000 min

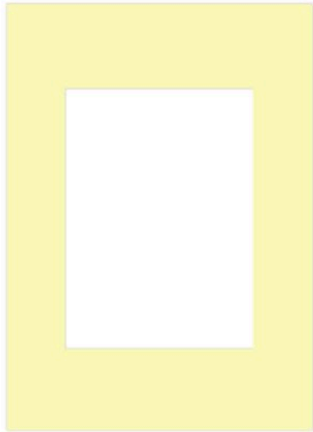


Surface: Temperature (degC)

FAÇADE WITH METAL CLADDING



Flat
external facade panel



Summer solar radiation =
1713.72 kWh.m²

Topology optimised
external facade panel



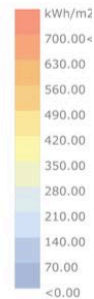
Summer solar radiation =
1693.70 kWh.m²



Winter solar radiation =
4523.10 kWh.m²



Winter solar radiation =
4360.16 kWh.m²

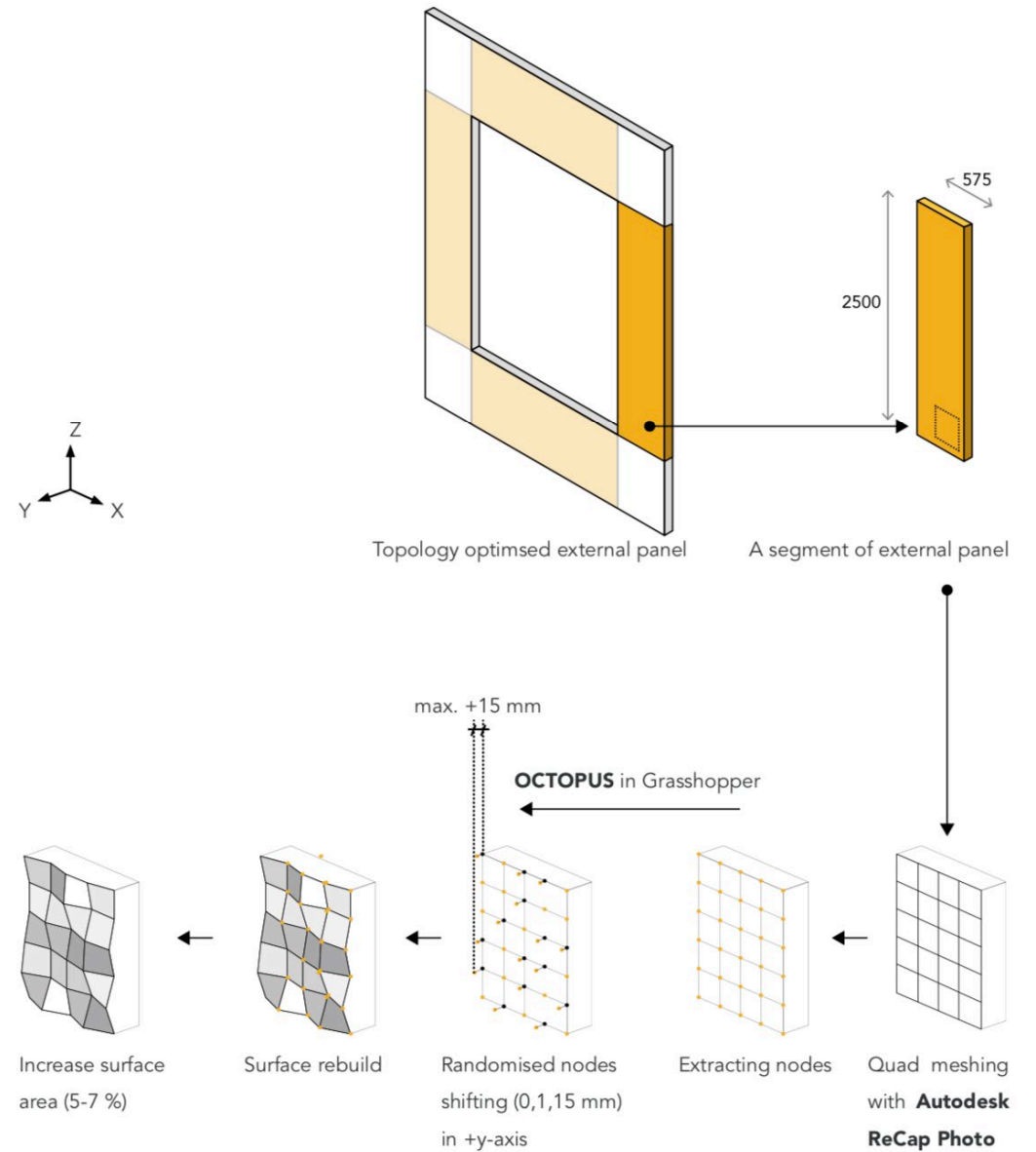


0800 hrs to 1800 hrs
facing South in Delhi, India

- 1.1 %
decrease in summer
solar radiation

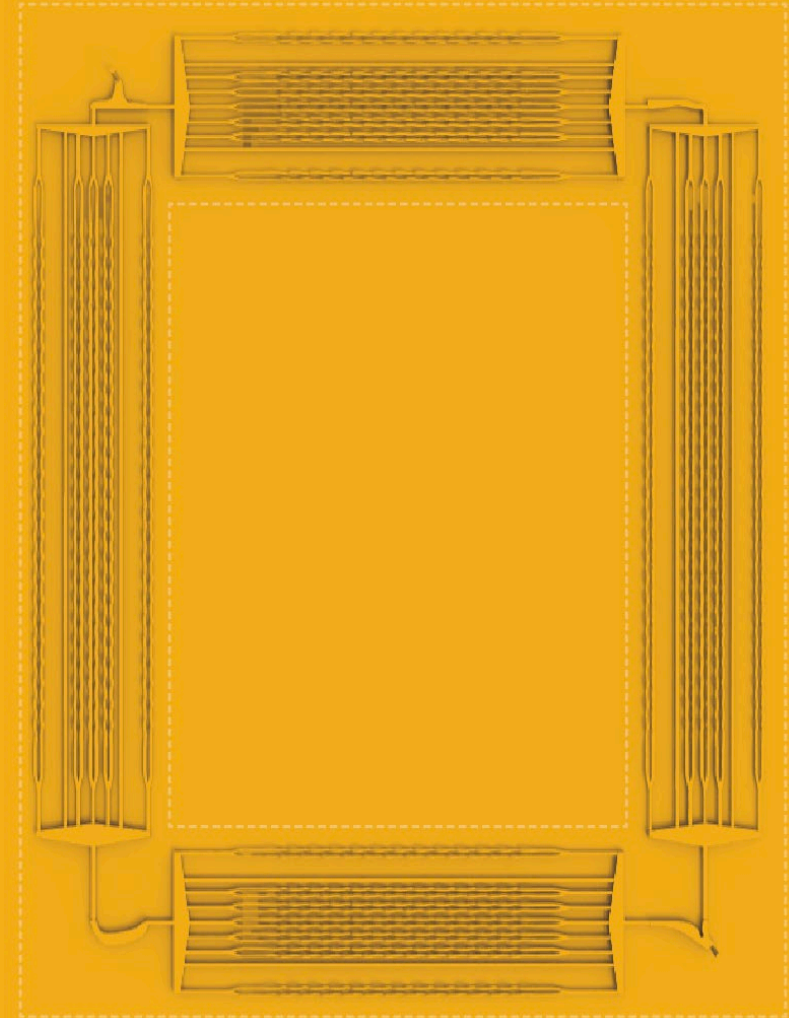
- 3.6 %
decrease in wintersolar
radiation

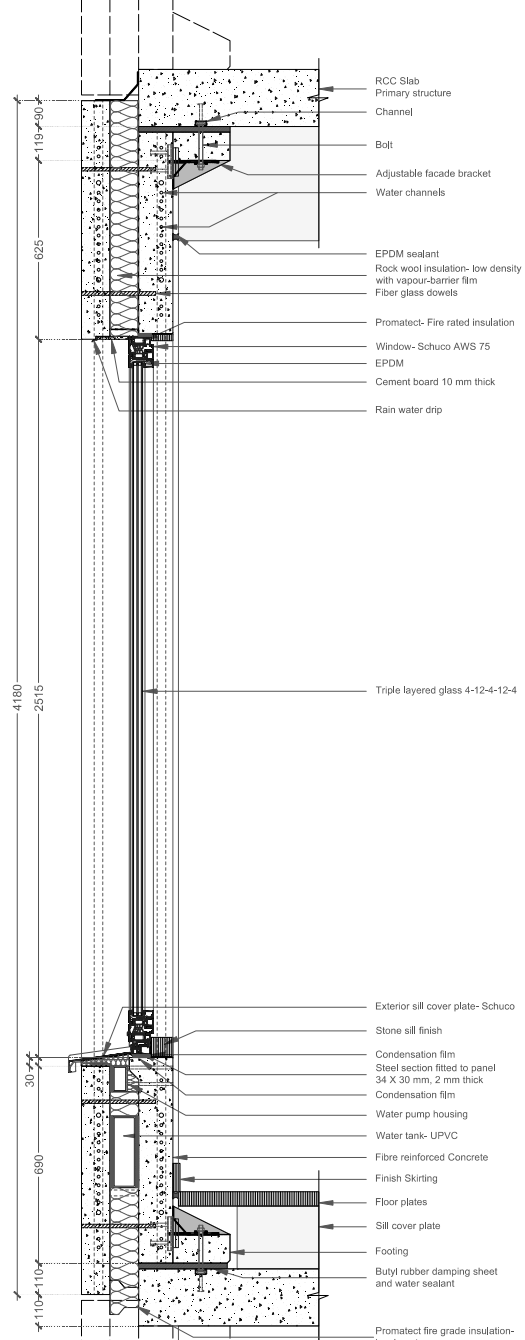
Step 02 Surface Modification



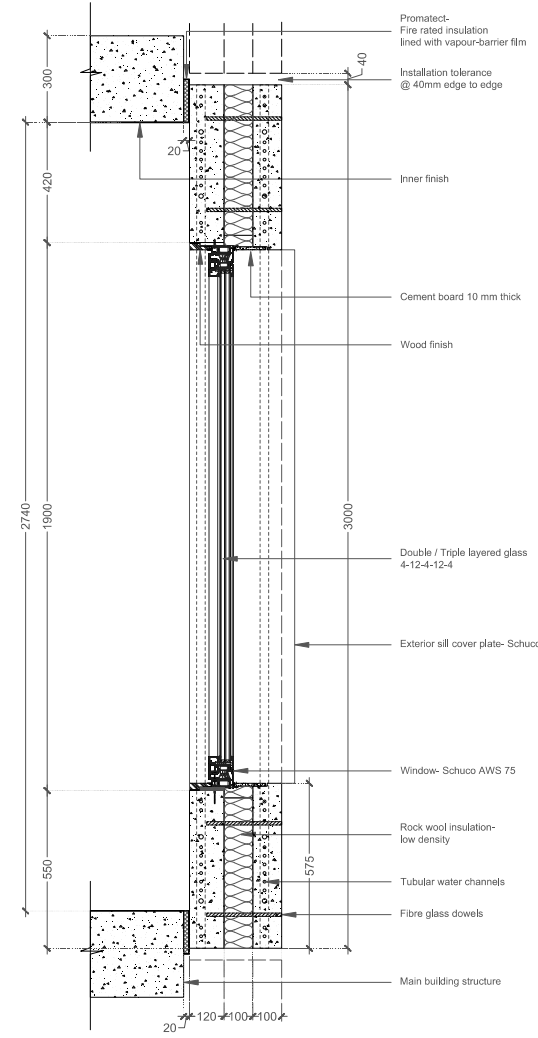
Network Geometry 06

Network Geometry	Change in diameter	Chanel network	Tube profile	Node optimisation	Total Network volume	Change in volume	Total pressure drop	Change in pressure drop
1	○○○	⌈		×	20.6 litres	NA	1235.34 Pa	Na
2	○○●	⌈		×	22.53 litres	+ 9.2 %	1167.96 Pa	+ 5 %
3	○○●	⌈		×	30.13 litres	+ 46 %	1332.34 Pa	+ 7.8 %
4	○○●	⌈	⌚	×	31.25 litres	+ 51.4 %	1463.10 Pa	+ 18.4 %
5	○○●	⌈	⌚	×	29.41 litres	+ 42.7 %	1319.69 Pa	+ 6.8 %
6	○○●	⌈	⌚	✓	28.11 litres	+ 36.4 %	62.51 Pa	- 94.9 %

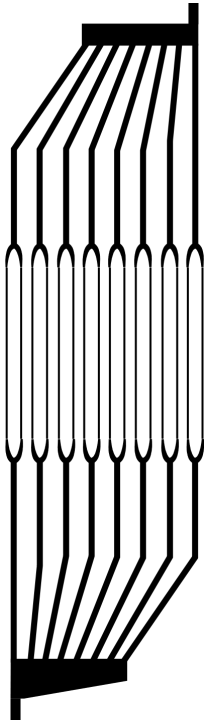




SECTION



PLAN



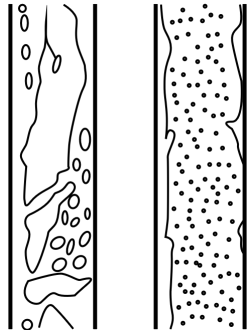
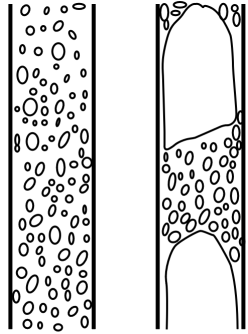
Spong3D

Sarakinioti, Turrin, Konstantinou, & Tenpierik (2018)



Inference: Heat transfer of water by convection





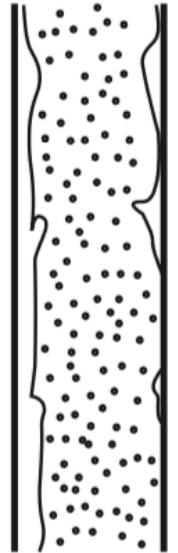
Bubble



Slug



Churn



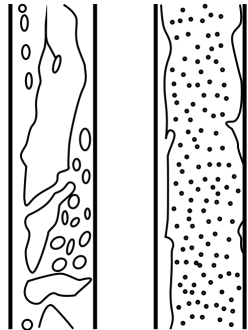
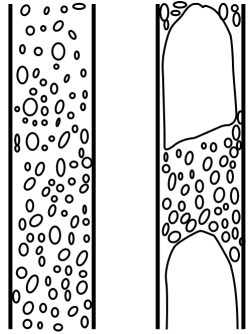
Annular

Flow patterns

Omebere- Iyari & Azzopardi (2007)

Inference: **Water flow in small diameter tubes & Pressure management**

SYSTEM - concept



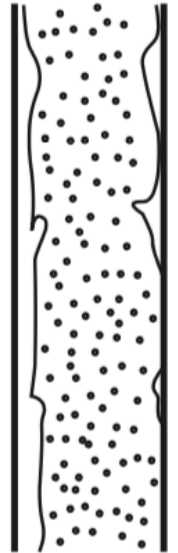
Bubble



Slug



Churn



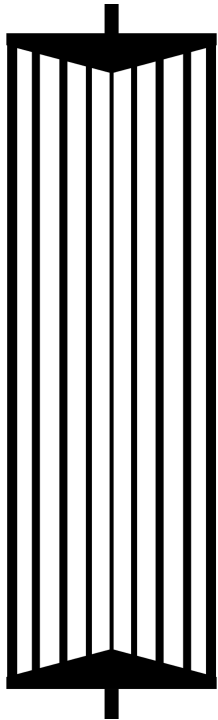
Annular

Flow patterns

Omebere- Iyari & Azzopardi (2007)

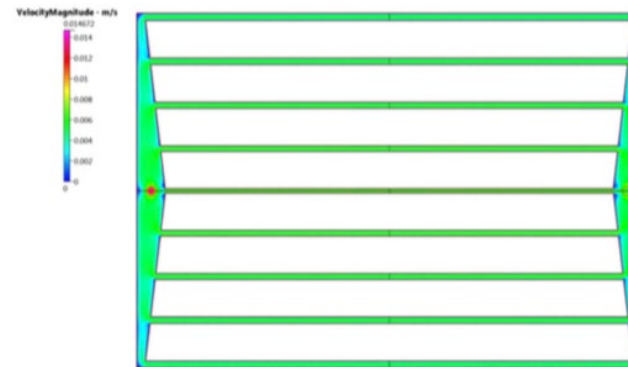
Inference: Fluid flow : Laminar
Fluid exchange time : 18 minutes

SYSTEM - concept

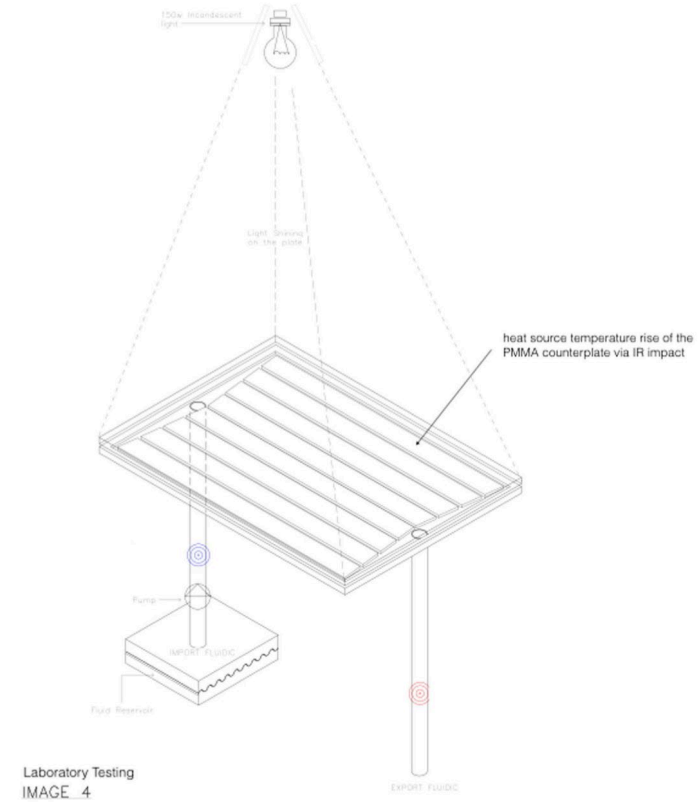


Leaf venation

Alston & Barber (2016)



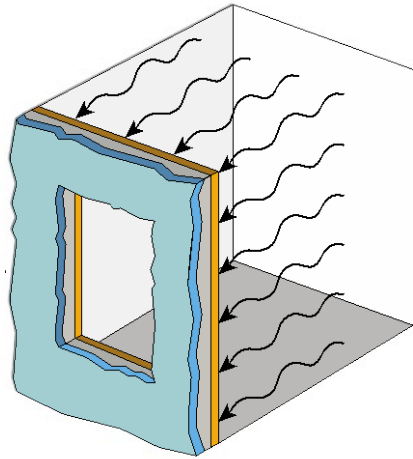
Inference: **Pressure management & Geometry**



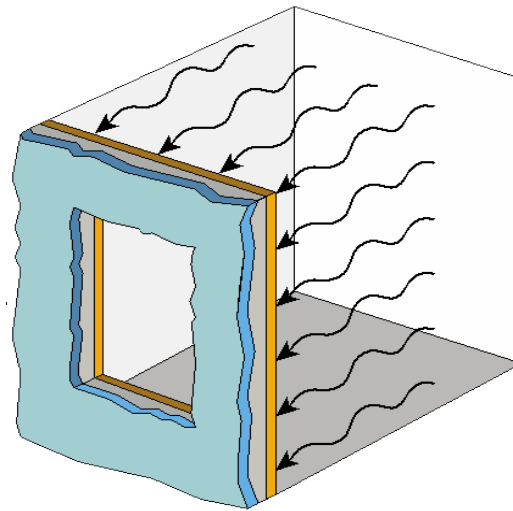
SYSTEM



NIGHT



DAY



Summer with hot days and hot nights