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

From the ground up:

Robotic Additive Manufacturing (RAM) of a structurally optimized earthen shell through computational design

themes:

- Robotic Additive Manufacturing (RAM)
- Structural Design Optimization
- Sustainable materials Innovation

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Tutors:

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Delegate examiner:

Dr. Andrej Radman

- Introduction
- Research by Design >>> Robotic fabrication workflow
- Design by Research >>> Digital design & Robotic simulation workflow
- Case study
- Conclusion
- Recommendations

adapted from source: United Nations Sustainable Development, (2019)

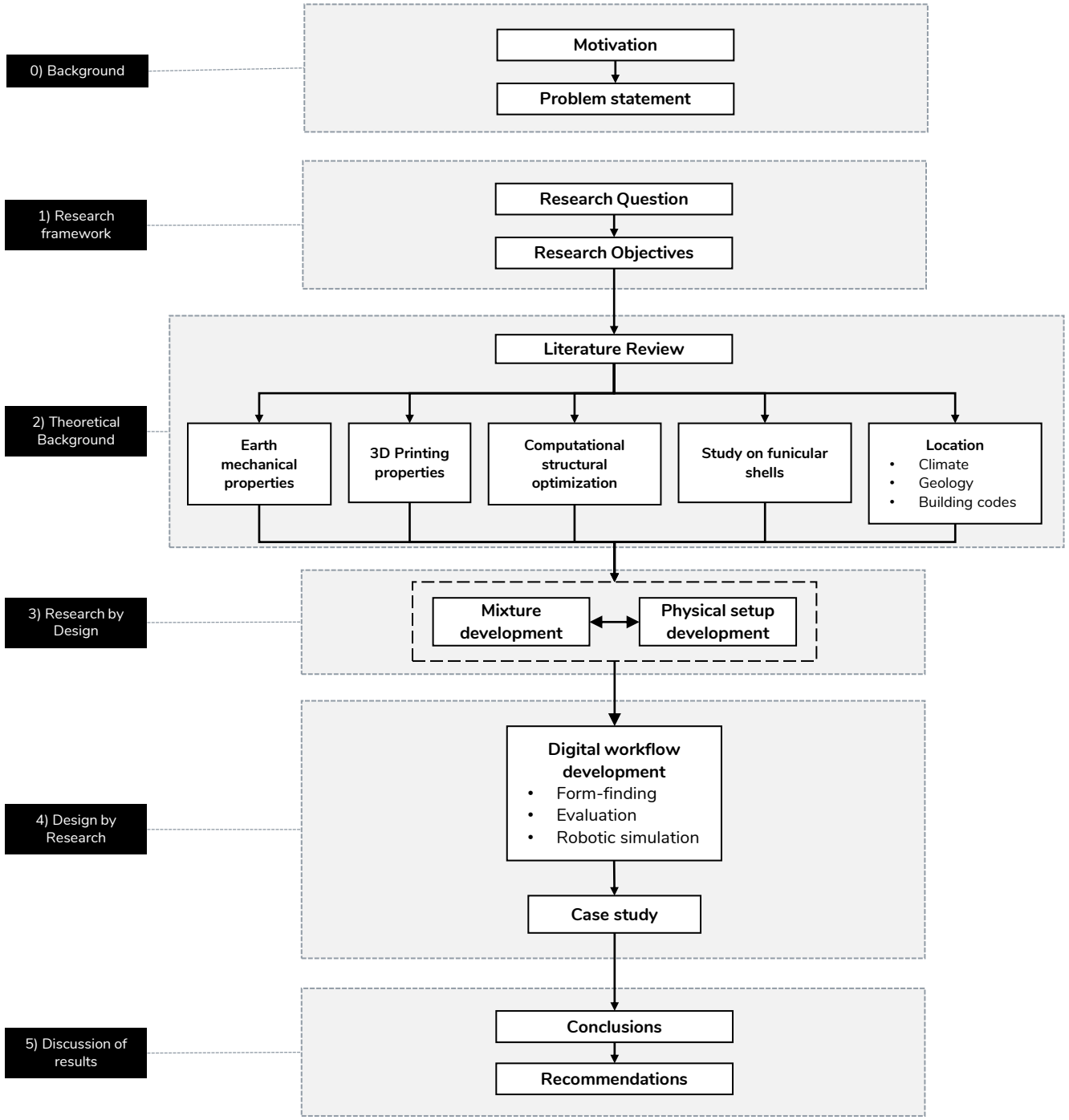
- Cost and energy of transportation and operation
- Energy intensive materials (non-local)
- Affordability in construction

- Material waste (e.g. formwork, demolition waste)
- Outdated production techniques (compared to other industries)
- Sub-optimal design (rationalisation)

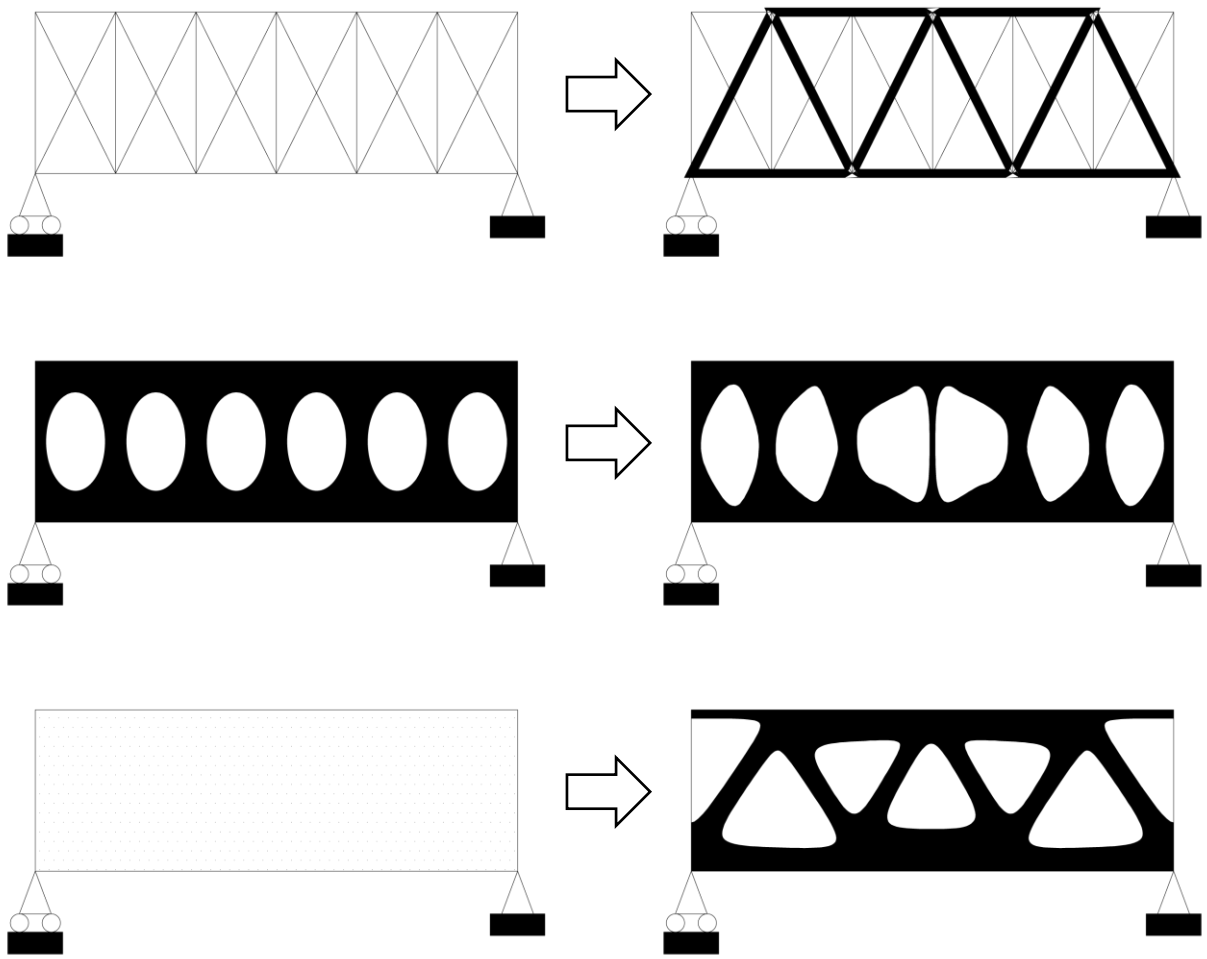
“How to develop a design to fabrication workflow for a structurally optimized shell towards robotic additive manufacturing by earth?”

Sub-Questions

1. What are the advantages and limitations of using earth in RAM? What is the effect of material parameters (mixture design /kiln /drying time) in the mechanical properties of the component and what are the required material qualities for the proposed setup?
2. What are the design and performance criteria involved in designing a robotically 3D printed component out of earth? What is the effect of printing parameters (infill, layer height & direction, extrusion speed)?
3. What is the projected cost and environmental impact of the proposed construction?

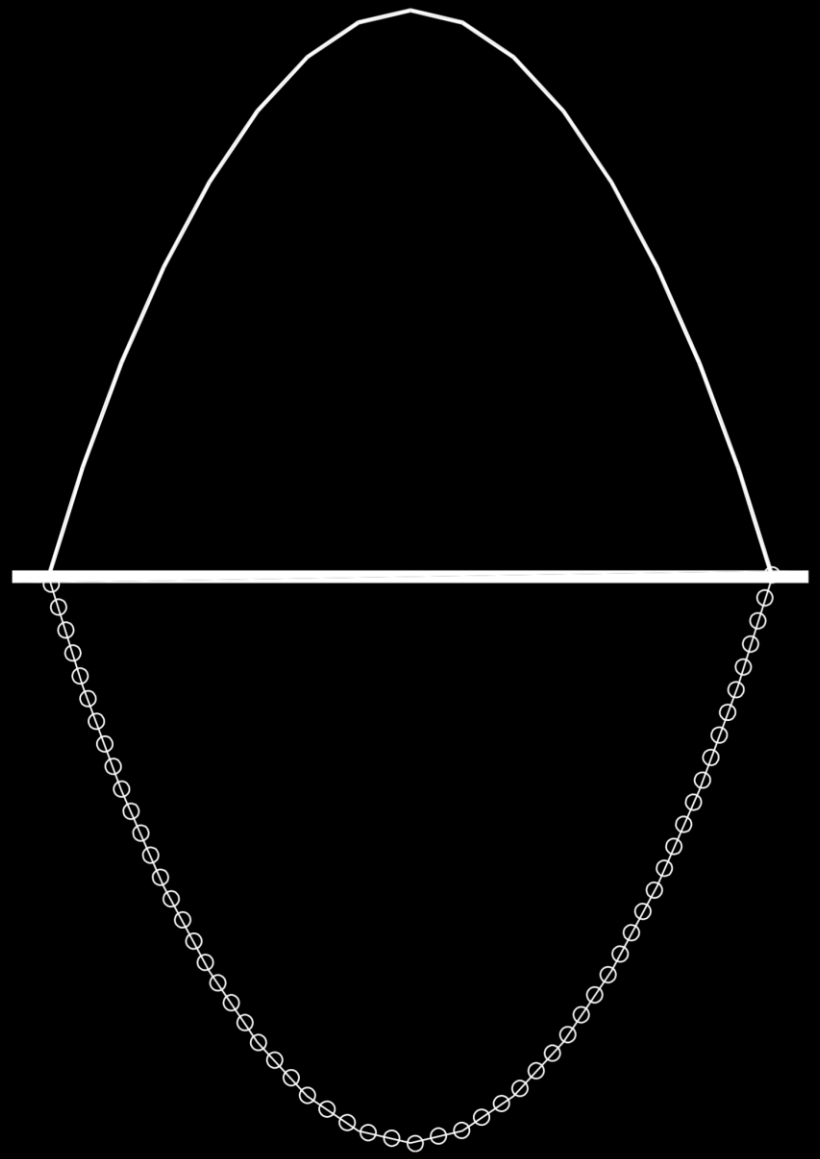

0) Background
Motivation
Problem statement
1) Research framework
Research Question
Research Objectives
2) Theoretical Background
Literature Review
Earth mechanical properties
3D Printing properties
Computational structural optimization
Study on funicular shells
Location
Climate
Geology
Building codes
3) Research by Design
Mixture development
Physical setup development
4) Design by Research
Digital workflow development
Form-finding
Evaluation
Robotic simulation
Case study
5) Discussion of results
Conclusions
Recommendations

				effects
Structural Parameters	Strength Parameters	Compressive Strength	Force vertical to cross section	dimensioning
		Tensile Strength βT	Cohesive strength	Wet (preparation)
				dry
			Splitting tensile strength	Shock resistance (quality control)
			Tensile adhesion strength βTA	Mortar adhesion
			Flexural strength	Load perpendicular to plane (bending)
		Buckling strength	Plastic buckling	Overhangs
		Shear strength	Internal stresses from horizontal loads	Load parallel to joint
		Torsional strength	Twisting load	Overhangs, Extruder motor
	Deformation Parameters	Load-Independent	Thermal strains	Expansion (+)
			Moisture strains (reversible)	Shrinking (-)
				Swelling (+)
			Chemically induced strains (permanent)	Chemical Shrinkage (-) (e.g. lime)
				Chemical Swelling (+) (e.g. gypsum)
		Load Dependent	Modulus of elasticity	• Dead loads • Other permanent loads • Live loads
			Poisson's ratio	

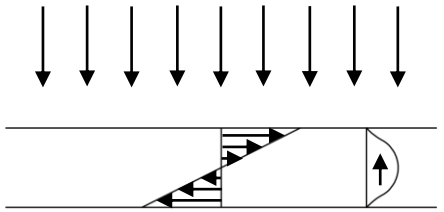


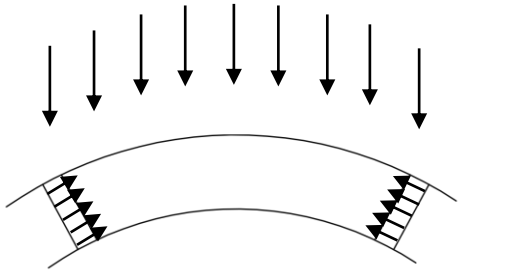
- **Size optimization**
- **Shape optimization**
- **Topology optimization**

Adapted from source: Francesco Mezzadri, Vladimir Bouriakov, Xiaoping Qian (2018)



Why shells?



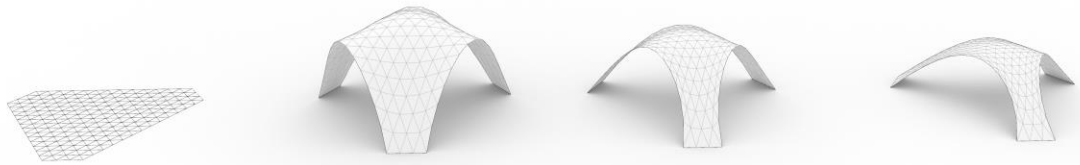


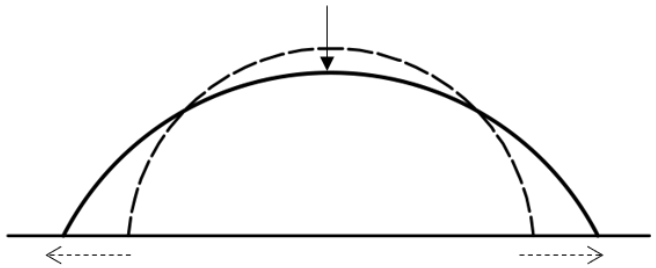
I. Plate / beam
transfers loads through:
- Bending &
- Shear action

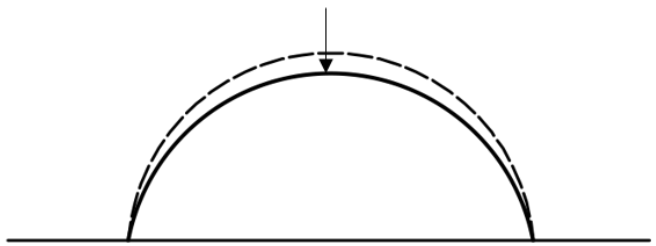
Compression & tension

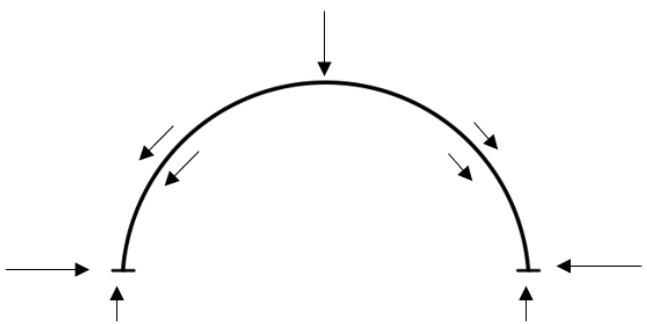
II. Arch / shell
transfers loads through:
- Membrane action

Compression only









I. In-extentional deformation

- Open shells (rigidity)
- Boundary conditions

II. Buckling

- Sensitivity to defects (ideal shape)
- Stress-based analysis

III. Kicking forces

- Support conditions

Possible functions are temporary or permanent constructions, such as:

- Temporary shelter/ housing
- Recyclable pavilions
- Roofing structures
- Shell floor
- Bridge design
- Warehouses
- Pop-up stores
- Exhibition spaces

Aren’t SHELLS supposed to be
EXPENSIVE & WASTEFULL ?

Main potentials

- Reduction of cost
- Environmental pollution mitigation
- Decrease of manufacturing time
- Quality production
- Integration of utilities
- Geometric freedom

Main Limitations

- Dimensions limited by the printing frame
- Introduction of overhangs reduces efficiency
- Reduced mechanical properties (orthotropic behaviour)
- More maintenance
- Not cost-effective for typical structural elements
- Certification issues

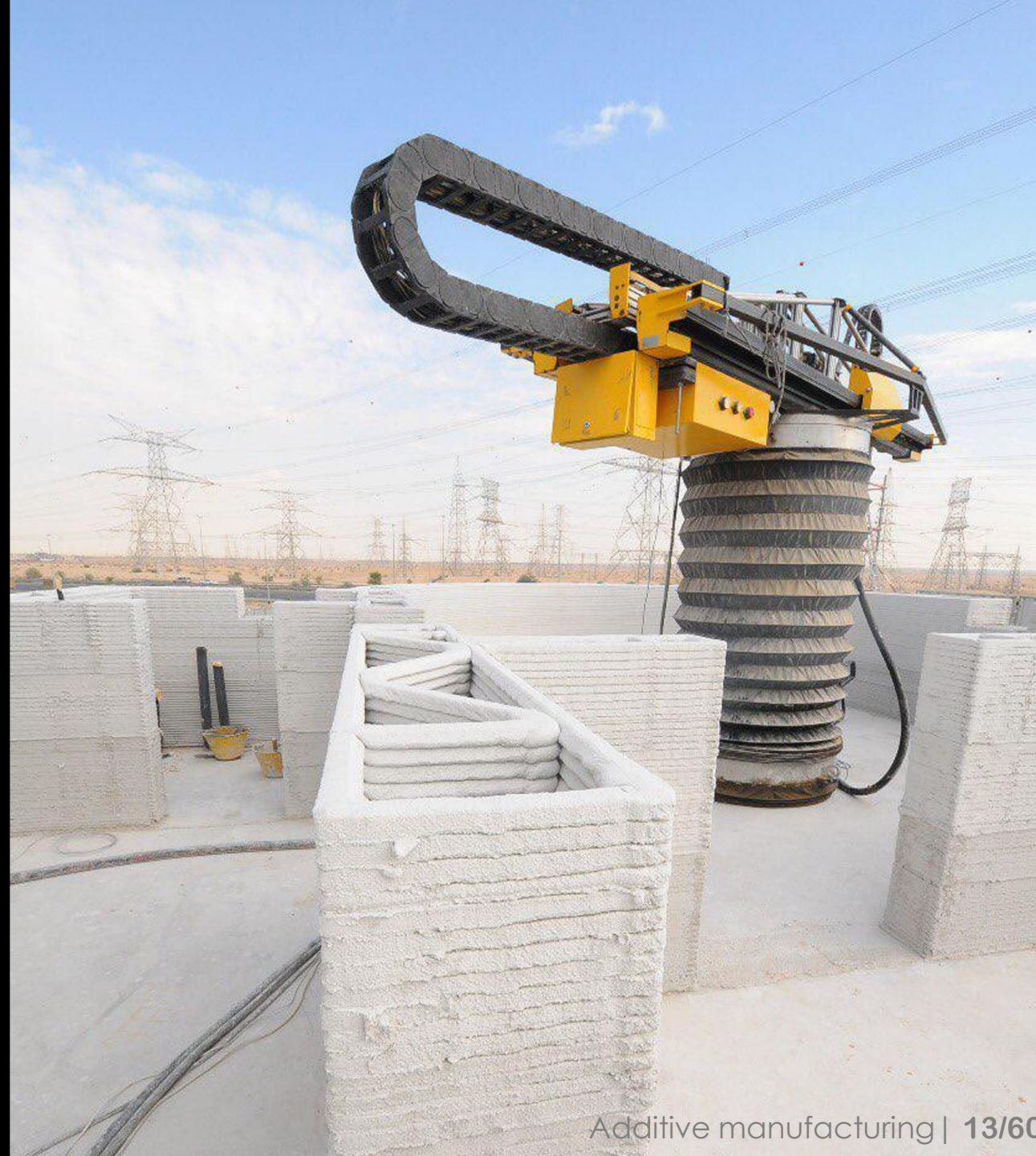


image source: Apis Cor (2019)

EVEN MORE SUSTAINABLE ?

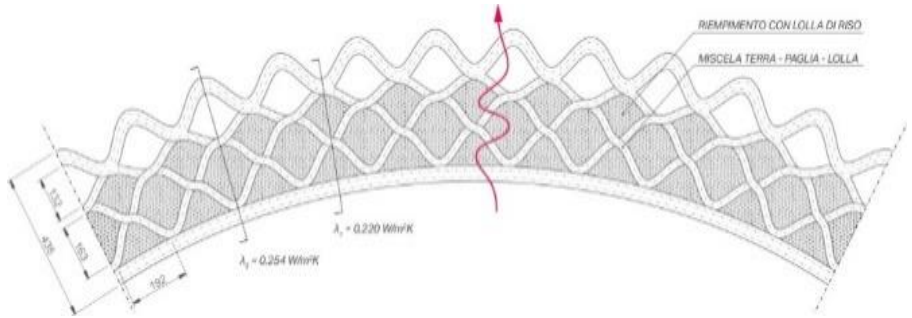
Main benefits

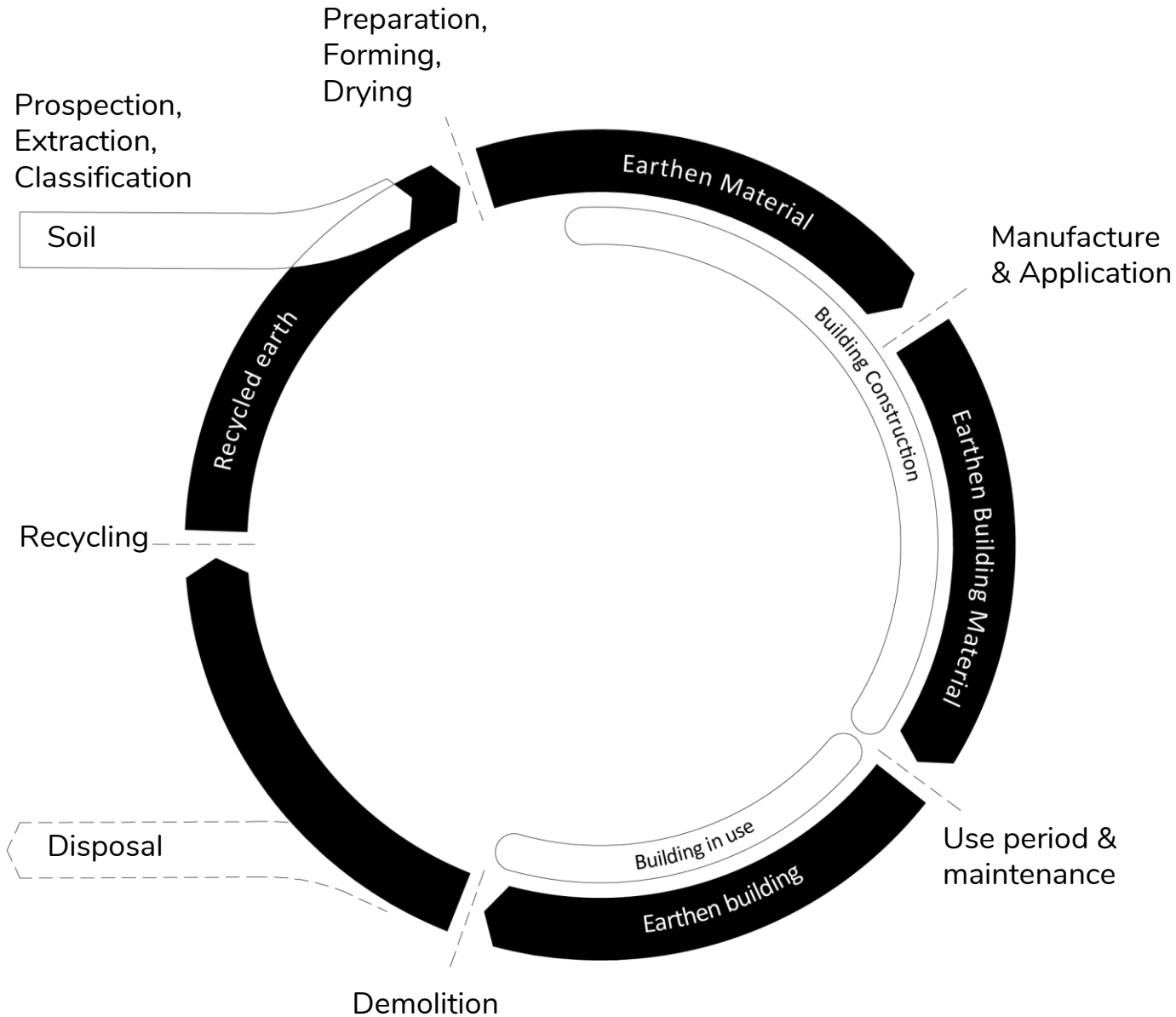
- Thermal mass
- Low environmental impact
- Endlessly recyclable
- Ubiquitous
- Stable relative humidity (50%)
- Extrudable

Main drawbacks

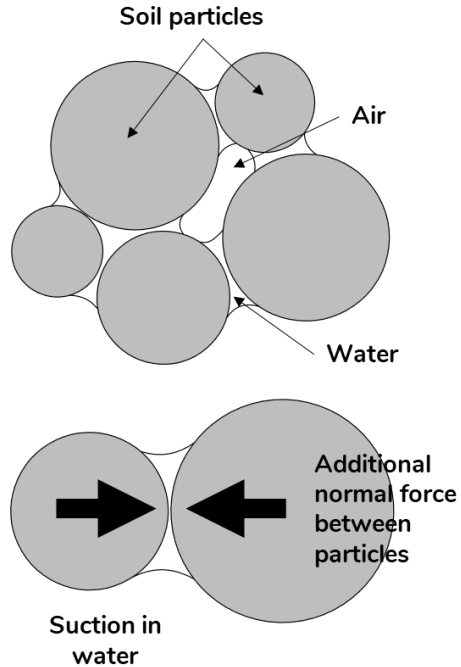
- Properties dependent on site
- Low compressive strength
- Very low tensile strength
- Shrinkage
- Low insulation
- Water-resistance (not 100%)
- Prejudice

source: GAIA project, WASP (2018)





Life cycle of earth as a building material



Building material	PEI [kWh/m^3]
Earth	0-30
Fired bricks	500-1140
Standard concrete	450-550
Non-imported timber	300-600

HOW TO FABRICATE ?

Safety factor: 2

Snow load: $s_k = 0.80$ [kN/m^2]

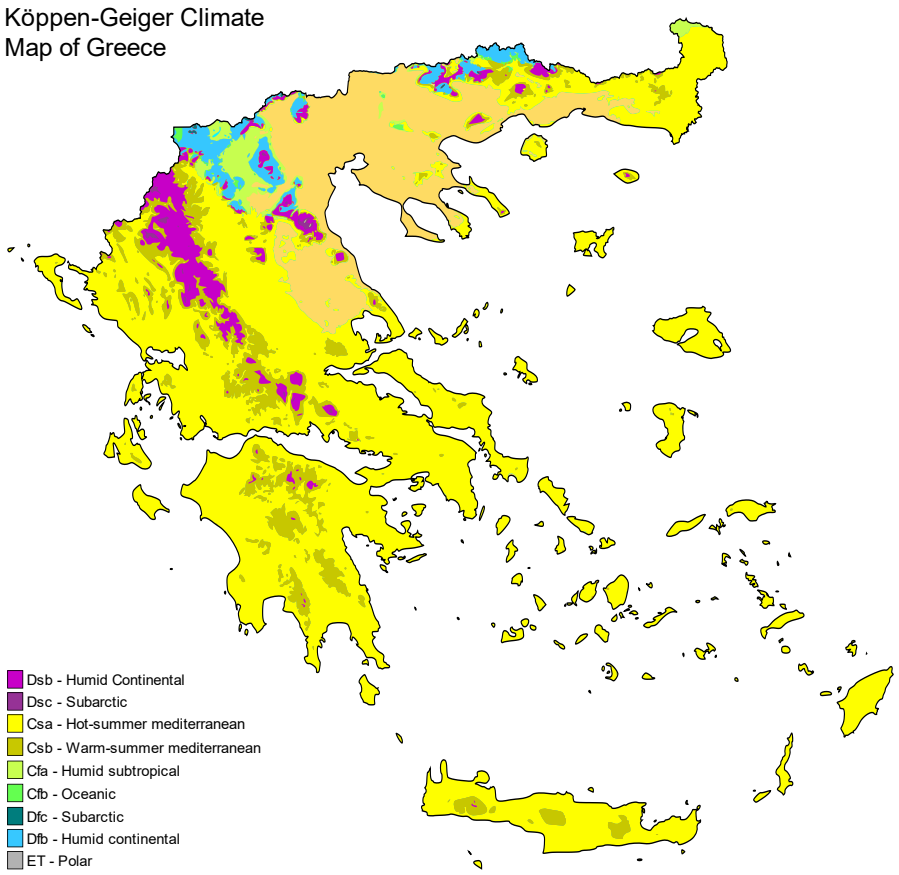
Wind load: $q_b = 0{,}46$ [kN/m^2]

Climate: Mediterranean BSk

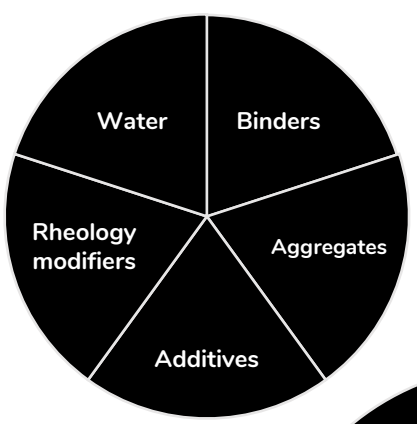
Precipitation: 59.5 [cm]

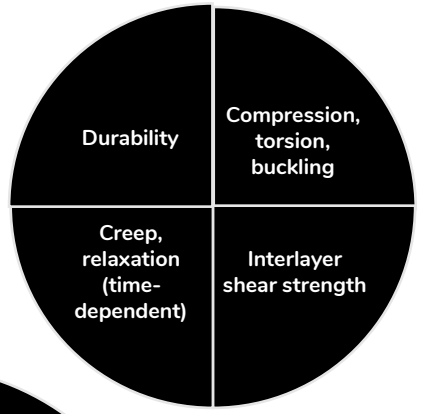
average temperature: 12.2 [°C]

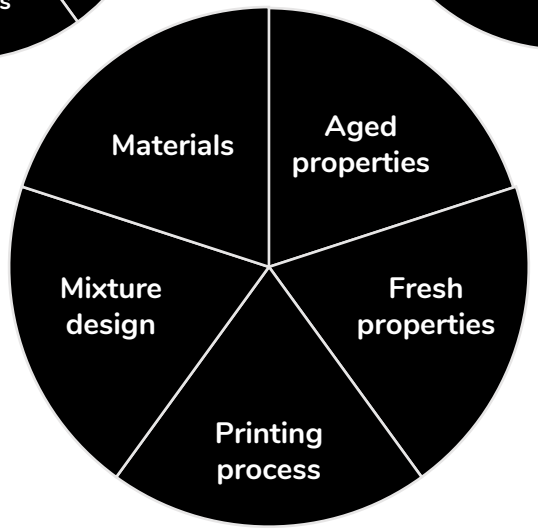
Heating days: 180

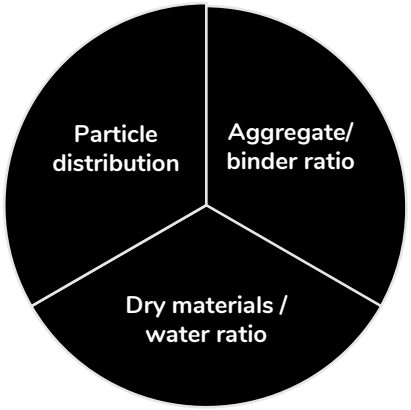


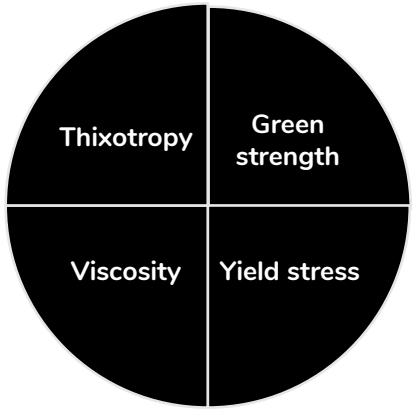
Climate classification of Greece (Beck et al., 2018)

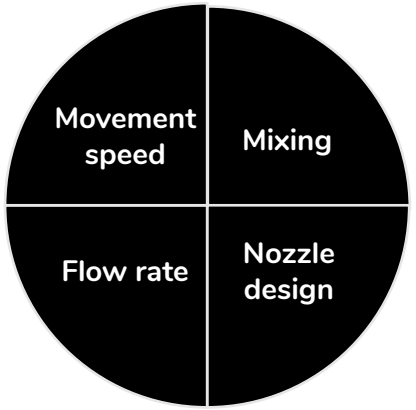






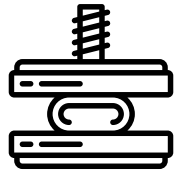




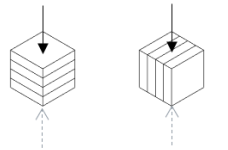


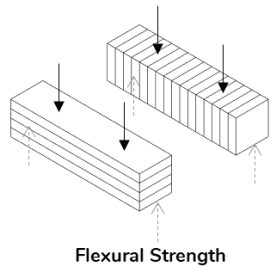
Microstructure study

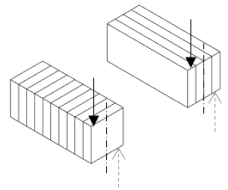
- Consistency
- Shrinkage
- Cracking
- Porosity
- Homogeneity
- Layer Adhesion
- Deformation
- Deposition

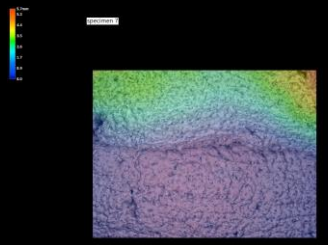


Laboratory testing schemes









#7

Layer interface

Clay coating

Buildability

#3

Layer adhesion

Clay coating

Flowability

#9

Particle distribution

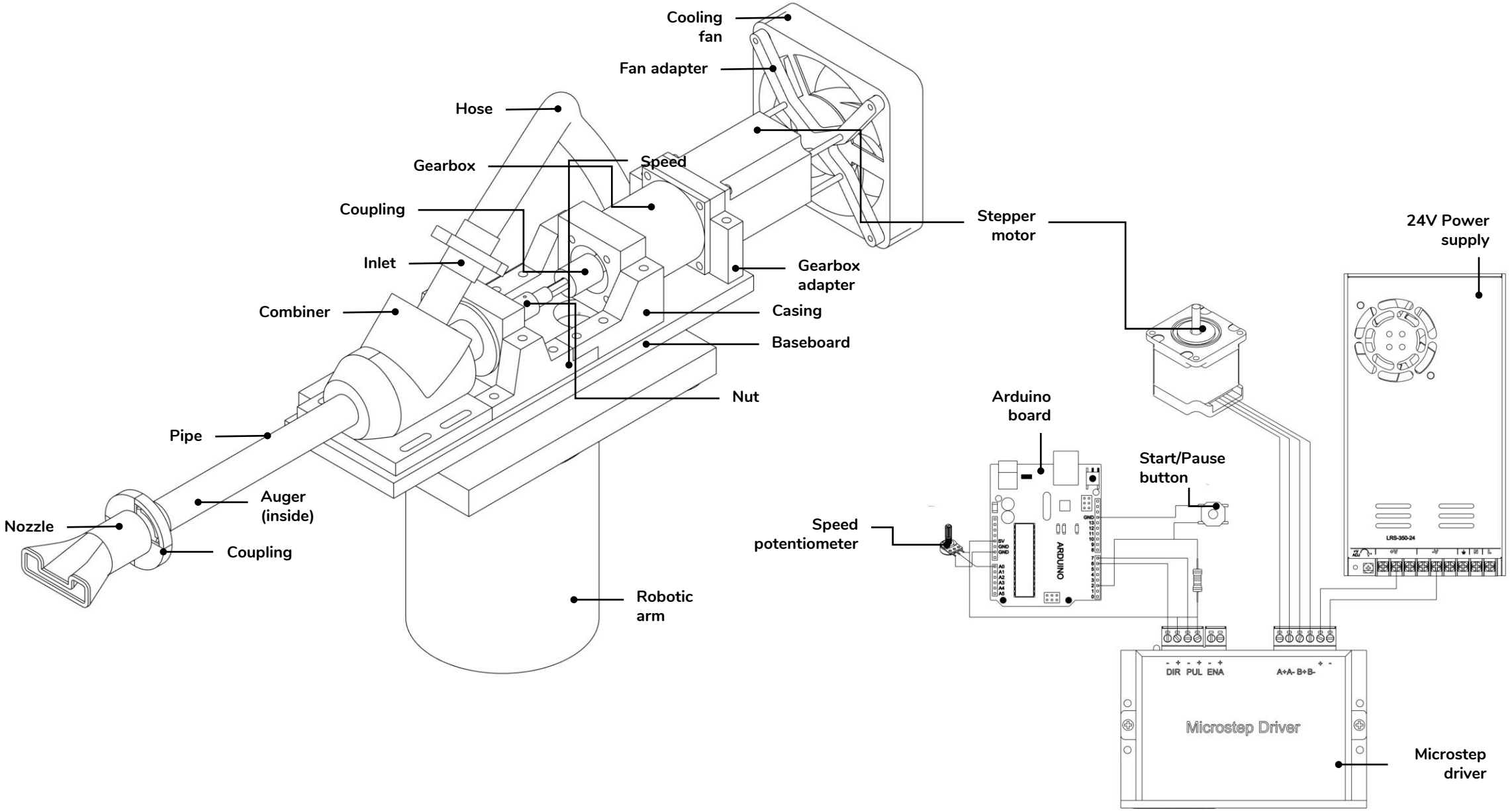
Fibers

Extrudability

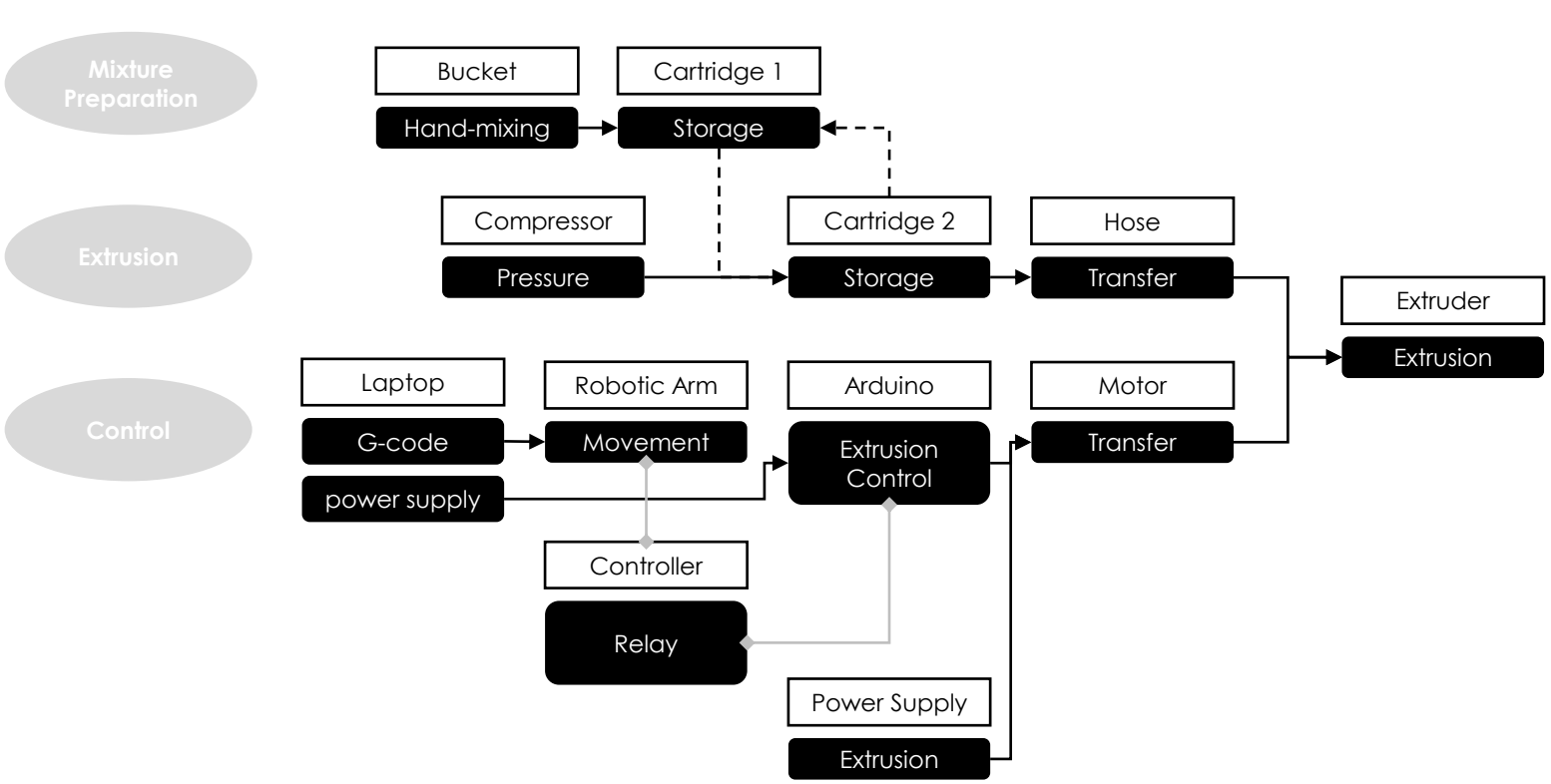
Mixture		1	2	3	4	5	6	7	8	9	10	11	12	13
Aggregates	Sand	70	50	70	70	70	60	30	70	70	70	70	70	70
	Straw	10	-	-	10	-	-	-	30	-	-	40	30	-
	H_20+ Cellulose	-	-	-	-	-	-	-	-	30	-	-	-	-
Additives	Clay	30	50	30	30	30	40	70	30	30	30	30	30	30
	Rice husk ash	-	-	-	-	-	-	-	-	-	-	-	-	-
	Milled grain	-	-	-	-	-	-	-	-	-	20	-	-	20
	Lime	-	-	-	-	-	-	-	-	-	-	-	-	-
Water		30	25	35	30	25	25	25	30	-	45	35	35	60

Note: all values are in volume parts

Evaluation Criteria						
	Extrudability E	1	E: ●●	PD: ●●●	LA: ●●●	B: ●●●●
		2	E: ●●●●	PD: ●●●●●	LA: ●●●●●	B: ●●●●●
		3	E: ●●●●	PD: ●●●	LA: ●●●	B: ●●●
	Particle Distribution PD	4	E: ●●	PD: ●●●	LA: ●●●	B: ●●●●●
		5	E: ●●●●	PD: ●●●	LA: ●●●	B: ●●●●●
		6	E: ●●●●	PD: ●●●●	LA: ●●●●	B: ●●●●●
	Layer Adhesion LA	7	E: ●●●●	PD: ●●●●●	LA: ●●●	B: ●●●●●
		8	E: ●	PD: ●●●	LA: ●●●	B: ●●●●
		9	E: ●	PD: ●●	LA: ●●	B: ●●●
	Buildability B	10	E: ●●●●●	PD: ●●●	LA: ●●●	B: ●●
		11	E: -	PD: ●	LA: ●●●	B: ●●●●●
		12	E: ●●	PD: ●●	LA: ●●●	B: ●●●
		13	E: ●●●●●	PD: ●●●	LA: ●●●	B: ●


Cooling fan
Fan adapter
Hose
Gearbox
Speed
Coupling
Inlet
Combiner
Gearbox adapter
Casing
Baseboard
Nut
Pipe
Auger (inside)
Nozzle
Coupling
Robotic arm
Stepper motor
24V Power supply
Arduino board
Start/Pause button
Speed potentiometer
ARDUINO
LRS-350-24
DIR PUL ENA
A+A- B+B-
Microstep Driver
Microstep driver

Physical setup



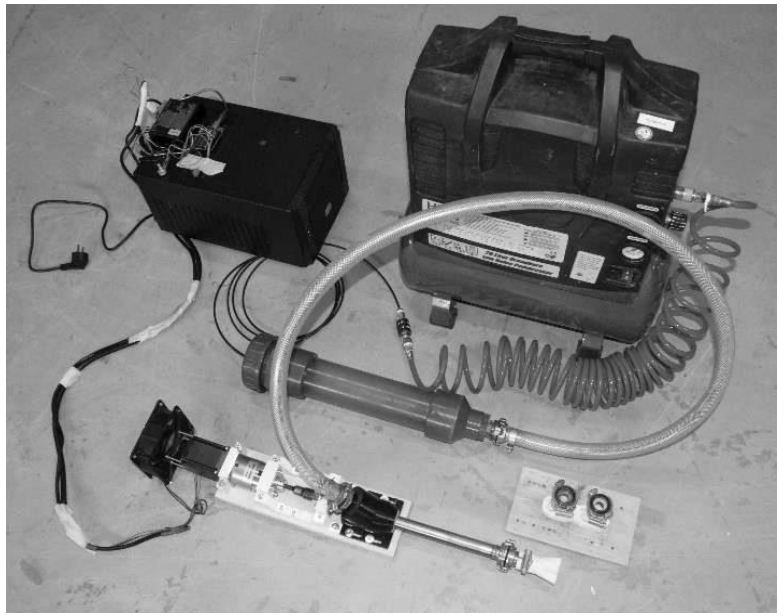


Photo by: Maximillian Mandat

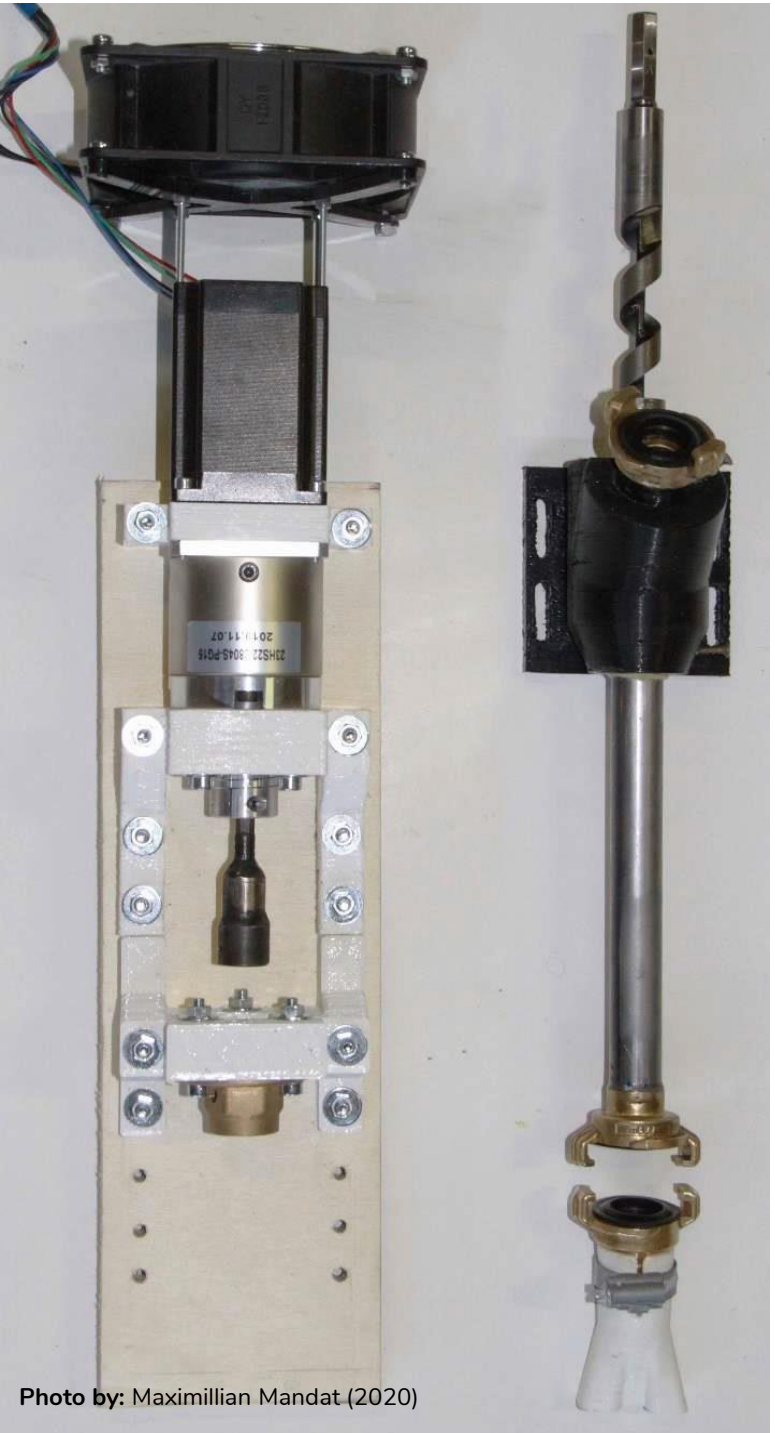
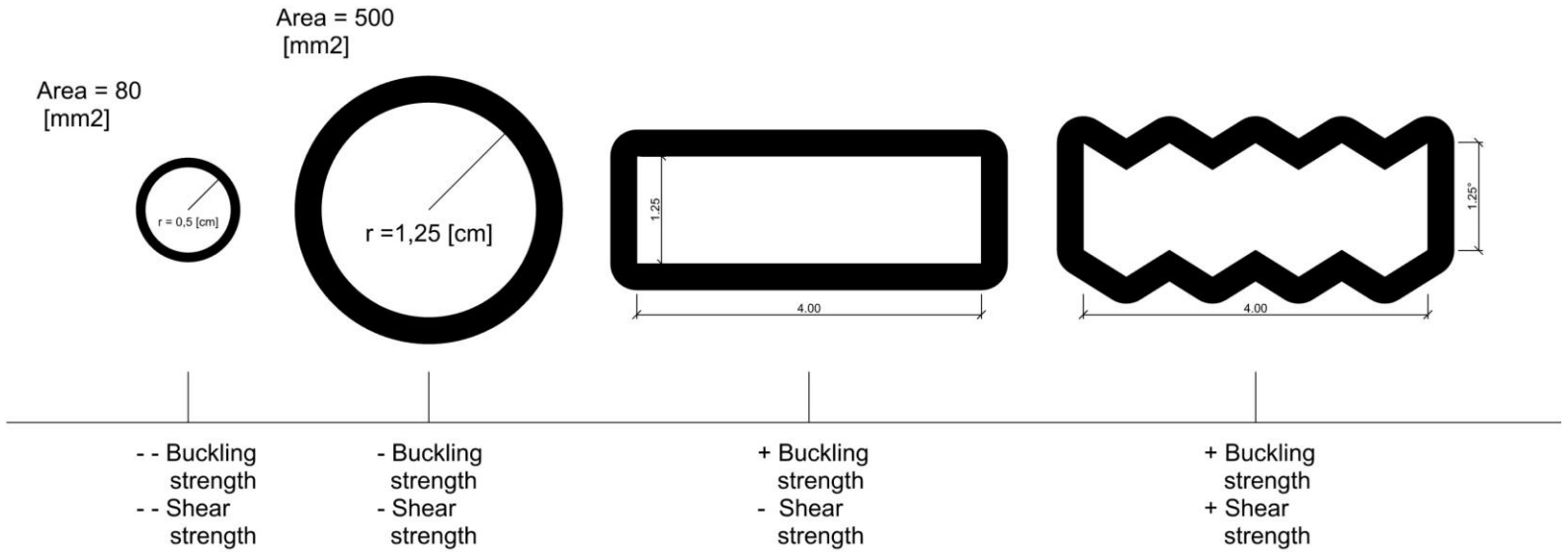
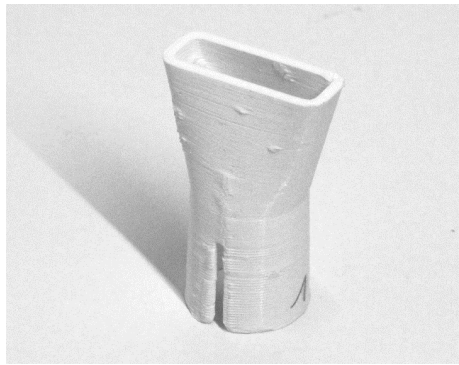
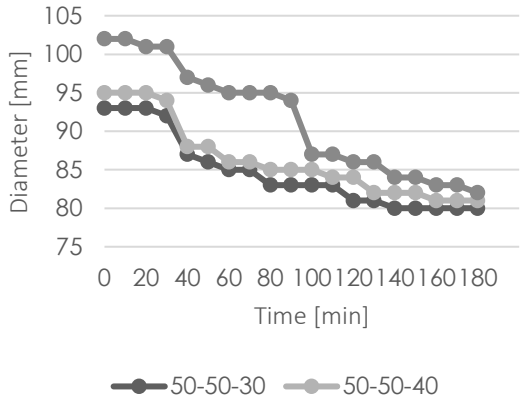


Photo by: Maximillian Mandat (2020)

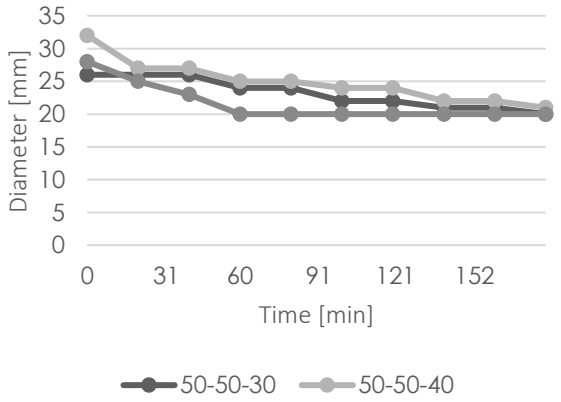




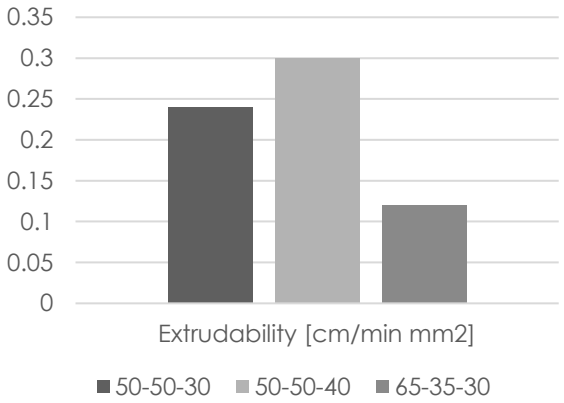
Flowability test results



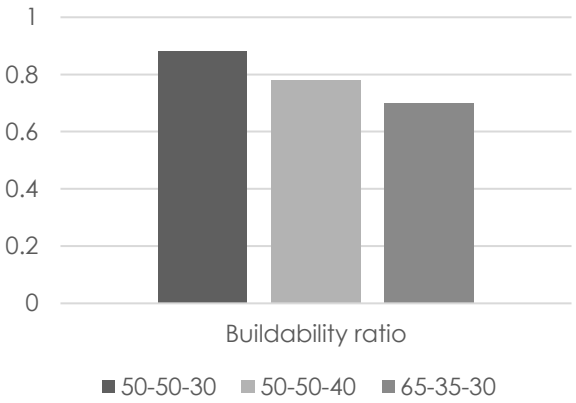
Open time test results



Extrudability test results



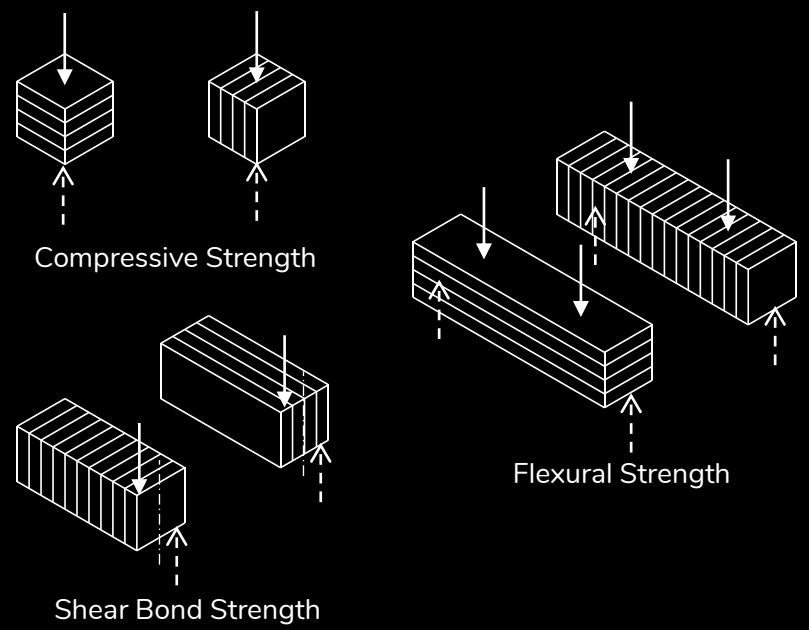
Buildability test results



Flowability

Open time

Buildability



Mechanical Properties 3DPE (Lab tests)

Property	Value	Unit
Density	1900	kg/m3
Orthotropic Elasticity		
Young's Modulus X direction	400	MPa
Young's Modulus Y direction	550	MPa
Young's Modulus Z direction	400	MPa
Poisson's Ratio XY	0.3	MPa
Poisson's Ratio YZ	0.3	MPa
Poisson's Ratio XZ	0.16	MPa
Shear Modulus XY	180	MP
Shear Modulus YZ	200	MPa
Shear Modulus XZ	180	MPa
Tensile Yield Strength	0.12	MPa
Compressive Yield Strength	4	MPa
Tensile Ultimate Strength	0.37	MPa
Compressive Ultimate Strength	5	MPa

Mechanical Properties 3DPE (Literature)

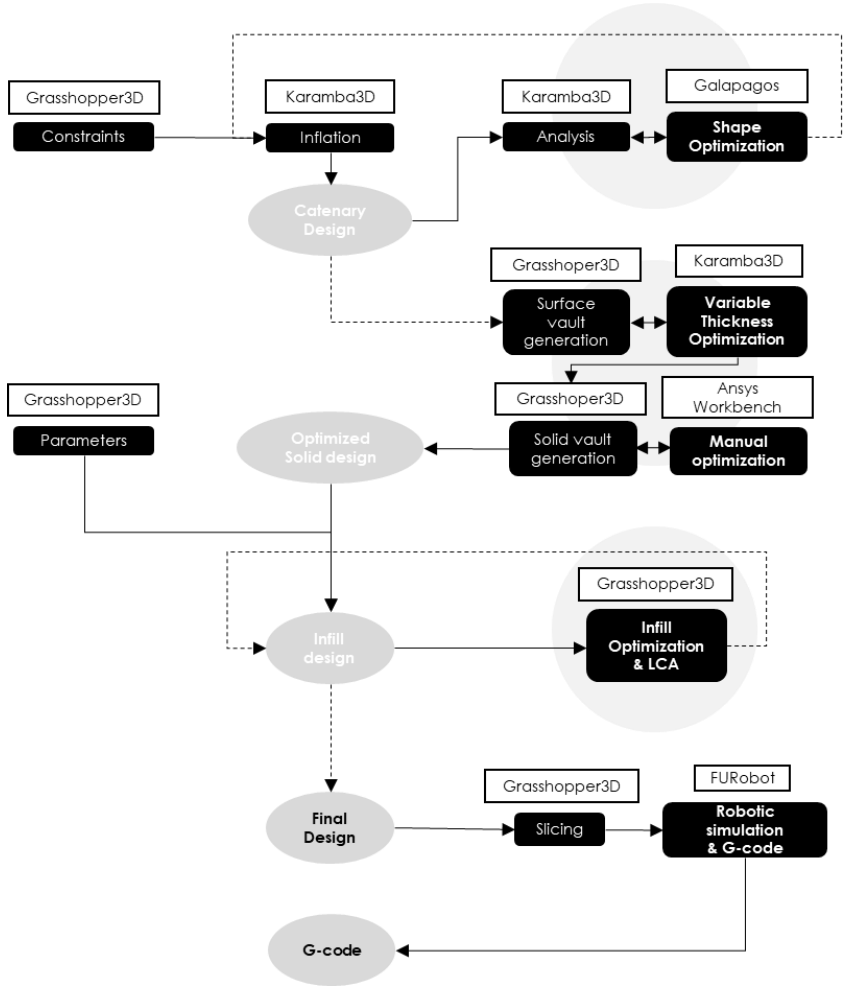
Determine failure theory >>> brittle materials fail by fracture

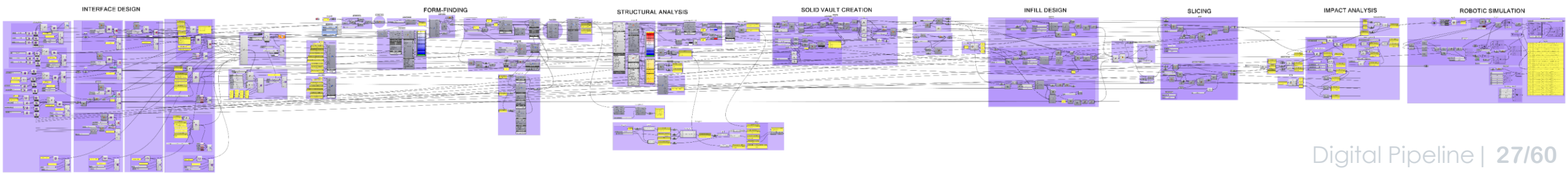
Rankine Maximum principal stress theory (acceptable for brittle materials)

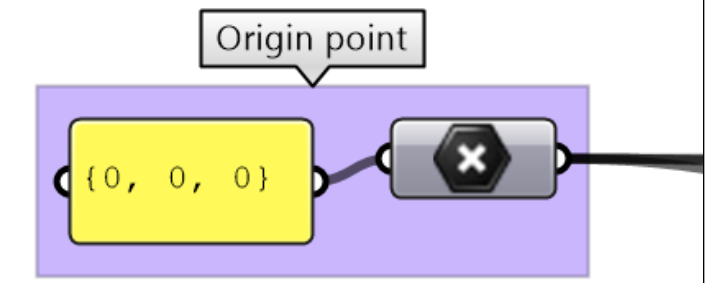
- Ultimate permissible stress: **0.12 MPa**

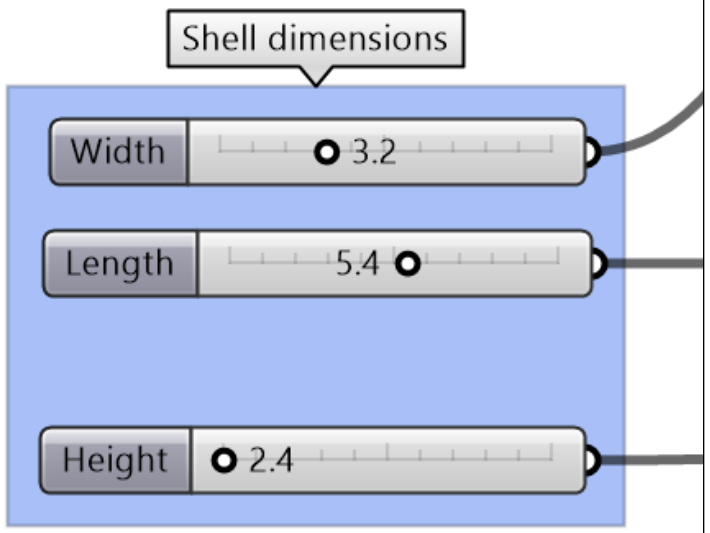
HOW TO DESIGN FOR ROBOTIC FABRICATION ?

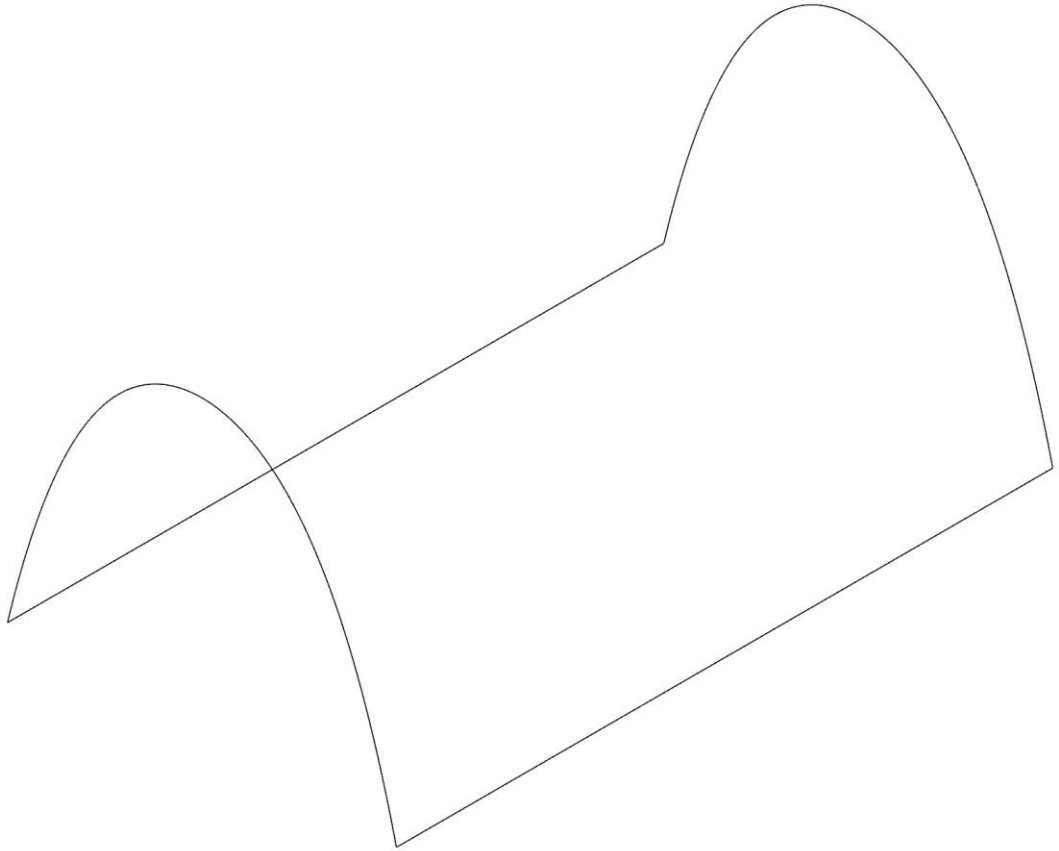
Digital workflow

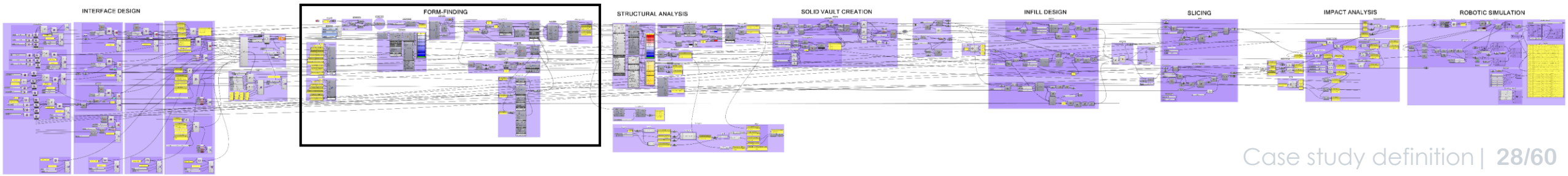




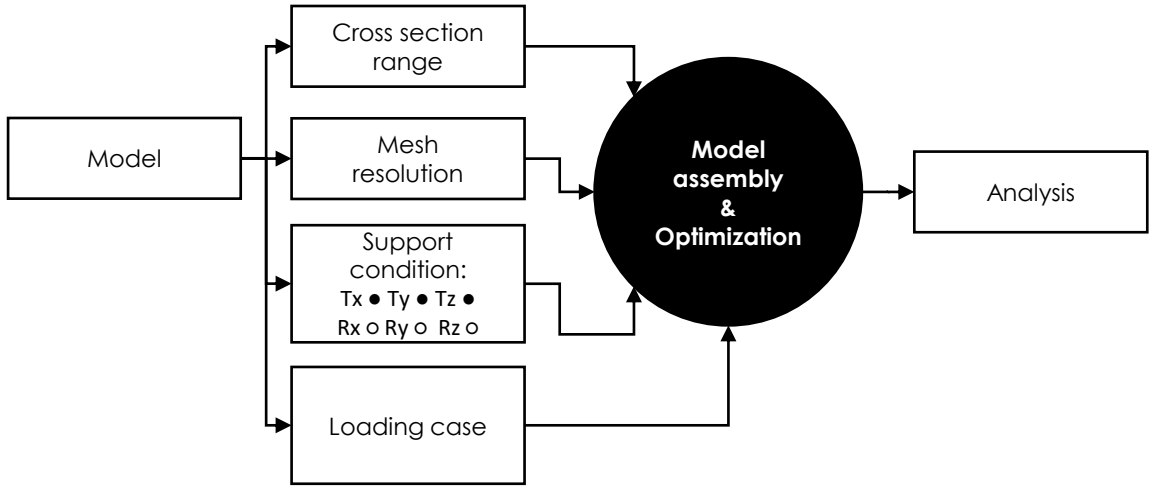

Origin point
{0, 0, 0}

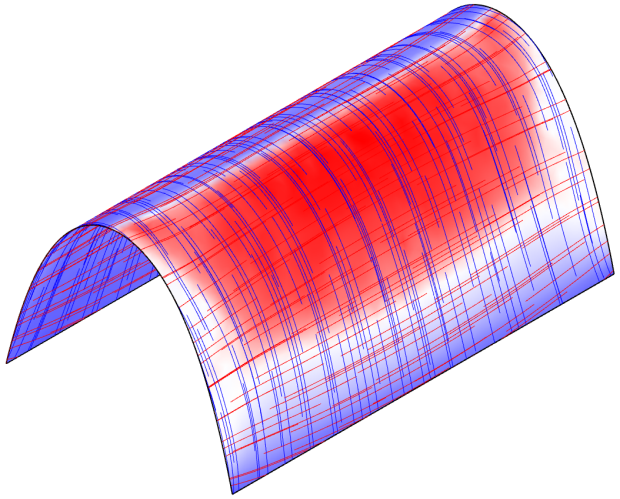

Shell dimensions
Width
3.2
Length
5.4
Height
2.4

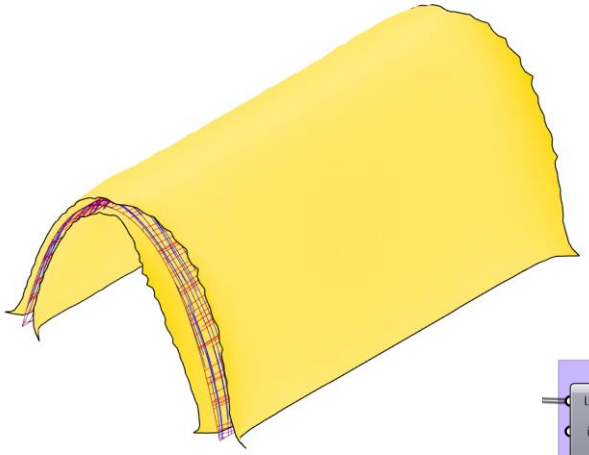


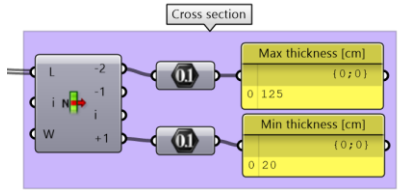

INTERFACE DESIGN
FORM-FINDING
STRUCTURAL ANALYSIS
SOLID VAULT CREATION
INFILL DESIGN
SLICING
IMPACT ANALYSIS
ROBOTIC SIMULATION

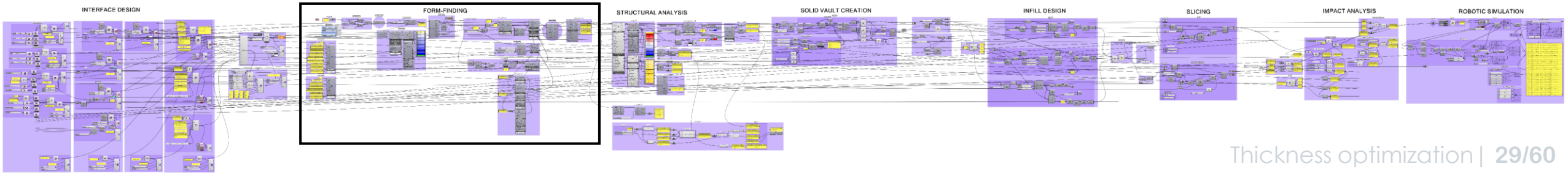
Cross section optimization

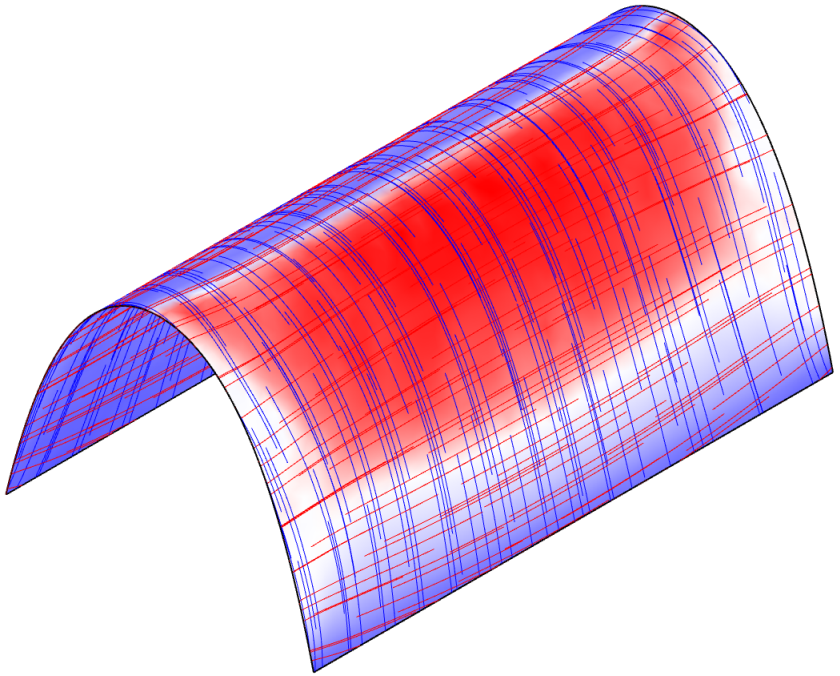




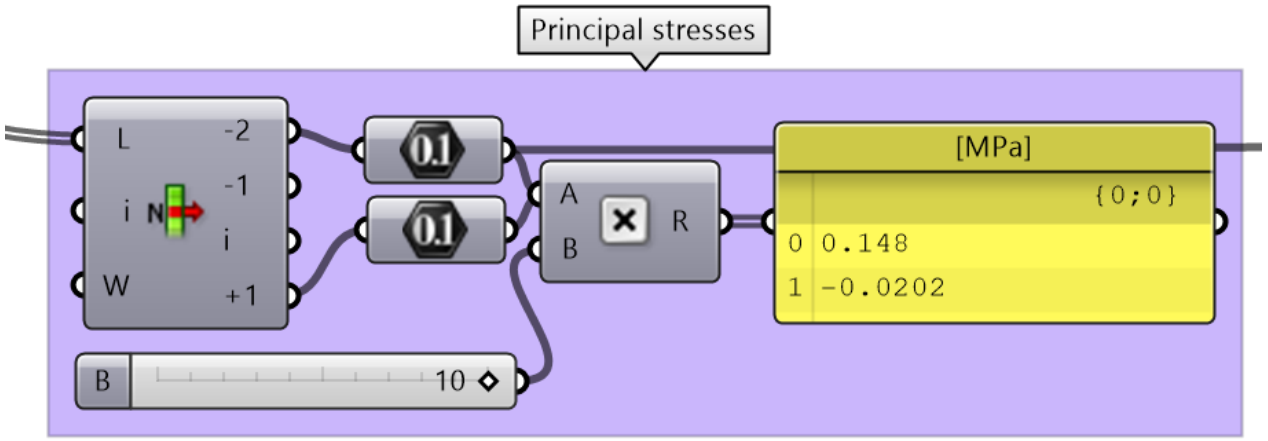




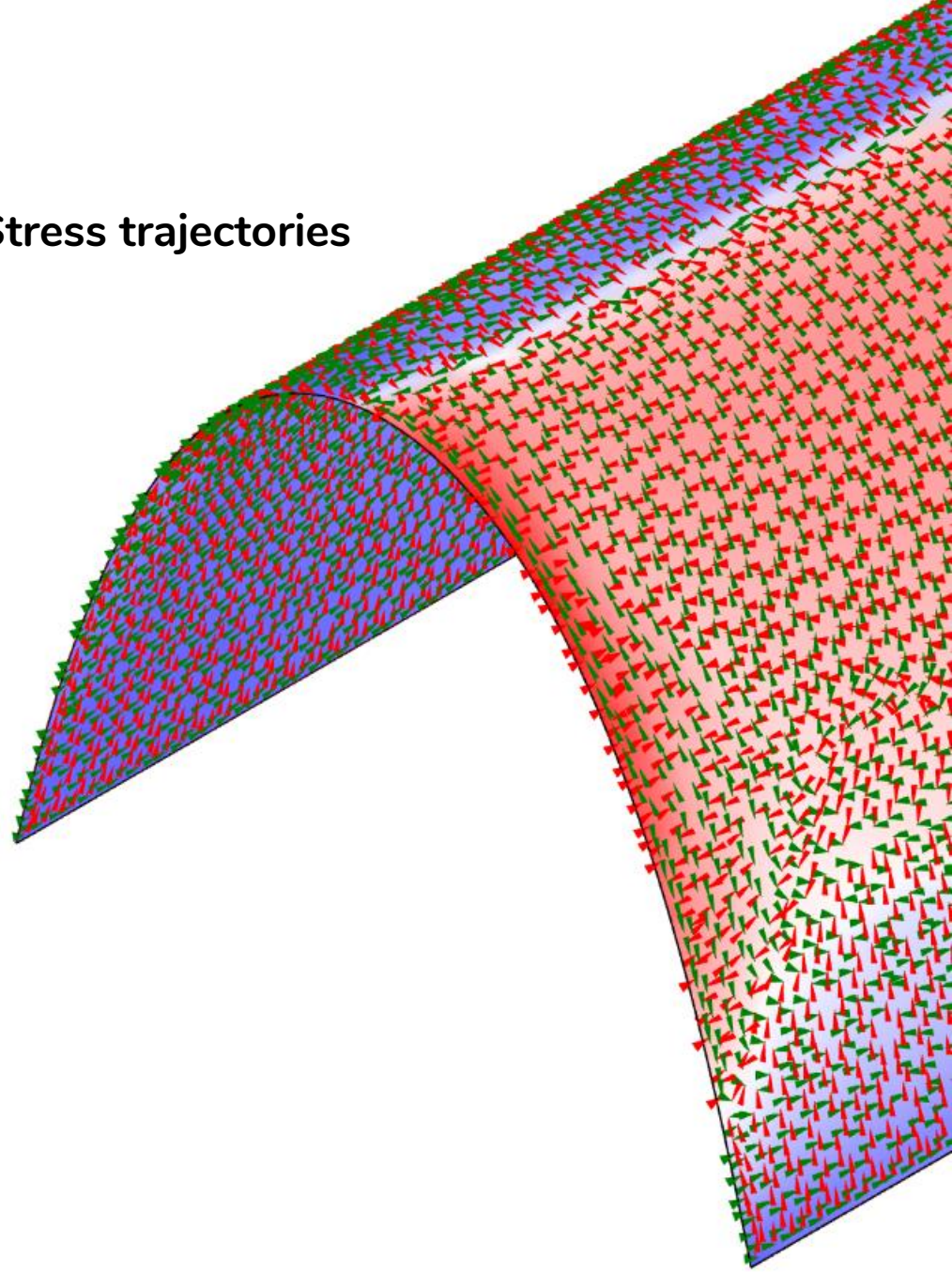


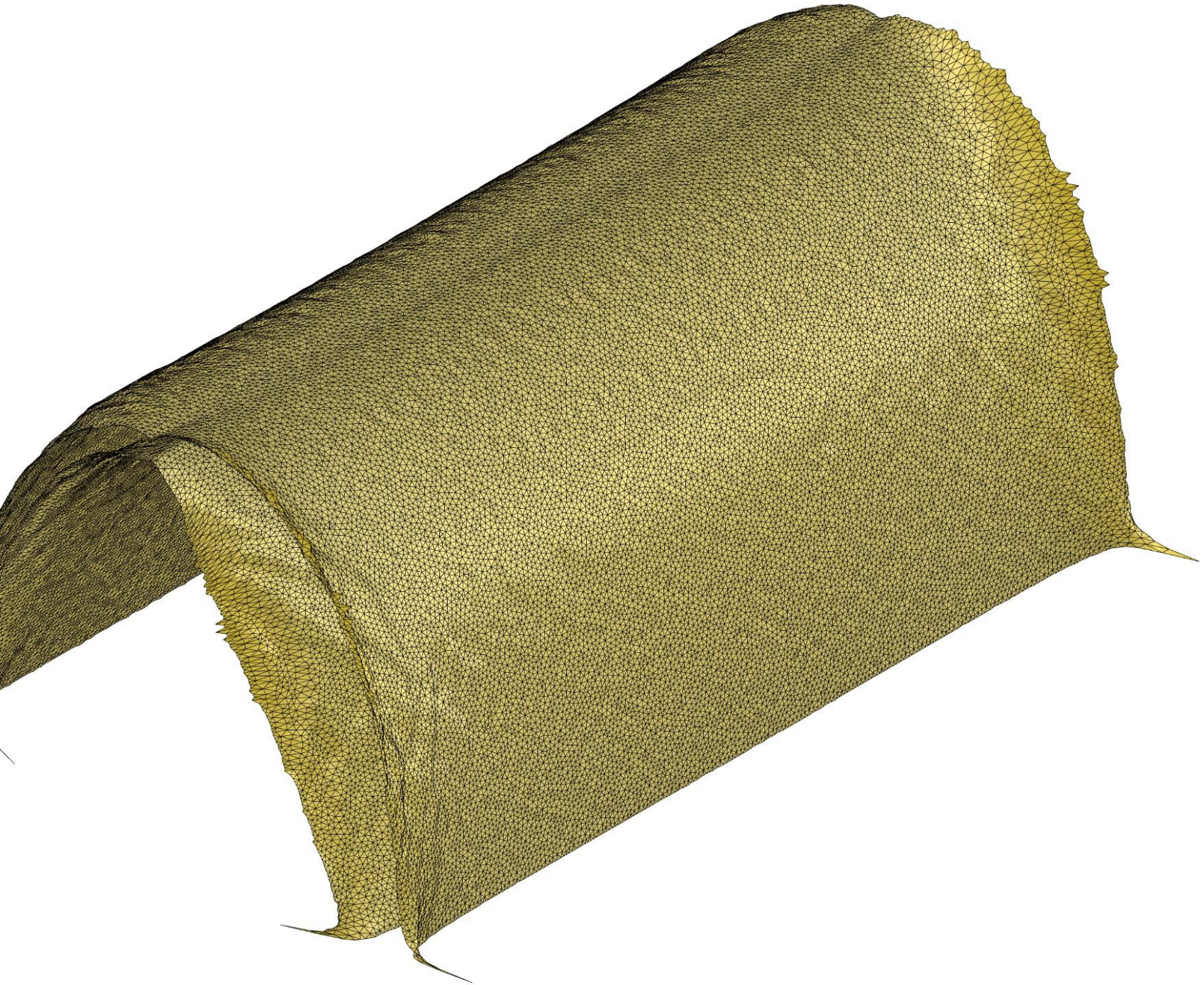


stress[kN/cm2]
-5.19e-03
-4.54e-03
-3.89e-03
-3.25e-03
-2.60e-03
-1.95e-03
-1.30e-03
-6.49e-04
0.00e+00
3.10e-03
6.20e-03
9.30e-03
1.24e-02
1.55e-02
1.86e-02
2.17e-02
2.48e-02



Stress trajectories





Karamba3D Limitations:

I. Cross-section optimization

>>> for ductile materials

(utilizes Van Mises criterion

For local buckling)

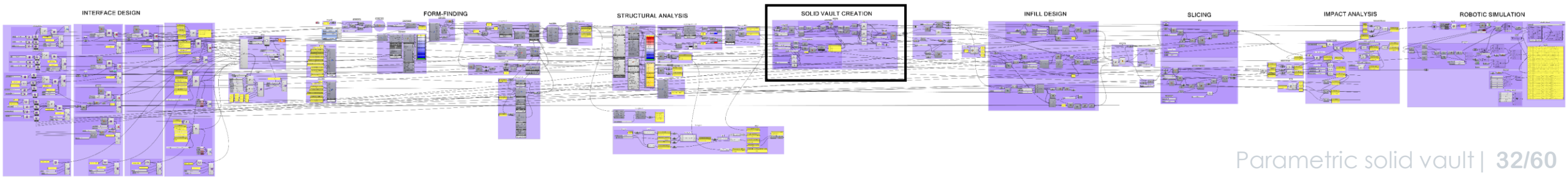
II. Triangular elements

>>> stiffness overestimation

III. Surface- based analysis

A solid based FEA software is needed

>>> ANSYS Workbench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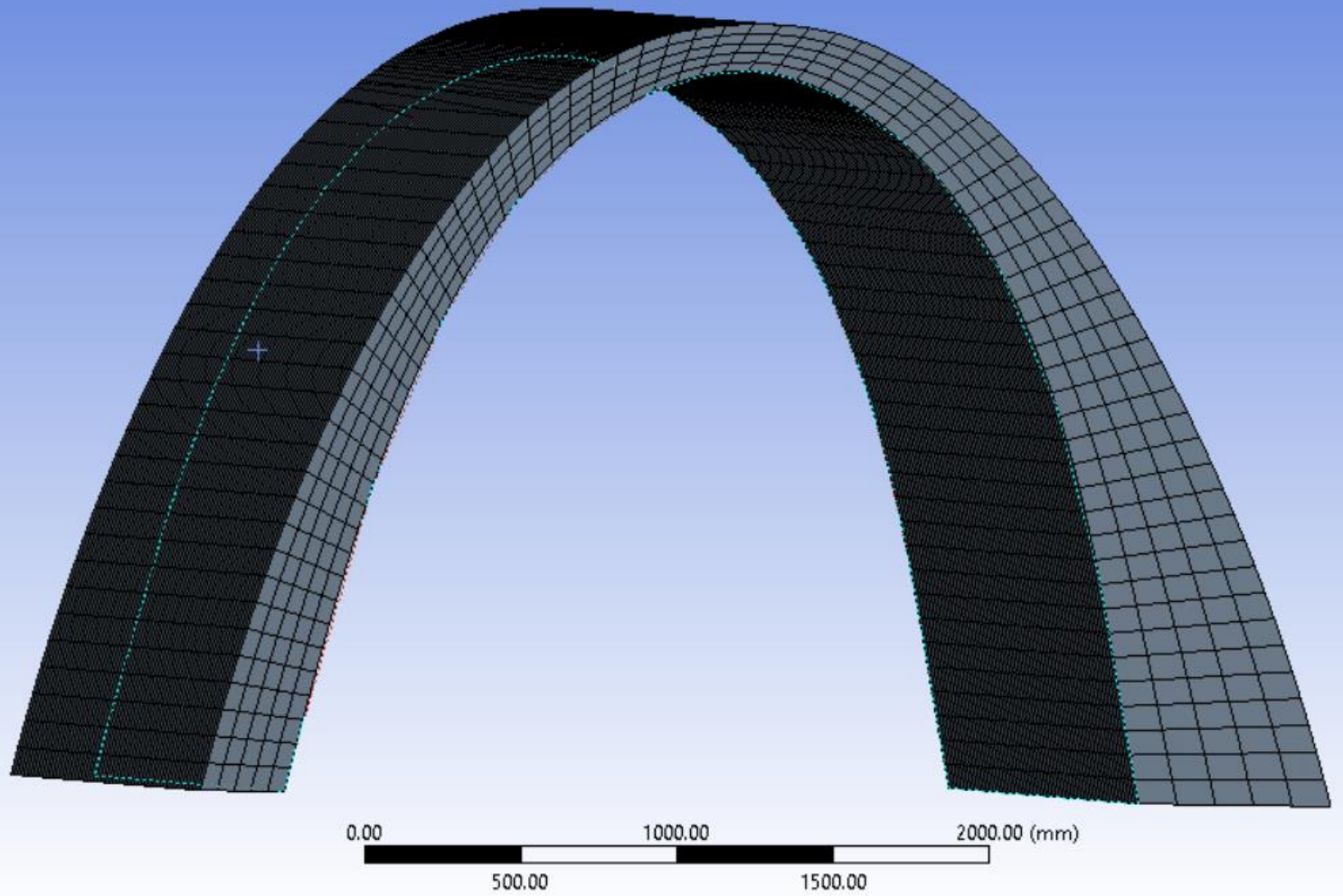
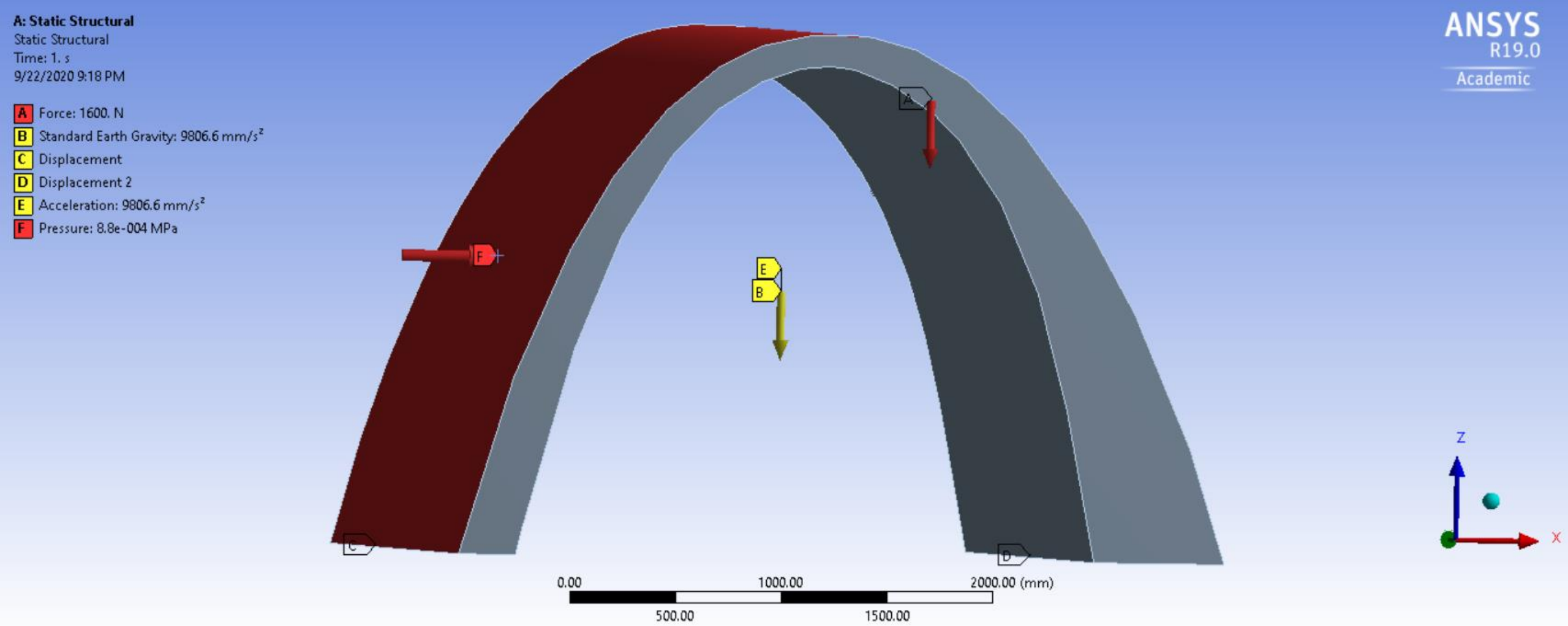
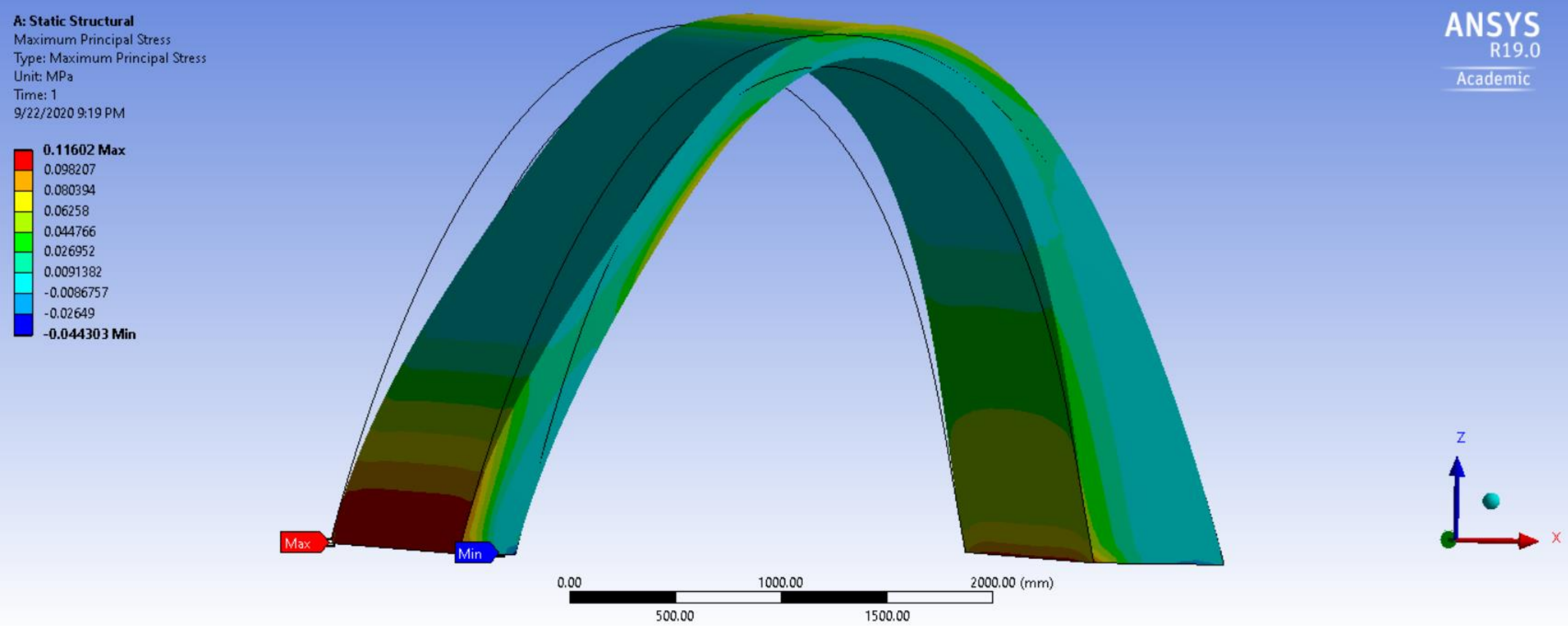


Element size [m]	0,08



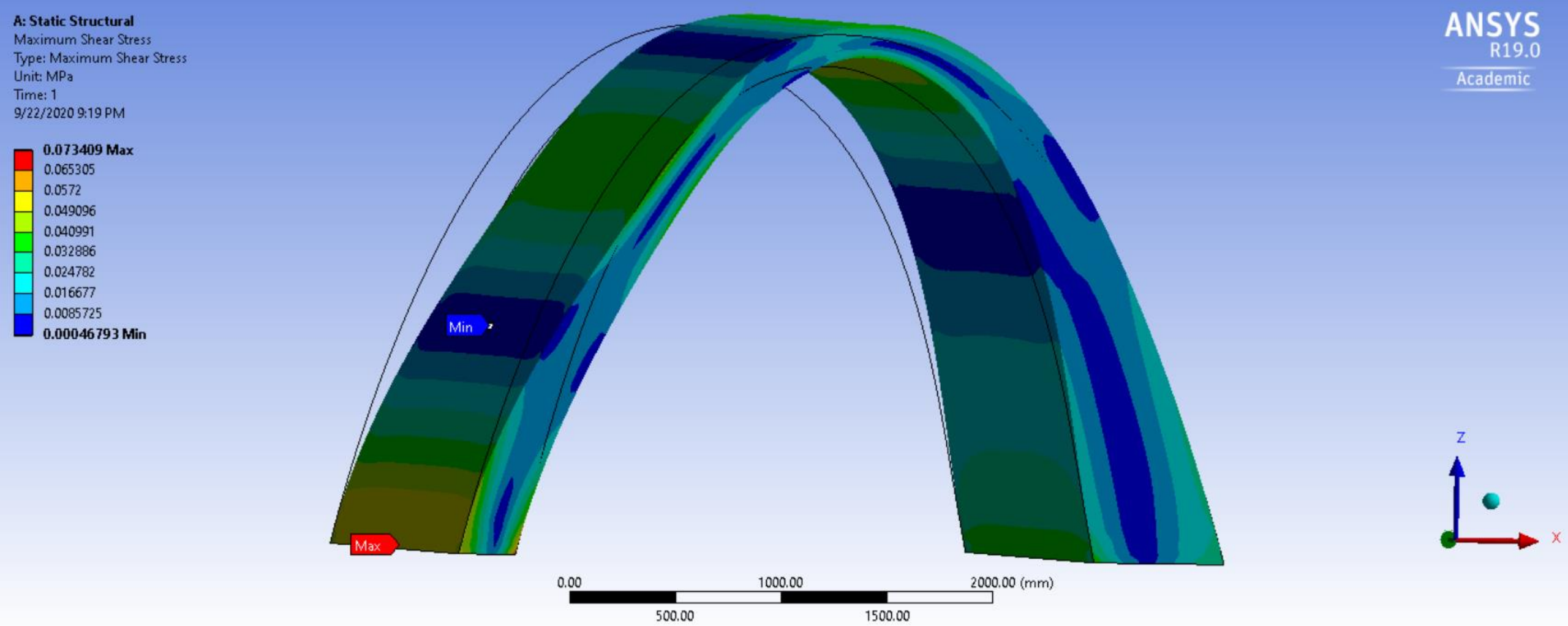
Load case (SF = 2)	
Snow load	s_k = 0.80 [kN/m2]
Wind load	q_b = 0,46 [kN/m2]



Maximum Principal Stress

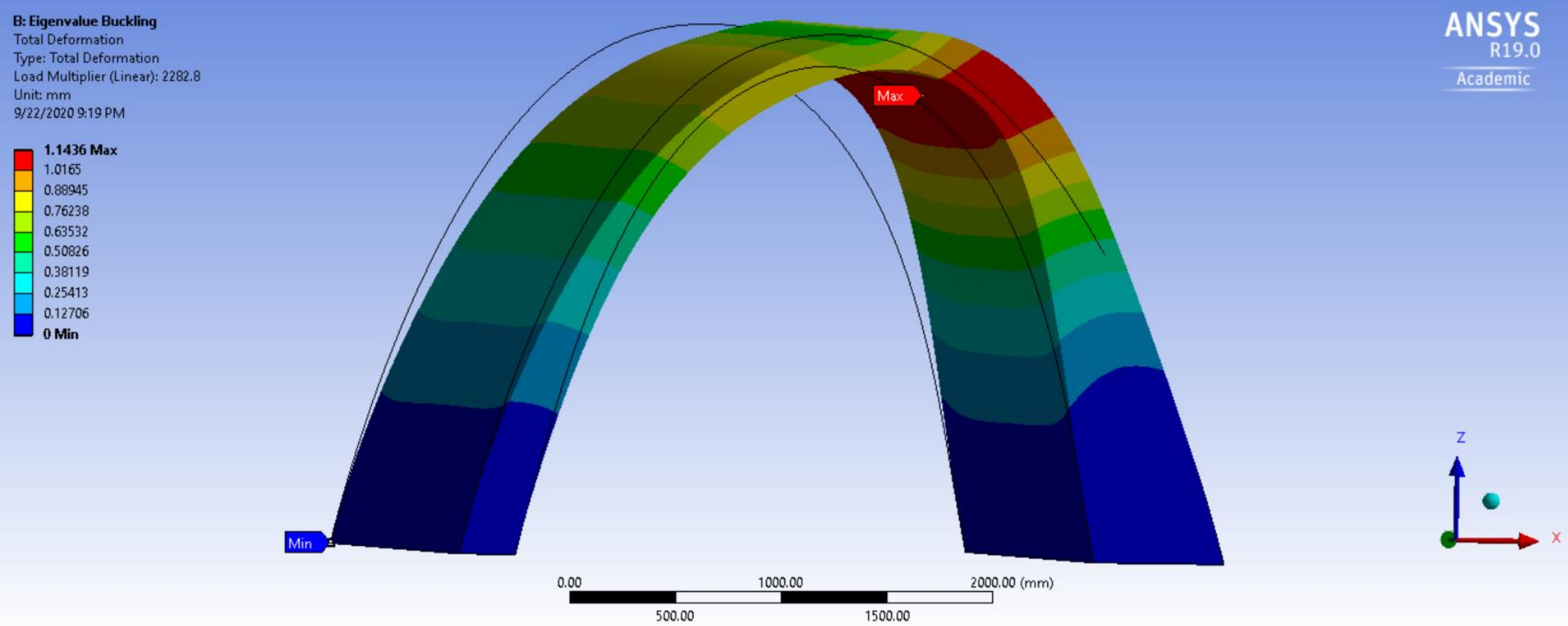
Minimum [MPa]	Maximum [MPa]
0.11602	1.567e-002

Ultimate permissible stress: **0.12 MPa**



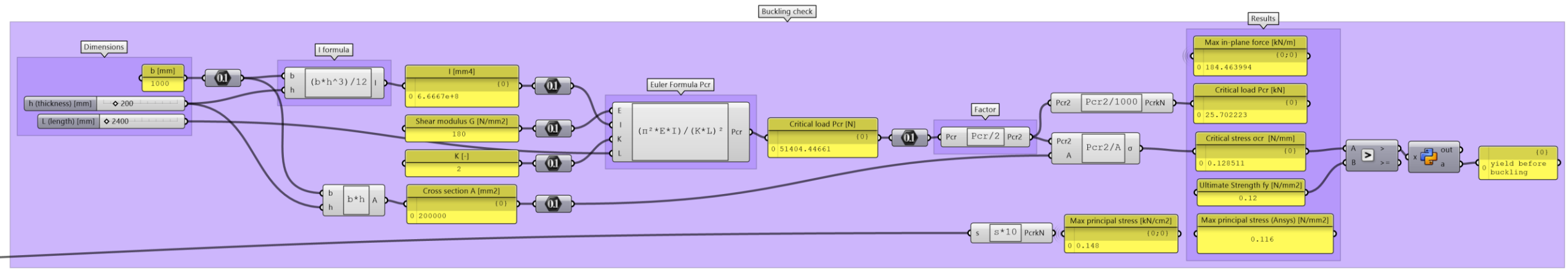
Maximum Shear Stress

Minimum [MPa]	Maximum [MPa]
0.00046793	0.073409



Buckling Analysis (Linear)

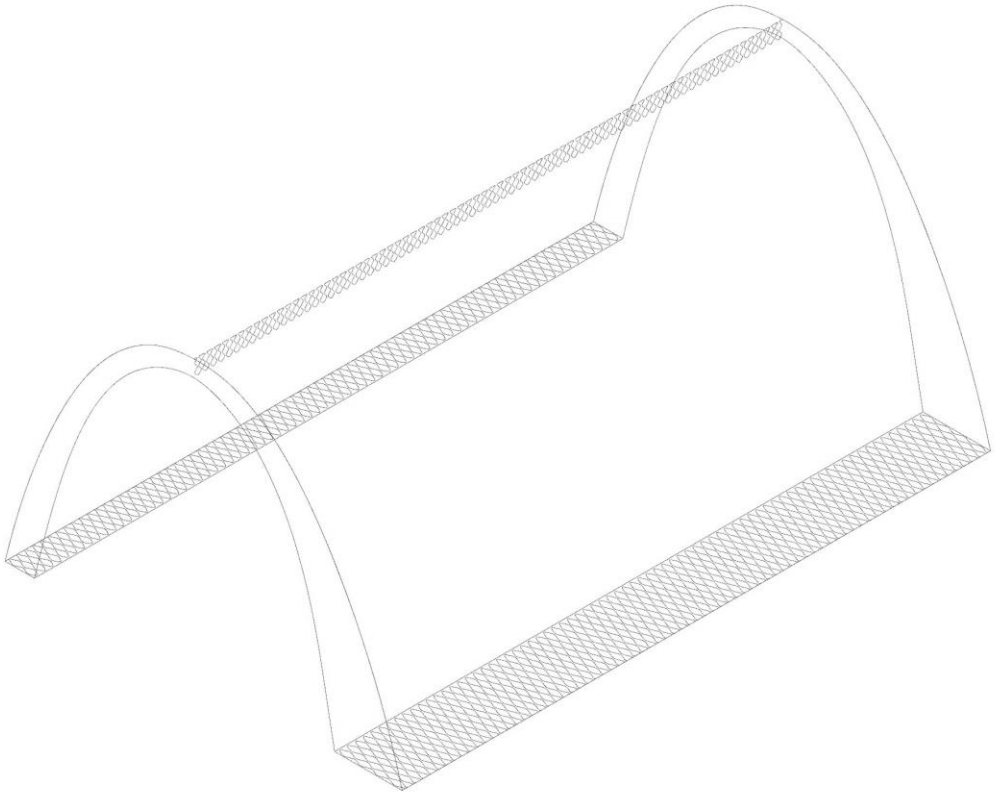
Factor	2228.8

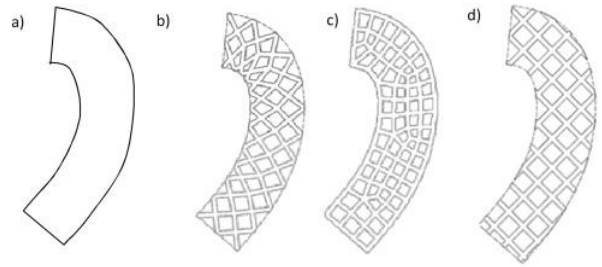

Buckling check
Dimensions
b [mm]
1000
h (thickness) [mm]
200
L (length) [mm]
2400
I formula
(b*h^3)/12
I [mm4]
6.6667e+8
Shear modulus G [N/mm2]
180
K [-]
2
Euler Formula Pcr
(π²*E*I)/(K*L)²
Pcr
Critical load Pcr [N]
51404.44661
Factor
Pcr/2
Pcr2/1000
PcrkN
Pcr2/A
σ
Cross section A [mm2]
200000
b*h
s*10
Max principal stress [kN/cm2]
0.148
Results
Max in-plane force [kN/m]
184.463994
Critical load Pcr [kN]
25.702223
Critical stress σcr [N/mm]
0.128511
Ultimate Strength fy [N/mm2]
0.12
Max principal stress (Ansys) [N/mm2]
0.116
yield before buckling

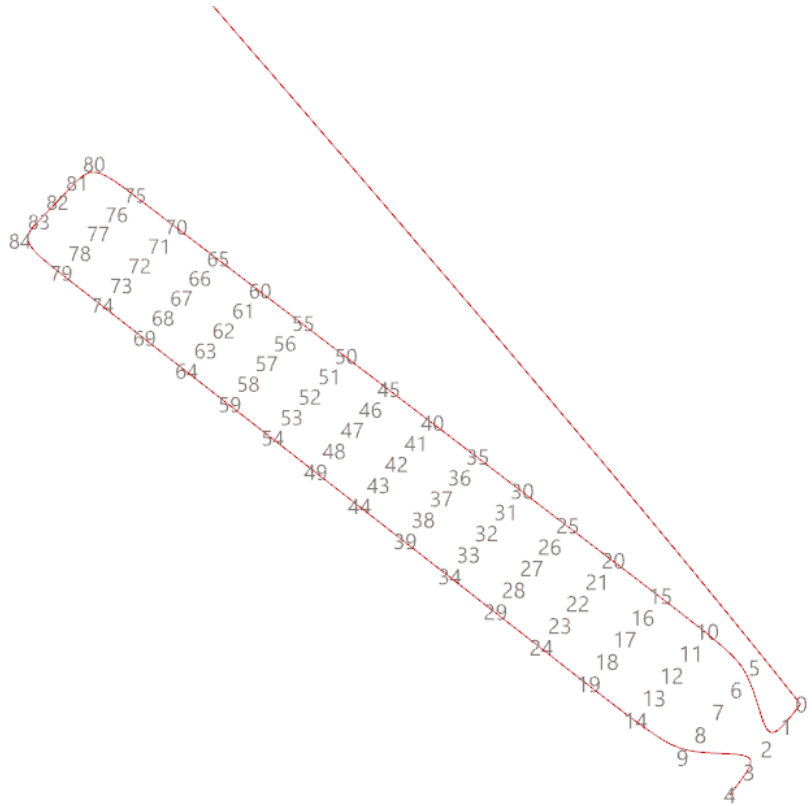
HOW TO MAKE IT 3D-PRINTABLE ?

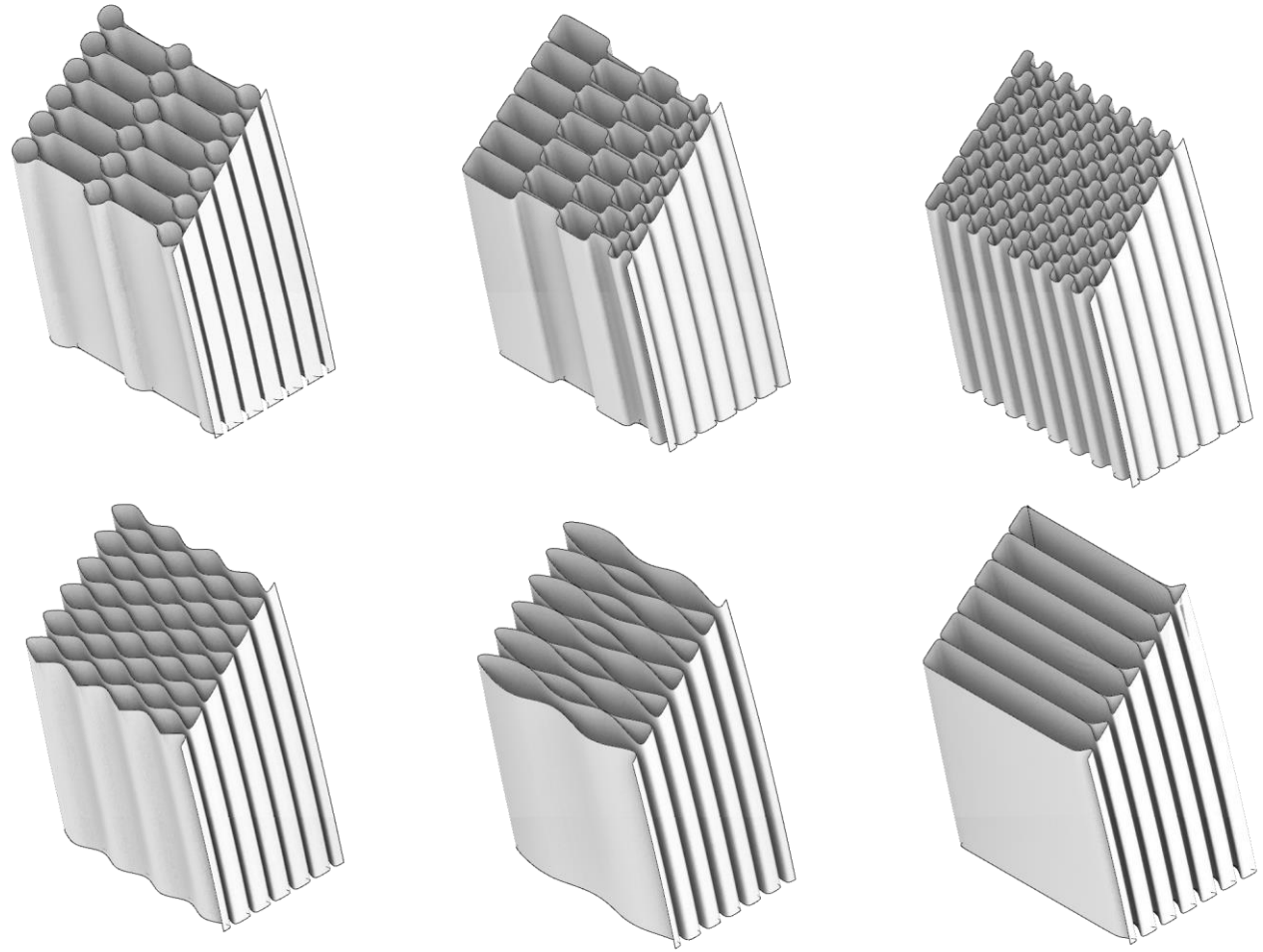
Infill requirements:

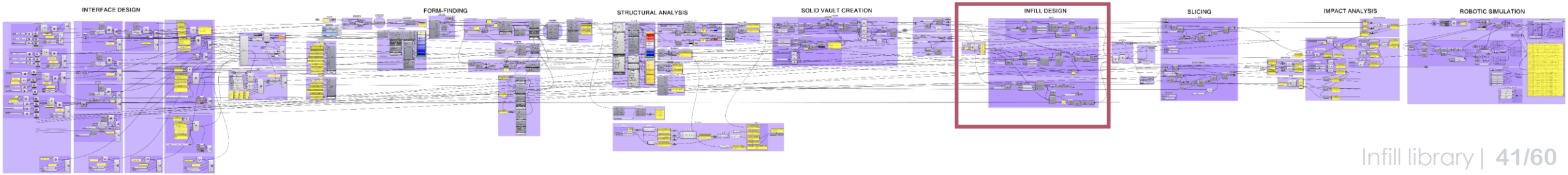
- **Sufficient infill density** (strength parameters)
- **Lateral stability** (alignment to principal stresses)
- **Constant speed for optimal deposition** (gradual transitions in corners)
- **Continuous lines with optimal overlapping** (nozzle dimensions)
- **Increase layer adhesion and buckling resistance** (through toolpath height, orientation, nozzle design)







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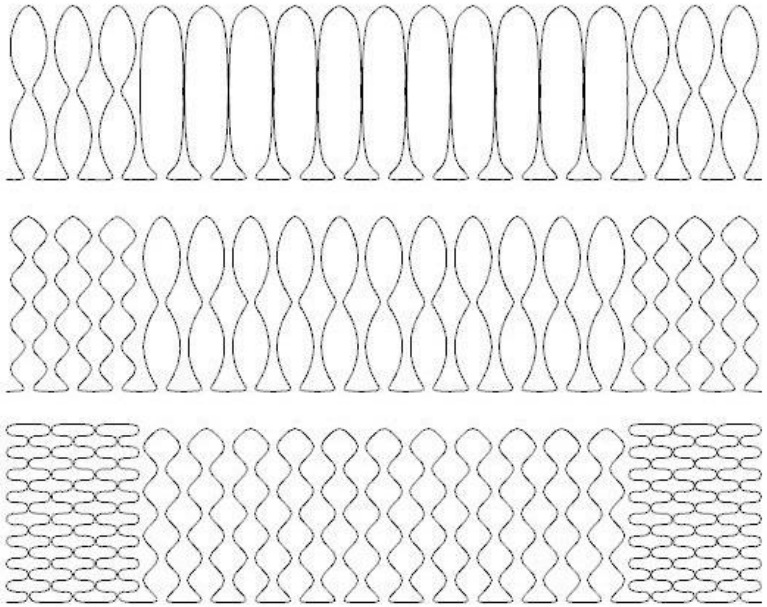
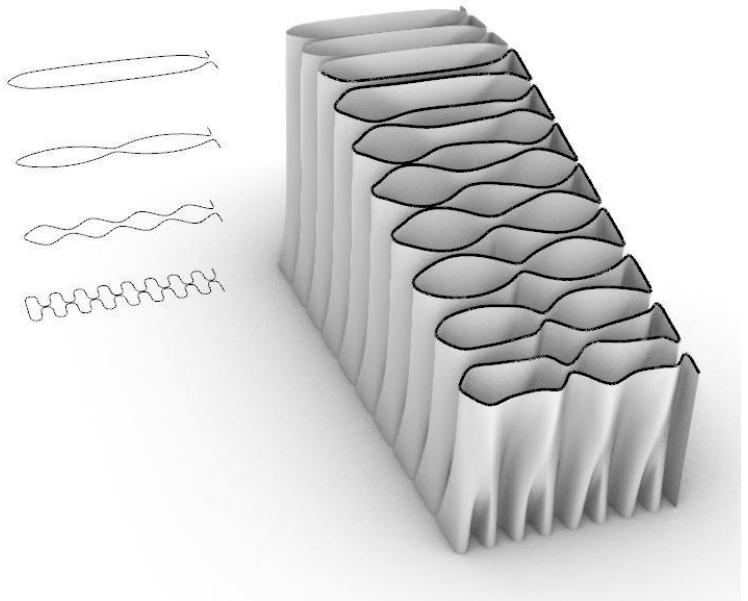


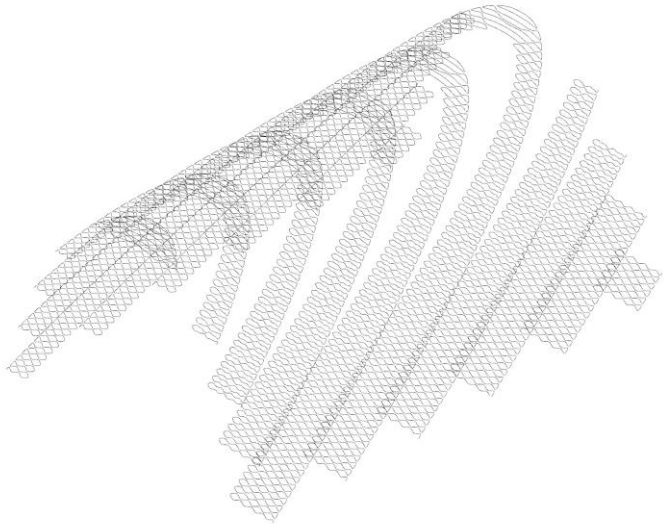
Modular infill
(adaptable use)

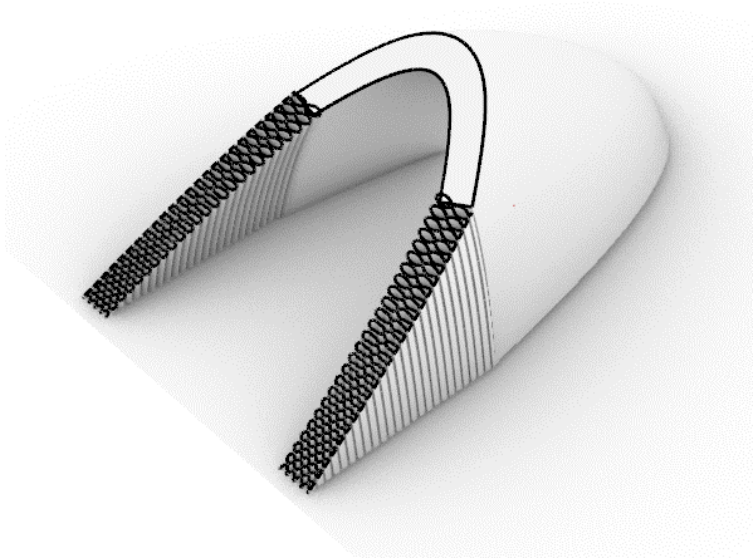


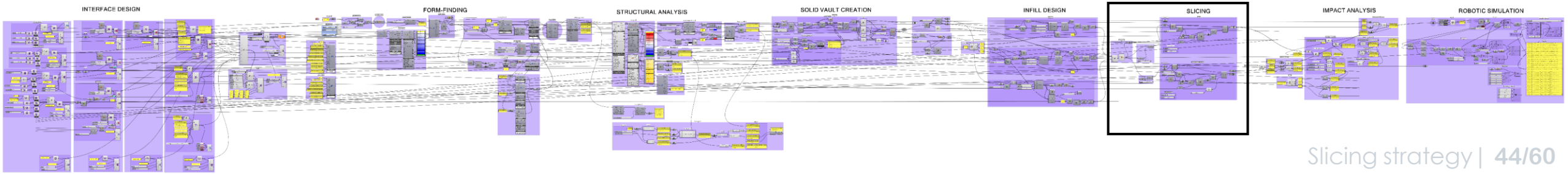
Varying infill (local performance)

INNOVATION inspired by TRADITION ?

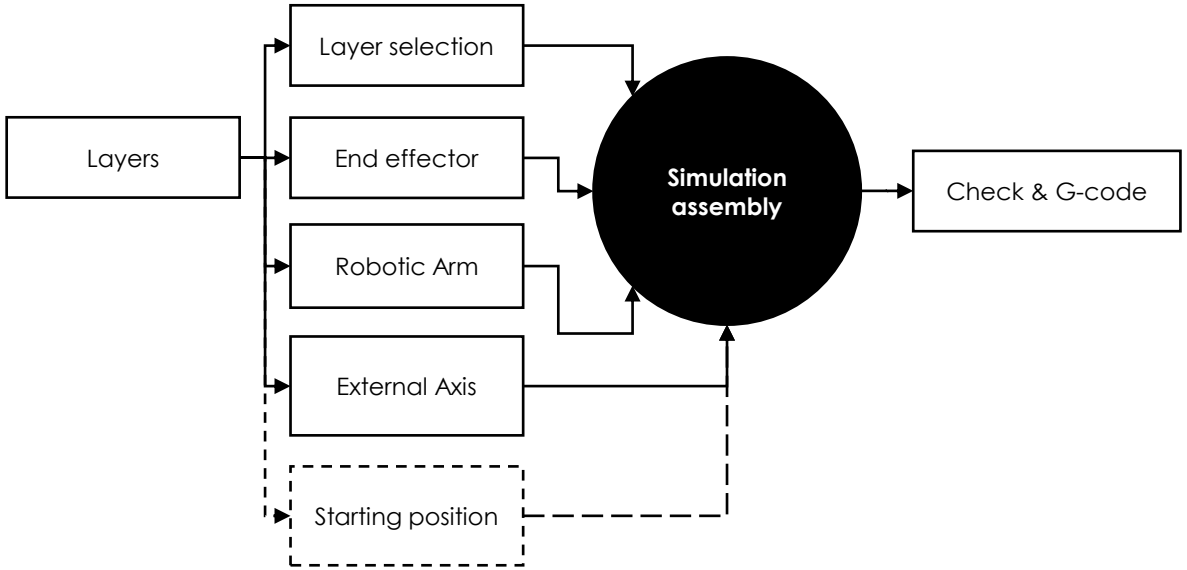
Nubian vault under construction showing guide lines for form, Aga Khan Award for Architecture (2009)

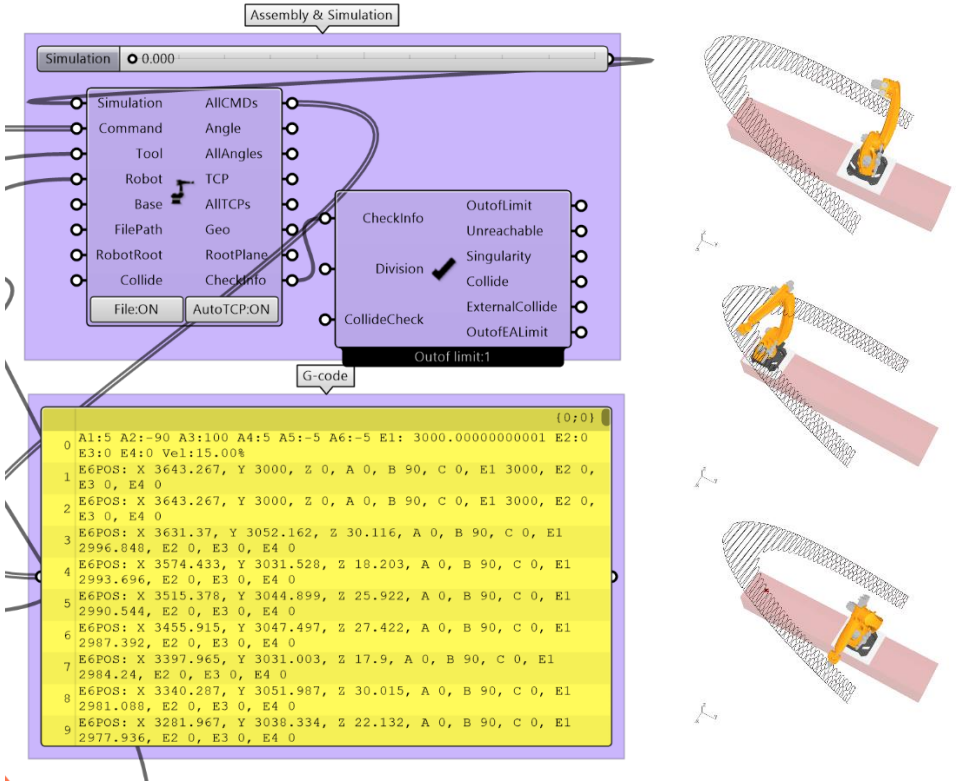


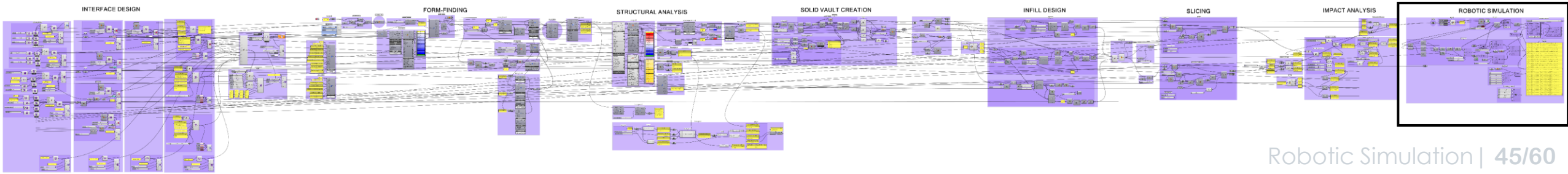


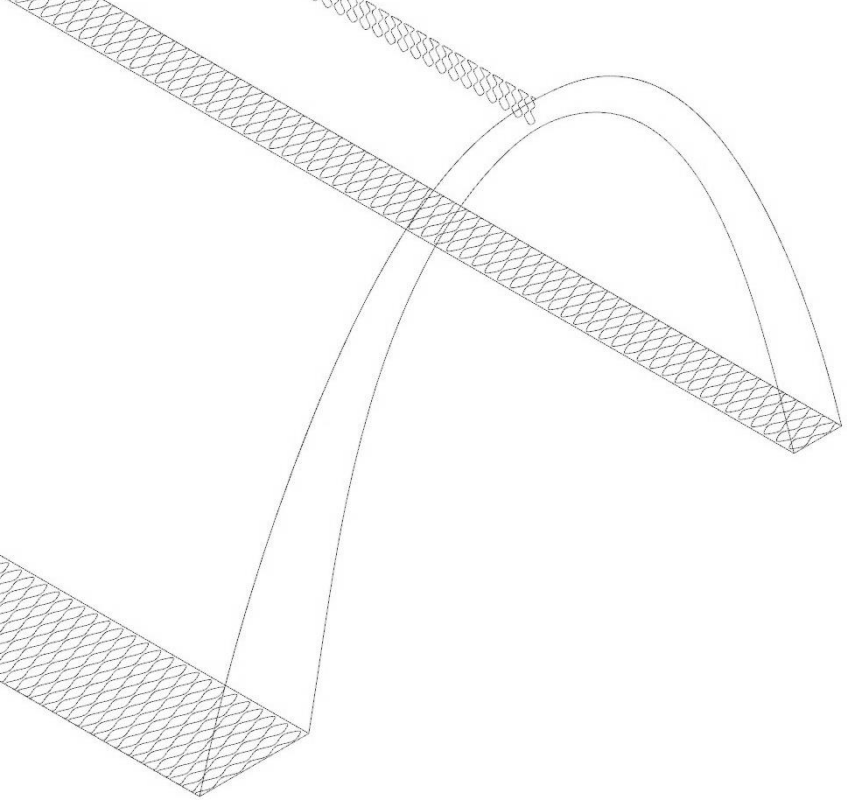


Robotic simulation



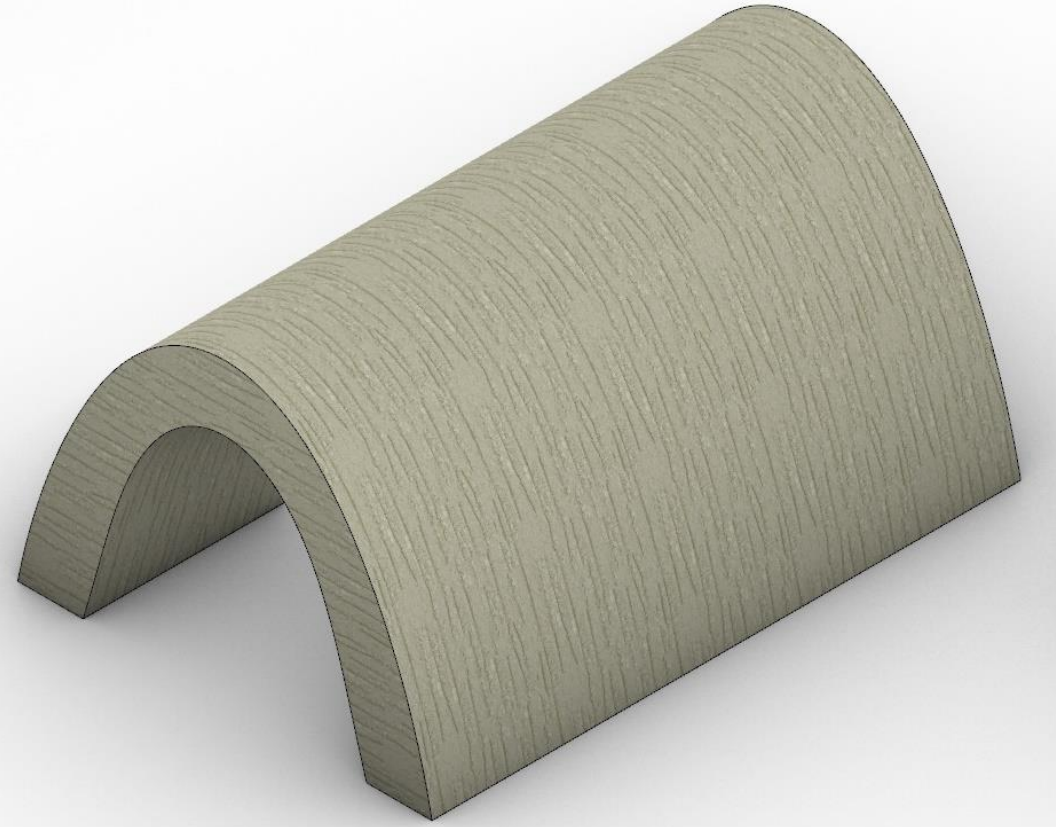


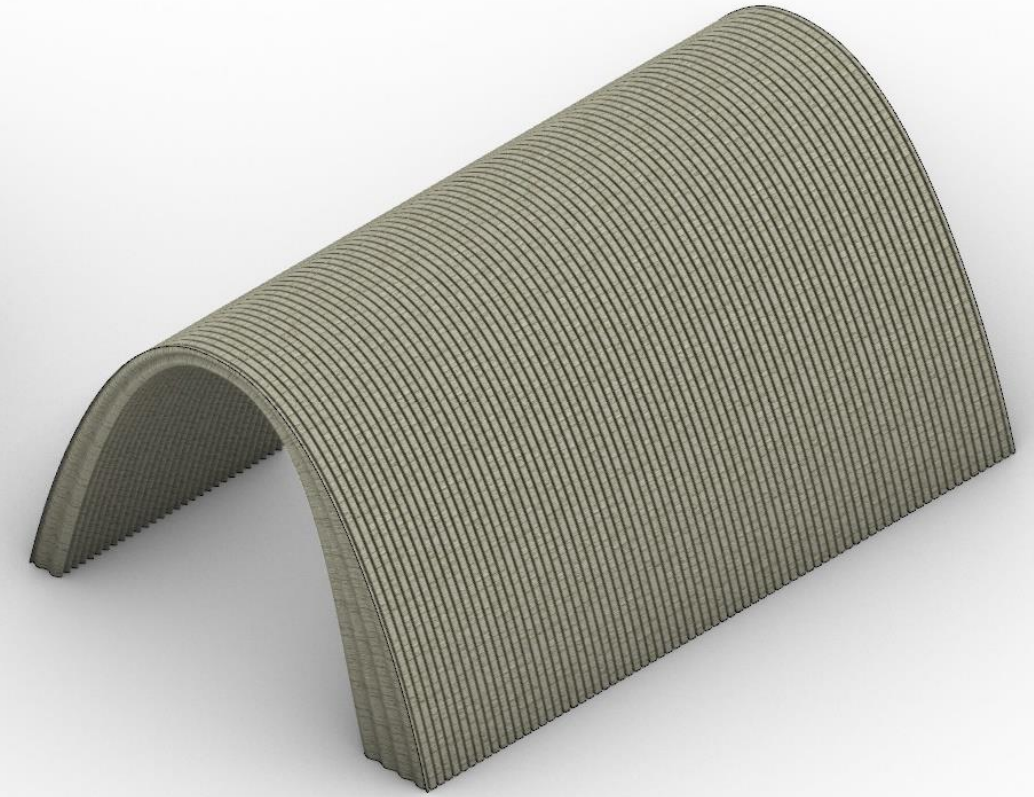




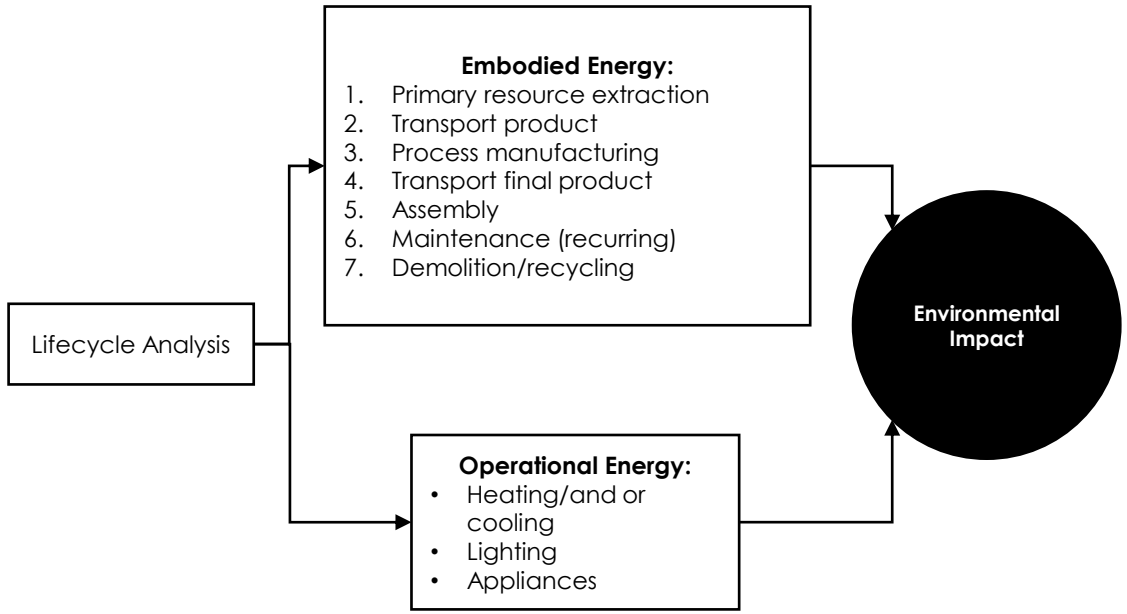
1:20
Aligned
infill
printing

1:100
“Nubian”
inspired
printing

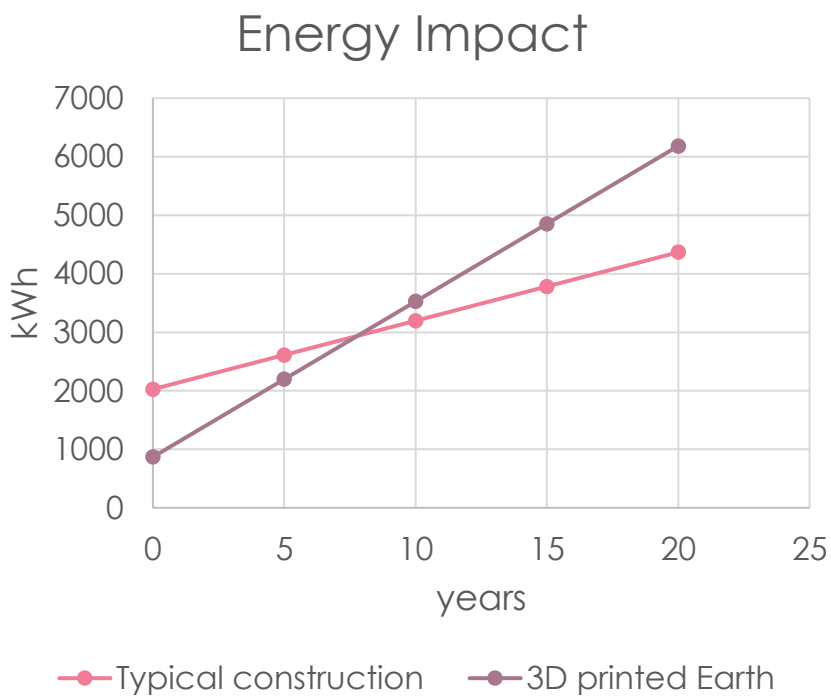


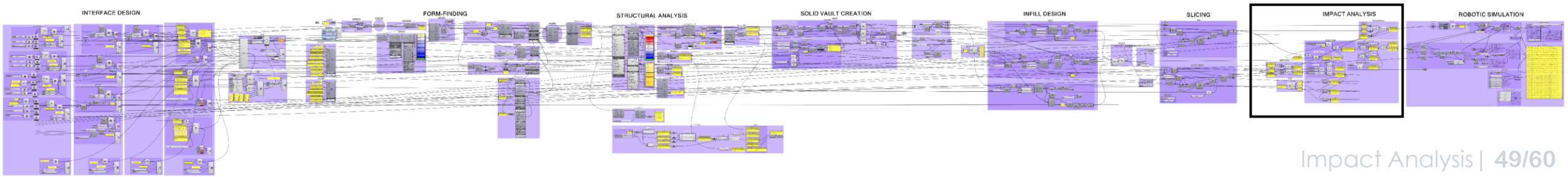


Mass before optimization: 39410.8 [kg]
Mass after optimization: 16970.8 [kg]
Reduction: 56%



	Embodied Energy [kWh/m2]	Embodied Carbon [kgCO2e/m2]	Operational Energy [kWh/m2 per year]
Typical construction	1440.5	486.77	117.16
3D printed earth	873	52	265.6





GEOMETRY PARAMETERS

Width 3.20

Length 5.40

Height 2.40

THICKNESS PARAMETERS

Left 0.270

Top 0.150

Right 0.620

INFILL PARAMETERS

Percentage 75

Pattern 3

Layer height 0.015

Layer width 0.015

CONSTRUCTION PARAMETERS

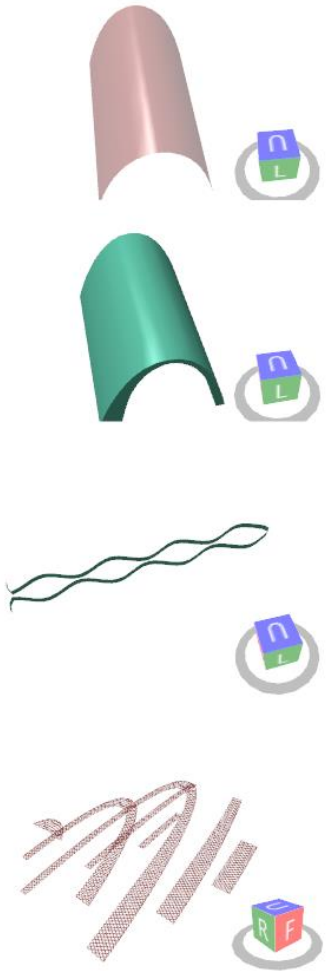
Mixture 65-35-30

Slicing angle 30

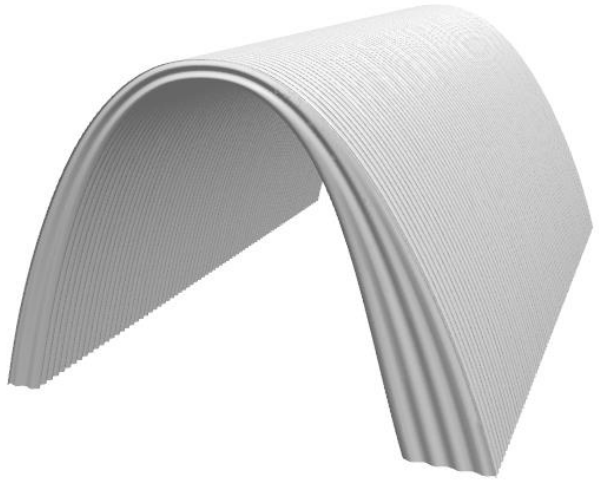
Printing speed [m/s] 0.02

Life time 8

PARAMETERS

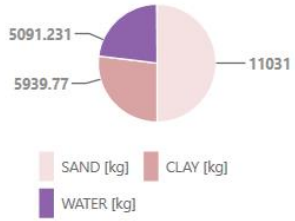


FORM EVOLUTION



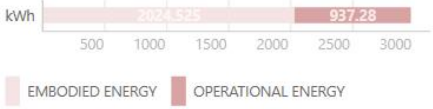
FINAL FORM

MATERIAL USE



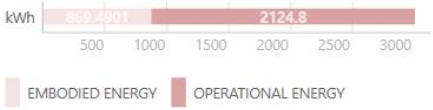
ENVIRONMENTAL IMPACT

STANDARD CONSTRUCTION

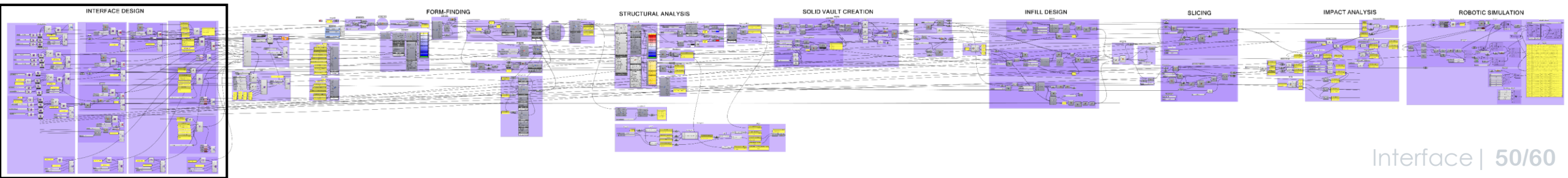


ENVIRONMENTAL IMPACT

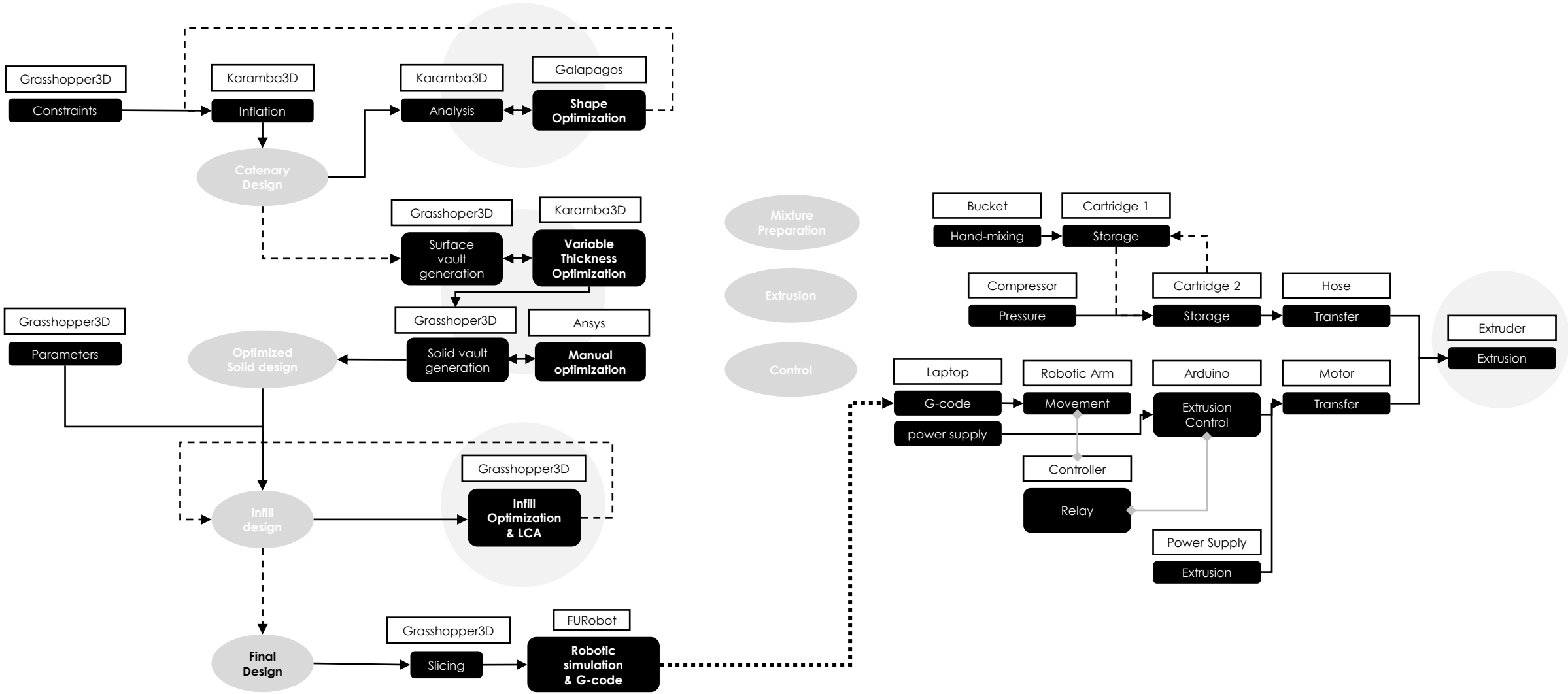
EARTHEN BUILDING

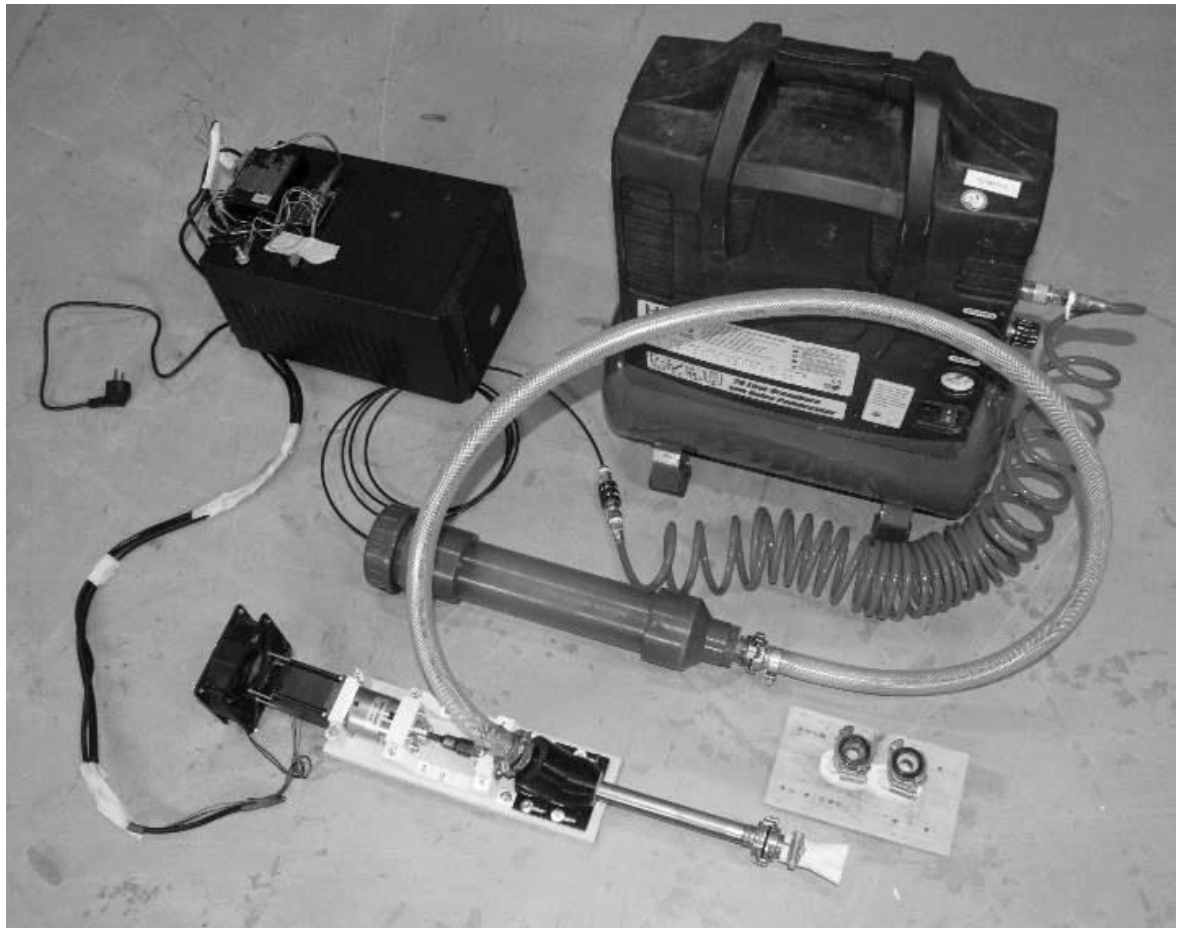


IMPACT ANALYSIS



Complete setup





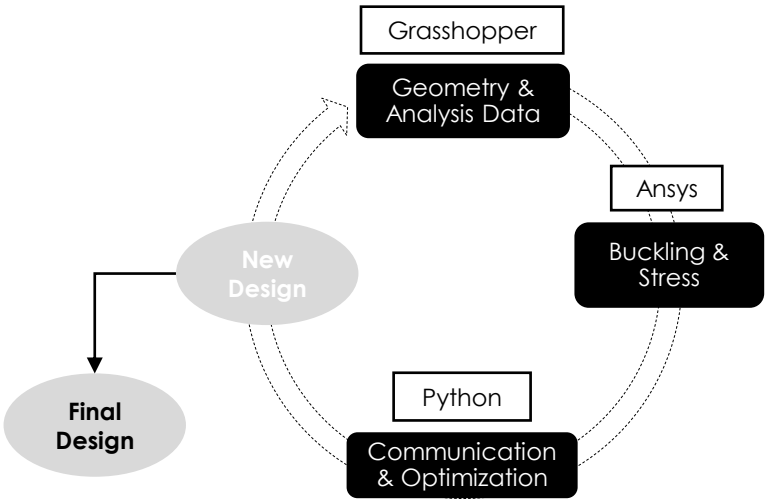
I. Imperfections
- Printing discontinuity (finite setup)
- Layer adhesion (e.g. lubrication)

II. Printing setup
- External axis

III. Printing speed
- Aging properties
- Extrusion system (snail)

IV. Material
- Additives
- Multi-material printing
- Sustainability

V. Standardization
- Workflow
- Conditions (environment)



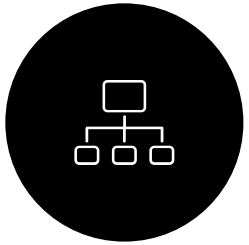
I. Form
- Stiffness
- Load case

II. Infill
- Monofunctional
- Analysis

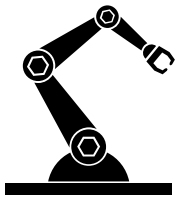
III. Robotic simulation
- Synchronization
- Substructure
- Sustainability

IV. Structural Evaluation
- Solid geometry (quadrangulation)
- Linear

V. Impact & Cost
- Criteria
- Database



1. **Design workflow** development with
    a. **Structural optimization,** as performance criterion
    b. **Shell structure,** as the investigated geometry



2. **Robotic fabrication workflow development** with
    a. **Additive manufacturing**, as a construction method
    b. **Earth,** as a structural material

“What are the **advantages and limitations of using earth** in RAM? What is the effect of material parameters (mixture design /kiln /drying time) in the **mechanical properties** of the component and what are the required material qualities for the proposed setup?”

I. **Advantages**
- Global availability
- Recyclability
- Thermal mass
- Extrudability

II. **Limitations**
- Water resistance
- Limited strength
- Lack of standardization
- Prejudice

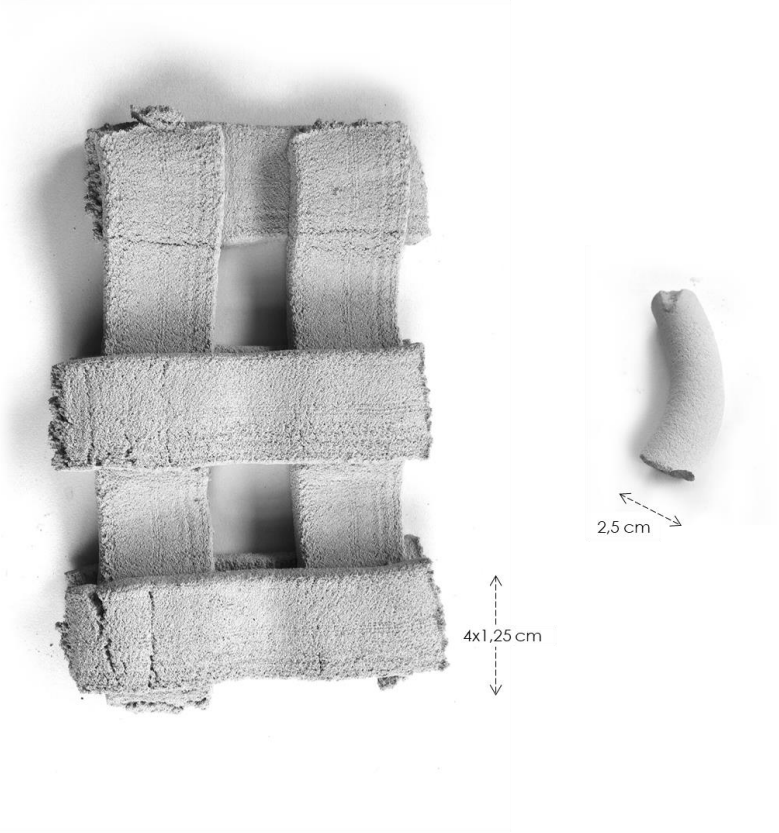
III. **Material Guidelines**
- Moisture content (close to Plastic Limit) while Extrudable
- More clay >>> higher cohesion, surface bonding, shear strength, plasticity, surface finish
- More sand >>> higher compressive strength, better shrinkage behavior
- Mixture homogeneity

IV. **Kiln**
- Increased strength
- Segmentation & assembly
- Energy intensive

V. **Drying time**
- Layer bonding
- Aging properties

VI. **Material qualities**
- Clay 35 to 50 %
- Earth 65 to 50 %
- Water 25 to 35 % (of dry components)

“What are the **design and performance criteria** involved in designing a robotically 3D printed component out of earth? What is **the effect of printing parameters** (infill percentage & pattern, layer height & direction, extrusion speed)?”



I. Material properties terminology

- Buildability (Compressive / Buckling / Shear strength)
- Extrudability / Flowability (rheological properties)
- Open time (Layer adhesion, aging properties)

II. Infill pattern guidelines

- Alignment to stresses (lateral stability)
- Infill percentage (Young’s modulus E, maximum stress σy)

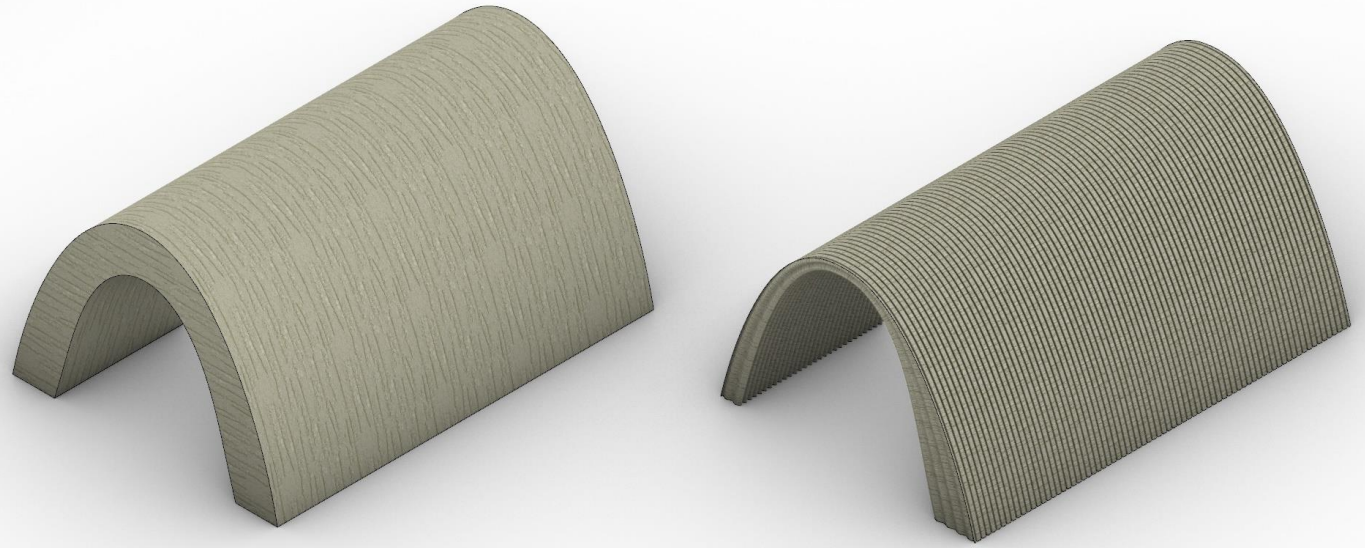
III. Slicing guidelines

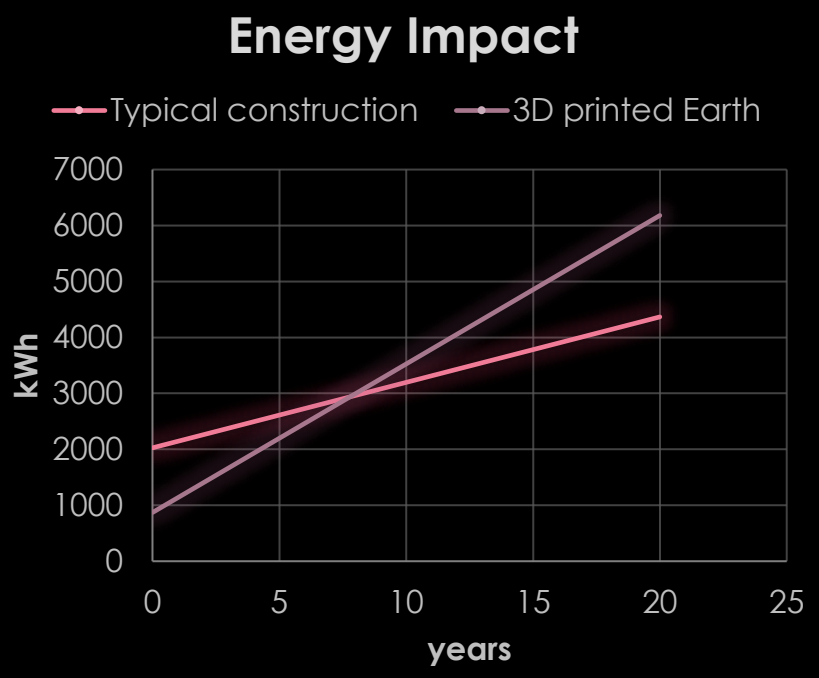
- Layer height (shear strength)
- Layer width (buckling strength)
- Direction (alignment to stress trajectories)

IV. Printing properties

I. Extrusion speed (open time)

“What is the projected **cost** and **environmental impact** of the proposed **construction**?”

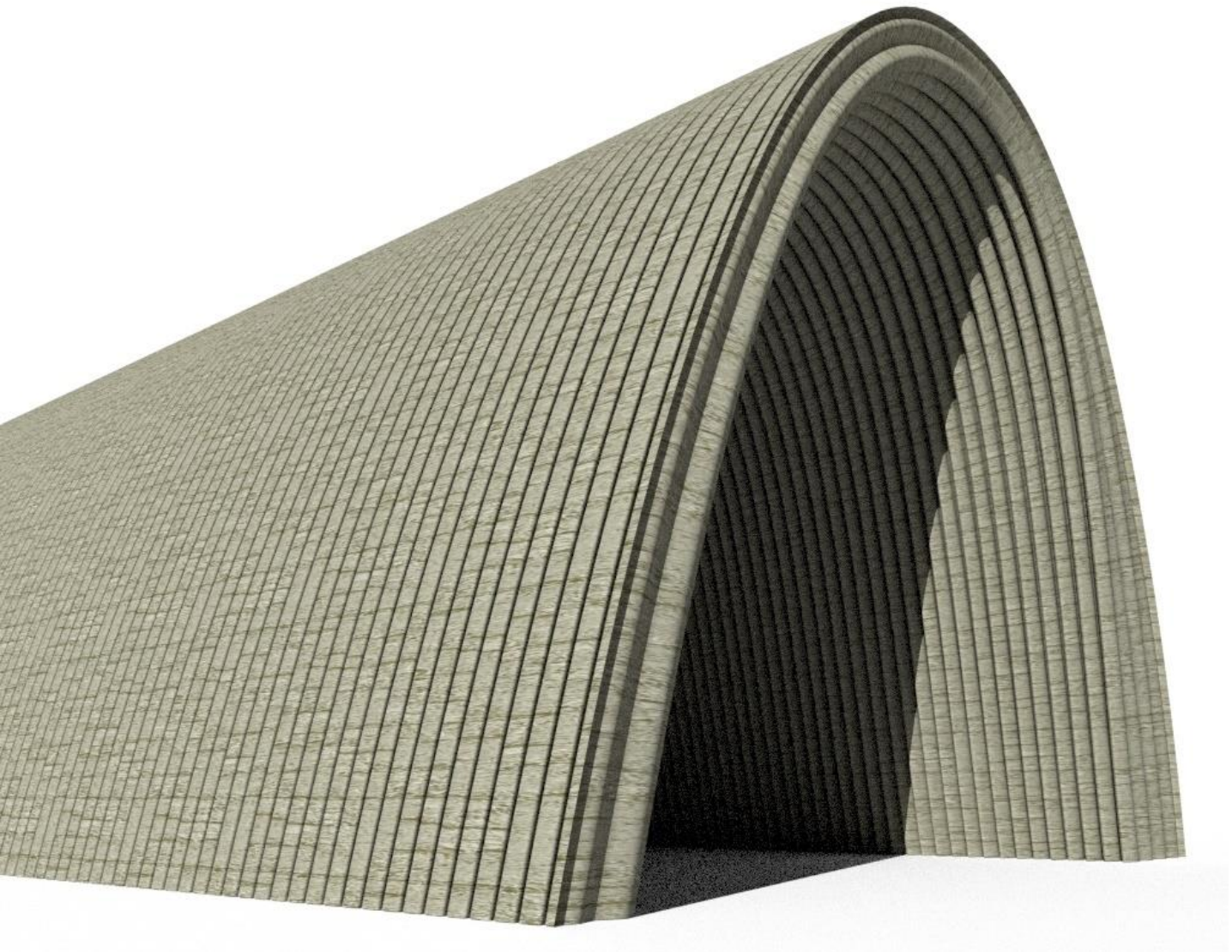




I. **System boundary**
   - Cradle to Grave

II. **Impact**
   - Embodied Energy: 869.5 [KWh]
   - Operational Energy (8 years): 2124.8 [KWh] (=660 EUR)

III. **Material reduction**
   - Up to 56% (compared to typical Nubian vault)



I. **Two-storey construction**
   - Slab over vault
   - Transverse openings

II. **Multi-storey construction**
   - Hybrid construction
     (e.g. structural timber)
   - Reinforcement integration

III. **Multi-objective optimization**
   - Comfort
   - Safety (Stability & Durability)
   - Sustainability

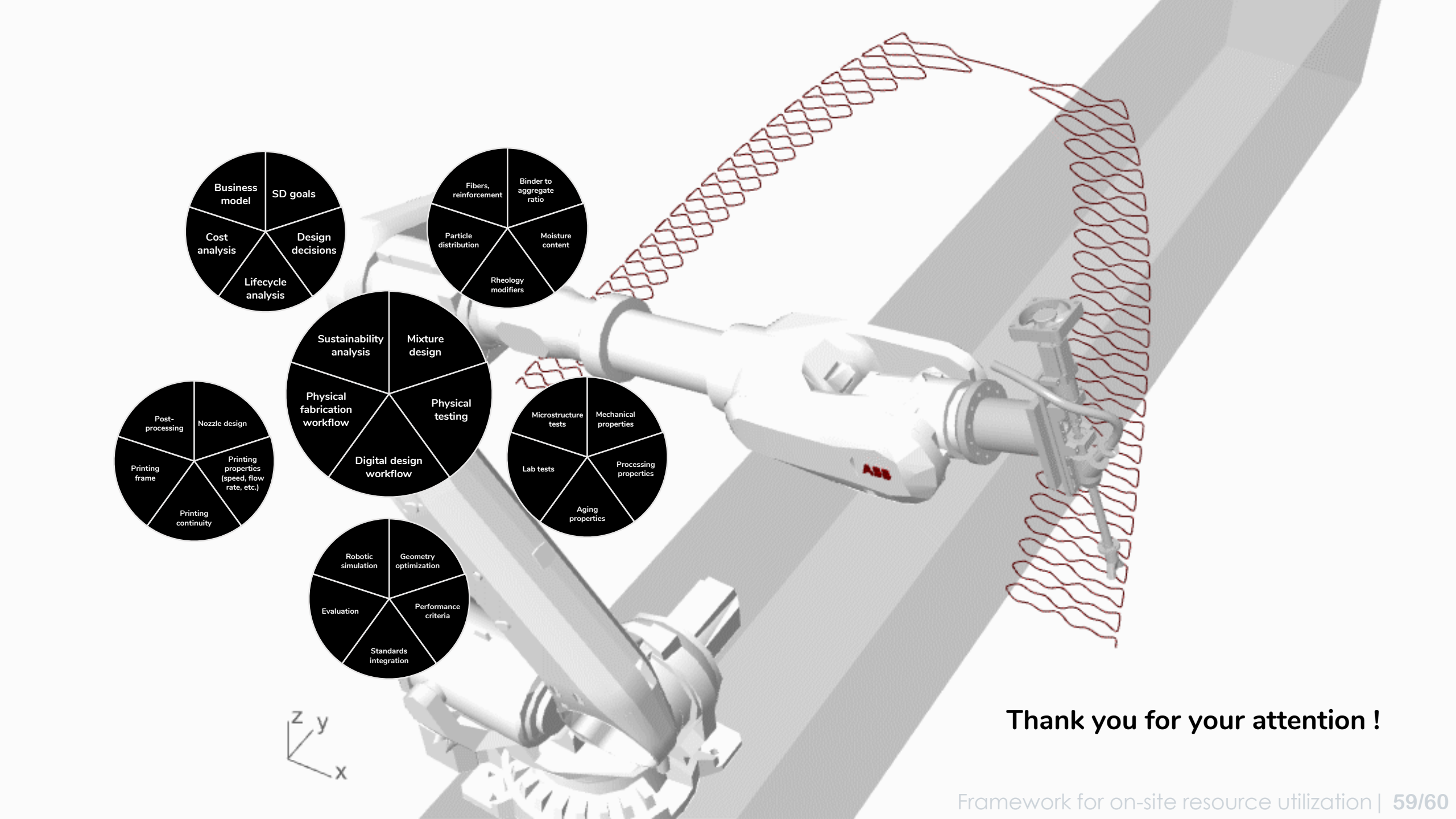
IV. **Analysis**
   I. LCA (Cradle to Cradle)
   II. Business model

From the ground up

https://youtu.be/1ataE-AWpAA

Robotic Additive Manufacturing (RAM)
of a structurally optimized earthen shell
through computational design

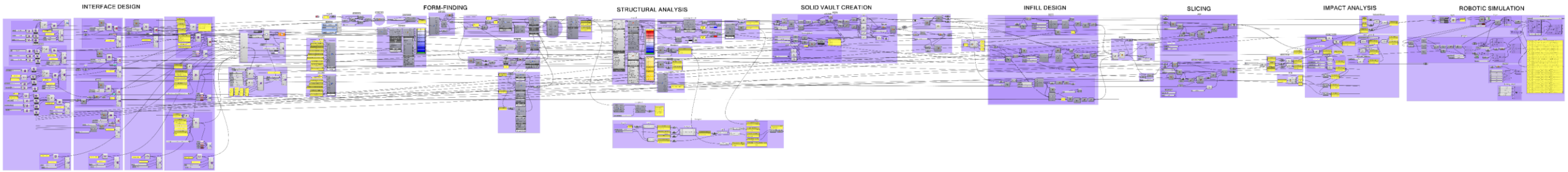
Athanasios Rodiftsis 4943295
TU Delft 2020



Thank you for your attention !

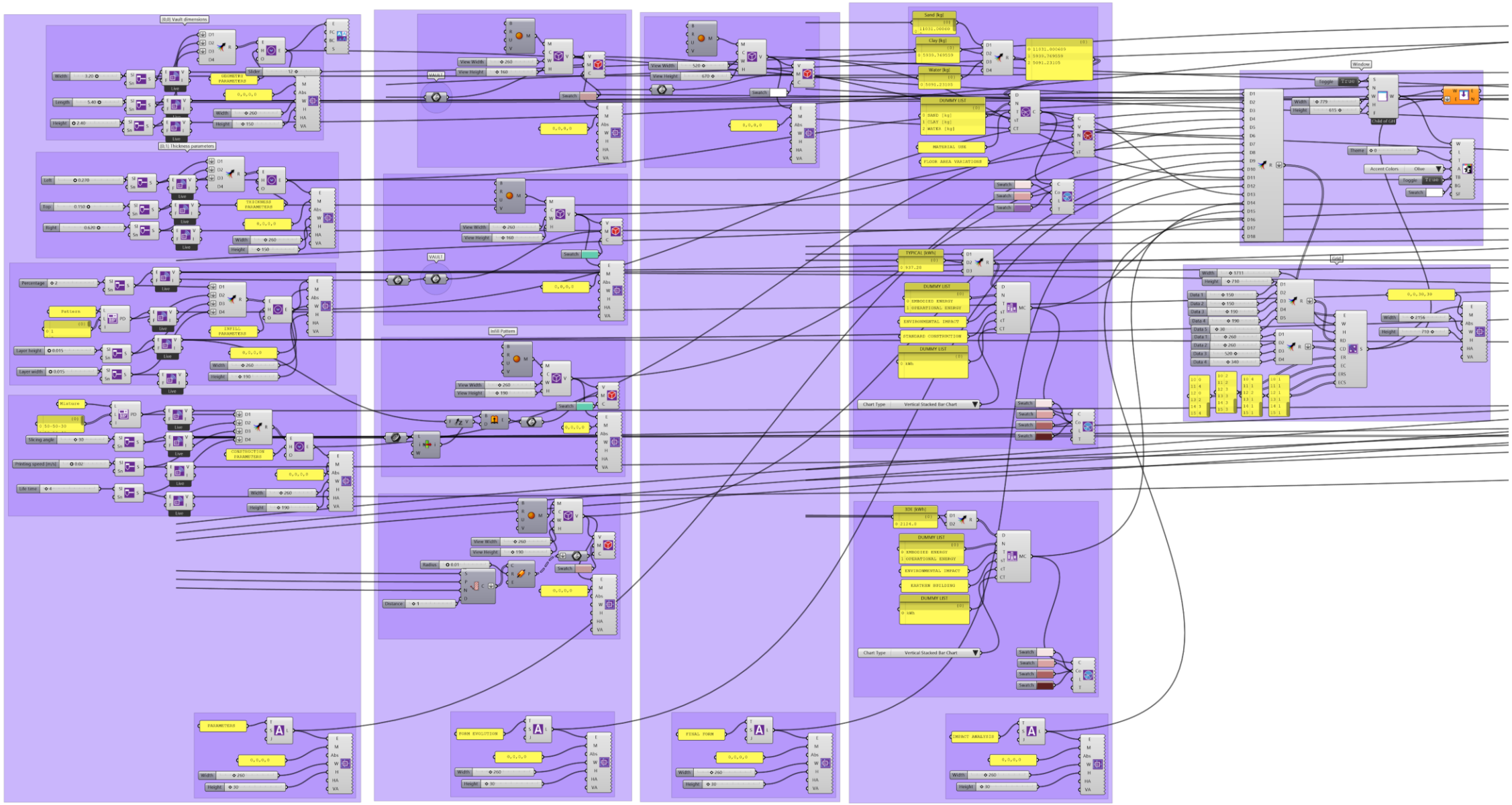
APPENDIX:

Grasshopper3D workflow definition



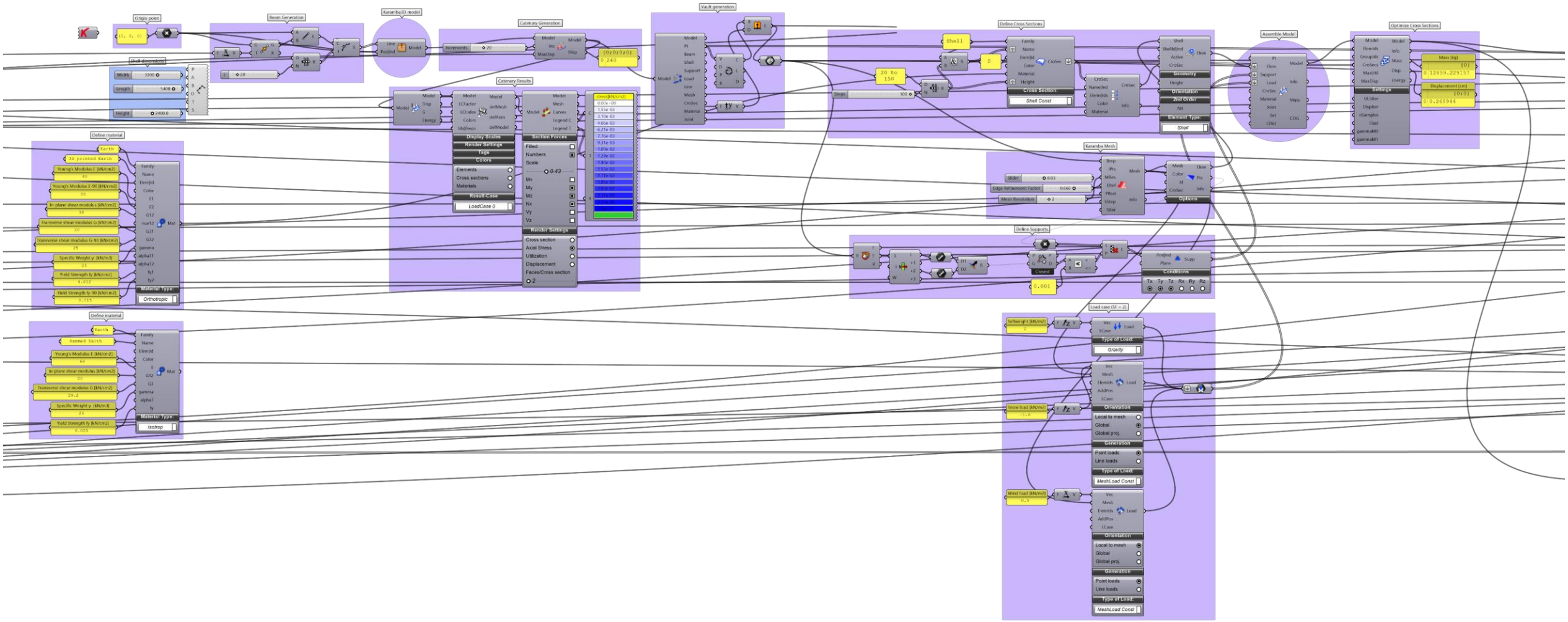
APPENDIX:

Interface definition



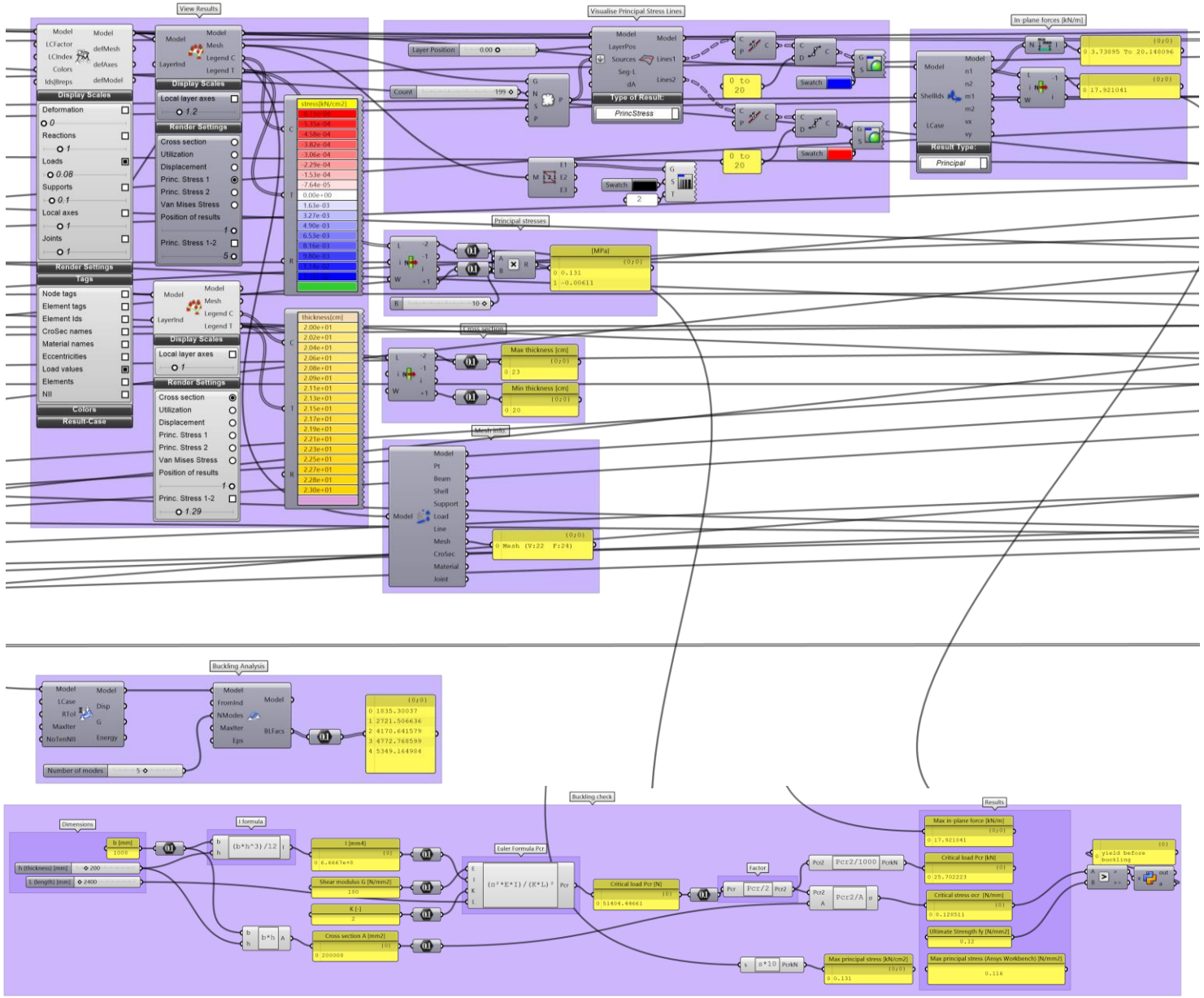
APPENDIX:

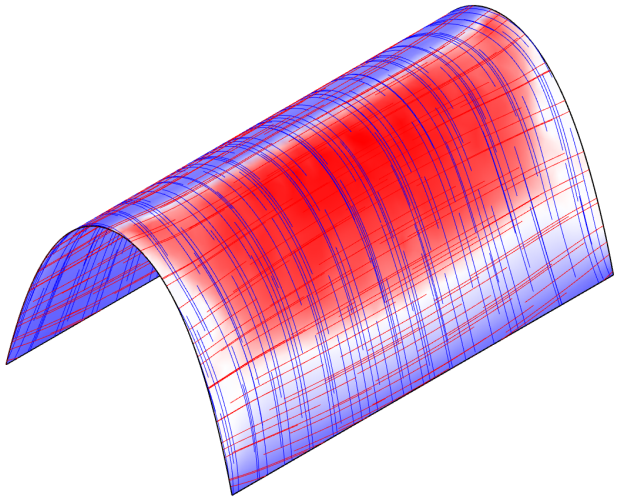
Form-finding definition



APPENDIX:

Structural Analysis definition

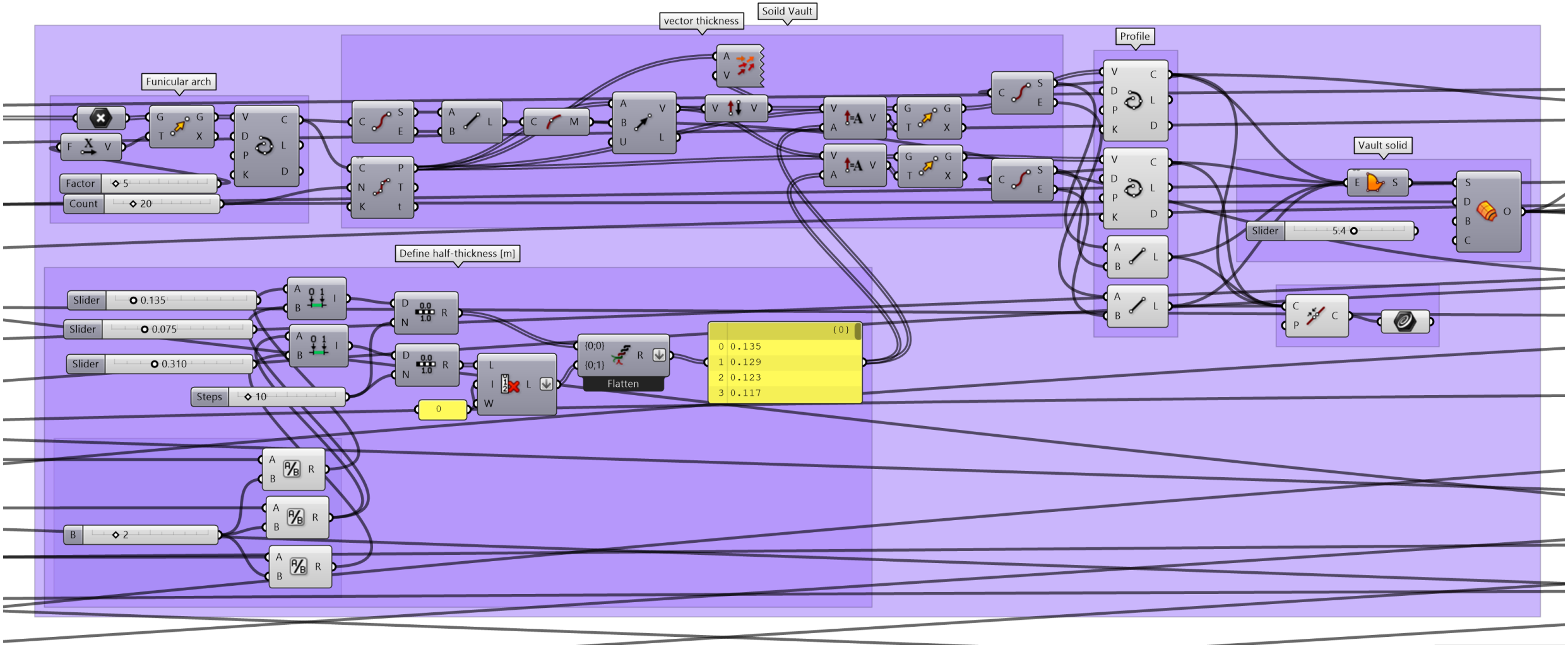




stress[kN/cm2]
-5.19e-03
-4.54e-03
-3.89e-03
-3.25e-03
-2.60e-03
-1.95e-03
-1.30e-03
-6.49e-04
0.00e+00
3.10e-03
6.20e-03
9.30e-03
1.24e-02
1.55e-02
1.86e-02
2.17e-02
2.48e-02

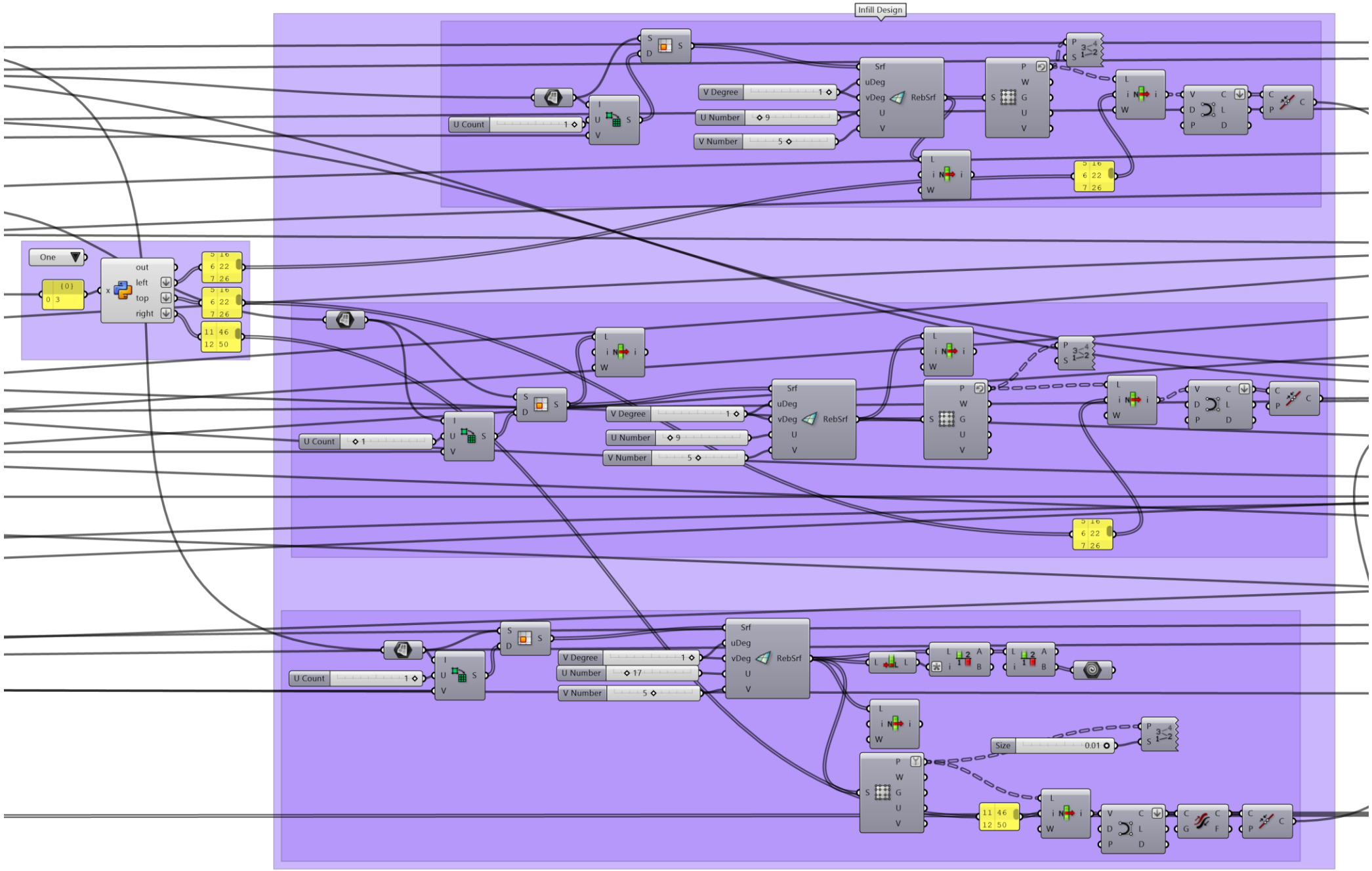
APPENDIX:

Solid Vault definition



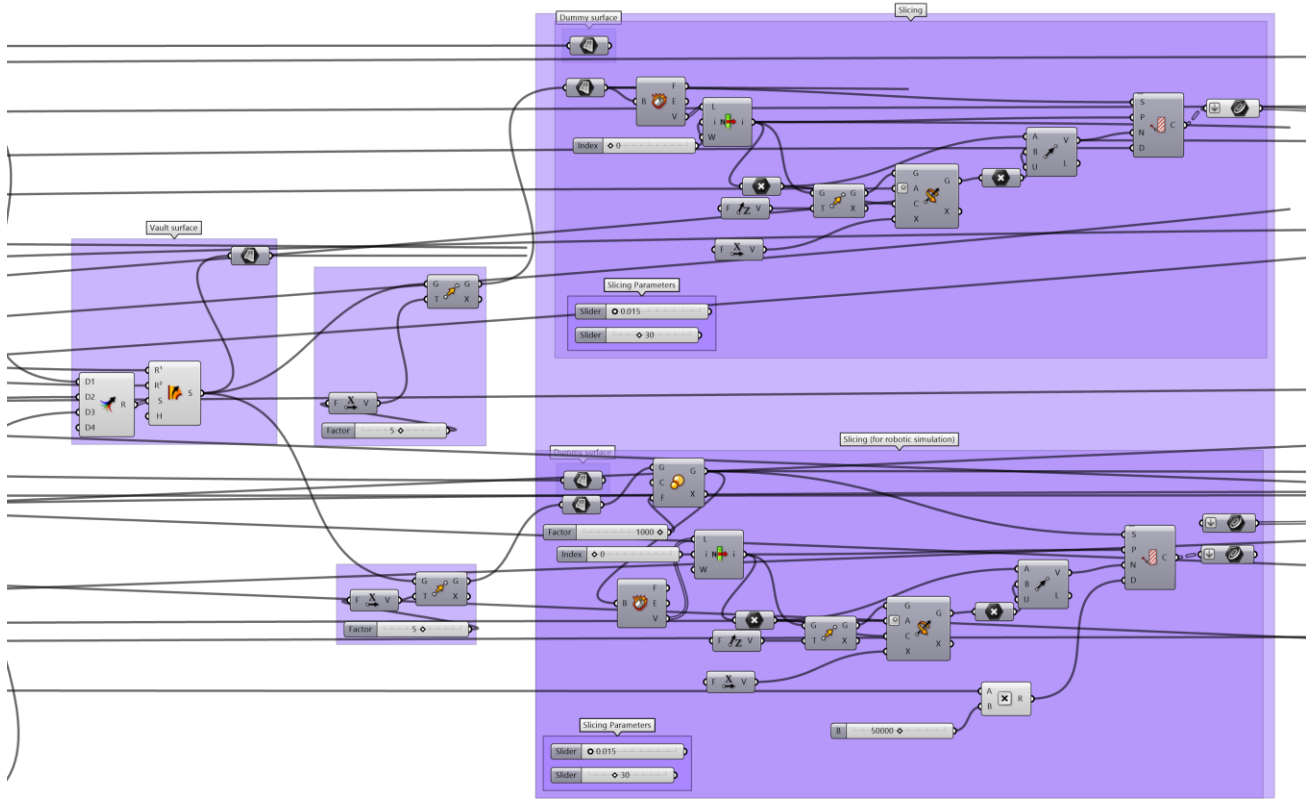
APPENDIX:

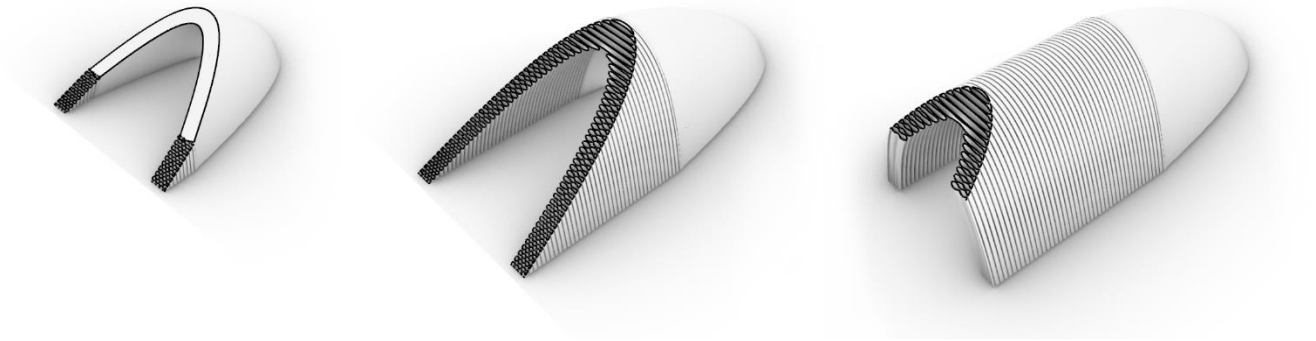
Infill definition

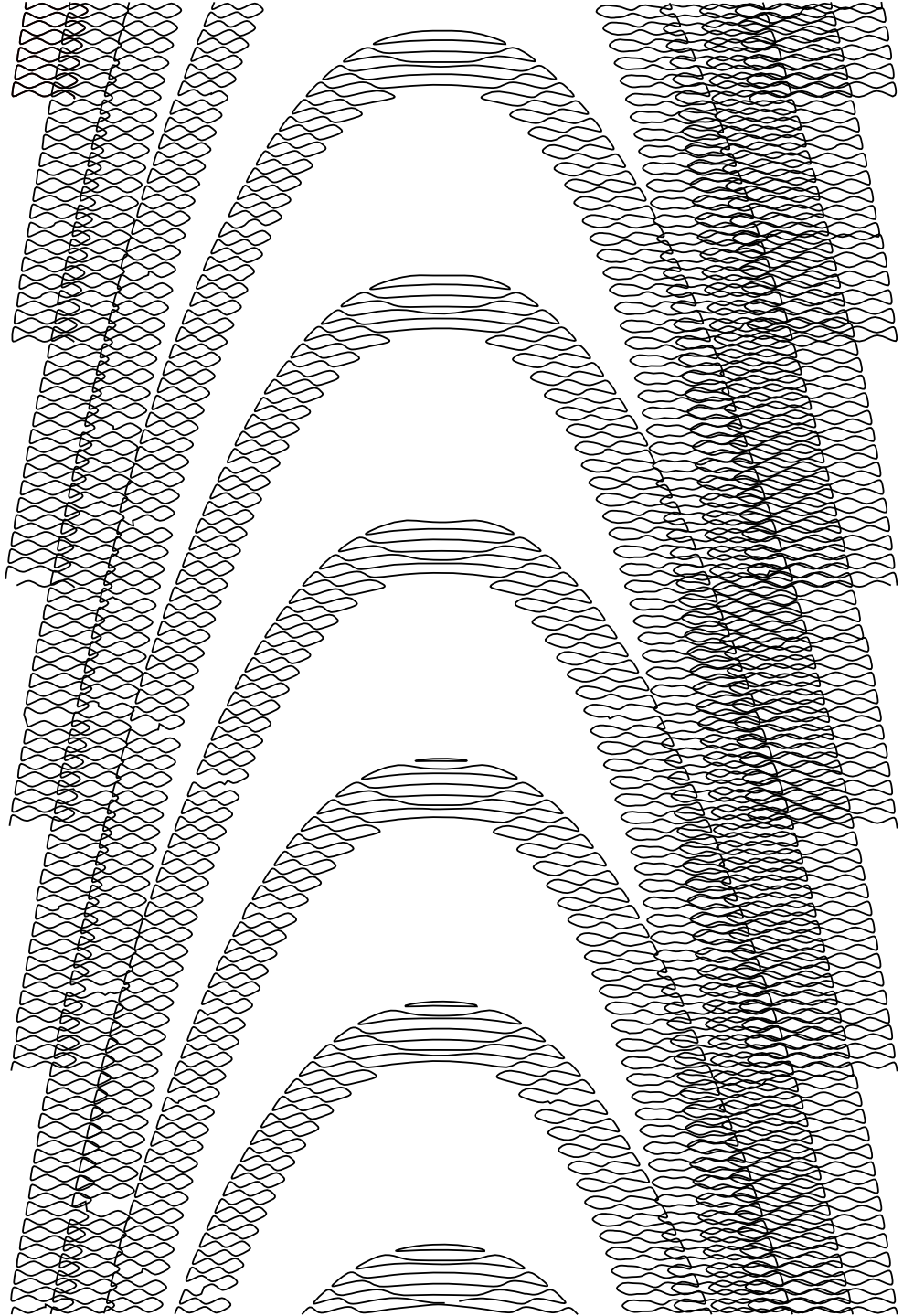


APPENDIX:

Slicing definition

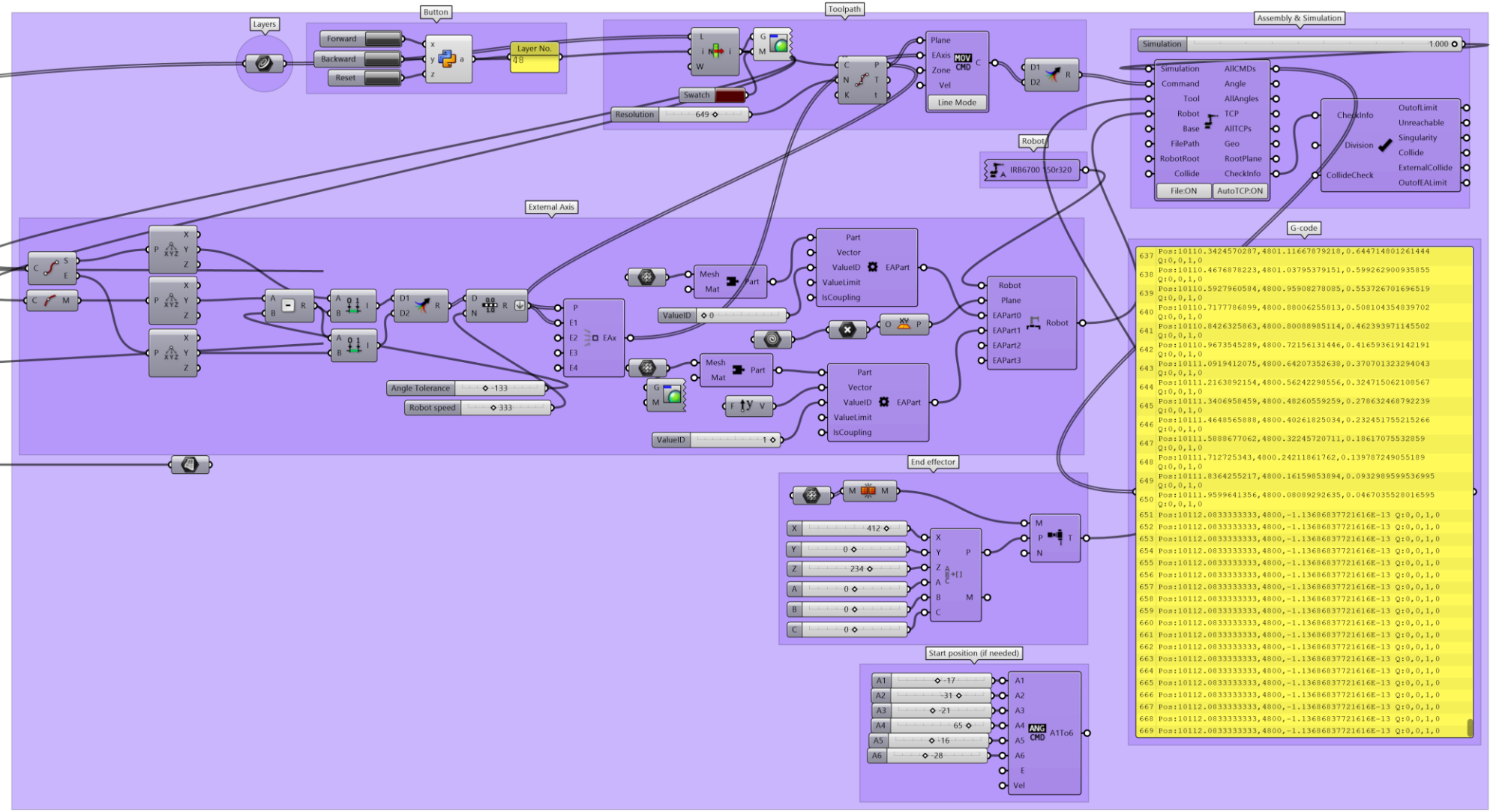


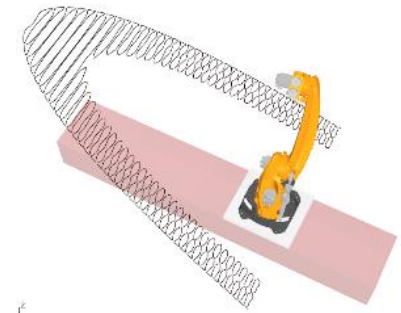


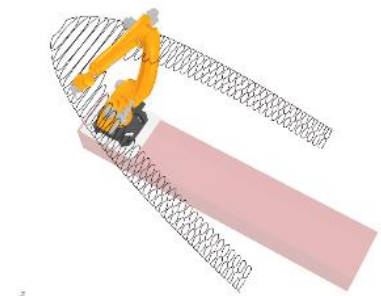


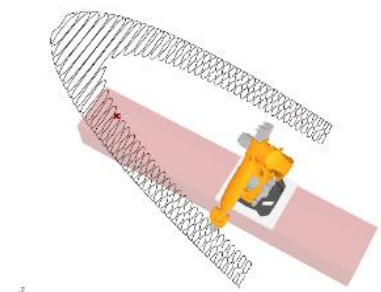
APPENDIX:

Robotic simulation definition









APPENDIX:

Impact analysis