

Digital Earthen Shelters

Additively Manufacturing Mass Customized Refugee Shelters Using On-Site Earthen Materials

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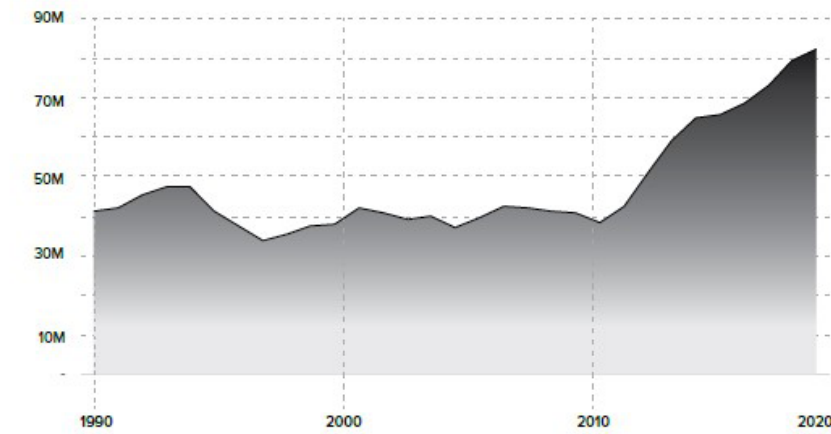
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Dr. Ir. Fred Veer

Examiner Ir. Robert Nottrot

Problem Statement

82.4 MILLION

FORCIBLY DISPLACED WORLDWIDE
at the end of 2020 as a result of persecution, conflict,
violence, human rights violations or events seriously
disturbing public order.



26.4 million refugees

20.7 million refugees
under UNHCR's mandate

5.7 million Palestine refugees
under UNRWA's mandate

48.0 million internally displaced people¹

4.1 million asylum-seekers

3.9 million Venezuelans displaced abroad²

Source: UNHCR 2020

Problem Statement



Source: US Department of State

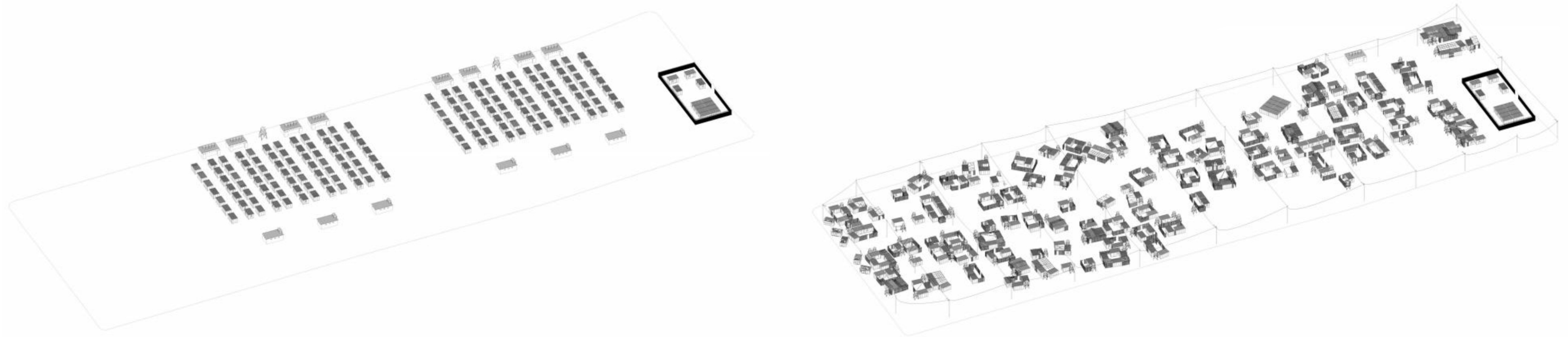
Problem Statement



INADEQUATE HOUSING

Source: NRC 2017

Problem Statement



SELF-ORGANIZATION

Source: Madi 2017

Problem Statement



MASS CUSTOMIZATION?

Source: Designboom / Ronald Rael

Problem Statement



BUILDING MATERIAL?

Problem Statement



**BUILDING MATERIAL?
EARTH!**

Research Question

How can **additive manufacturing** be employed in creating **mass-customized refugee shelters** using **on-site earthen materials**?

Secondary Research Questions



What are earthen materials? How are they used in construction?

What is the composition of earth found on site in the cases of Zaatari and Azraq refugee camps?

What additives need to be incorporated into the material mixture in order to create printable structures using earth?

How do the different earth mixtures perform in terms of extrudability, shrinkage, cracking, ... etc.?

Secondary Research Questions



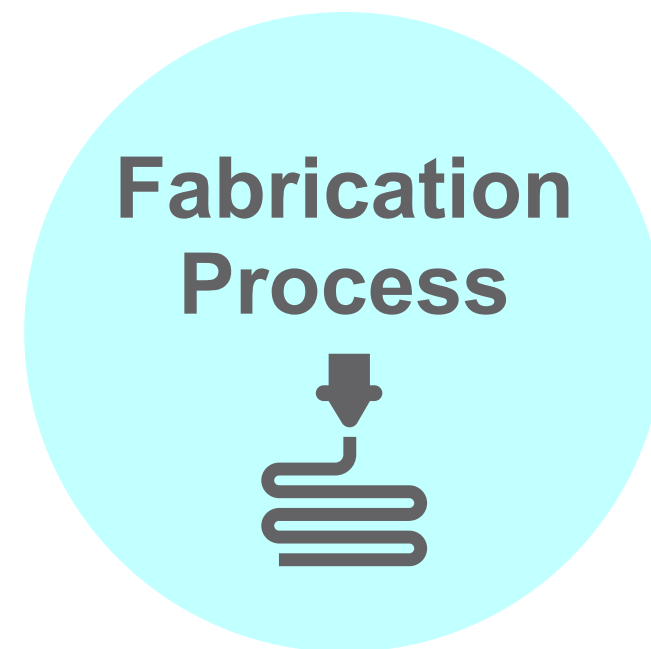
What are the user needs of refugee families for shelter designs?

How can shelters be designed to accommodate user needs?

How can user needs be translated into mass-customized designs using computation methods?

How can these designs be optimized for fabrication using additive manufacturing?

Secondary Research Questions

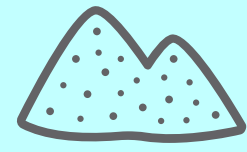


Which printing methods and machines allow for quick deployment and low cost execution of the proposed shelter designs?

What does the printing process look like from extracting the material until producing the prototype?

Objectives

Material



Investigate material properties of earth found on-site (earth samples from camp location)

Experiment with Additives and optimize mixture for printability and strength

Shelter Design



Identify refugee and shelter needs to influence design parameters

Develop a generative dwelling design tool for refugee shelters that can produce customized designs in-situ and create printing toolpaths

Produce prototypes for iterations generated by design tool (PLA)

Fabrication Process

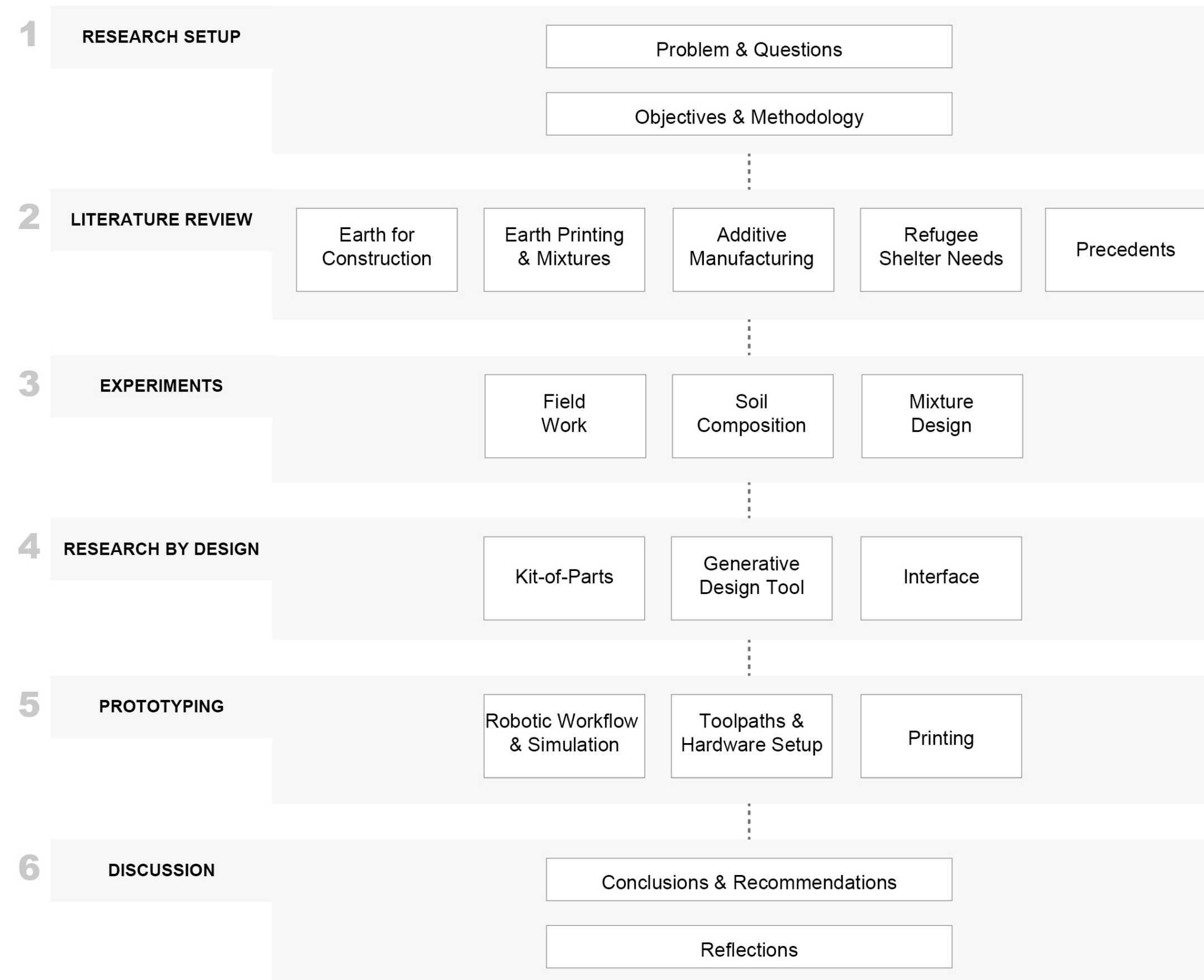


Identify most suitable additive manufacturing process and machine

Generate printing toolpaths and test with generated designs

Produce prototype for small part of example dwelling wall as a proof of concept using earth mixture

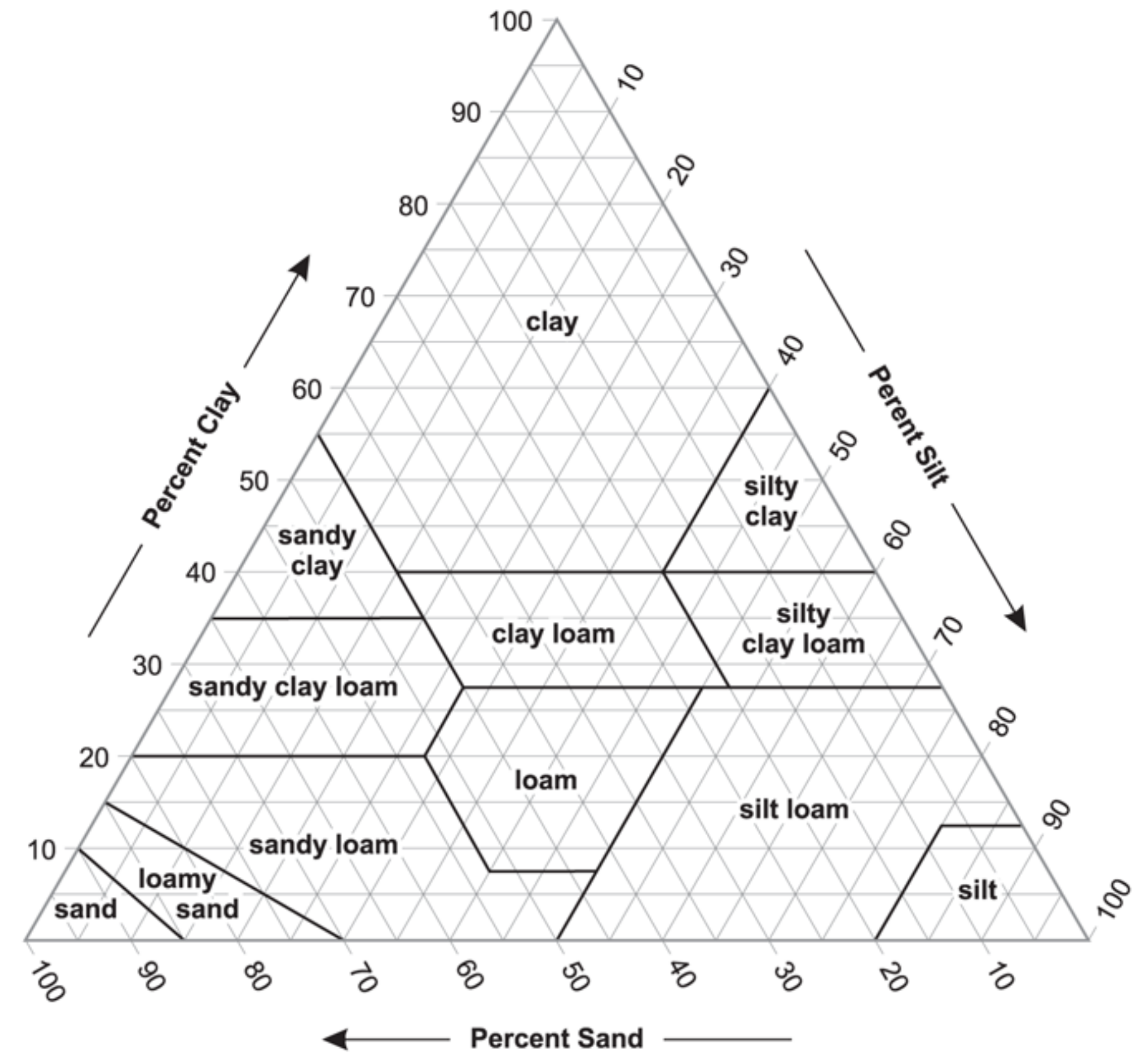
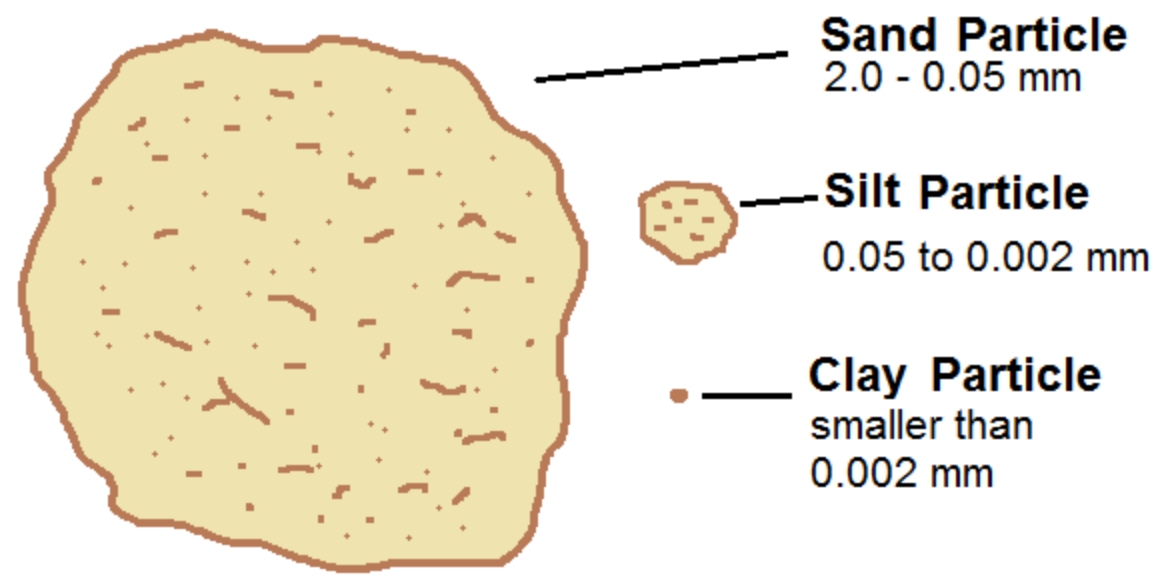
Methodology



Material

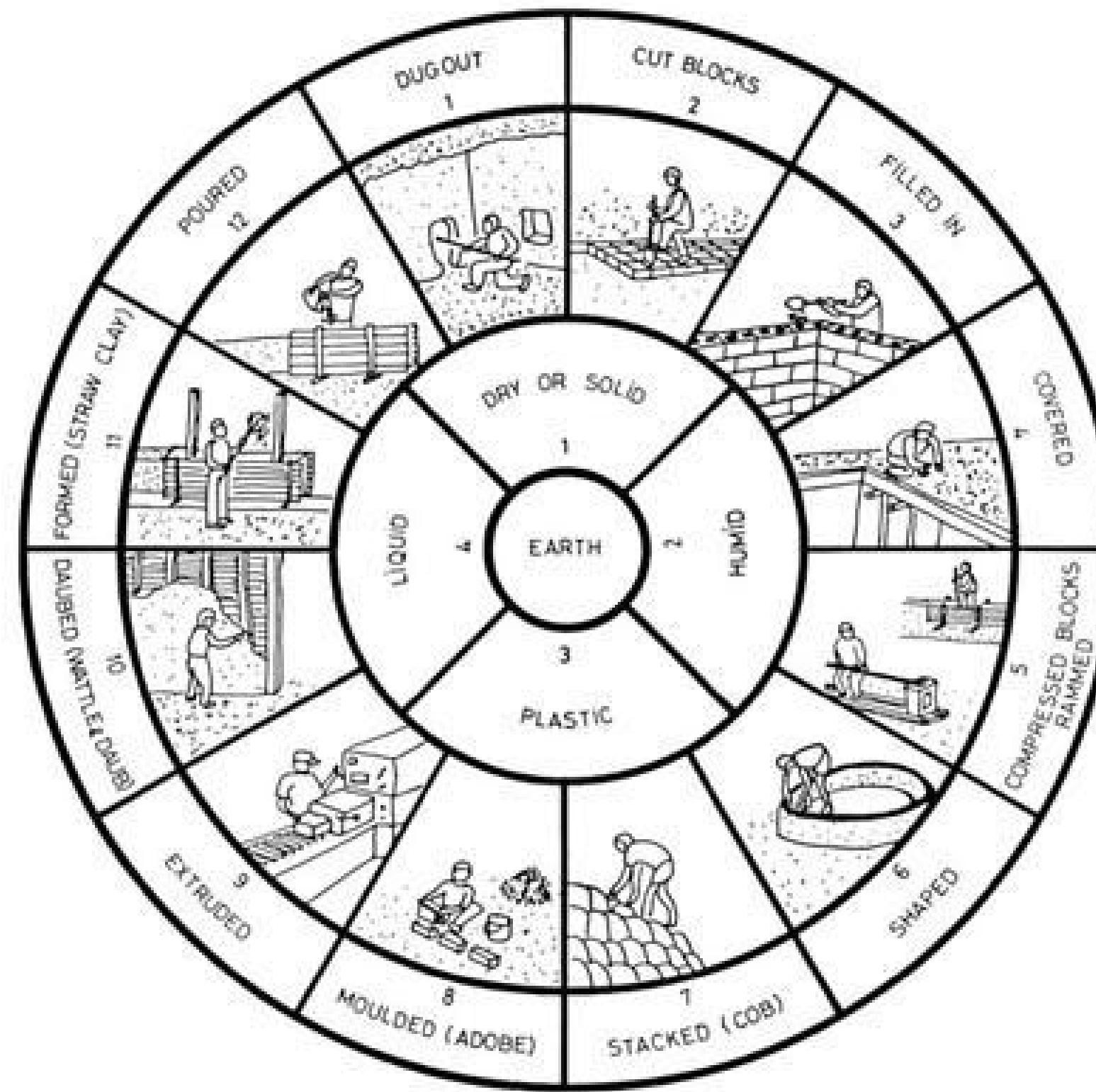


Properties of Earth



Source: USDA 2017

Earth in Construction



Source: Giuffrida, Caponetto, & Cuomo, 2019

Historic Precedents



Corbelled Dome Villages in Syria

Communal Building

Transition from Square to Dome

Cultural Reference

Similar Material Composition

No Formwork

Source: Mecca & Dipasquale, 2009

Historic Precedents



Stranglehm Technique

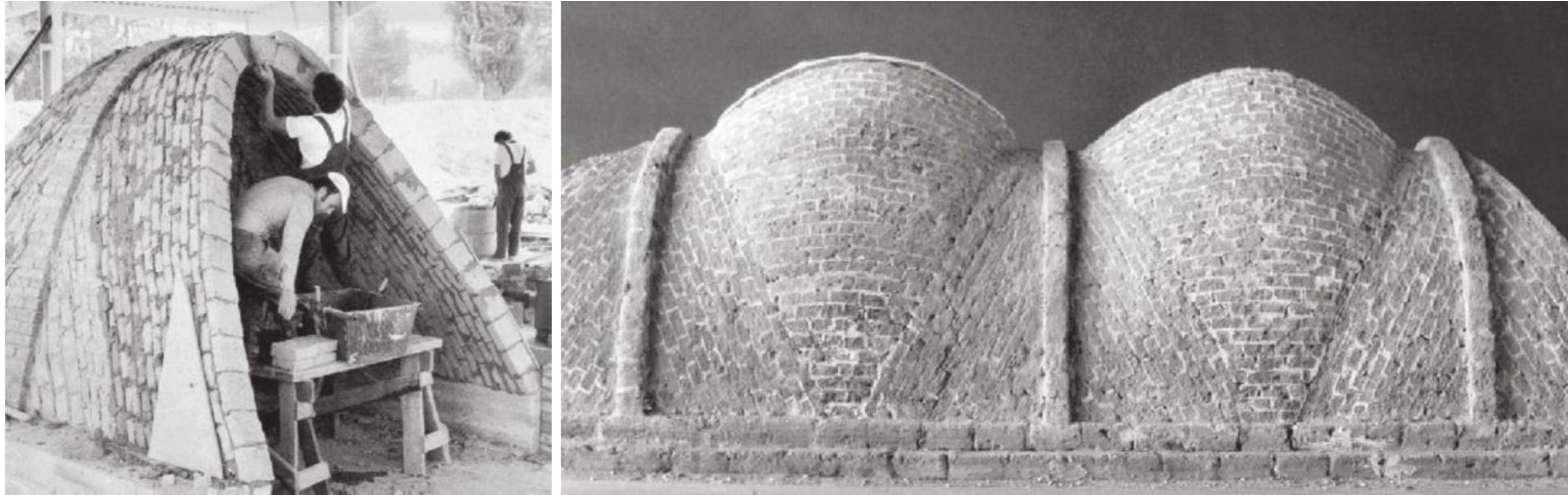
Extrusion Method

Plasticity

Precedent to 3D Printing Earth

Source: Minke, 2012

Historic Precedents



Nubian Vaults and Domes

No Formwork

Compression Only Forms

Structures Still Standing for Centuries

Source: Minke, 2012

Benifits & Circularity

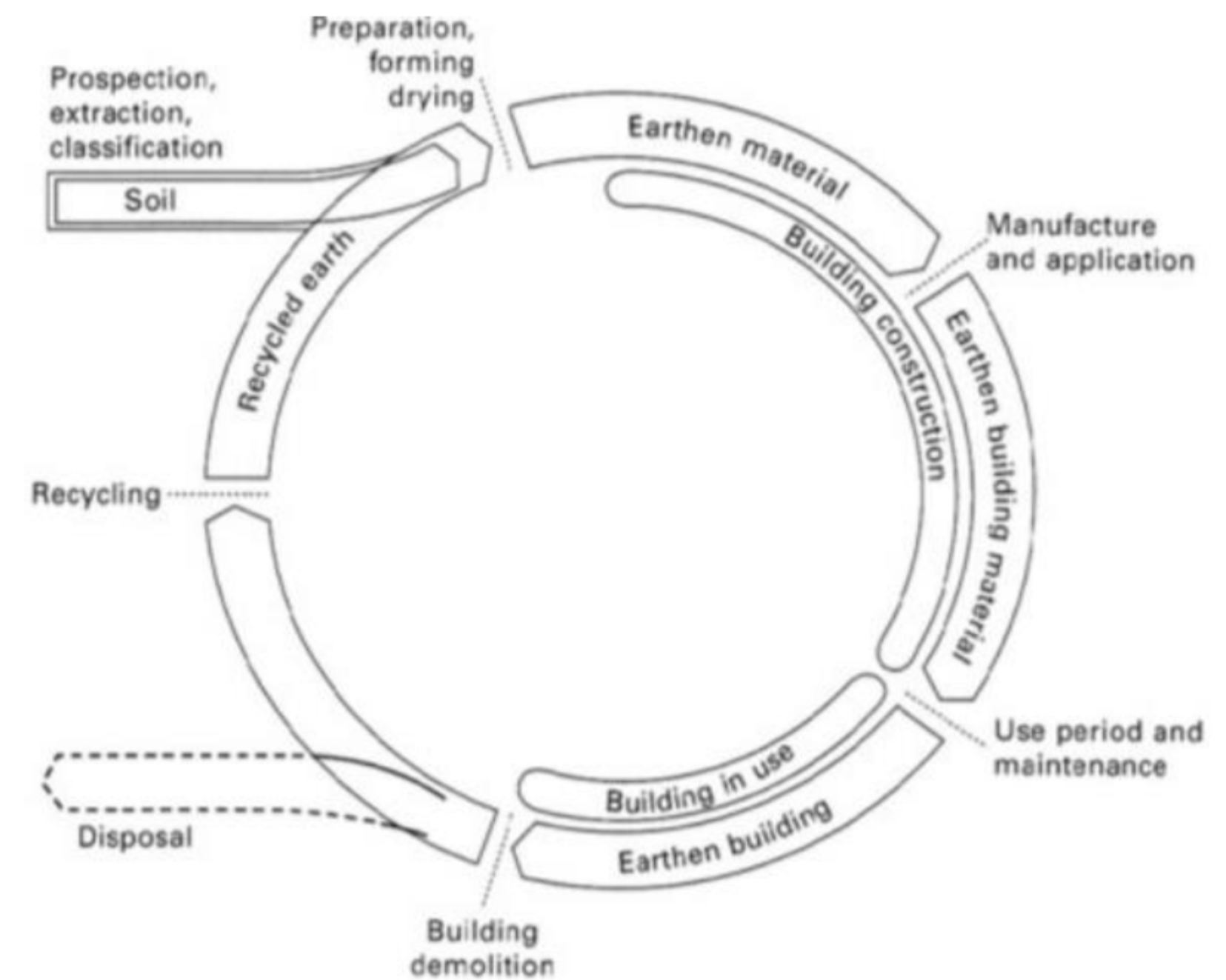
Biodegradable & Recyclable

No Transport

Minimal Processing

Passive Climate Control

Balances Humidity



Source: Schroeder, 2016

Challenges

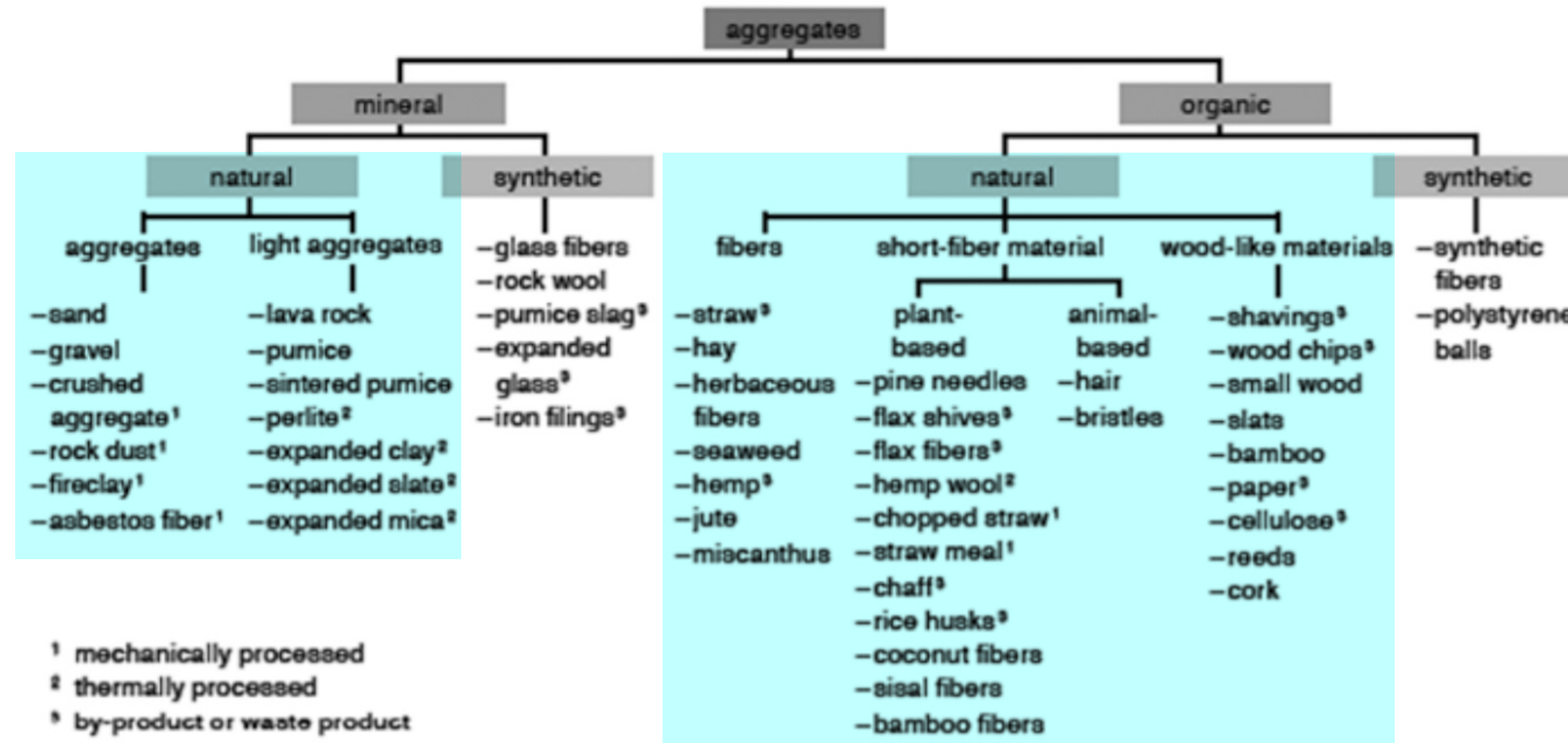
Weather Resistance

Shrinkage

Consistency

Source: Schroeder, 2016

Aggregates



Improve Physical Properties

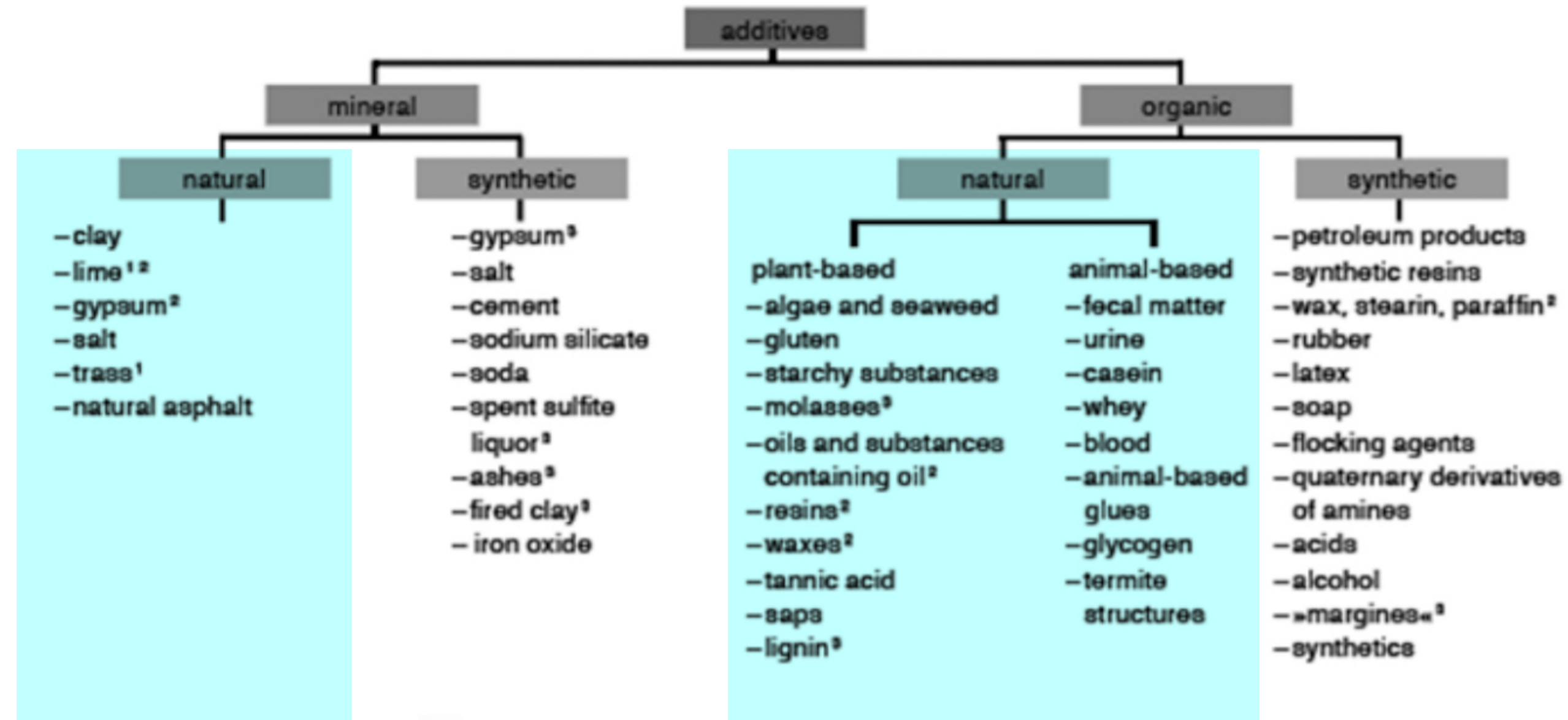
Increase Tensile Strength

Decrease Erosion

Decrease Shrinkage

Source: Schroeder, 2016

Additives



Improve Chemical Properties

Increase Compressive Strength

Reducing Swelling & Shrinkage

Water Resistance

Source: Schroeder, 2016

3D Printing Earth Precedents



TECLA - WASP

Printing Robot: TECLA Crane
Mixture: Local Soil, Rice Husk, Binder
Roof Type: Glass Panels
Location: Lombardo, Italy

Print Time: 200 Hours
Height: 4.2 m
Openings: Self-Supported
Area: -

Source: WASP, 2021

3D Printing Earth Precedents



TECLA - GAIA

Printing Robot: TECLA Crane
Mixture: Local Soil, Rice Husk, Straw, Lime
Roof Type: Timber
Location: Lombardo, Italy

Print Time: 10 Days
Height: approx.. 3.5m
Openings: Supported by Roof
Area: 30 m2

Source: WASP, 2021

3D Printing Earth Precedents



MUD Frontiers

Printing Robot: SCARA 3D Printer
Mixture: Local Soil, Straw, Water
Roof Type: -
Location: New Mexico

Print Time: -
Height: approx. 4m
Openings: Supported by Wood Beams
Area: 21 m²

Source: Rael 2020

3D Printing Earth Precedents



Marsha - AI Spacefactory

Printing Robot: Industrial Robot

Mixture: Basalt Composite, Corn, Sugar Cane

Roof Type: Aluminum & Plexiglass

Location: Mars (Prototype Made Indoors)

Print Time: 30 Hours

Height: 4.5 m

Openings: Aluminum Supports

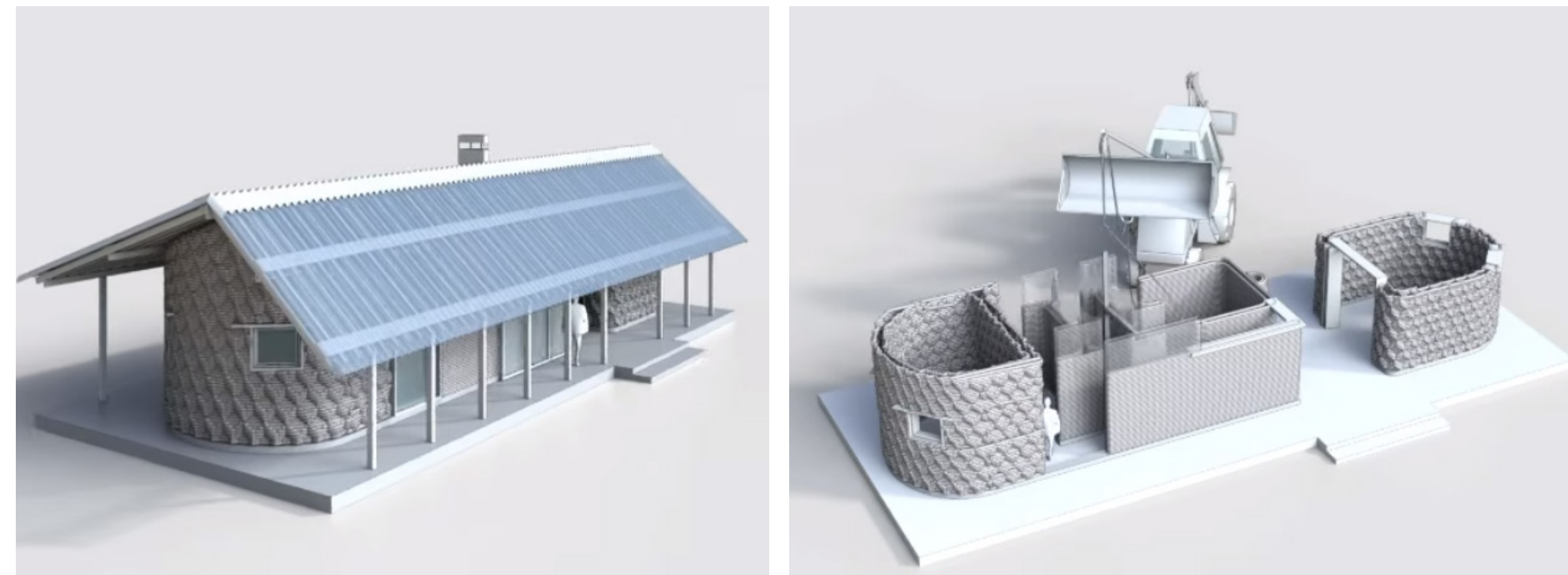
Area: -

Source: AI Spacefactory 2020

3D Printing Earth Precedents



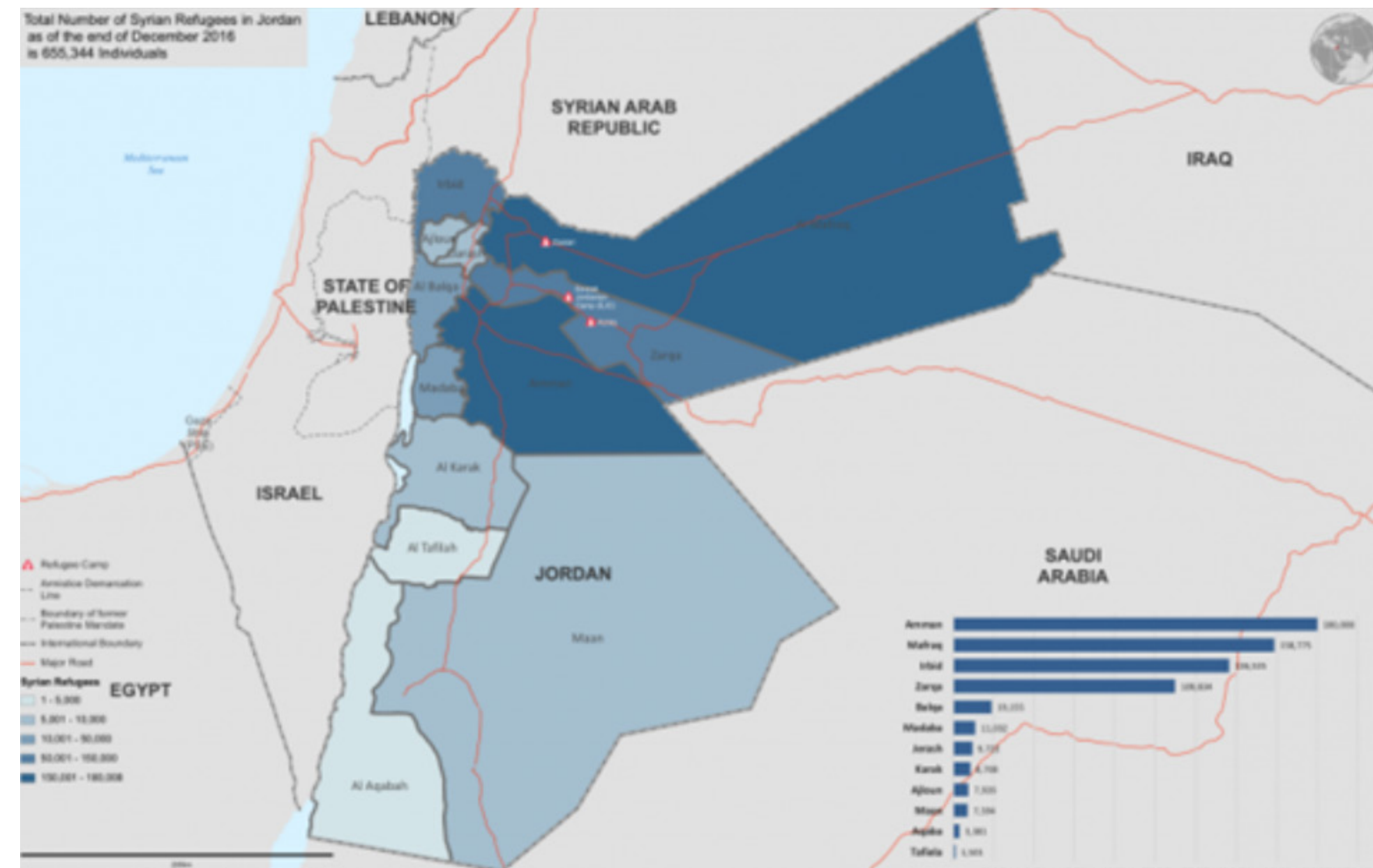
IAAC OTF



3D Printed House - Ronald Rael

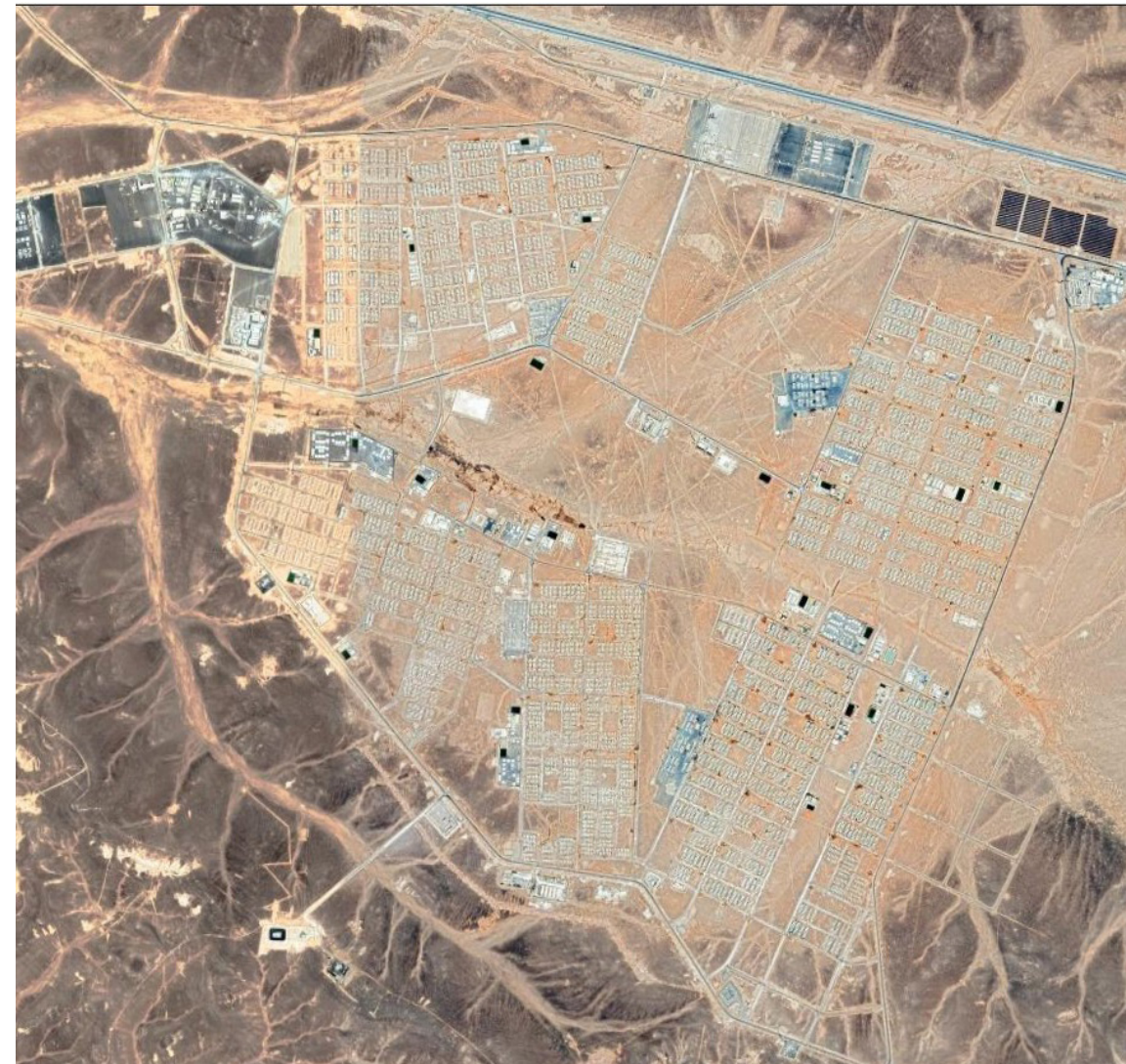
Source: IAAC / Rael

Syrian Refugee Crisis



Source: UNHCR

Refugee Camps

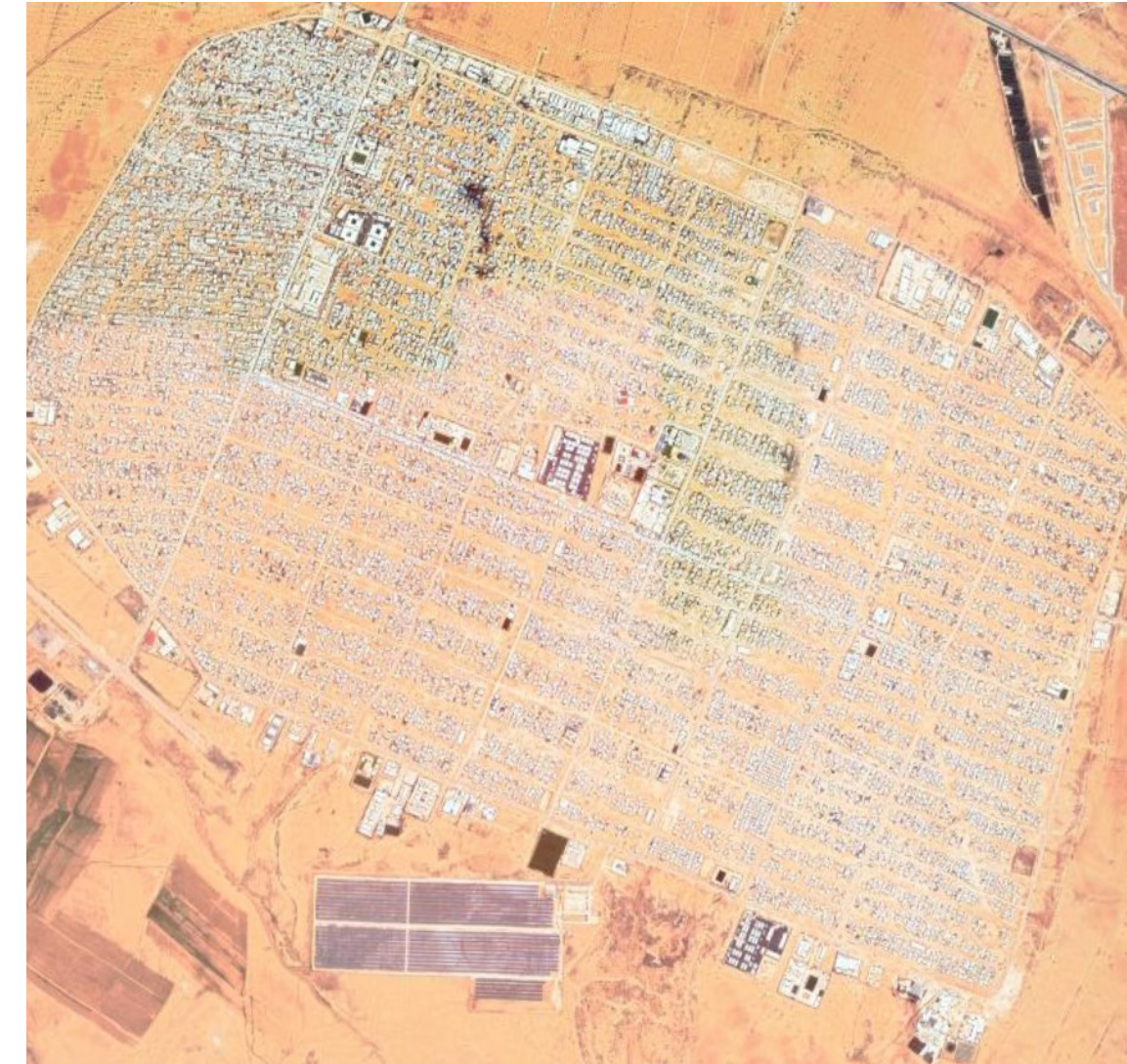


Azraq Refugee Camp

Opened 2014

37,000 People

Rigid



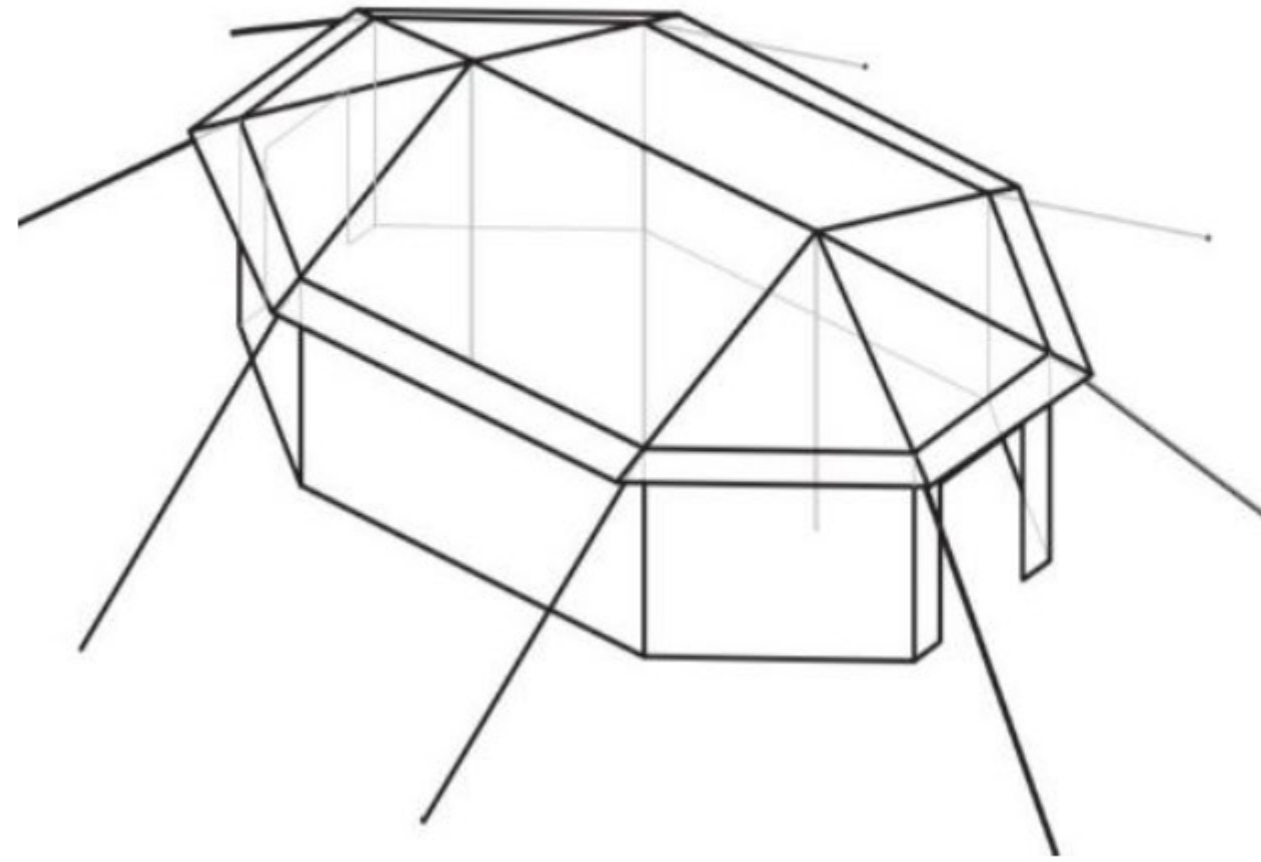
Zaatari Refugee Camp

Opened 2012

80,000 People

Self Re-Organized

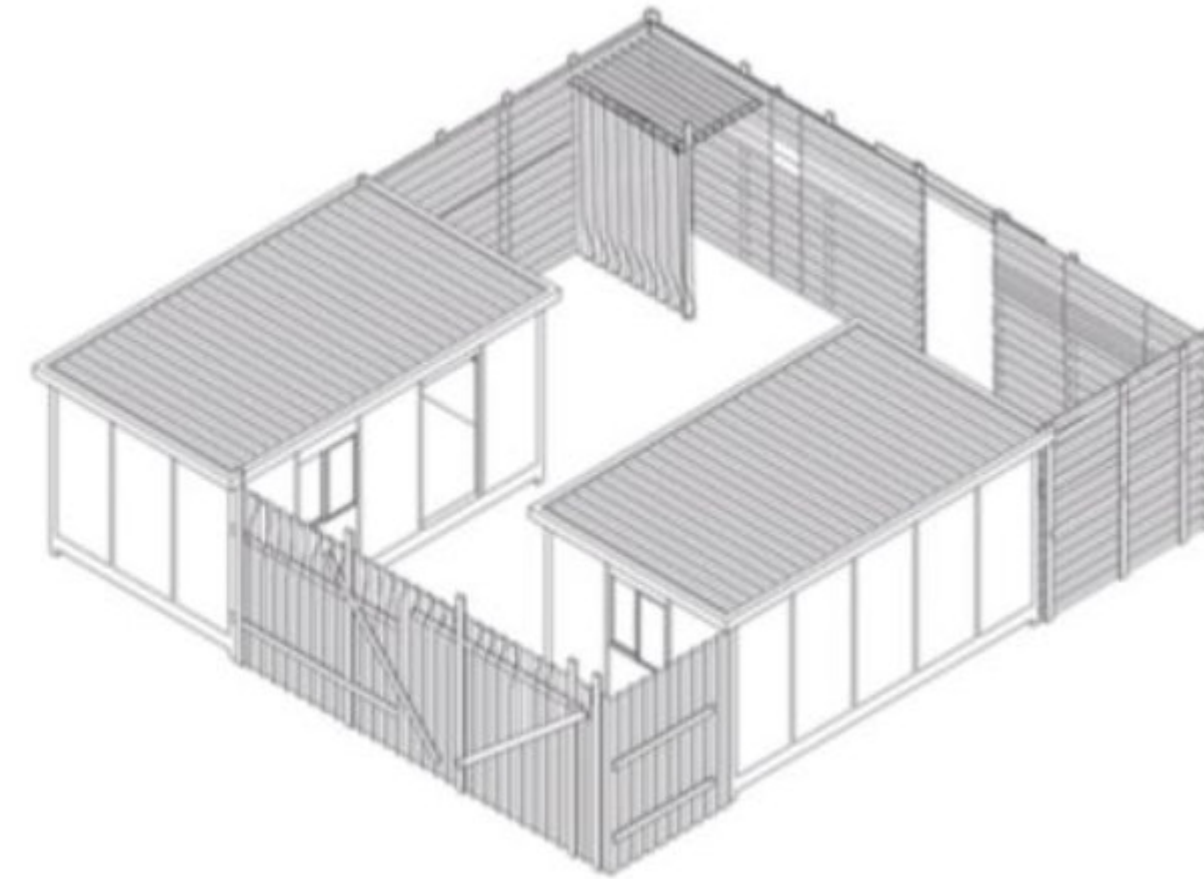
Syrian Refugee Crisis



Tent



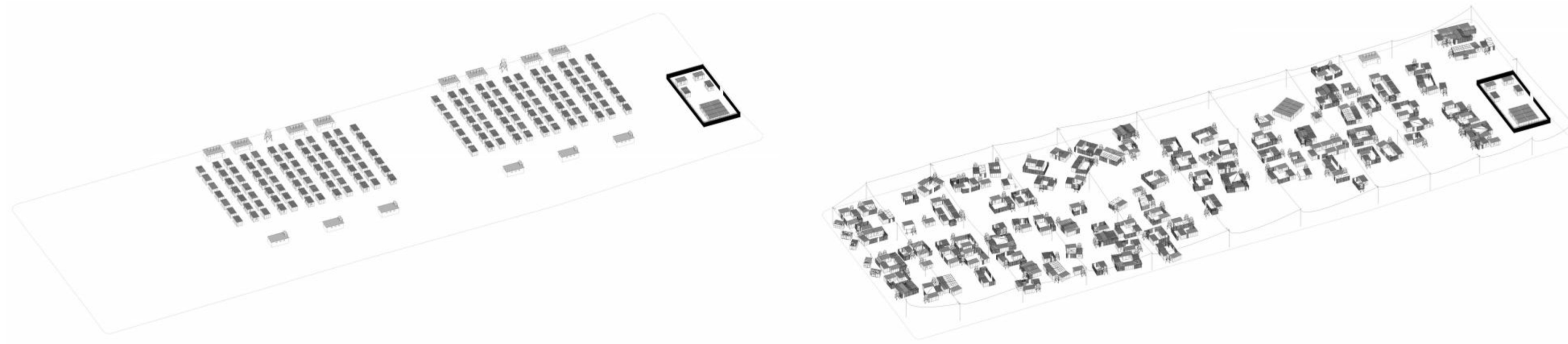
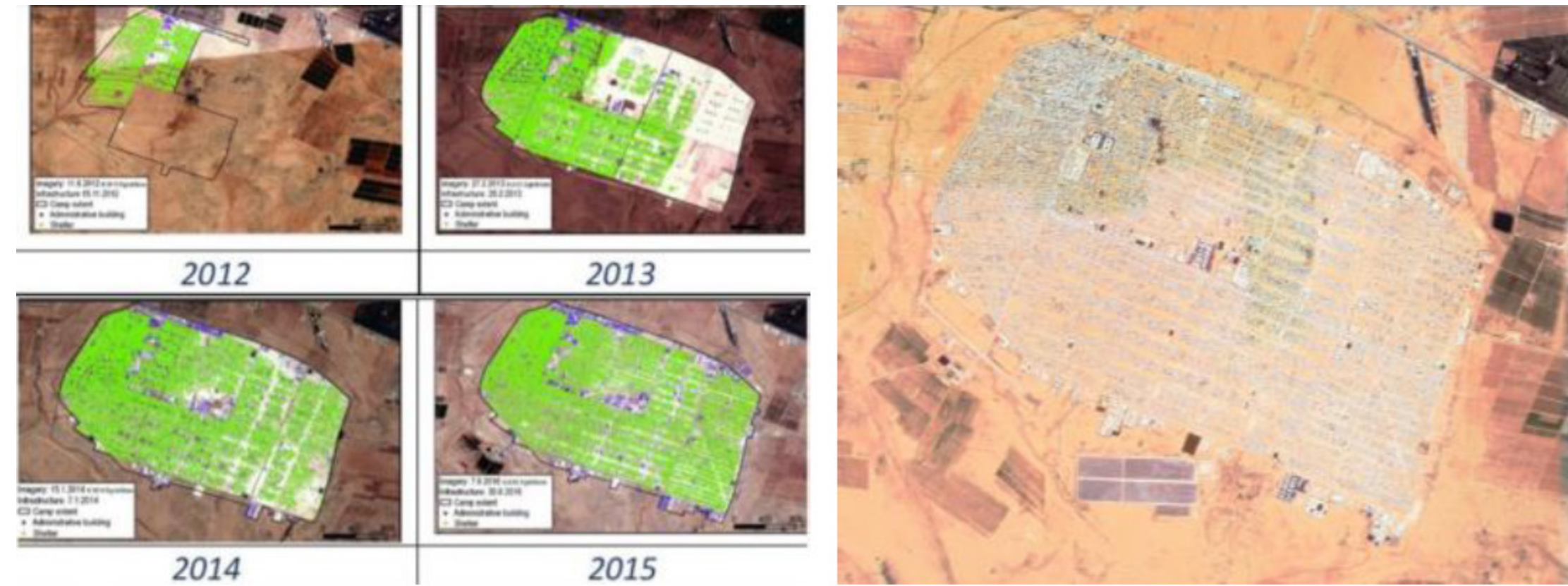
Caravan



**Multi-Caravan
Cluster**

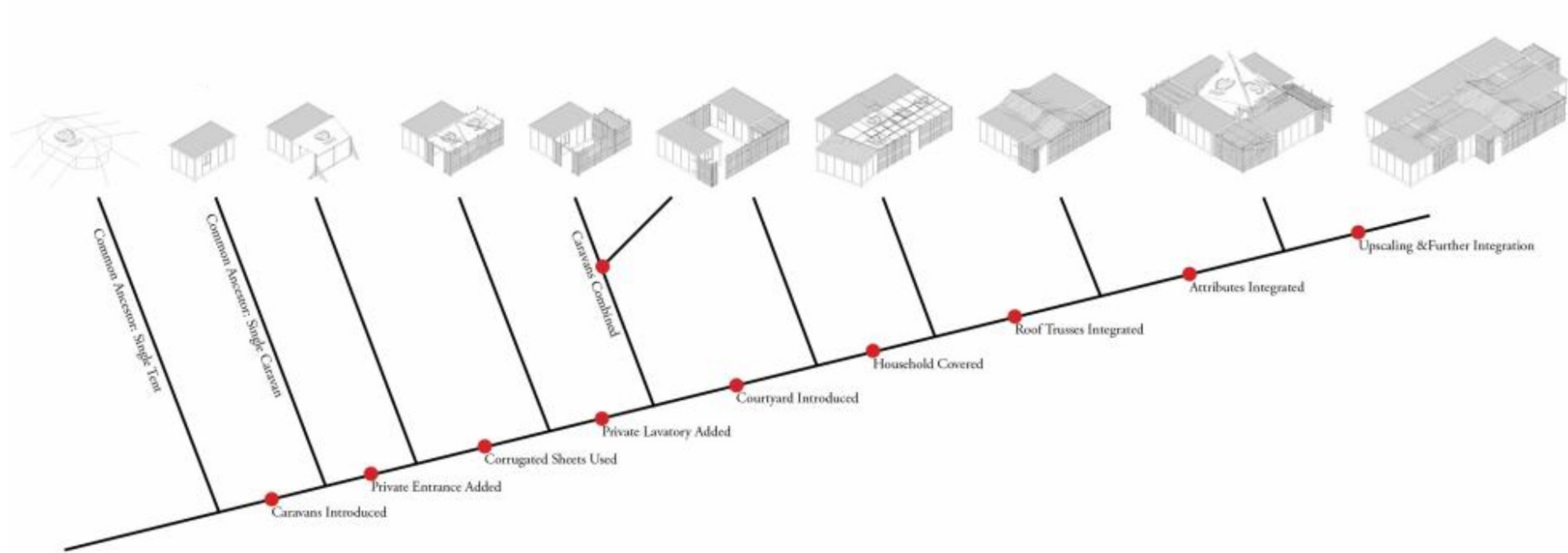
Source: Slater 2014, Madi 2017

Permanent Impermanence



Source: Madi 2017

Self-Organization



Privacy Gradient	Bedrooms	Inner Courtyard or Divisor Space	Inner Lavatories
	Family Living Room		Kitchen
	Guest Room Majlis		Outer Lavatories
	Outer Courtyard		
	Dwelling Entrance		
	Neighborhood & Street		
The Public Realm			
Public			

Source: Madi 2017

Self-Organization



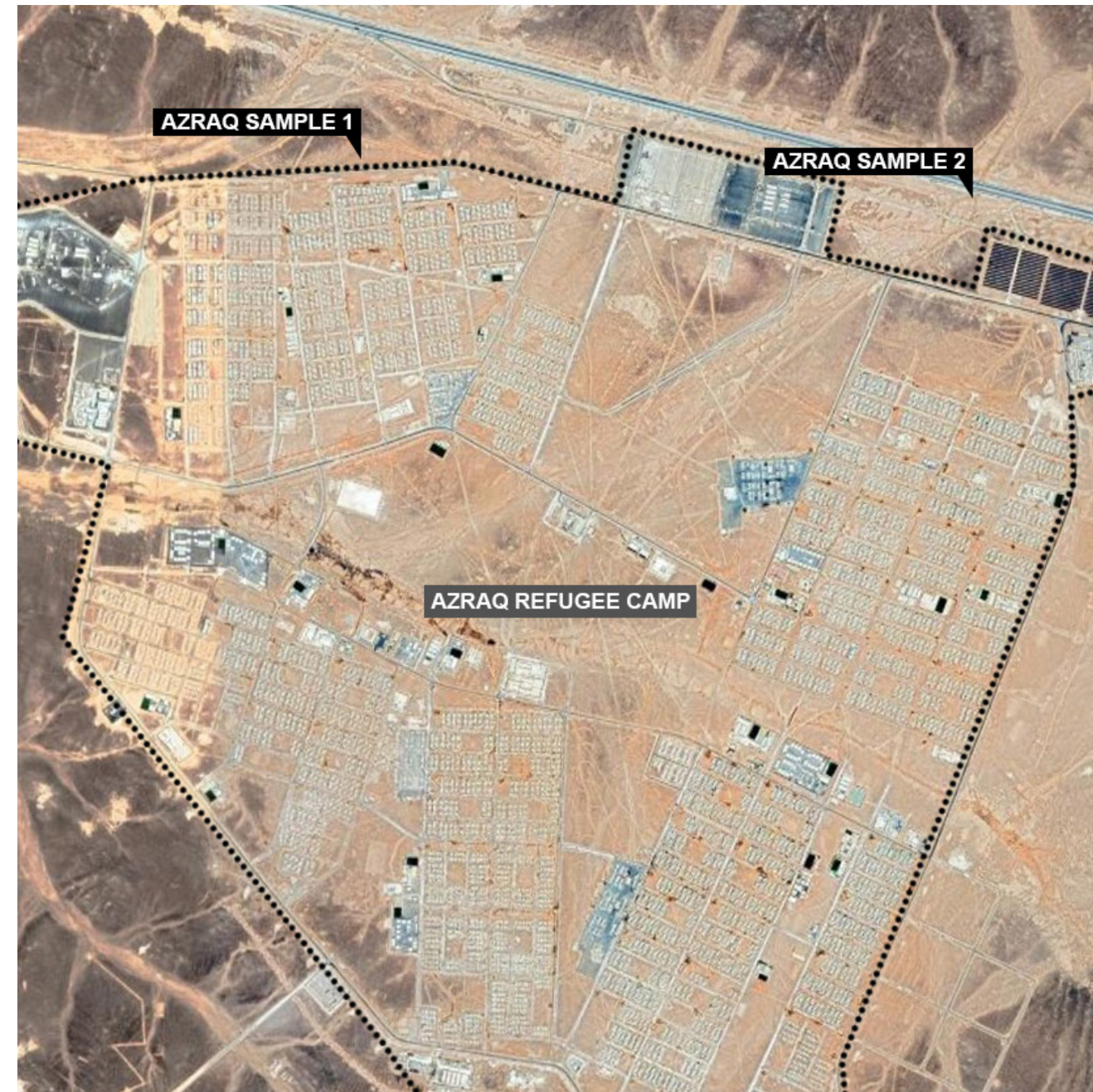
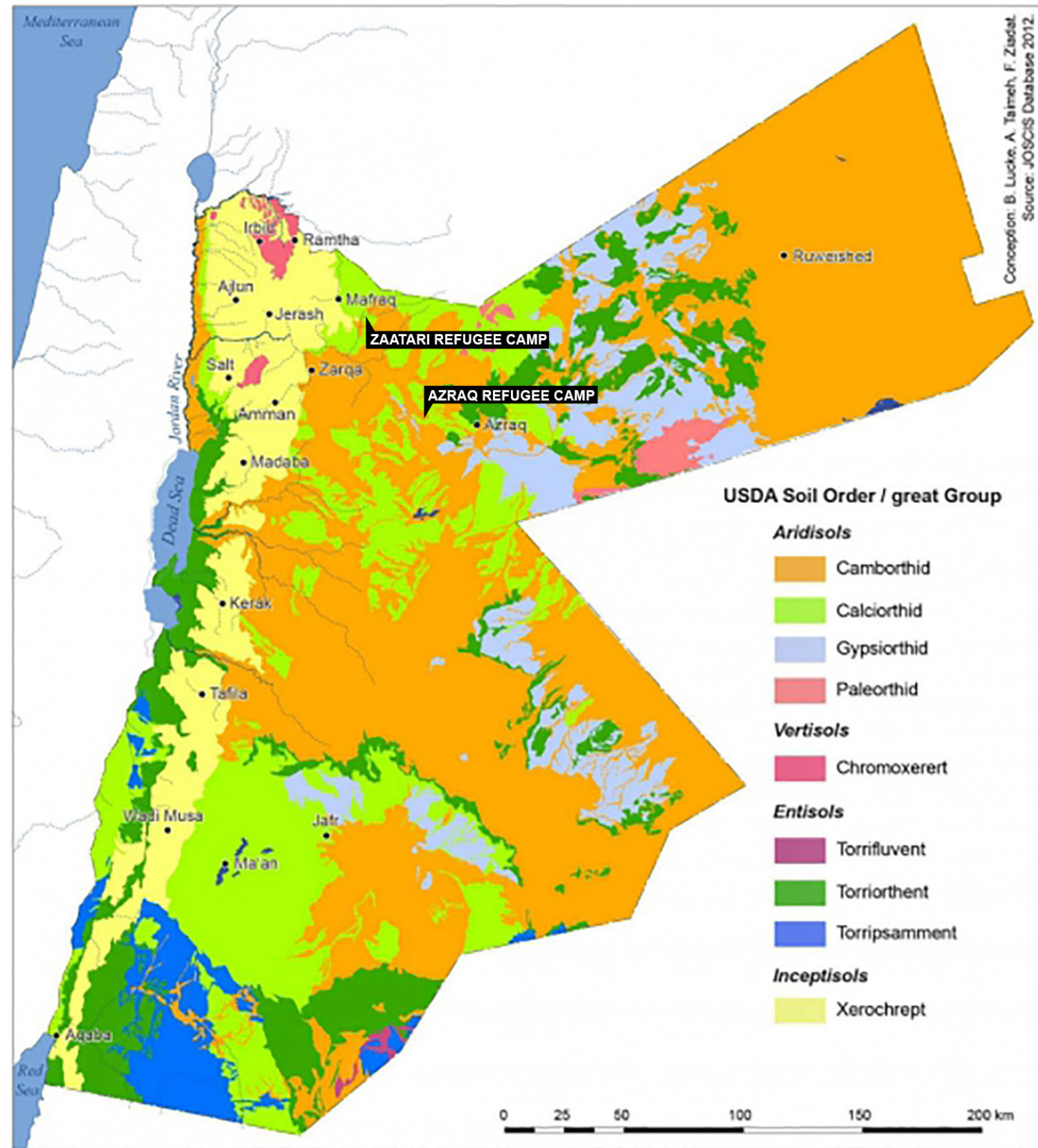
Source: Madi 2017

Refugee Design Needs

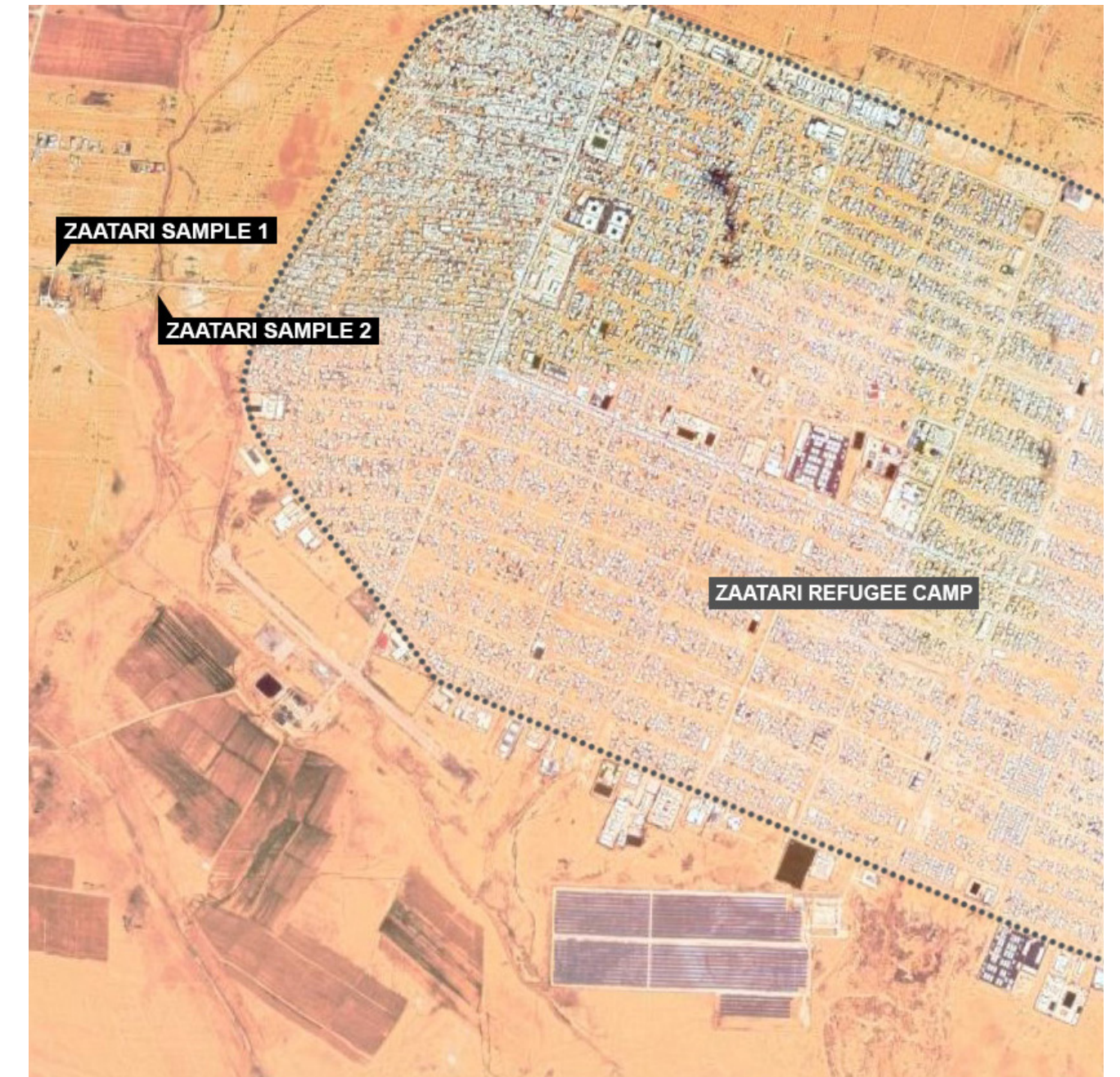
<p>Safety and Security</p> <ol style="list-style-type: none"> 1. Fear protection 2. Fire safety 3. Structure protection 4. Hygiene of shelter spaces 5. On-site sewage system 6. Size of camp's block 7. Close distance between shelters and travelling time 8. Maintain shelter 	<p>Comfort</p> <ol style="list-style-type: none"> 9. Air temperature 10. Humidity in interior air 11. Wind direction 12. Air speed 13. Sun radiation 14. Precipitation 15. Planning of suitable plot 16. Determination 17. Wind sound 18. Sound permeability 19. Acoustic insulation 20. Air quality 21. Glare, Illumination and color 	<p>Shelter comfort</p> <ol style="list-style-type: none"> 22. Settlement 23. Land characteristics 24. Shelter elements weight 25. Shelter height 26. Shelter lifting 27. Considering disabled users 28. Shelter wall 29. Shelter floor 30. Foundation appropriate 31. Window size 32. Glazing 33. Cross ventilation 34. Roof characteristics 35. Shelter's water drainage channel 36. Preventing dust 37. Providing shaded areas 38. Insect screen 	<p>Social context</p> <ol style="list-style-type: none"> 39. Accessibility and integration 40. Adding portable elements 41. Involving refugees in the construction of shelters 42. Ability to repair 43. Productivity-small scale commercial activities 44. Intimacy between people 45. Oriented shelters and streets in the same community 46. Community road organization 47. Access to shelter 48. Visual boundaries 49. Protection 50. Participation
<p>Stability</p> <ol style="list-style-type: none"> 51. A pattern of independent existence/stability 52. Structure stability 53. Dignity- with new community connectivity 	<p>Being Demountable</p> <ol style="list-style-type: none"> 58. Light material 59. Build efficiently to minimize temperature variation 60. Structure elements 61. Joint connection-details 62. Considering fixed base of shelter 63. Considering time of erecting shelter 64. Ability to repair-usability 	<p>Flexibility and Modularity</p> <ol style="list-style-type: none"> 65. Separate technical system / Coding 66. Enabling mechanical system 67. System complexity 68. Ability to extend 69. Less cutting- consider the frequency of replacing and building shelters (affordability) 	<p>Independent constant energy</p> <ol style="list-style-type: none"> 70. Addressing shelter 71. Energy produced for local grid 72. Collecting solar radiation/ adding elements 73. Material storage / Cooling and Heating capacity 74. Rain harvest 75. Grey water system
<p>Durability/Adaptability</p> <ol style="list-style-type: none"> 54. Available local sources 55. Robust strong material 56. Shelter skin 57. Mechanical ventilation system 			

Source: Aburamadan & Trillo, 2018

Soil Collection



Azraq Sample 1: 31°54'55.6"N 36°34'42.8"E
Azraq Sample 2: 31°54'53.9"N 36°35'47.4"E



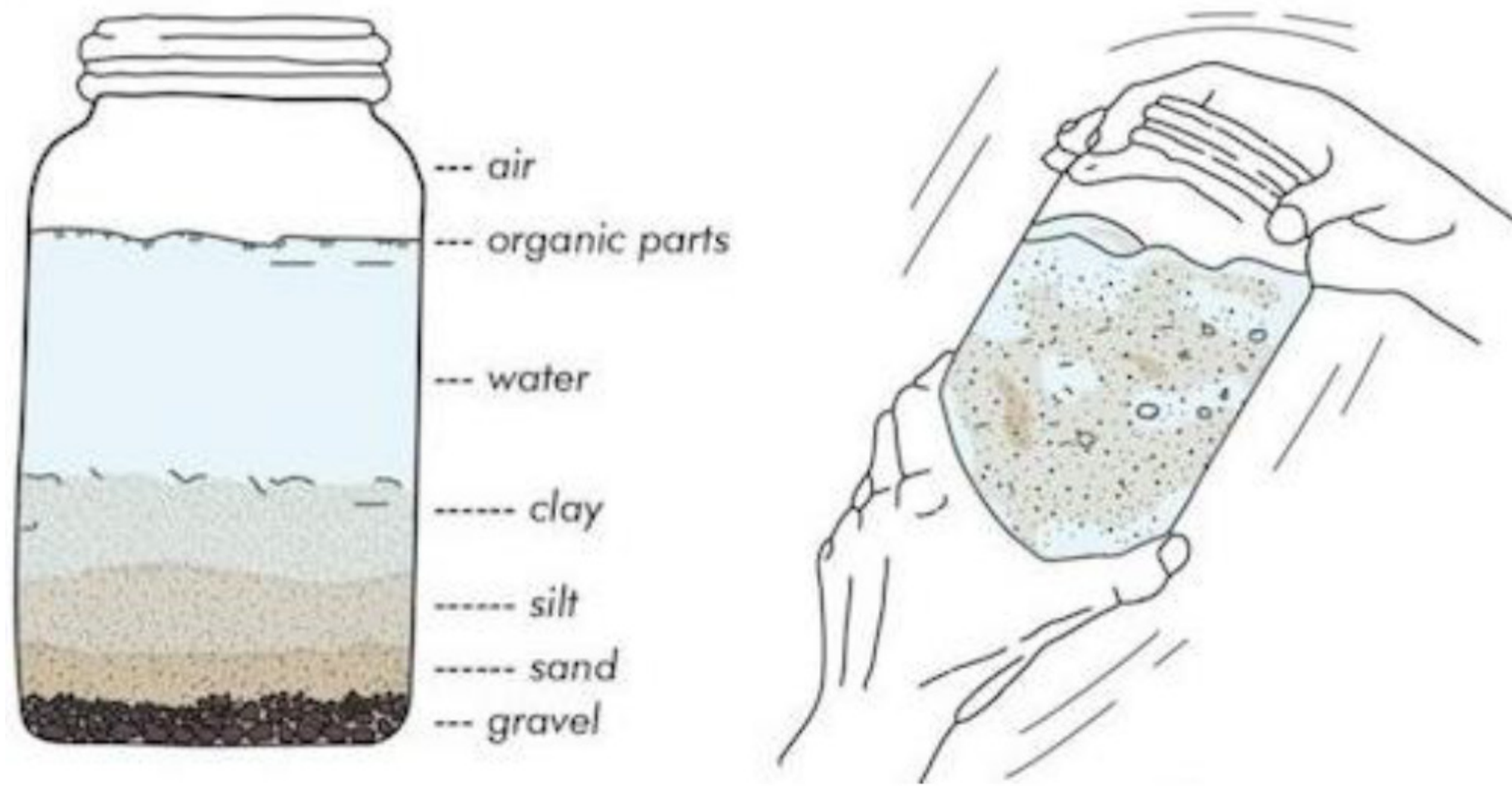
Zaatari Sample 1: 32°17'51.9"N 36°18'18.9"E
Zaatari Sample 2: 32°17'48.7"N 36°18'33.8"E

Source: Adapted from Ababsa, Lucke, Ziadat, & Taimeh, 2013

Soil Collection

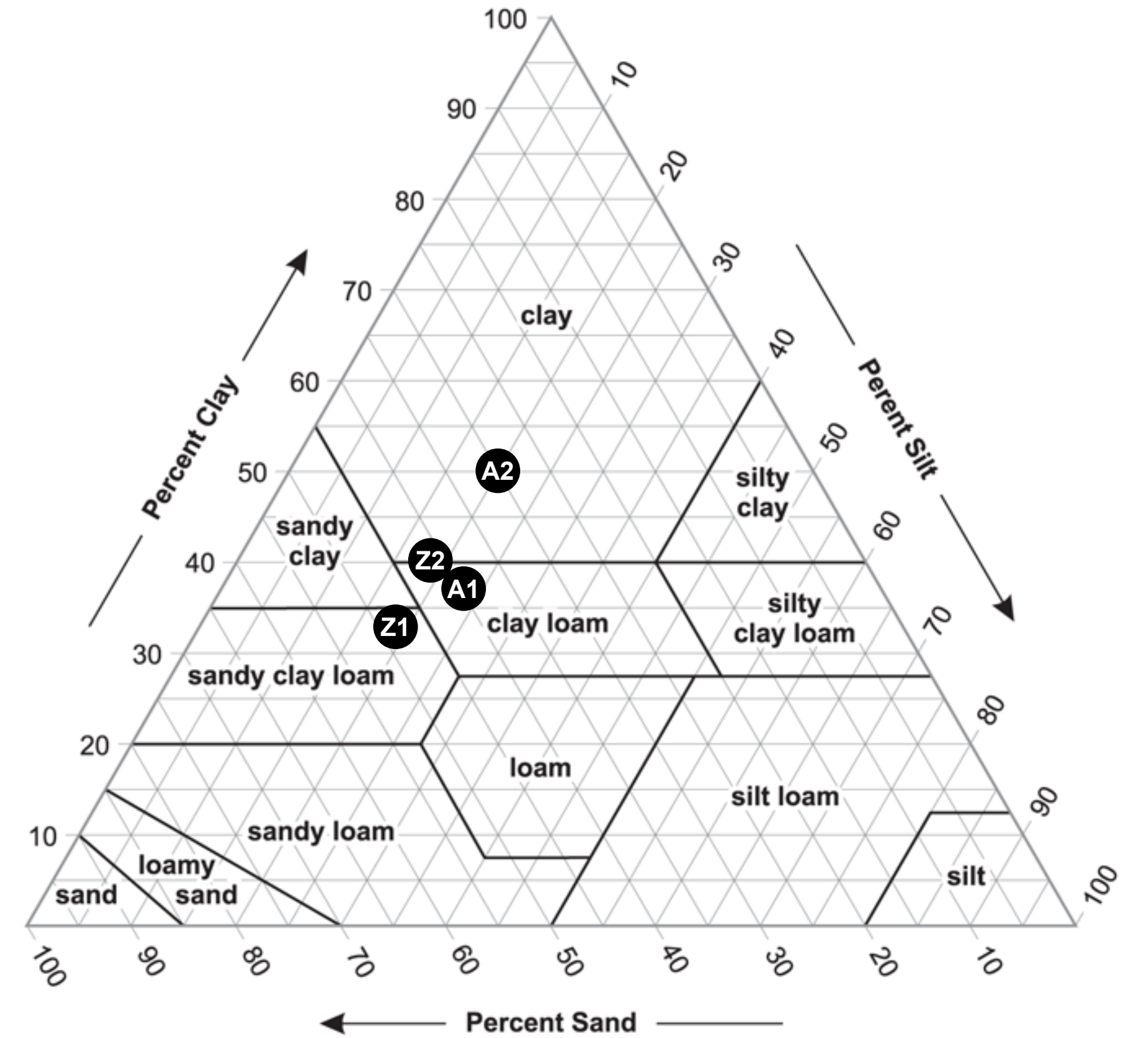
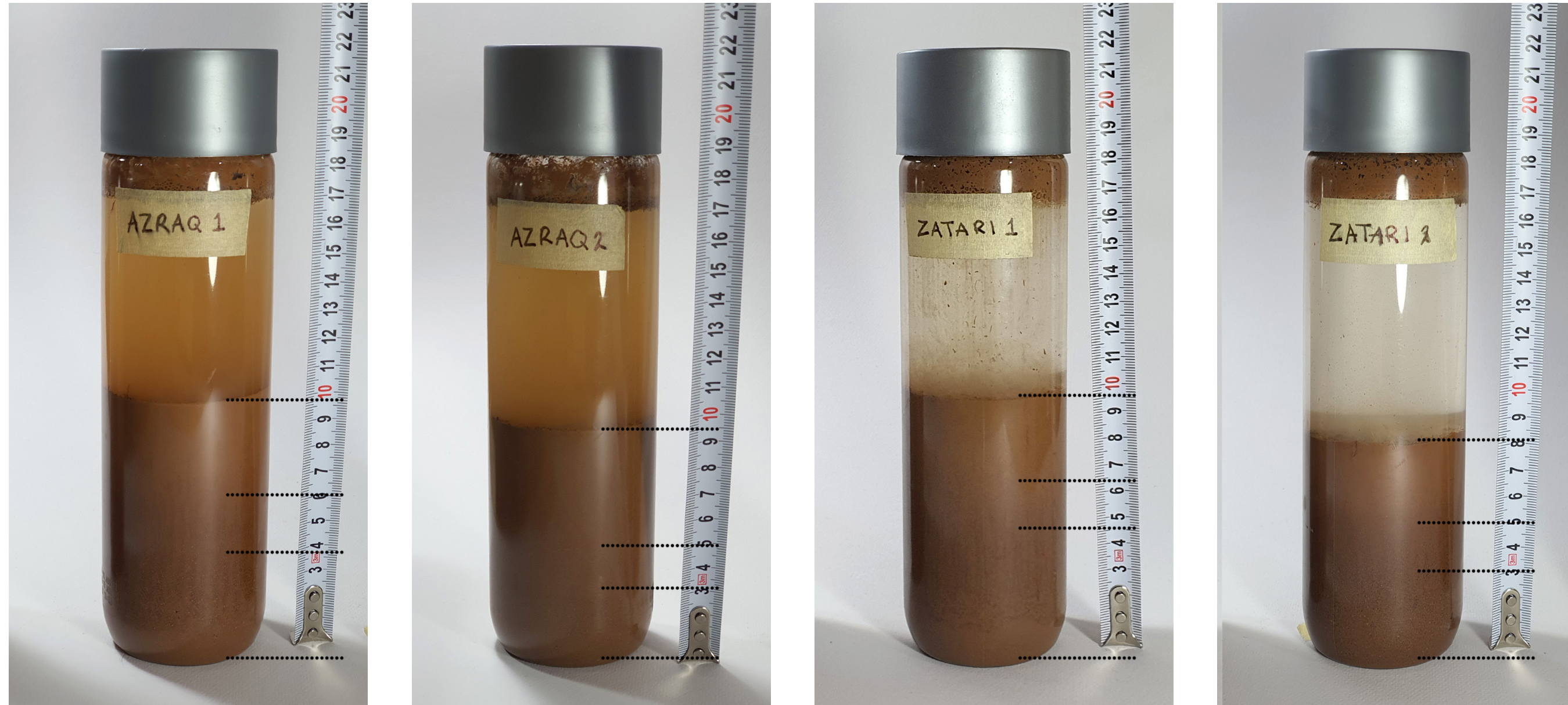


Jar Test



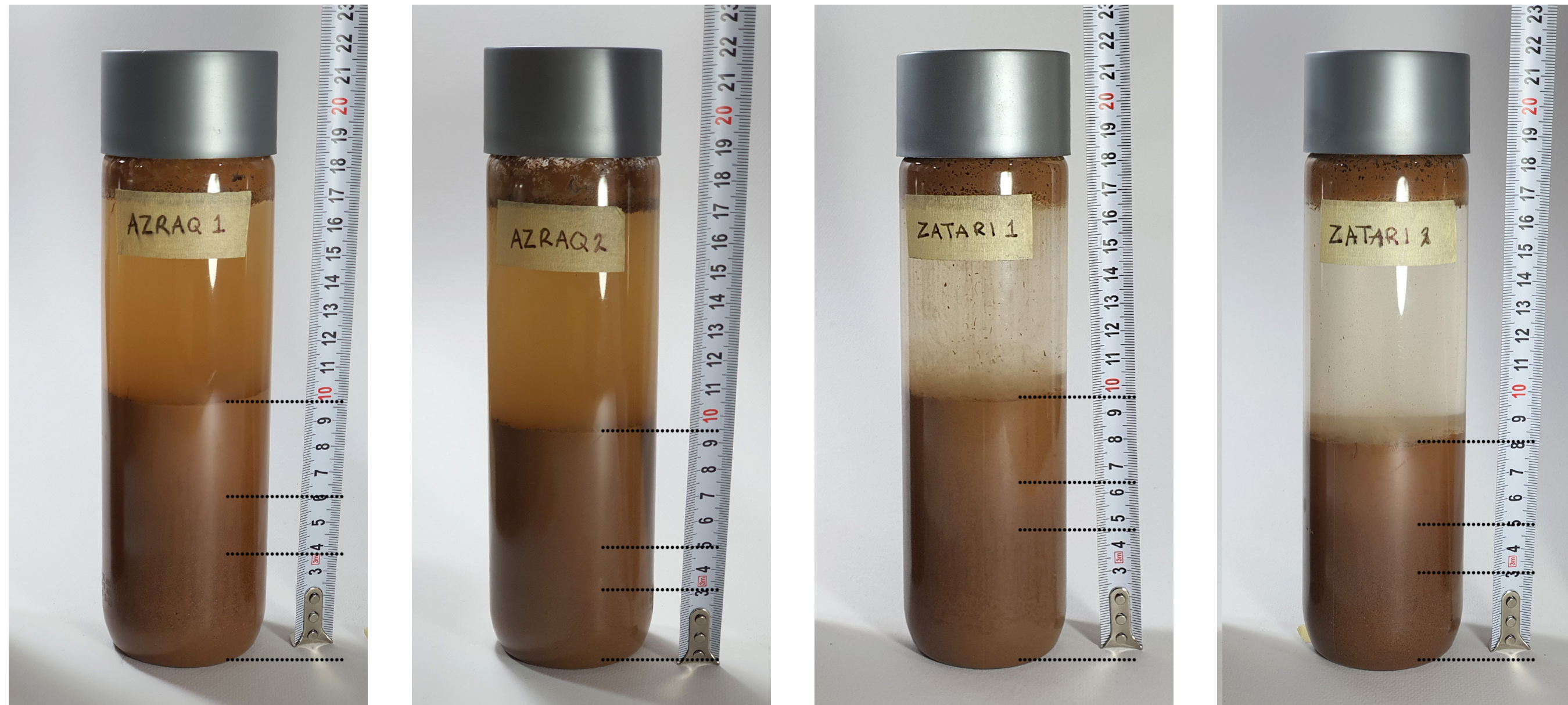
Source: van Stigt, Esposti, & Kufirin, 2021

Jar Test Results



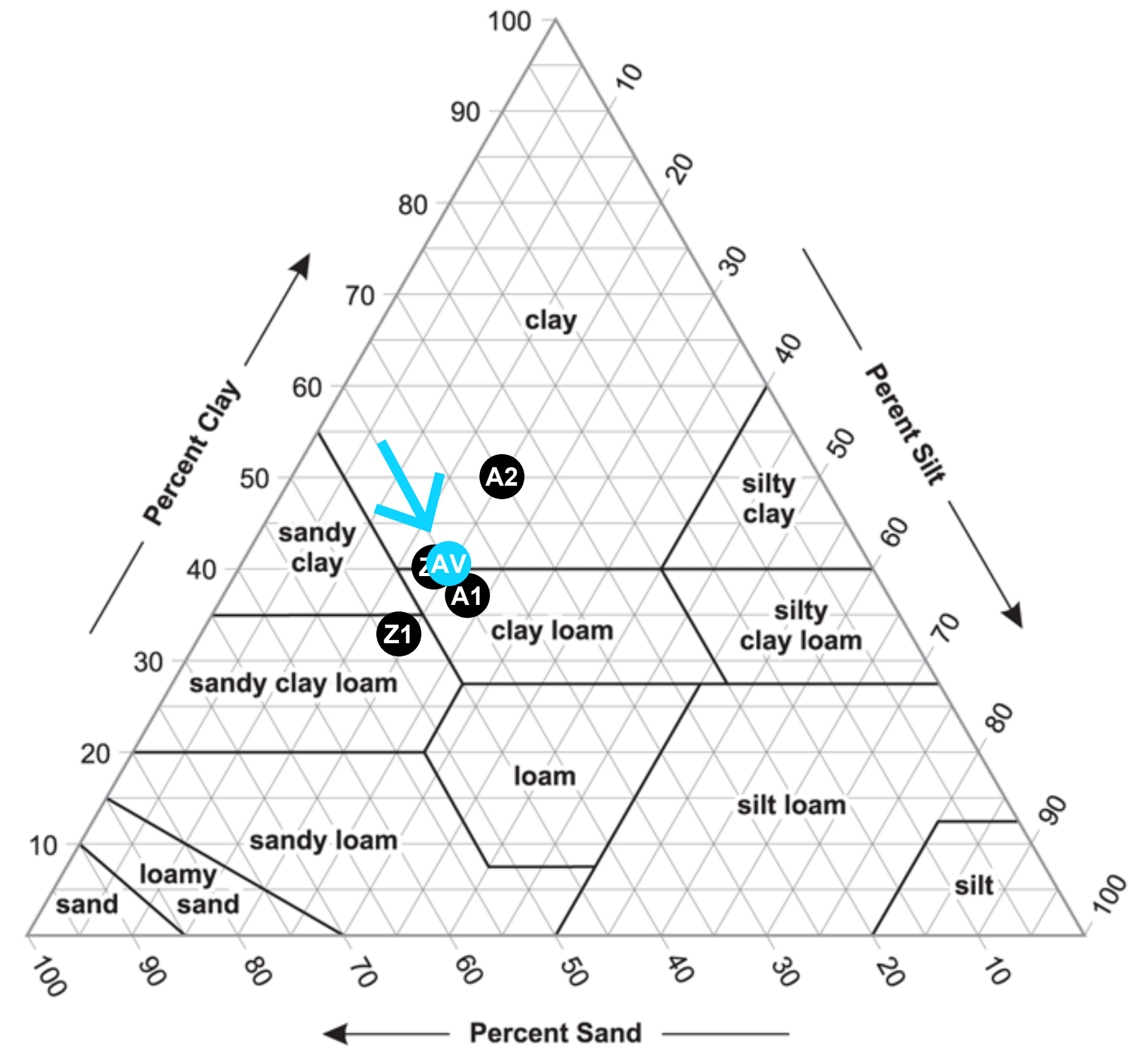
	Azraq 1	Azraq 2	Zaatari 1	Zaatari 2
Sand	40.8%	30.5%	49.3%	39.8%
Silt	22.5%	19.3%	18.1%	22.2%
Clay	36.7%	50.2%	32.5%	37.9%

Jar Test Results

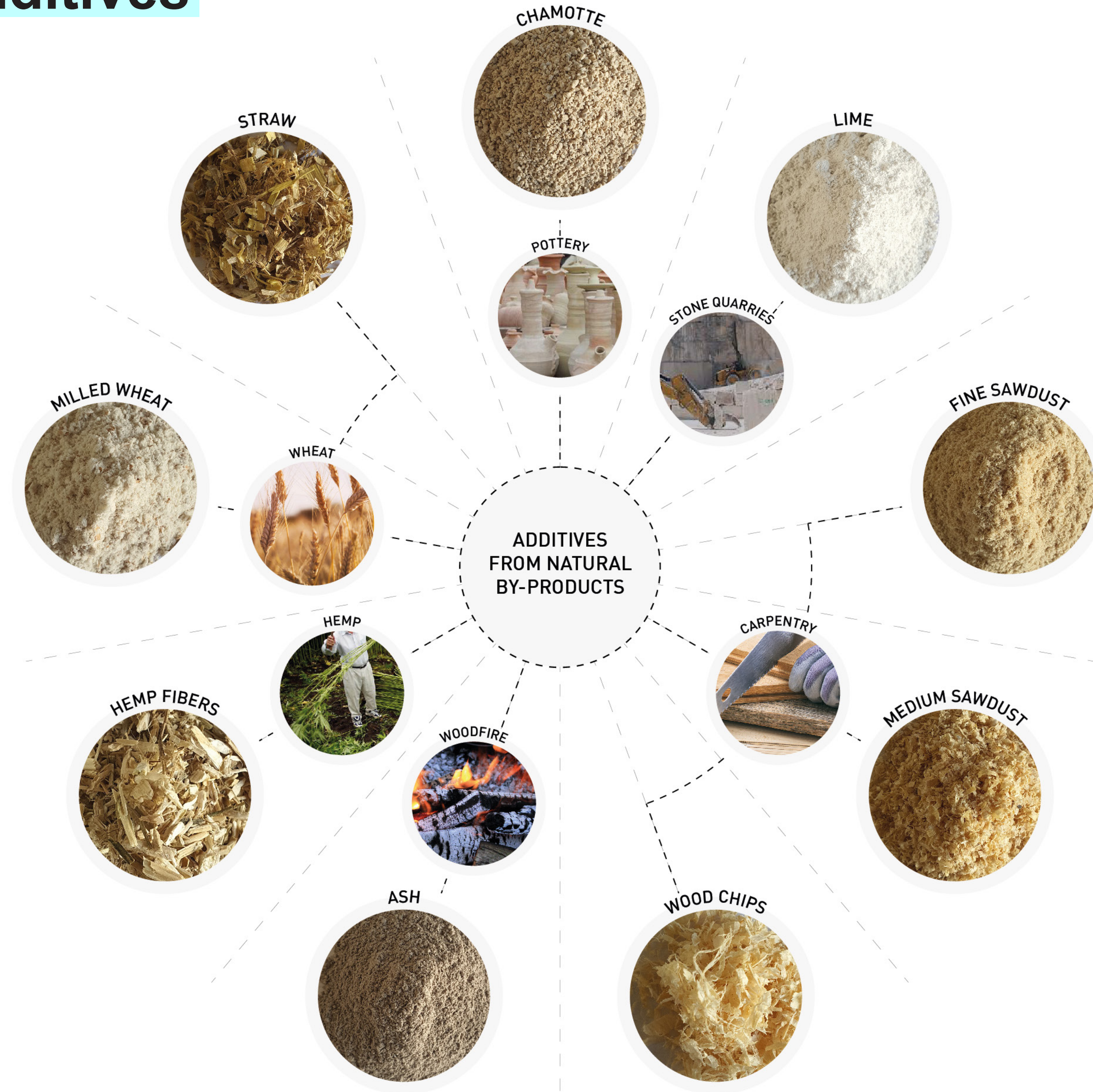


	Azraq 1	Azraq 2	Zaatari 1	Zaatari 2	Average
Sand	40.8%	30.5%	49.3%	39.8%	40.1%
Silt	22.5%	19.3%	18.1%	22.2%	20.5%
Clay	36.7%	50.2%	32.5%	37.9%	39.3%

**40% Sand
60% Clay**



By-Products as Additives



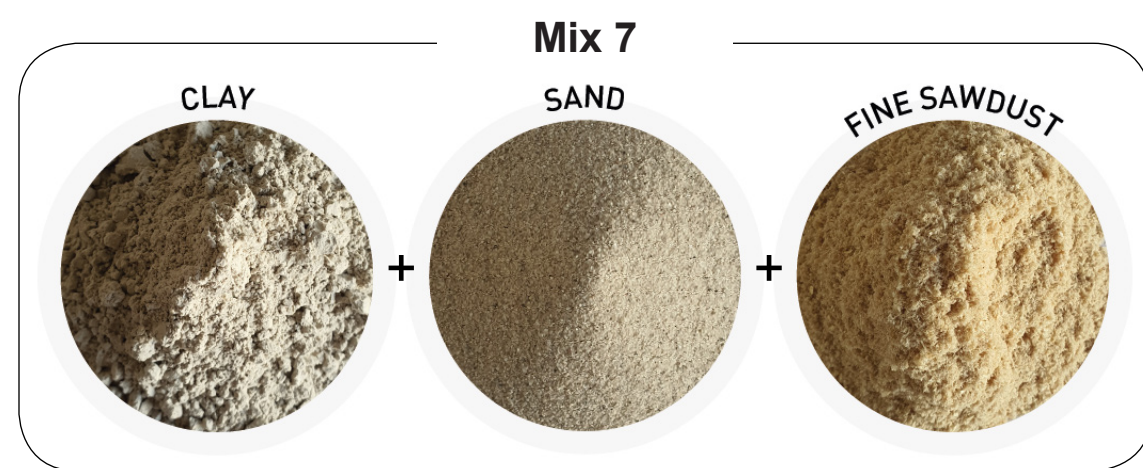
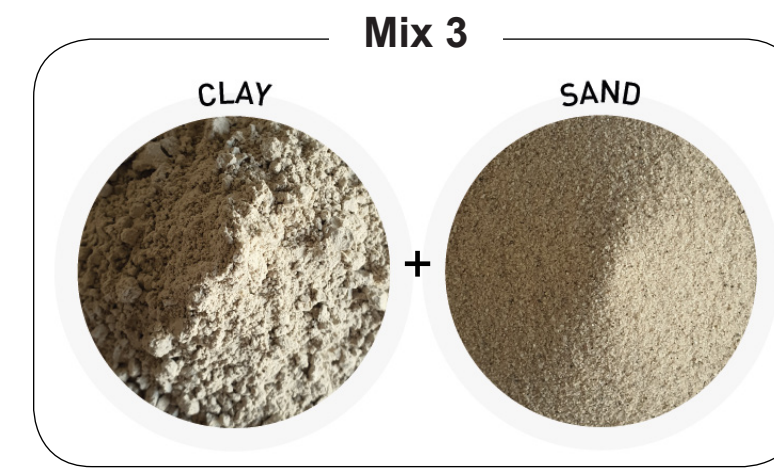
Expected Benefits of Additives

	CHAMOTTE	LIME	ASH	MEDIUM SAWDUST	MILLED WHEAT	STRAW	HEMP FIBERS
Lighter Weight			•	•		•	•
Less Cracking	•	•	•			•	•
Less Shrinkage	•	•	•	•	•	•	•
Faster Drying	•			•		•	•
Surface Hardening	•	•	•				
Increased Tensile Strength				•		•	•
Increased Binding		•			•		
Insulation				•		•	•
Water Resistance		•	•				

Additives

Additive	Mix 1		Mix 2		Mix 3		Mix 4		Mix 5		Mix 6		Mix 7		Mix 8		Mix 9		Mix 10		Mix 11		Mix 12	
	Vol. %	Wt.%	Vol. %	Wt.%	Vol. %	Wt.%	Vol. %	Wt.%	Vol. %	Wt.%	Vol. %	Wt.%	Vol. %	Wt.%	Vol. %	Wt.%	Vol. %	Wt.%	Vol. %	Wt.%	Vol. %	Wt.%	Vol. %	Wt.%
Clay	100	100	60*	-	60	46	45	34	45	38	45	40	45	43	45	44	45	45	45	39	45	44	45	44
Sand	-	-	40*	-	40	54	30	40	30	45	30	48	30	52	30	53	30	53	30	47	30	53	30	53
Sampled Soil	-	-	100	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Chamotte	-	-	-	-	-	-	25	26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Lime	-	-	-	-	-	-	-	-	25	17	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ash	-	-	-	-	-	-	-	-	-	-	25	11	-	-	-	-	-	-	-	-	-	-	-	-
Fine Sawdust	-	-	-	-	-	-	-	-	-	-	-	-	25	5	-	-	-	-	-	-	-	-	-	-
Medium Sawdust	-	-	-	-	-	-	-	-	-	-	-	-	-	-	25	3	-	-	-	-	-	-	-	-
Wood Chips	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	25	2	-	-	-	-	-	-
Milled Wheat	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	25	14	-	-	-	-
Straw	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	25	3	-	-
Hemp	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	25	3
Water	25	34	20	17	20	18	20	18	25	24	20	21	22	24	20	22	20	22	27	27	20	22	20	22

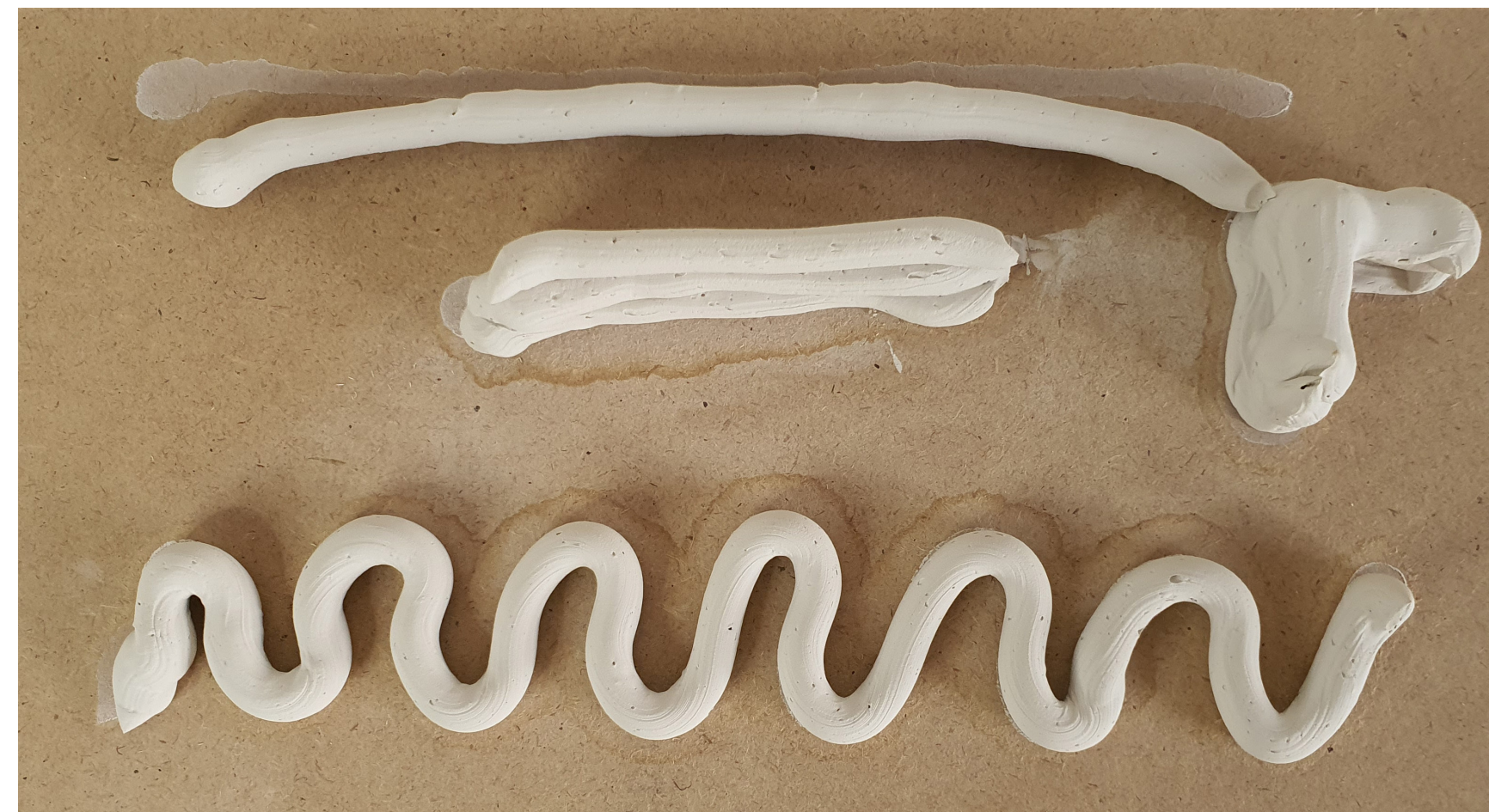
Mixture Design



Evaluation Criteria



Criterion	Evaluation Method	Rating Key (1-5)
Shrinkage	Measuring length at 0h & 48h	1=High → 5 =Low
Deformation	Visual inspection after 48h	1=High → 5 =Low
Weight Loss	Measuring weight at 0h & 48h	1=High → 5 =Low
Interlayer Bonding	Visual inspection of dry cut layers	1=Low → 5 =High
Extrudability	Ease of extruding wet mixture	1=Low → 5 =High
Cracking	Visual inspection after 48h	1=High → 5 =Low
Water Needed	Amount of water needed to be workable	1=High → 5 =Low
Drying Speed	Measured weight loss difference (0, 12, 24, 36, & 48h)	1=Slow → 5 =Fast
Surface Hardness	Difficulty to break sample by hand	1=Low → 5 =High
Lightness	Density of mixture	1=High → 5 =Low



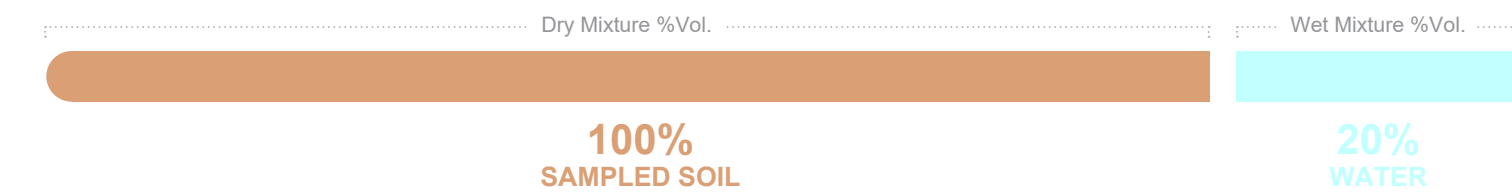
Results



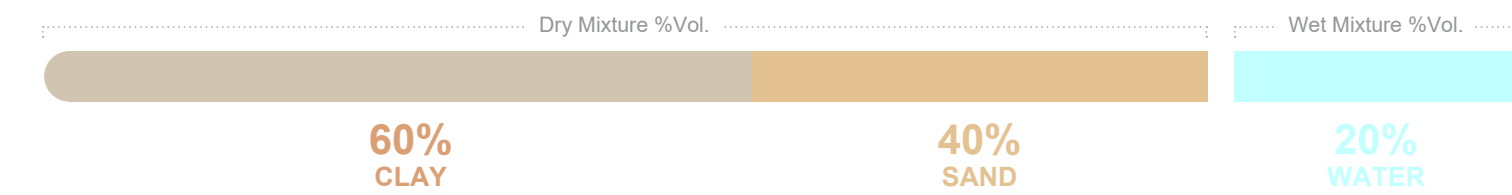
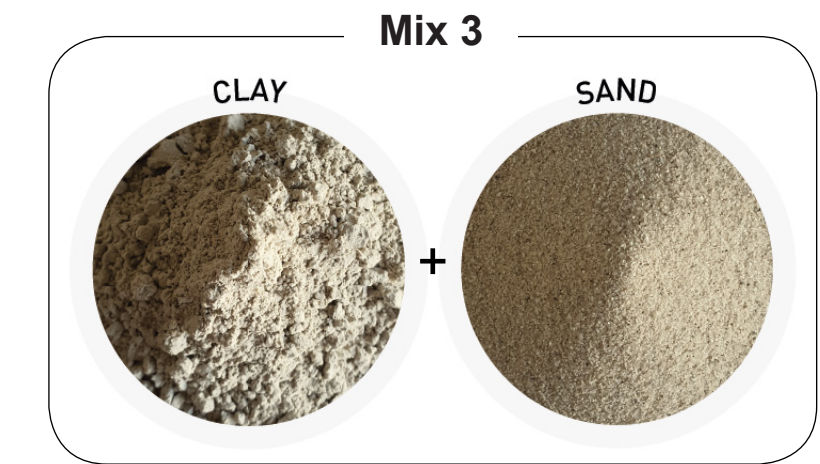
Results



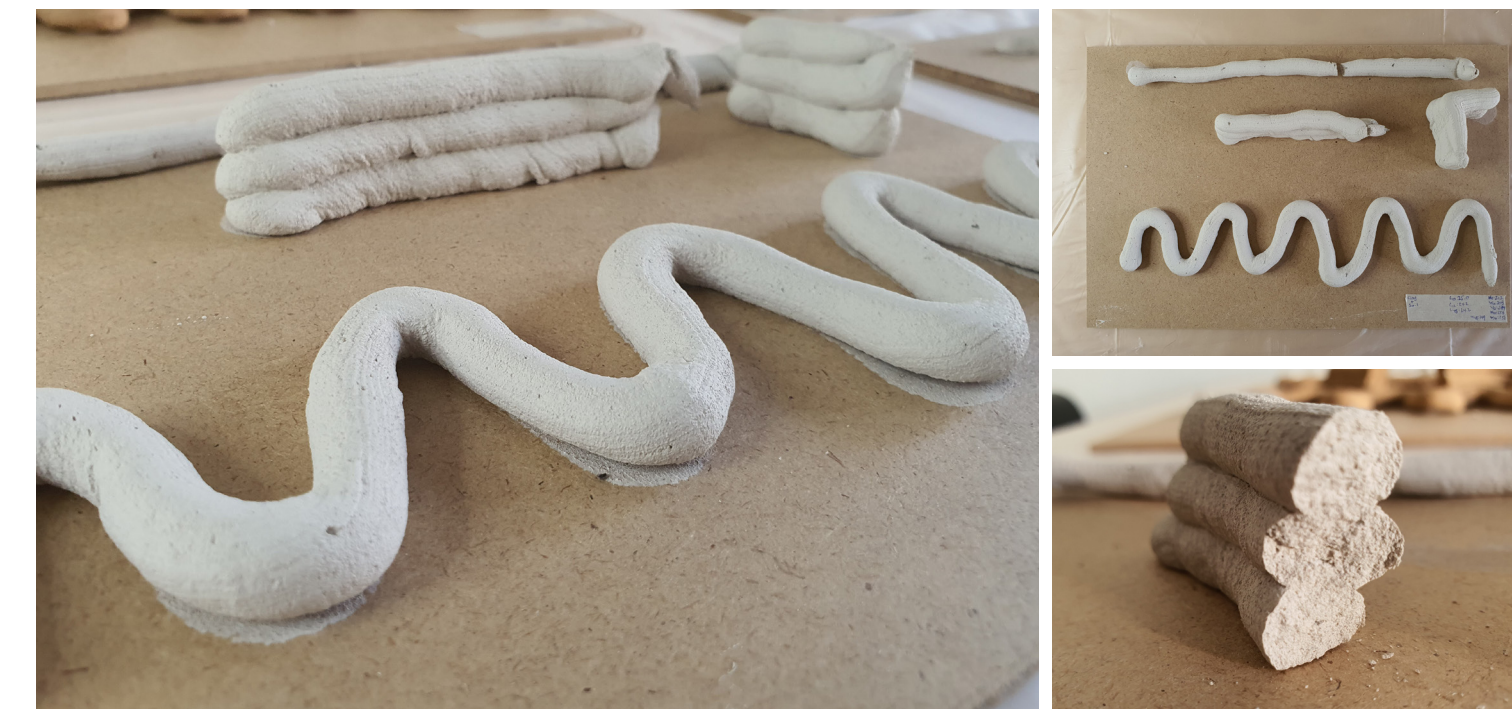
Shrinkage	•	(8.9%)
Deformation	•	
Weight Loss	•	(28.4%)
Interlayer Bonding	••	
Extrudability	•••••	
Cracking	•••	
Water Needed	•••••	(25.0%)
Drying Speed	••	
Surface Hardness	•	
Lightness	••	



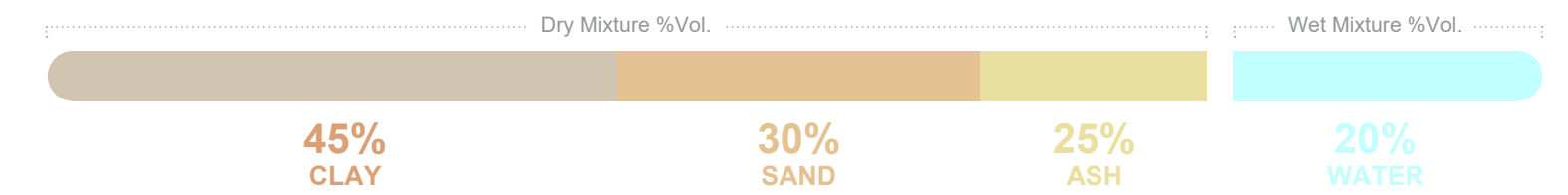
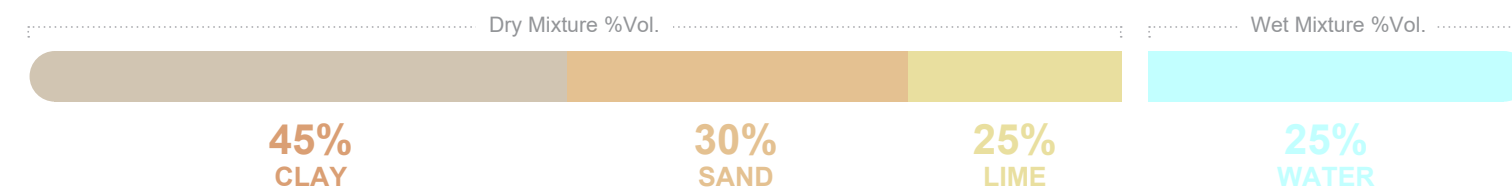
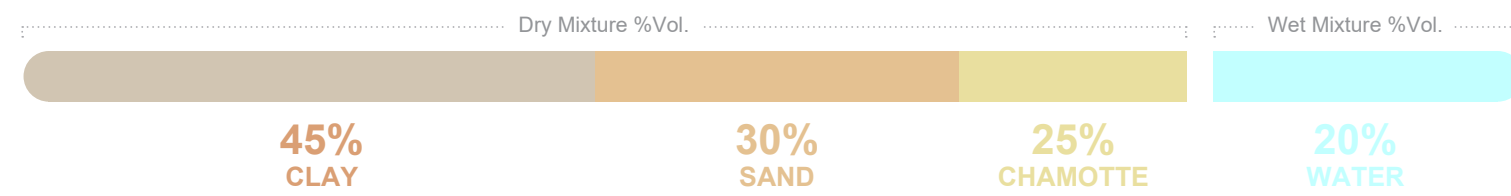
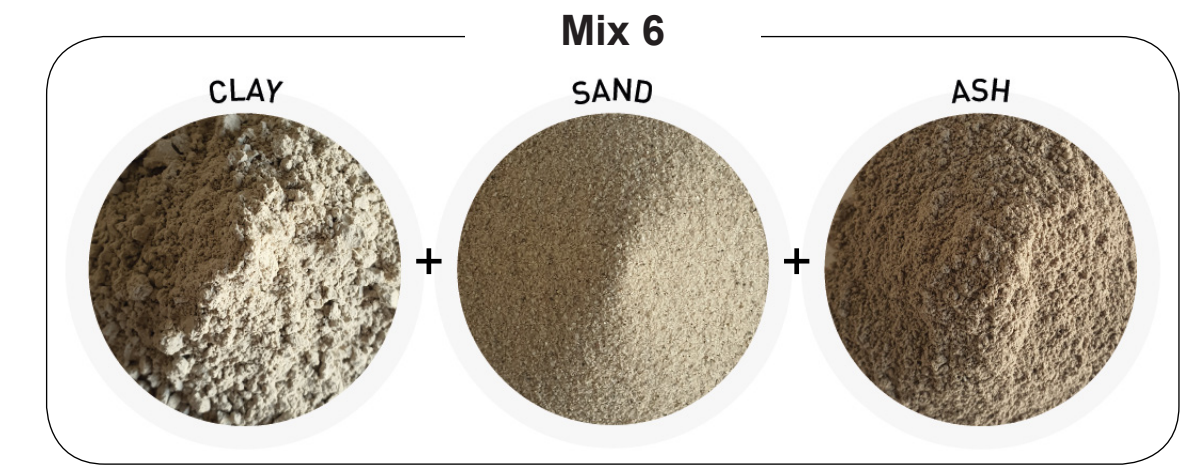
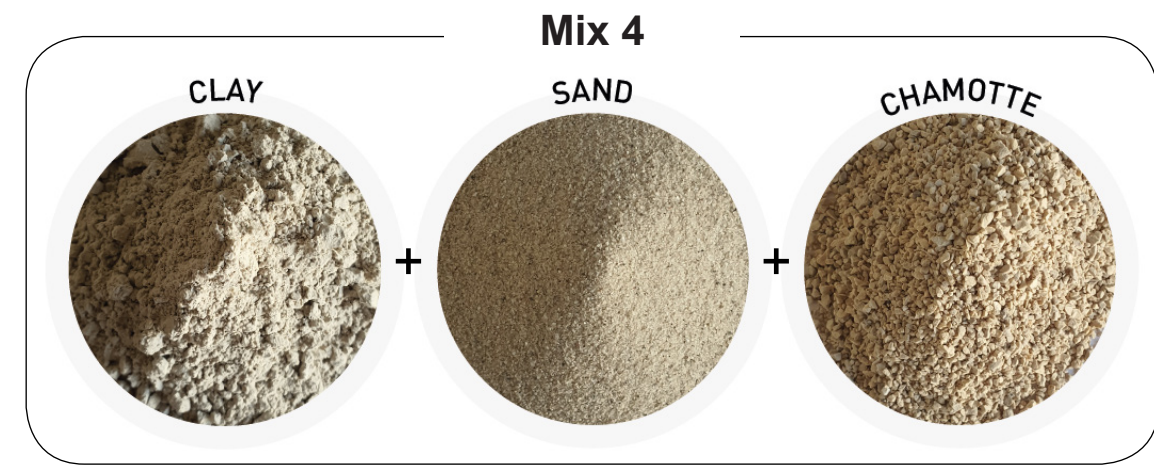
Shrinkage	••	(7.2%)
Deformation	•	
Weight Loss	•••	(19.3%)
Interlayer Bonding	••••	
Extrudability	••••	
Cracking	••	
Water Needed	•••	(20.0%)
Drying Speed	•••	
Surface Hardness	•••	
Lightness	•	



Shrinkage	••••	(3.2%)
Deformation	••	
Weight Loss	•••	(17.8%)
Interlayer Bonding	•••	
Extrudability	••••	
Cracking	••	
Water Needed	•••	(20.0%)
Drying Speed	•••	
Surface Hardness	••	
Lightness	•	



Results



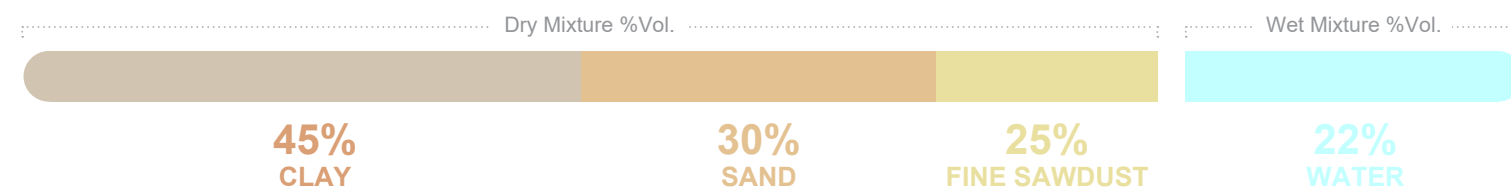
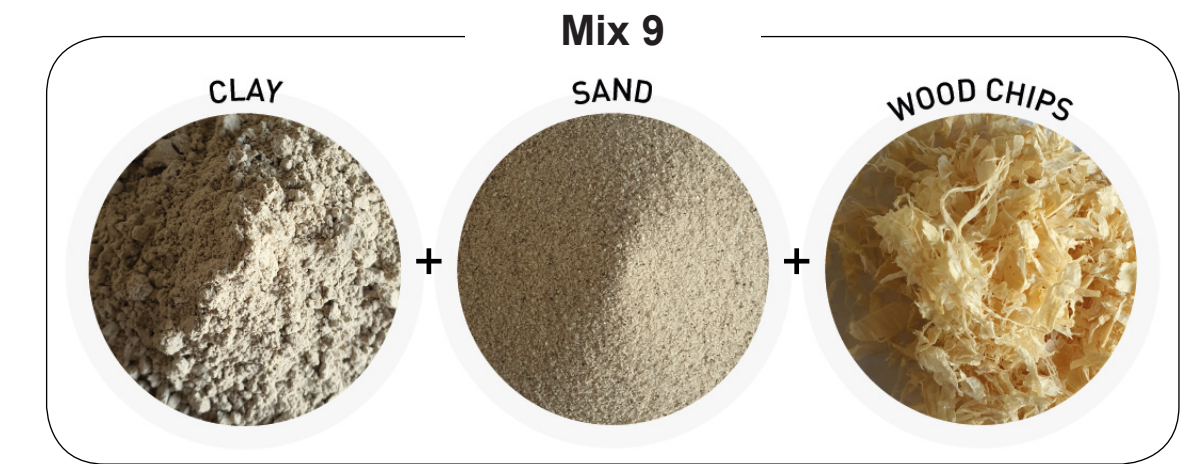
Shrinkage	•••••	(0.8%)
Deformation	•••••	
Weight Loss	•••	(18.2%)
Interlayer Bonding	•••	
Extrudability	••	
Cracking	••••	
Water Needed	•••	(20.0%)
Drying Speed	•••••	
Surface Hardness	•••	
Lightness	•	

Shrinkage	•••••	(1.5%)
Deformation	••••	
Weight Loss	••	(23.8%)
Interlayer Bonding	••••	
Extrudability	•••••	
Cracking	•••••	
Water Needed	••	(25.0%)
Drying Speed	•••••	
Surface Hardness	••••	
Lightness	••	

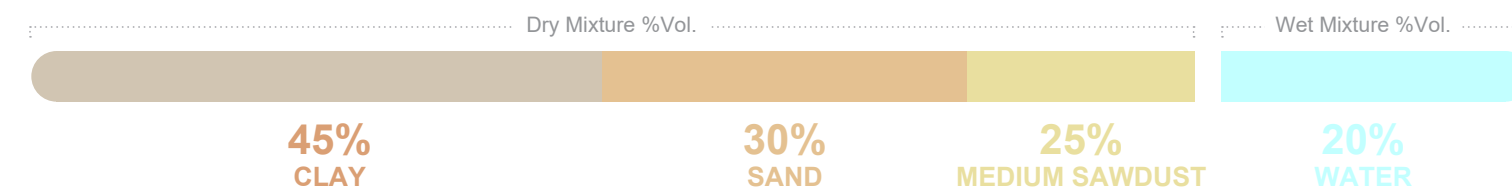
Shrinkage	••••	(2.0%)
Deformation	•••	
Weight Loss	•••	(21.0%)
Interlayer Bonding	••••	
Extrudability	••••	
Cracking	•••••	
Water Needed	•••	(20.0%)
Drying Speed	•••••	
Surface Hardness	•••••	
Lightness	••••	



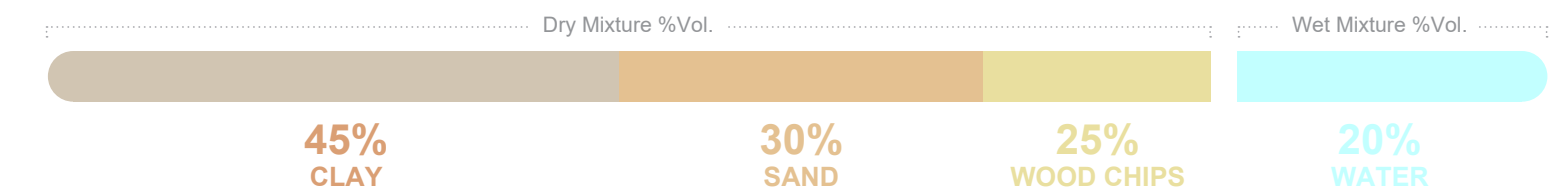
Results



Shrinkage	••••	(1.6%)
Deformation	•••	
Weight Loss	••	(25.4%)
Interlayer Bonding	•••	
Extrudability	••••	
Cracking	•••••	
Water Needed	•••	(22.0%)
Drying Speed	•••••	
Surface Hardness	••••	
Lightness	••••	



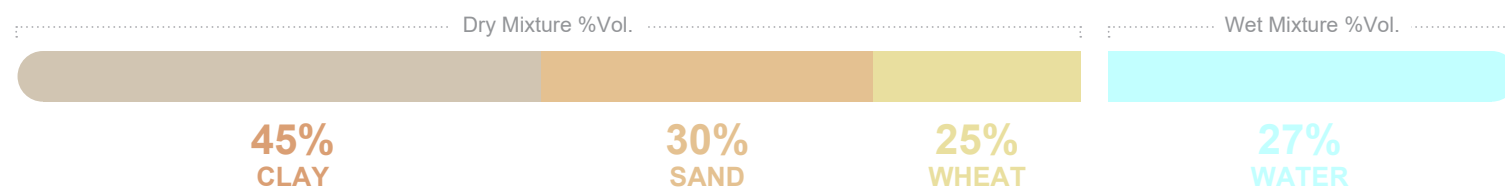
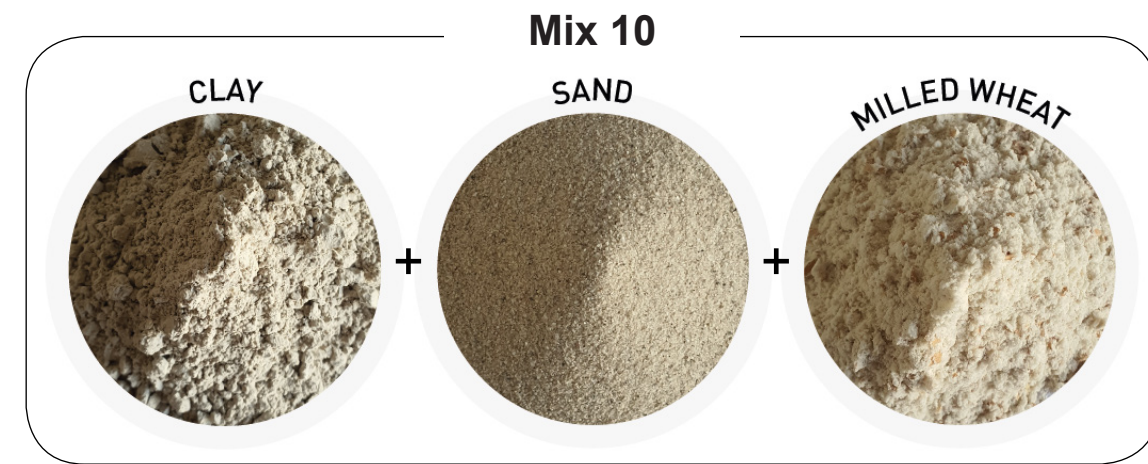
Shrinkage	•••••	(0.8%)
Deformation	•••	
Weight Loss	••	(23.1%)
Interlayer Bonding	•••	
Extrudability	••	
Cracking	•••••	
Water Needed	••••	(20.0%)
Drying Speed	•••••	
Surface Hardness	••	
Lightness	••••	



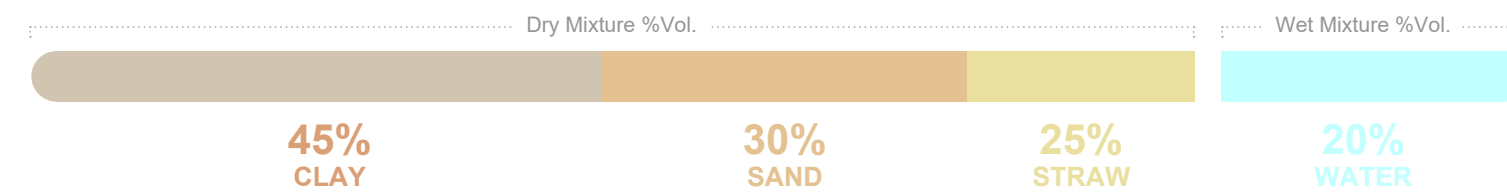
Shrinkage	•••	(4.5%)
Deformation	•••	
Weight Loss	•	(36.8%)
Interlayer Bonding	-	
Extrudability	•	
Cracking	•••••	
Water Needed	••••	(20.0%)
Drying Speed	••	
Surface Hardness	••	
Lightness	•••••	



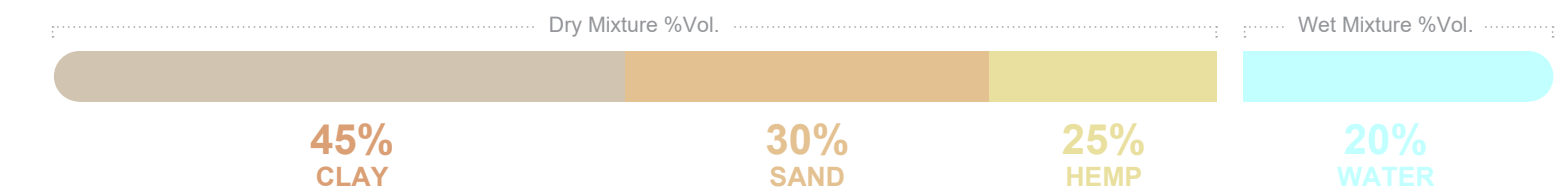
Results



Shrinkage	•	(6.0%)
Deformation	••••	
Weight Loss	•	(28.6%)
Interlayer Bonding	••	
Extrudability	•••	
Cracking	••	
Water Needed	•	(27.0%)
Drying Speed	•	
Surface Hardness	••••	
Lightness	•••	



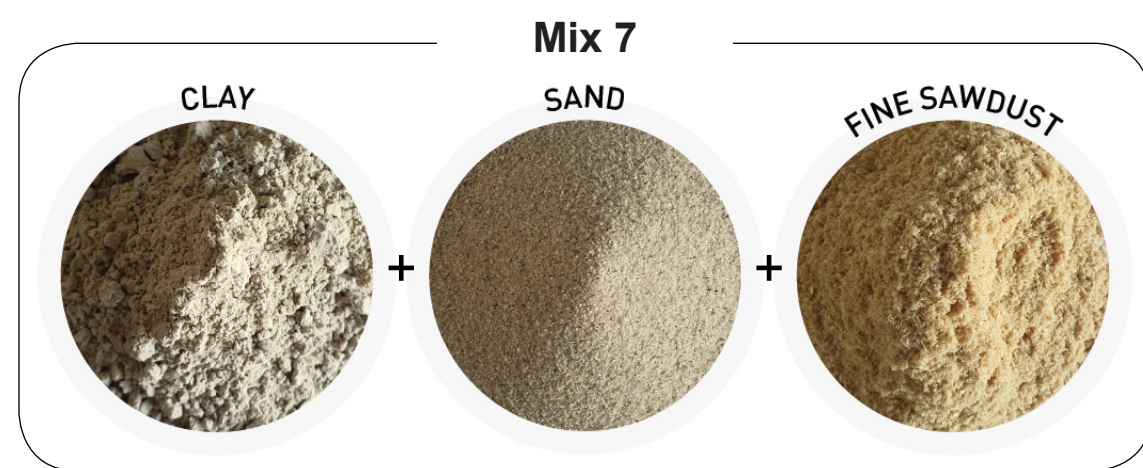
Shrinkage	•••	(1.7%)
Deformation	•••	
Weight Loss	••	(25.8%)
Interlayer Bonding	-	
Extrudability	•	
Cracking	••	
Water Needed	•••	(20.0%)
Drying Speed	•••••	
Surface Hardness	•	
Lightness	•••••	



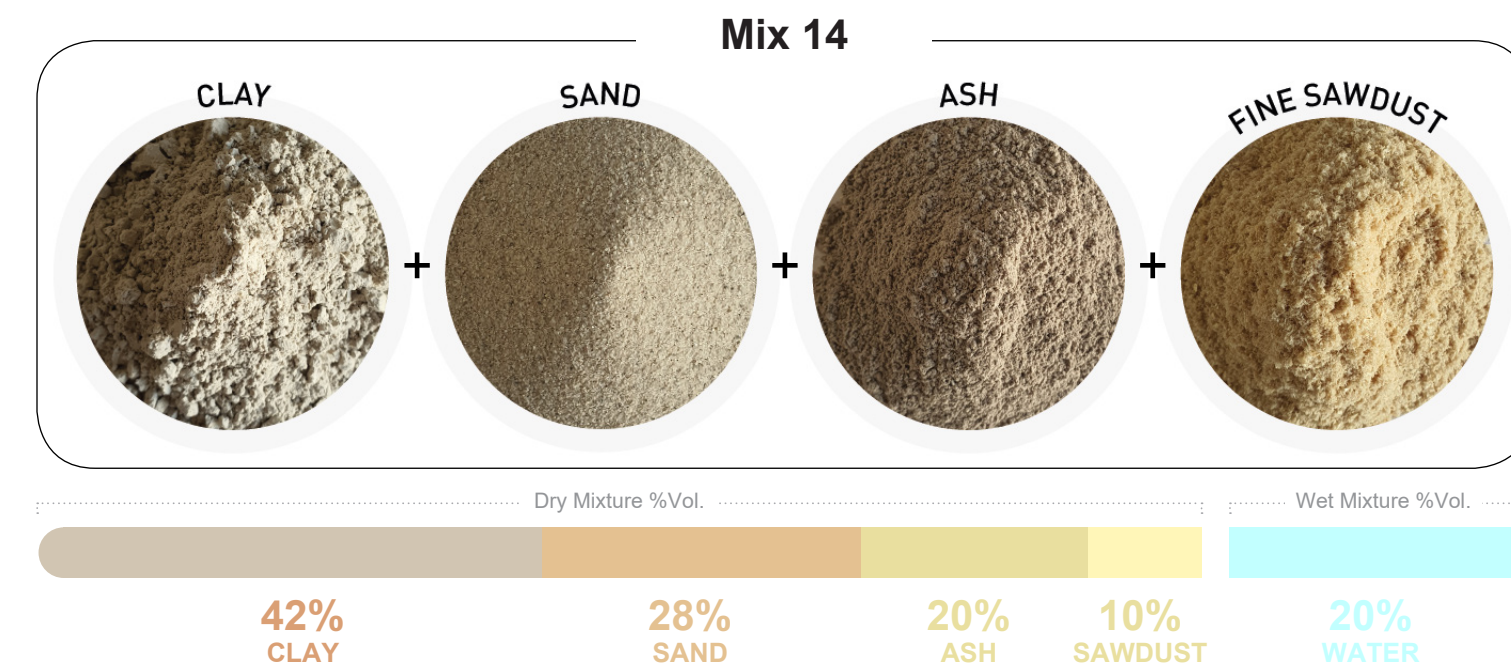
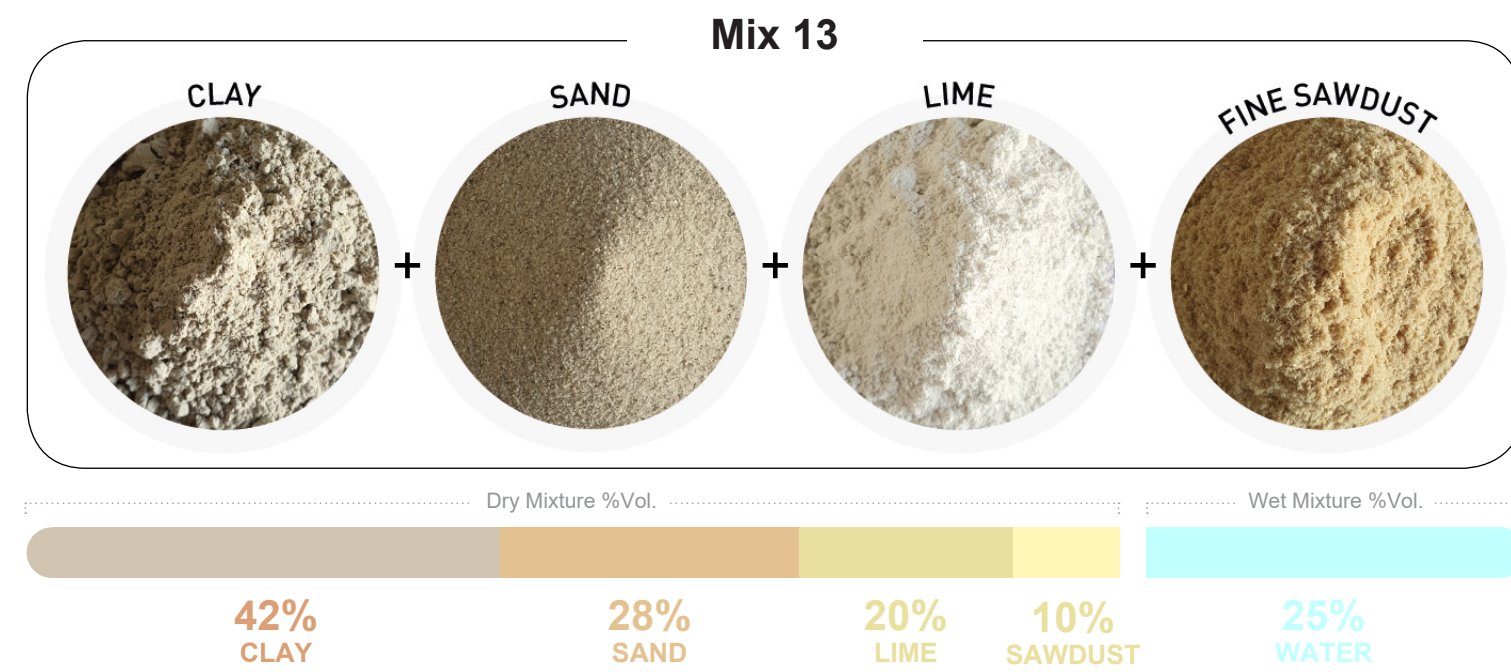
Shrinkage	••••	(0.9%)
Deformation	•••	
Weight Loss	••	(23.6%)
Interlayer Bonding	-	
Extrudability	•	
Cracking	••••	
Water Needed	•••	(20.0%)
Drying Speed	••••	
Surface Hardness	••	
Lightness	•••••	



Mixture Design



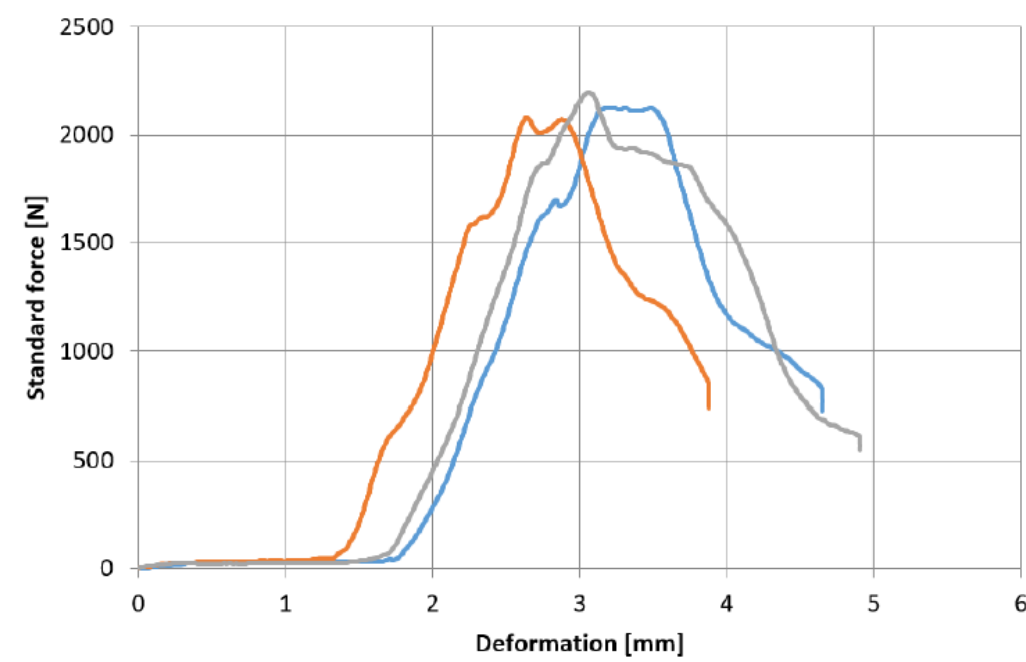
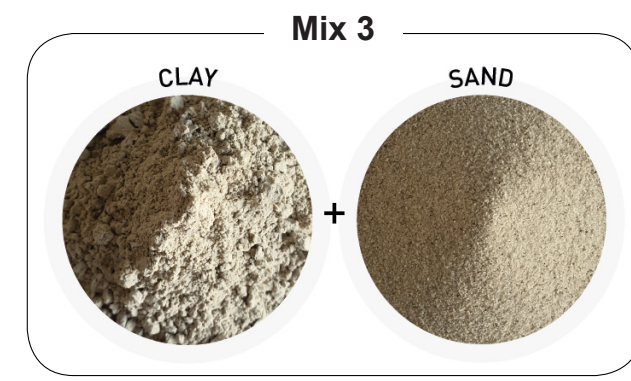
Refined Mixtures



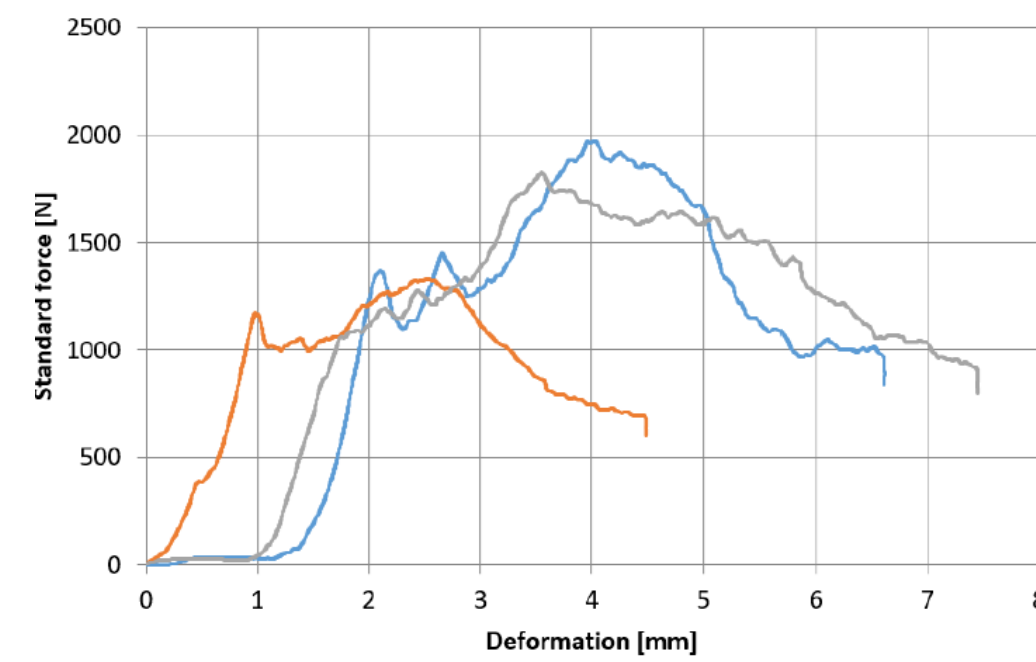
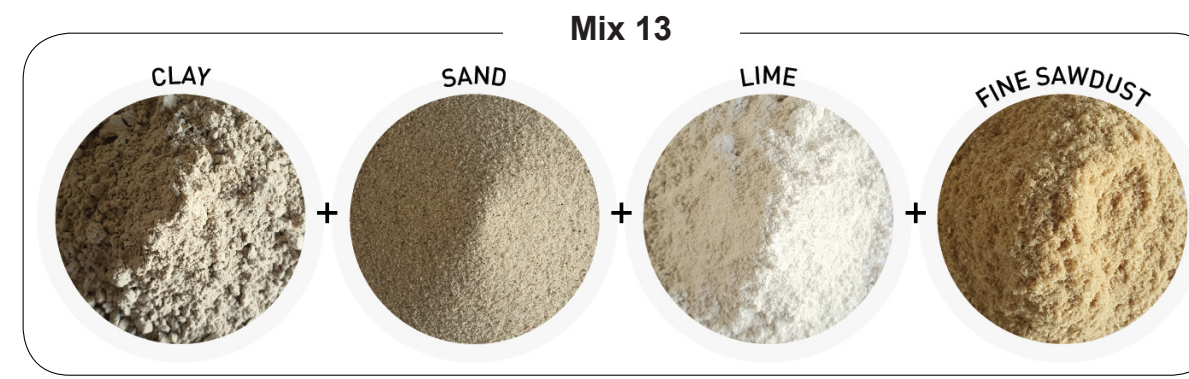
Strength Tests



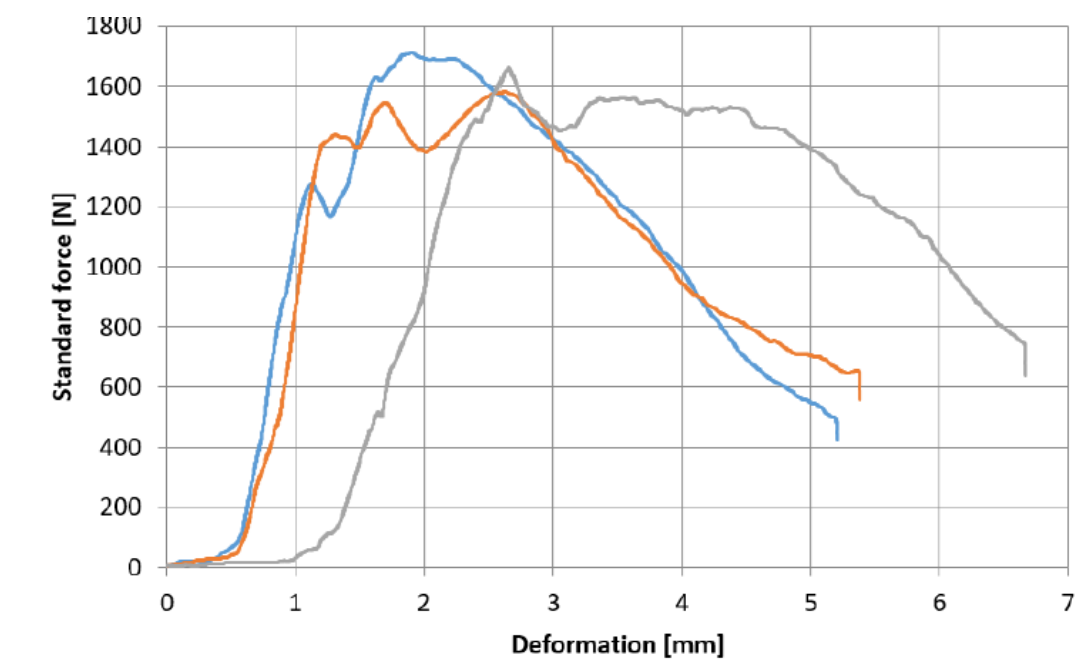
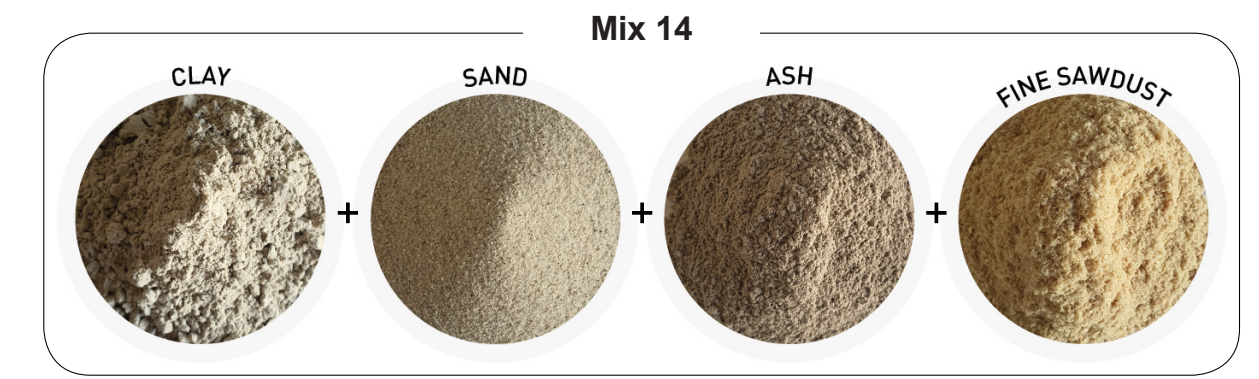
Strength Tests



2133 N
0.59 MPa

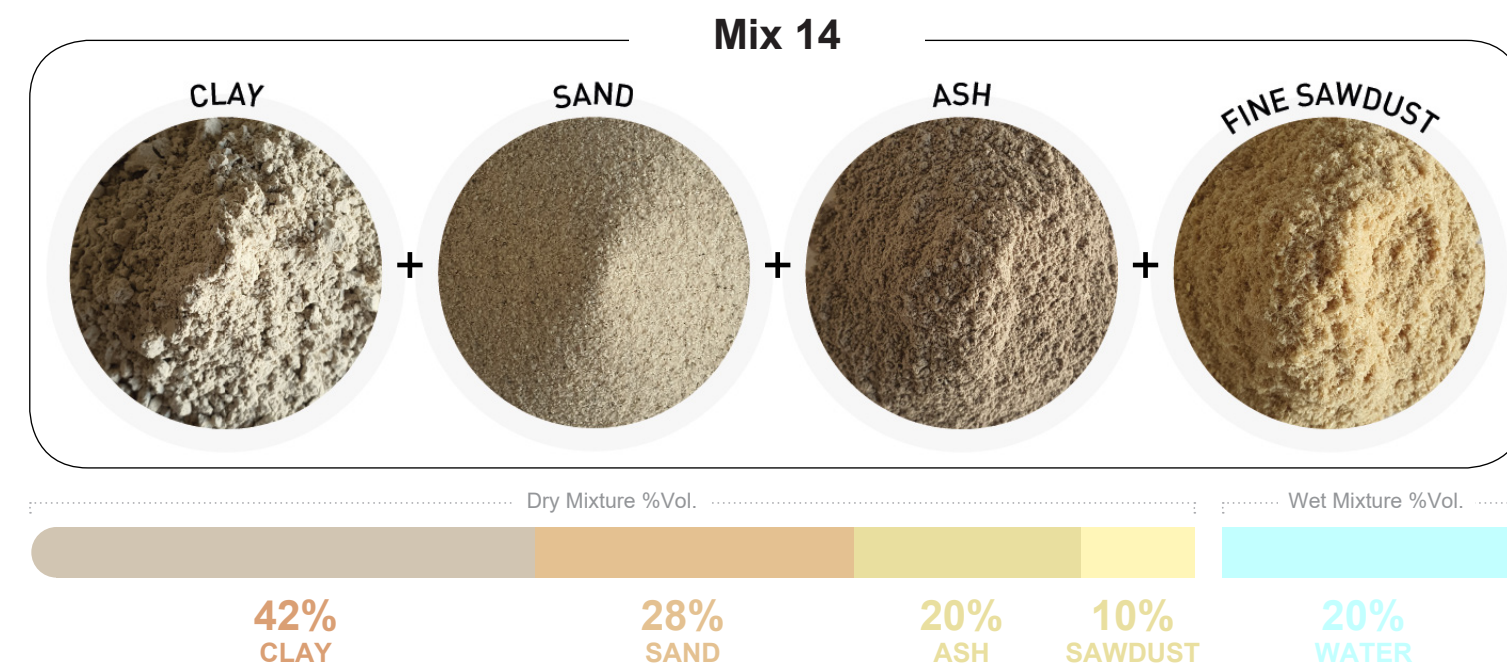


1708 N
0.47 MPa



1652 N
0.46 MPa

Chosen Mixture



Variables for Customization



Family Size

Size of Rooms
Number of Rooms
Courtyard Size
Communal Potentials
Extended Family
Expansion



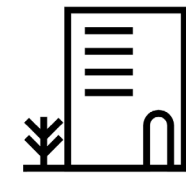
Privacy

Degree of Openings
Courtyard
Layout
Entrance Privacy
Orientation
Enclosure Degree



Additional Functions

Commercial Space
Garden
Shared Spaces
Water Storage
Guest Areas
Working Space

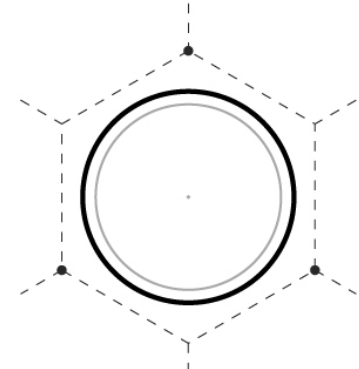


Aesthetics

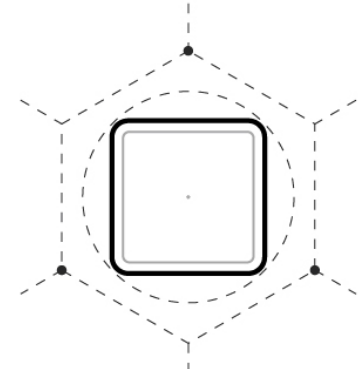
Printing Patterns
Window Shapes
Door Shapes
Furniture
Finishings

User Input

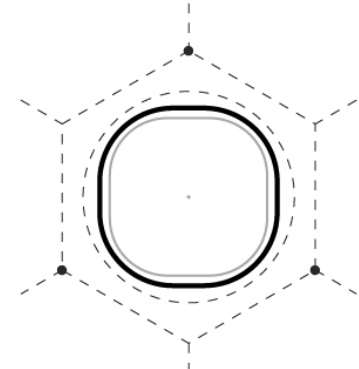
1 BASE SHAPE



Circle

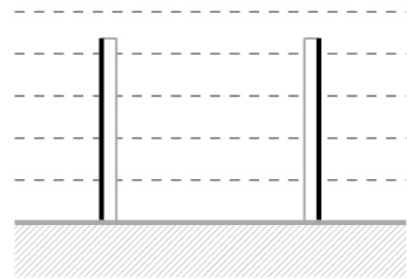


Square

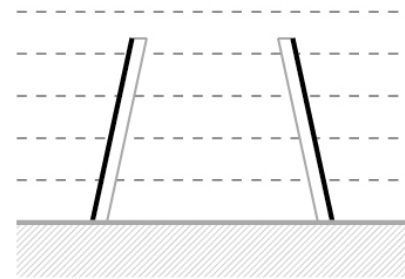


Rounded Square

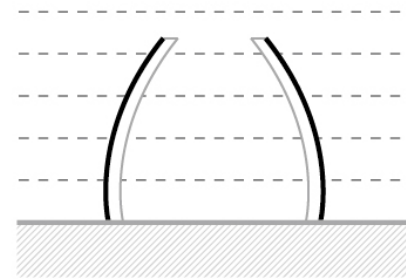
2 WALL PROFILE



Straight

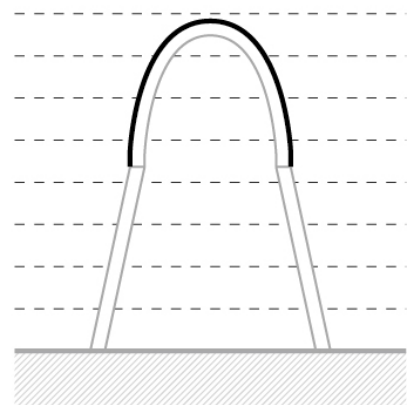


Inclined

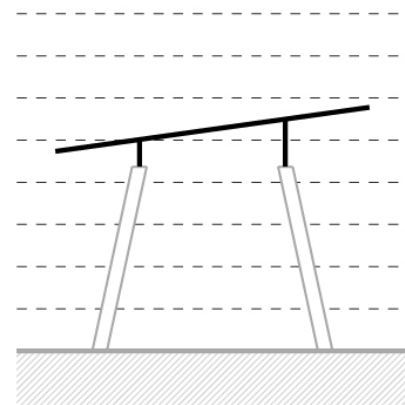


Curved

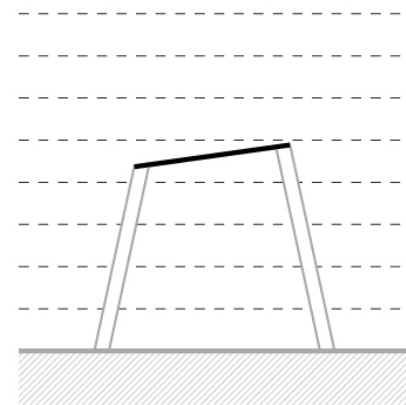
3 ROOF TYPE



Earth Dome

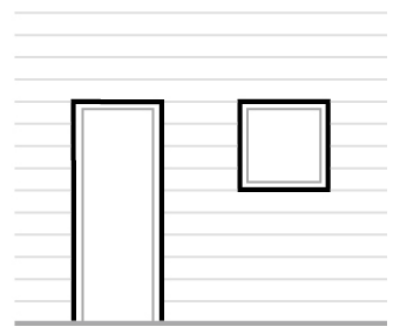


Hybrid

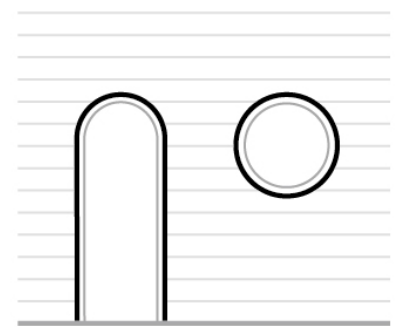


Skylight

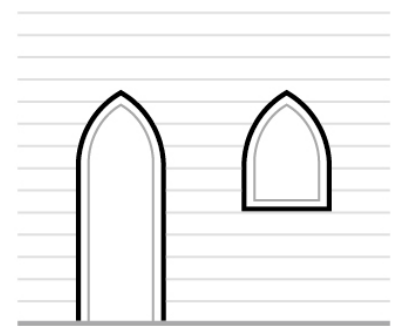
4 OPENINGS SHAPE



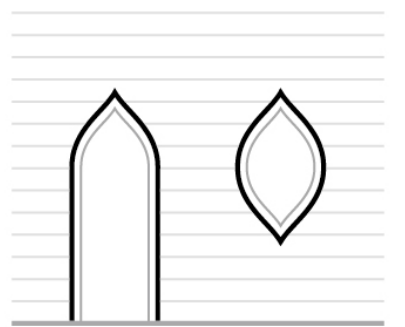
Square



Circle

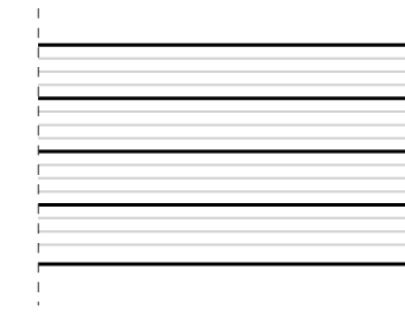


Pointed Arch

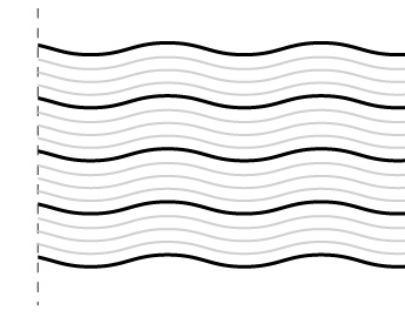


Teardrop

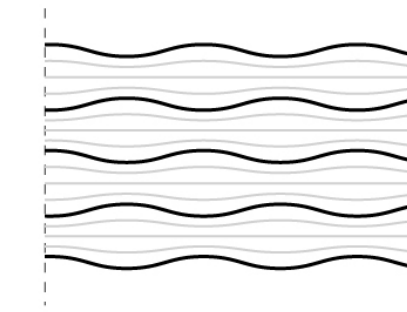
5 WALL PATTERN



Smooth

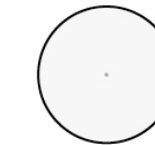


Wave Horizontal

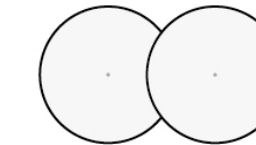


Wave Horizontal + Vertical

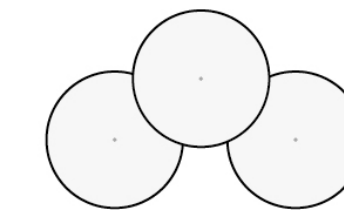
6 NO. UNITS



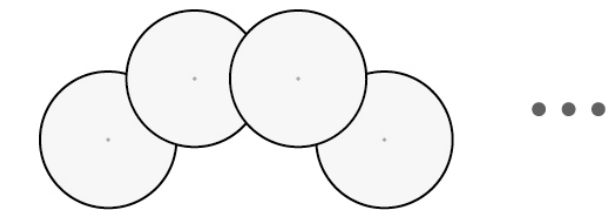
One



Two

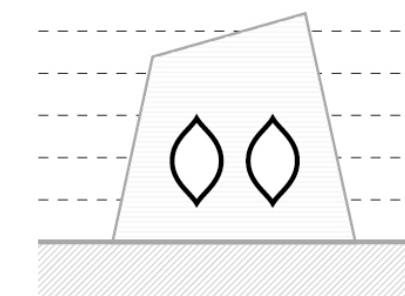


Three

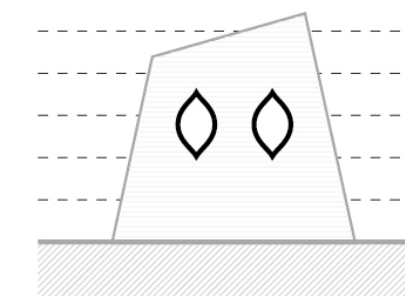


Four ...

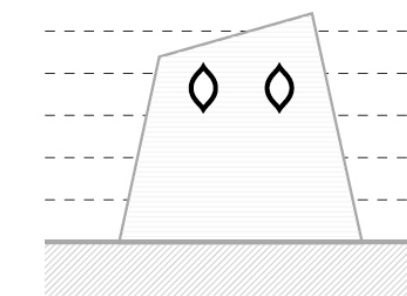
7 PRIVACY (OPENINGS)



Low Privacy

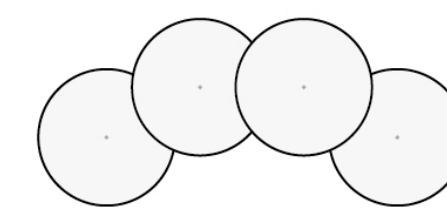


Medium Privacy

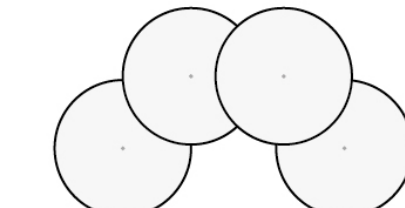


High Privacy

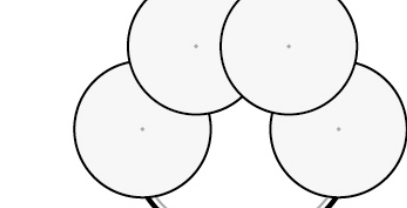
8 PRIVACY (LAYOUT)



Open

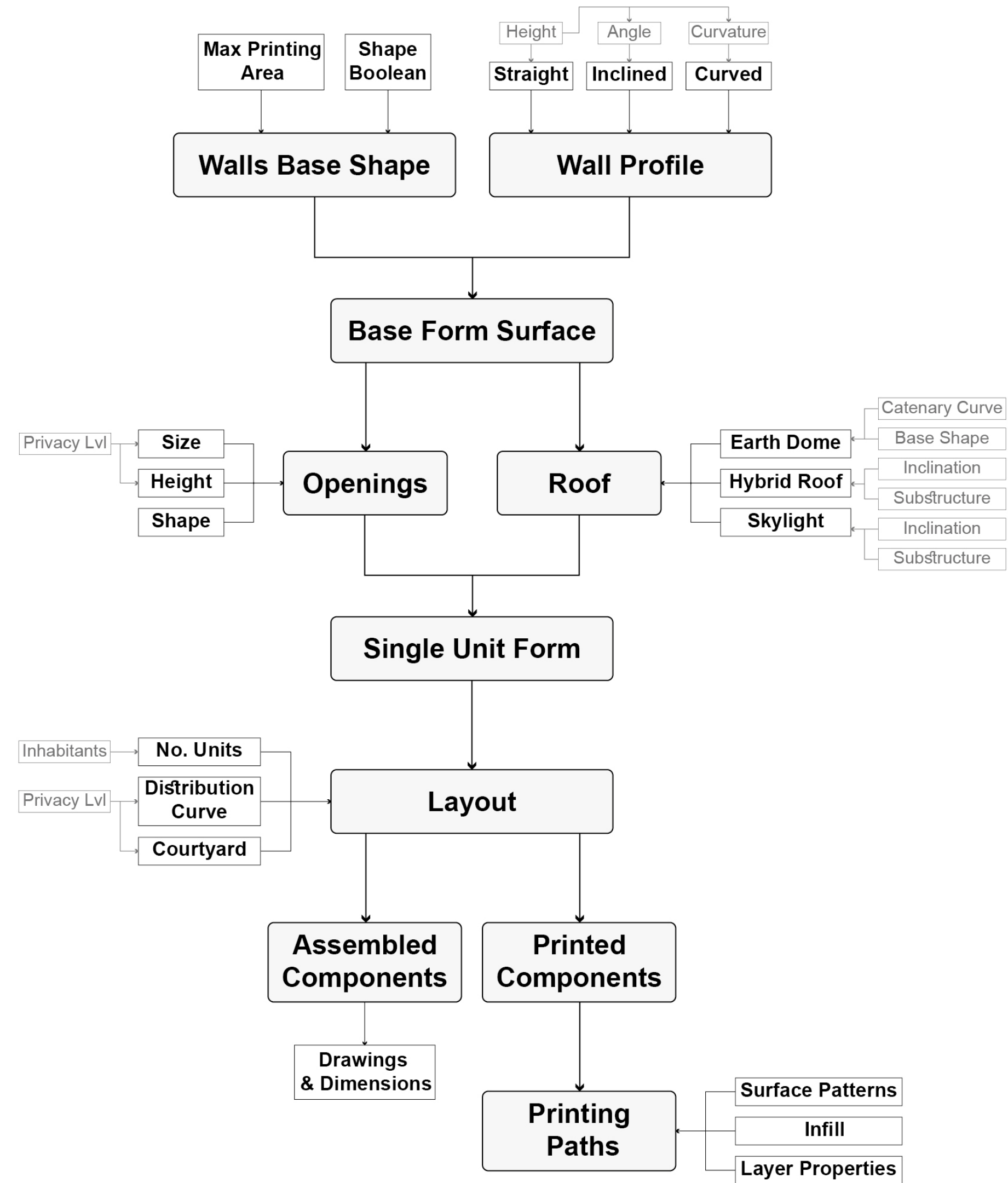


Semi-Enclosed

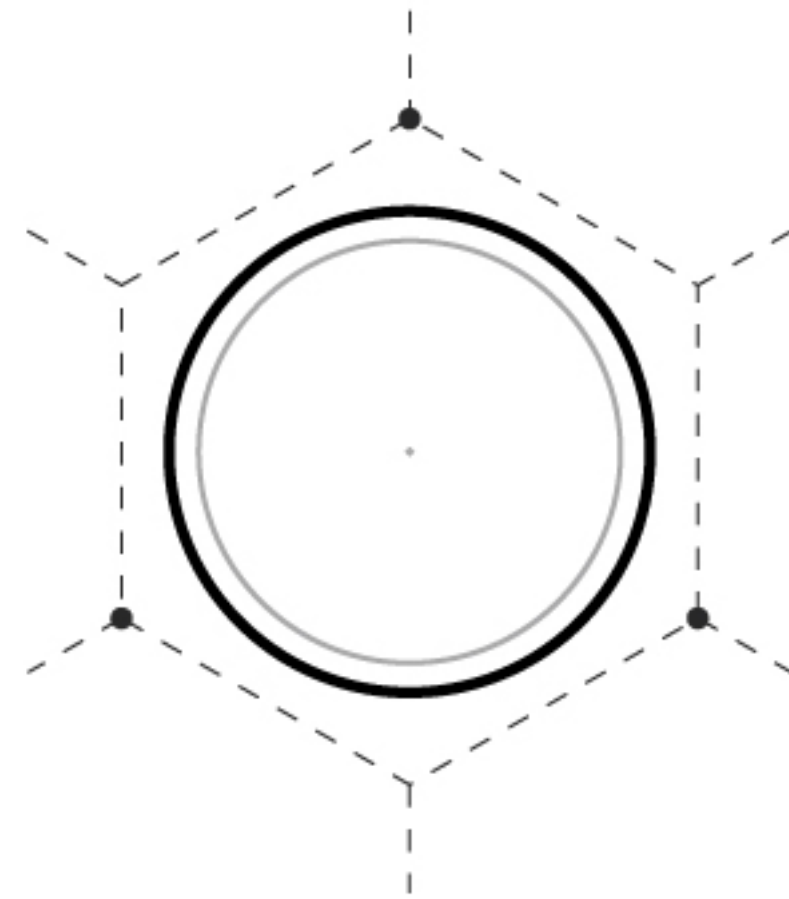


Enclosed

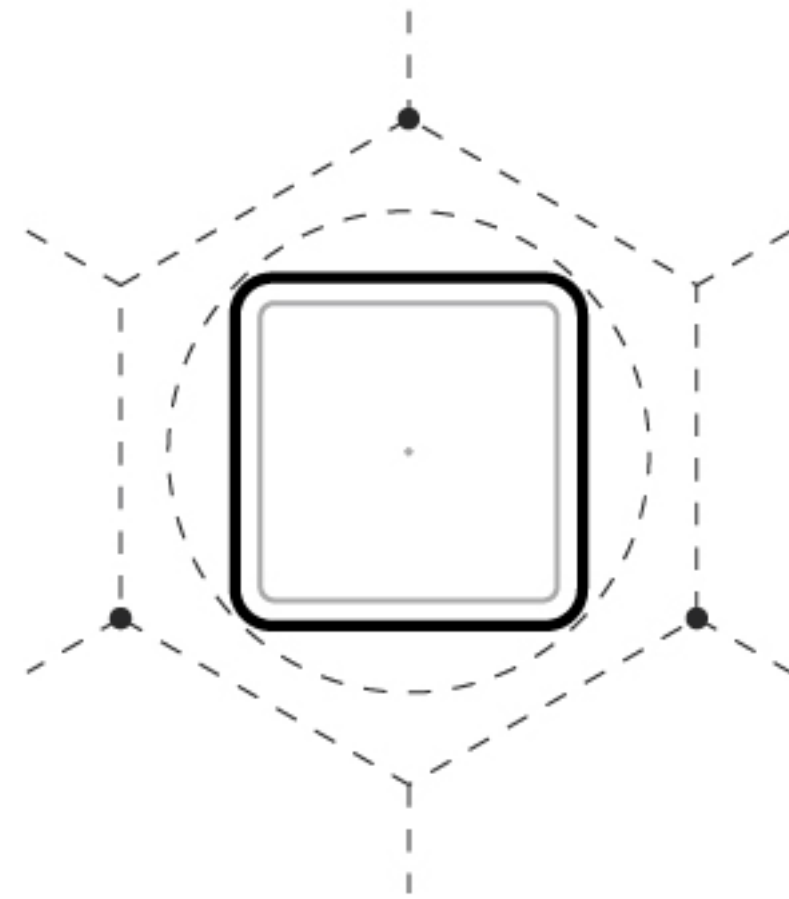
Computational Model Flowchart



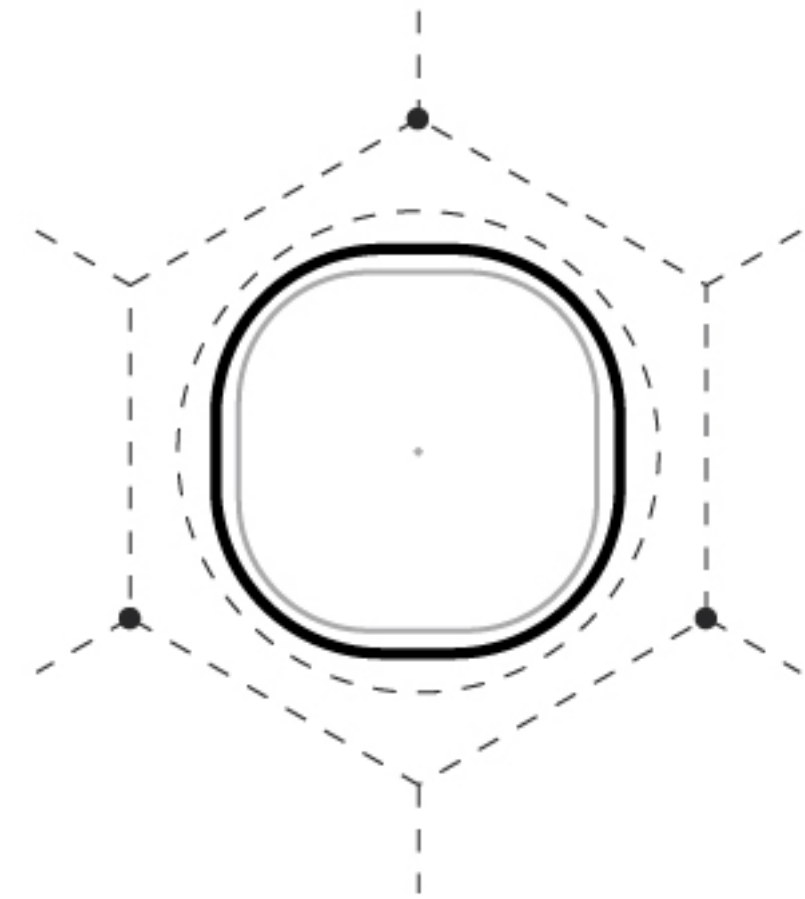
Base Shape



Circle

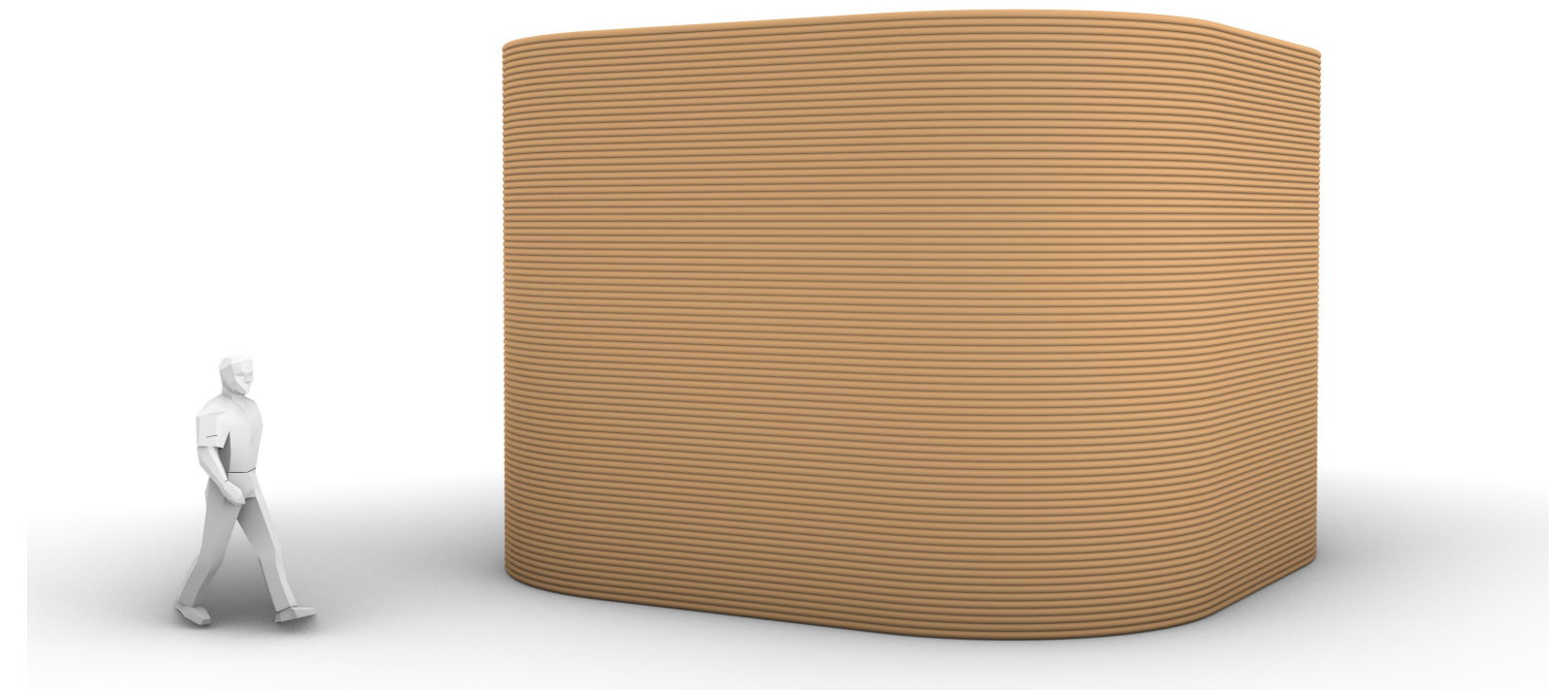
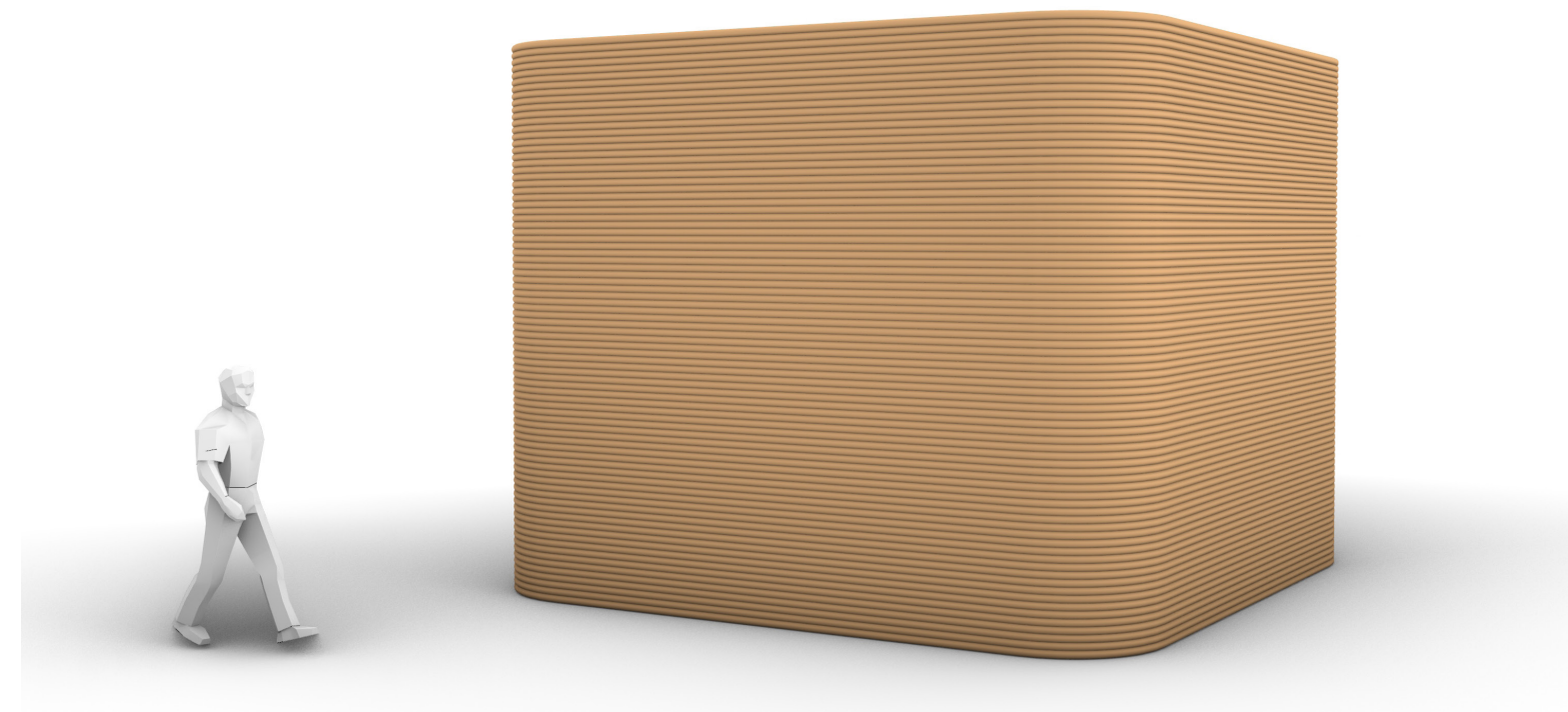
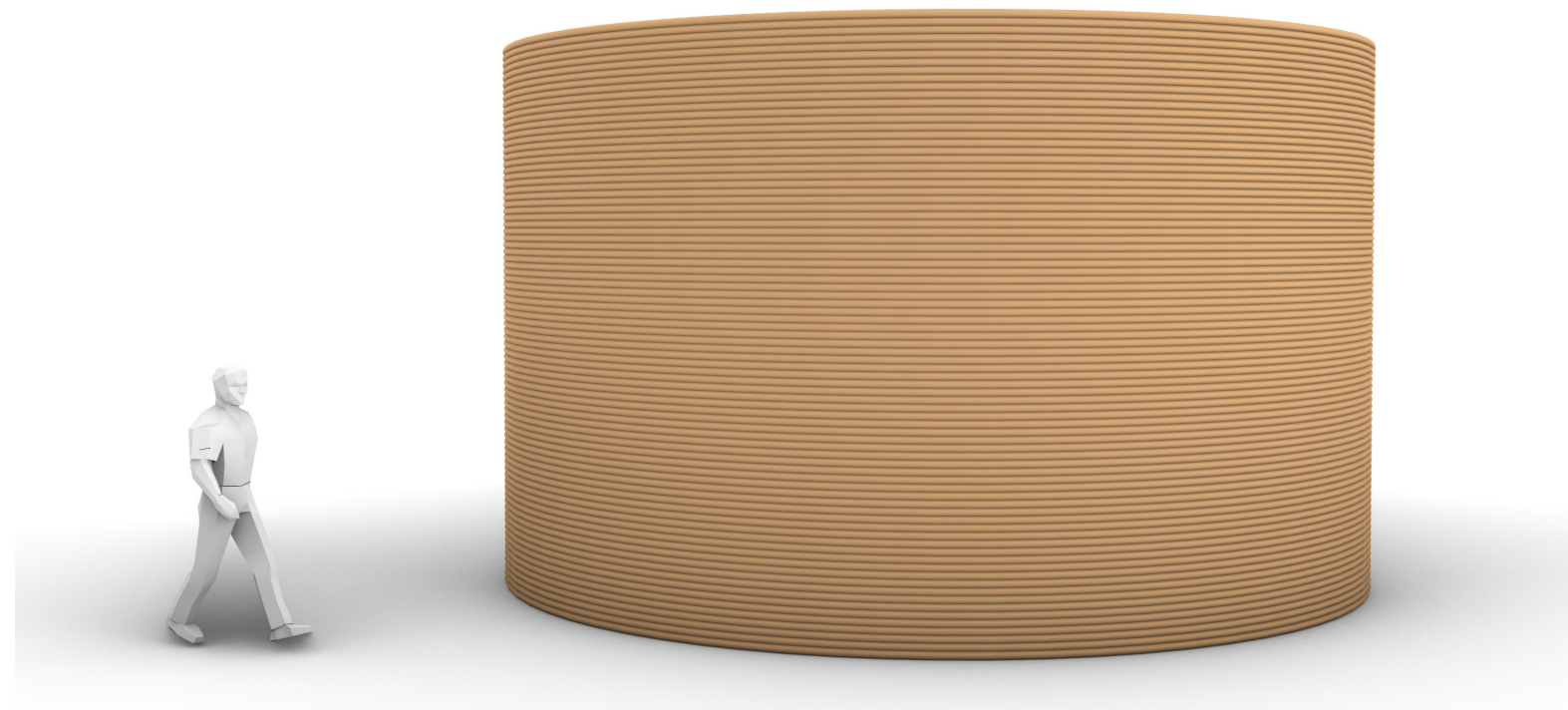


Square



**Rounded
Square**

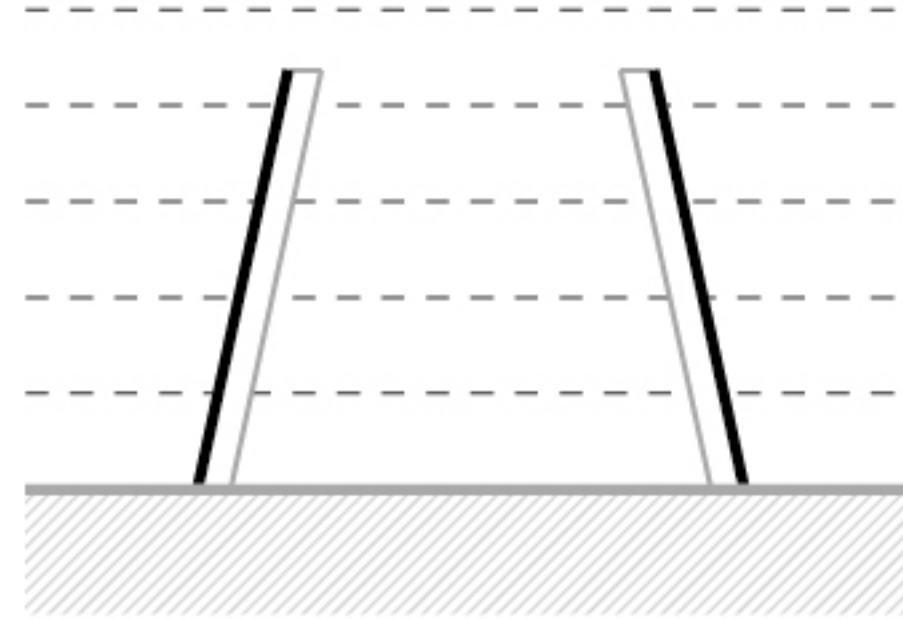
Base Shape



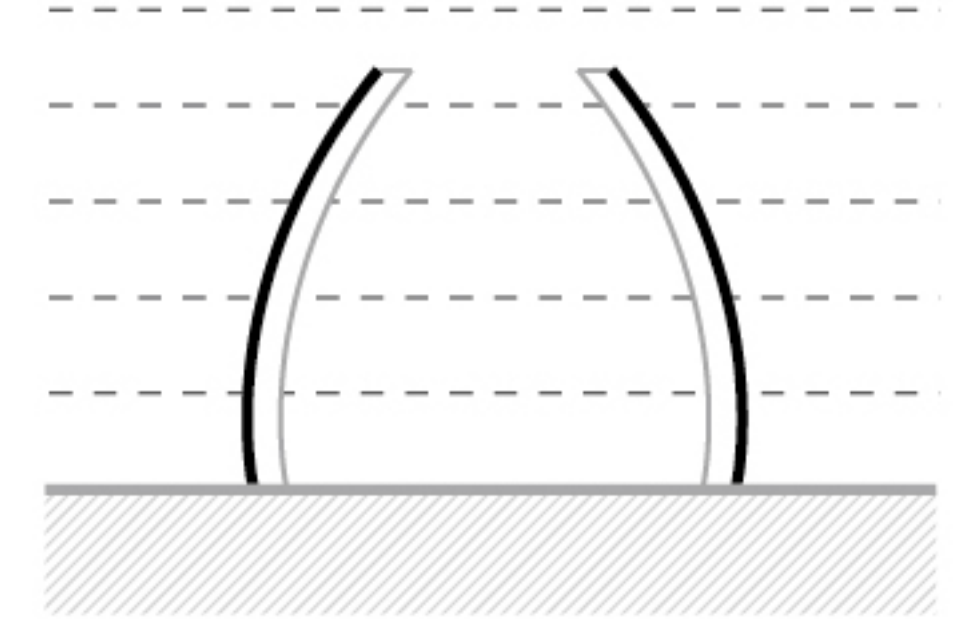
Wall Profiles



Straight

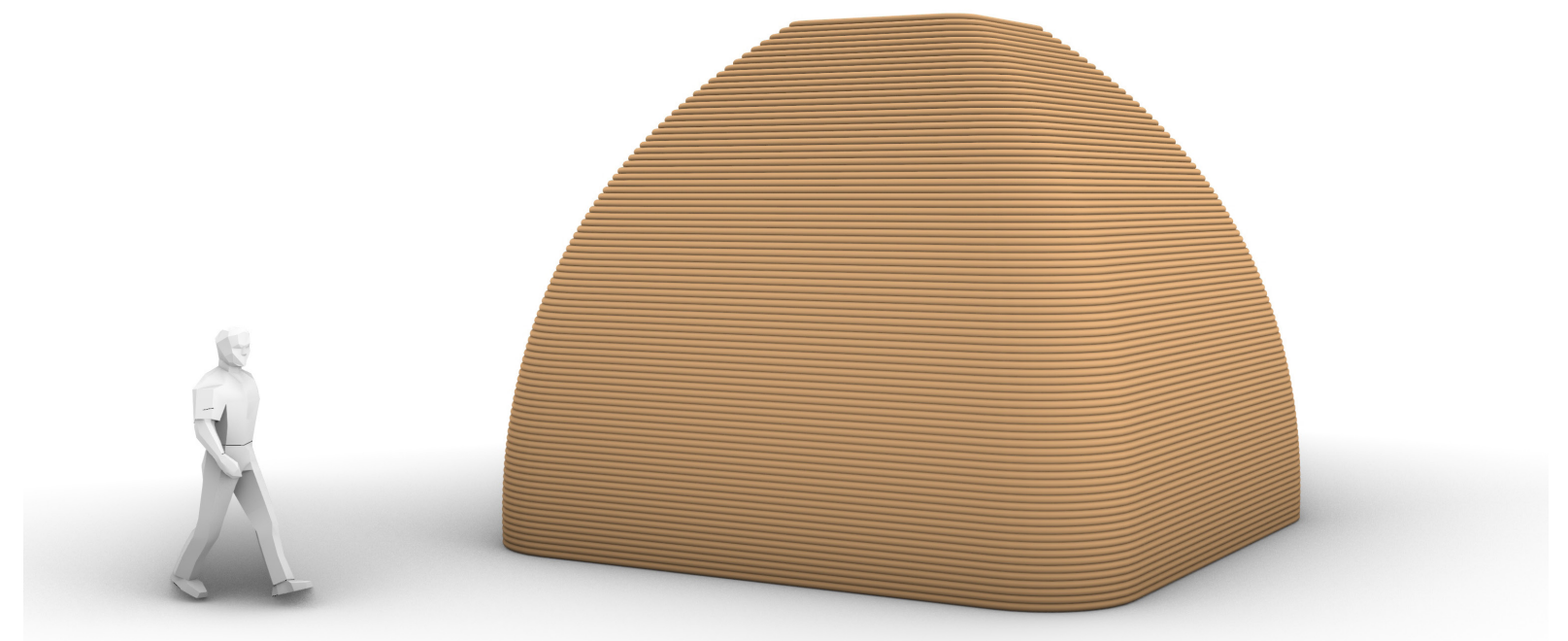
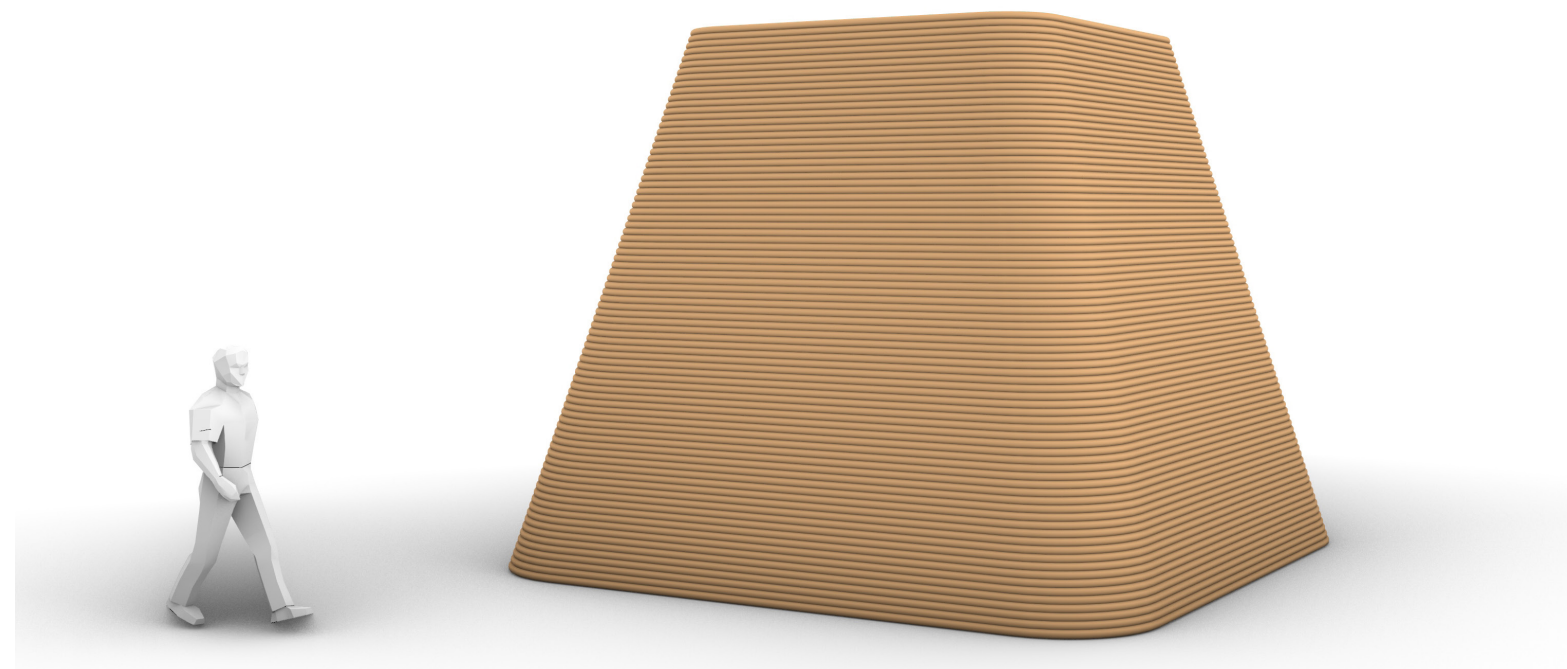
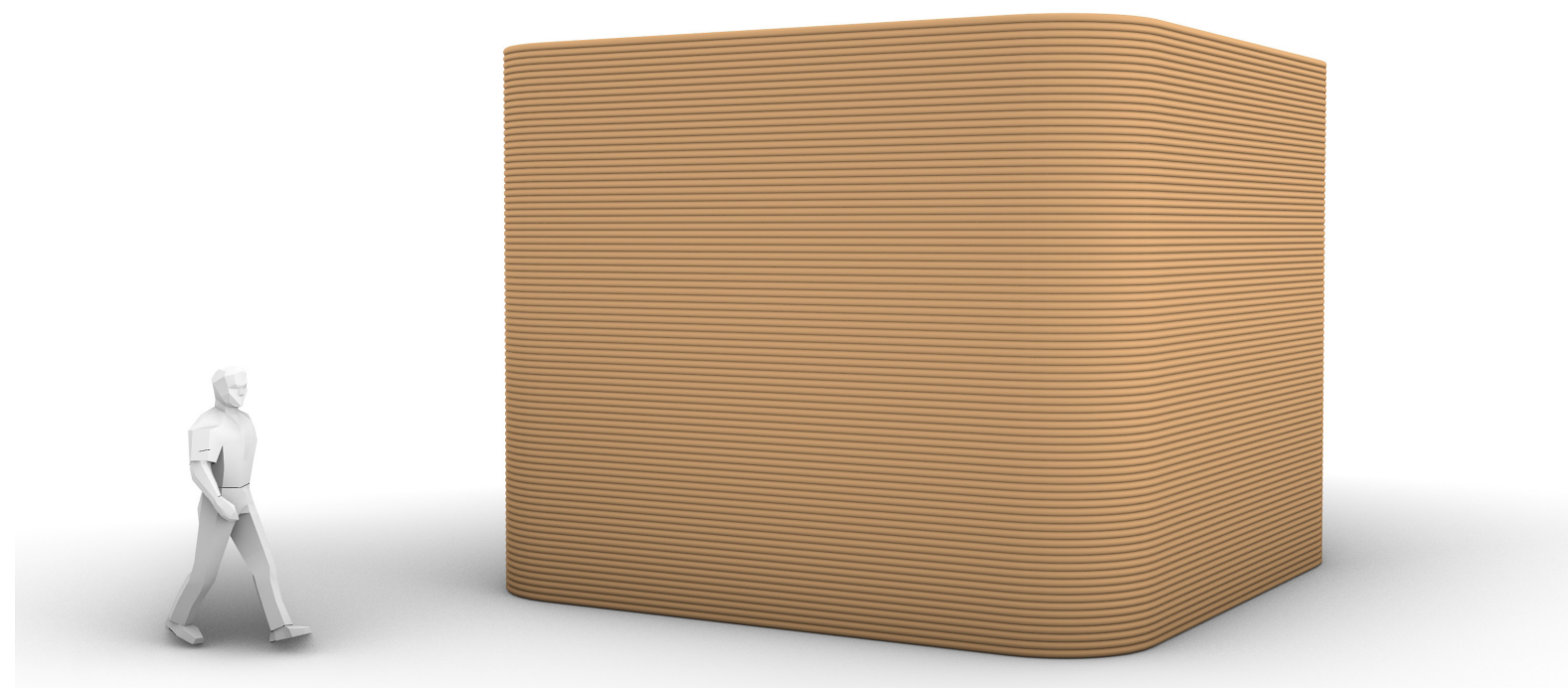


Inclined

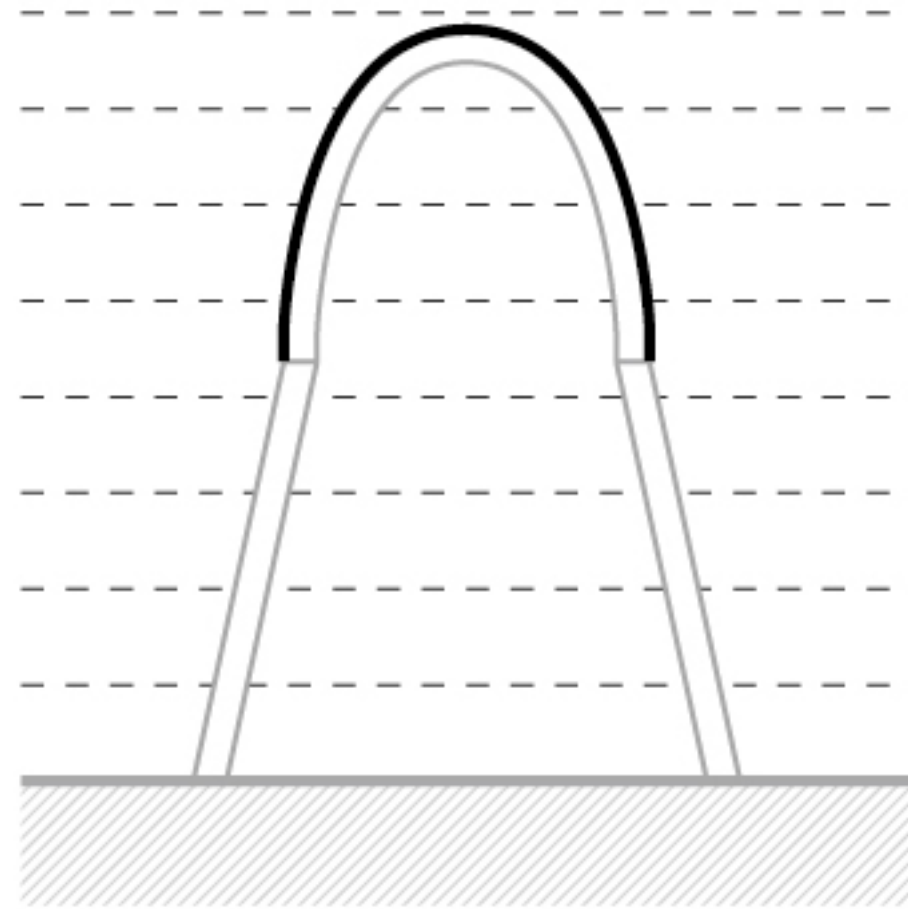


Curved

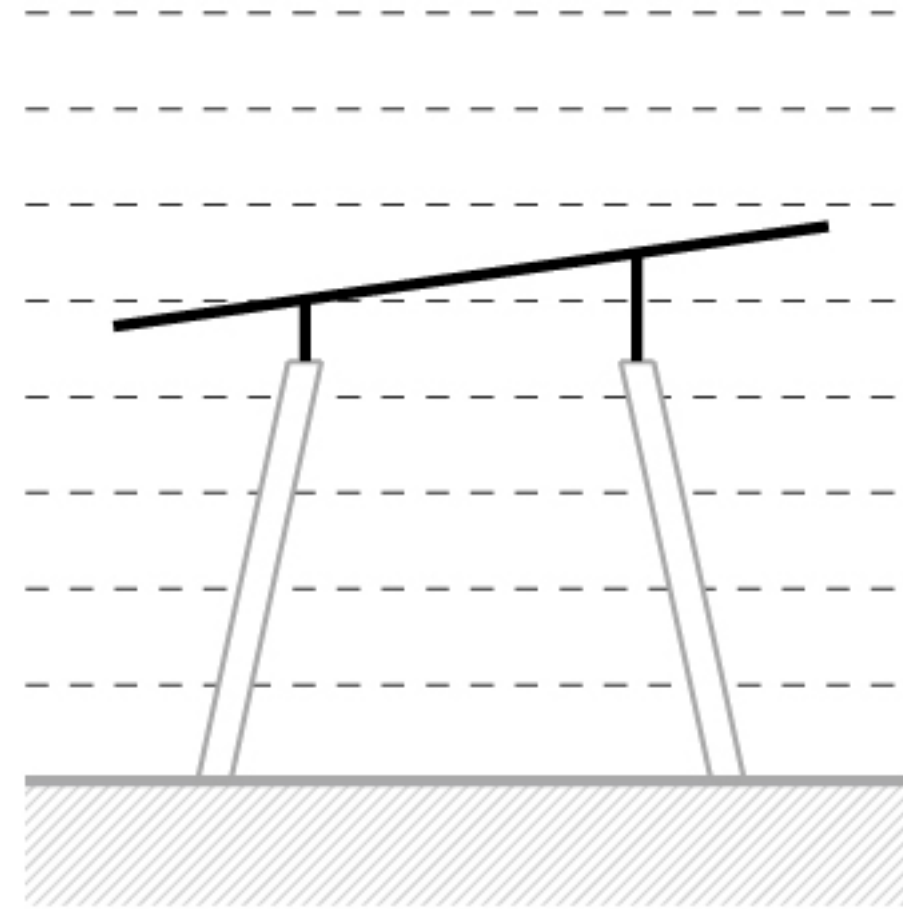
Wall Profiles



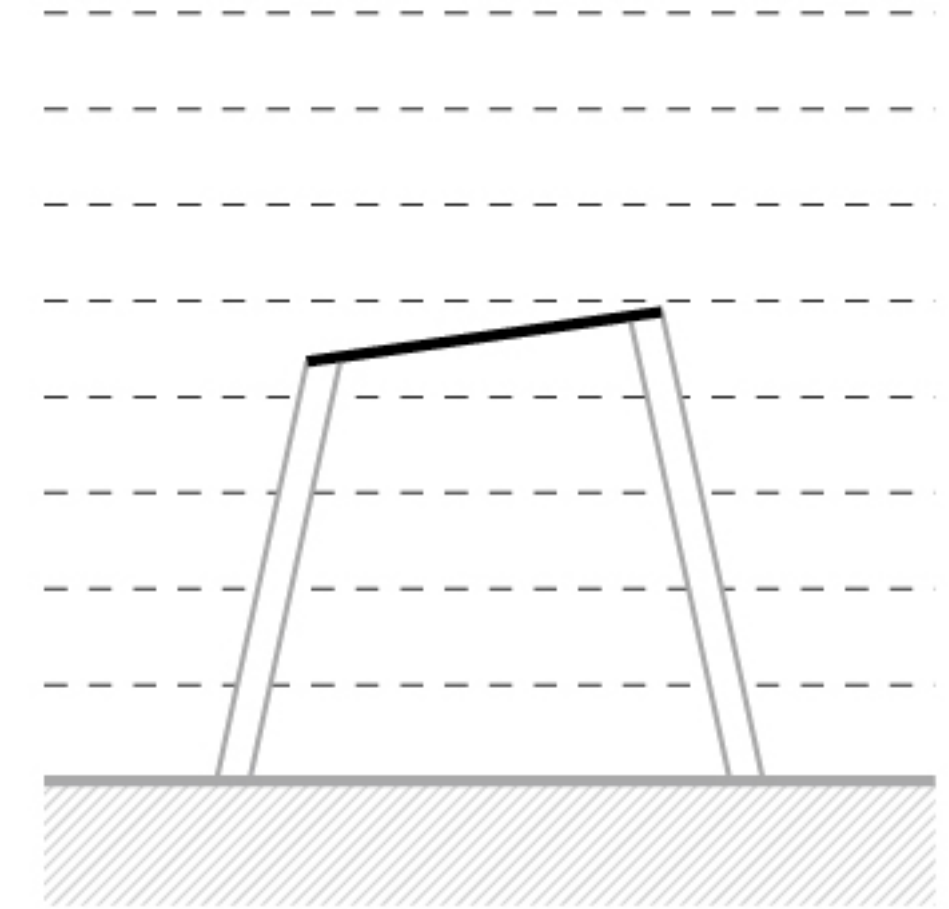
Roof Type



**Earth
Dome**

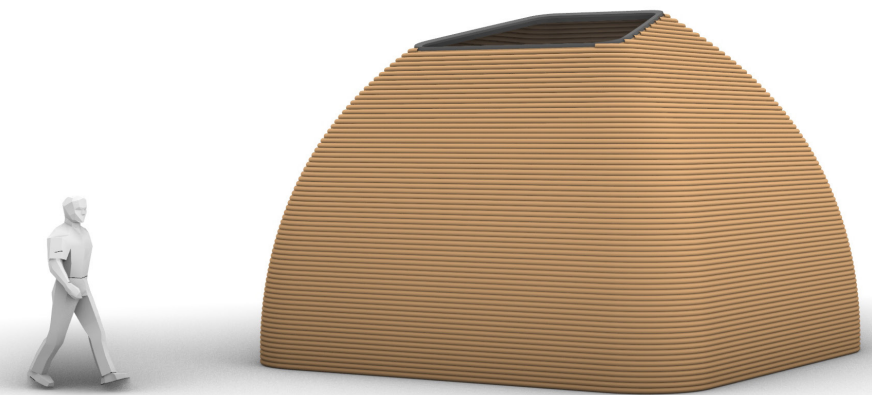
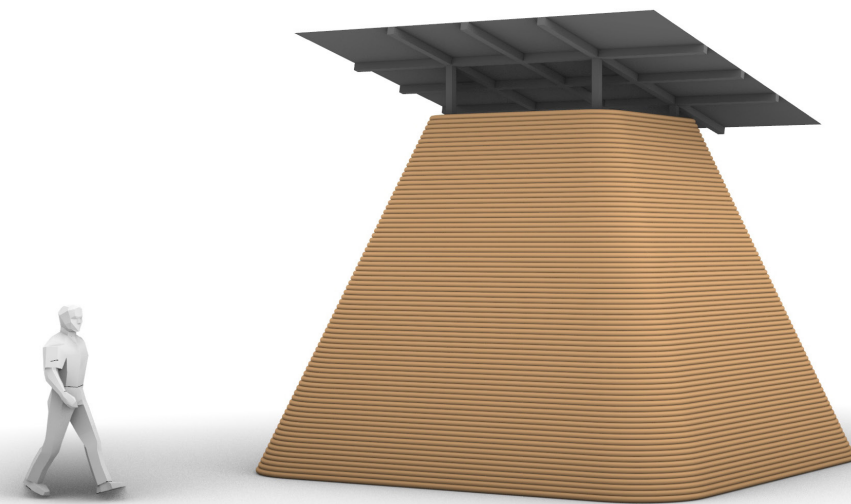
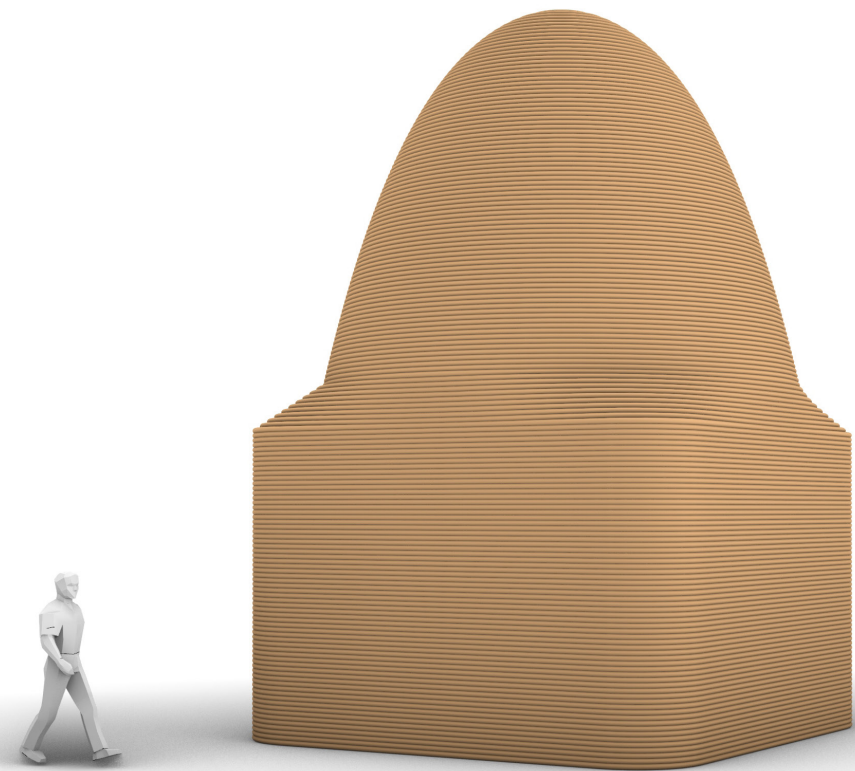
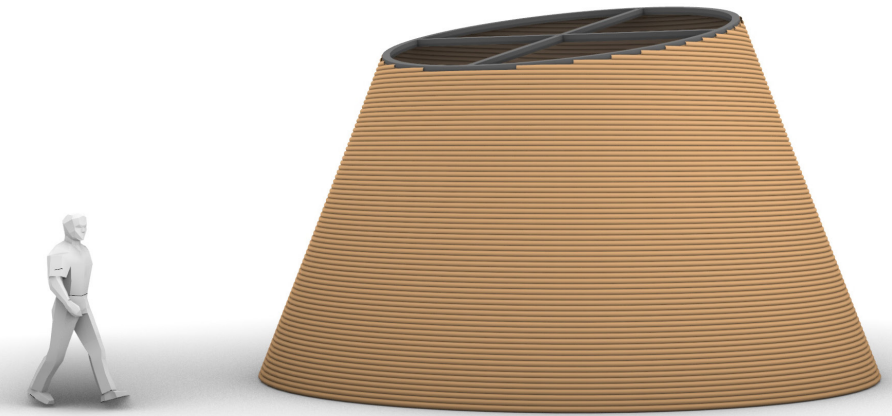
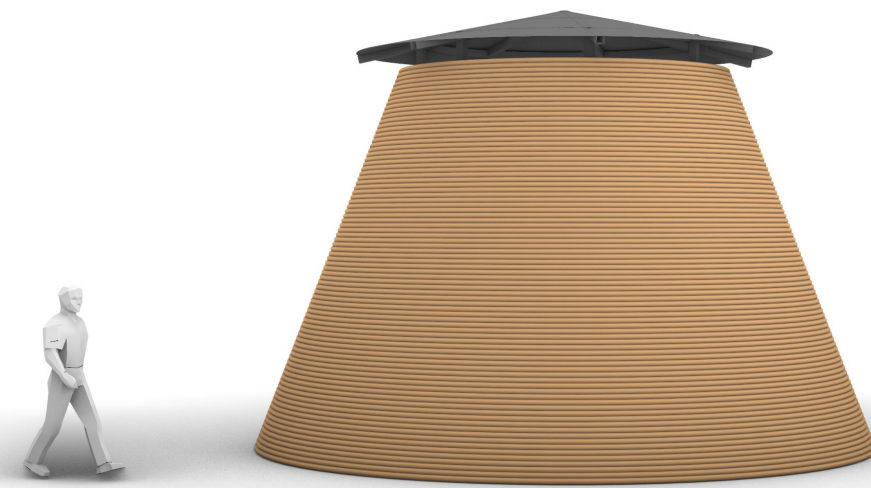
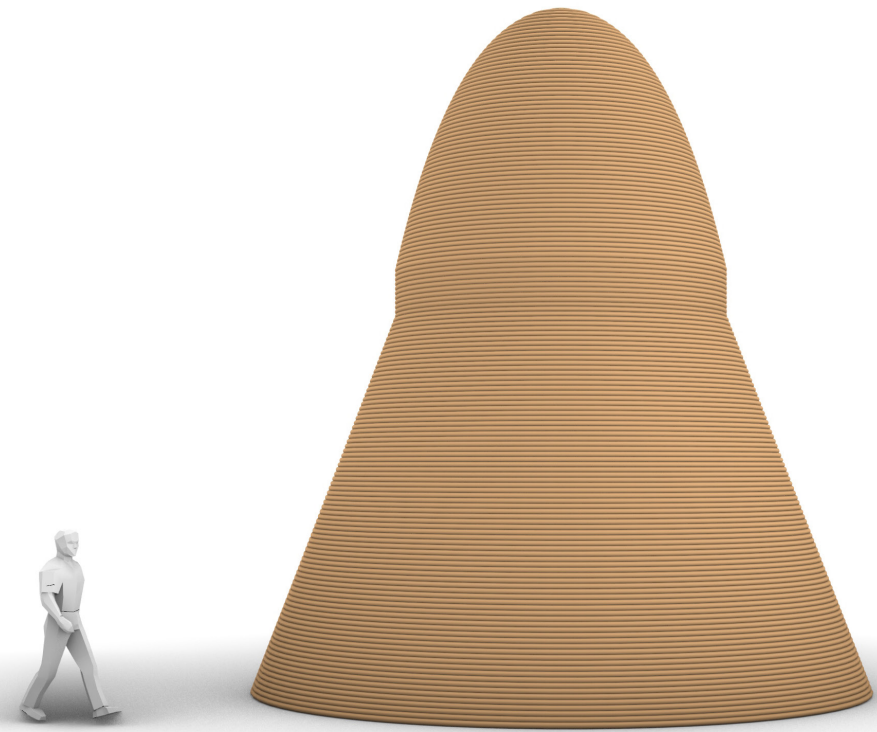


Hybrid

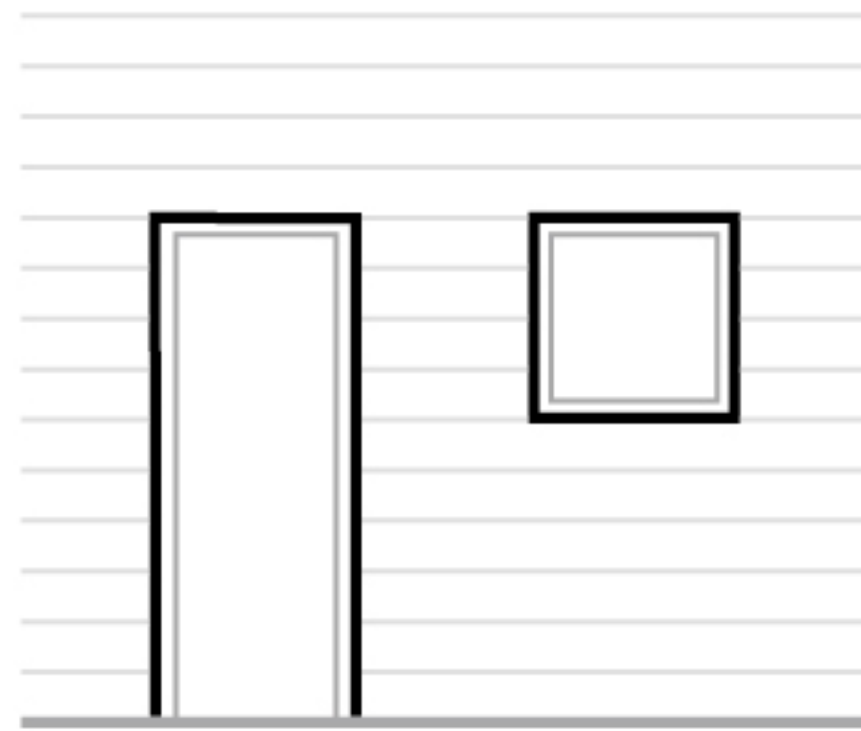


Skylight

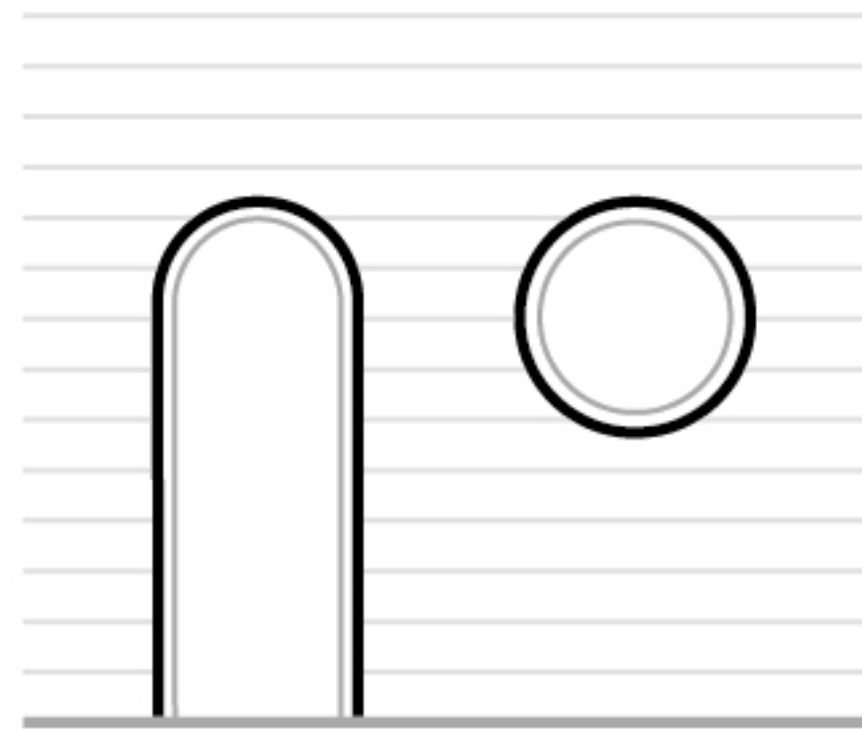
Roof Type



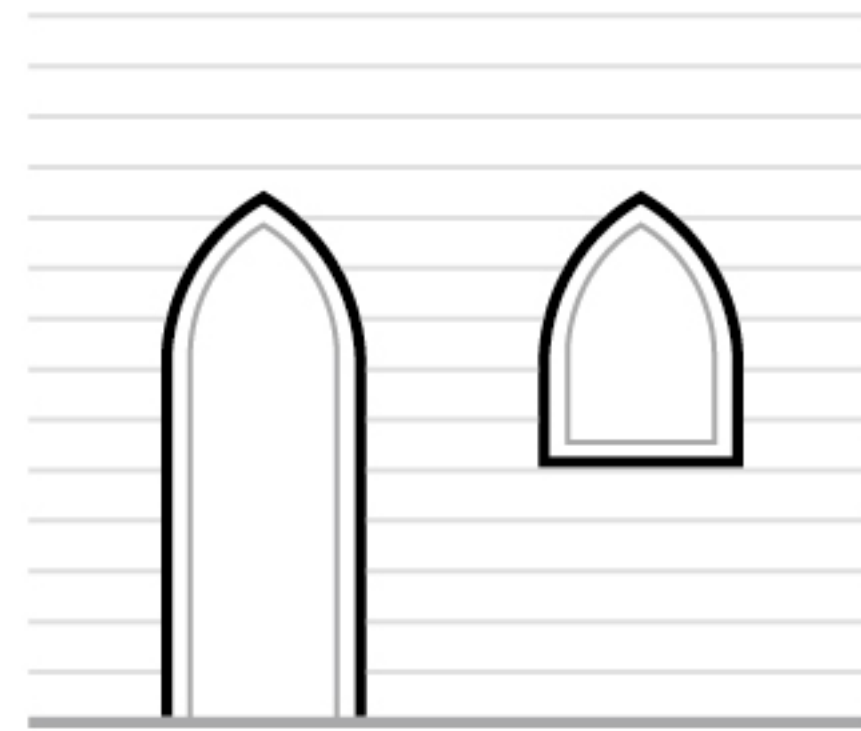
Opening Shape



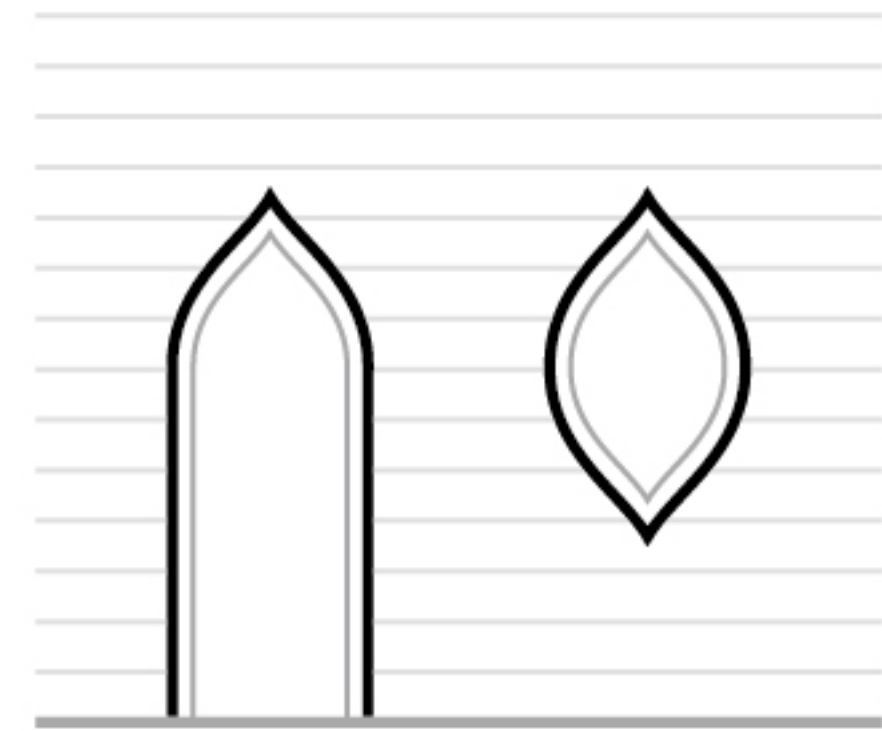
Square



Circle

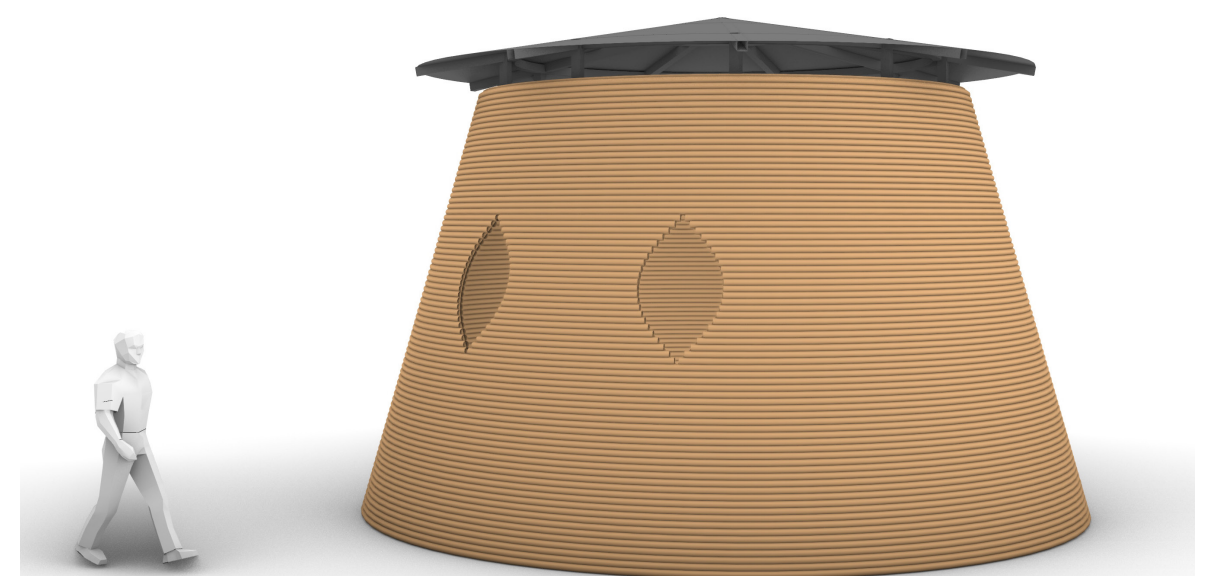
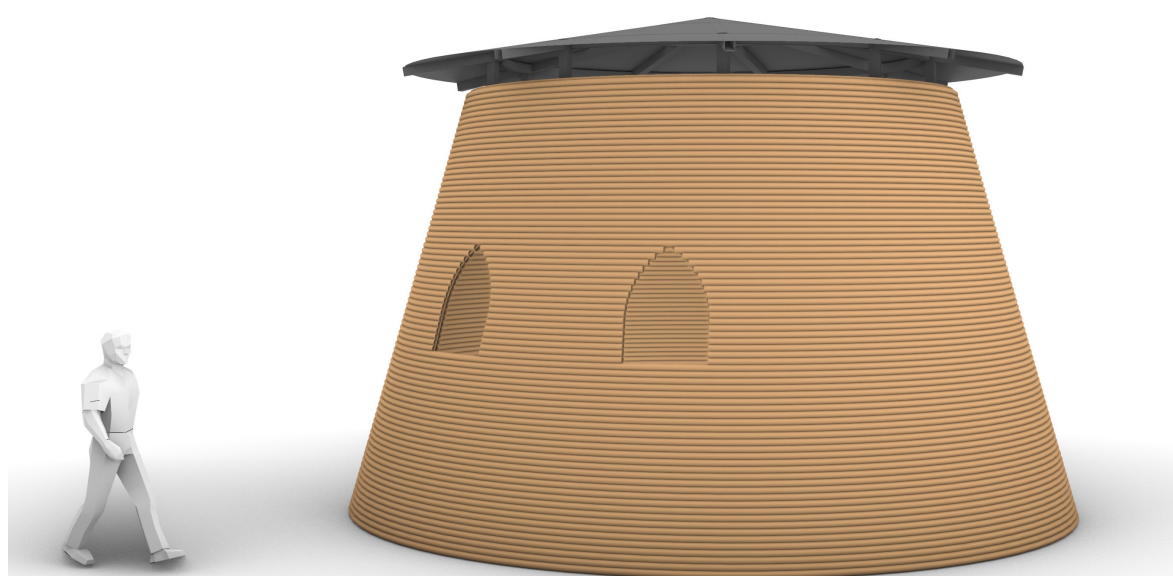
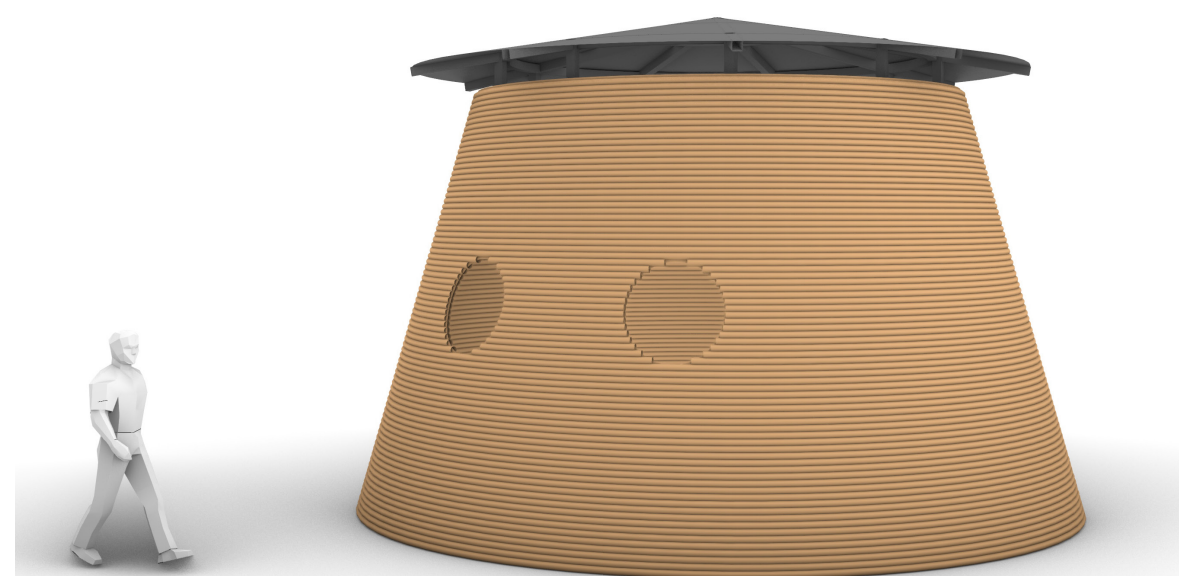
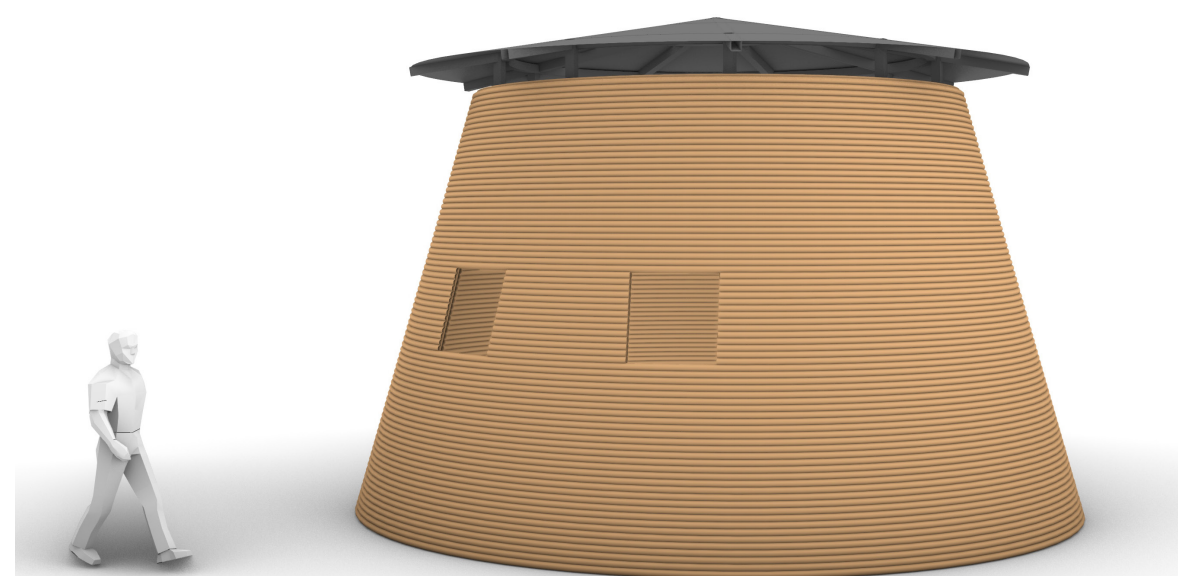
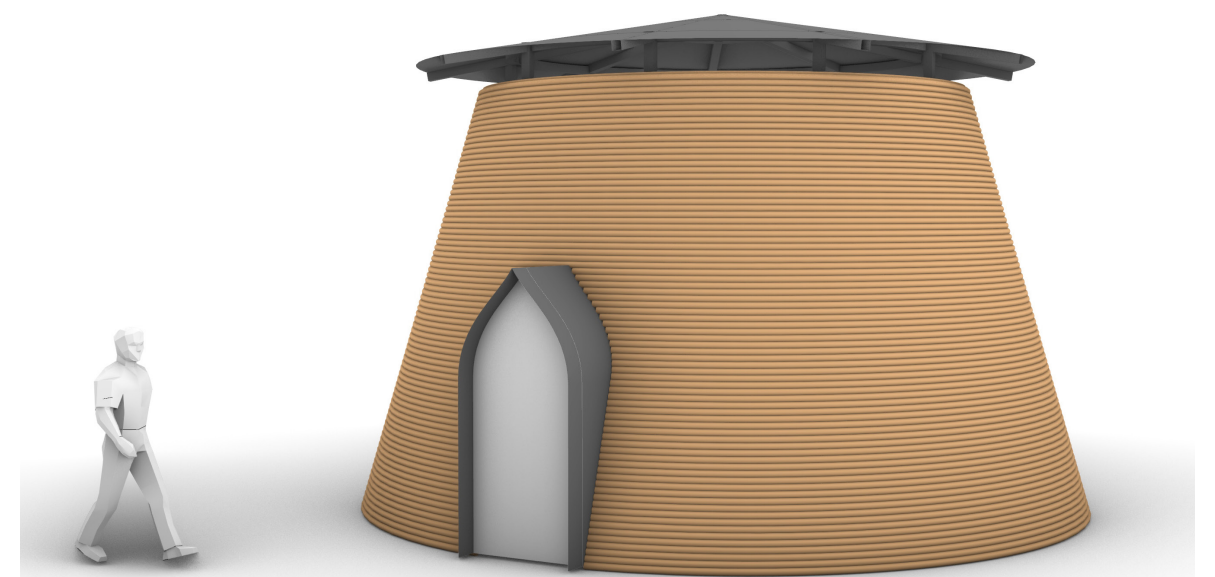
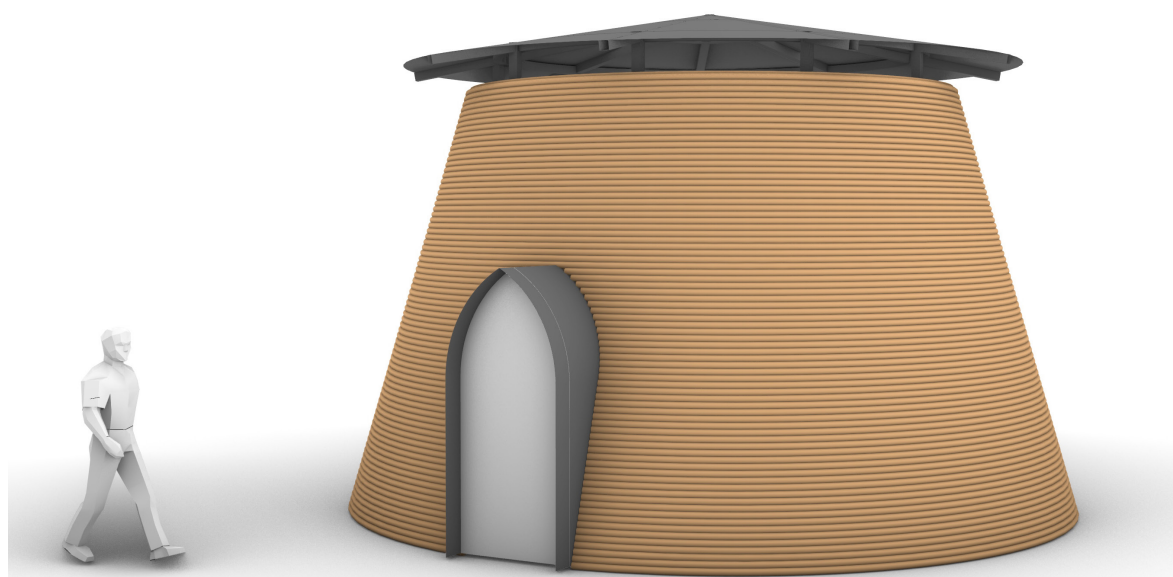
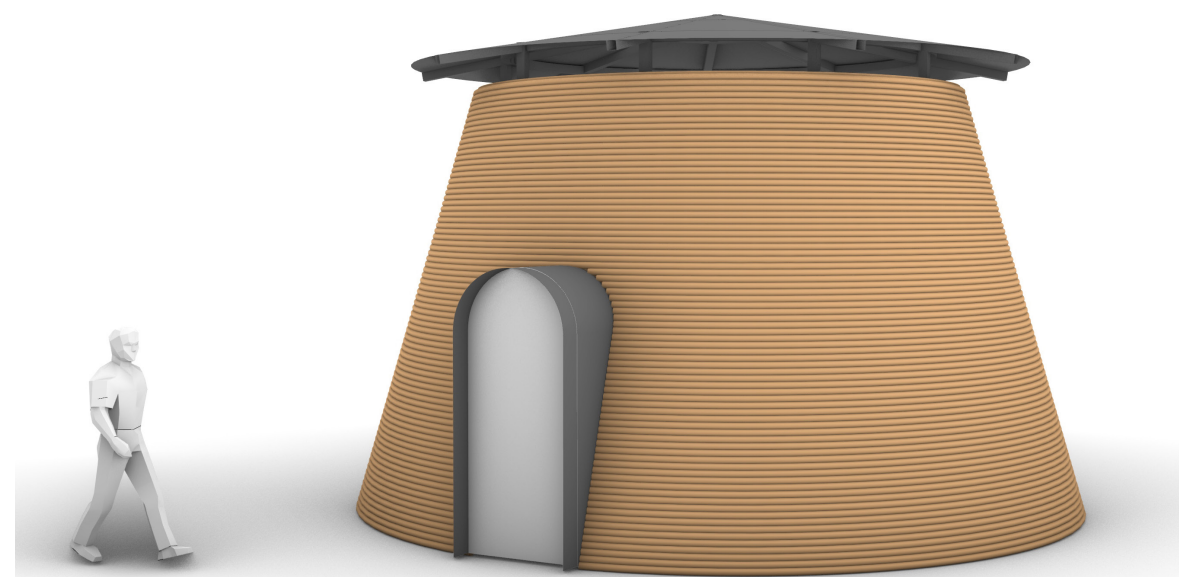
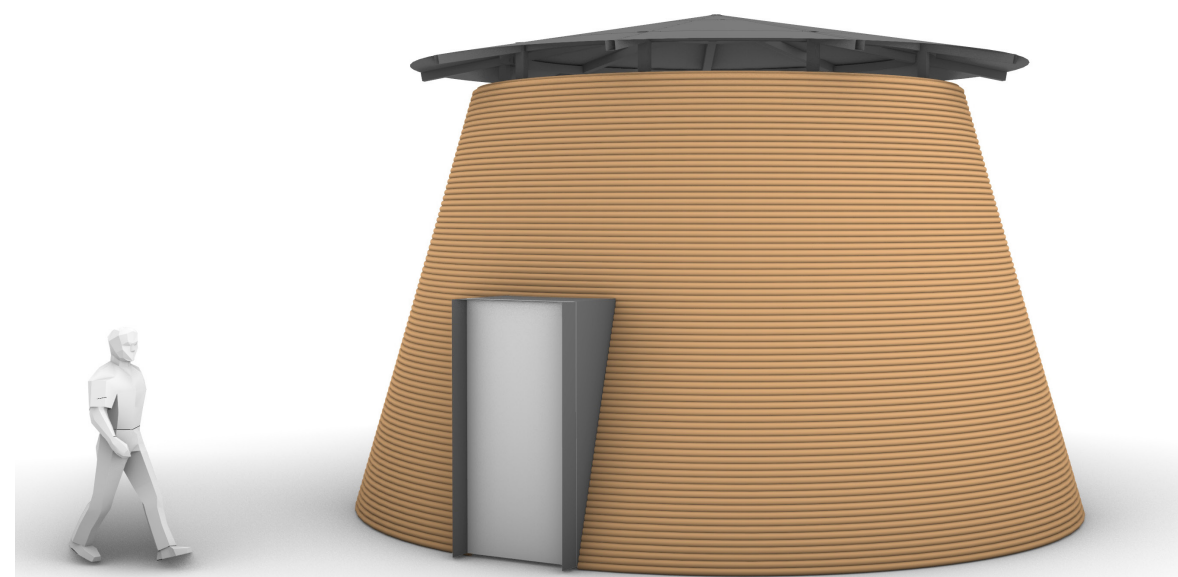


Pointed
Arch



Teardrop

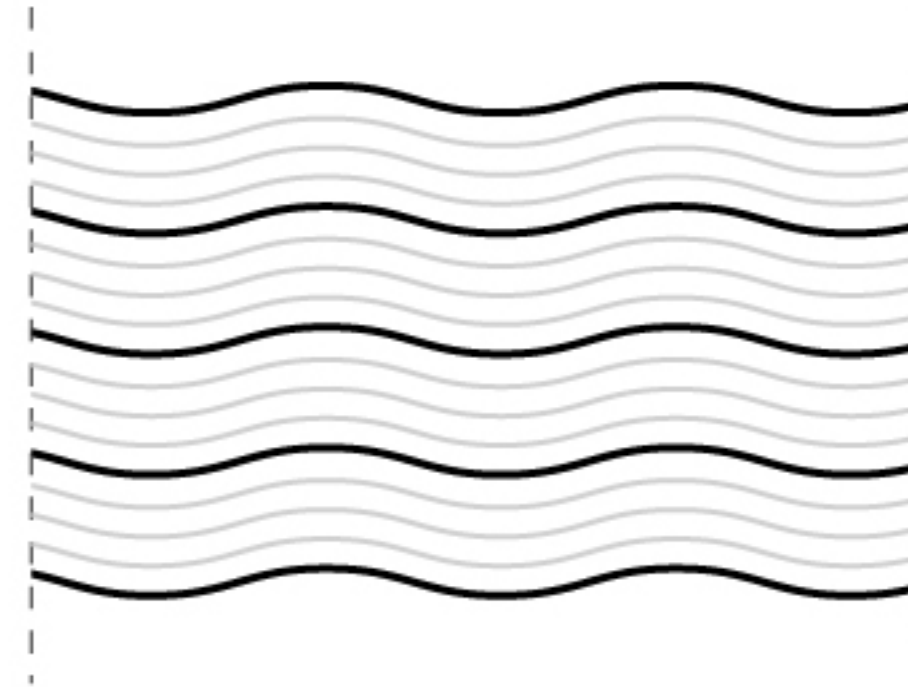
Opening Shape



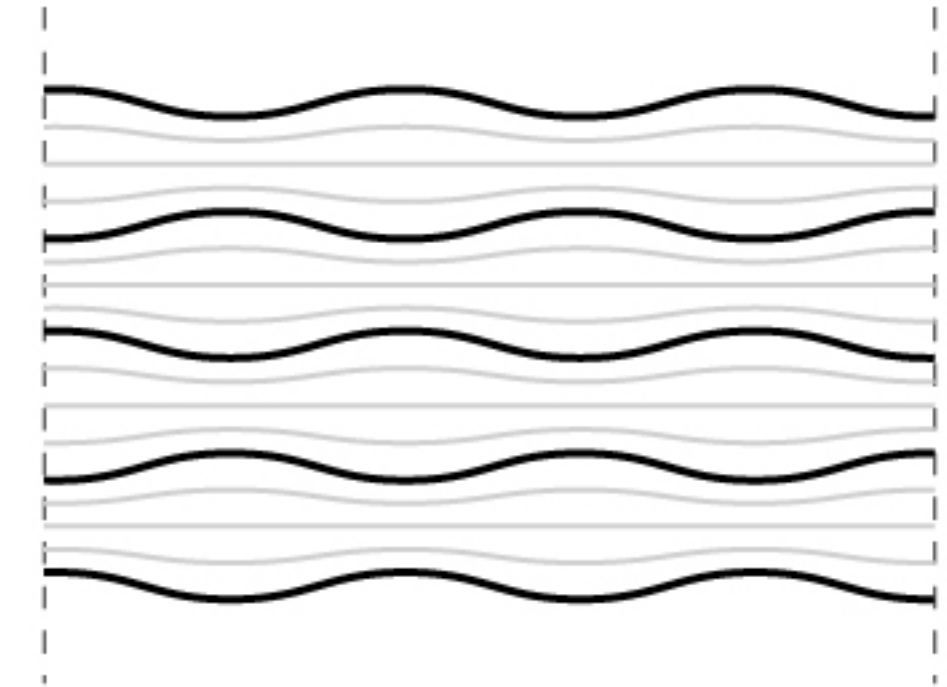
Wall Patterns



Smooth

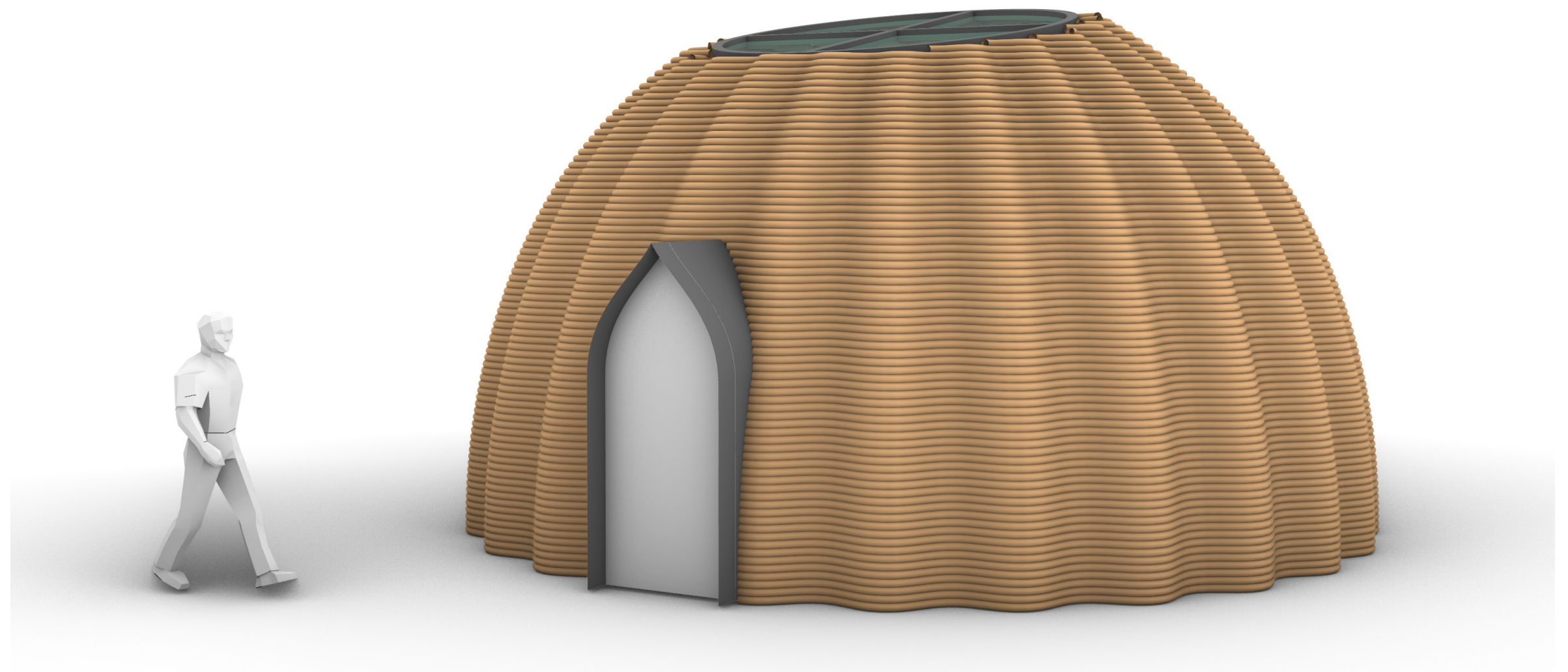
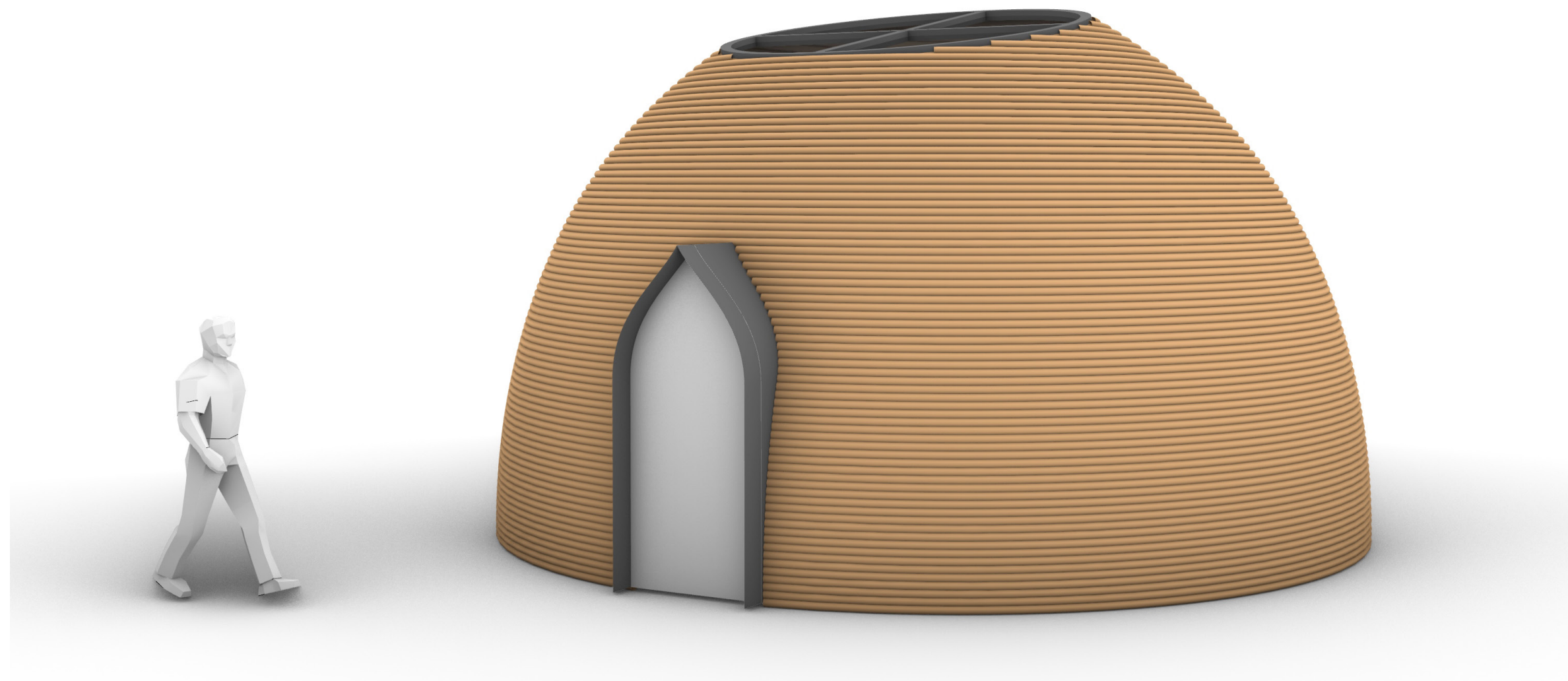


**Wave
Horizontal**

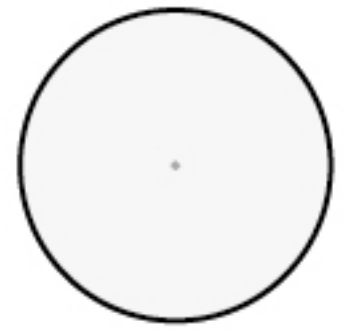


**Wave
Horizontal + Vertical**

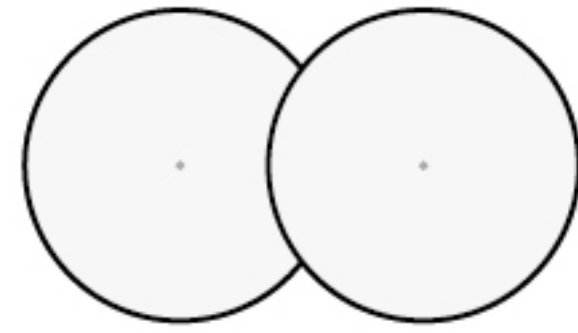
Wall Patterns



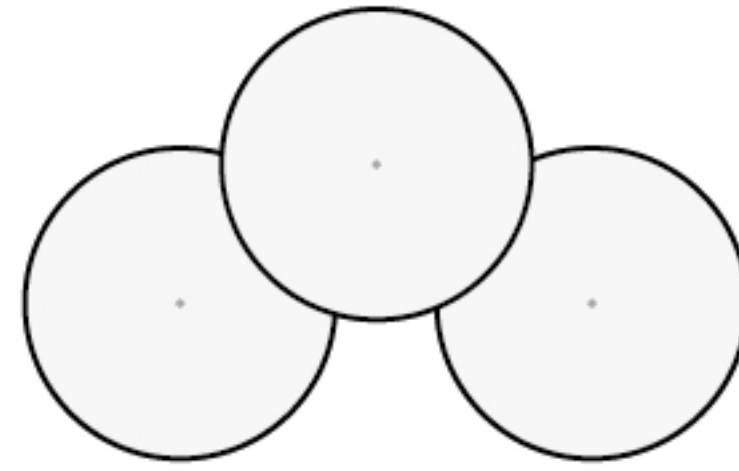
No. Units



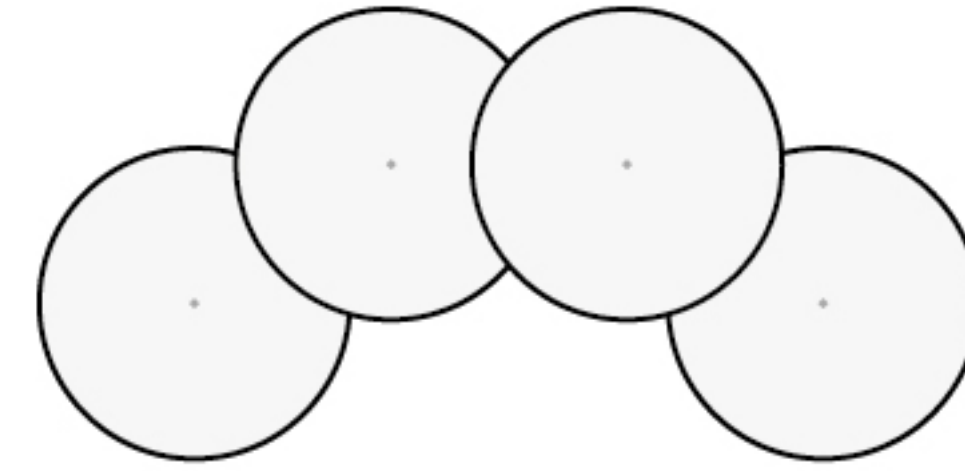
One



Two



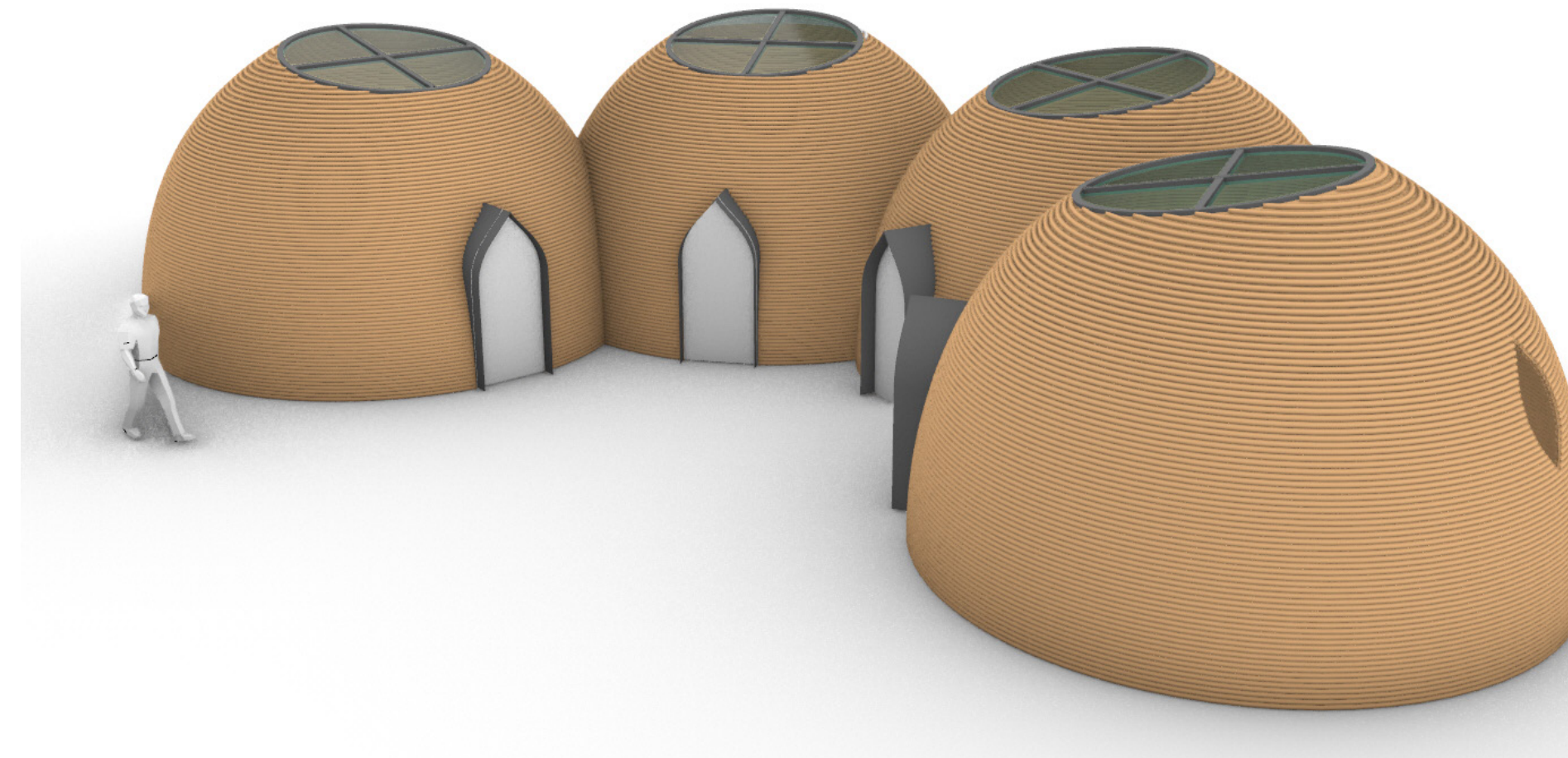
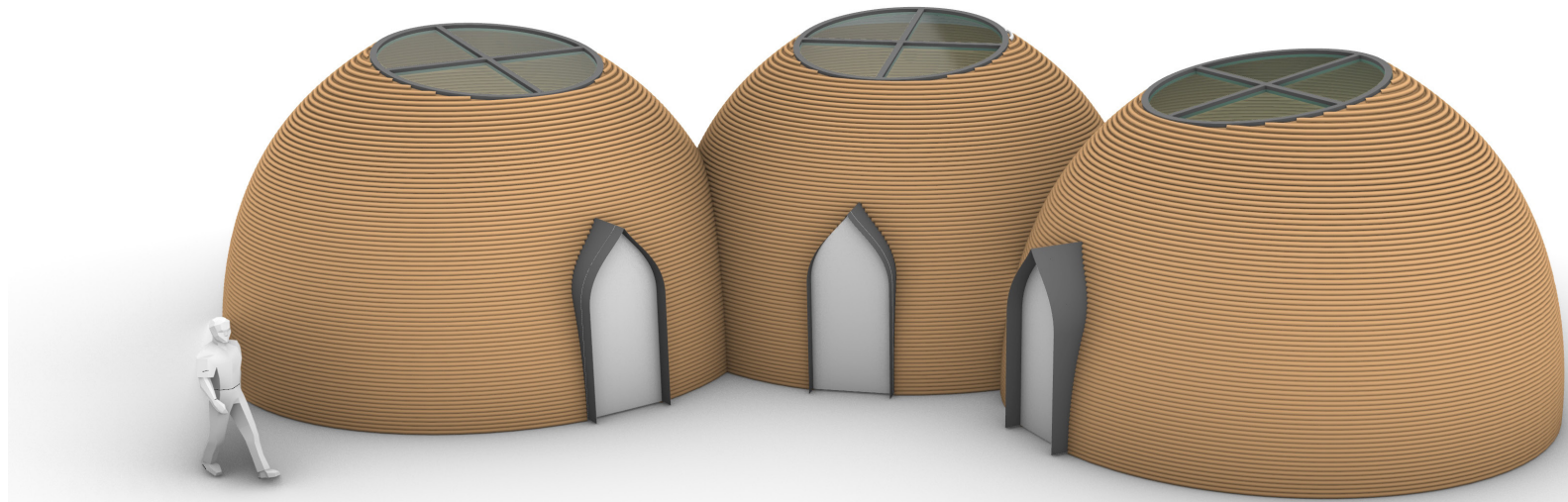
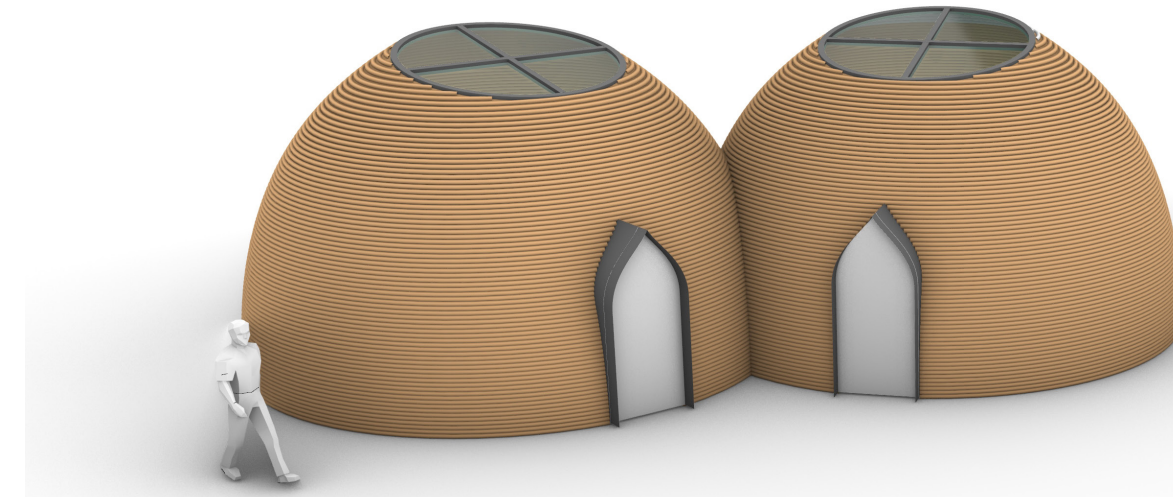
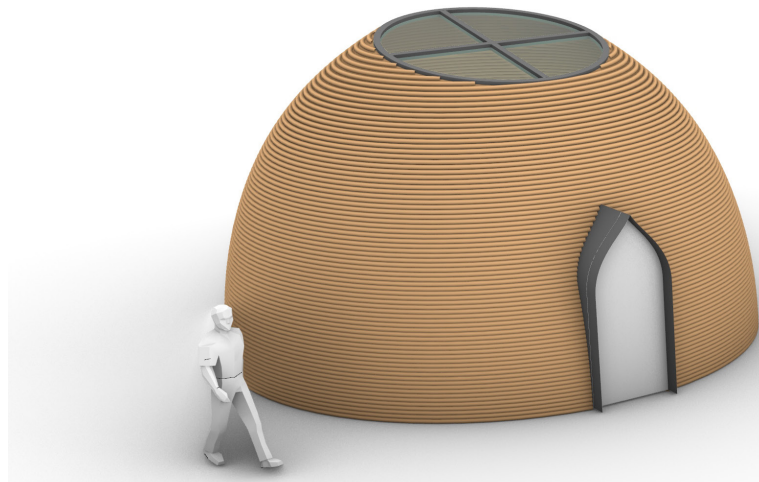
Three



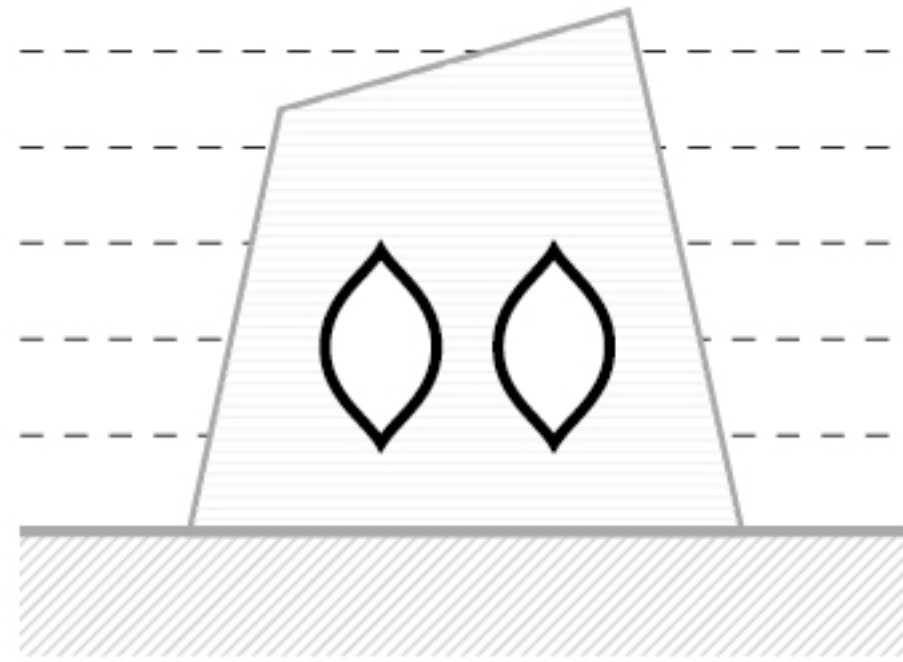
Four ...



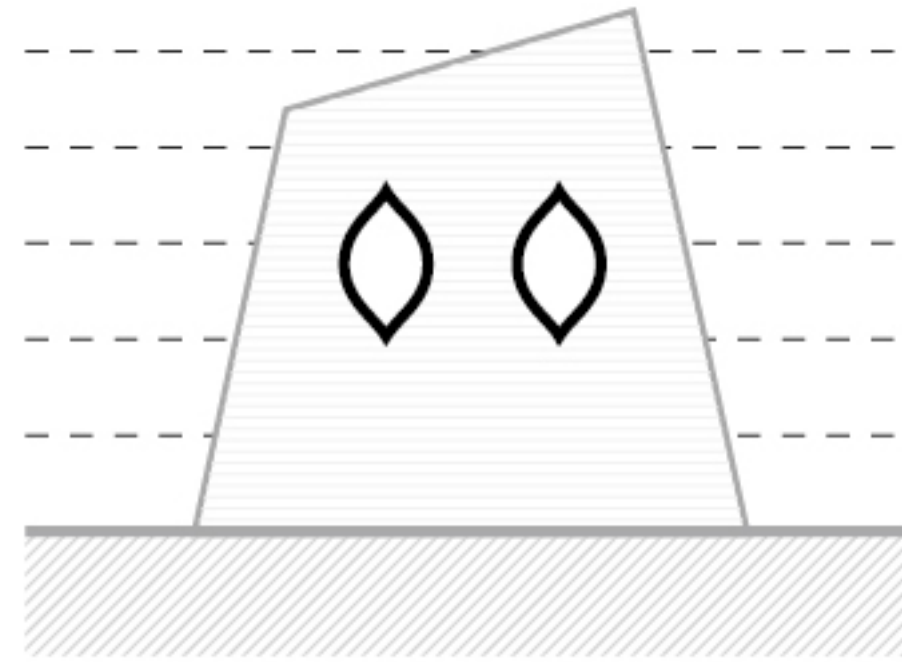
No. Units



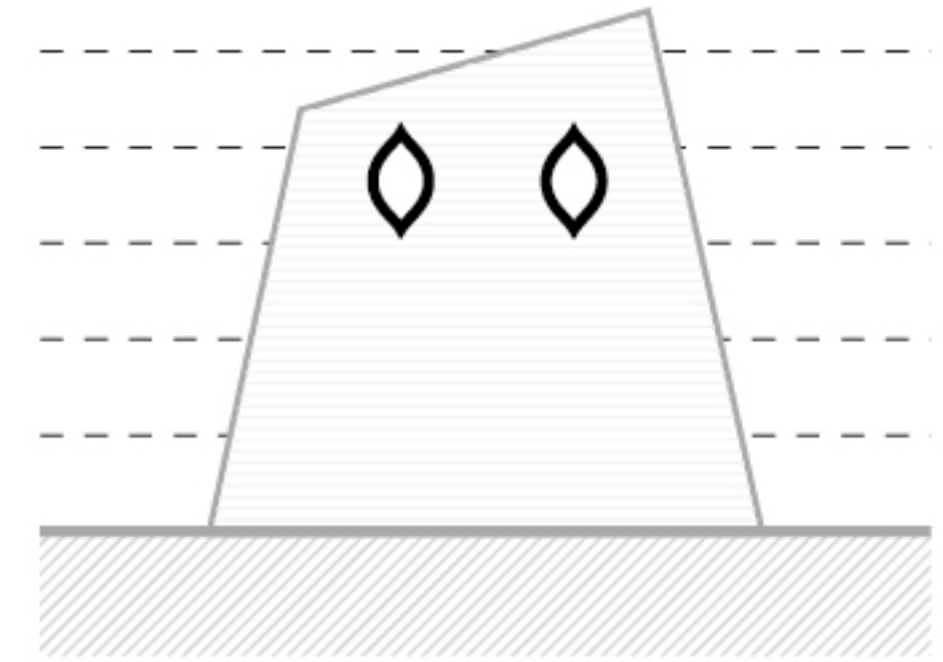
Openings Privacy



**Low
Privacy**

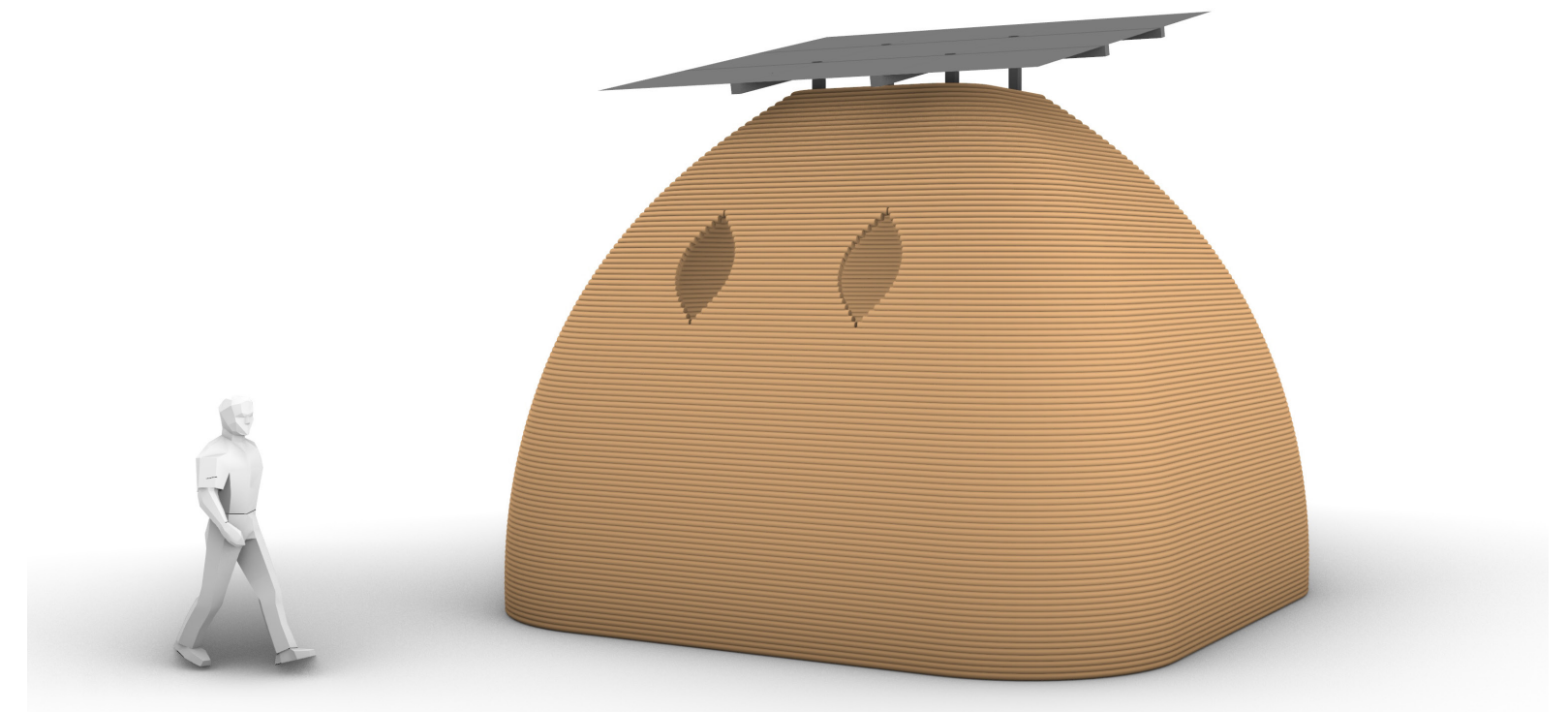
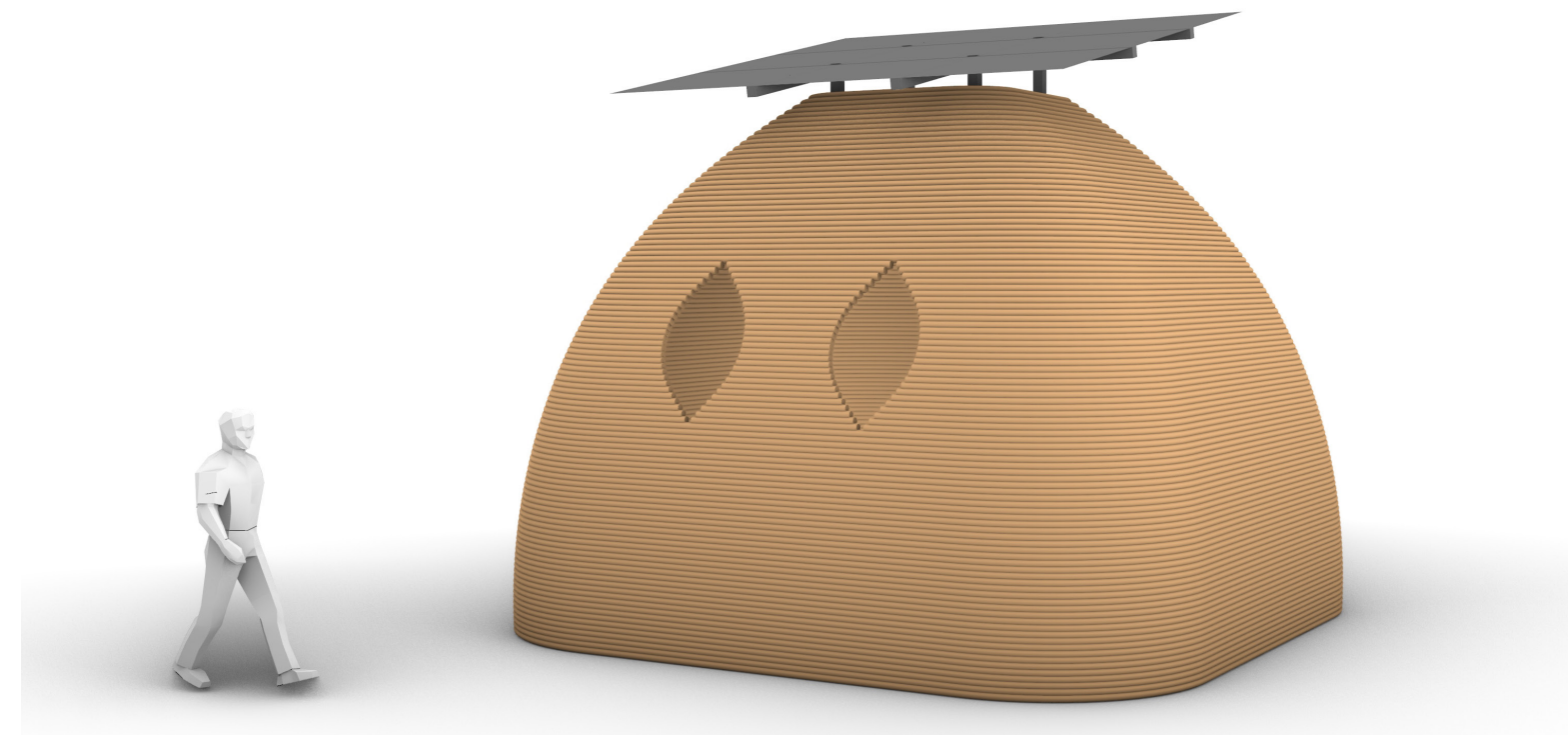
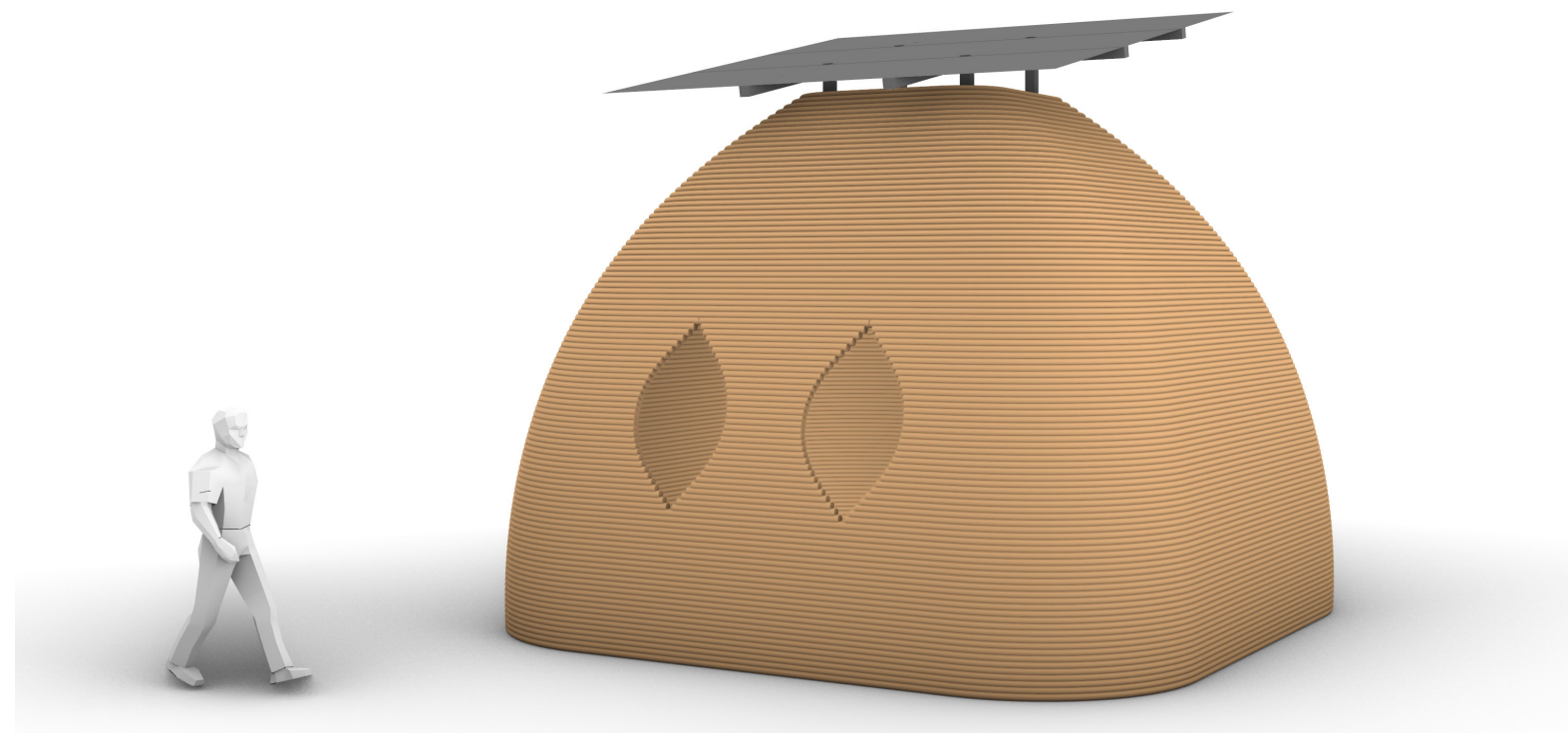


**Medium
Privacy**

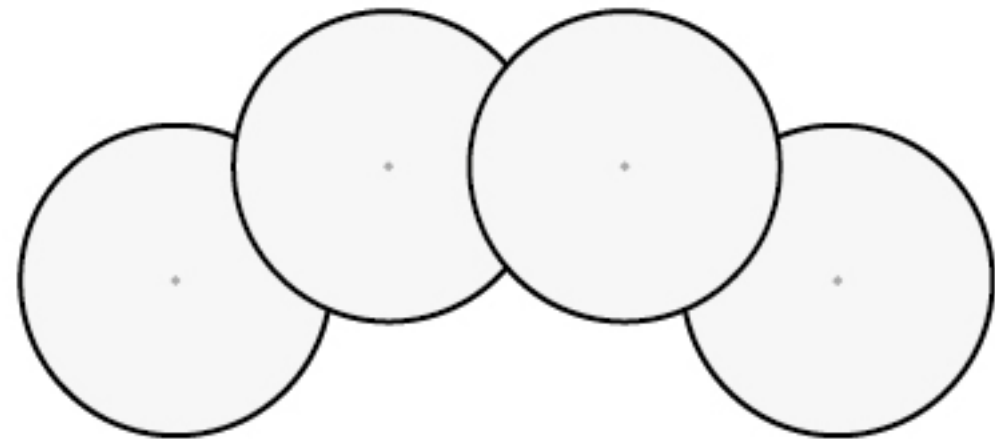


**High
Privacy**

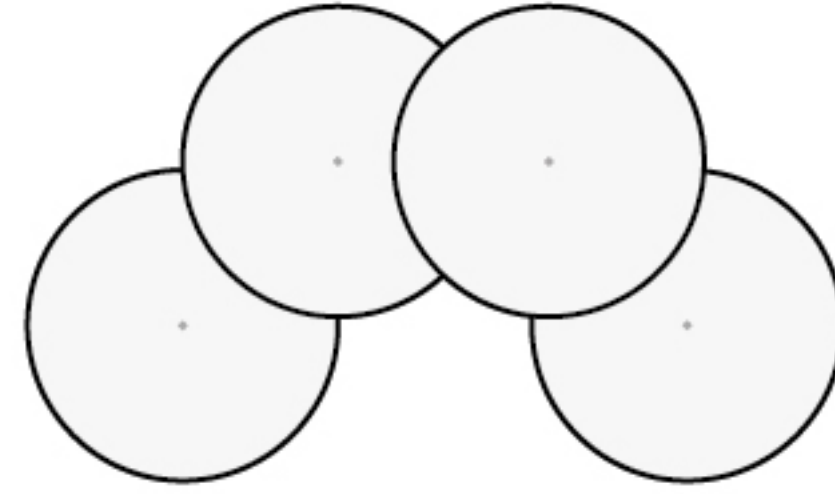
Openings Privacy



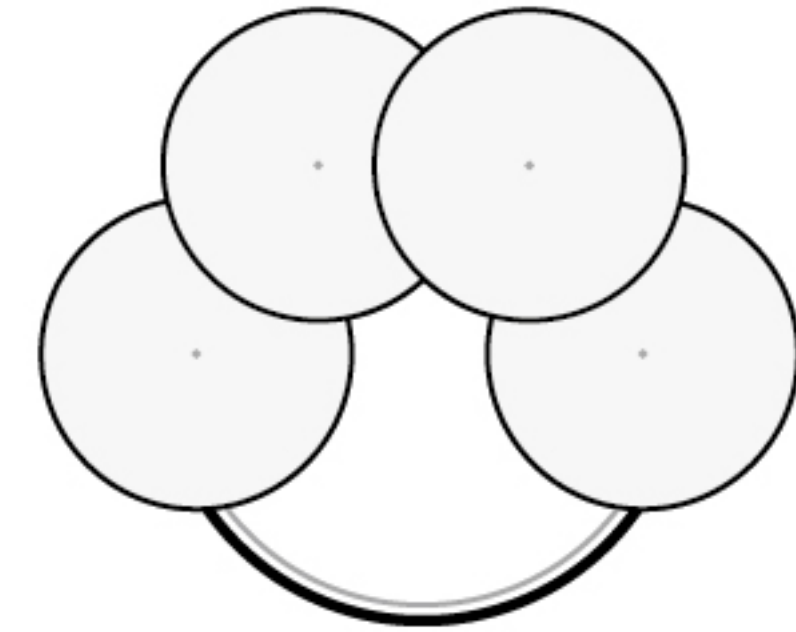
Layout



Open

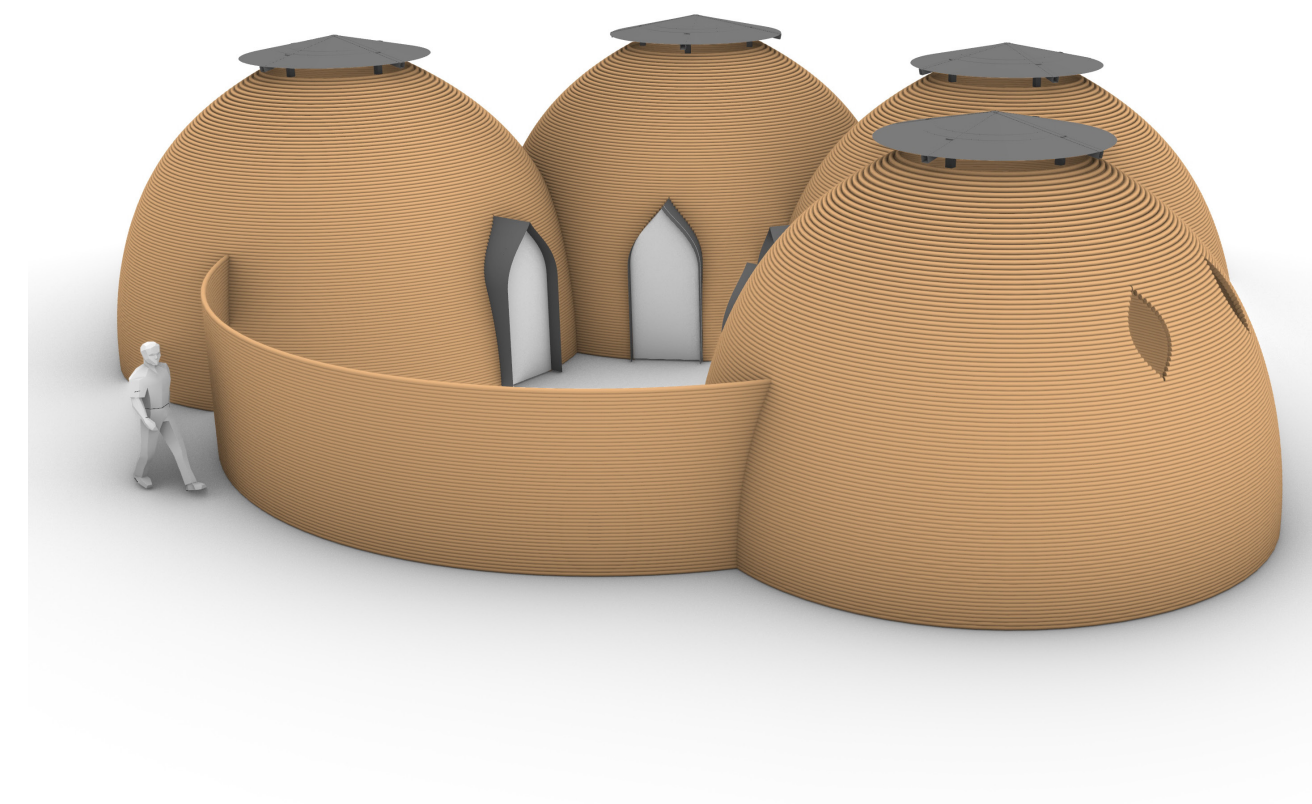
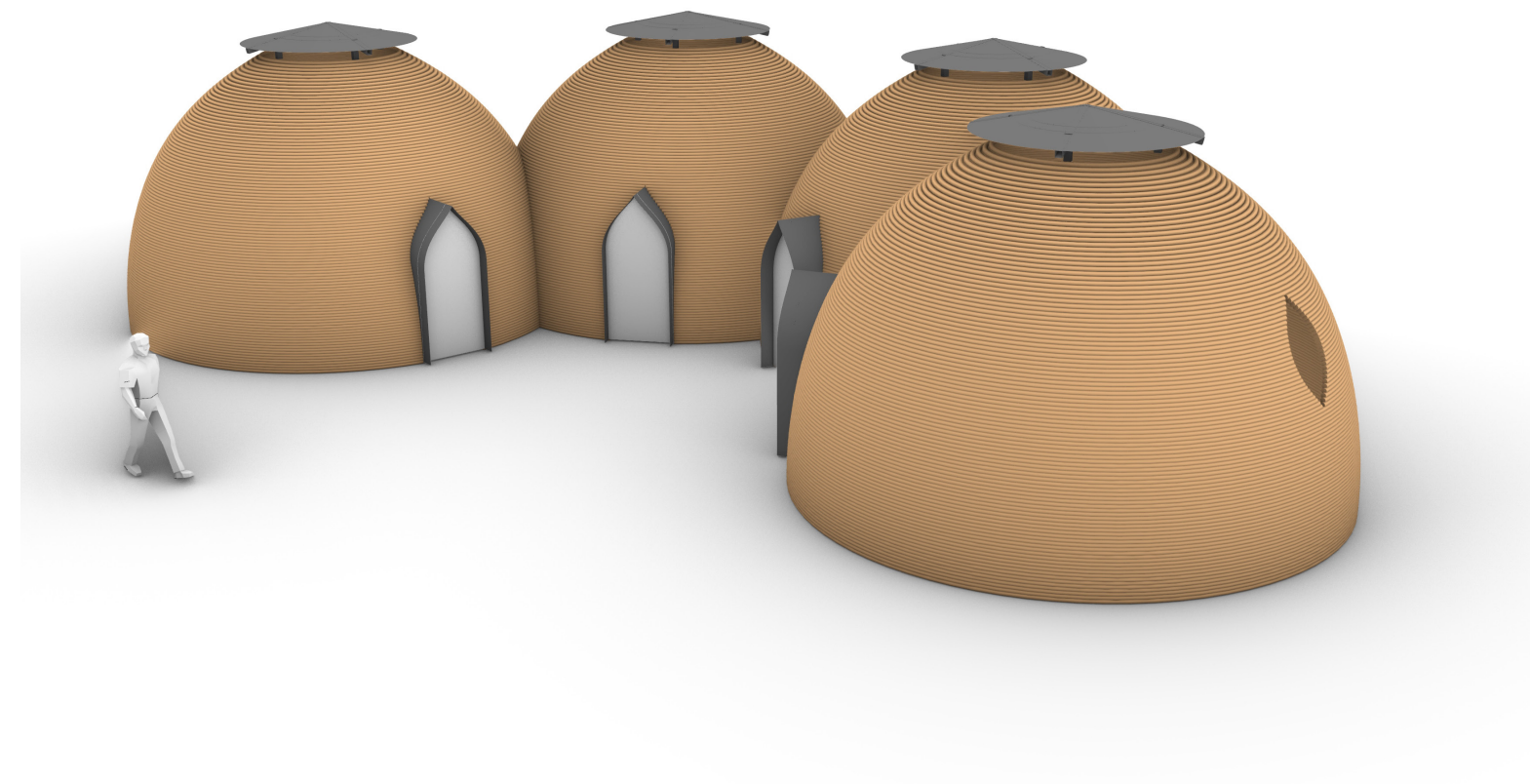
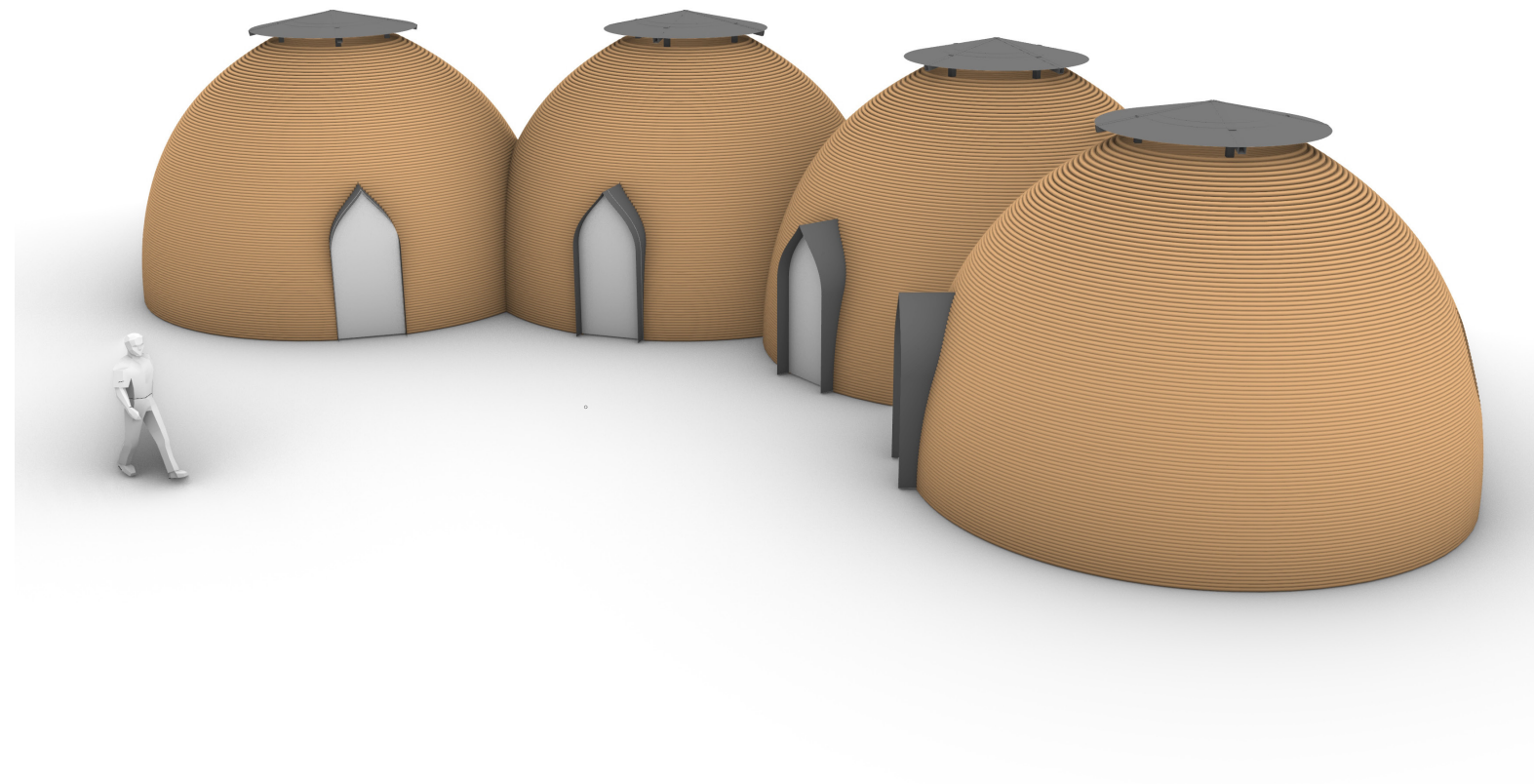


Semi-Enclosed

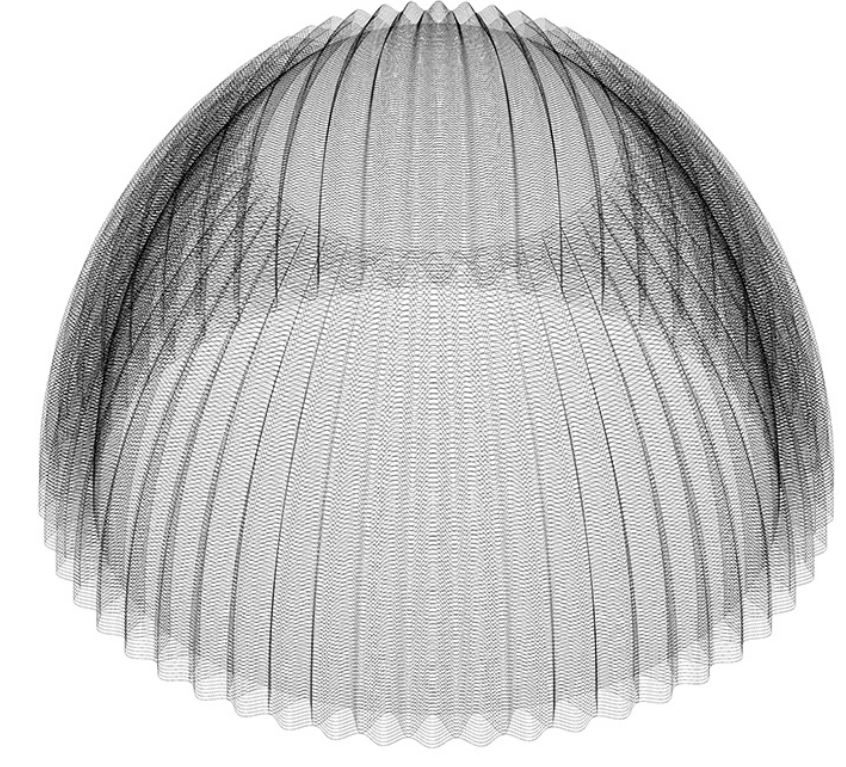
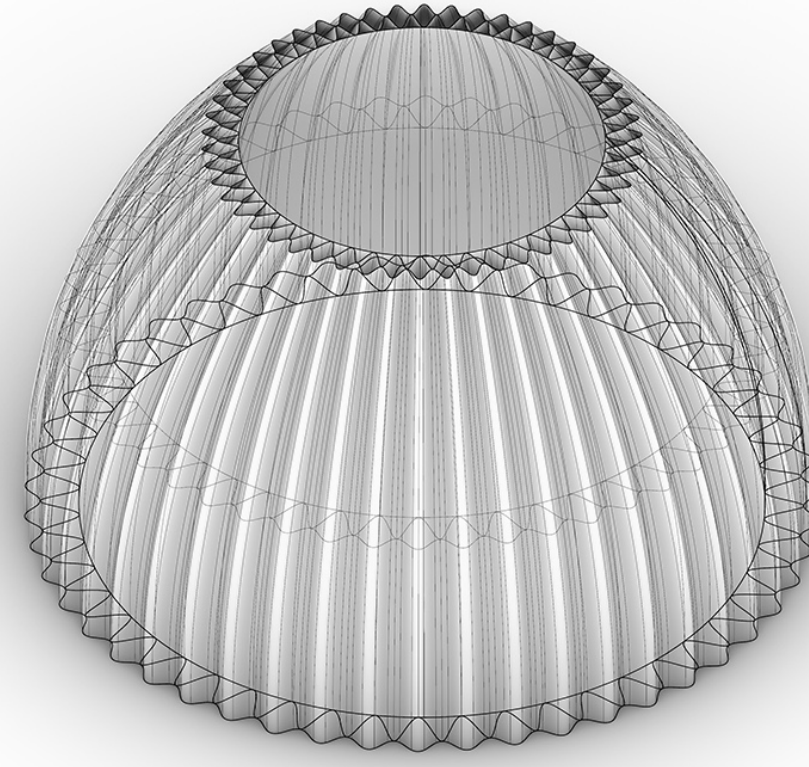
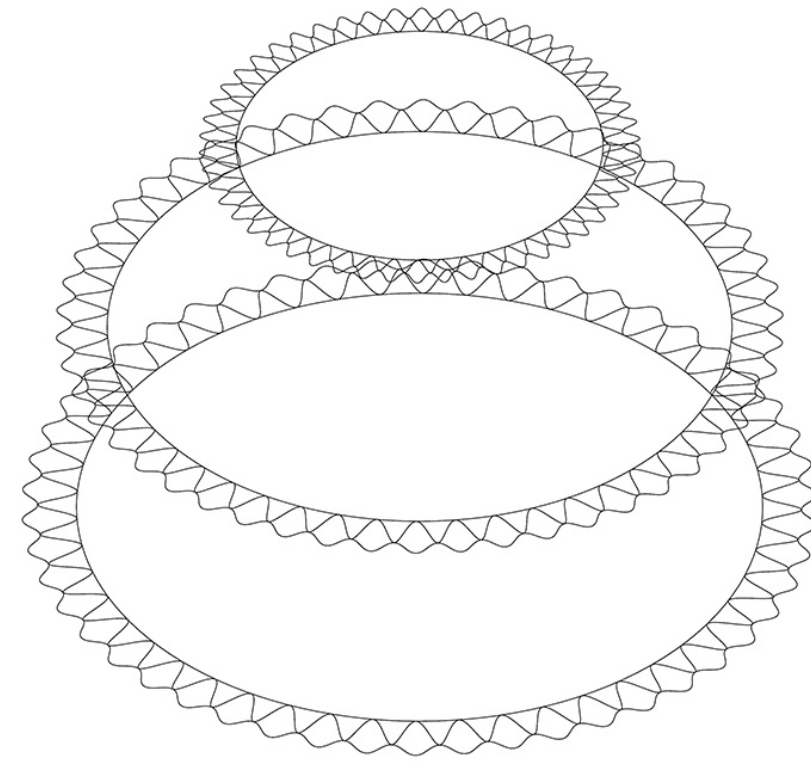
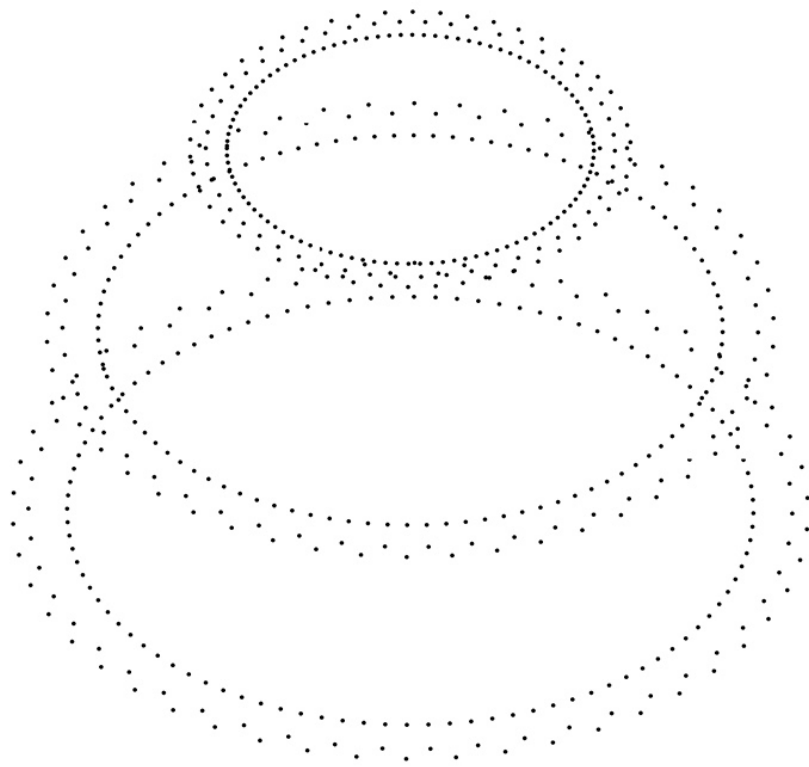
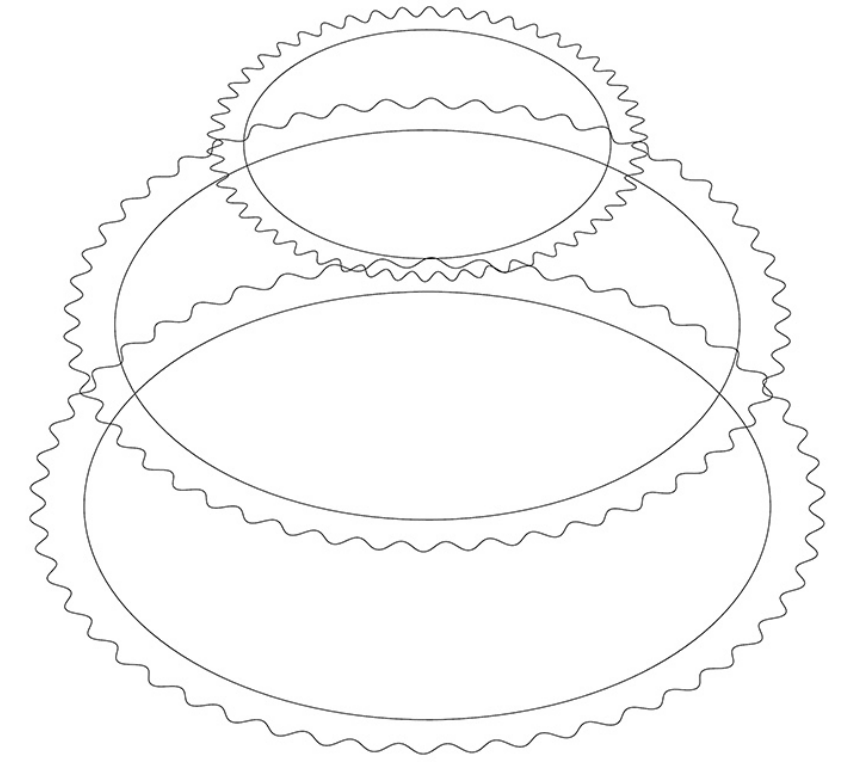
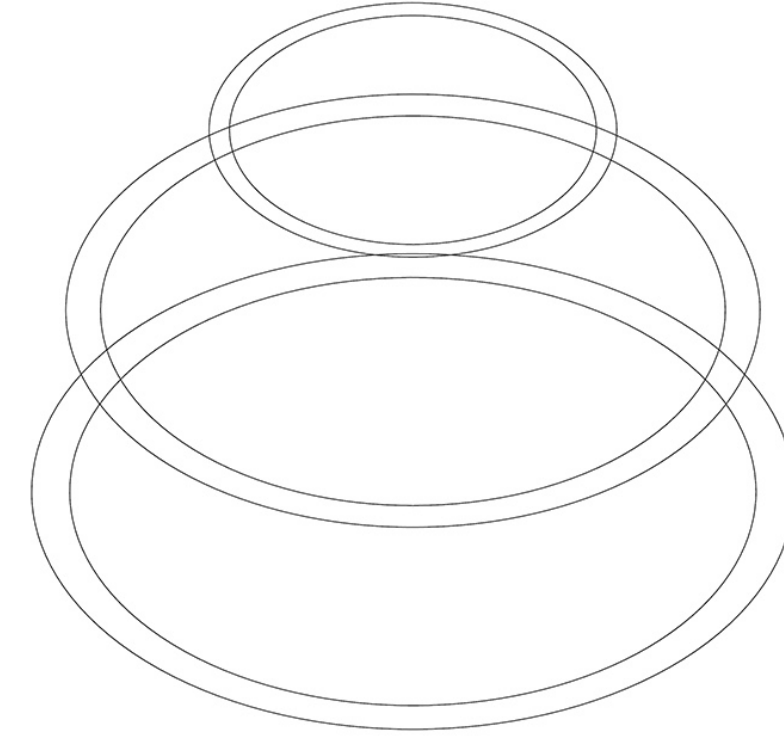
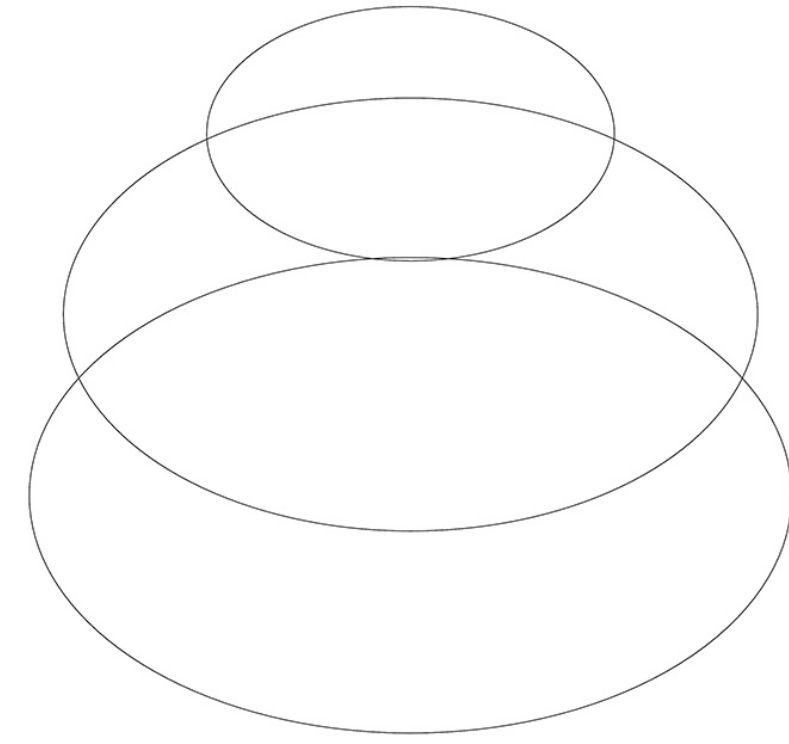
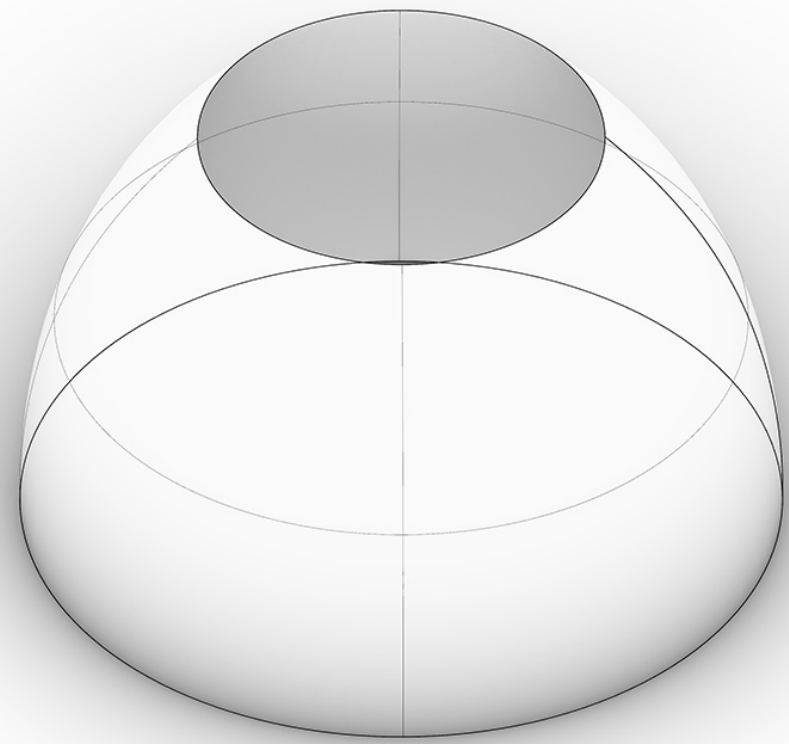


Enclosed

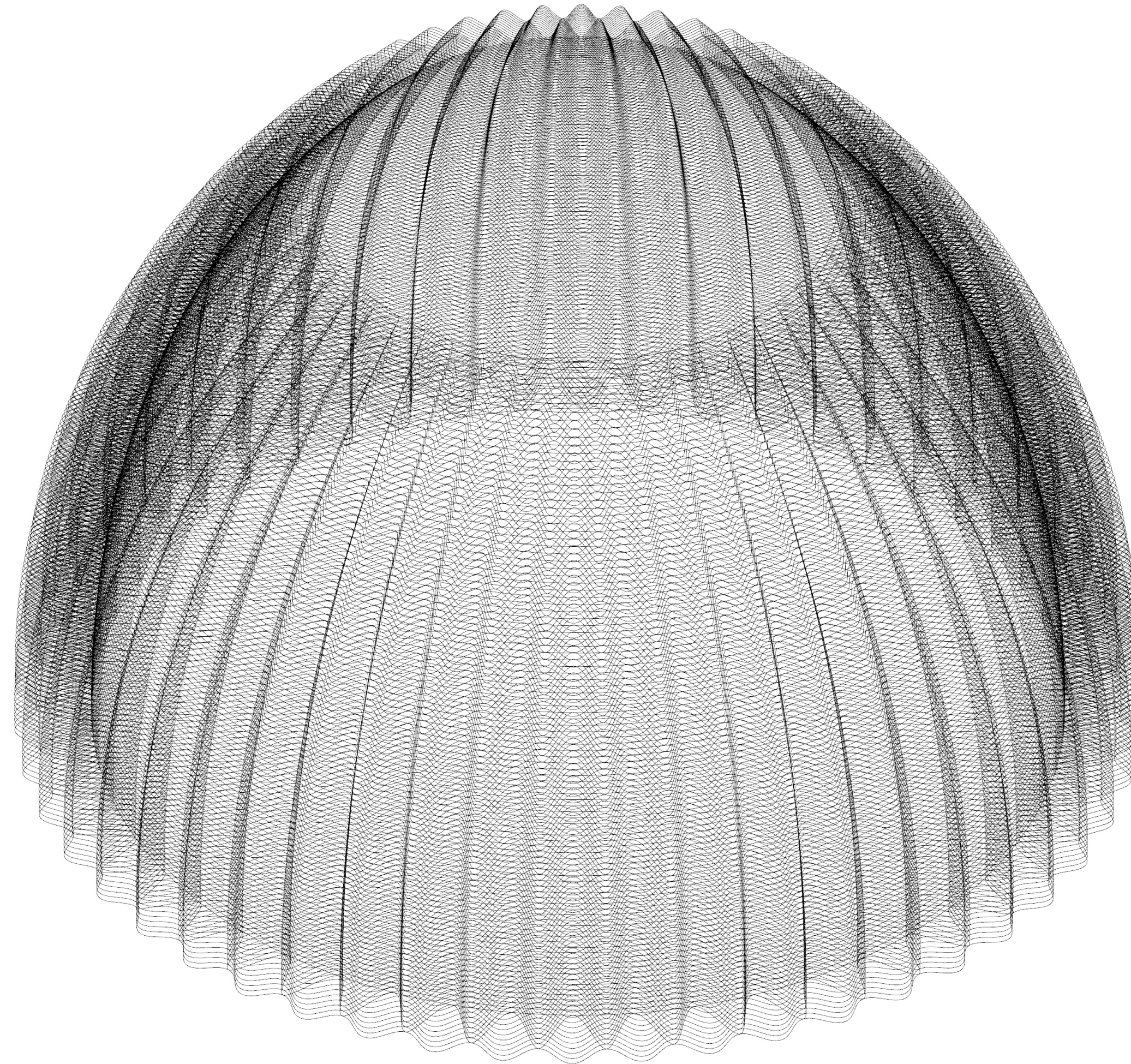
Layout



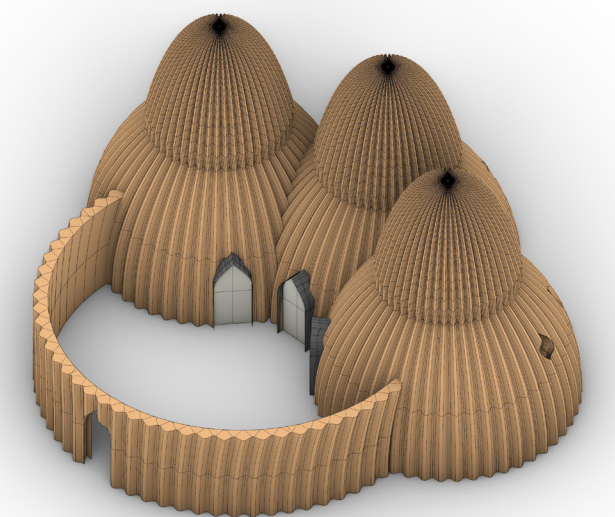
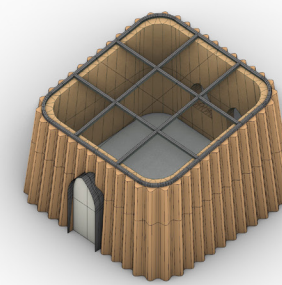
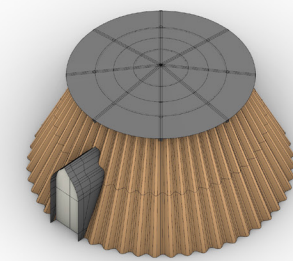
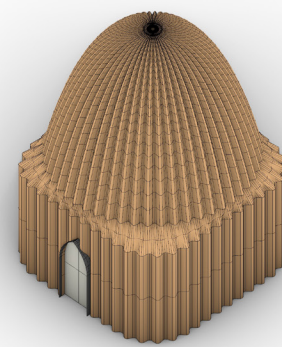
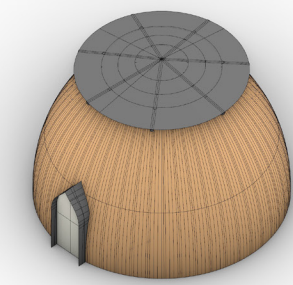
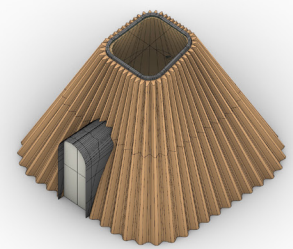
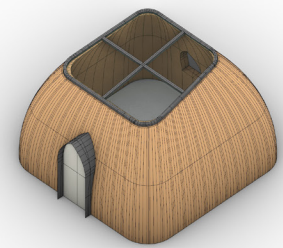
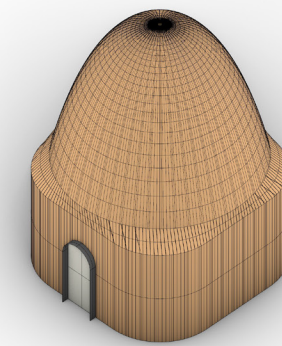
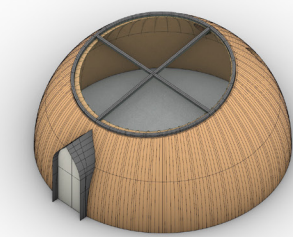
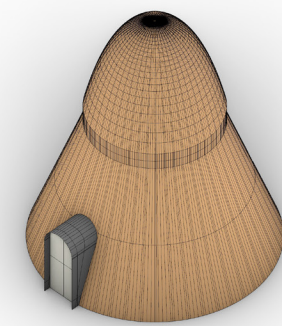
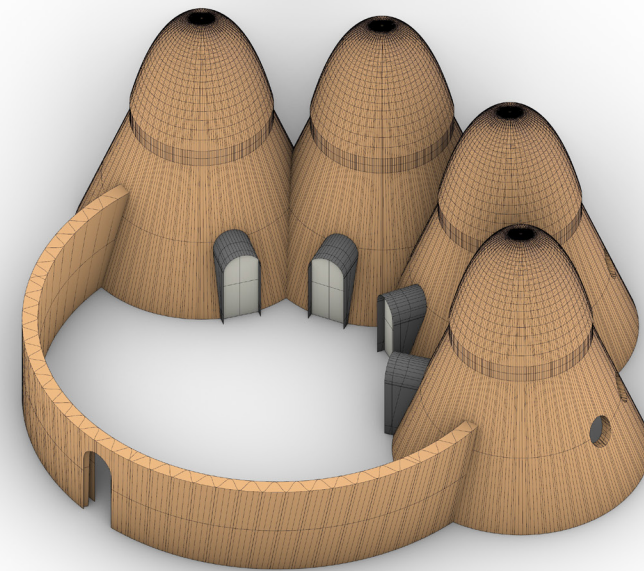
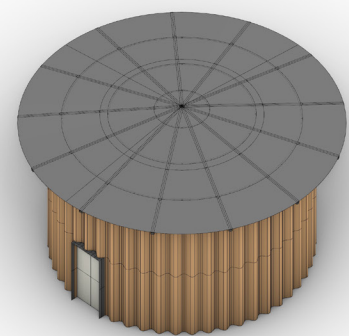
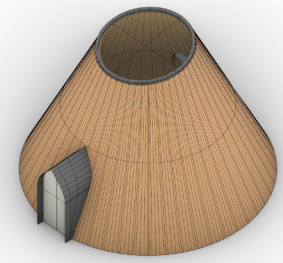
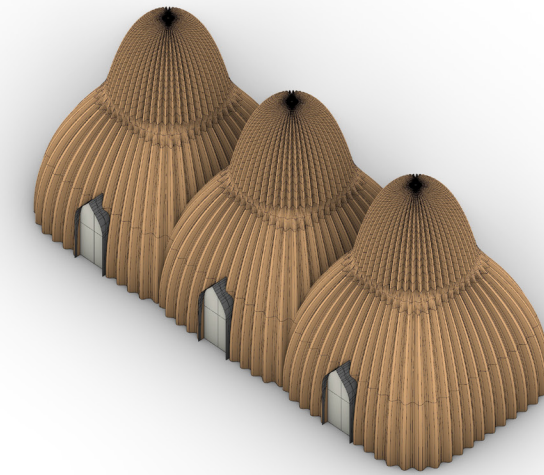
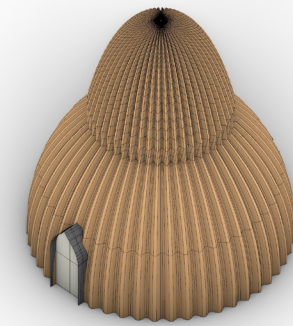
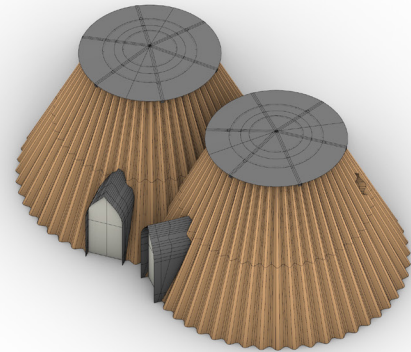
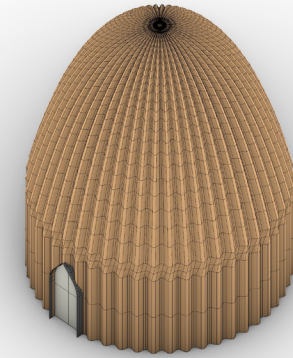
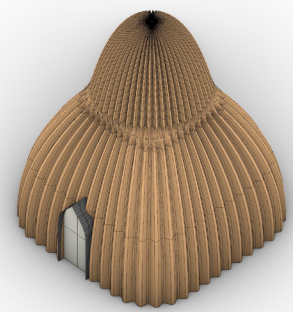
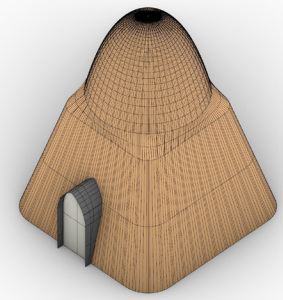
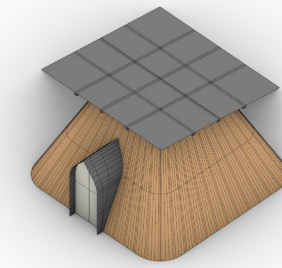
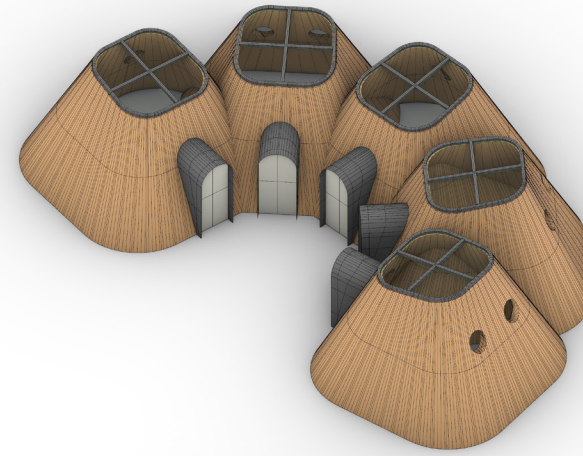
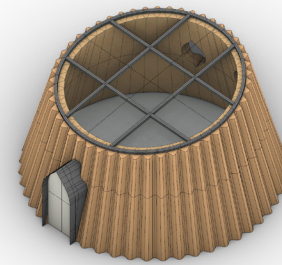
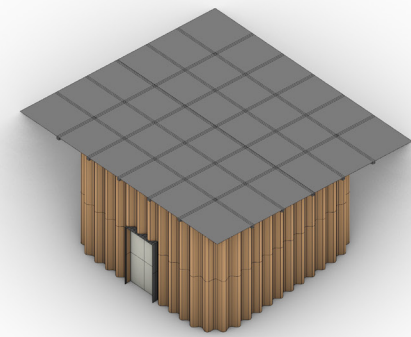
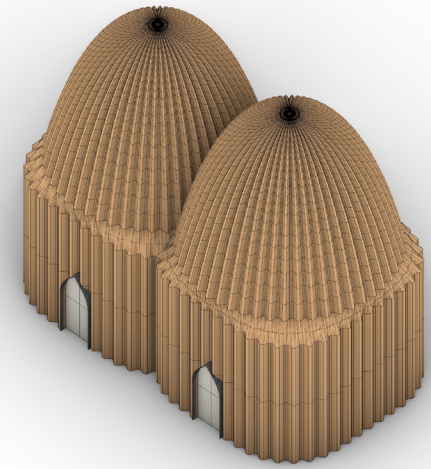
Wall Infills



Wall Infills



Resulting Design Iterations



User Interface

The interface is divided into several key sections:

- Top Bar:** Contains navigation and utility buttons: "Export Options", "Help/Tutorial", "Language", "EN", "?", and a share icon.
- View Controls:** "Displayed View" (3D View) and "Display Mode" (Rendered).
- User Input Panel (Left):** A vertical sidebar with sections for:
 - No. of Units:** Slider set to 4.
 - Base Shape:** "Circular" selected. Includes sliders for "Corner Radius" and "Max Printing Radius" (set to 3.3).
 - Walls:** "Curved" selected. Includes sliders for "Wall Inclination" and "Wall Height" (set to 3.6).
 - Roof:** "Earth Dome" selected. Includes a slider for "Roof Tilt" (set to 12).
 - Openings:** "Teardrop" selected. Includes a slider for "Privacy Level" and a "Courtyard" toggle.
- 3D View:** The central workspace showing a rendered 3D model of a circular earthen shelter with four units and a central courtyard.
- Model Info Panel (Bottom Right):** A table displaying key metrics:

Model Info	
Floor Area	108 m ²
Print Time	86 h
Total Height	4.15 (m)
Material Volume	12.3 (m ³)
Material Weight	28531 (kg)
Non-Earth Material Amount	High
- Print Layer Slicing:** A vertical slider on the right side of the 3D view.

End Users



**Occupants
(Refugee Families)**



**Humanitarian
Agencies**

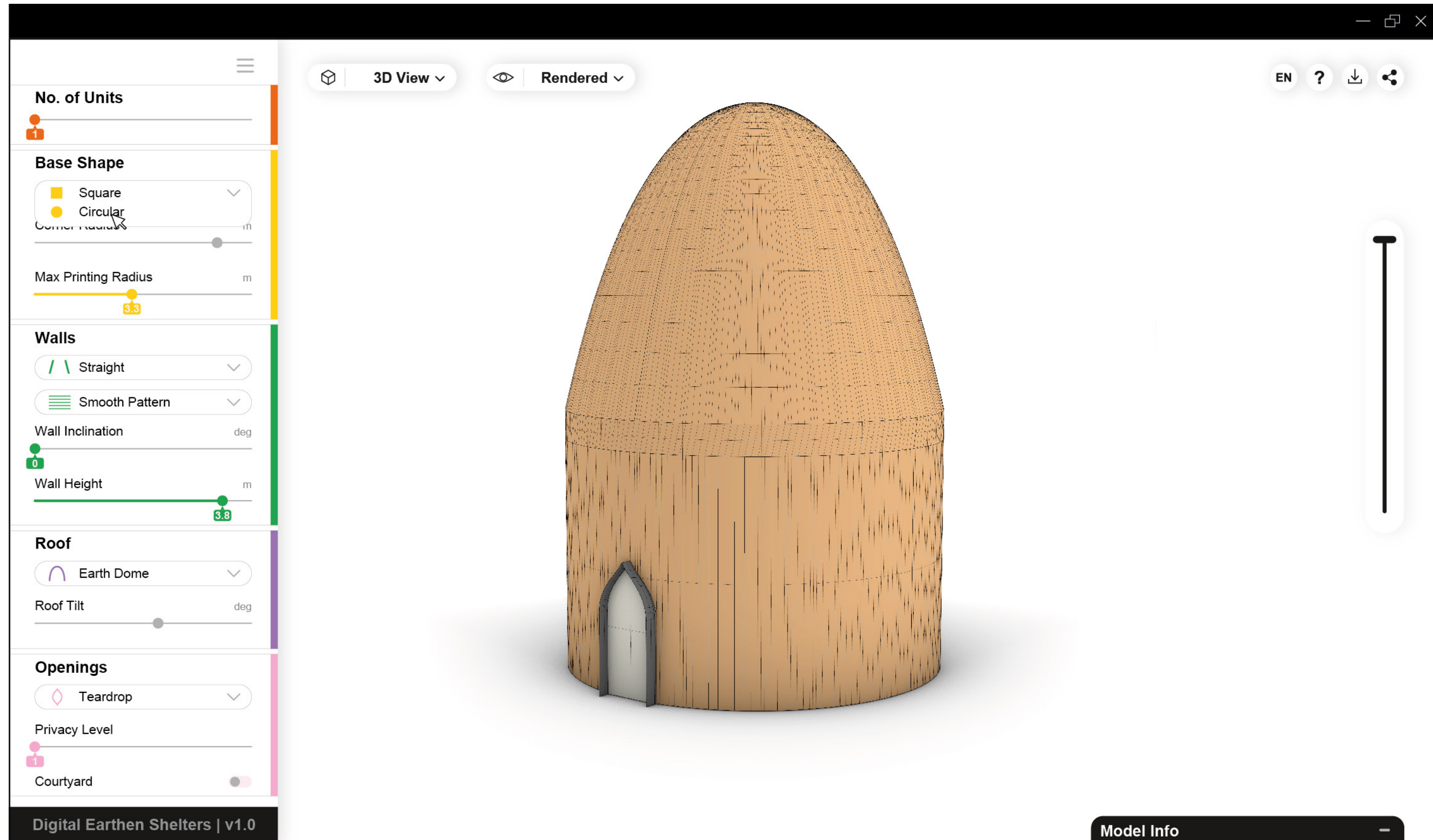


**Governmental
Agencies**

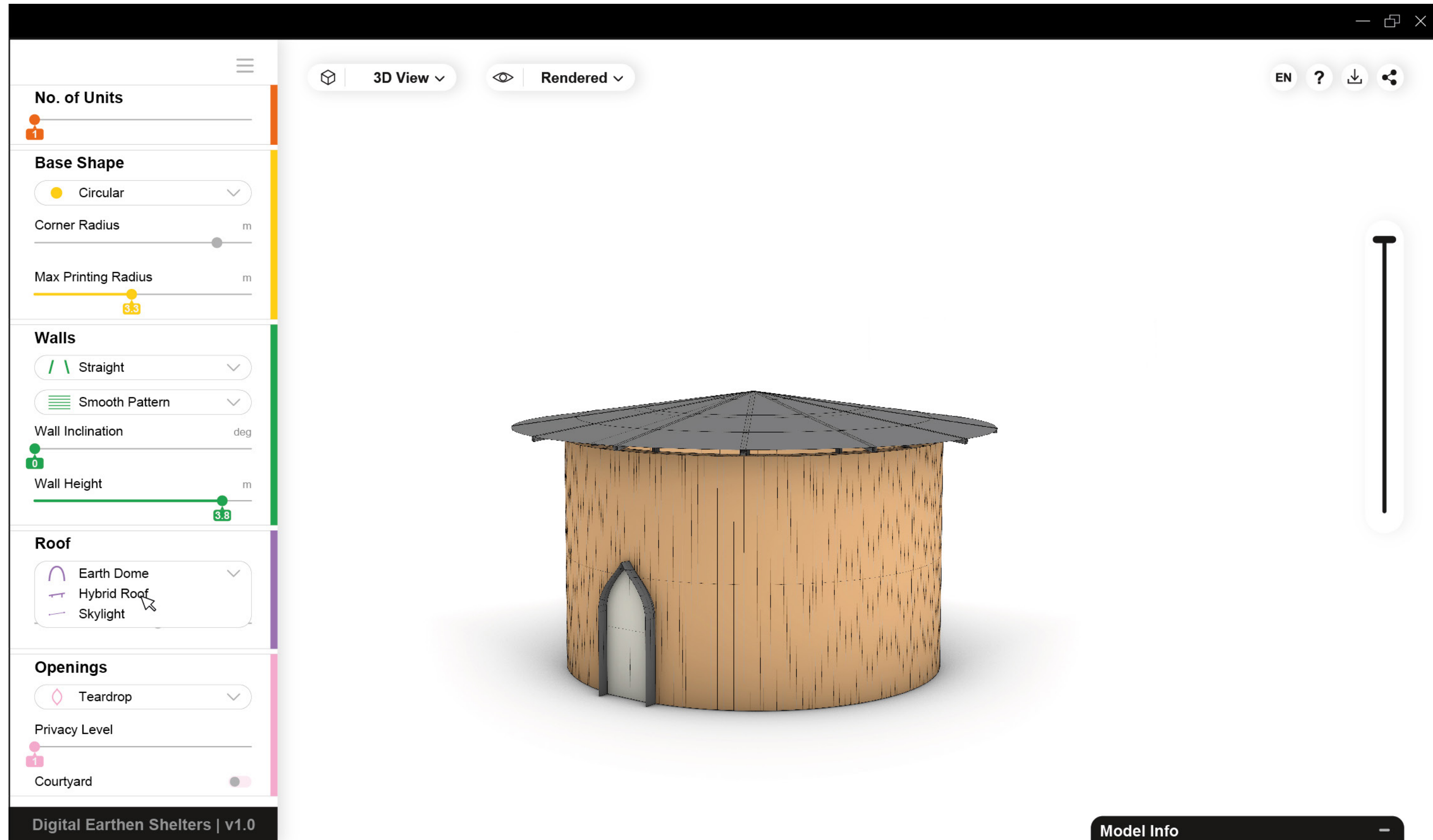


**Construction Personnel
Architects/Designers**

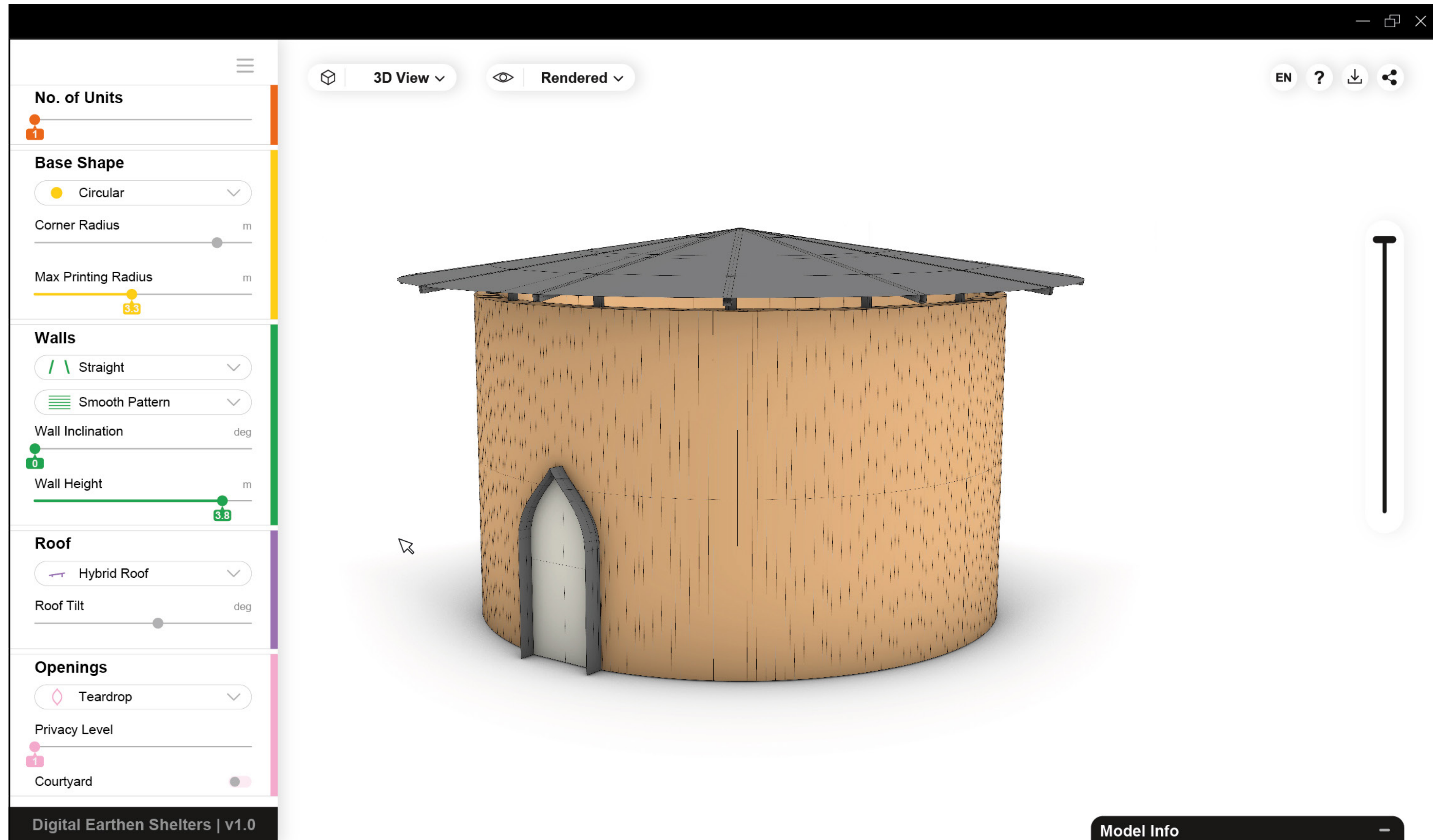
User Interface



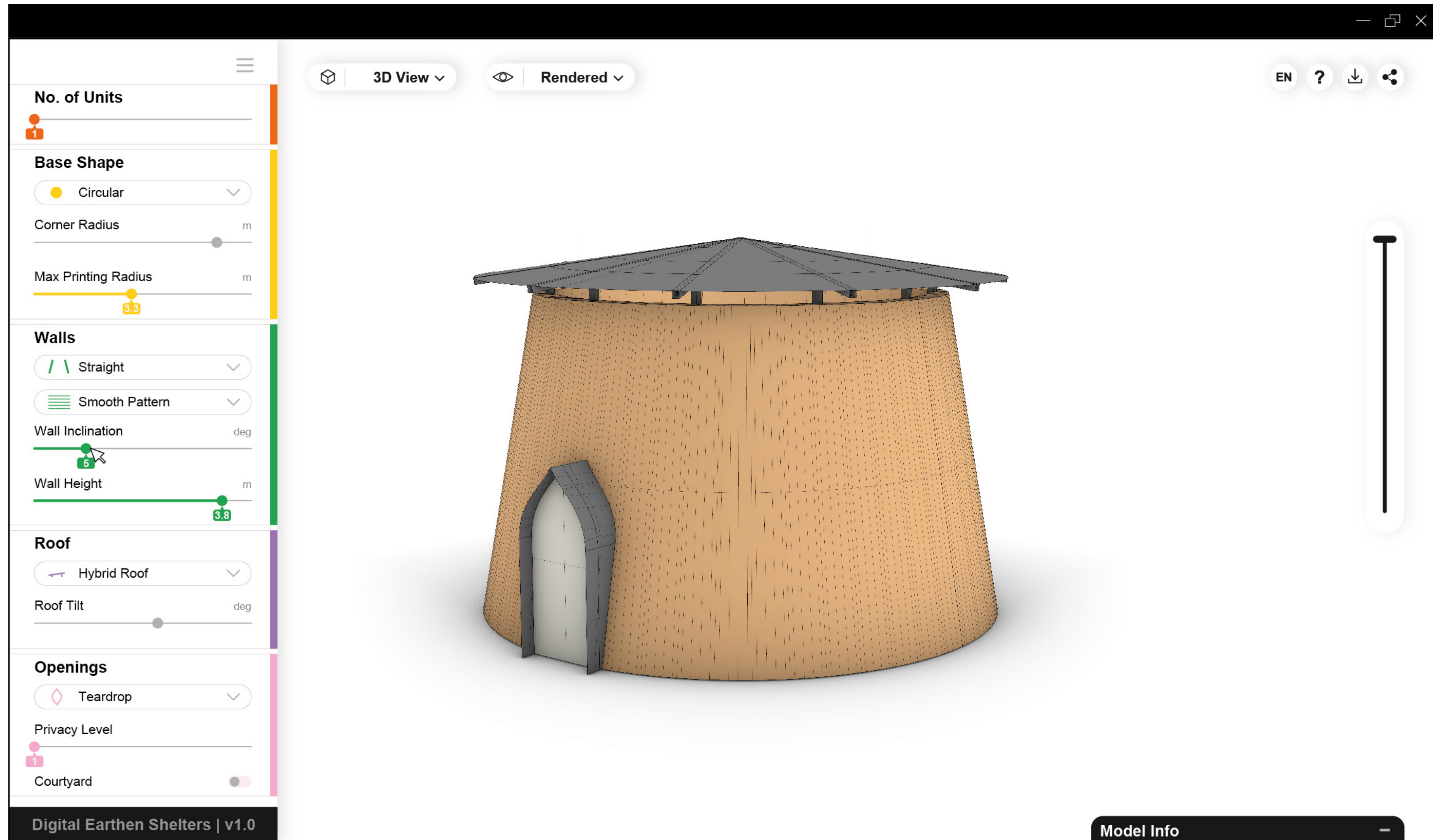
User Interface



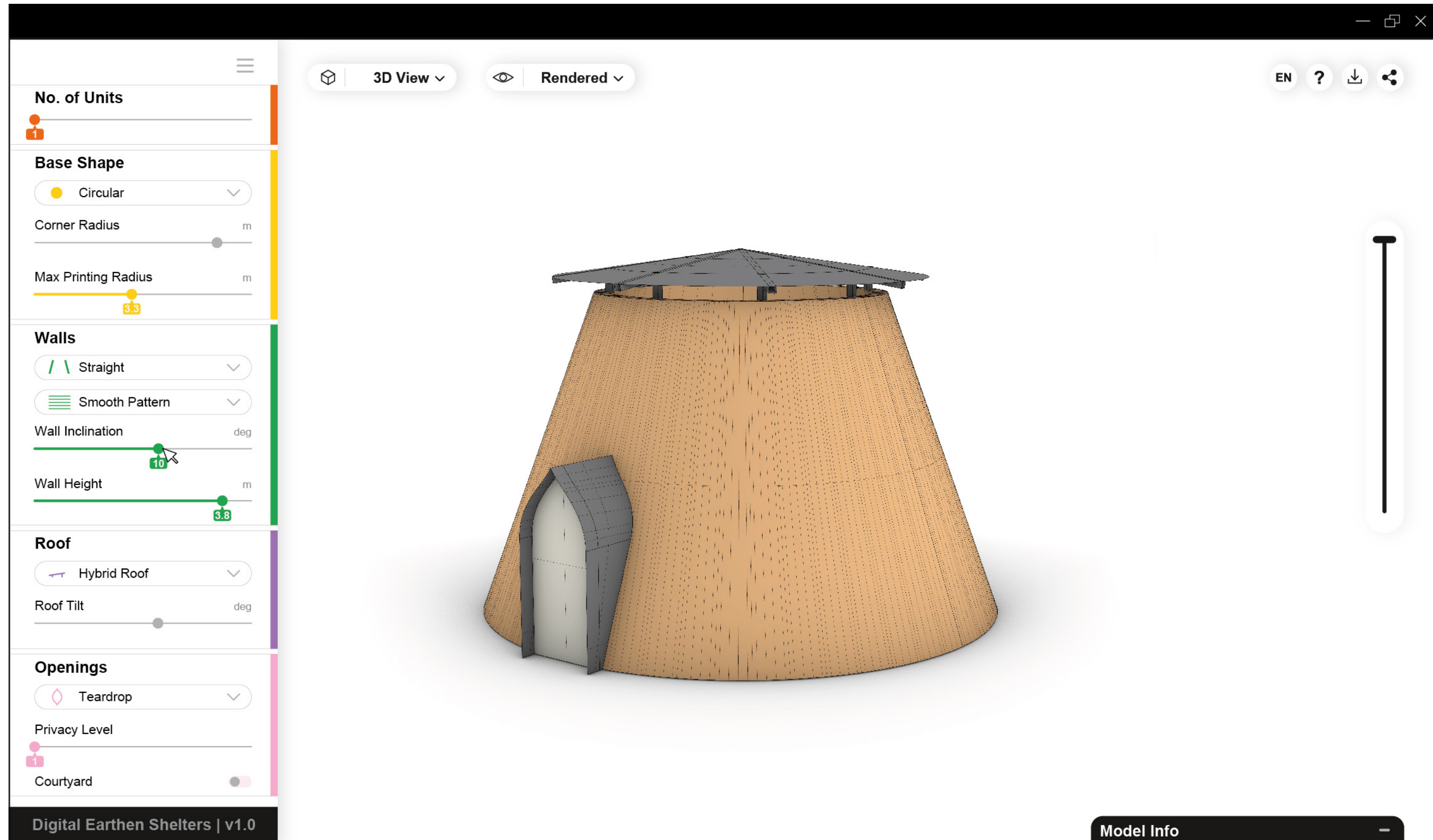
User Interface



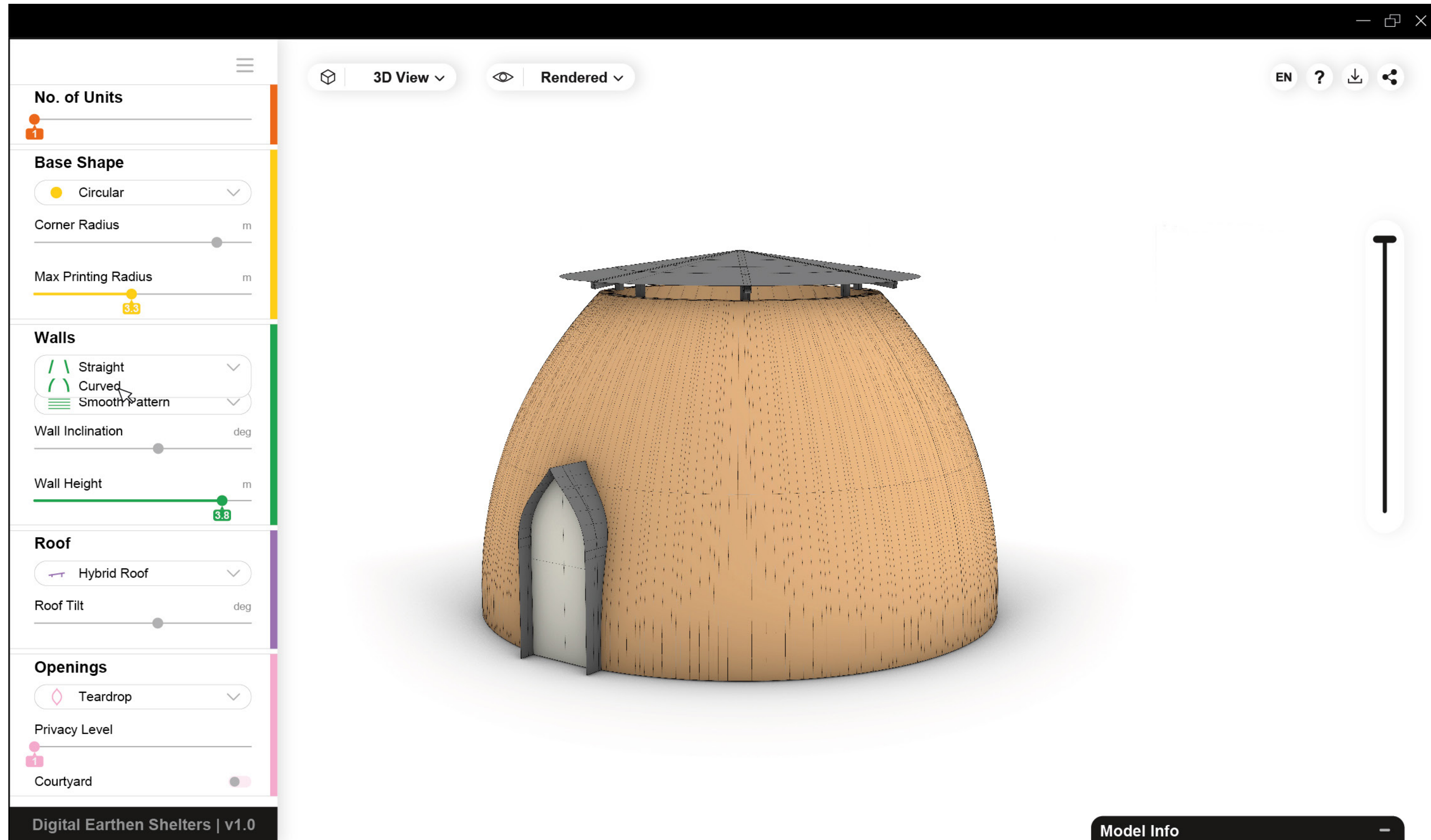
User Interface



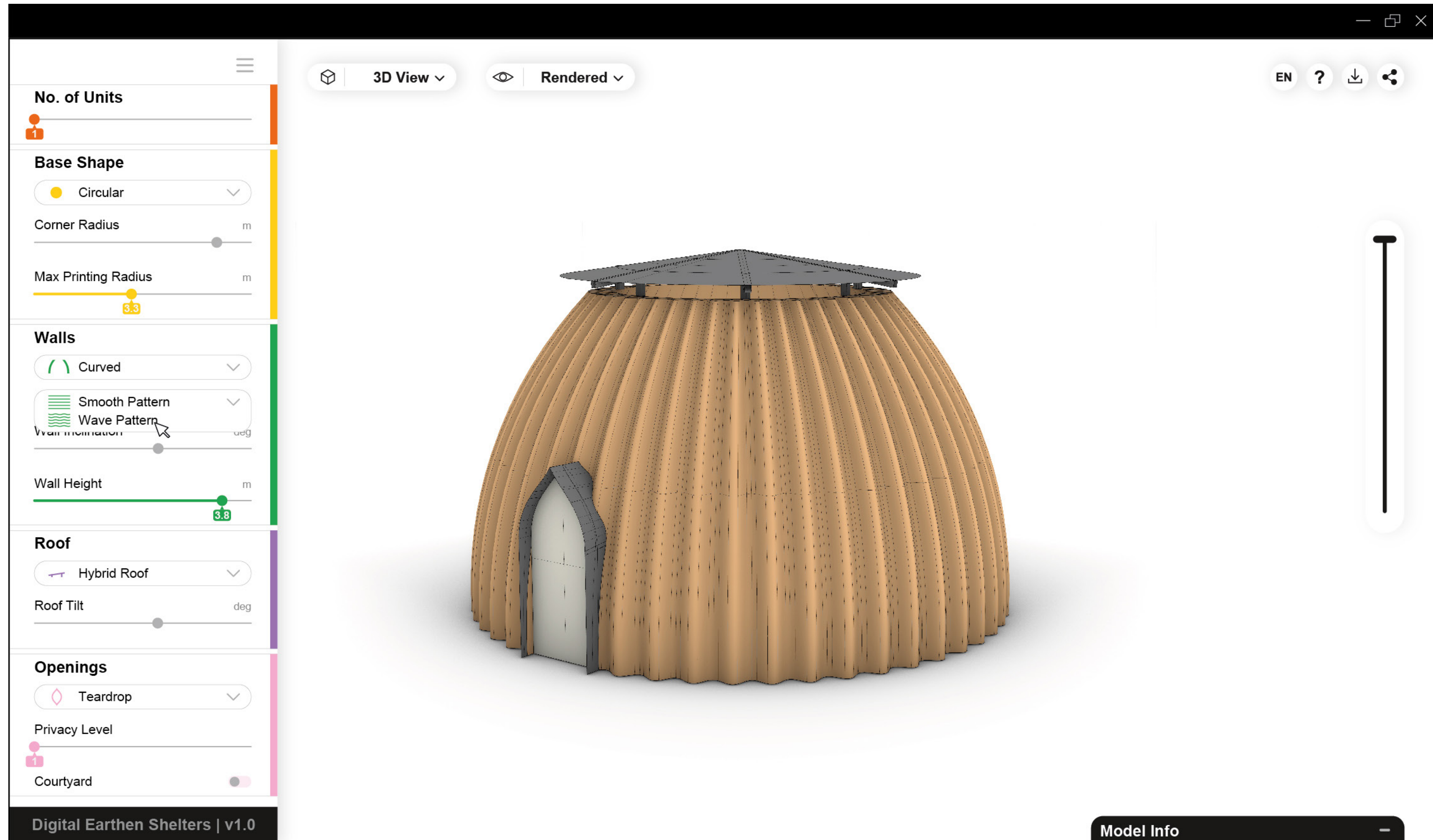
User Interface



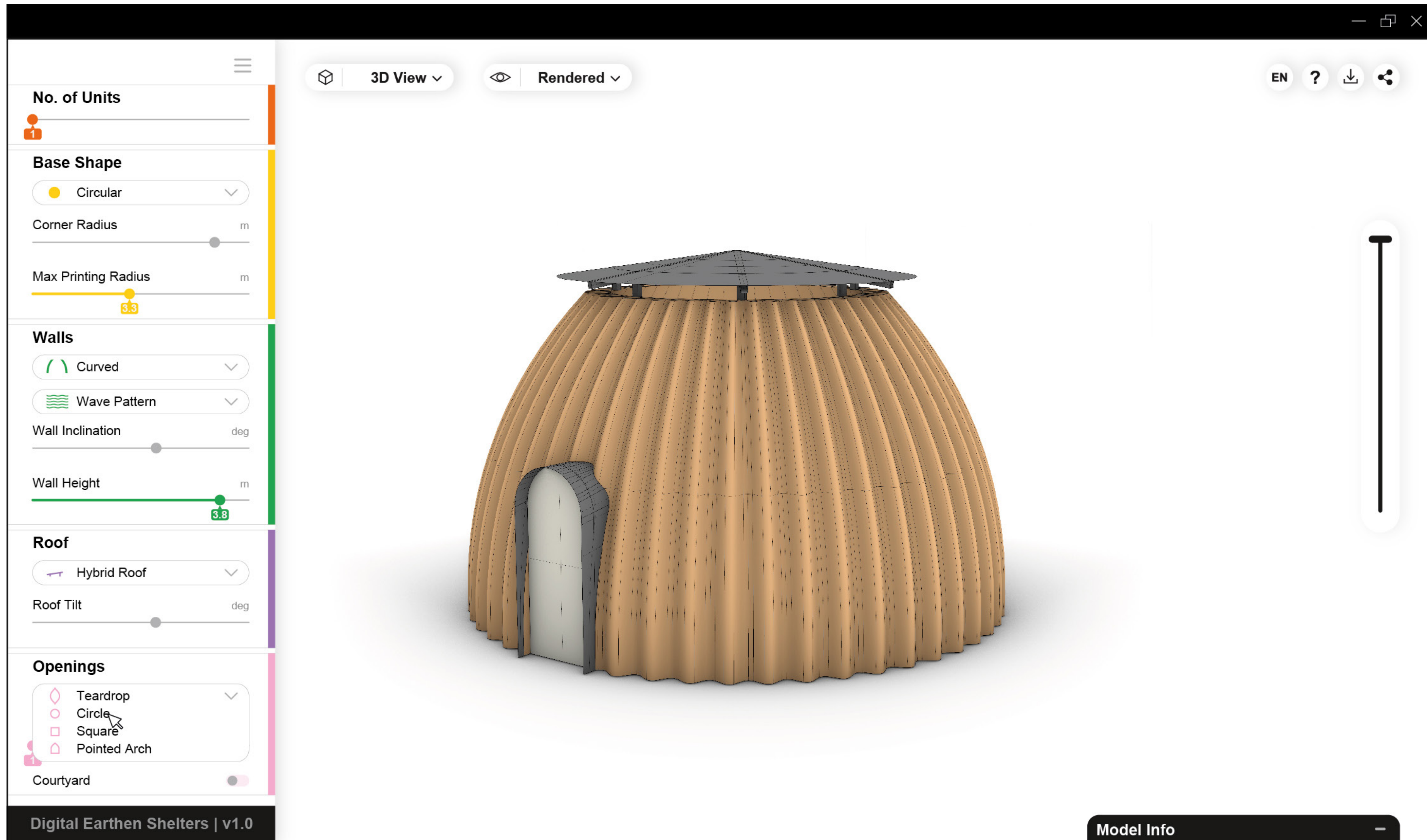
User Interface



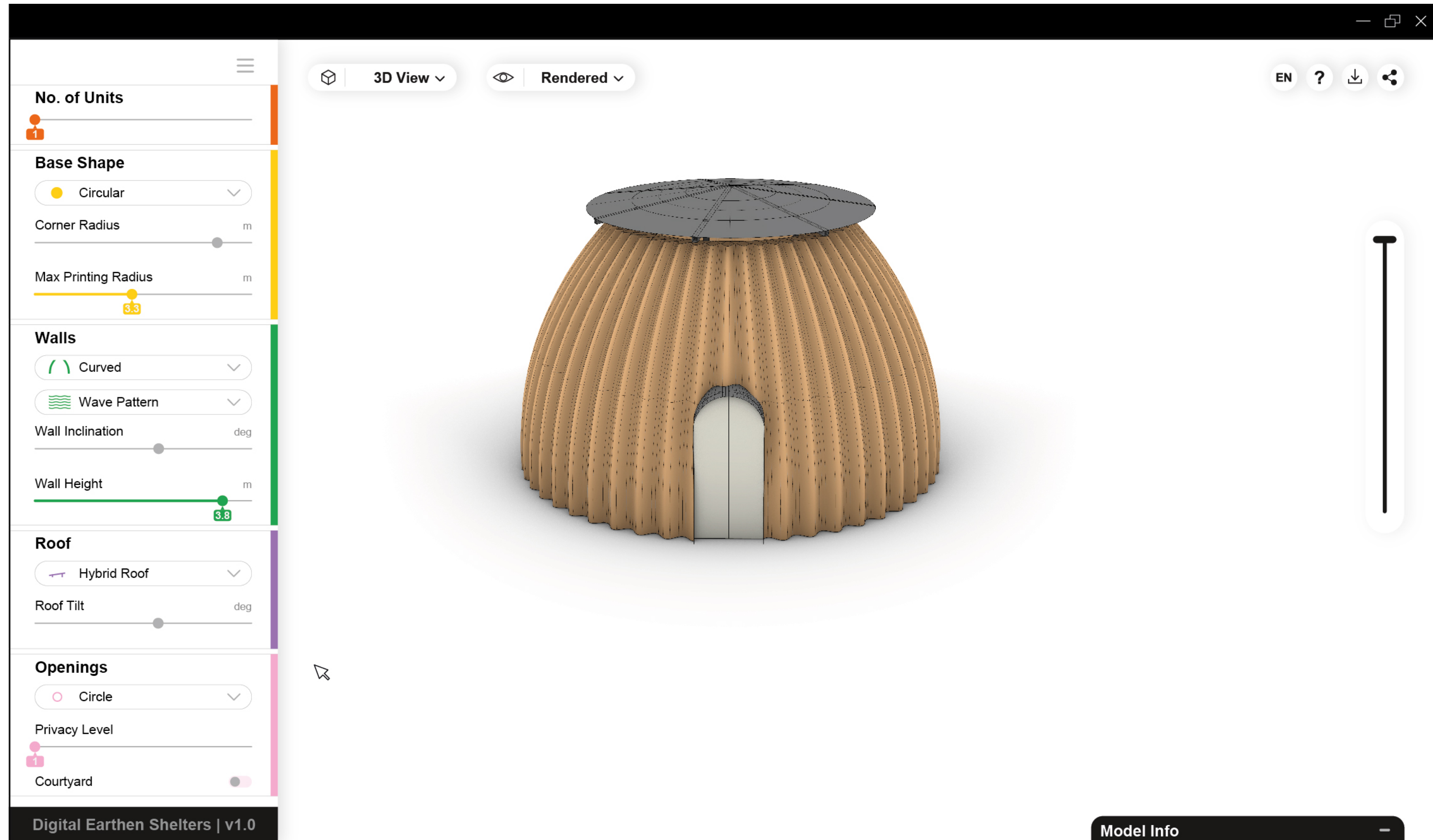
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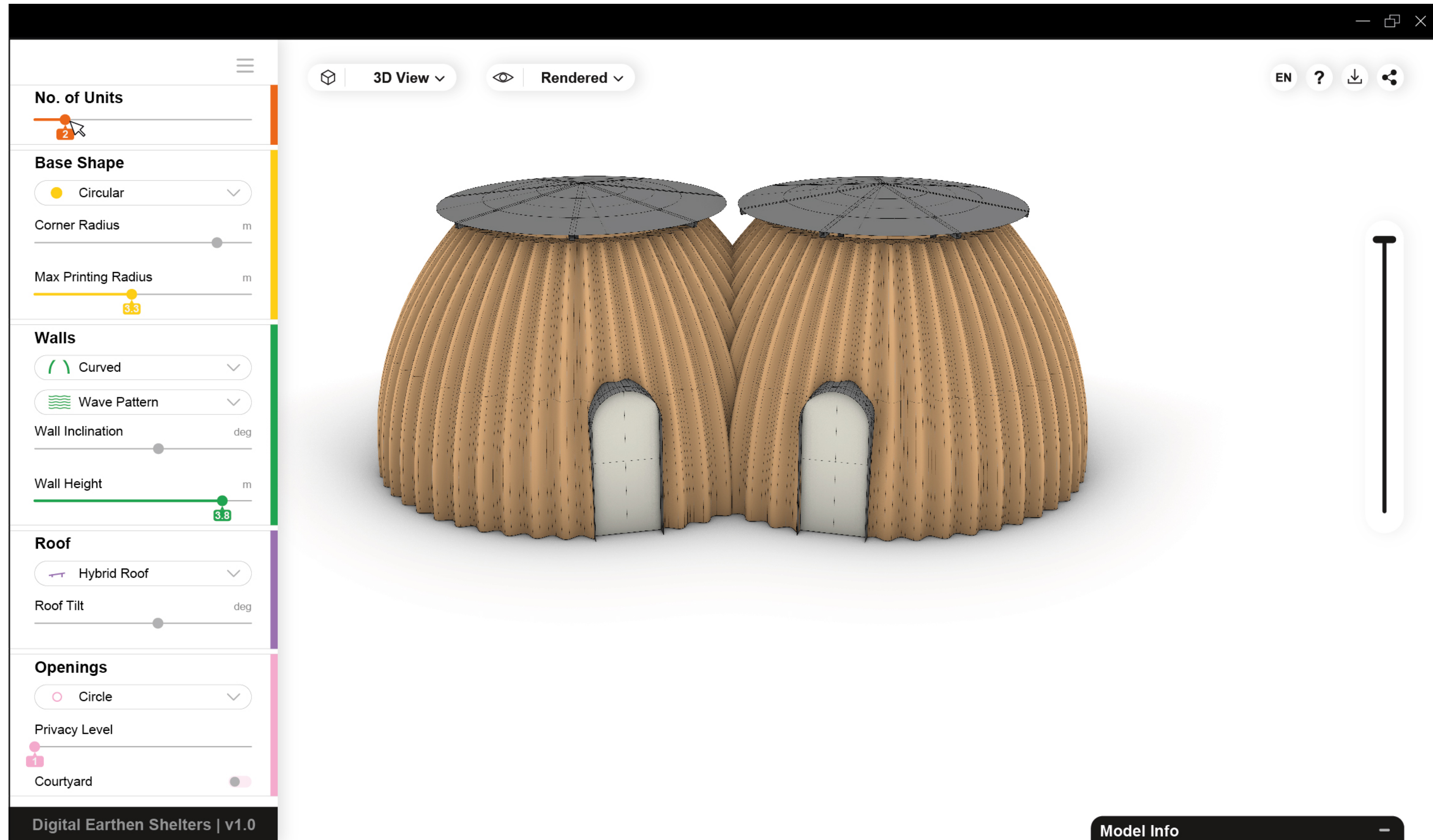
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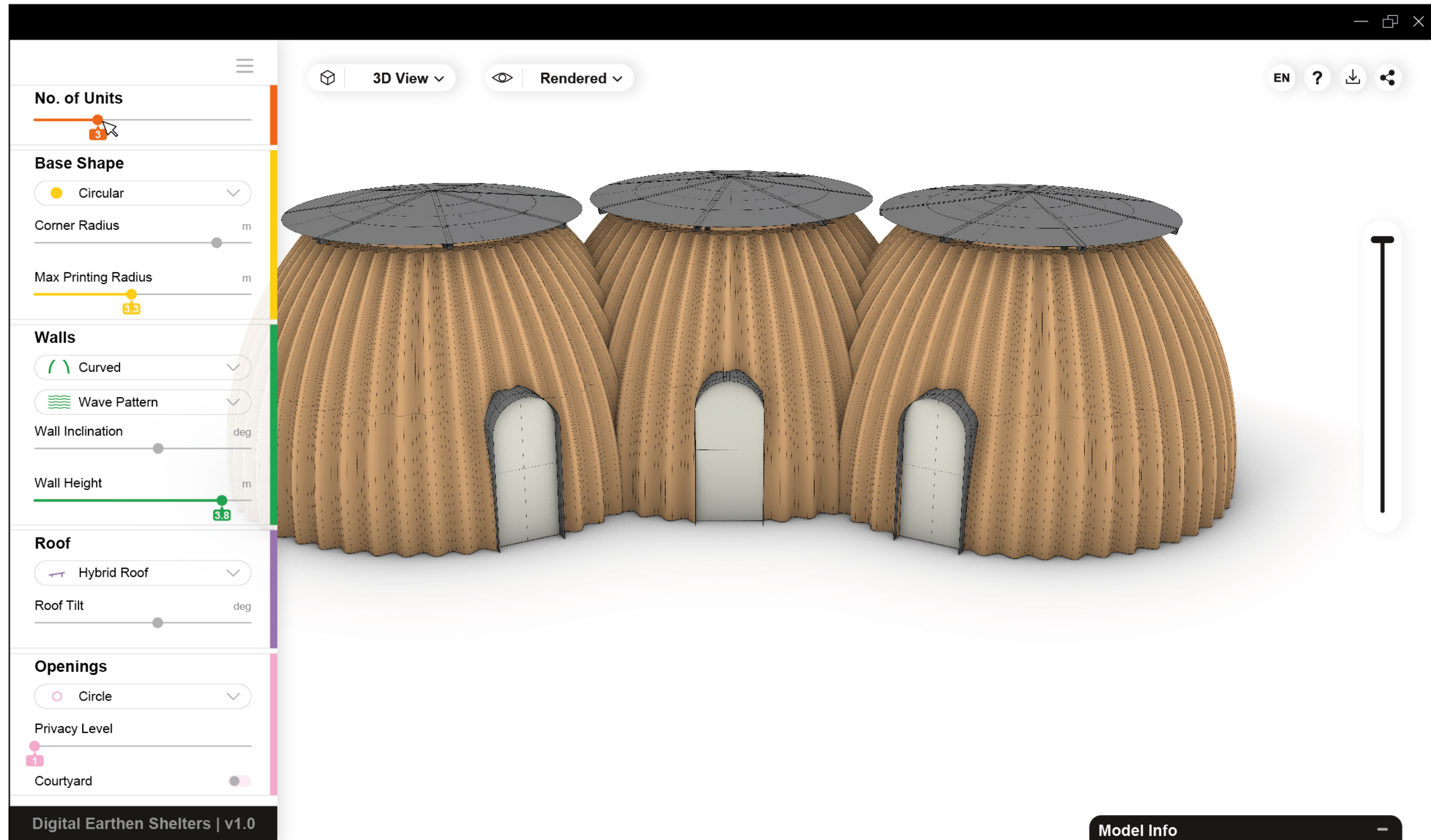
User Interface



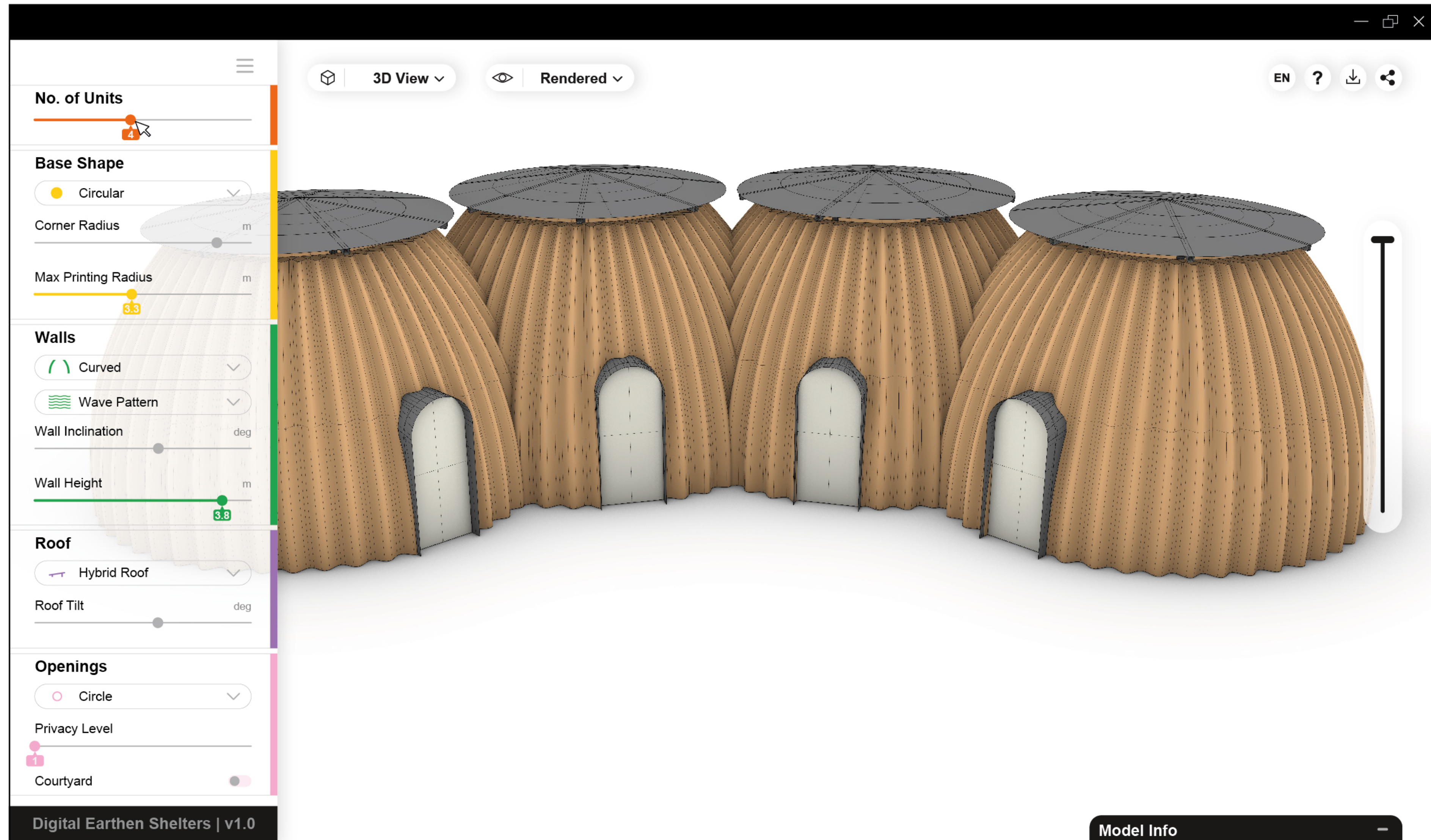
User Interface



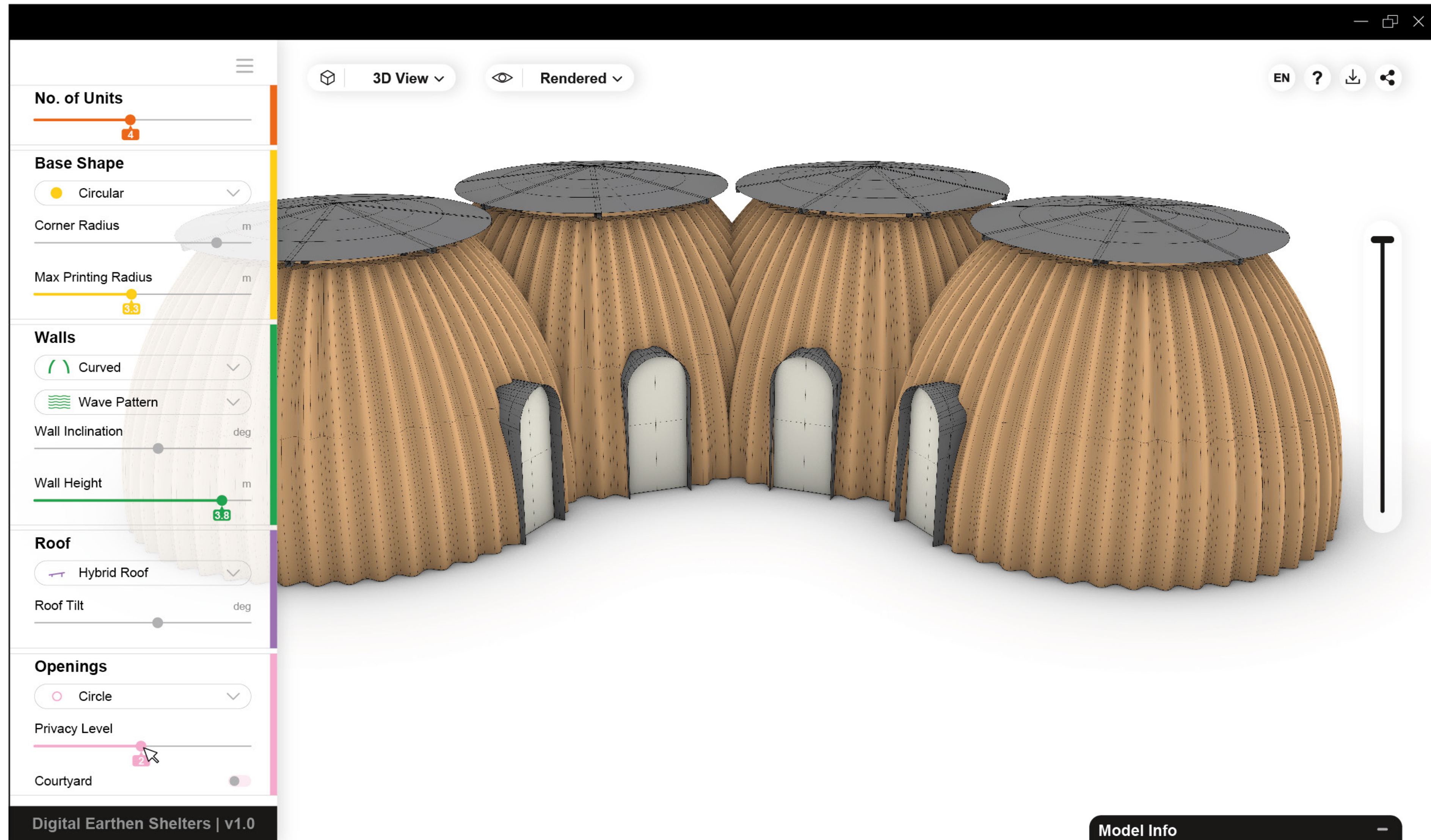
User Interface



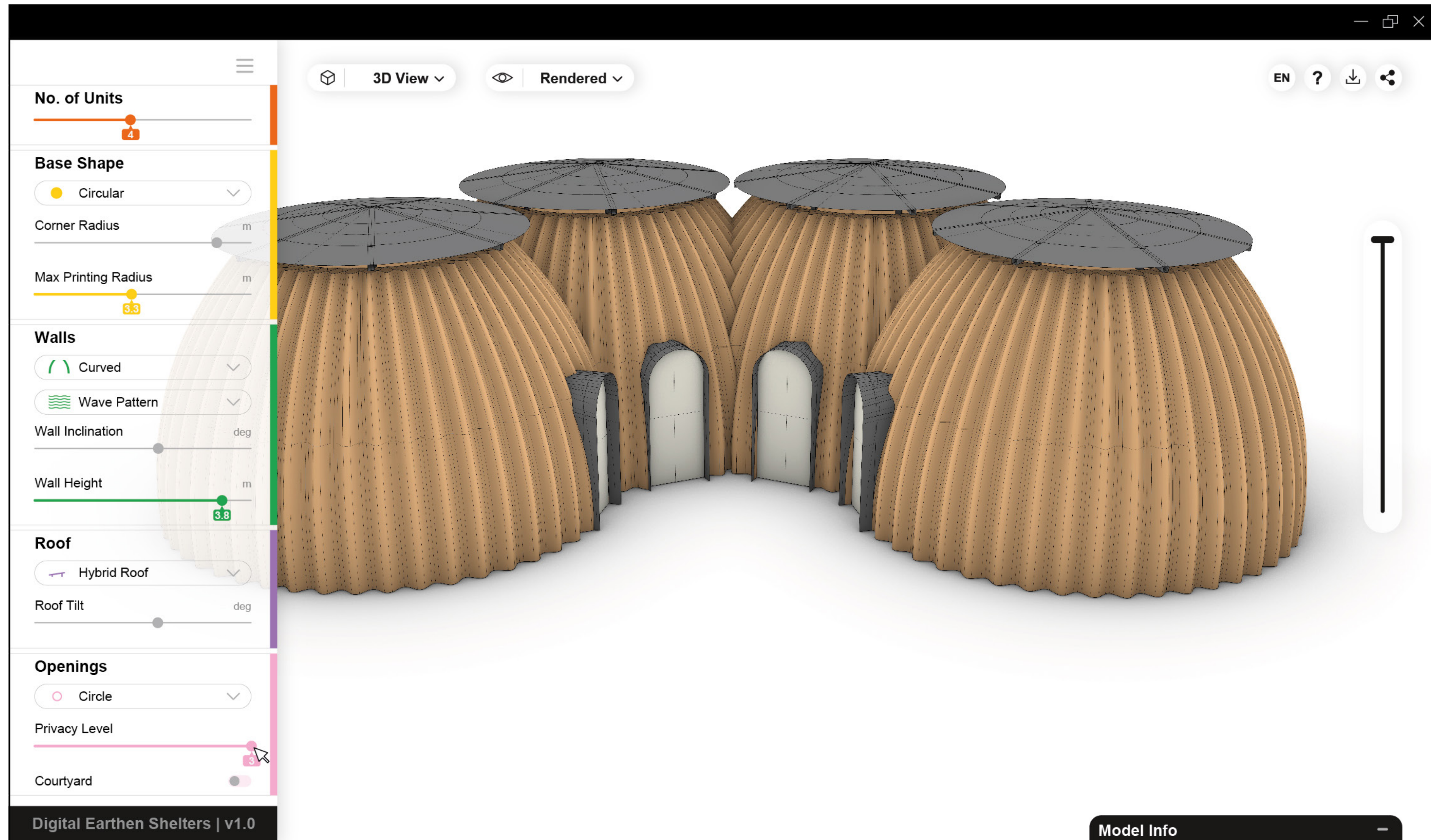
User Interface



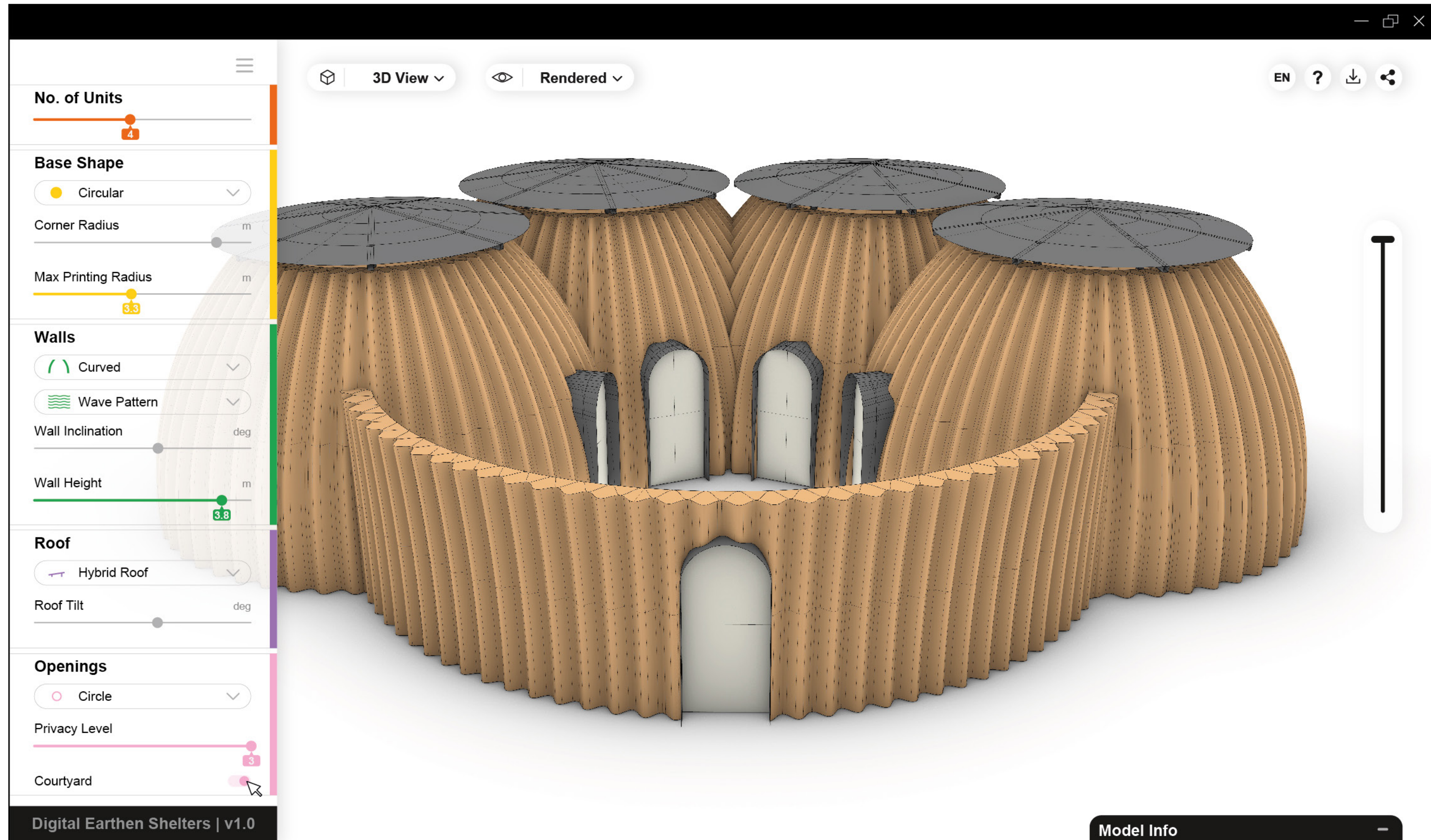
User Interface



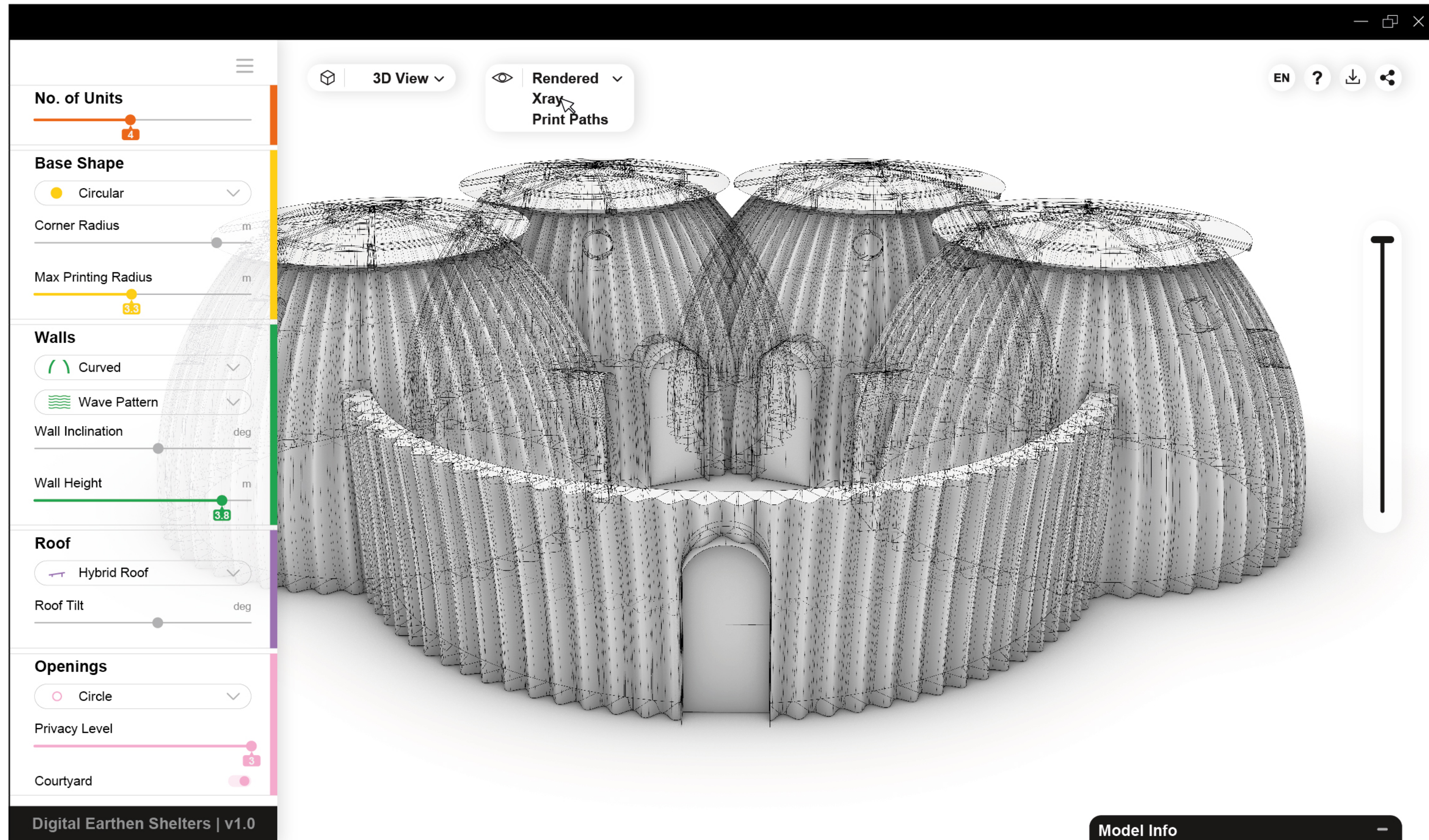
User Interface



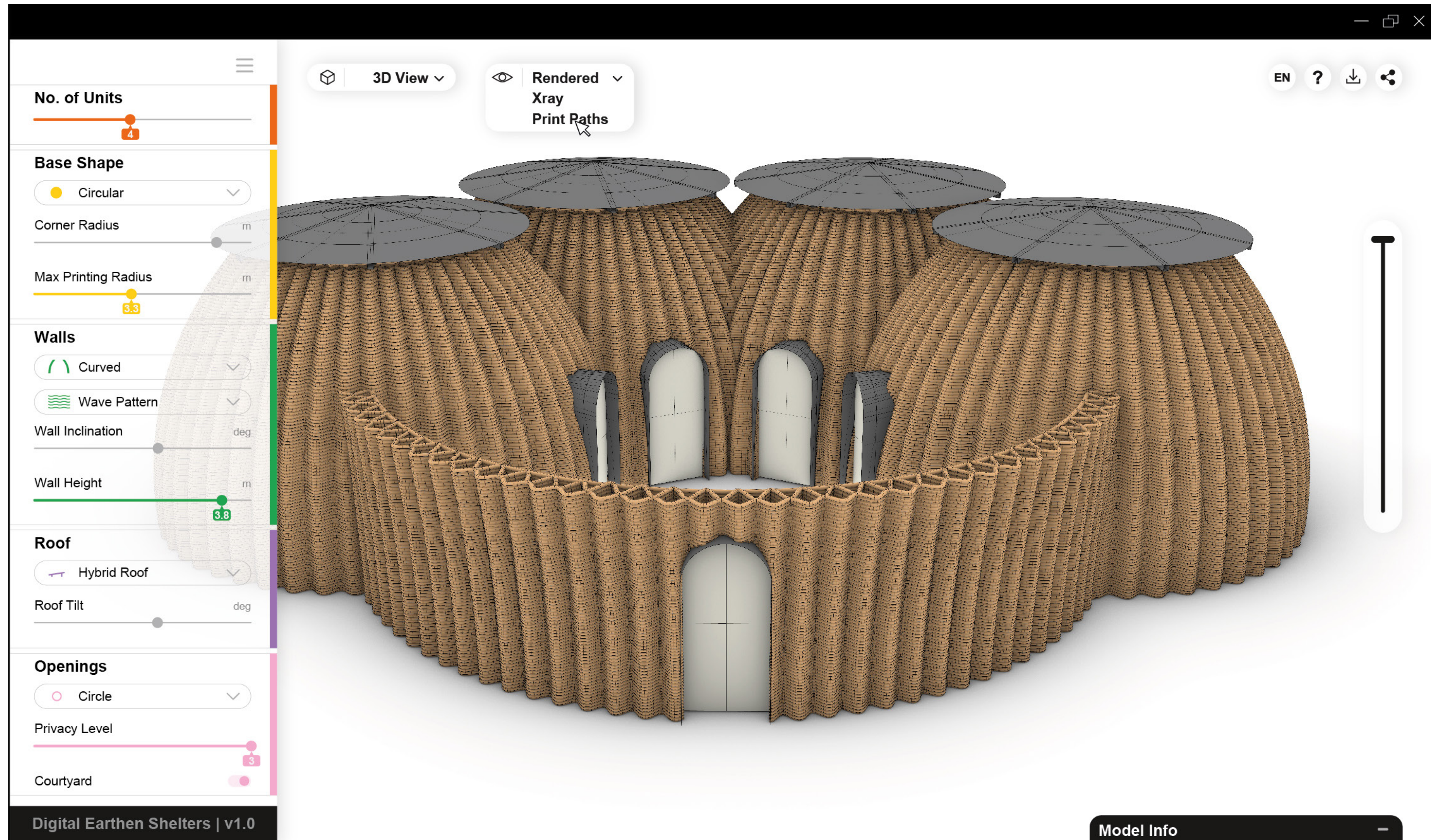
User Interface



User Interface



User Interface



User Interface

The screenshot displays the user interface for 'Digital Earthen Shelters | v1.0'. The central 3D view shows a cluster of four domes with a woven texture, each featuring a central arched entrance. The interface includes a control panel on the left and a 'Model Info' panel on the right.

Control Panel Settings:

- No. of Units:** 4
- Base Shape:** Circular
- Corner Radius:** m
- Max Printing Radius:** 3.3 m
- Walls:** Curved
- Wave Pattern:** (disabled)
- Wall Inclination:** deg
- Wall Height:** 3.8 m
- Roof:** Hybrid Roof
- Roof Tilt:** deg
- Openings:** Circle
- Privacy Level:** 3
- Courtyard:** (disabled)

Model Info:

Floor Area	108 m ²
Print Time	86 h
Total Height	4.15 (m)
Material Volume	12.3 (m ³)
Material Weight	28531 (kg)
Non-Earth Material Amount	High

User Interface

The interface features a central 3D view of a cluster of four domes with a central courtyard. The left sidebar contains several control panels:

- No. of Units:** A slider set to 4.
- Base Shape:** A dropdown menu set to 'Circular'. Below it are sliders for 'Corner Radius' and 'Max Printing Radius' (set to 3.3).
- Walls:** A dropdown menu set to 'Curved'. Below it are sliders for 'Wall Inclination' and 'Wall Height' (set to 3.8).
- Roof:** A dropdown menu set to 'Hybrid Roof'. Below it is a slider for 'Roof Tilt'.
- Openings:** A dropdown menu set to 'Circle'. Below it are a slider for 'Privacy Level' (set to 3) and a toggle for 'Courtyard'.

At the top of the interface, there are view controls: '3D View' (selected) and 'Print Paths'. On the right side, there are utility icons for language (EN), help (?), download, and share. A vertical zoom slider is also present on the right.

Model Info

Floor Area	108 m ²
Print Time	86 h
Total Height	4.15 (m)
Material Volume	12.3 (m ³)
Material Weight	28531 (kg)
Non-Earth Material Amount	High

Digital Earthen Shelters | v1.0

User Interface

The interface features a central 3D view of a circular earthen shelter with a complex, layered structure. The left sidebar contains several control panels:

- No. of Units:** A slider set to 4.
- Base Shape:** A dropdown menu set to 'Circular', with sliders for 'Corner Radius' and 'Max Printing Radius' (set to 3.3).
- Walls:** A dropdown menu set to 'Curved', with sliders for 'Wall Inclination' and 'Wall Height' (set to 3.8).
- Roof:** A dropdown menu set to 'Hybrid Roof', with a slider for 'Roof Tilt'.
- Openings:** A dropdown menu set to 'Circle', with a slider for 'Privacy Level' (set to 3) and a toggle for 'Courtyard'.

At the top, there are view controls for '3D View' and 'Print Paths', along with language ('EN'), help ('?'), download, and share icons. A vertical zoom slider is located on the right side of the 3D view.

Model Info

Floor Area	108 m ²
Print Time	86 h
Total Height	4.15 (m)
Material Volume	12.3 (m ³)
Material Weight	28531 (kg)
Non-Earth Material Amount	High

Digital Earthen Shelters | v1.0

User Interface

The interface features a central 3D view of a circular earthen shelter. The left sidebar contains several control panels:

- No. of Units:** A slider set to 4.
- Base Shape:** A dropdown menu set to 'Circular'. Below it are sliders for 'Corner Radius' and 'Max Printing Radius' (set to 3.3).
- Walls:** A dropdown menu set to 'Curved'. Below it are sliders for 'Wall Inclination' and 'Wall Height' (set to 3.8).
- Roof:** A dropdown menu set to 'Hybrid Roof' and a slider for 'Roof Tilt'.
- Openings:** A dropdown menu set to 'Circle'. Below it are a 'Privacy Level' slider (set to 3) and a 'Courtyard' toggle switch.

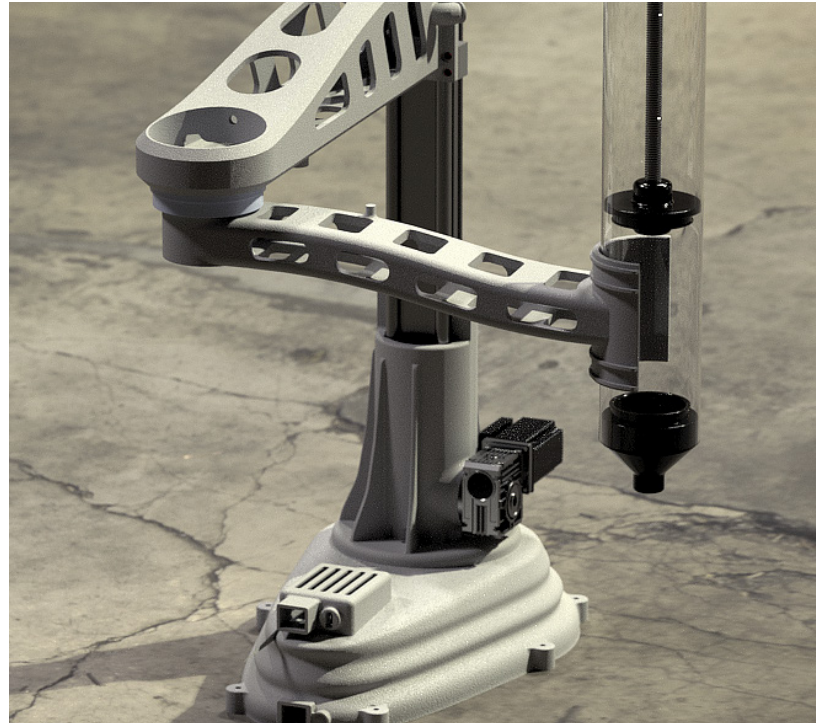
At the top of the interface, there are view controls: '3D View' and 'Print Paths'. On the right side, there are utility icons for language ('EN'), help ('?'), download, and share. A vertical zoom slider is also present on the right.

Model Info

Floor Area	108 m ²
Print Time	86 h
Total Height	4.15 (m)
Material Volume	12.3 (m ³)
Material Weight	28531 (kg)
Non-Earth Material Amount	High

Digital Earthen Shelters | v1.0

Robot Choice and Design Limitations



**3D Potter
Potterbot Scara HD**

3 - Axis
 41 kg weight
 ~115 kg payload
 2.75 m print height
 ~\$23,000
 Setup Difficulty: Easy
 Software Use: Easy
 Rotation: Infinite
 Can be Mobile (Track)
 Modular
 3DPE Specialized



**6-Axis Industrial Robot
w/ Industrial Printing Head**

6 - Axis
 ~1500 kg weight
 up to 500 kg payload
 3.00 m print height
 up to \$150,000
 Setup Difficulty: Advanced
 Software Use: Advanced
 Rotation: Limited
 Fixed / Mobile
 Not Modular
 Not Specialized



**WASP
Wasp Crane**

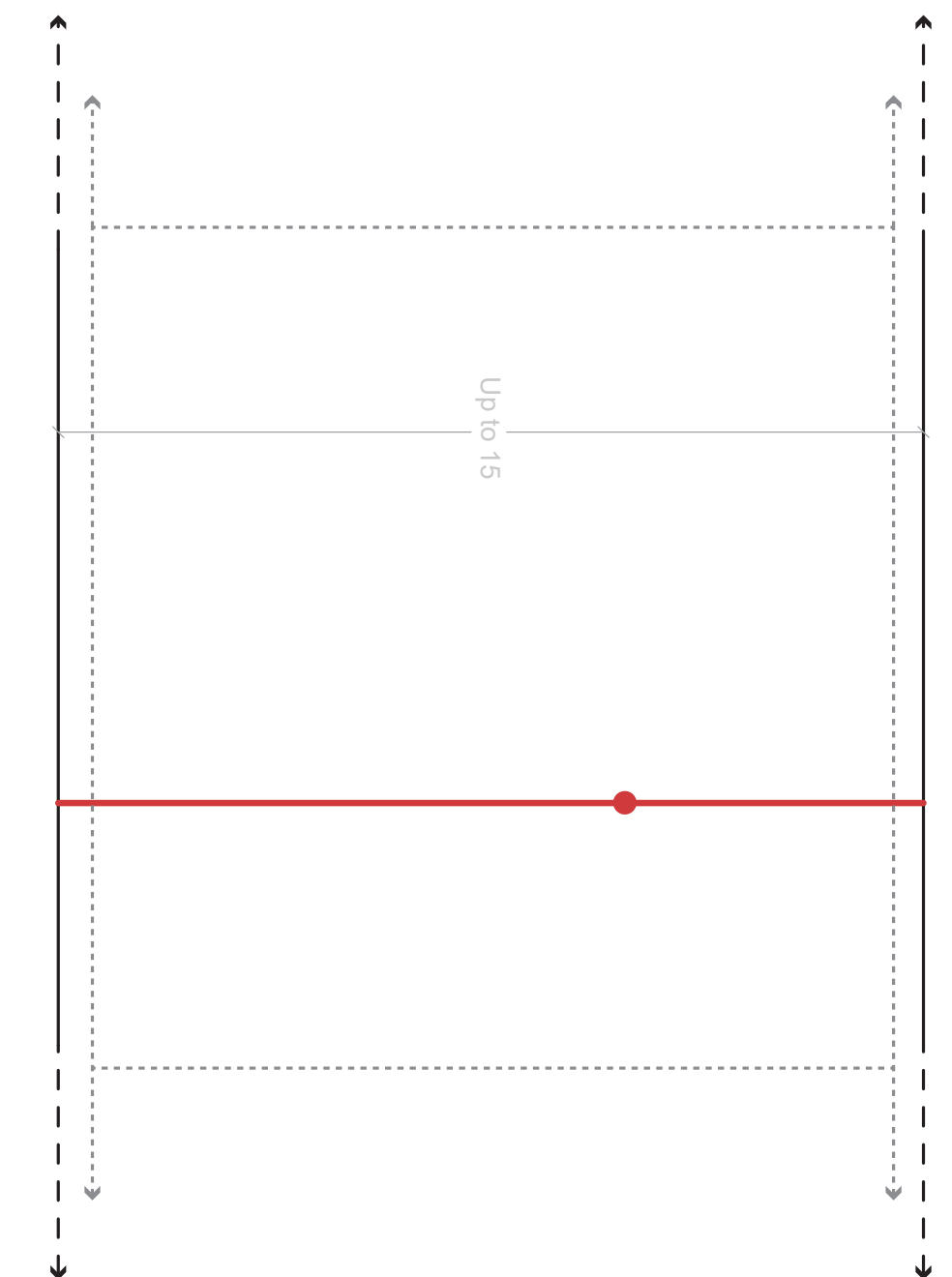
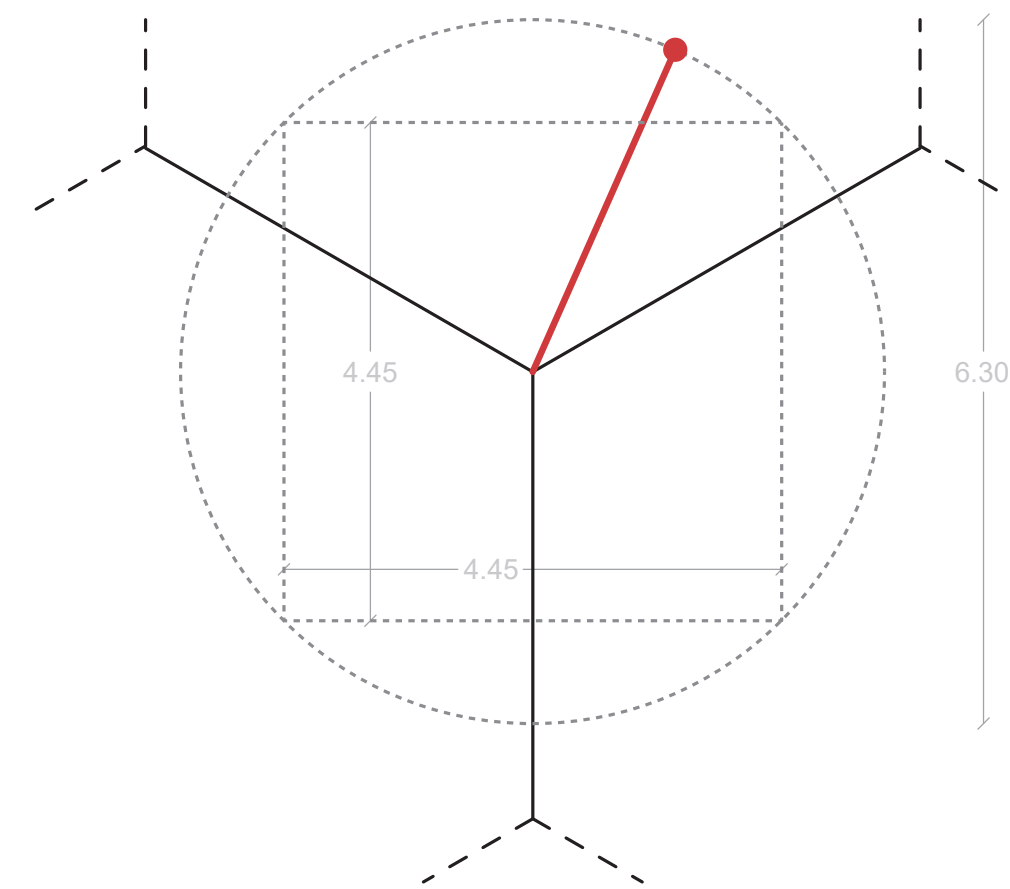
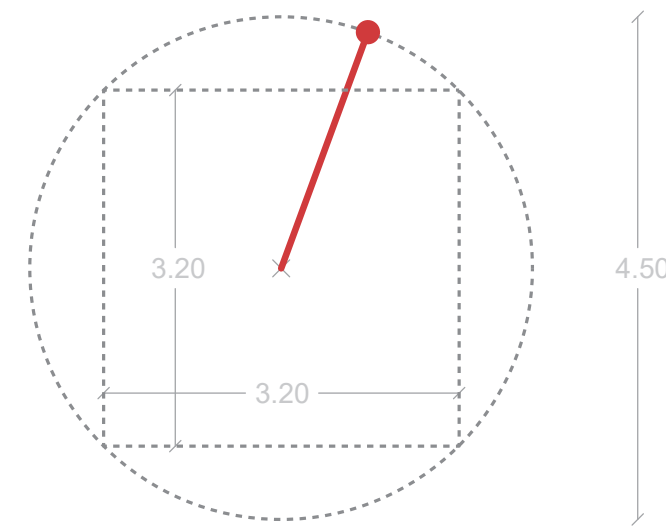
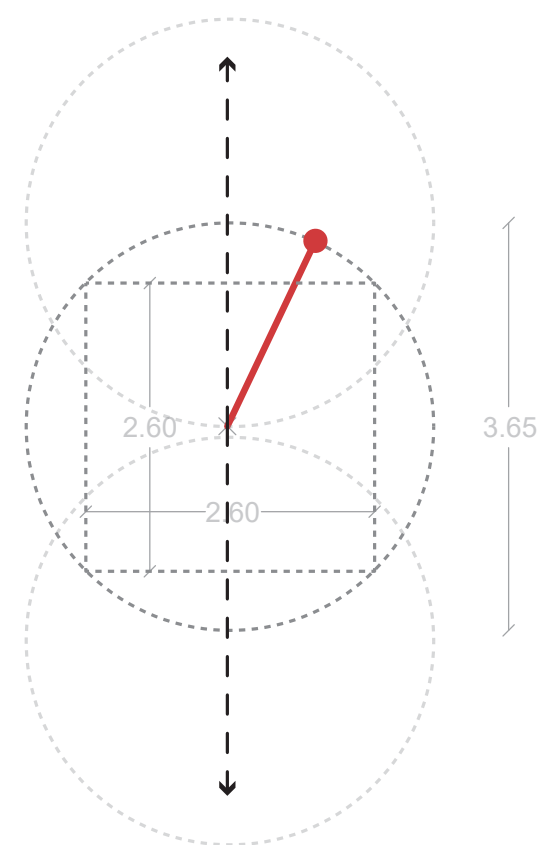
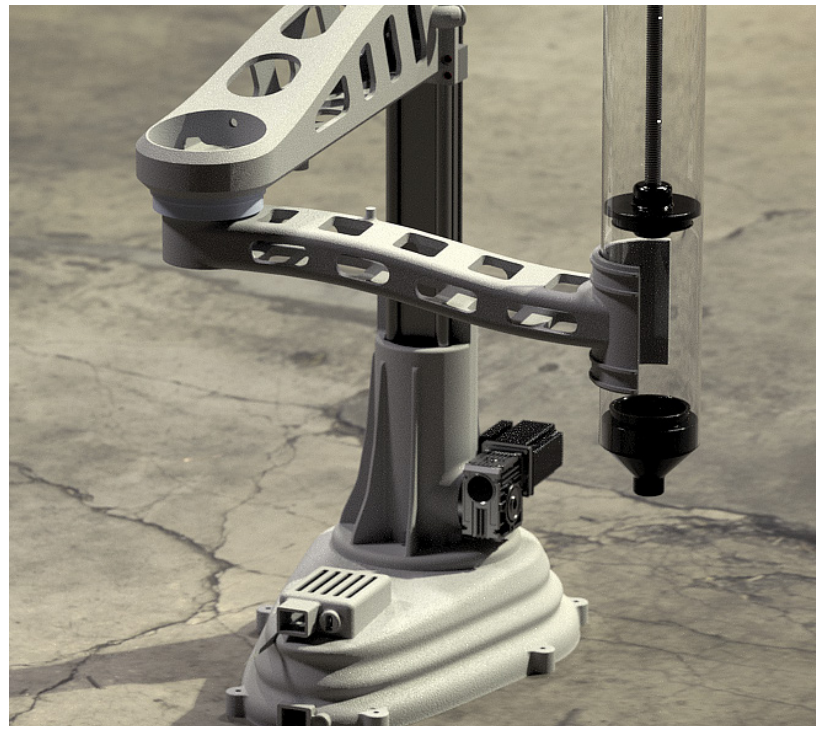
3 - Axis
 150 kg weight +structure
 NA kg payload
 3.00 m print height
 ~\$150,000
 Setup Difficulty: Medium
 Software Use: Advanced
 Rotation: Infinite
 Fixed
 Modular
 3DPE Specialized



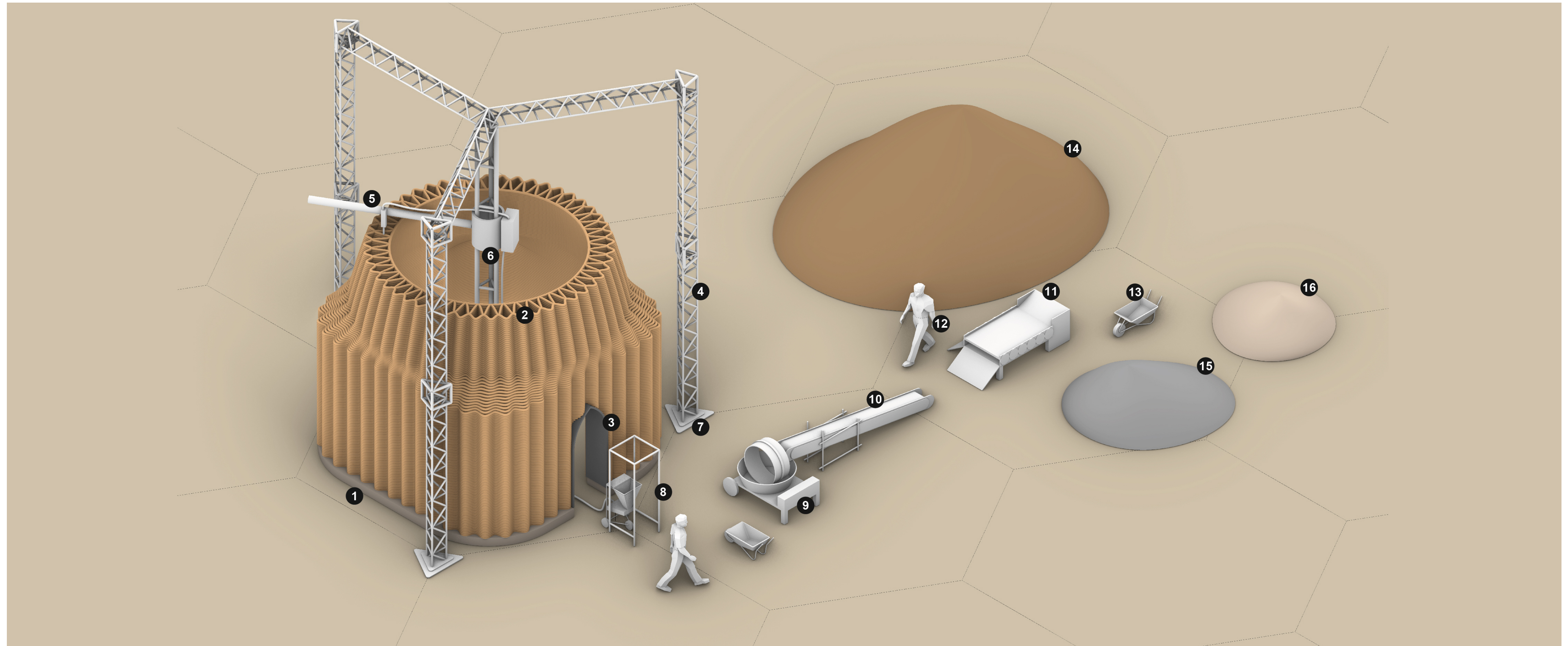
**COBOD
Bod2**

3 - Axis
 NA kg weight
 ~30 kg payload
 10.00 m print height
 \$180,000 - \$950,000
 Setup Difficulty: Difficult
 Software Use: Easy
 Rotation: Infinite
 Fixed
 Modular
 3DPC Specialized

Robot Choice and Design Limitations



Construction Sequence



1 Stone Foundation
2 Printed Structure

3 Assembled Components
4 Modular Trusses

5 LDM Extruder
6 Movement Core

7 Truss Column Base
8 Feeding System

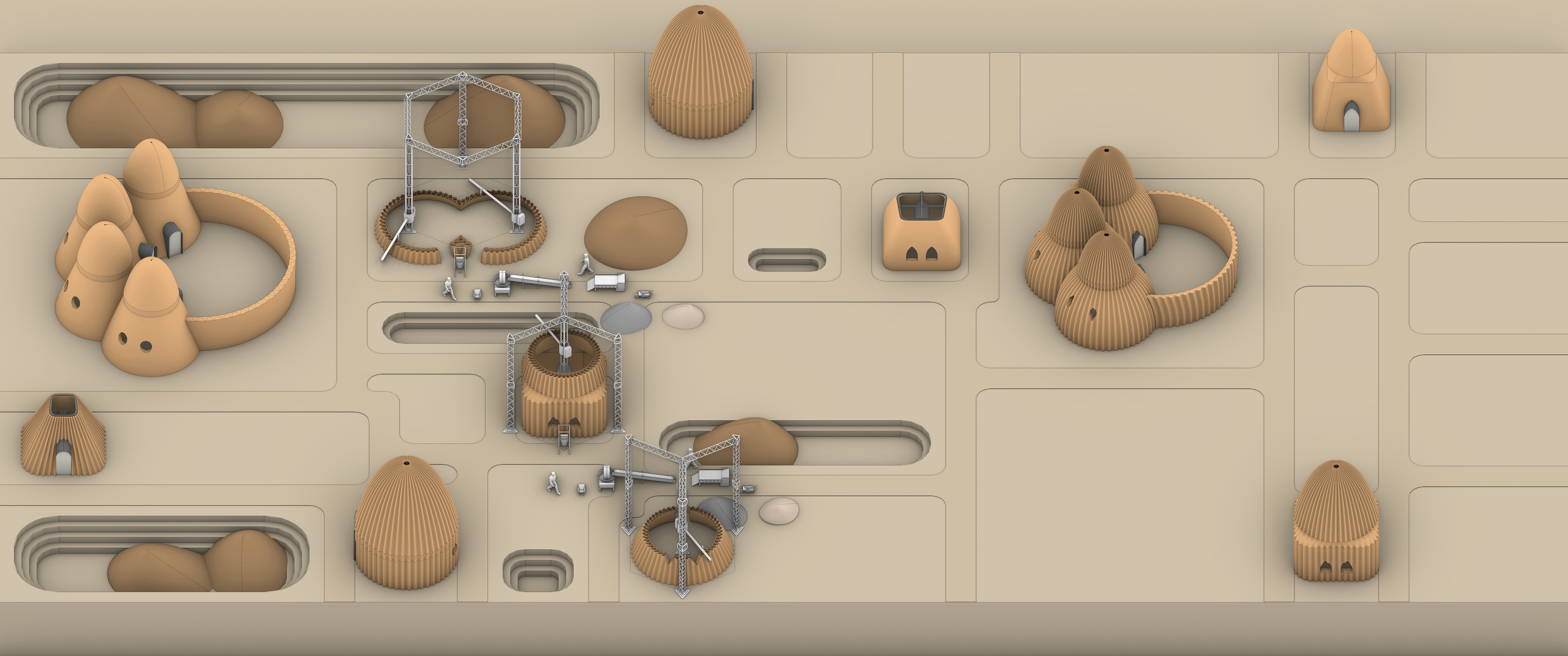
9 Mixing Station
10 Conveyor Belt

11 Screening Station
12 Operators (2)

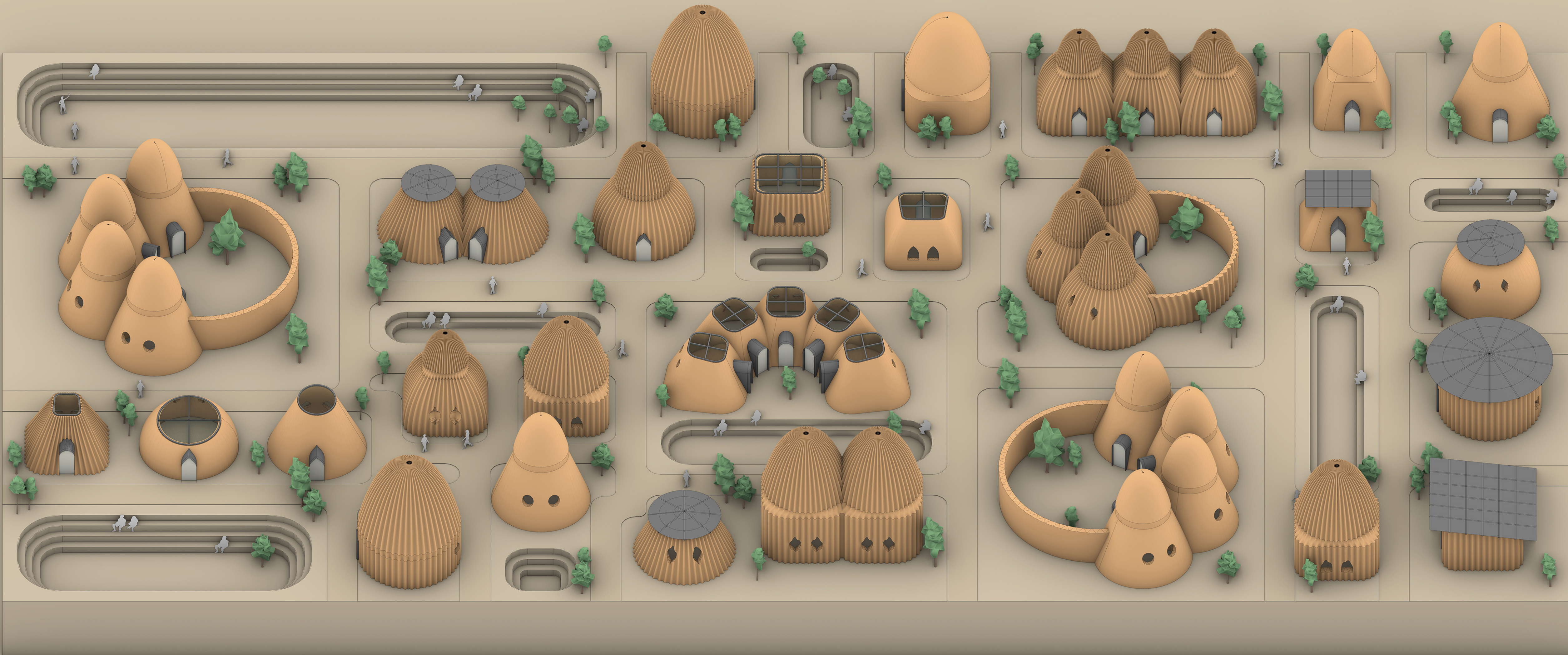
13 Trolleys
14 Excavated Earth

15 Additive Material 1
16 Additive Material 2

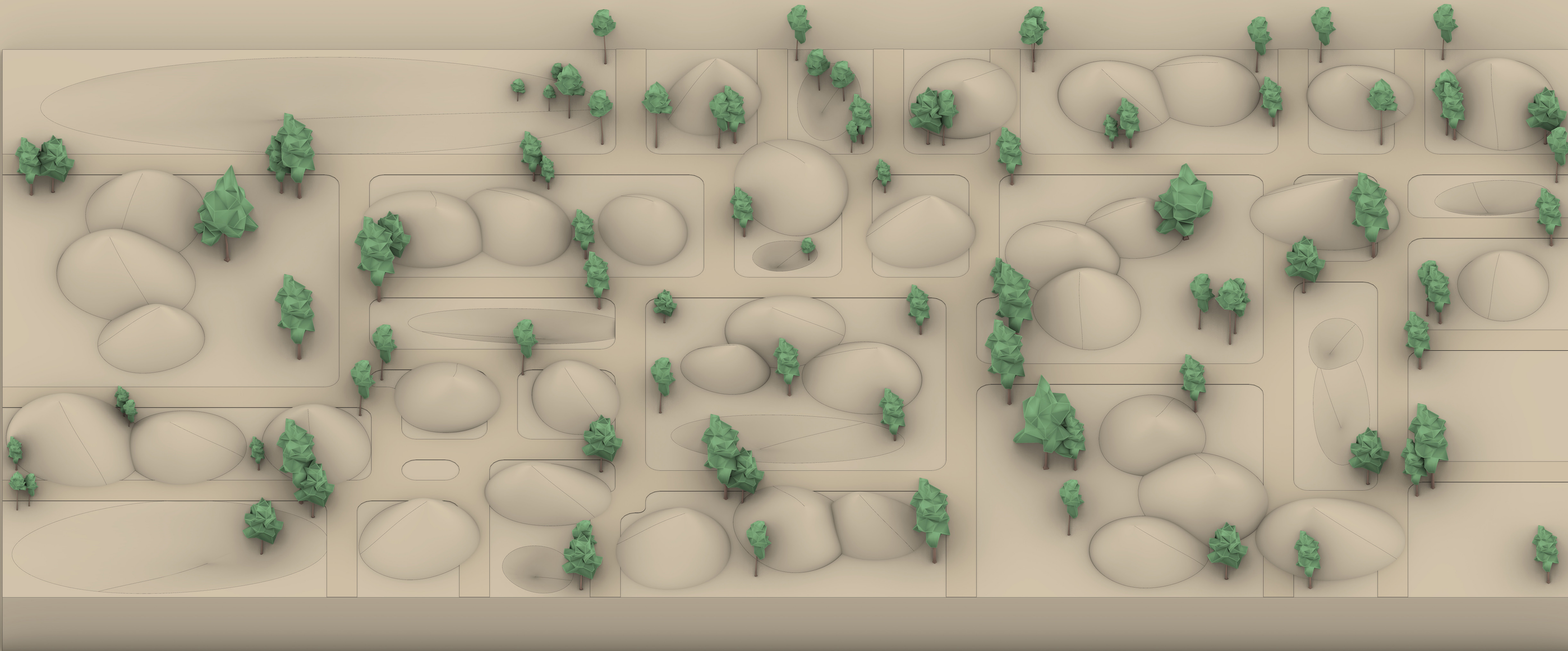
Construction Sequence



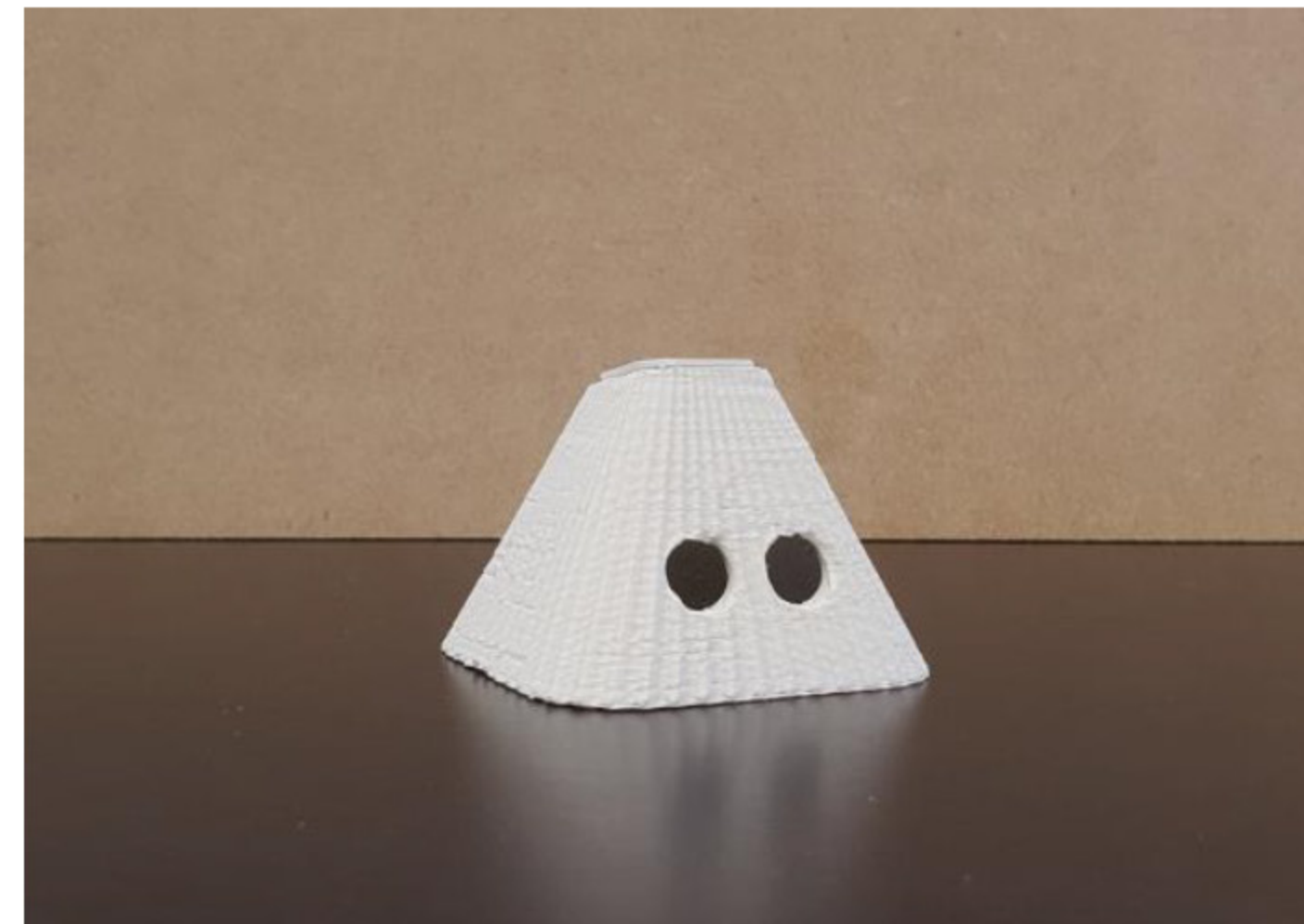
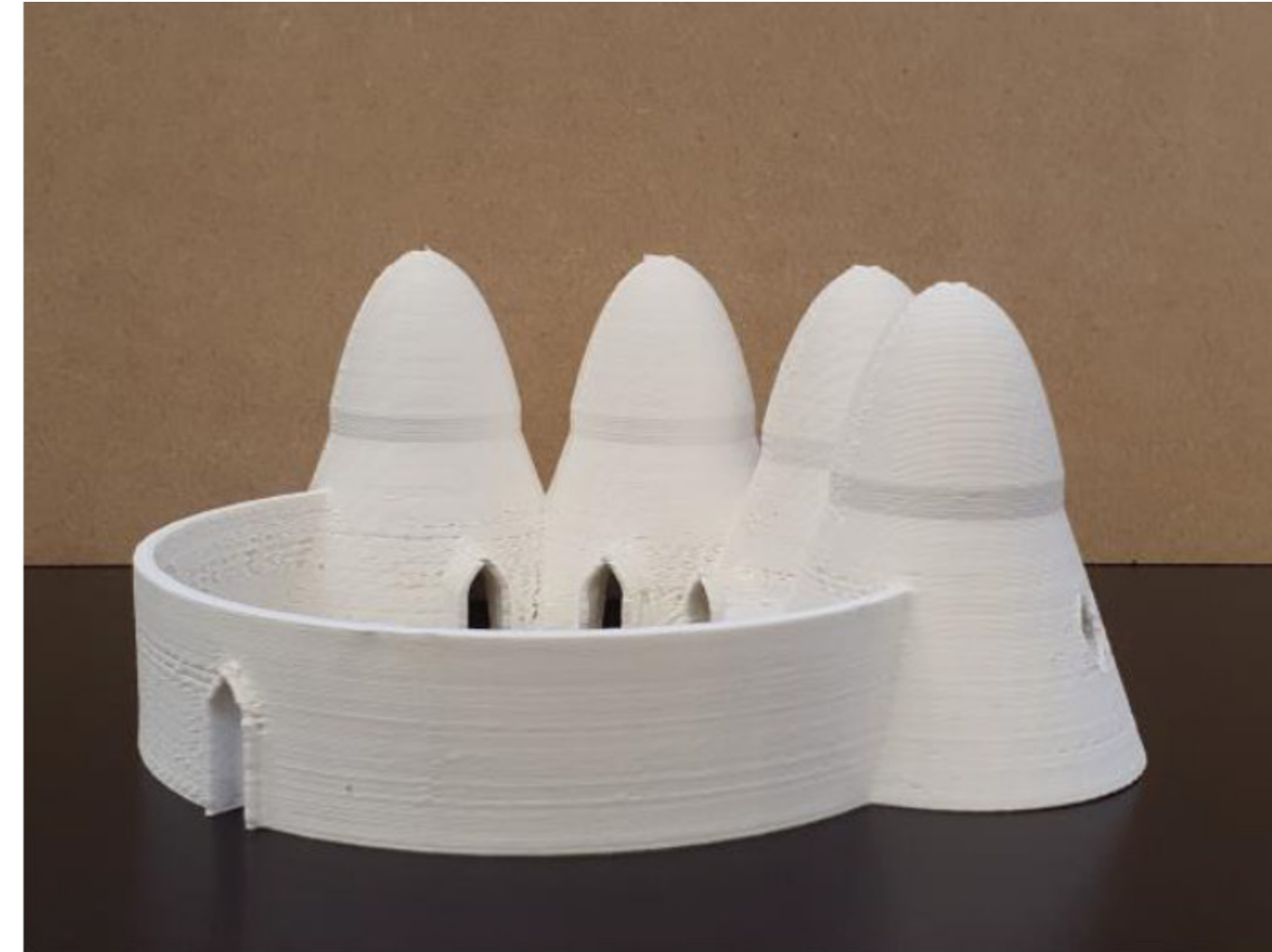
Construction Sequence



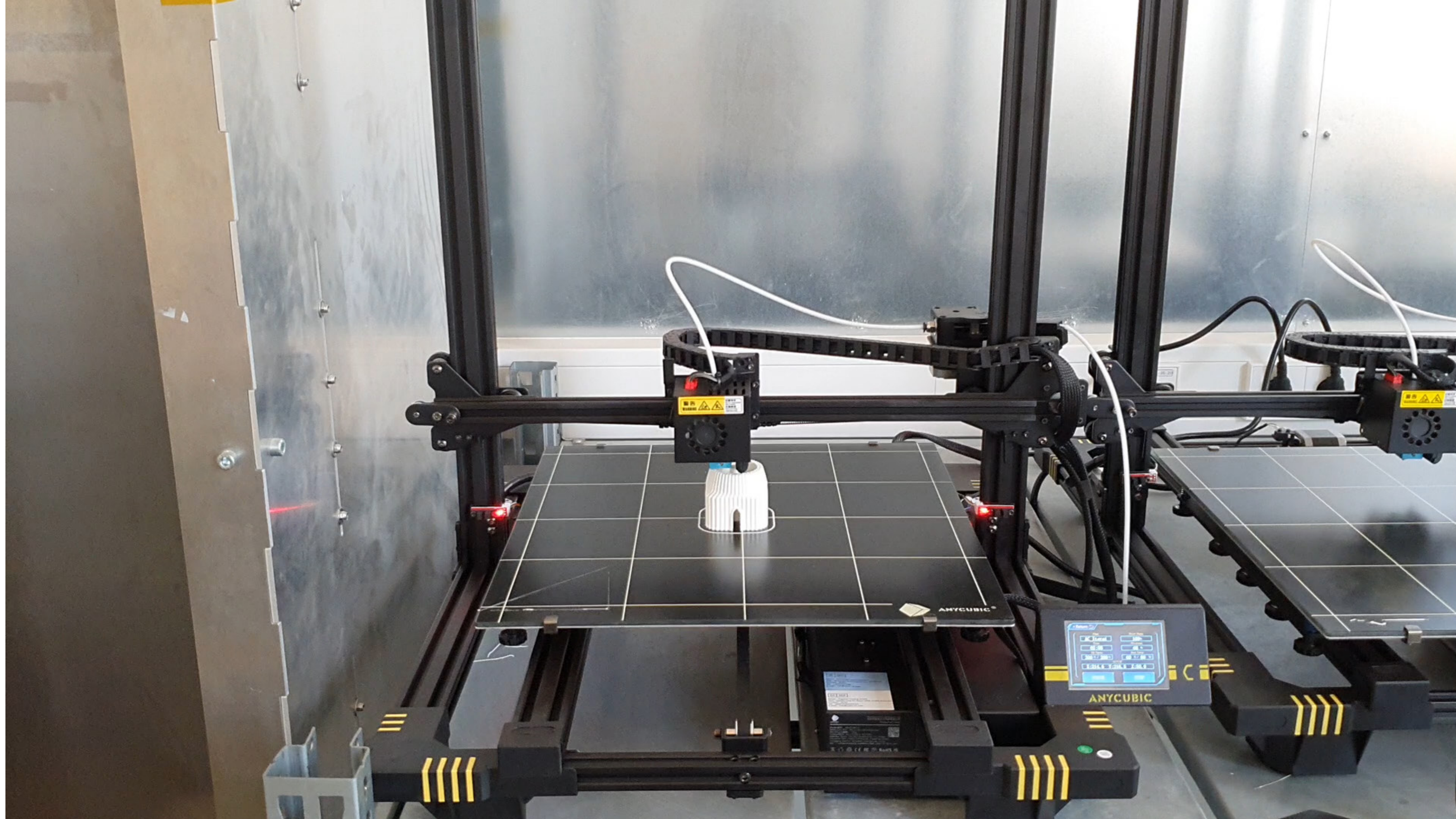
Construction Sequence



PLA Models



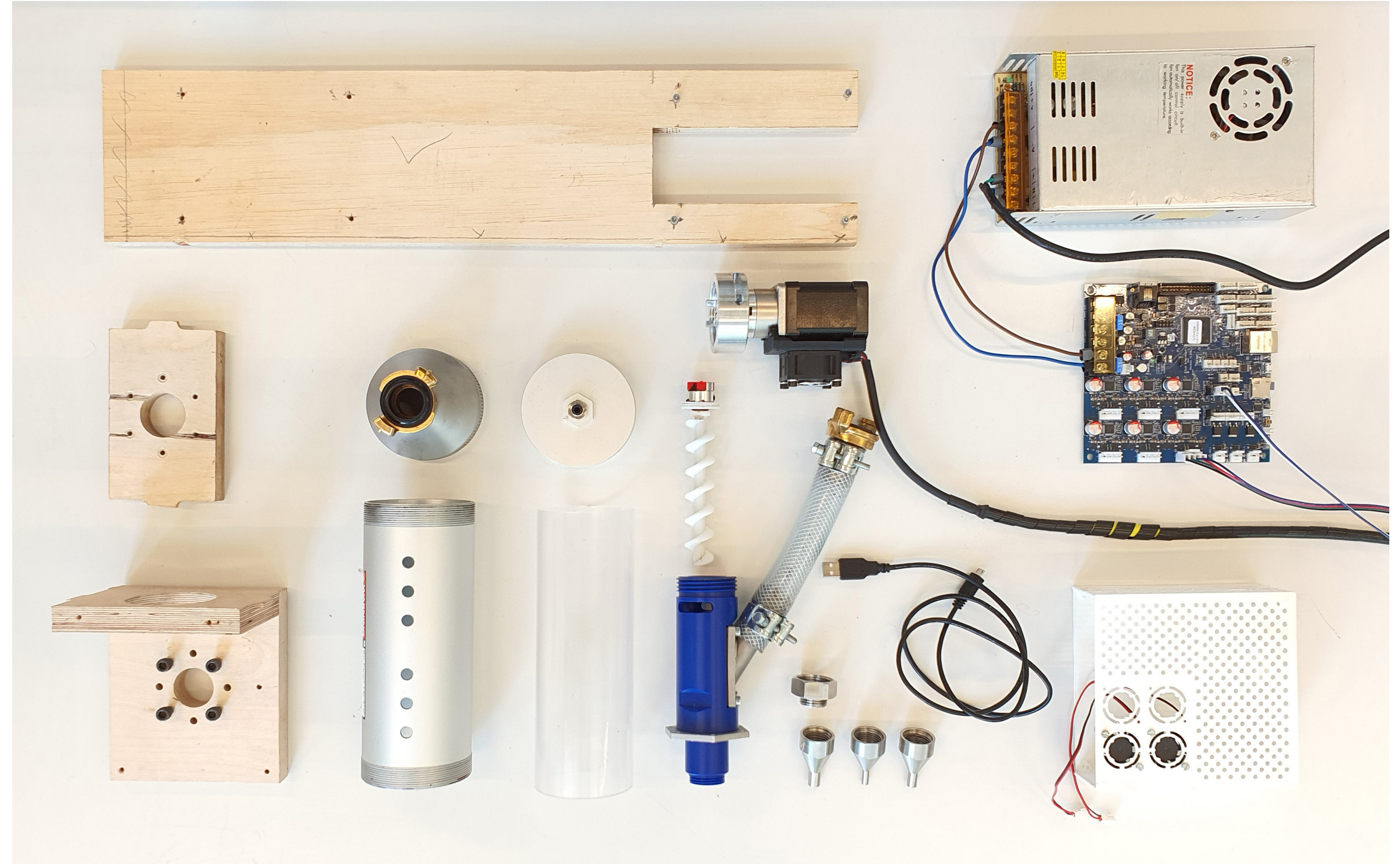
PLA Models



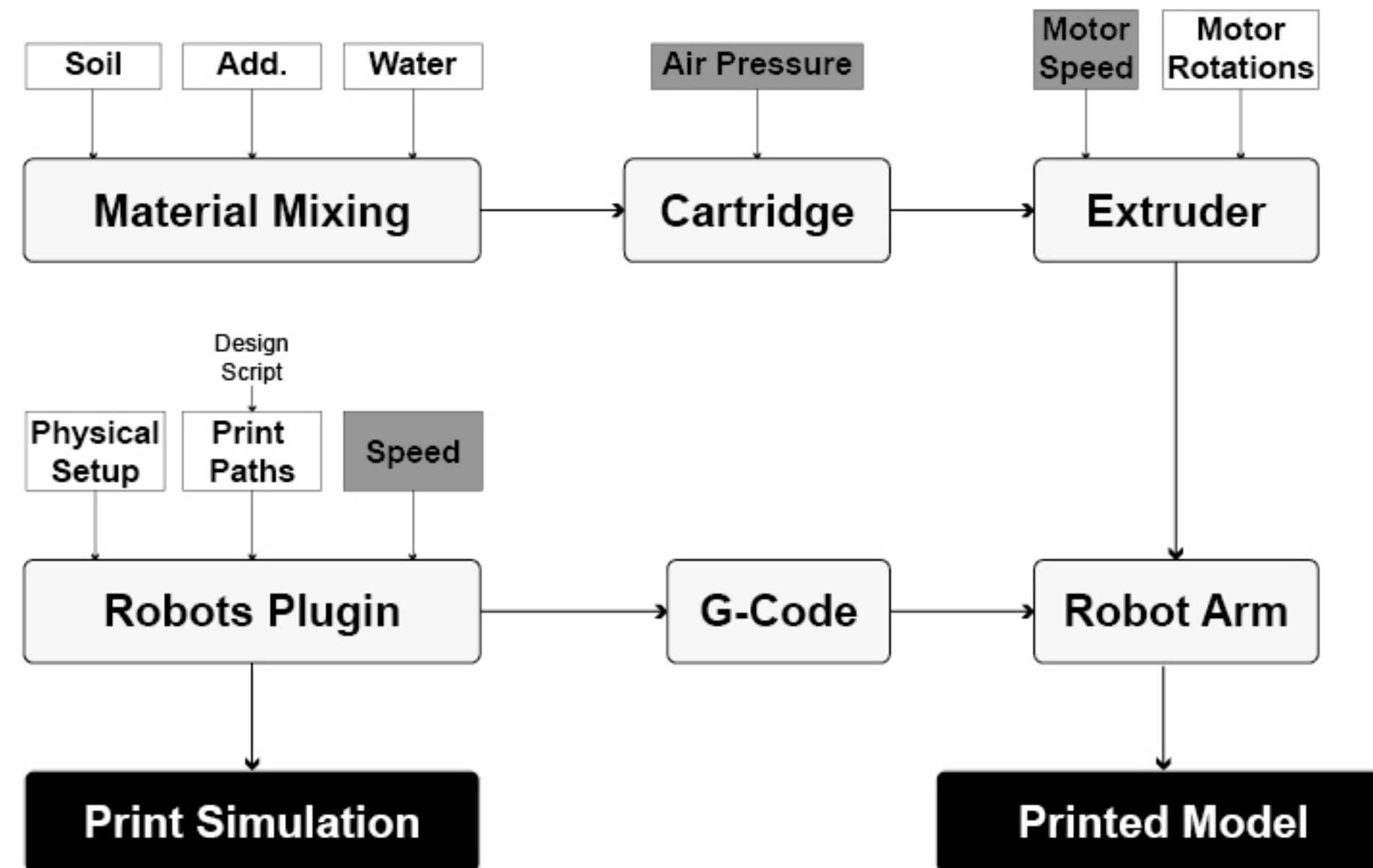
Earth Prototype



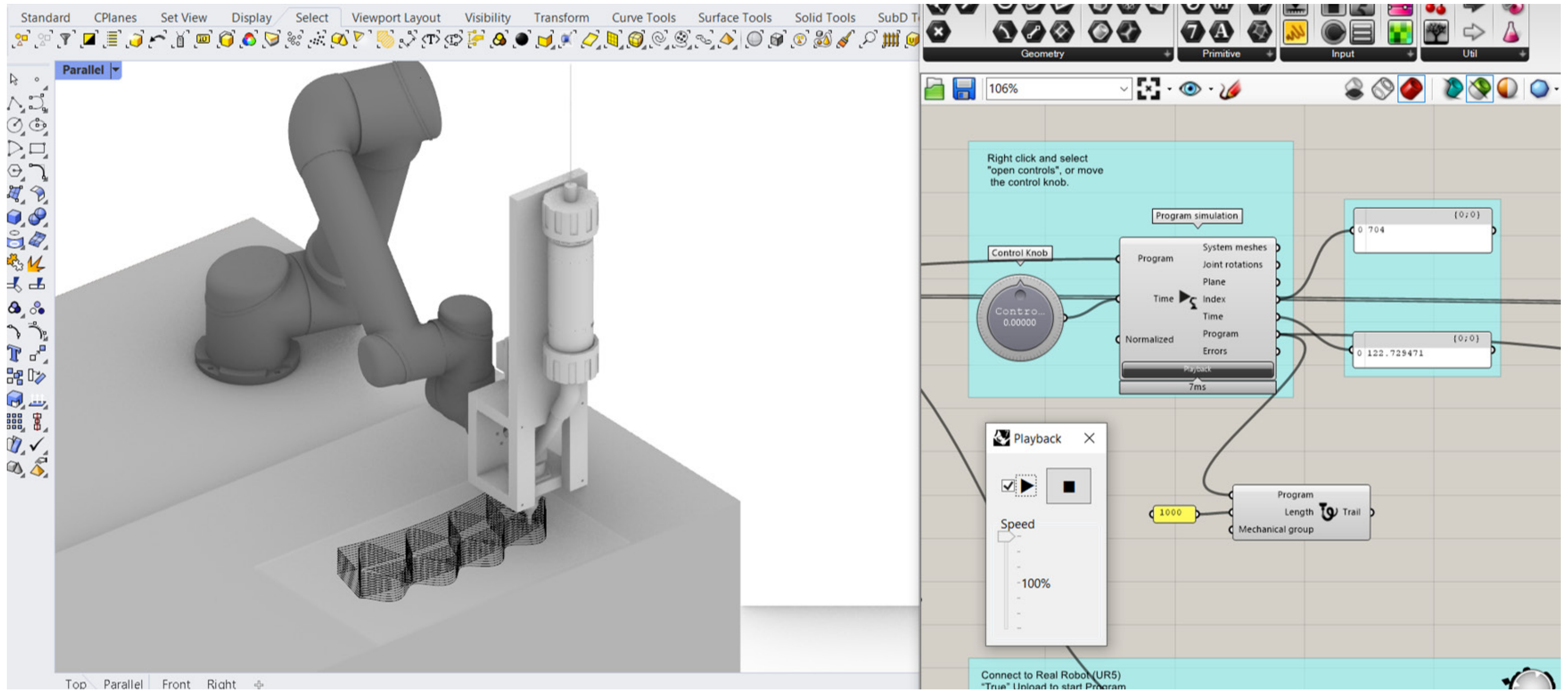
Tools



Printing Workflow



Printing Simulation



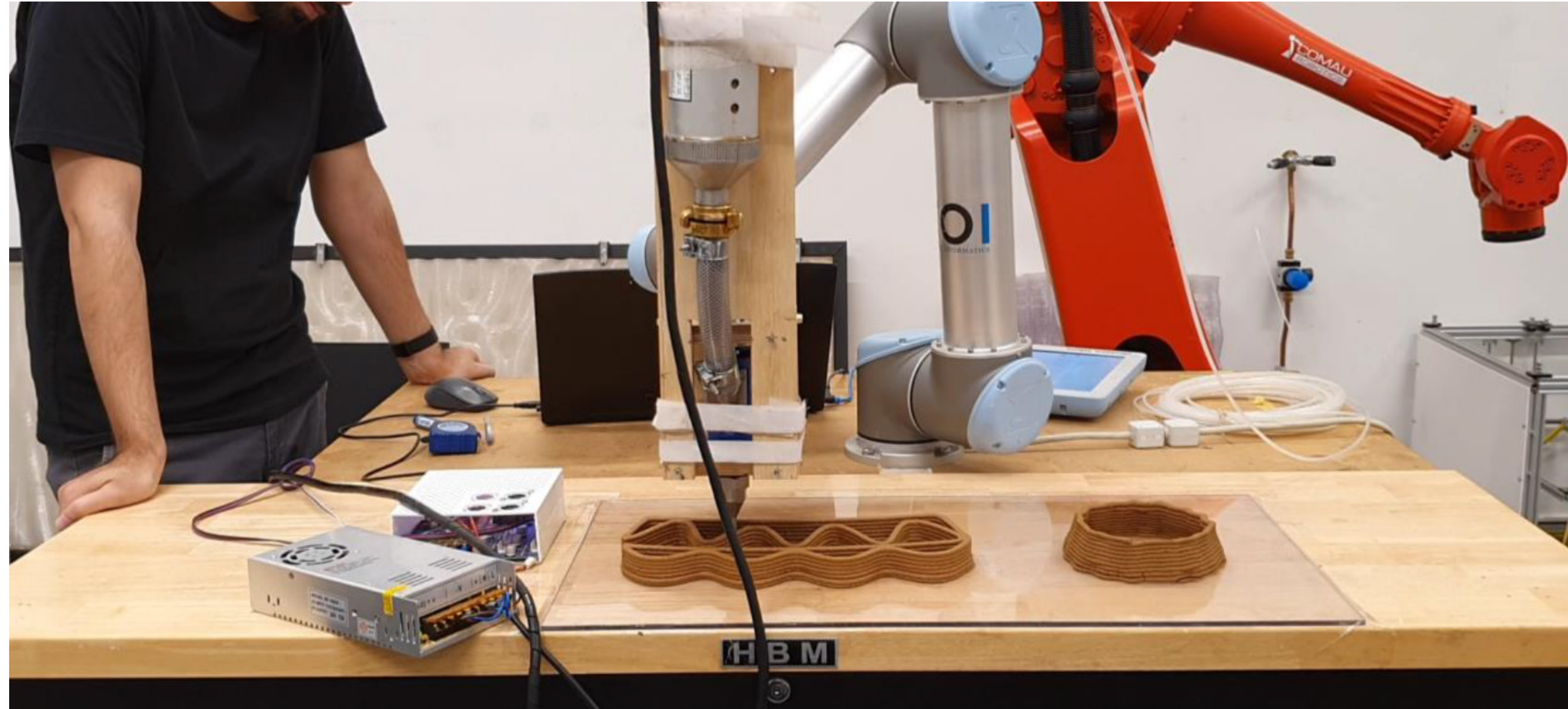
Extruder Calibration



3D Printed Earth Prototypes



3D Printed Earth Prototypes



Reflection

The background of the slide is a detailed architectural rendering of a village. It features numerous dwellings with conical, ribbed domes and small arched windows. The buildings are arranged in a grid-like pattern, with narrow streets and courtyards interspersed between them. The color palette is muted, consisting of earthy tones like beige, light brown, and soft green, which gives the scene a serene and traditional feel.

Scale

Material

Building Performance

Structural Optimization

Social Impact

Internal Layouts

Dwellings

The background is a detailed architectural rendering of a sustainable settlement. It features numerous conical huts with ribbed exteriors, arranged in clusters and around circular courtyards. The huts have small, arched or circular openings for entrances. The courtyards are landscaped with small trees and walkways. The entire scene is presented in a top-down perspective, rendered in a muted, earthy color palette of browns and greens. The overall impression is one of a well-planned, community-oriented living environment.

Thank you!

Questions?



Thank you!

Questions?