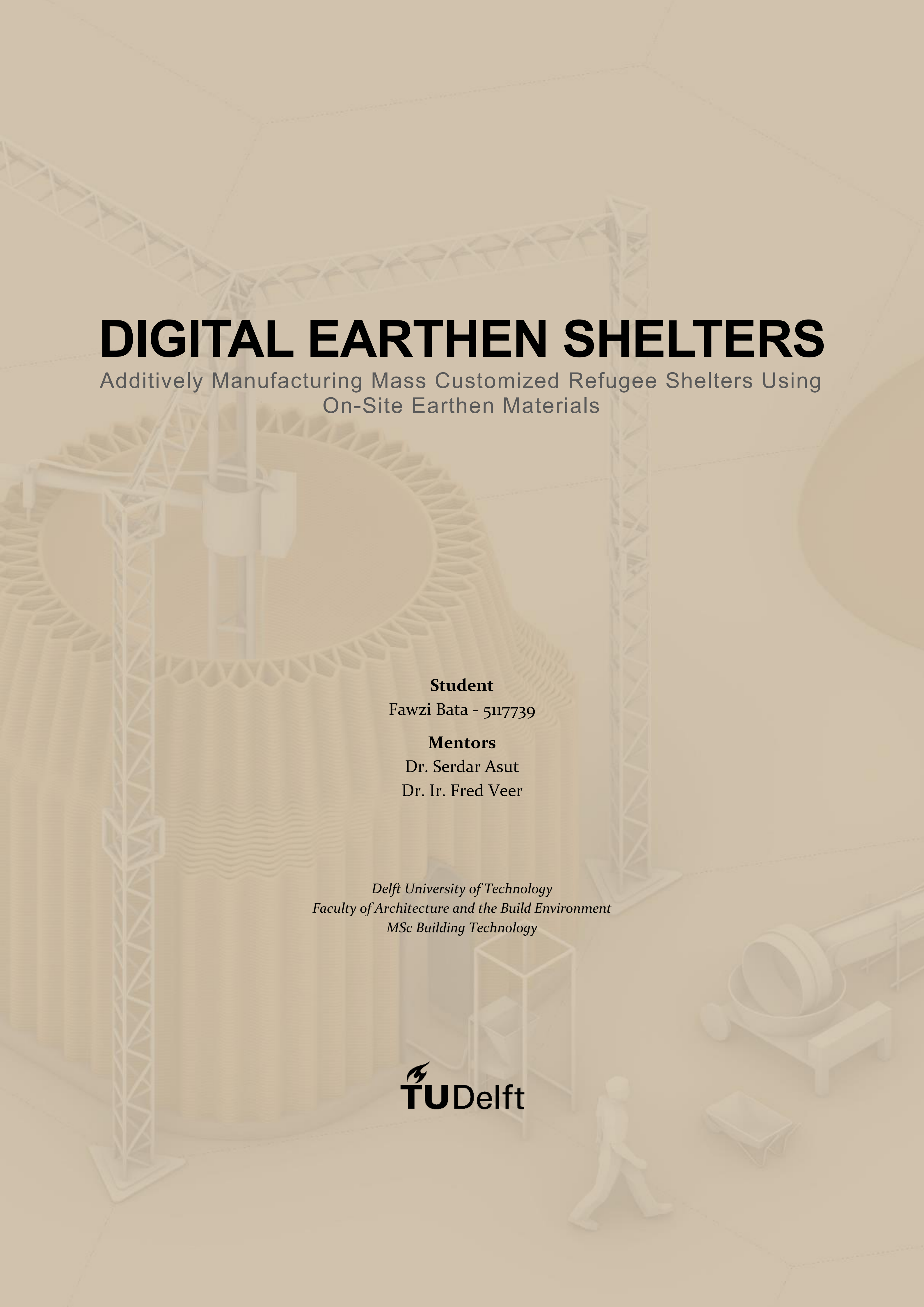

DIGITAL EARTHEN SHELTERS

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

Student
Fawzi Bata - 5117739

Mentors
Dr. Serdar Asut
Dr. Ir. Fred Veer

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TUDelft

Acknowledgements

I would like to express my sincere gratitude to my mentors Serdar Asut and Fred veer for their valuable input and guidance throughout this research, and in helping me overcome the many challenges. I would also like to thank the delegate examiner for his input and time. I’d like to also thank the LAMA lab staff and my colleagues who worked at the lab alongside me. Thank you to the Justus & Louise van Effen Foundation for providing me with the opportunity and support to study at TU Delft. To my circle of friends who pushed me through especially when the lockdown was in place.

To my family and parents for their continued love and care, for always being there in support of following my passions.

Contents

1 Introduction

1.1 Background

Continued humanitarian crises have caused the amount of forcibly displaced people to increase rapidly in recent years, having reached a record high upwards of 82 million individuals at the end of 2020, with numbers expected to grow even further in coming years (UNHCR, 2020). This increase in refugee numbers creates an urgent need for constructing adequate sheltering to house the displaced. Governments and international organizations attempt to accommodate the growing demands by subsidizing and mass producing temporary transitional shelters that do not always meet all the emerging needs of refugee families.

Many of these settlements are planned with a temporary use in mind, however more often than not, they end up growing and turning into more permanent parts of cities themselves. This phenomenon is exemplified in the case of Palestinian refugee camps in Jordan that were established in the mid-twentieth, most of which are still active to this day.

More recently and in the case of Syrian refugees, several camps were set up in Jordan as an emergency response to accommodate the displaced families, namely in the Zaatari camp in 2012 and Azraq camp in 2014, with Zaatari camp being the largest Syrian refugee camp globally. These camps have now existed for nearly a decade, which collides with the original intentions of them being temporary, and are gradually becoming more permanent. When refugees first arrive they are in need of immediate sheltering and assistance, as time goes by their needs change and evolve in order to adapt to a more long-term setting. At the current rate refugees are occupying their substandard shelters beyond the recommended lifespan resulting in housing that is largely inadequate (3RP, 2021).

Due to the rigid nature of the shelters provided to refugees, some families in the Zaatari camp for example, have been rearranging the units provided to them in order to accommodate their specific spatial needs. These self-made rearrangements are clearly shown to have evolved over time and are becoming more intricate, showing a need for adapting and evolving the one-size-fits-all structures provided by international agencies into more customized solutions corresponding to individual family needs.

Additive Manufacturing in construction is an emergent technology that has garnered the attention of many researchers and developers recently, with new developments being constantly made in the field of 3D printing buildings and building components. Researchers such as Akeila, Wong, and Kuok (2019), argue that 3D printing as a construction technique can be a valid alternative overcoming the limits and shortcomings of typical construction methods of refugee shelters being used currently, and can fulfil the requirements of adequate housing for refugees.

Earth presents itself as a construction material with various functional and environmental benefits for the construction of shelters. Moreover, earth has been widely used in buildings for thousands of years around the world and has demonstrated its ability to stand the test of time. Buildings made using earth are reusable, recyclable, and are inherently biodegradable allowing vegetation to grow back into them after use leaving no waste behind (Rael, 2009). Furthermore, earth is a material that is readily available on-site in many locations needing minimal transport compared to other materials, which in combination with its other properties enables building structures with very little embodied energy (Volhard, 2016).

Mass customization is inherent to the process of additive manufacturing where robots can produce customized designs in an iterative process and no two models have to be alike, which in combination with using earth found on site as a medium for printing, could make it a viable approach to constructing shelters that would meet individual refugee family needs. This research aims to investigate the possibilities of doing so.

1.2 Problem Statement

Main Problem Statement

Current refugee shelters are being made with a transitional temporary use in mind and in a manner that does not take individual family needs into account but rather have a one-size-fits-all design. The shelters are also subsidized by governments which in many cases do not have the resources required to supply anything but shelters that only provide immediate protection, and using materials that are transported into the site with minimal regard to circularity and longevity. This calls for a mass-customizable and circular dwelling that caters to individual refugee family needs. Many developments are being made regarding 3D printing structures with earth, however mass customizing these structures has not yet been explored in depth although it is inherent to additive manufacturing techniques.

Sub-Problem Statements

The composition of earth found on site varies by geographic location. A certain ratio of constituents is necessary in order for earth to be suitable for using as a construction material, meaning there should be a standardized method of mixing-in different soils to achieve the desired earth composition. Furthermore, in order for the earth to be used in a 3D-printing setup it needs to achieve a certain viscosity, strength, shrinkage ratio, etc., which can be done by mixing-in additives that would need to be tested and compared.

Shelter inhabitants come from a certain cultural background having preferences and needs for their living spaces that need to be understood. The rigid shelters provided to them do not always meet these needs, therefore an alternative customized solution is required. Their individual needs should be studied carefully and translated into spatial design components that can be put together as a library of parts that can be combined per each household’s different requirements.

3D printing earth on-site is a novel construction method with developments being constantly made. Along with finding a proper mixture of printing medium to be used, a printing workflow should be developed and simulated, along with finding the suitable assembly of hardware and robotics for printing. Quick deployment, feasibility, and efficiency are crucial aspects of this process.

1.3 Objectives

General Objective

The general objective of this research is to identify a method to design and construct mass-customized 3D printed shelters for refugee families catering to their longer-term needs, and by using earthen materials that are found on-site.

Sub Objectives

The main objective of this research is divided into three subcomponents of material, shelter design, and fabrication process as shown below.

Figure 1. Subcomponnents of Research Objectives

Material

- Investigate material properties of earth found on-site (earth samples from camp location)
- Experiment with Additives and optimize mixture for printability, strength, and water resistance
- Develop testing toolkit to be used on-site for different locations along with manual for mixture design

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 1:20 prototypes for iterations generated by design tool (PLA/Clay)

Fabrication Process

- Identify most suitable additive manufacturing process and machine
- Generate printing toolpaths and test with generated designs
- Produce 1:1 prototype for small part of example dwelling wall as a proof of concept using earth mixture

1.4 Research Questions

Main Research Question

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

Sub-Research Questions

The sub-research questions also correspond to the three sub-objectives of material, shelter design, and fabrication process as follows:

Material

- 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.?

Shelter Design

- How can shelter designs respond to the changing needs of refugee families?
- 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?

Fabrication Process

- Which printing methods and technologies 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?

1.5 Approach and Methodology

Methodology Diagram

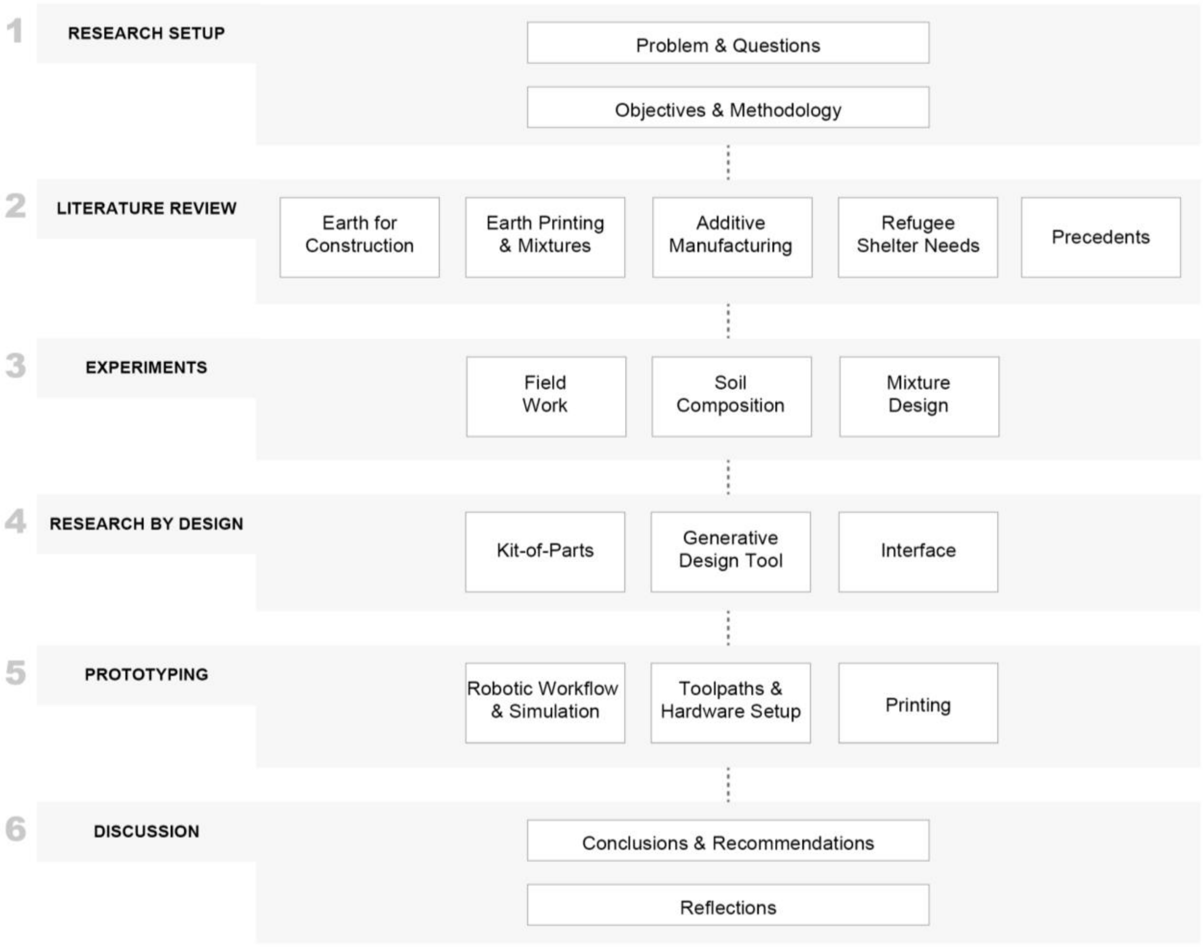


Figure 2. Methodology Diagram
Source: Author

Research Setup:

Some background and context research is done in order to identify the problem statements. Which is then followed by reaching research aims and objectives

Experiments:

Experiments will be done by replicating the earth composition collected from the chosen sites, and then testing different mixture possibilities. The experiments will be conducted to test for mixture printability.

Literature Review:

A literature review is required to investigate the material properties of earth as well as for additives to create a printable mixture. The literature review will also cover a state-of-the art analysis of current additive manufacturing techniques in construction as well as precedents in 3d printing using earth. It will also aid in understanding refugee needs in order to create mass-customized designs based on those needs.

Research by Design:

A design tool will be developed computationally for generating refugee shelter designs based on individual needs from a library of designs/ a kit-of-parts.

Prototyping:

In order to verify the printability, robotic simulations, and the robotic workflow design, prototyping using earth mixtures in a 1:1 scale will be explored. A smaller scale (around 1:20) of prototypes will be produced to test the iterations of dwelling designs produced by the generative design tool that will be developed.

Discussing Results:

The research will be concluded with the recommendations along with the results of the design tasks. The conclusion will also include answers to the posed research questions A reflection will be made on the process and limitations of the research as well.

1.6 Relevance

Societal Relevance

The social component is central to this research as it concerns the current state of refugee sheltering and livelihood. Refugee numbers are unfortunately rapidly increasing in recent years due to humanitarian crises globally with a need for adequate and less temporary sheltering solutions that meet their individual needs.

Scientific Relevance (Projected Innovation)

Additive manufacturing in the field of construction is an emerging technology with new developments being constantly made as we transition into a more digital workflow. Sustainability and circularity are also present in this research through additively manufacturing on-site earthen materials which are biodegradable, require minimal transport, and require minimal processing which results in constructions with minimal embodied energy. The process also employs advanced robotic fabrication techniques to achieve the envisioned structures.

1.7 Planning and Organization

Research Team

The research team consists of:

Student:

Fawzi Bata

Mentors:

Dr. Serdar Asut | *Architectural Engineering + Technology - Design Informatics*

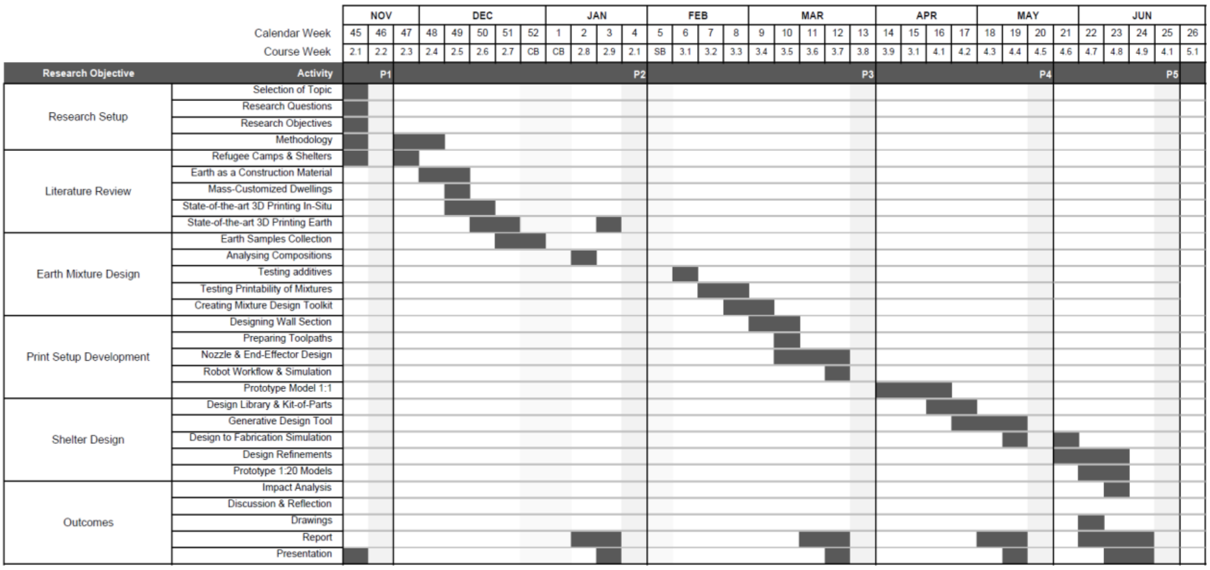
Dr. Ir. Fred Veer | *Architectural Engineering + Technology – Structural Design & Mechnics*

Delegate Examiner:

Ir. Robert Nottrot

Timeline (Work Plan)

The following table shows the stages of work planned per week for the duration of this thesis leading up to the final presentation and report.



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	Course Week	2.1	2.2	2.3	2.4	2.5	2.6	2.7	CB	CB	2.8	2.9	2.1	SB	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	3.1	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	4.1	5.1
Research Objective	Activity		P1										P2									P3							P4					P5	
Research Setup	Selection of Topic	■																																	
	Research Questions	■																																	
	Research Objectives	■																																	
	Methodology	■		■	■																														
Literature Review	Refugee Camps & Shelters	■		■																															
	Earth as a Construction Material				■	■																													
	Mass-Customized Dwellings					■																													
	State-of-the-art 3D Printing In-Situ					■	■																												
	State-of-the-art 3D Printing Earth						■	■				■																							
Earth Mixture Design	Earth Samples Collection							■	■																										
	Analysing Compositions										■																								
	Testing additives														■																				
	Testing Printability of Mixtures															■	■																		
	Creating Mixture Design Toolkit																■	■																	
Print Setup Development	Designing Wall Section																	■	■																
	Preparing Toolpaths																		■																
	Nozzle & End-Effector Design																		■	■	■														
	Robot Workflow & Simulation																				■														
	Prototype Model 1:1																						■	■	■										
Shelter Design	Design Library & Kit-of-Parts																								■	■									
	Generative Design Tool																									■	■	■							
	Design to Fabrication Simulation																											■		■					
	Design Refinements																													■	■	■			
	Prototype 1:20 Models																														■	■			
Outcomes	Impact Analysis																															■			
	Discussion & Reflection																																		
	Drawings																														■				
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	Presentation	■										■									■							■				■	■		

Table 1. Work Timeline
Source: Author

2 Literature Review

This chapter is concerned with reviewing the relevant literature in order to build a better theoretical understanding of the different components of the research as described in the methodology. The first part of the literature review dives into the material of earth in order to understand its potentials as a medium for 3D printing shelters. This is followed by reviewing the state-of-the-art of current additive manufacturing technologies and precedents in 3d printing with earth. And lastly, a section about the current state and needs of refugees and refugee camps in the chosen sites of Zaatari and Azraq.

2.1 Material

Earth has been used as a construction material for thousands of years, with nearly one third of the world's population living in houses made from earth today (Minke, 2012). The material chosen to construct the shelters is earth due to its many benefits and vast availability on site in most locations of the world, as well as its ability to be 3D printed. The following section reviews the properties of earth, its use in construction, its various benefits, challenges, the use of earth throughout history, and potential enhancing additives.

Properties of earth

Earth, also known as loam, is a product of eroded rock found in the earth's crust and is mainly made of clay, silt, sand, and sometimes aggregate with varying percentages of each component depending on the geographic location. The smallest particle size of under 0.002 mm is called clay, followed by silt being between 0.002 and 0.06 mm, sand being between 0.06 and 2 mm, with any particles larger than sand being called gravels and stones (Minke, 2012).

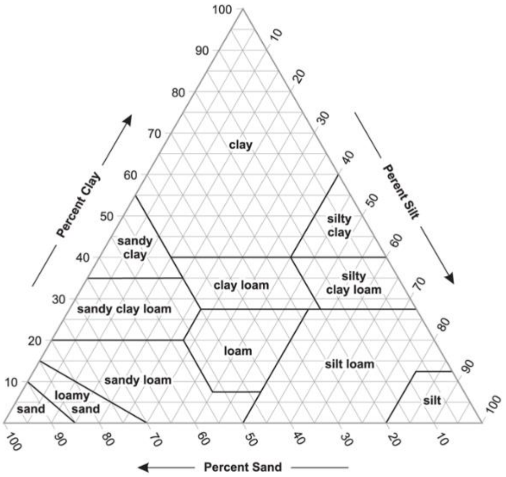


Figure 3Triangle Graph for Classifying Soil Based on Percentages of Clay, Silt, and Sand
Source: (USDA, 2017)

Earth can grouped into textural classifications based on the ratios of sand, silt, and clay present in the soil (USDA, 2017). Clay acts as a binder in the soil, and depending on which component is dominant in the loam, we can call it clayey, sandy, or silty. Additionally, when extracting soil from a depth of under 40cm, it usually contains organic matter from plants or humus (Minke, 2012). For the purpose of using earth in building materials, having organic matter is not desirable unless certain conditions are met and where the matter is dry as in the case of added straw for example.

In order to activate the binding forces in the earth, water is to be added. The water acts in three ways; water of crystallization (chemically bound), absorbed water (electrically bound), and capillarity water (absorbed). Wetting dry soil causes it to swell and increases the distances between the lamellas which in turn increases its plasticity, and when this water dries up it causes the distance between the lamellas to reduce and arranges them in a parallel pattern increasing the compressive and tensile strengths of the clay (Minke, 2012).

Earth in Construction

With earth being a material that is available almost everywhere, it has been used in construction in many different ways for centuries, and depending on the composition of the soil it can be used for different methods of building. These different building methods using earth are summarized in the CRATerre wheel which can help understand the possibilities of using earth for construction, and it is split in to three main categories; brickwork, structure, and monolithic building (Giuffrida, Caponetto, & Cuomo, 2019).

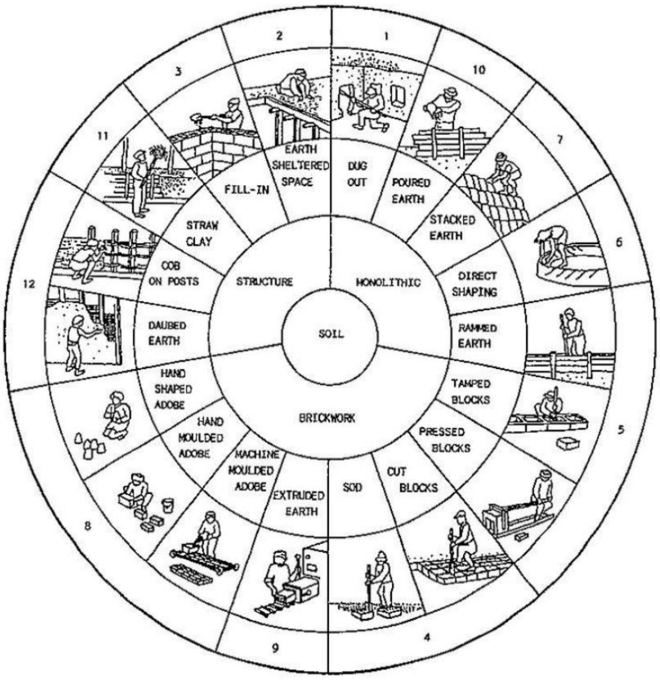


Figure 4 The Different Techniques of Earth Construction
Source: (Giuffrida, Caponetto, & Cuomo, 2019)

For the 3D printing of earth, a high clay content of 25-40% as in rammed earth and adobe constructions allows for the material to be more plastic and extrudable. However the higher clay content can lead to higher shrinking and cracking rates, so the mixture should be as dry as possible without cause too much strain on the printing hardware (Curth, Darweesh, Arja, & Rael, 2020).

Historic Precedents

Mud has been used in constructing buildings for centuries with many historic examples of earthen architecture. A few of these examples that relate to this research are highlighted here due to their relevance in terms of cultural background, or being situated in similar hot and arid regions as in the chosen sites of Zaatari and Azraq refugee camps, or forms that could be referenced for using the same principles as extruding the material through additive manufacturing.

Earthen architecture is deeply rooted in Syrian culture, and this is exemplified in the corbelled earthen domes villages across Syria (Mecca & Dipasquale, 2009). The dome structures are made by stacking sun-dried without the need for formwork in order to achieve the final shape, and in order to combat weather conditions and water damage, the structures are made resistant by applying a coat of plastering that contains lime and foundations made of stone (Kassatly, 2019). The transition of form from rectilinear at the bottom walls into dome for the roof is done in order to maximize the amount of usable space, where it is also more convenient to organize furniture in a square shaped dwelling than in a circular one.

Figure 5. Drawings and Image of Corbelled Domes Villages in Syria
Source: (Mecca & Dipasquale, 2009)

The Stranglehm technique is a way of constructing earth buildings through the direct forming of extruded wet earth mixture that was developed at the Building Research Institute in 1982 and can be used for making walls, arches, and domes (Minke, 2012). The process uses a machine that made to extrude the loam mixture in sections 2m long, which are then stacked by hand to achieve the wall forms in parts that are 3-5 layers high per day allowing for the layers to dry and avoiding deformation before stacking the following layers. This method can be seen as a precedent to the 3D printing of earth constructions that have been recently gaining popularity, as it employs similar methods of extrusion to form the material albeit using manual labor to stack the layers instead of a robot.

Figure 6. the Stranglehm Technique
Source: (Minke, 2012)

Nubian vaults and domes are another method of constructing earthen buildings that has been used in Egypt for centuries using adobe requiring no formwork (Minke, 2012). Vaults are built using reclining arches that are stacked at an angle in order to achieve the final form. The form of these arches and domes should be catenary in order to avoid tensile stresses (Minke, 2012). This method is labor intensive as it requires the forming of special wedges and the laying of small pieces of adobe, it is nevertheless an important historical precedent to many developments that followed.

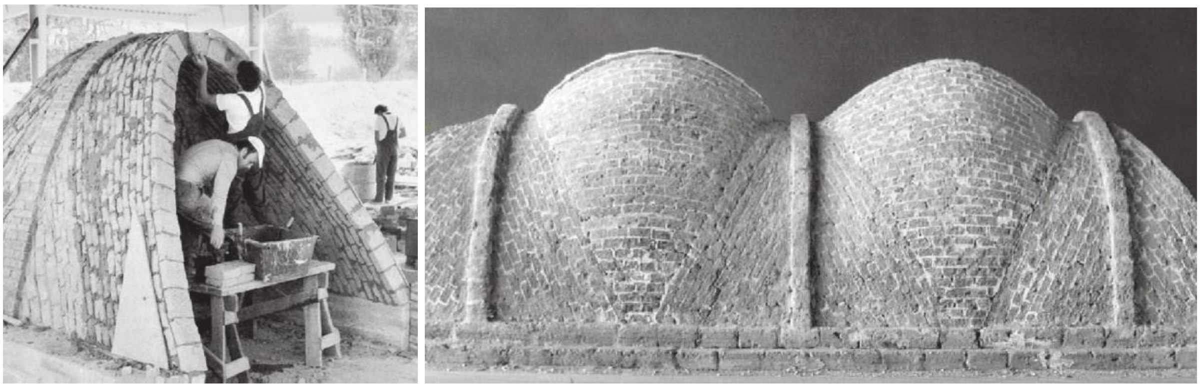


Figure 7. Nubian Vaults and Domes
Source: (Minke, 2012)

Benefits and Circularity

With the construction industry currently consuming up to 40% of the world's total emissions and being the largest consumer of raw materials, a return to more circular approaches such as building with earth is necessary (San Fratello & Rael, 2020).

Minke (2012) states that earth is inherently biodegradable and is therefore infinitely recyclable, making a material with no waste that causes no harm to the environment. Furthermore, earth is found almost everywhere meaning there is no need to transport it for use as a building material, where the soil dug for creating the foundations can itself be used to build the structure.

Minimal processing is required to transform earth into a building material and can be done with minimal natural additives This in turn leads to buildings made with earth having minimal embodied energy and causing no pollution. Walls made of earth store heat and act as a passive measure to regulate the indoor climate in areas with high diurnal temperature differences through its high thermal mass properties. Earth construction is also able to absorb and desorb humidity faster than any other construction material allowing it to efficiently balance indoor air humidity.

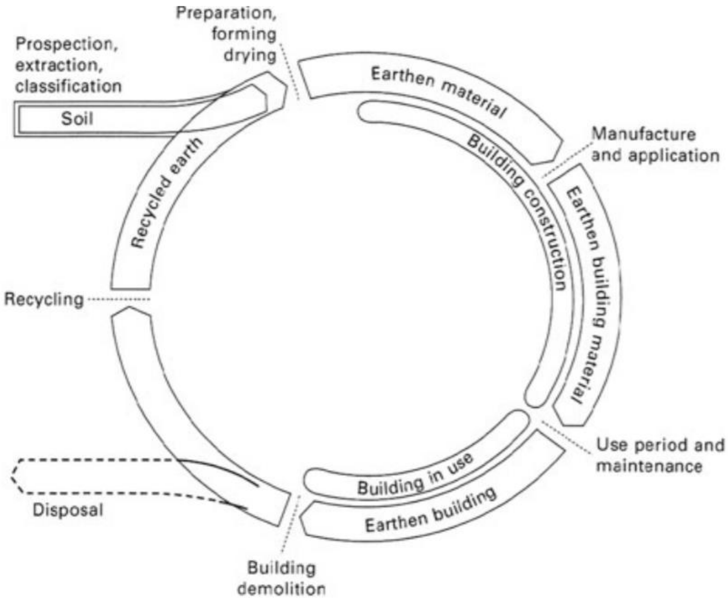


Figure 8. Life Cycle of Earth as a Construction Material
Source: (Schroeder, 2016)

Challenges

Although building with earth has many benefits, Minke (2012) states that there are also some challenges facing the construction of buildings with earthen materials. The main challenge being that raw earth is not resistant to weather conditions and must be protected against rainfall. This challenge can however be overcome through incorporating roof overhangs, adding water resistance surface coatings, or through the use of additives to stabilize against water erosion.

Another challenge is that earth mixtures shrink when drying which can lead to undesirable cracking. Adding water is required in order to shape the material and for the mixture to activate its binding strength. The linear shrinkage ratio can be anywhere between 0.3% - 12% depending on the water content of the mixture. This shrinkage can be minimized through using additives or through optimizing the water and clay content as well as the grain distribution (Minke, 2012).

Earth not being a standardized building material is a further challenge, where its characteristics differ per location. In order to alter these characteristics, it is necessary to understand the specific composition of the soil and then adjust its composition where required through the use of additives (Minke, 2012).

Additives

Raw earth on its own does not meet all the requirements of being used as a construction material, therefore a mixture needs to be designed with certain additives incorporated in order to improve the extrudability, strength, water resistance, shrinkage resistance, crack resistance, stability, and overall durability of the resulting structure. As per Schroeder (2016) there are two categories for materials that are added to the mixture of earth in order to improve the mixture's characteristics; **Aggregates** and **Additives**.

Aggregates are the materials that improve the physical properties of the earth building material. These properties include increasing tensile strength, decreasing erosion, and decreasing shrinkage when drying. The figure below shows the different types of aggregates which can be either from a mineral or organic source (Schroeder, 2016).

Additives are the materials that improve the chemical properties of the clay in the earth building material, which include reducing swelling and shrinkage, and increasing compressive strength (Schroeder, 2016).

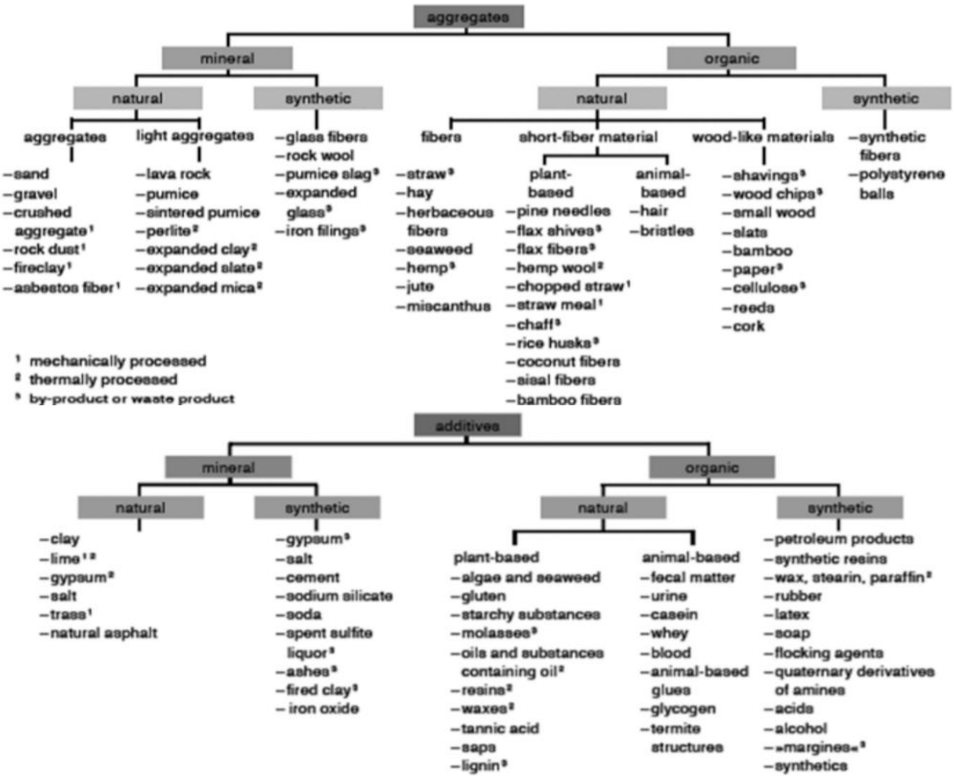


Figure 9. Aggregates and Additive for Earth Building Materials
Source: (Schroeder, 2016)

In order for the constructed shelters to be ideally biodegradable and fully recyclable, the additives and aggregates incorporated in the earth mixture should be completely natural. Therefore, for the purpose of this research those will be the materials investigated further.

2.2 3D Printing Earth

3D printing is becoming more popular with rapid advances being made in the construction industry recently, and when paired with the use of earth as the printing medium it can take advantage of the many demonstrated benefits of earth. This section studies a few recent examples of 3D printing with earth and the robotics used in each. The figure below summarizes the different aspects of 3D printing buildings on-site using earthen materials (Bajpayee, et al., 2020).

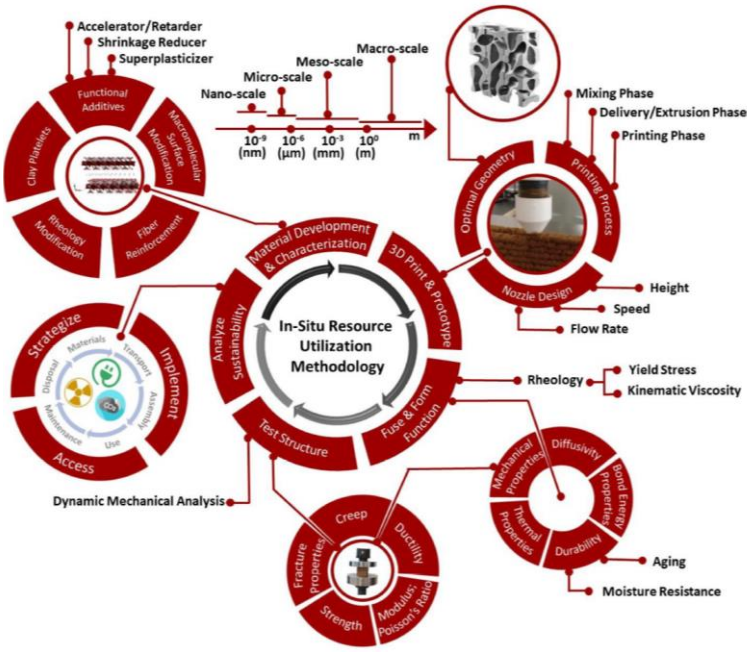


Figure 10. Schematic representation of a proposed process flow for in situ resource utilization
Source: (Bajpayee, et al., 2020)

Precedents

Tecla – WASP

The Tecla house is 3D printed house designed by Mario Cucinella Architects, and engineered and constructed by Wasp. It is printed using WASP's 'Crane' 3D printer and is their first project that was printed using two print heads simultaneously. The WASP crane system is a modular 3D printing system that allows for a printing area of 50sqm per printer head and can be used to build in hexagonal modules.

Figure 11. Images of the Tecla Project by WASP During Construction and Completed Building
Source: (WASP, 2021)

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: -

Gaia – WASP

Gaia is another 3D printed house project by WASP using natural waste materials and local soil. Rice husk is used in large percentages to increase the thermal insulation of the walls. The walls are smoothed and coated with linseed oil to increase water resistance.

Figure 12. Gaia 3D Printed House by WASP During Construction and After Completion
Source: (WASP, 2018)

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 m^2

Mud Frontiers

Mud frontiers is a project by Ronald Rael and Virginia San Fratello aiming to explore the possibilities of printing soils directly from the work site. The SCARA 3D printer was developed for this project and is relatively inexpensive compared to other earth printing robots requiring only 1-2 people to install and operate it. Custom software ‘Potterware’ was also develope to have a simple web interface and to generate the forms and print layers.

Figure 13. Images of structures built throught the Mud Frontiers Project
Source: (San Fratello & Rael , 2020)

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 m^2

IAAC OTF

The Institute for Advanced Architecture has a post-graduate program relating to 3D printing clay and earth. For their projects they typically collaborate with WASP. For one of their projects they created highly performative 3D printed digital adobe bricks.

Figure 14. Adobe Project by IAAC and Dome Clay Printing by IAAC
Source: (IAAC OTF, 2018)

Marsha – AI Spacefactory

Marsha was designed as a part of NASA’s Martian Habitat competition, and was printed in only 30 hours with minimal human intervention using an industrial robot. Following the competition, Tera was also developed by the same company as a habitat on earth based on the same principles Marsha was designed with. The materials used take advantage of local soils along with biodegradable plant based additives.

Figure 15. Martia and Tera 3D printed structures by AI Spacefactory
Source: (AI Spacefactory, 2020)

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: -

2.3 Refugee Shelters & Needs

Syrian Crisis

Political unrest in Syria began on 15 March 2011 as part of the 2011 Arab Spring protests, which grew out of discontent with the Syrian government. Now in its 11th year, the ongoing armed conflict has killed over 600,000 civilians, forced around 6.8 million Syrians to flee the country as asylum-seekers, and displaced another 6.7 million within Syria (Syrian Observatory for Human Rights, 2022), (World Vision, 2021).

As of March 2021, the number of registered Syrian refugees in Jordan was more than 672,000 refugees, but the actual number is estimated to be around 1.3 million when those not registered are taken into account (ACAPS, 2021).

Jordan hosts 5 Syrian refugee camps, 3 of which are official. For this research, the author will look into Zaatari and Azraq refugee camps, as they are the largest and most populated.

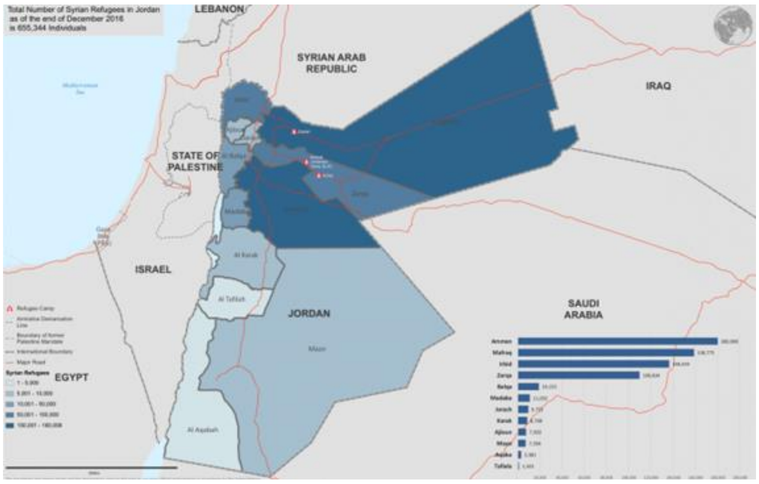


Figure 16. Map showing the distribution of Syrian refugees in Jordan with the permanent 3 camps in the north. The Majority of refugees are undocumented and reside in urban areas and central Jordanian cities. Source: UNHCR

Zaatari Refugee Camp

Al Zaatari Refugee Camp is located in Mafraq Governorate and is the largest Syrian refugee camp in the world and the fourth largest city in Jordan. The camp is funded by the United Nations, partner organizations, and the Jordanian government (Affordable Housing Institute, 2014).

First opened in 2012 as an emergency response to the surge of refugees entering the Kingdom, Al Zaatari camp quickly transformed from an empty desert to a makeshift home for almost 150,000 refugees at its peak, over half of whom are children.

The formal arrangement of the standardized caravans did not suit the refugees' way of life, so in order to meet their needs, they'd adapted their living units by taking apart vacant units and extending their own, buying and selling parts among one another, rearranging the row layout to form U-shaped clusters for extended families, and overriding the formal grid of streets and decentralized services to establish a lively market dubbed the “Champs-Elysées”. Despite the strict prevention of development of any infrastructure or construction (in order to restrict the thought of permanence), residents of Al Zaatari camp have appropriated this plot in the desert to make it their home.

Figure 17. Azraq Camp (left) and Zaatar Camp (right)
Source: US Department of State (left) NRC (right)

Azraq Refugee Camp

A confined area in the vast Jordanian desert, Al Azraq camp appears like an added layer above the sloped terrain. The camp is composed of multiple “villages”, which act as independent, decentralized satellite clusters lacking a defined central body. It is separated from the surrounding urban fabric by a vast desert which stretches 20 kilometers West of the city of Azraq and 90 kilometers from the Jordan–Syria border.

The 15 km2 camp has the capacity to host 130,000 refugees, but currently houses around 37,000. Out of the almost 35,000 available shelter units only 8,700 units are inhabited in 4 out of the 6 villages, while the rest remain vacant.

First opened in 2014, Al Azraq refugee camp is relatively young, which is reflected by the enduring rigidity of its urban form. As a temporary settlement this may be only the beginning of its evolution, as observed through other cases of refugee camps in Jordan which transitioned from temporary shelters to permanent dwellings as time went on, softening the harsh planned grid through overlapping their daily interactions, and slowly formed the “informality” which responded to their needs at the time.

Current State

“Slum” is a word authorities shy away from when referring to refugee camps, although it perfectly describes the current state of Al Zaatari camp, and forecasts a similar future for Al Azraq camp.

At the beginning of their establishment, refugees protested against the inhumane living conditions including lack of food, water, electricity and proper sanitation facilities (Affordable

Housing Institute, 2014). Although their needs were documented and reported, authorities did very little to respond, arguing the case of the settlement's temporality.

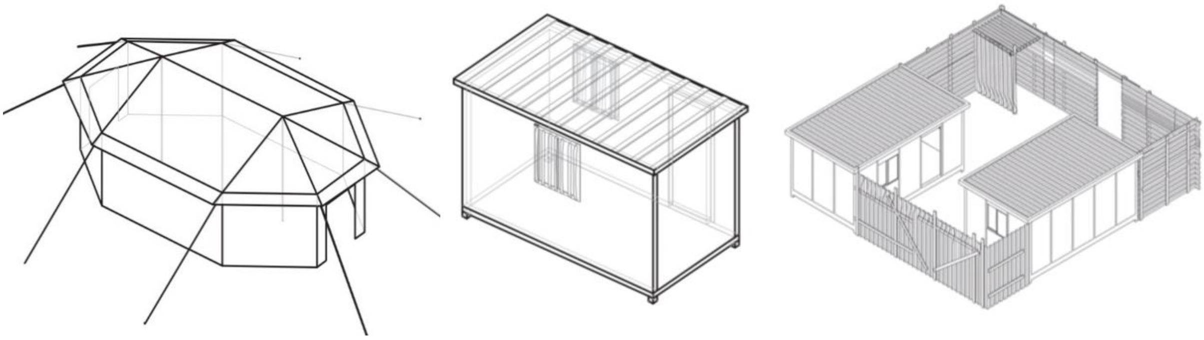


Figure 18 Current Shelters in Zaatari, Tents (left) Caravans (center), and Multi-Caravan Clusters (right)
Source: (Slater, 2014) (left and center) (Madi, 2017) (right)

Shelters transitioned from tents at the early stages of the emergency to caravans, neither of which meet the inhabitants' needs for privacy and provide a decent standard of living. This has forced the refugees to resort to stealing, selling, taking apart and updating their units themselves, changing the overall layout in order to resemble something they could inhabit.

Currently, Al Zaatari camp is closer to a slum status than Al Azraq camp. It could be argued, however, that due to the smaller number of inhabitants in the latter, authorities could control and prevent the "slumification" from occurring. Despite the refugees' attempts to improve their shelters and adapt them to their needs, they still suffer a lack of basic amenities and services, and an overall decline in their quality of life which remains unresolved (Affordable Housing Institute, 2014).

Adequate Sheltering Standards

According to the UNHCR emergency handbook, a shelter is defined as a "habitable covered living space providing a secure and healthy living environment with privacy and dignity" (UNHCR, 2018).

The handbook also states that the best solutions for emergency shelters require "using the same locally available, sustainably sourced materials and construction methods as would be normally used by the refugees themselves or the local hosting population". This is not the case in the refugee camps in question, as the shelters are usually shipped from other countries (KSA donated 24,000 units for example) (Affordable Housing Institute, 2014), they are always prefabricated, and do not take into consideration the context in terms of climate (hot arid desert with extremely high temperatures and freezing winters) or culture (privacy and community needs), while disregarding the building traditions and skills of local labor and the abundance of on-site materials for construction.

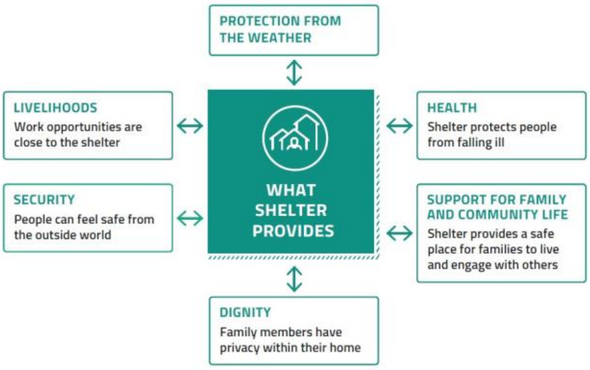


Figure 19. Functions of Appropriate Emergency Shelters
Source: (Sphere Association, 2018)

It is also worth mentioning that the handbook states that wherever possible, persons of concern should be empowered to build their own shelters, with the necessary organizational and material support. This will help to ensure that the shelter will meet their particular needs, promote a sense of ownership and self-reliance, and reduce costs and construction time considerably. This is definitely not taken into consideration, as refugees in Al Azraq and Zaatari camps have no control over the design and construction of their own units, and are heavily penalized should they attempt to alter it.

The minimum standards for floor space of a shelter unit (in tropical or warm climates) as cited in the handbook are a minimum 3.5m2 covered living space per person, excluding cooking facilities or kitchen (it is assumed that cooking will take place outside), with a minimum height of 2m at the highest point (UNHCR, 2018). Needless to say that the standard caravans provided for refugees barely meet the minimum (area of standard T-shelter prototype is 24m2).

Permanent Impermanence

Refugee camps are deployed rapidly as an emergency response to unprecedented events, from natural disasters to political instability and warfare. Using the fastest and cheapest resources, such settlements are not designed with permanence in mind, but rather to perpetuate the notion of temporary residence until the situation pre-emergency is restored.

11 years into the Syrian conflict, temporary shelters have become a home to most, considering that over 80% of the registered asylum seekers who have entered Jordan since 2011 have not returned (UNHCR, 2020), not to mention the unregistered refugees, who already reside in main cities and urban centers around the country.

Strict restrictions of construction and development of existing poor infrastructure are the main methods by which authorities establish impermanence. No road should be paved or tree planted as residents remain in a state of limbo. Aburamadan,Trillo and Makore (2020) discuss the reflections of the social fabric, habits and organization of the refugees' community through the spatial configuration of the Al Zaatari camp as it gradually transitions into more than an ephemeral city (Aburamadan, Trillo, & Makore, 2020).

The socio-spatial schema that makes up the foundation of everyday places within "permanent" cities is traceable and evident in the make-up of refugee camps, Al Zaatari being the most prominent case in that regard. As people continue to occupy and inhabit the environment and proceed to perform uninterrupted acts of daily life, questions are raised regarding the temporality of established spaces and their suitability to meet the evolving needs and demands of a permanent population.

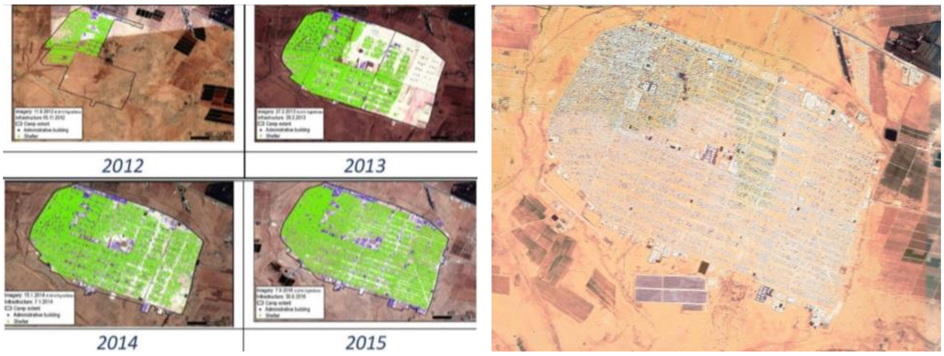


Figure 20. Expansion of the Zaatari Camp (left) and its current state (right)
Source: (Aburamadan, Trillo, & Makore, 2020) (left) and Google Earth (right)

Self-Organization

The unique spatial phenomenon of refugee camps presents challenging and sometimes complicated hierarchies and structures. As the rigidity of the formal grid master plan clashes strongly with the way Syrian cities and villages are experienced, refugees inhabiting camps continuously make changes to adapt the spatial organization to what best suits their needs.

Organic layers begin to formulate and override the grid as space is continually reproduced and rearranged in Zaatari camp. Abourahme (2014) argues that the social production of space "complicates the permanent temporariness of encampment" (Abourahme, 2014) where matter, space and events overlap to create the same complexity which shapes urban commons.

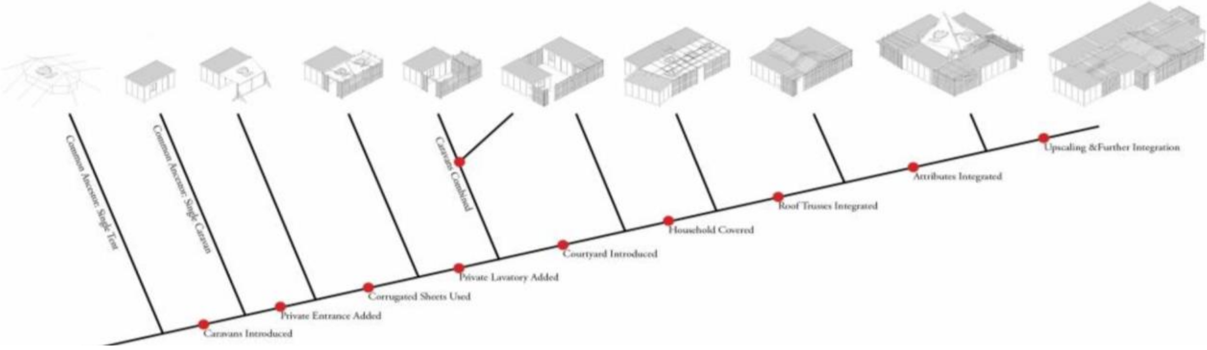


Figure 21. Diagram Showing the Evolution of Self-Organized Households in Zaatari Camp
Source: (Madi, 2017)

Social structures and hierarchies formulate within refugee camps, where certain groups delegate the needs of residents to authorities for example, others broker spare parts to upgrade living units and establish micro-economies within the camp borders. This informal framework is reflected spatially as well, affecting how refugees move throughout and use different spaces and facilities. The lively “Champs-Elysées” market street in Zaatari camp, established and operated by refugees, is a prime example of such organization.

Figure 22. Planned vs. Actual District in Zaatari Camp
Source: (Madi, 2017)

Lefebvre’s right to the city and production of space communicates the notion of space as a work or art, constantly being updated and changed through social interaction (Lefebvre, 1974). Considering this, what right could refugees have to their makeshift cities, if they had any right to claim at all beyond the confinements of their small caravan? Beginning with this notion urges reconsideration of the authority and ownership provided to refugees inside camp borders, and questions the stakeholders’ commitment to improving the quality of life for another decade.

Refugee Needs for Design

Aburamadan & Trillo (2018) argue that the current shelters only meet basic need with a gap existing in what refugees require for better living conditions and what is provided to them by organizations. For this reason, they proposed a set of criteria for the design of adequate sheltering as shown in the figure below.

Figure 23. List of Critera for the Design of Adequate Refugee Shelters
Source: (Aburamadan & Trillo, 2018)

The criteria are; safety and security for the protection of refugees from natural and man-made disasters. Comfort to ensure the wellbeing of refugees which includes factors such as temperature, lighting, and noise. Social context which relates to the attachment to cultural and social practices. Demountability refers to the ability to take apart the restructure and rebuild it where necessary. Durability relates to the structures being resistant against harsh weather conditions, as well as flexibility in building operation. Independent energy is order for the camps to be self-sufficient and to have energy coming from natural resources.

Safety and Security	Comfort	Shelter comfort	Social context
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	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	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	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
Stability	**Being Demountable**	**Flexibility and Modularity**	**Independent constant energy**
51. A pattern of independent existence/stability 52. Structure stability 53. Dignity- with new community connectivity	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	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)	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
Durability/Adaptability			
54. Available local sources 55. Robust strong material 56. Shelter skin 57. Mechanical ventilation system			

Table 2. Expanded Design Criteria for Refugee Shelters
Source: Adapted from (Aburamadan & Trillo, 2018)

The self-organized shelters in the case of the Zaatari camp show a core need for privacy, where for most of the adapted clusters, a courtyard was introduced creating a transition of privacy as shown in the figure below. This also corresponds to the findings of Albadra et al. (2020) where refugees were asked to adapt or draw their own designs in a series of participatory design workshops.

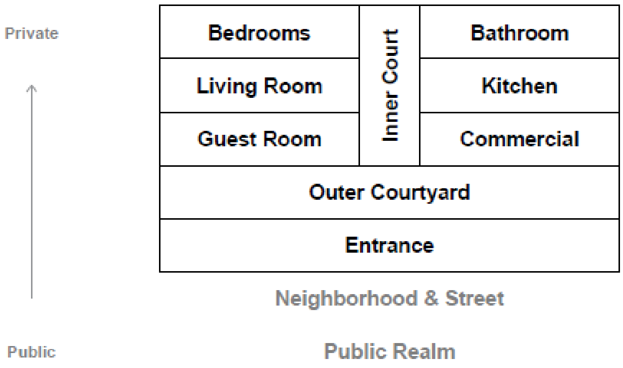


Figure 24. Privacy Transition in Self-Organized Shelters of Zaatari
Source: Adapted from (Madi, 2017)

3 Material Mixture Design

This chapter covers the process of developing a mixture to be used as a 3d printing medium for the construction of the shelters. First, and in order to gain a better understanding of the composition and properties of earth located in the Azraq and Zaatari refugee camps, some samples were collected from the sites. These samples are then analyzed to determine the percentages of constituents within each sample.

The collected samples are then recreated using raw materials in order to further experiment with the replicated compositions in a lab environment in the Netherlands. Various mixtures are then developed with additives from by-products that would be accessible in the context of the refugee camps. Furthermore, a manual extrusion experiment is conducted for each of the developed mixtures and evaluated in order to determine the most suitable mixtures to be nominated to the next stages of experiments. A few more mixtures are then refined and undergo a mechanical test. Lastly, a mixture is chosen and a toolkit showing the process of achieving this mixture is presented.

3.1 Soils of Jordan

The chosen Azraq and Zaatari refugee camps shown on the soil taxonomy map of Jordan in the figure below (Ababsa, Lucke, Ziadat, & Taimeh, 2013) are located in areas where the soil group Aridosols is present. Aridosols are found in dry/hot areas usually contain minimal organic matter and often contain calcium carbonate, or gypsum, or other salts. Having minimal organic matter is desirable for creating an earth mixture for construction.

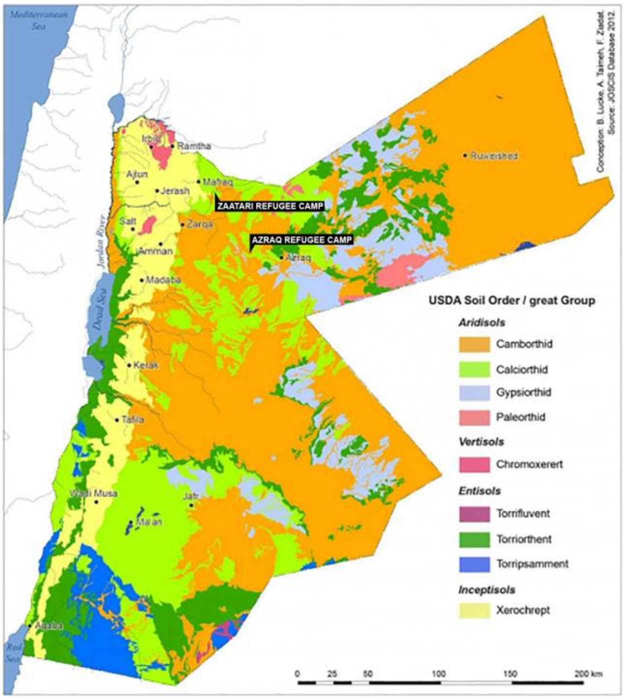


Figure 25.. Location of Zaatari and Azraq Refugee Camps on Taxonomy of Soils in Jordan Map
Source: Adapted from (Ababsa, Lucke, Ziadat, & Taimeh, 2013)

3.2 Soil Collection

The soil samples were collected from four locations, two from the Zaatari camp and two from the Azraq camp. In each camp one sample was taken from as close to the camp grounds as possible, and another from the nearest natural water assimilation point, by looking for the nearest culvert where the water would drain through during rainfall. This was done to examine the potential differences in content between the two sample locations for each site.

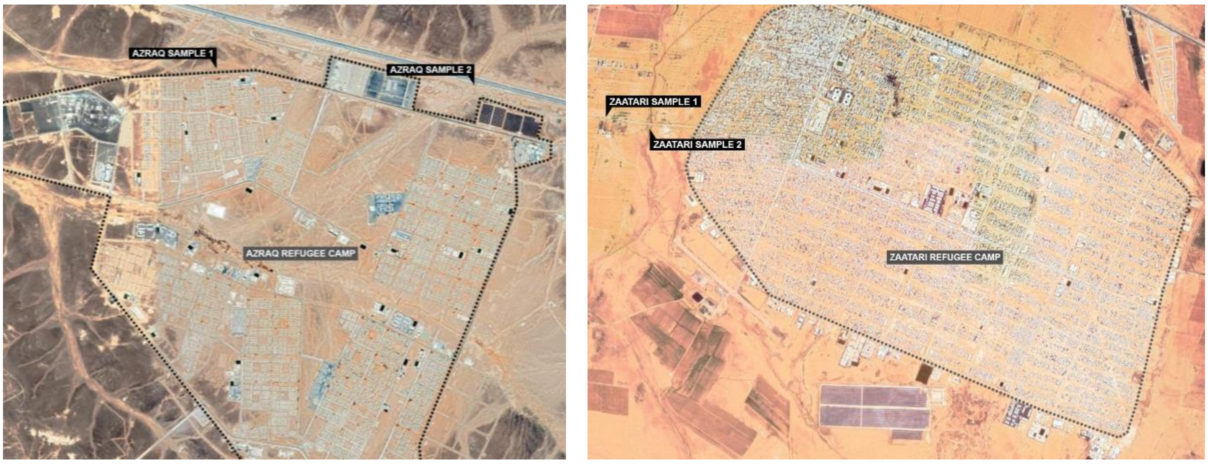


Figure 26. Azraq & Zatari Camp Soil Sample Locations
Source: Adapted from Google Earth

The Coordinates of the locations are as follows, with samples named 2 being near the natural water drainage points & culverts:

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

Figure 27. Images of Earth Sample Collection Near Azraq and Zaatari Camps
Source: Author

3.3 Soil Composition - Jar test

Tools and Method

The collected soils were then used to conduct an initial sedimentation experiment in order to determine the composition of the soils. For this a jar test is carried through, where the soil sample is placed in a jar and mixed well with water, then placed on a flat surface allowing the largest particles to settle at the bottom first (gravel and sand) followed by the medium sized particles (silt) and finally the finest particles (clay) and as shown in the diagram below (van Stigt, Esposti, & Kufrin, 2021). This method is not the most accurate, but is usually used on site to get an estimate of the soil composition, and is sufficient for the purposes of construction using earth.

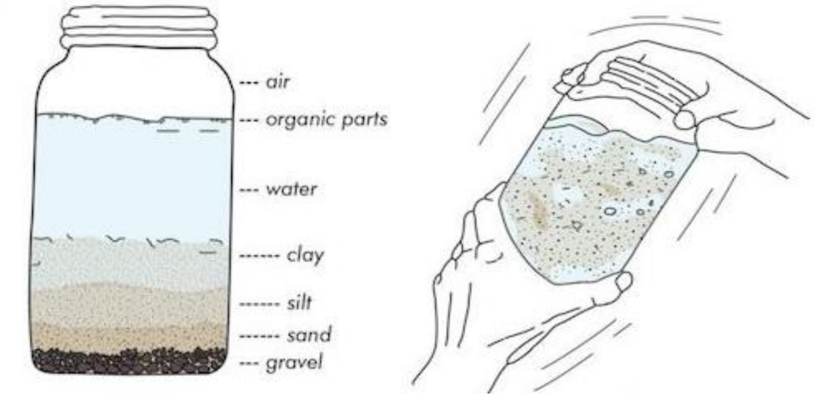


Figure 28. Jar Sedementation Test
Source: (van Stigt, Esposti, & Kufrin, 2021)

Before conducting the sedimentation tests the collected soil samples were sifted through a 2mm sieve in order to remove any large undesirable particles and leave behind particles that are 2mm and under (sand, silt, and clay) as shown in the images below. This sifting process should also be replicated on-site when extracting the material to be used in the mixture for the 3d printing of the shelters.

Figure 29. 2mm Sieve Used to Sift Soil
Source: Author

Results

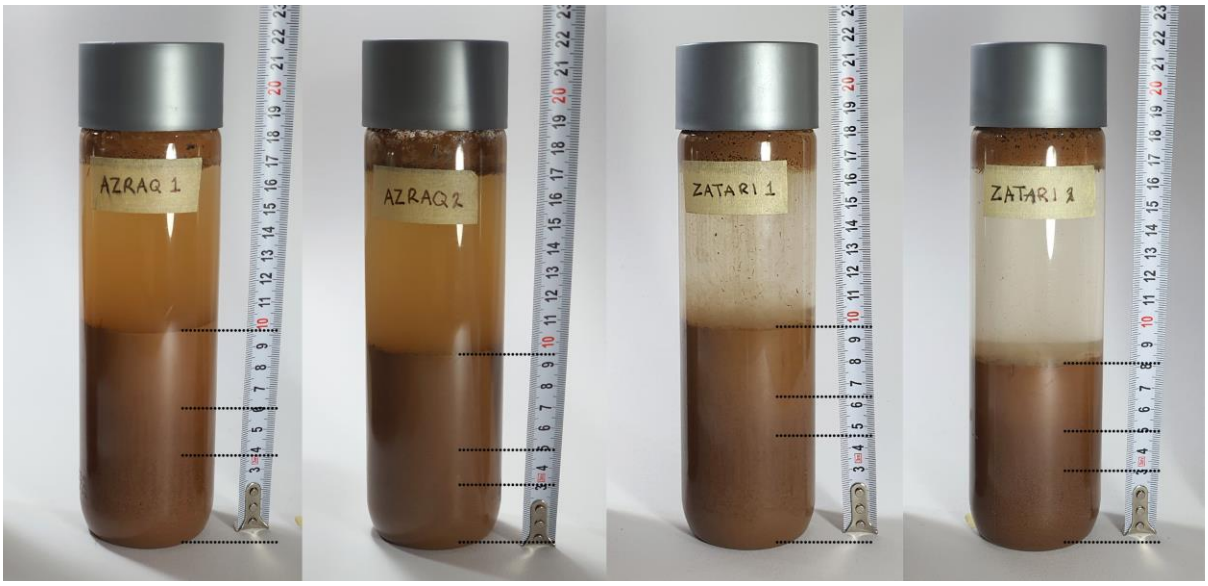


Figure 30. Jar Test Conducted on Collected Soil Samples
Source: Author

After conducting the sedimentation test for the soil samples as shown in the figure above, the samples collected near natural water drainage points (Azraq 2 and Zatari 2) had a higher clay content compared to those collected closer to the camps (Azraq 1 and Zatari 1). The Azraq soil had a larger clay content in general than the Zatari soil. The silt percentages were around the same range in all of the samples. These percentages are represented in the table below.

	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%

Table 3 Percentages of Sand, Silt, and Clay in each of the samples and Average Percentage

Since all samples have similar ratios of sand, silt, and clay in their composition, an average was calculated in order to be used for the recreation of the soil in a lab environment using raw materials that can be procured in the Netherlands. The soil samples are represented in the following figure showing the textural classification of each as well as the average which is in between the classification of clay loam and clay. The percent of clay is rather high and this is suitable for the use of construction where clay acts as the binding agent in the earth mixture, with the sand providing additional compressive strength.

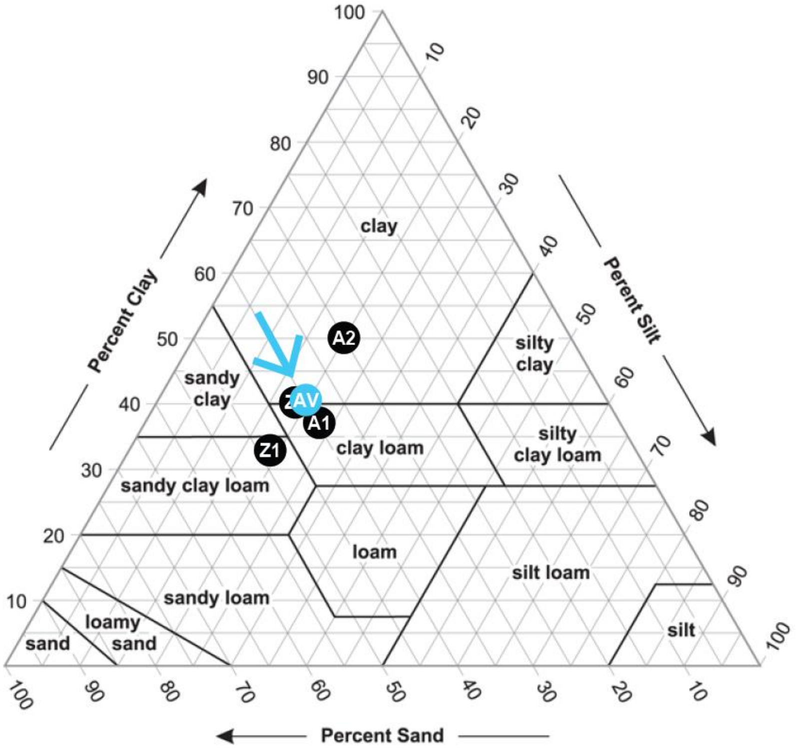


Figure 31 Triangle Graph for Classifying Soil Based on Percentages of Clay, Silt, and Sand
Source: Adapted from (USDA, 2017)

A small amount of the collected samples was also transported to the Netherlands to conduct the next set of experiments on, however then limited quantity is not sufficient for all the intended experiments, calling for the reproduction of these samples to further experiment with.

3.4 Mixtures

For using earth construction applications, several additives are usually incorporated in the mixture to improve its performance. A mixture design is developed through combining different ratios of soil, additives, and water followed evaluating the resulting mixtures according to a fixed set of criteria.

Additives from Byproducts

In order to enhance the mixture's properties such as printability, reduce shrinkage, increase strength, increase insulation qualities, reduce density, and more, a set of potential natural and preferably biodegradable additives were explored. In order for the printed structure to be reusable and to have a minimal environmental impact, it is important that the entire mixture including the additives is made up of natural materials. Furthermore, the various additives should be locally available and easy to procure and transport to the construction site.

With a focus on sustainability, several waste products from various locally available industries that could be viable additives were explored. Where these by-products would normally be disposed of, they can have a second life. This in turn plays into the larger scheme of a developed circular economy where products and materials are reused and minimal waste is produced.

The following table shows the chosen additive materials to test in mixtures, and the expected benefits of each additive, with a diagram following the table showing the materials as byproducts from the various identified local industries.

	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		●	●				

Table 4 Expected Benefits of the Chosen Additive Materials
Source: Author

Figure 32 Sourcing Diagram of Additives Materials as Byproducts of Various Local Industries
Source: Author

Twelve Mixtures are developed as shown in the following diagram, with the first mixture consisting of only clay to act as a benchmark, the second mixture using the sample collected from the site, the third mixture containing sand and clay in ratios that follow the sedimentation test of the collected samples in order to recreate them, and the nine more mixtures that are made up of the recreated soil along with a different additive for each.

Figure 33 The Twelve Mixtures to be Evaluated
Source: Author

The following table shows the percentages of materials in each of the mixtures in terms of volume and weight, as well as the percentage of water that was needed to achieve an extrudable consistency for each of the combinations.

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

Table 5 Mixture Compositions by Weight and Volume Percentages

3.6 Manual Extrusion Experiment

After Identifying several mixture options, a manual extrusion test that replicates the extruder that would be placed on the end-effector of a robot is performed. The following section highlights the tools, methods, and results of this experiment.

Tools and Method

Figure 34 Tools Used for Extrusion Experiment, Example of Wet Mixture, Example of Dry Extrusions
Source: Author

The objective of this experiment is to determine the effects of the various additives on the earth mixtures through observing a set of extrusions and evaluating them according to a series of criteria based on the literature review. The tools used for this experiment consist mainly of an automatic caulking gun along with empty cartridges that were filled with the wet mixture and extruded one at a time.

In order to create the mixtures, the materials are first sifted through a 2mm mesh to get rid of any clumps and ensure better cohesiveness. The components of each mixture are combined according to volume ratios, but were also weighed to determine their weight ratios. Water is then added gradually until an extrudable consistency is reached which is determined by visually inspecting the viscosity of the mixture. The mixture is then placed inside an empty caulking cartridge to be used with the automatic caulking gun. The caulking gun is set to the lowest speed setting to increase control of the extrusion's shaping.

Four different extrusions are made for each mixture sample in order to observe them based on the criteria set forth. Measurements and inspections are made at intervals of 12 hours until the samples are dry. Each sample is rated on a scale of 1 to 5, with 5 being the best possible score for that criterion. The criteria shown in the table below are as follows:

Shrinkage: Determined by measuring the length of a straight line of extruded material while it is wet (hour 0), then measuring the same line after it has dried (hour 48), and determining the ratio of shrinkage between the two.

Deformation: A visual inspection determines how much each extrusion has changed its shape or curved after it has dried up completely. The scores are based on observing how much each the samples deformed compared to one another.

Weight Loss: First the empty wooden boards being used for each sample are weighed in order to be deducted from the weights of the samples. The weight loss percentage is then determined by comparing the weight of the wet extrusions (hour 0) to the weight of the dry extrusions (hour 48).

Interlayer Bonding: For each sample an extrusion is made with multiple layers to observe how well each layer sticks to the next. The layered extrusion is cut in half and then visually inspected to see how well the layers have bonded to one another. This is followed by attempting to pull the layers apart and determining the difficulty of separating them.

Extrudability: Determined by how easy or difficult it is for the wet mixture to be pushed out of the cartridge, and if the power output needed to be increased in order to achieve a smooth extrusion process.

Cracking: Determined by visually inspecting the amount and size of cracks in each of the samples after they have dried.

Water Needed: The percentage of water in each mixture that is needed to achieve a sufficient consistency and viscosity in order to be extruded. It is important to note that having the lowest possible amount of water while maintaining an extrudable consistency is preferred in order for the layers to hold their shape and not deform while wet under their own weight.

Drying Speed: Determined by measuring the weight of the samples at 12 hour intervals and then calculating the speed in which each sample loses its water content until it is completely dried.

Surface Hardness: After the samples are dry, they are broken by hand. The surface hardness is determined by how difficult it is and how much power it takes until the samples is broken into two pieces.

Lightness: Determined by measuring the weight and volume of the mixtures and then calculating the resulting density.

Critereon	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

Table 6 Evaluation Criteria for Manual Extrusion Experiment
Source: Author

Most of the assessments are made using simple measurement tools or visual inspections. This could lead to some slight inconsistencies in the measurements. Some of the assessments are not quantifiable, therefore they are estimated on a scale of 1 to 5, whereas the quantifiable measurements are directly interpolated to a scale of 1 to 5.

Results

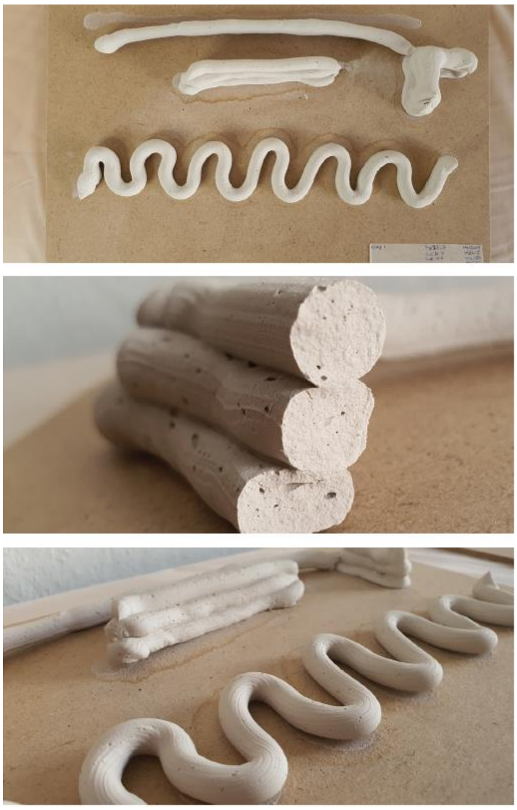
The figure below shows the twelve extruded mixture samples after they have dried completely.

Figure 35 All Extruded Samples
Source: Author

Mix 1 :
Clay

This Extrusion sample made up of only clay and water is used as a benchmark with no additives. Although very smooth and easy to extrude, the dry extrusions were very brittle. Furthermore, the observed shrinkage and deformation amounts were very high.

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



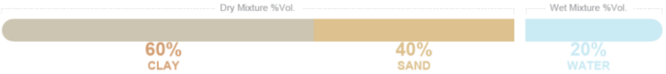
Mix 2 :
Soil

An extrusion made from the limited quantity of collected soil samples. This extrusion was easy to extrude and performed slightly better than the clay mixture on its own. However, the shrinkage is still rather high and there is visible deformation. The dry sample is significantly stronger than the clay sample.

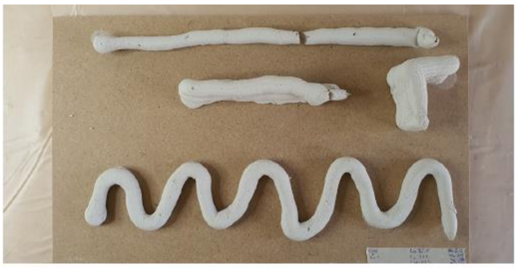
Shrinkage	• •	(7.2%)
Deformation	•	
Weight Loss	• • •	(19.3%)
Interlayer Bonding	• • • •	
Extrudability	• • • •	
Cracking	• •	
Water Needed	• • •	(20.0%)
Drying Speed	• • •	
Surface Hardness	• • •	
Lightness	•	

Mix 3 : Clay + Sand

This sample is the recreation of the soil sample composition analyzed in the sedimentation test. The same ratio of sand and clay are used for the rest of the extrusion samples with further additives. The addition of sand reduced shrinkage and increased its strength. The larger sand granules do make it slightly more difficult to extrude. Cracking is also visible.

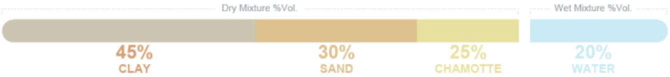


Shrinkage	• • • •	(3.2%)
Deformation	• •	
Weight Loss	• • •	(17.8%)
Interlayer Bonding	• • •	
Extrudability	• • • •	
Cracking	• •	
Water Needed	• • •	(20.0%)
Drying Speed	• • •	
Surface Hardness	• •	
Lightness	•	



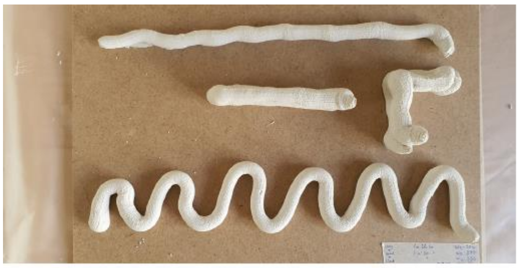
Mix 4 : Clay + Sand + Chamotte

The addition of chamotte (grinded fired clay) increased the strength of the extrusions and decreased the shrinkage and deformation. However, due to the large granule size, the extrudability is not optimal as the layers do not extrude easily and smoothly.

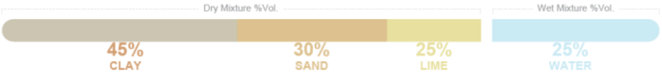


Shrinkage	• • • • •	(0.8%)
Deformation	• • • • •	
Weight Loss	• • •	(18.2%)
Interlayer Bonding	• • •	
Extrudability	• •	
Cracking	• • • •	
Water Needed	• • •	(20.0%)
Drying Speed	• • • •	
Surface Hardness	• • •	
Lightness	•	

Mix 5 : Clay + Sand + Lime



Adding Lime to the sand and clay mixture improved its properties significantly resulting in one of the two best performing samples. The surface hardness is very high. Shrinkage and deformation are low. It does however need additional water to reach the proper viscosity and the resulting extrusions are still quite dense.



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

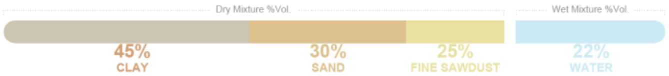
Mix 6 : Clay + Sand + Ash

This extrusion sample which included ash as an additive to the clay and sand, is another of the two best performing samples. The surface hardness is very high, there are no visible cracks, the light ash reduces the density of the mixture, shrinkage and deformation are low, and the mixture is relatively easy to extrude.

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

Mix 7 : Clay + Sand + Fine Sawdust

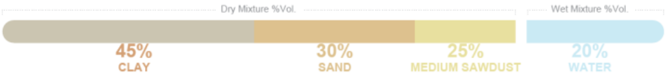
This was the more successful extrusion sample using sawdust out of the three due to the small particle size used in this sample. The sawdust reduces the density, deformation, cracking, and shrinkage of the extrusion but does require a slightly higher amount of water in the mixture to reach the desired consistency.



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

Mix 8 : Clay + Sand + Med. Sawdust

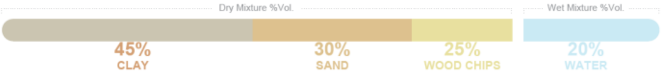
This extrusion sample performed similarly to the sample containing fine sawdust, however due to the larger particle size it was a bit more difficult to extrude. The sawdust particles are also slightly lighter resulting in an even less dense extrusion sample.



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

Mix 9 : Clay + Sand + Wood Chips

This extrusion was not successful due to the large size of the wood chips which resulting in jamming the cartridge causing the caulking gun to exert too much pressure, which in turn lead to small bursts of the material and eventually complete blockage.



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

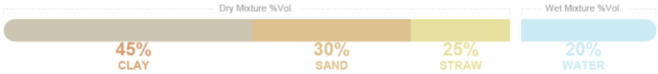
Mix 10 : Clay + Sand + Milled Wheat

This extrusion included wheat which resulted in a relatively strong result with low shrinkage. However, the mixture required a high amount of water to reach an extrudable consistency which caused a lot of deformation and required a long time to dry. The wheat also caused the layers to separate and not stick to the surface or to each other.

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

Mix 11 : Clay + Sand + Straw

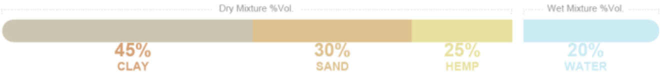
Although straw fibers were expected to significantly increase the tensile strength of the extrusions and the insulation qualities, the large size and random direction of the fibers in the mixture cased the cartridge to clog resulting in an unsuccessful extrusion sample.



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

Mix 12 : Clay + Sand + Hemp Fibers

The mixture containining hemp fibres performed rather well at first until it eventually clogged the cartridge as well. The parts that did extrude had increased performance in terms of shrinkage, lightness, deformation, and drying speed. Ultimately this mixture was not successful due to the clogging.



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

Summary

After experimenting and creating mixtures with multiple additives from by-products, the two most successful were the mixtures containing ash and lime. They showed an increase in performance in terms of strength, shrinkage, deformation, drying time, and interlayer bonding. The ash mixture was slightly less dense that the lime mixture but not as light as the mixture containing fine sawdust. The mixtures containing hemp fibers showed potential in increasing the performance but eventually clogged the cartridge. This could however on a larger scale still be possible but was eliminated for the purpose and scale of this research. For the following steps two refined mixtures were created in an attempt to combine the benefits of the most successful mixtures.

3.7 Compressive Strength Test

Refined Mixtures

From the findings of the previous extrusion experiment, two further refined mixtures are developed. These additional mixtures are made up of sand and clay as a base with sawdust as an additive in both of them to increase the insulation quality and reduce the density. Mix 13 has lime as an additive and mix 14 has ash as an additive as these were the two better performing additives as found in the previous experiment. These two mixtures undergo a series of mechanical tests to determine the strength of each and compare them to the strength of the mixture of just clay and sand (mix 3) without any additives as a reference point. The two additional mixtures are shown in the figure below;

Figure 36 Refined Mixtures Composition
Source: Author

Tools and Method

Cubes were made for each of the three mixtures measuring 6x6x6cm and cured for 10 days. They then were put through compressive strength tests to determine how the samples compare to one another and if their strength is sufficient for use as a construction material. This was done a by applying a gradually increasing force onto the face of each sample until the material failed, and then calculating the maximum compressive strength from the maximum force applied to the cross section area. The test was performed three times for each mixture in order to evaluate the consistency of the results and to calculate an average reducing the error margins. The machine used is the Zwick Z100 testing machine located in the Material science faculty lab. For reference, the compressive strength of cob used for construction is around 0.6 MpA and is sufficient for a building of up to 3 stories high (Azil, et al., 2022).

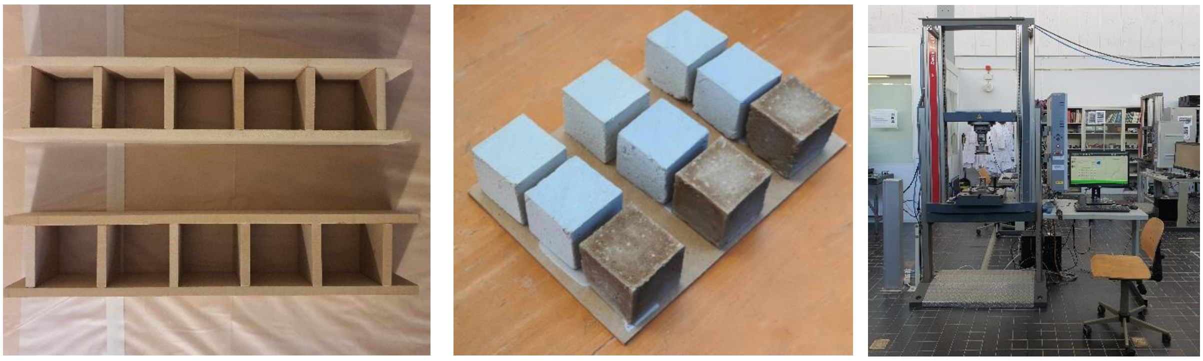


Figure 37 Wooden Molds, Cube Specimens, and Experiment Setup
Source: Author

Results

Mix 3: Clay + Sand

- Average Maximum Force Applied: 2133N
- Cross Section: 6x6 cm²
- Average Compressive Strength: 0.59 Mpa

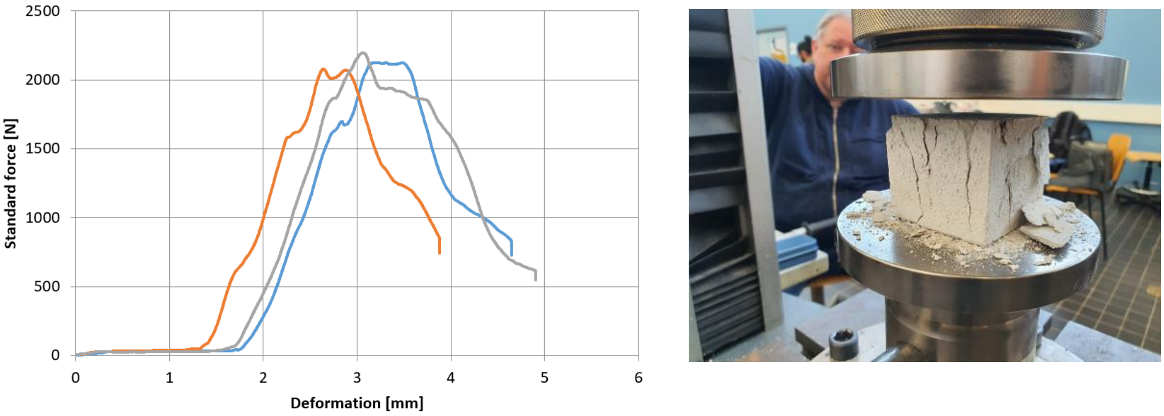


Figure 38 Mix 3 Compression Test Results
Source: Author

Mix 13: Clay + Sand + Lime + Fine Sawdust

- Average Maximum Force Applied: 1708 N
- Cross Section: 6x6 cm²
- Average Compressive Strength: 0.47 Mpa

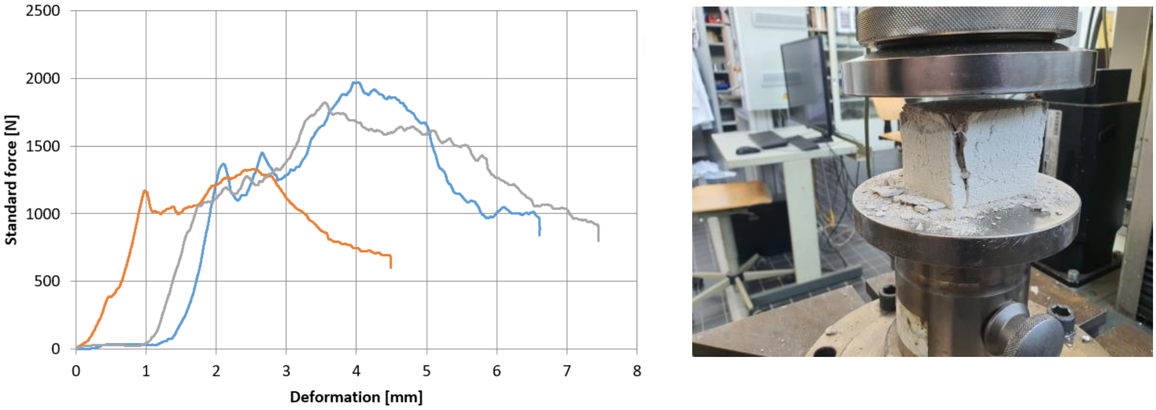


Figure 39 Mix 13 Compression Test Results
Source: Author

Mix 14: Clay + Sand + Ash + Fine Sawdust

- Average Maximum Force Applied: 1652 N
- Cross Section: 6x6 cm²
- Average Compressive Strength: 0.46 Mpa

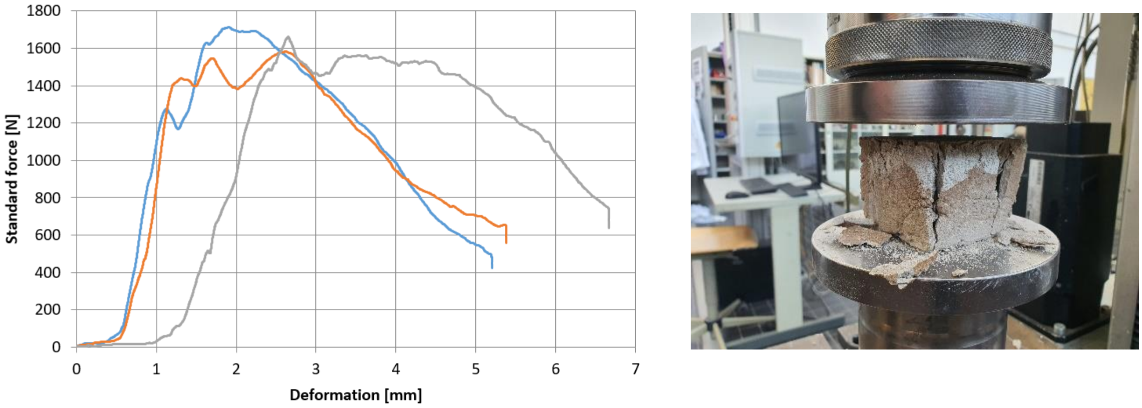


Figure 40 Mix 14 Compression Test Results
Source: Author

Discussion

The final chosen mixture is Mixture 14 composed of clay (42%), sand (28%), ash (20%), and fine sawdust (10%), with the ratios of sand and clay based on the ratios found in the composition of soil samples collected from the sites of Azraq and Zaatari refugee camps.

The results showed that the sand and clay mixture was slightly stronger than the mixtures with additives, which could in turn mean that the water percentage should be adjusted in the mixtures with additives to adjust for the more absorbing materials and in future tests could lead to better results.

Although the sand and clay mixture surprisingly resulted in a slightly higher compression strength, the added benefits of using ash and sawdust in the mixture are what influenced outweighed the small difference in compressive strength. It was also chosen in favor of lime as ash is widely available as a waste material that is easily produced and is usually disposed of with limited other uses for the material giving it a second life. In comparison to using clay on its own, the resulting mixture is shown to improve the qualities of extrusions in terms of shrinkage, compressive strength, tensile strength, drying speed, deformation, cracking, insulation qualities, lightness, and interlayer bonding. Now that the material mixture is developed, a design tool for generating bespoke shelters can follow taking the material properties into account.

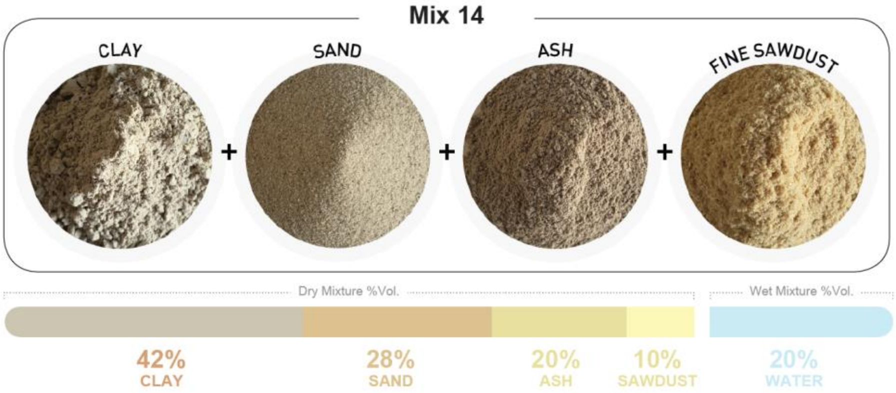


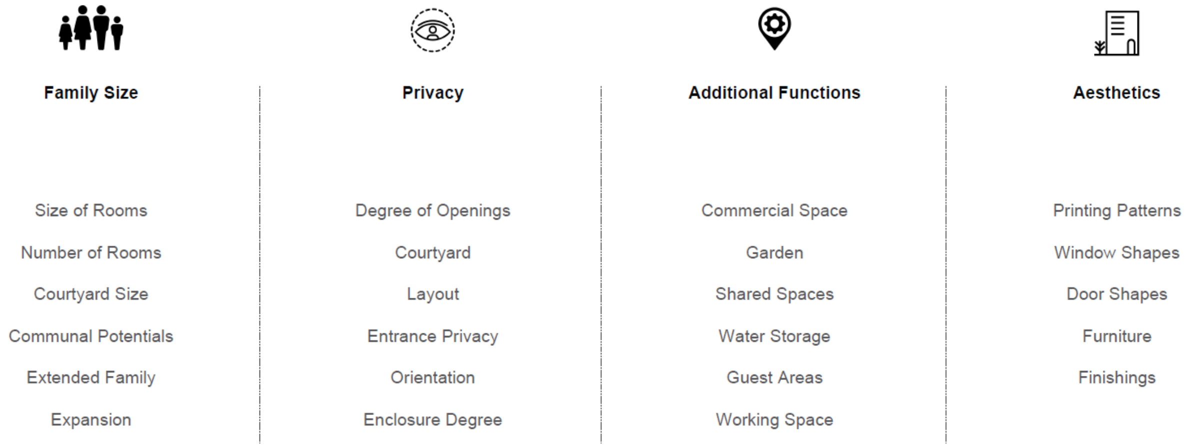
Figure 41 Final Mixture Composition
Source: Author

4. Shelter Design Tool

This chapter covers the development of a printable refugee shelter design tool. Design requirements derived from the literature review are shown followed by the process of creating tangible design variables from these requirements. The design variables take into consideration the constraints of 3d printing in creating a set of inputs to be controlled by the end users through a friendly interface to customize shelter designs that fit their specific needs. These variables are explored in detail in terms of digital workflow development. Furthermore, a market study is conducted in order to decide on feasible robotic construction methods required to realize the produced shelter designs.

4.1 Design Brief

A set of design requirements derived from the literature review on the current state of refugee shelters in the Zaatari and Azraq refugee camps, as well as relevant literature on refugee needs for proper living conditions. An important reference is the way in which refugees adapted the identical mass-produced shelters provided to them in imaginative ways to fit each of the families' specific needs. The derived requirements are split into four main categories. The family size influences the size and number of required rooms along with the possibility of hosting extended family members or fried. Privacy is an important component in many of the refugees' adaptations stemming from how their homes from which they fled originally are. Privacy can influence the entrance space, the openings, courtyard, layout, and degree of enclosure. Moreover, many of the adaptations included additional functions to accommodate for a commercial space, working spaces, water storage, or other space. Aesthetical considerations are also important in achieving a personalized home increasing the inhabitants' sense of belonging.



Family Size	Privacy	Additional Functions	Aesthetics
Size of Rooms	Degree of Openings	Commercial Space	Printing Patterns
Number of Rooms	Courtyard	Garden	Window Shapes
Courtyard Size	Layout	Shared Spaces	Door Shapes
Communal Potentials	Entrance Privacy	Water Storage	Furniture
Extended Family	Orientation	Guest Areas	Finishings
Expansion	Enclosure Degree	Working Space	

Figure 42 Variables for Shelter Design Requirements
Source: Author

4.2 Digital Workflow Design

A digital tool for mass-customization is developed based on the derived design requirements. This is done by translating the requirements into a set of tangible variables that the end user can control. This section explains these variables in detail along with the developed computational logic.

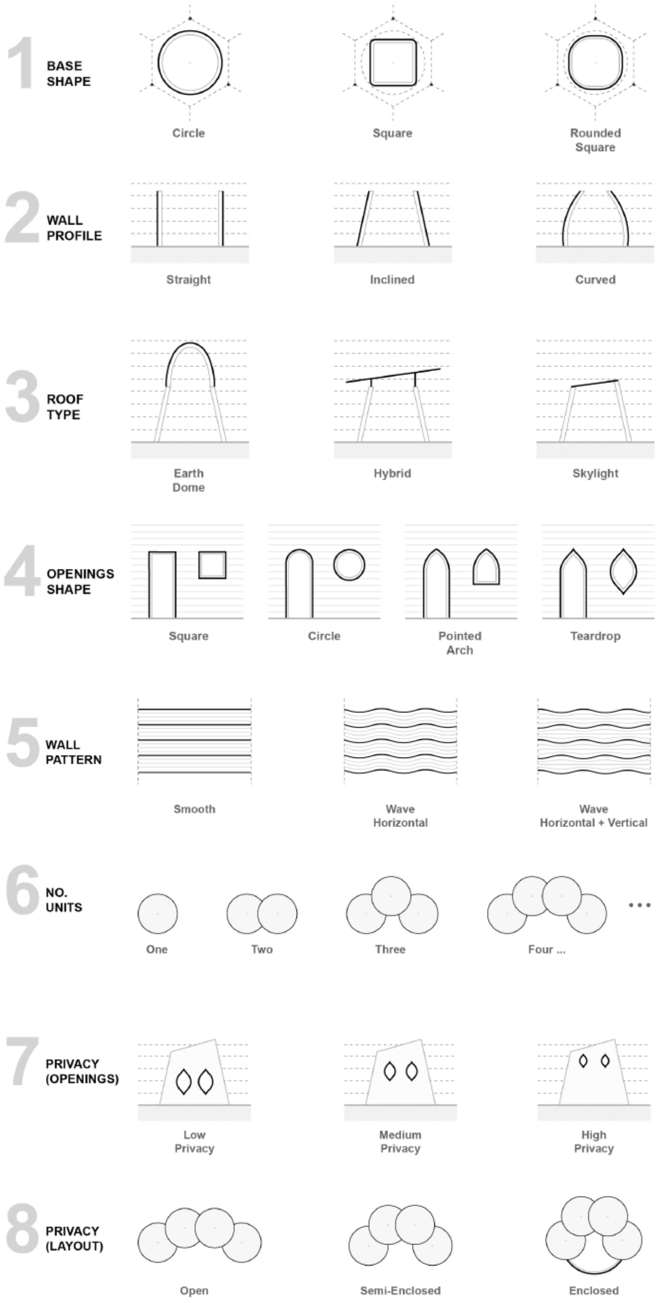


Figure 43 Design Input Variables
Source: Author

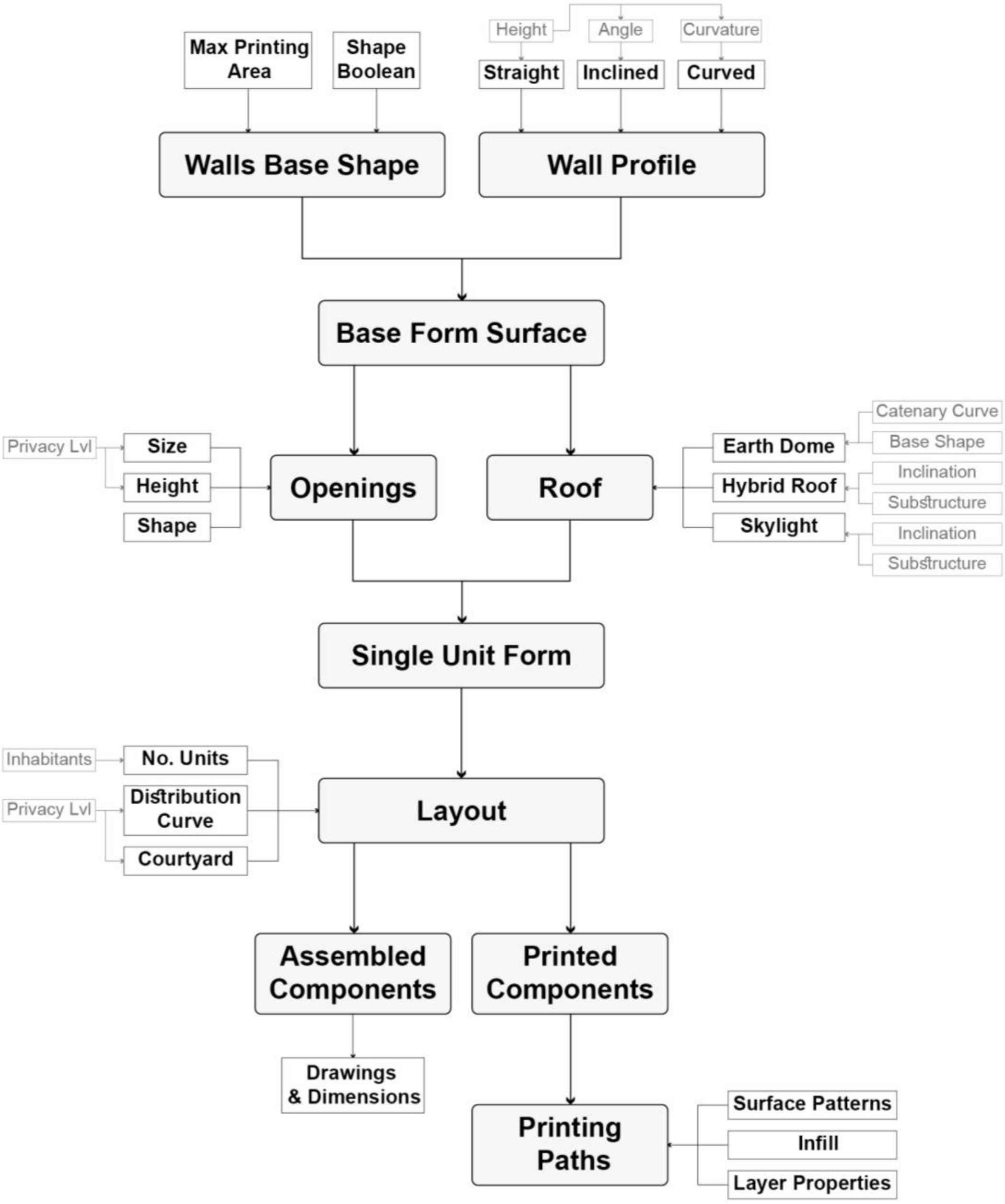


Figure 44 Digital Workflow Diagram
Source: Author

Base Shape

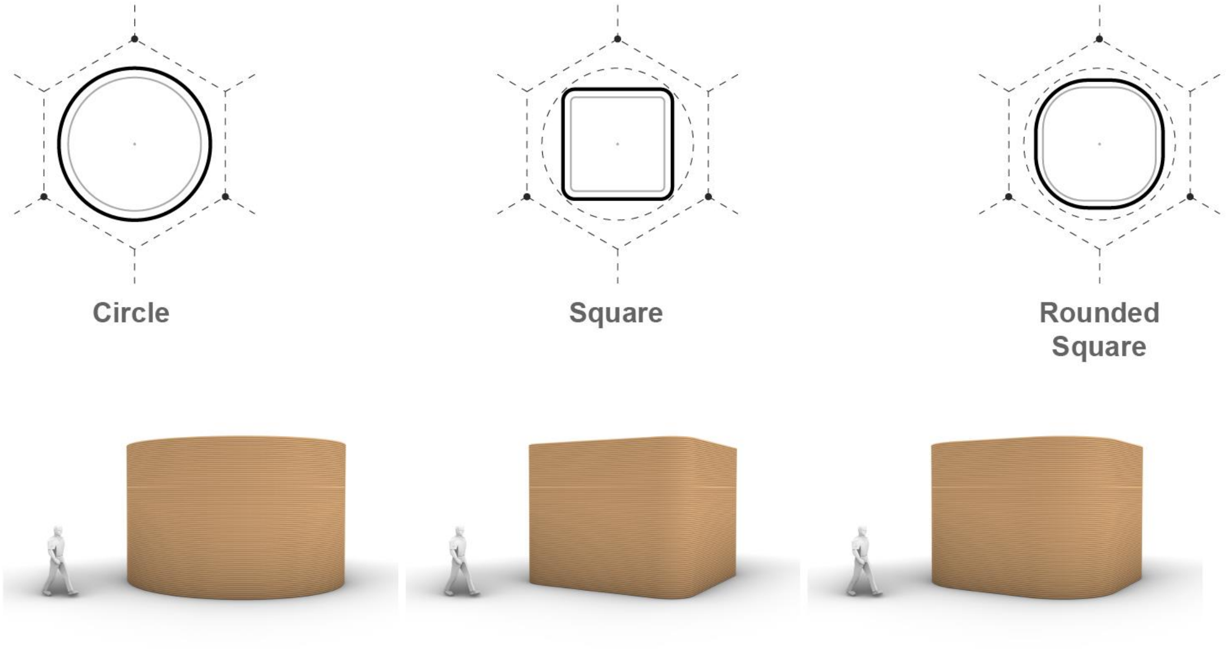


Figure 45 Base Shape Variables
Source: Author

The script begins by specifying the base shape of the shelter's form. From a given printer's maximum printing area, three shapes can be derived as follows;

Circle: A circular path based on the maximum printing area gives the most efficient use of material to area ratio. This allows for the robot to dispose the material in a continuous uninterrupted path and having curved walls throughout the shelter assists in increasing its structural stability. One downside is that standard furniture items are typically rectilinear making it difficult to organize the furniture within a circular floorplan. For this reason, the users are given further options to choose from based on their preferences.

Square: A square shaped floorplan inscribed within the maximum printable circular shape of the printing area. This options allows for a more comfortable distribution of furniture items within the space and is more familiar to most people. A slight rounding of the corners is necessary here to prevent the accumulation of material in the corners during the printing process.

Rounded Square: Rounding the square's corners further and in a variable degree creates a hybrid solution where a higher area of space is achieved with a more efficient use of material quantities. A formula is derived so that no matter the radius of the rounded corners, the resulting rounded square is always fitted and inscribed perfectly within the circle of the maximum printing area.

Wall Profile

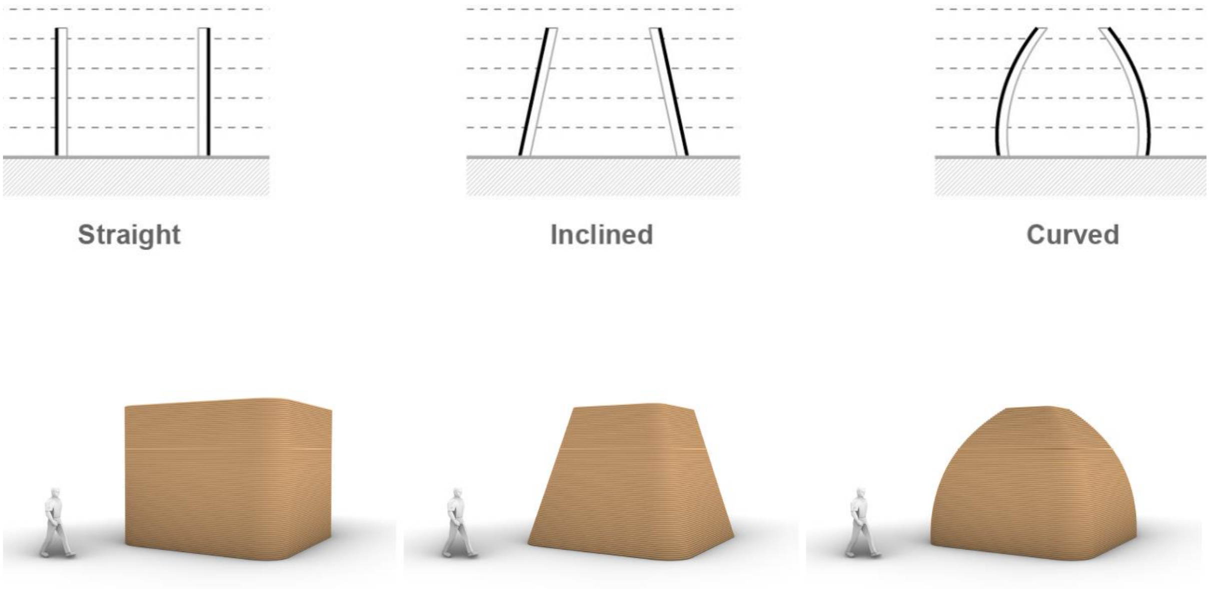


Figure 46 Wall Profile Variables
Source: Author

After choosing a base shape, the user is able to choose a wall profile and this influences multiple attributes. Having inclined or curved walls allows for more efficient material usage by reducing the volume of space while maintaining the same floor area amount. This also allows for the roofing to be made smaller and in turn use less material. Using less material also means increasing the speed of printing and thus the time it takes for the shelter’s construction to be completed.

A maximum tilt angle of 25 degrees is set as to ensure the layers do not fall over while printing, warranting that the wall profile always remains within the center of gravity with no excessive overhangs. This is also the case for the curved profile wall option where the curvature tangents are set to never exceed a 25-degree angle.

The wall tilt angle which is input by the end user is translated into a scaling ratio for the top part of the shelter in order to achieve said angle, meaning no rotation actually happens ensuring the print paths are always parallel to the ground plane.

Roof Type

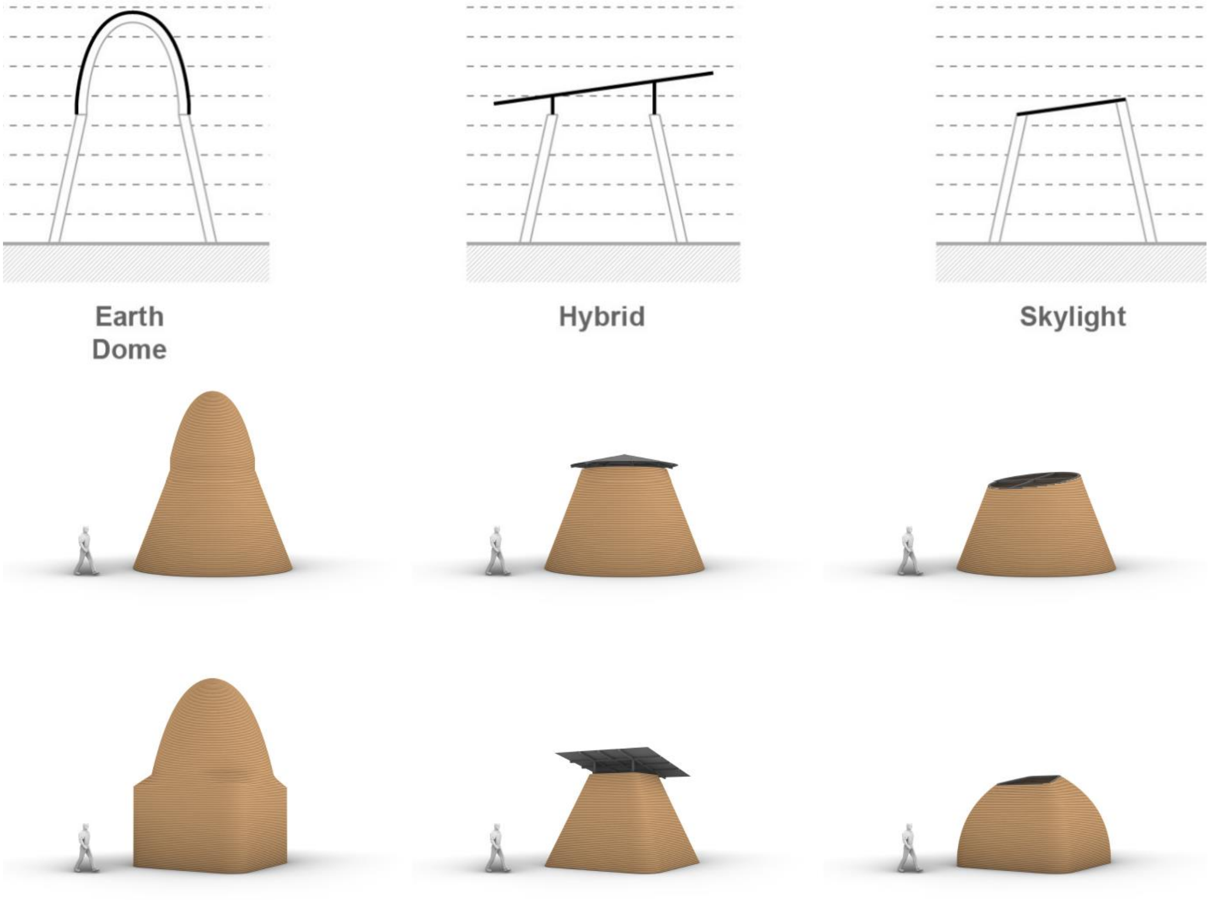


Figure 47 Roof Type Variables
Source: Author

Three roof options that adapt to the form of the shelter's base can be chosen.

Earth Dome: This option is fully printable with no need for additional external materials. The same limitation for wall tilt angles is present hear in ensuring the domes inclination never reaches a point where the layers fall outside the center of gravity. The dome is drawn from catenary curves helping with load distribution where no additional reinforcement is necessary.

Hybrid Roof: This roof type is made from recycled parts taken from the existing prefab shelters. The roof shape adapts to the span of the printed walls underneath, automatically generating a substructure grid of tubes where required. This roof type allows for stack ventilation as both ends remain open.

Skylight Roof: A skylight made of glass and steel tubes is placed in a tilted angle on top of the printed walls. This option allows for additional sunlight to enter the space. Depending on the span the substructure is also automatically generated.

Openings Shape

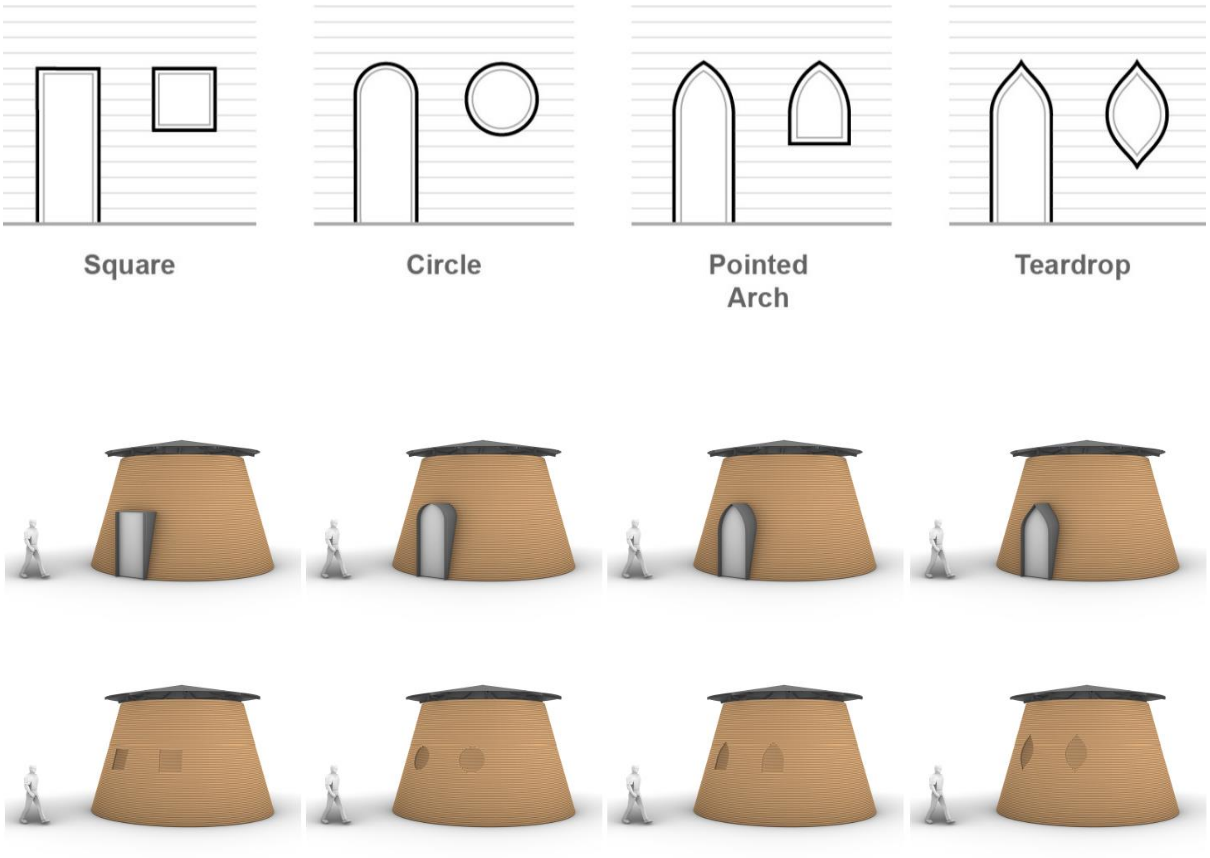
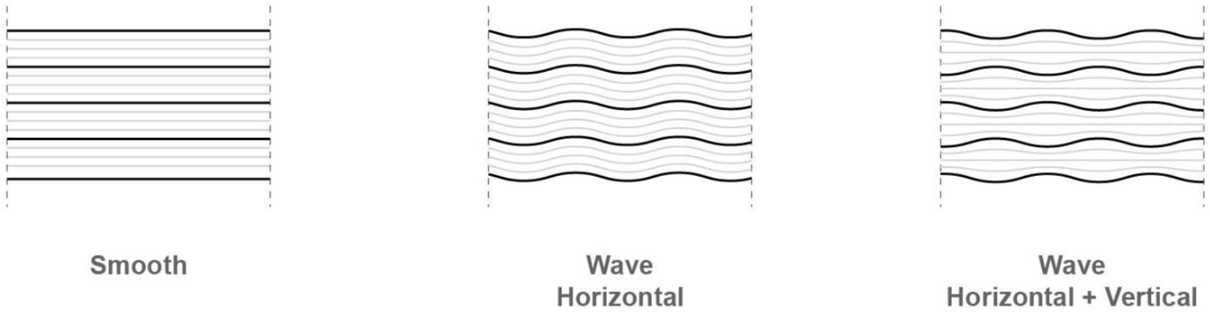


Figure 48 Openings Shape Variable
Source: Author

The user is able to choose between several opening shapes. This applies to the shape of the windows as well as the shape of the entrance door. The square and circle shape require additional structure to support the overhanging material at the top whereas the pointed arch and teardrop shapes can be printed without needing any additional support as the tile angle of the sides is always within the allowed limit.

These shapes are mostly an aesthetic preference and the end-user is able to choose whichever option is more appealing.

Wall Pattern



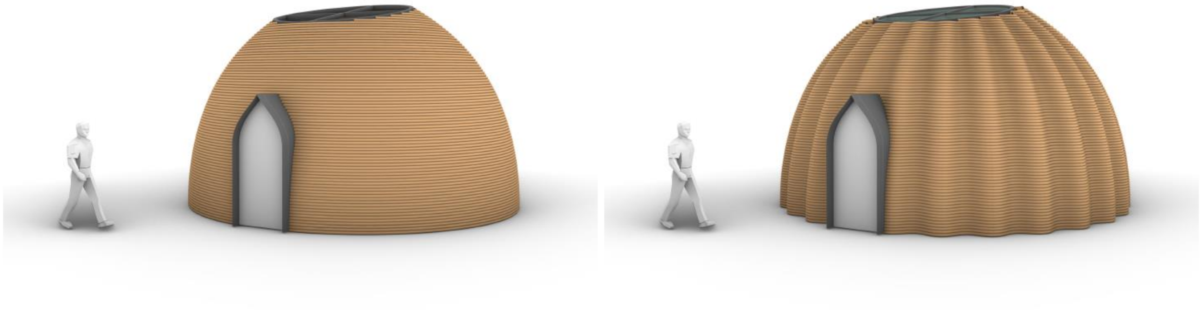


Figure 49 Wall Pattern Variable
Source: Author

After generating the printing paths, there are three options for the wall patterns; smooth, horizontal waves, and horizontal + vertical waves. These options differ in appearance but also can have an effect on the building’s performance. Having wavy printing paths ensures the layers are more stable during the printing process and are more forgiving in accuracy of the robot. The waves also allow for self-shading which would lower the inside temperature in a hot dessert climate. The waves can also help in increasing acoustic insulation qualities. The end-user is free to choose between the three options in order to generate the final paths to be exported to the robot to print.

Number of Units

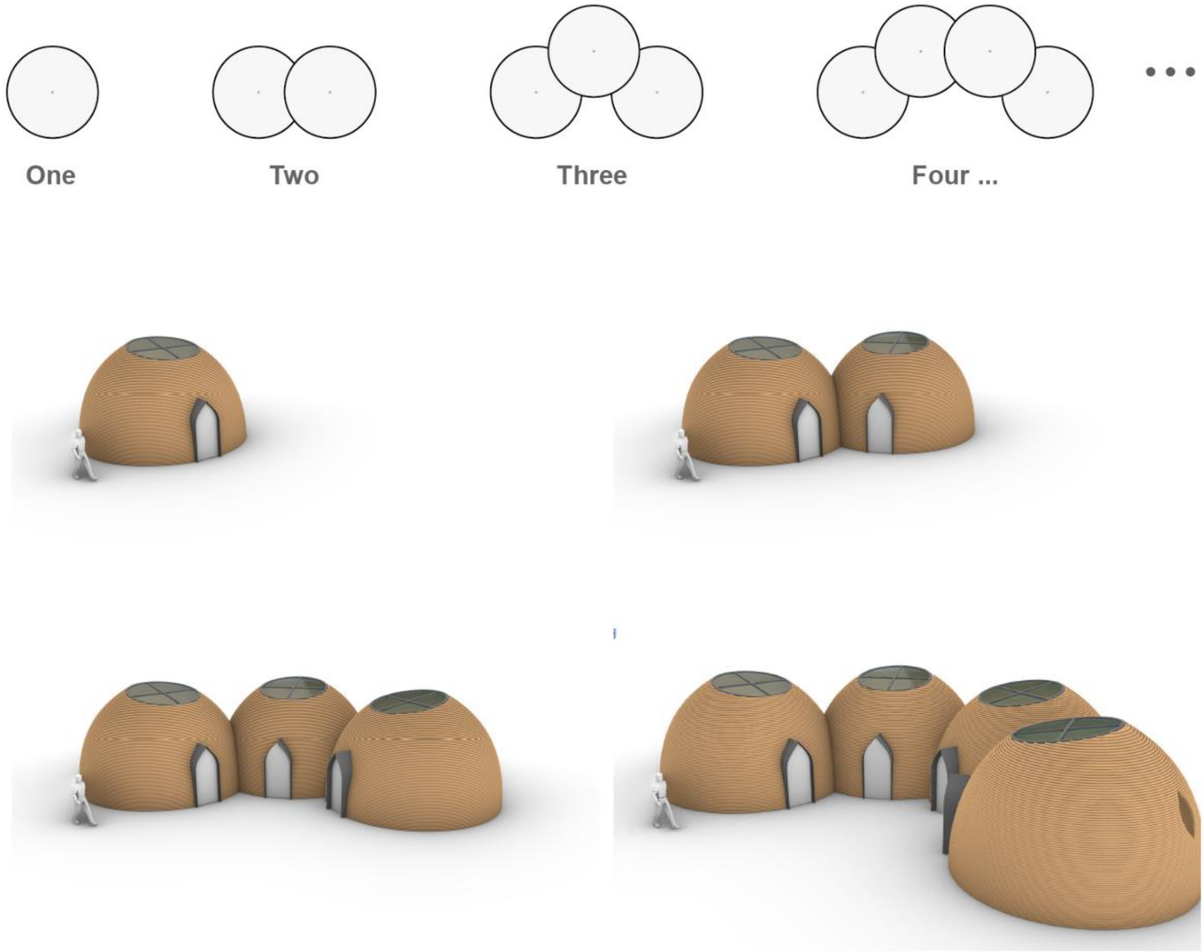


Figure 50 Number of Units Variable
Source: Author

Based on the number of users expected to inhibit each shelter, the user can choose the number of units to be printed. The units are distributed equally on a circular curve with arch-like openings being generated along the intersections of the units. The maximum number of units is relative to the openness of the curve they are distributed along, which in turn is relative to the degree of privacy.

Privacy (Openings)

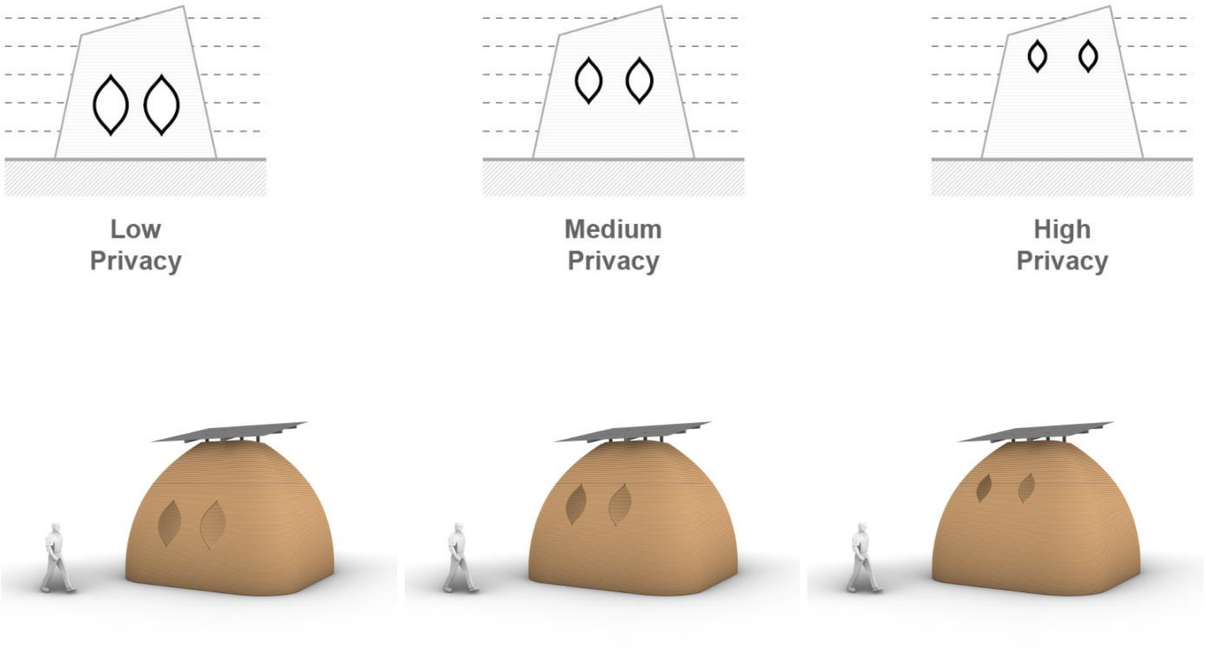


Figure 51 Opening Privacy Variable
Source: Author

The user can choose between three levels of privacy; 1,2, and 3. The level of privacy chosen has an effect on the window size and placement. Choosing level one results in large windows that are placed in the lower section of the wall. Choosing level two results in medium sized windows placed in the middle section of the wall. Choosing level three results in having small windows in the upper section of the wall ensuring maximum privacy while maintaining a sufficient influx of natural lighting.

Privacy (Layout)

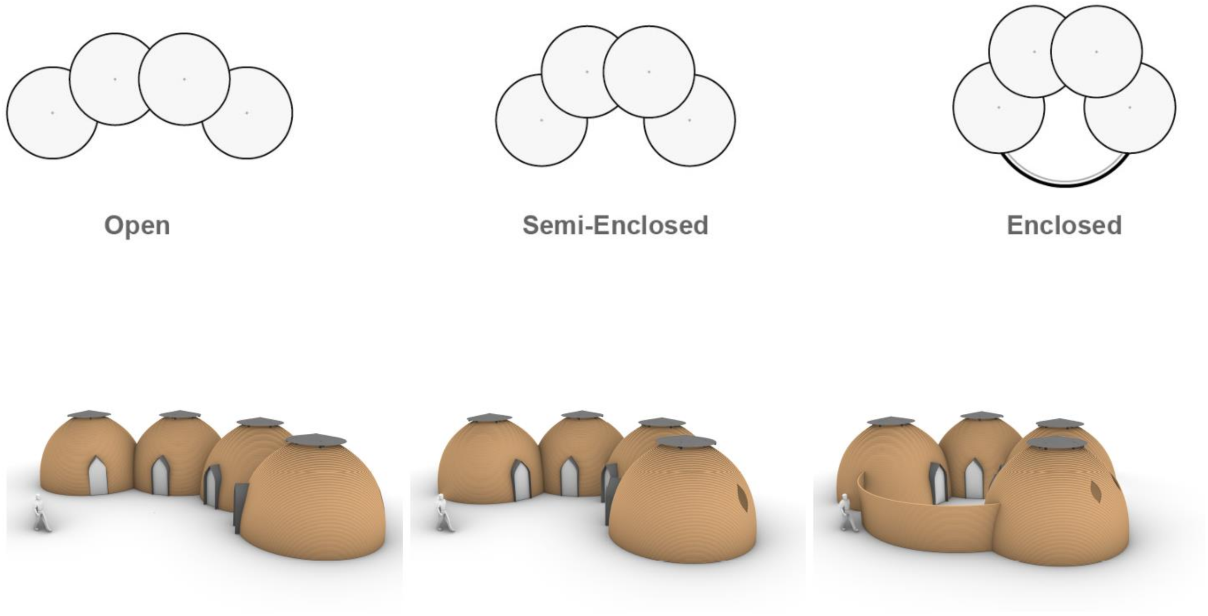


Figure 52 Layout Privacy Variable
Source: Author

The degree of chosen privacy also influences how much the units are enclosed. Choosing a lower degree of privacy results in the units being distributed along a larger circular curve that is more open to its surroundings. Choosing a higher degree of privacy incrementally reduces the arc radius along which the units are distributed resulting in a more closed off layout of the units. The user can also choose between having a courtyard wall that completely wraps around the central space.

Wall Infills

After Achieving the base surfaces of the intended design, it is then prepared for creating stable printing paths with a wall thickness and an adequate wall infill. This is done by first converting the surface into a series of curves that are then offset with the desired wall thickness. The desired wall pattern is then applied on the outer set of curves (wavy or smooth). This is then followed by dividing the outer and inner into a series of points and creating a weave patter between the outer and inner points. The weave pattern is then converted into an interpolated curve which makes up the main infill line. The infill density can be controlled by changing the point division number of the outer and inner curves. The resulting curves are then lofted to create an outer surface, an inner surface, and an infill surface.

These surfaces are generated automatically for all the different possible design varioations within the same computational workflow. This is followed by creating the openings and dividing the final surfaces into the printing paths with the required layered height according to the extruder's nozzle size. This process os illustrated in the figure below.

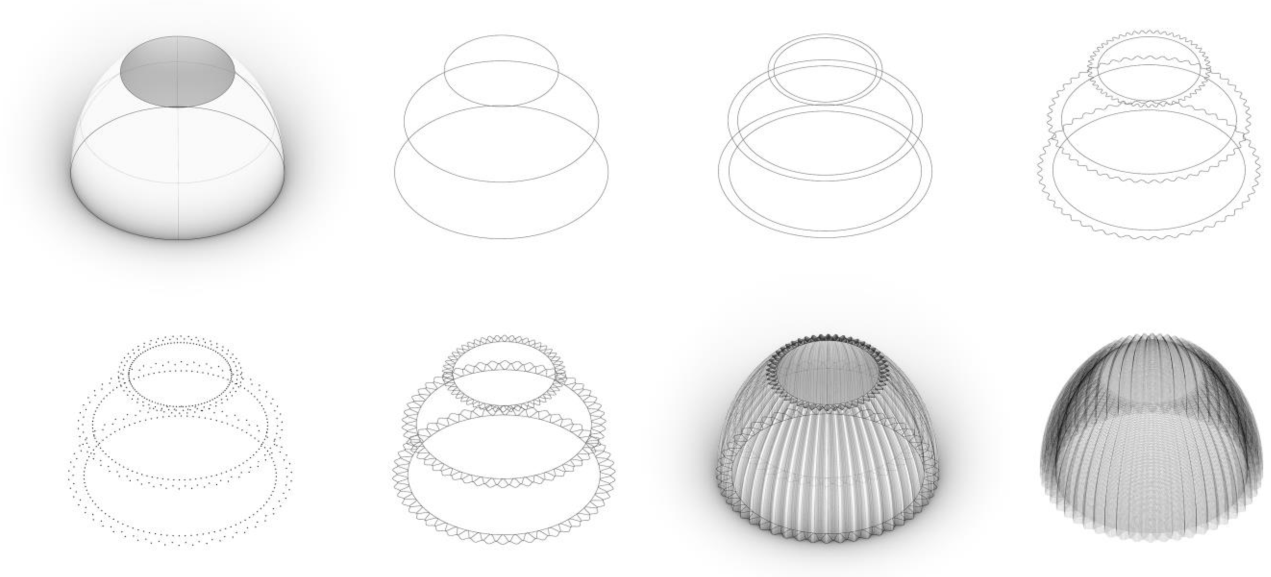


Figure 53 Generating Wall Infill Patterns
Source: Author

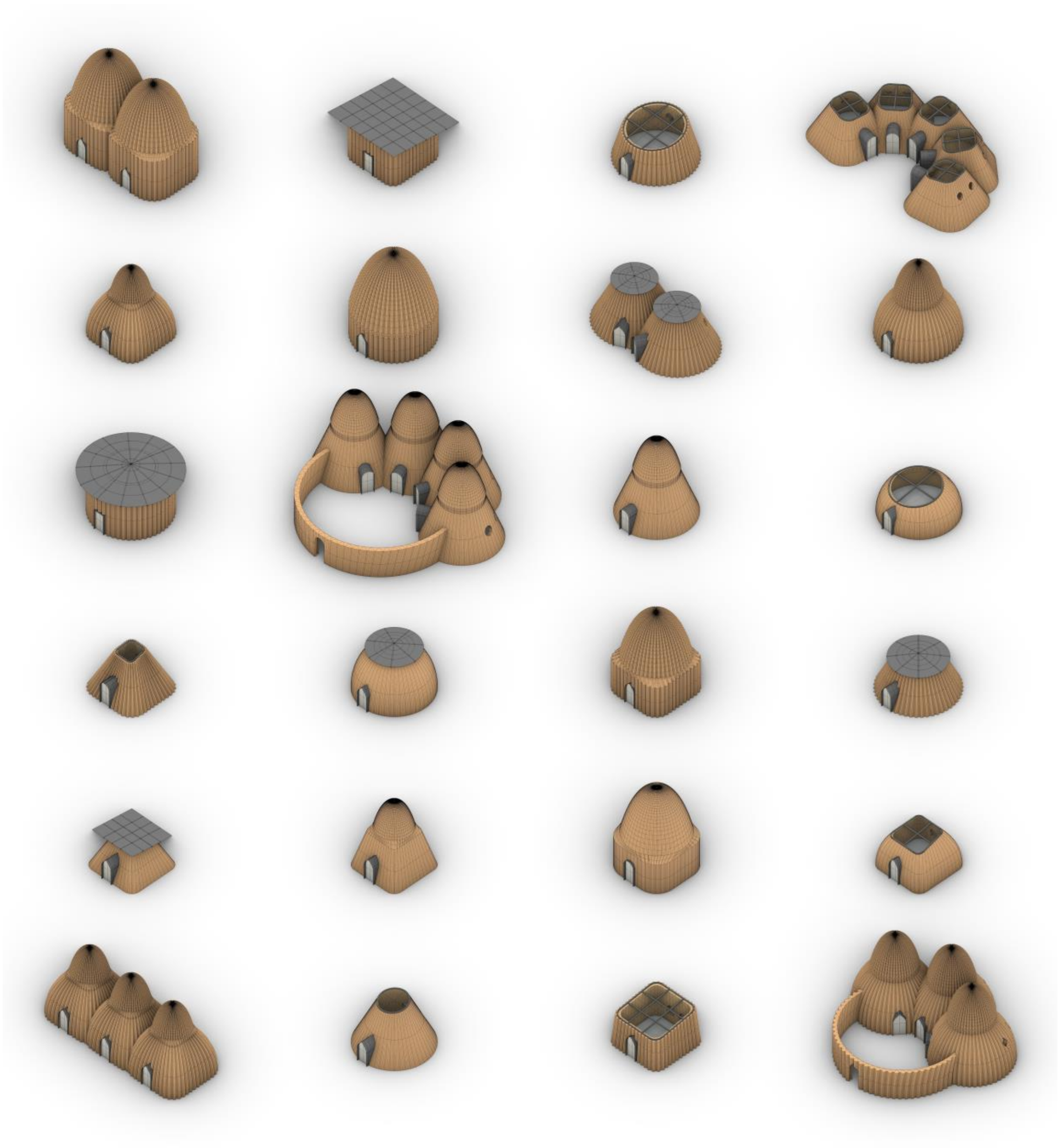
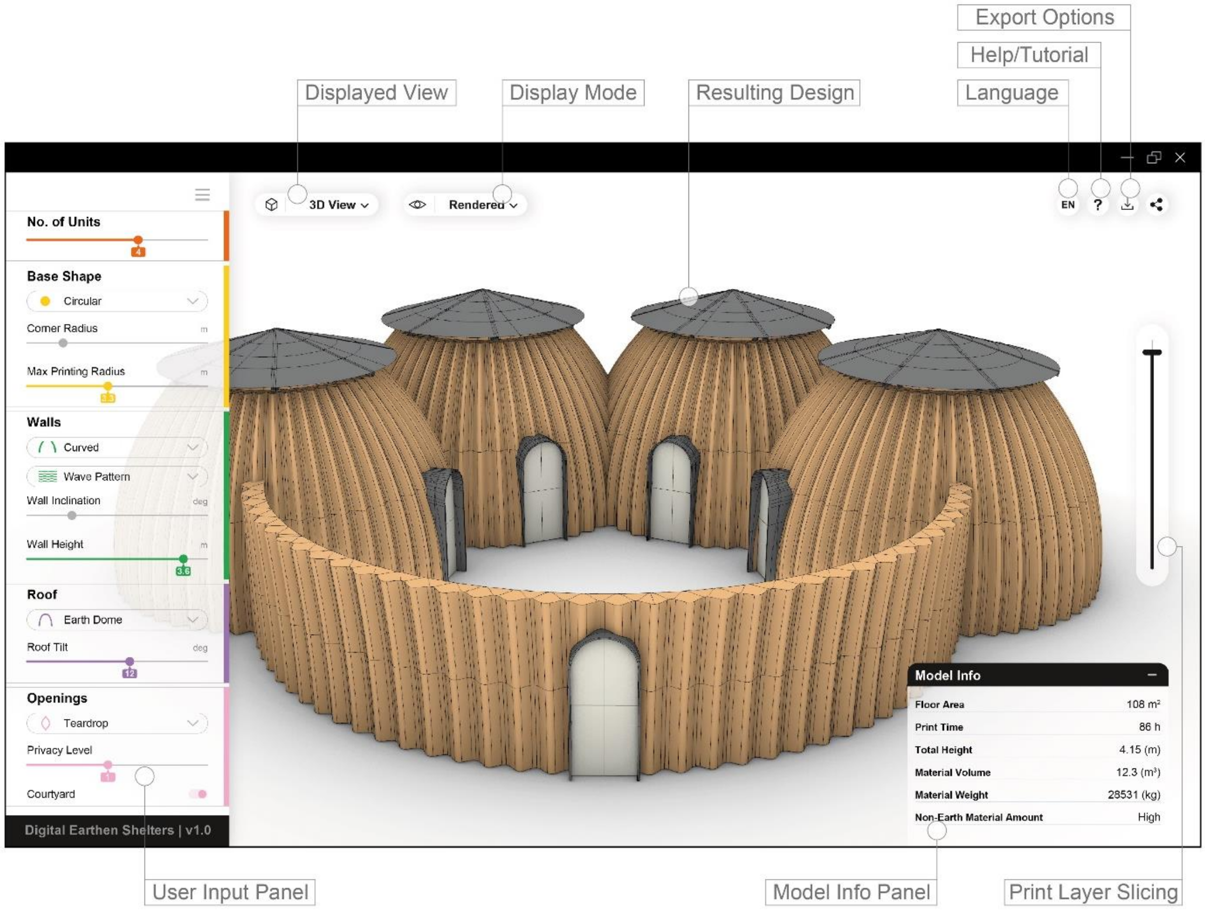


Figure 54 Generated Design Iterations
Source: Author

4.3 User Interface

The computation script is intended to be converted into a user friendly tool that can be used easily by anyone. It will also be made accessible to everyone by hosting the interface on a web based platform that anyone with a web browser could use. The figure below shows a mockup design of the user interface for the design tool.



No. of Units: 4

Base Shape: Circular

Corner Radius (m)

Max Printing Radius (m): 3.3

Walls: Curved

Wave Pattern

Wall Inclination (deg)

Wall Height (m): 3.6

Roof: Earth Dome

Roof Tilt (deg): 12

Openings: Teardrop

Privacy Level: 1

Courtyard

Digital Earthen Shelters | v1.0

Model Info

Floor Area	108 m²
Print Time	86 h
Total Height	4.15 (m)
Material Volume	12.3 (m³)
Material Weight	28531 (kg)
Non-Earth Material Amount	High

Figure 55 User Interface Design
Source: Author

UI Elements

Input Panel: This is the main panel where users are able to input their preferences and needs using simple drop down menus and sliders that function as explained in the previous section.

Displayed View: Different options for the displayed view including; 3d view, top view, side view, plan view, and section vie.

Display Mode: Users can choose how to visualize the model which includes; rendered mode, x-ray, and printing paths.

Resulting Design: A viewport to display the design generated from the individual inputs.

Language: Due to the diverse group of intended end users, users are able to choose between different operating language options.

Export Options: This allows users to export useful files such as the printing paths/gcode for the robotic construction, construction drawings for the additional material (aside from earth), and the 3d model for use in other software.

Help: This takes the users to a documentation website that also contains tutorials on how to use the UI if anyone finds it difficult to understand.

Sharing: Users can share the resulting designs with the relevant stakeholders or within their social circles directly from the tool.

Print Layer Slicing: A slider that allows for the simulation and display of the printing layers by height from the ground. The aids in understanding how the shelter will be printed/constructed.

Model Info/Outputs: The user interface Displays a set of outputs aiding the user in making a decision on their generated design. These outputs include; printing time, material volume, cost, built up area, printing path lengths, and more. These outputs are already calculated for each design variation within the computational workflow.

End Users

The design tool and user interface are meant to be as accessible as possible to a wide spectrum of users in order to enable a collaborative process where any combination of stakeholders can generate and share designs with easy. The relevant stakeholders and intended users shown in the figure below are as follows;

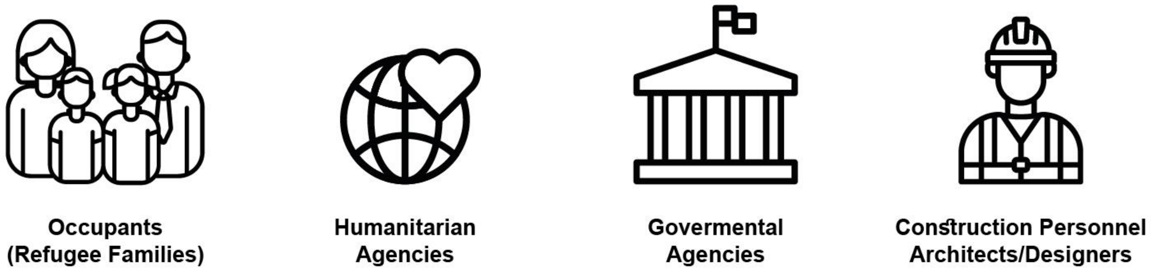


Figure 56 UI Intended User Groups
Source: Author, Icons: thenounproject

Refugee families (occupants): as the main target group, refugee families are able to tinker with the various controls and inputs depending on their preferences and needs and visualize the resulting design within the main UI screen. The tool also enables them to share the resulting designs within their circles and with the relevant agencies.

Humanitarian agencies: Agencies such as the UNHCR and other NGOs usually taking a leading role in the design and planning of refugee camps are able to visualize the different design possibilities and the resulting logistical outputs of each design option prior to implementation which can be helpful in the planning stages.

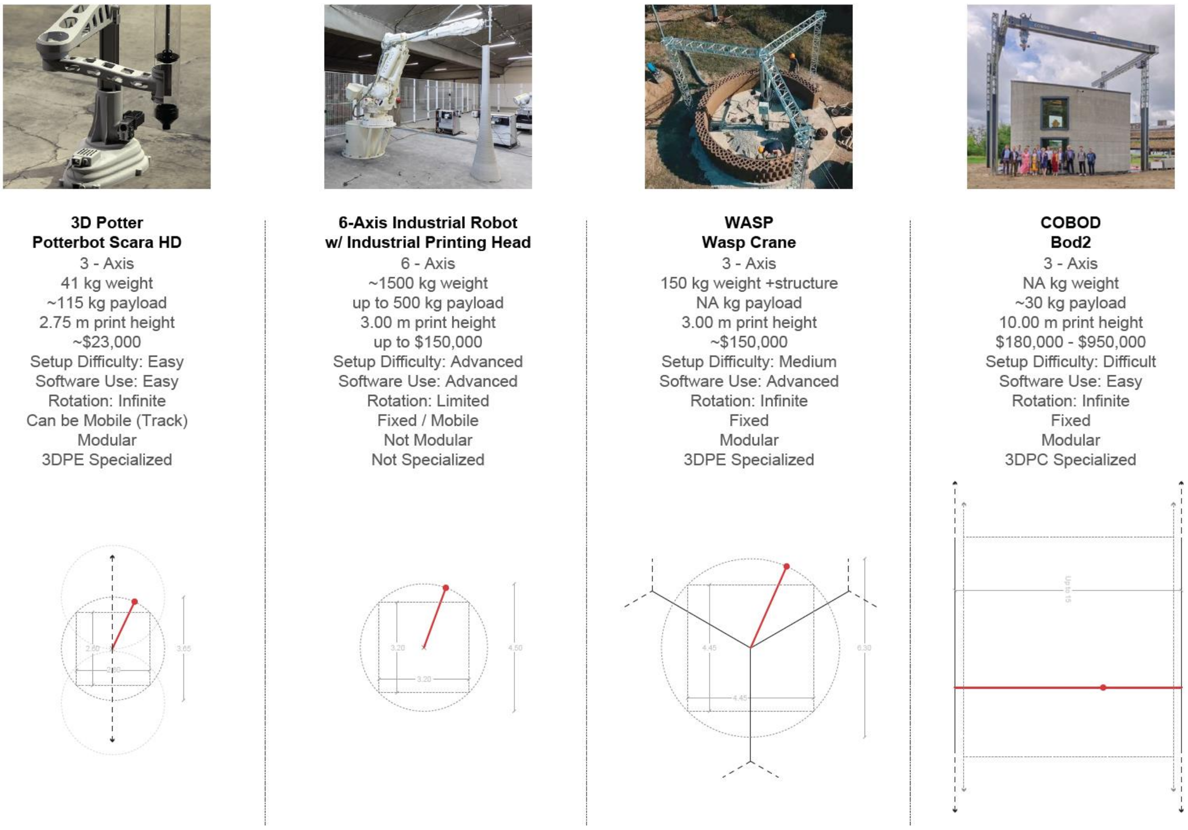
Governmental Agencies: Along with humanitarian agencies, governmental agencies overseeing camp planning, and making the top level decisions, are able to visualize the various shelter design alternatives and assist them in making informed decisions.

Construction Personnel: Workers operating on the construction site and working with the robots are able to export the printing paths directly from the UI as well as view all relevant design drawings.

Designers: Designers are able to collaborate with the different stakeholders in helping them understand their needs and assisting in using the UI to generate various designs. Designers are also able to use the tool to inform the urban planning and urban design stages refugee camps.

4.4 3DPE Robotics Market Study

From the available robots that can be used for 3d printing the WASP crane robot is chosen. This 3-axis robot is made specifically for 3d printing earth and although more expensive than the Potterbot printer it is more versatile as it allows for a considerable larger printing area. It is also modular and allows for the connection of multiple printing heads that can work simultaneously. The figure below shows the robot options and their respective specifications.



3D Potter **Potterbot Scara HD**	**6-Axis Industrial Robot** **w/ Industrial Printing Head**	**WASP** **Wasp Crane**	**COBOD** **Bod2**
3 - Axis	6 - Axis	3 - Axis	3 - Axis
41 kg weight	~1500 kg weight	150 kg weight +structure	NA kg weight
~115 kg payload	up to 500 kg payload	NA kg payload	~30 kg payload
2.75 m print height	3.00 m print height	3.00 m print height	10.00 m print height
~$23,000	up to $150,000	~$150,000	$180,000 - $950,000
Setup Difficulty: Easy	Setup Difficulty: Advanced	Setup Difficulty: Medium	Setup Difficulty: Difficult
Software Use: Easy	Software Use: Advanced	Software Use: Advanced	Software Use: Easy
Rotation: Infinite	Rotation: Limited	Rotation: Infinite	Rotation: Infinite
Can be Mobile (Track)	Fixed / Mobile	Fixed	Fixed
Modular	Not Modular	Modular	Modular
3DPE Specialized	Not Specialized	3DPE Specialized	3DPC Specialized

Figure 57 Available Robotic Options Comparison Chart
Source: Scara, Vertico, Wasp, Cobod

4.5 Construction Sequence

After the printing paths and g-code are generated from the software, construction on site can commence. This begins by creating stone foundations in order to prevent water damage to the walls, which is followed by setting up aluminum truss frames that are a part of the chosen WASP Crane modular system, installed with base plates and a liquid deposit modeling extruder and a movement core.

The earth material is extracted from the site and tested to determine its composition. The soil is first sifted then mixed with the required additive materials at the mixing station. The mix is fed into a continuous feeding and cleaning system to the extruder's nozzle and the printing can start. Window and door frames are fitted as the print continues. If the chosen roof material is not earth, then the roof is installed after the printing has finished. This process is the same for shelters made up of multiple units where more than one extruder is used to print simeltanously.

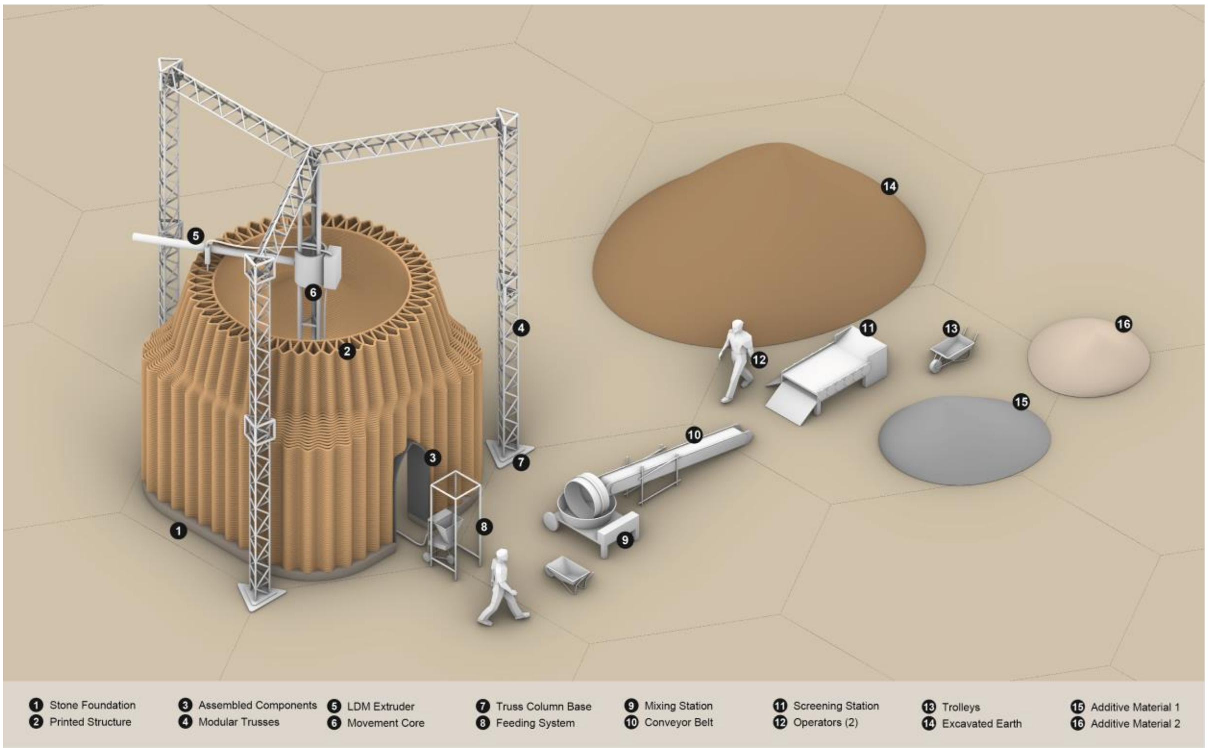


Figure 58 Urban Construction Sequence
Source: Author

On the urban scale, site features such as open air amphitheaters can be created with the extracted material being used in printing the shelters. These excavations are first made where nearby shelters are to be constructed, meaning the material will require minimal transport and makes itself available as needed. Multiple printing robots can be used and reused to print a neighborhood as in the example shown in the figure below where it can be printed within a few weeks using 3-4 robots.

After the refugees leave the camp, the non-earthen building components can be disassembled and later reused or recycled, with the remaining bulk of the structures being biodegradable, leaving the site with minimal to no damage. Vegetation will have grown large enough meaning trees could survive on their own resulting on a net positive impact on the site.

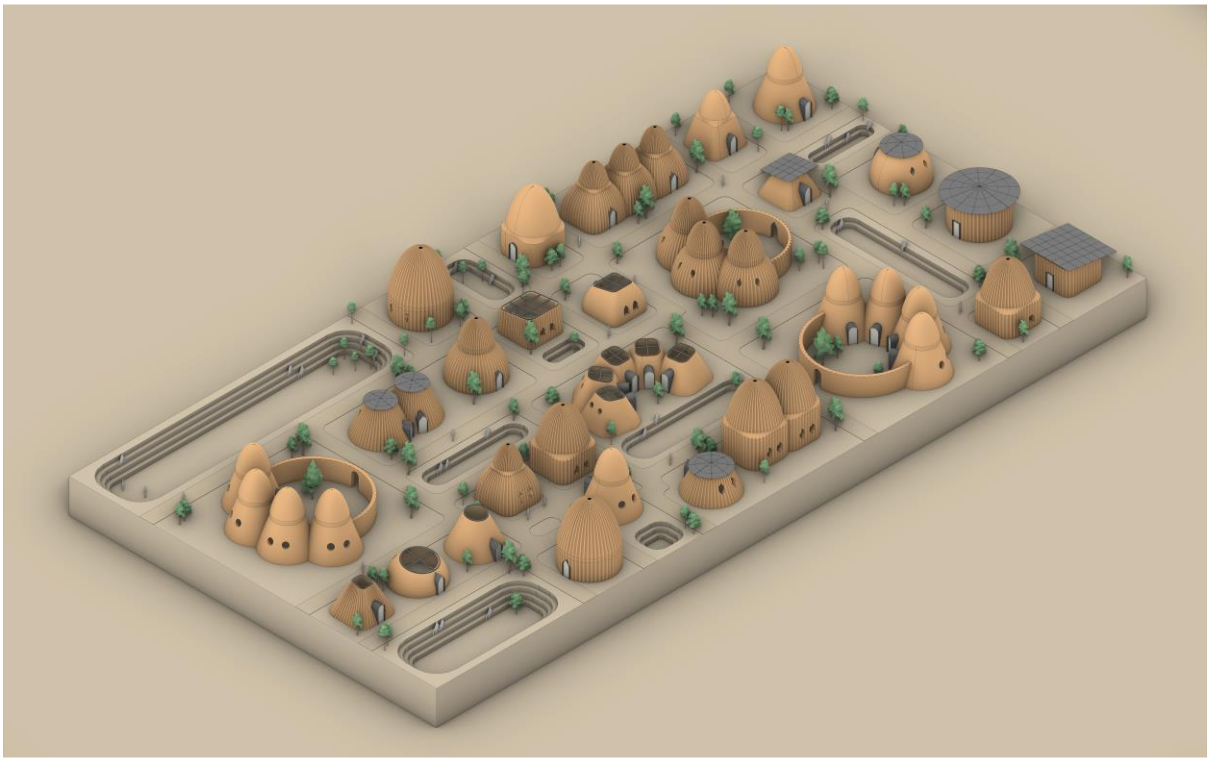


Figure 59 Constructed Camp Sector Scenario
Source: Author

Discussion

With the developed computational tool and user interface, refugees are able to customize their shelter designs for 3d printing with earth. A set of simple inputs and sliders allow them to generate bespoke solutions that cater to their individual needs and preferences. The versatile computational design tool can generate a wide range of up to thousands of different design options resulting in an expansive library of potential alternatives for users to choose from.

5. Robotic Production

This chapter consists several prototyping experiments in order to mimic the real world application of printing the produced shelters but on a smaller scale first with commercial 3d printers using PLA and then followed by using the soil collected on site to print a slightly larger scale prototype using a 6 axis robot.

5.1 PLA Models

These models will showcase a sample of the wide variety of alternatives that can be generated from the design tool. They will also act as a preliminary proof-of-concept before moving onto the 6-axis robot and will allow for design adjustments to be made based on observations from the models. The models will demonstrate an array of different forms of design iterations generated by the design tool, and their ability to be printed layer by layer without the use of additional supports, which mimics how a full scale model would be printed using earth materials.

Tools Used: Anycubic Chiron 3D Printer at the faculty's lab for additive manufacturing, 0.4mm nozzle, white PLA plastic, Cura slicing software.

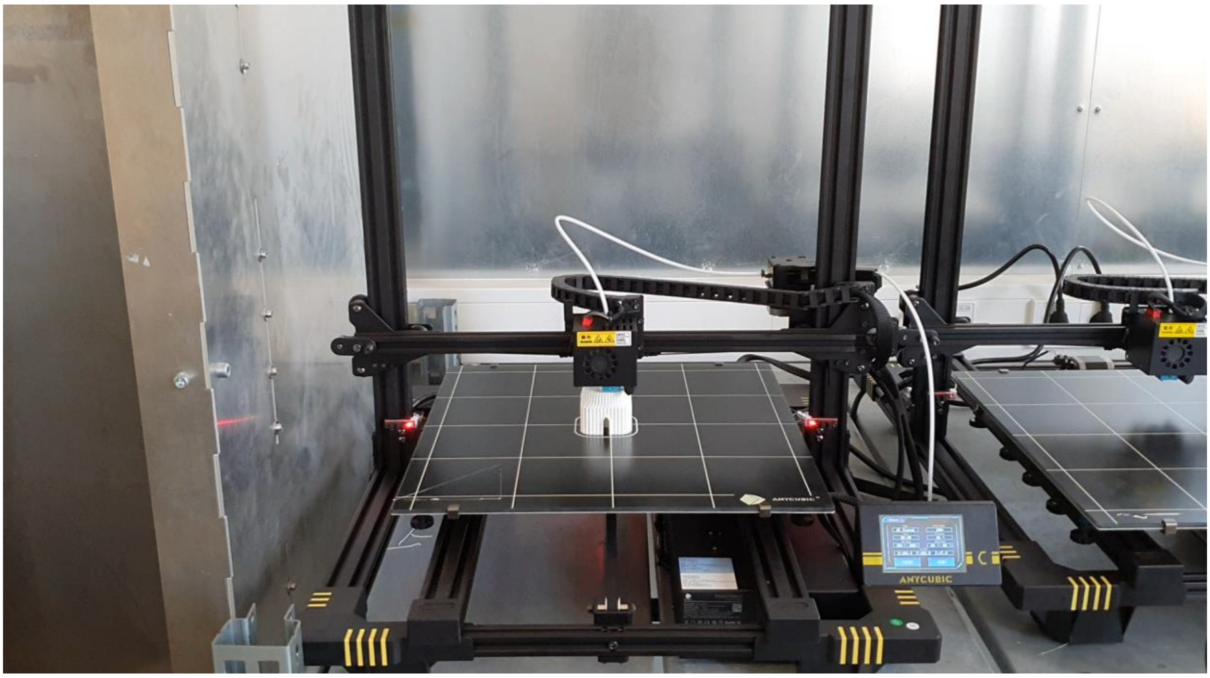
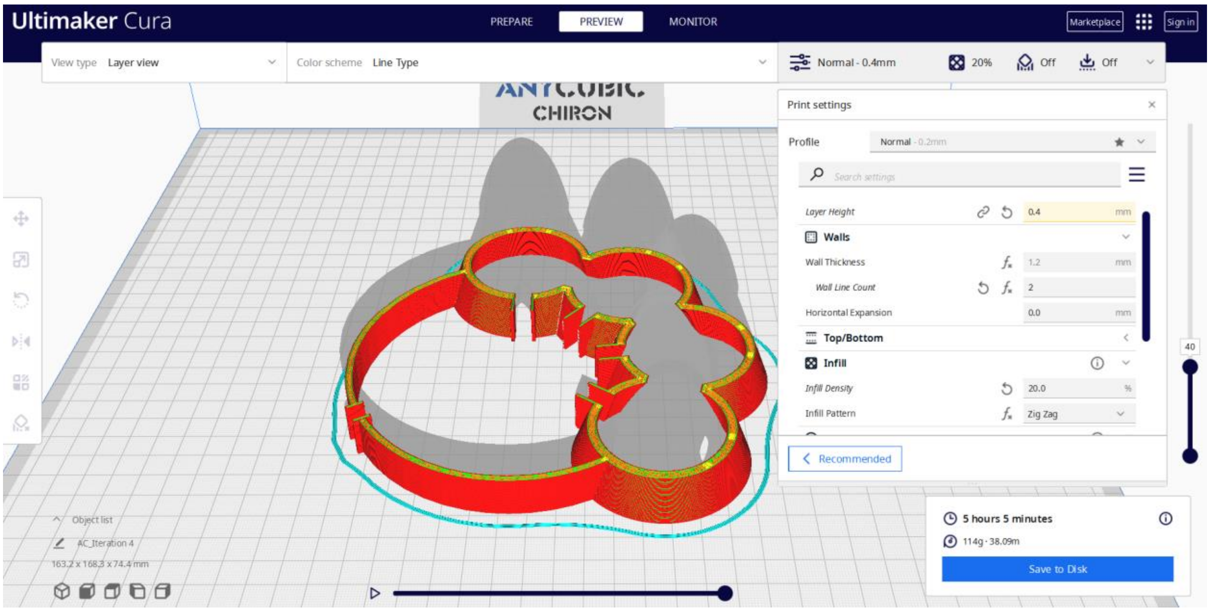


Figure 60 3D Printer at the LAMA Lab Printing a Design Iteration
Source: Author



View type: Layer view
Color scheme: Line Type
Normal - 0.4mm · 20% · Off · Off

Profile: Normal - 0.2mm
Layer Height: 0.4 mm
Wall Thickness: 1.2 mm
Wall Line Count: 2
Horizontal Expansion: 0.0 mm
Infill Density: 20.0 %
Infill Pattern: Zig Zag

5 hours 5 minutes
114g · 38.09m

Figure 61 Print Settings and Software

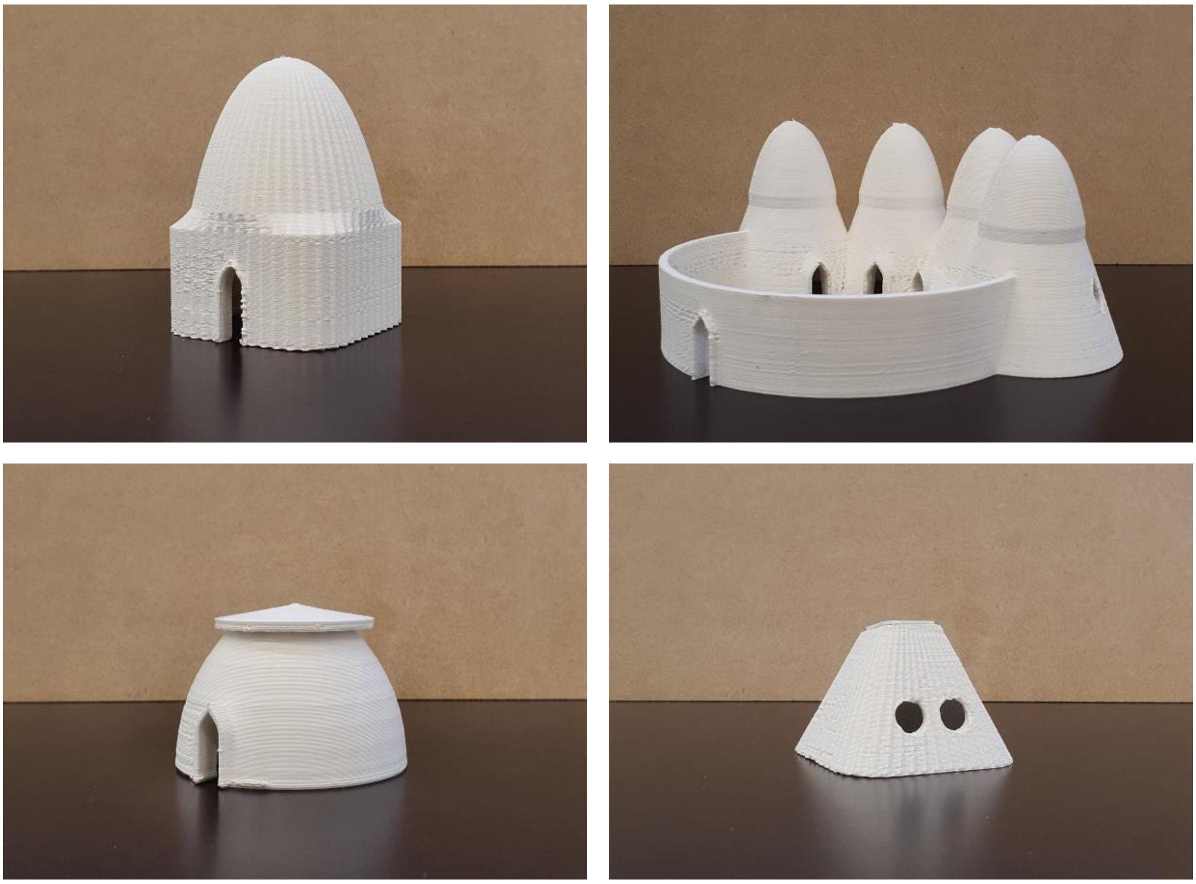


Figure 62 1:100 3D Printed PLA Models
Source: Author

5.2 Clay Prototype

For the clay prototypes a number of 1:5 scale models were printed in order to test the material's printability, demonstrate the design to robotic production workflow, and experiment with the different print settings and variables.

Tools Used

The printing took place in the LAMA lab and made use of the available resources in the lab suitable for clay 3d printing. The tools used are as follows;

UR5 Robot Arm: A robotic arm with a user friendly input panel that has a 5kg payload capacity.

Extruder: WASP XL LDM extruder with 4, 6, and 8mm nozzles, a stepper motor, a feeding tube, a main shaft, and plastic screw barrel.

Mount: A custom made mount for connecting the extruder to the UR5 robot arm. This mount was developed by Christopher Bierach.

Control Board: A circuit board enabling the control of the extruders settings and power connection.

Printing Bed: A board set in a fixed position with a known height and reference point for the print material to be extruded onto.

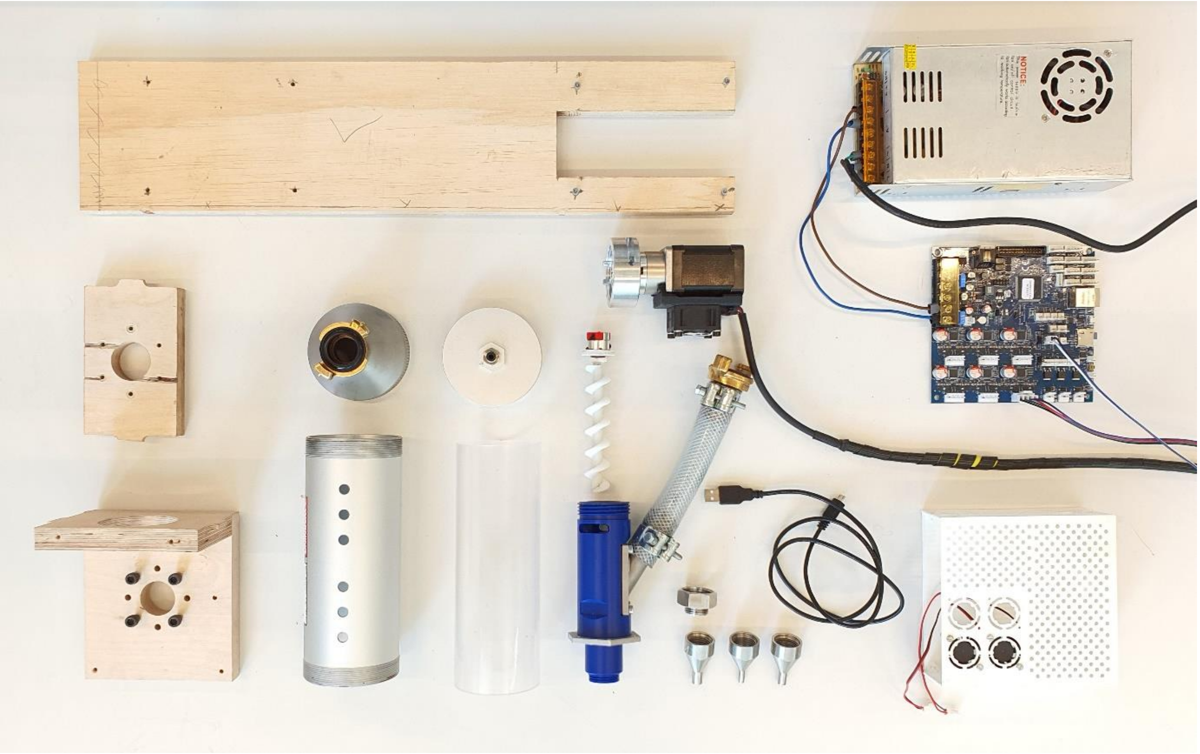


Figure 63 Extruder Setup Components

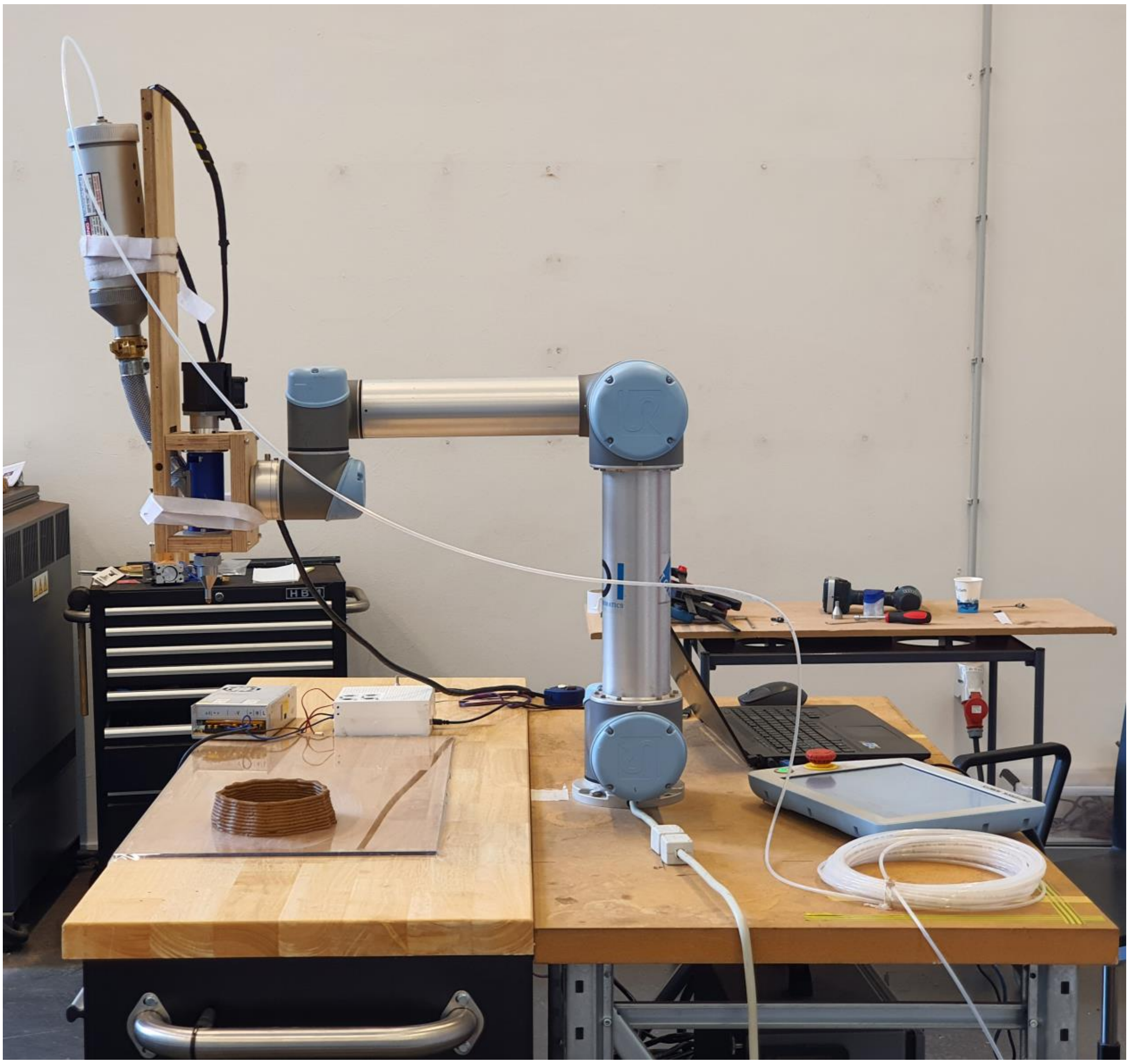


Figure 64 Printing Setup
Source: Author

Method

From the sliced surfaces generated in the design tool, printing paths are created which are then fed into a script using the “Robots” plugin within Grasshopper. This script converts the printing paths into robot movements with the desired end effector and generates the g-code to be fed to the robot arm. Before printing, a simulation is produced within the software in order to observe the robot movements and determine if everything all the movements are correct before proceeding to physically printing.

The material is then prepared by mixing the correct ratios of soil, additives, and water in order to reach the intended viscosity. This material is then filled into the cartridge while taking extra care that there are no air bubbles present, then the cartridge is connected to the LDM extruder. An air compressor is connected to the cartridge from the other end to ensure material flow.

Once the setup is ready, the generated g-code is transferred from the computer to the robot arm, and the extruder is simultaneously turned on and controlled through a computer connection.

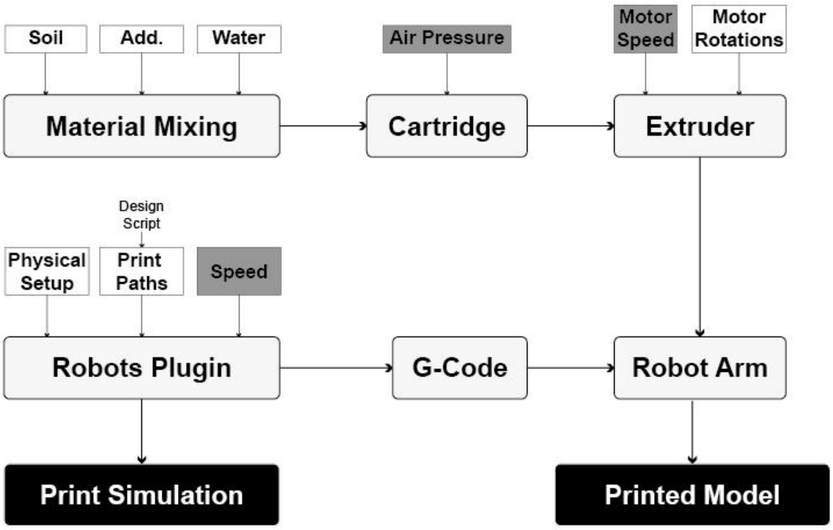
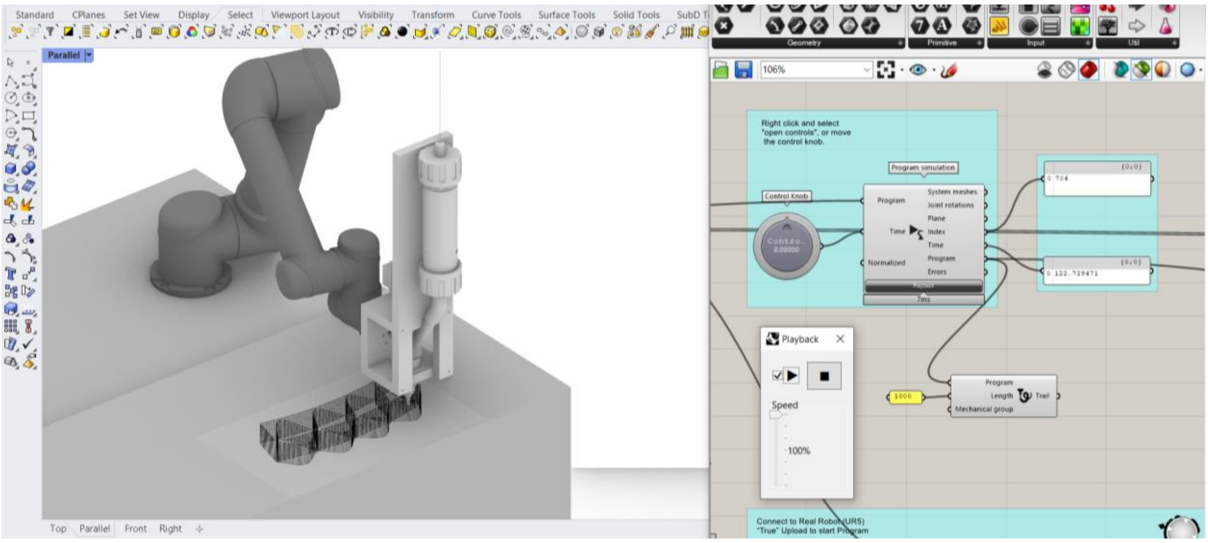


Figure 65 Clay Prototype Production Workflow
Source: Author

The speed of printing is determined by three variables which need to be in sync through trial and error in order to achieve a smooth controlled print. These variables are; air pressure, motor rotation speed, robot arm movement speed.

Simulation

Before moving on to printing using the robot, first a simulation is done through the Robots plugin. This will aid in setting the printer speed and defining the printing path locations which can then be exported to the robot. Simulating the printing process proved to be an important step as it helps in discovering any potential issues before actually printing. This setup was developed in collaboration with Christopher Bierach.



Right click and select "open controls", or move the control knob.

Connect to Real Robot (UR5) "True" Upload to start Program

Figure 66 Robotic Simulation
Source: Author

Extruder Test

Before moving onto the final printing stage, a manual extrusion test is done with the extruder alone in order to determine the correct settings (air pressure, motor speed, etc) before attaching it to the robot arm. The test reslts are shown in the figures below. Earth and sand are used here in place of soil from the site due to its limited available quantity.

Figure 67 Extruder Test Results
Source: Author

Prototype Printing

A number of printed play prototypes are produced using the developed earth mixture and with the soil collected from the camp sites. This will also act as a proof of concept with observations to learn from knowledge that can be transferred as recommendations for printing at a 1:1 scale.

The models printed are a 1:5 wall section with wall infills using a 6mm nozzle and printing 8 layers, as well as a 1:20 scale print of the outer shell of an example shelter.

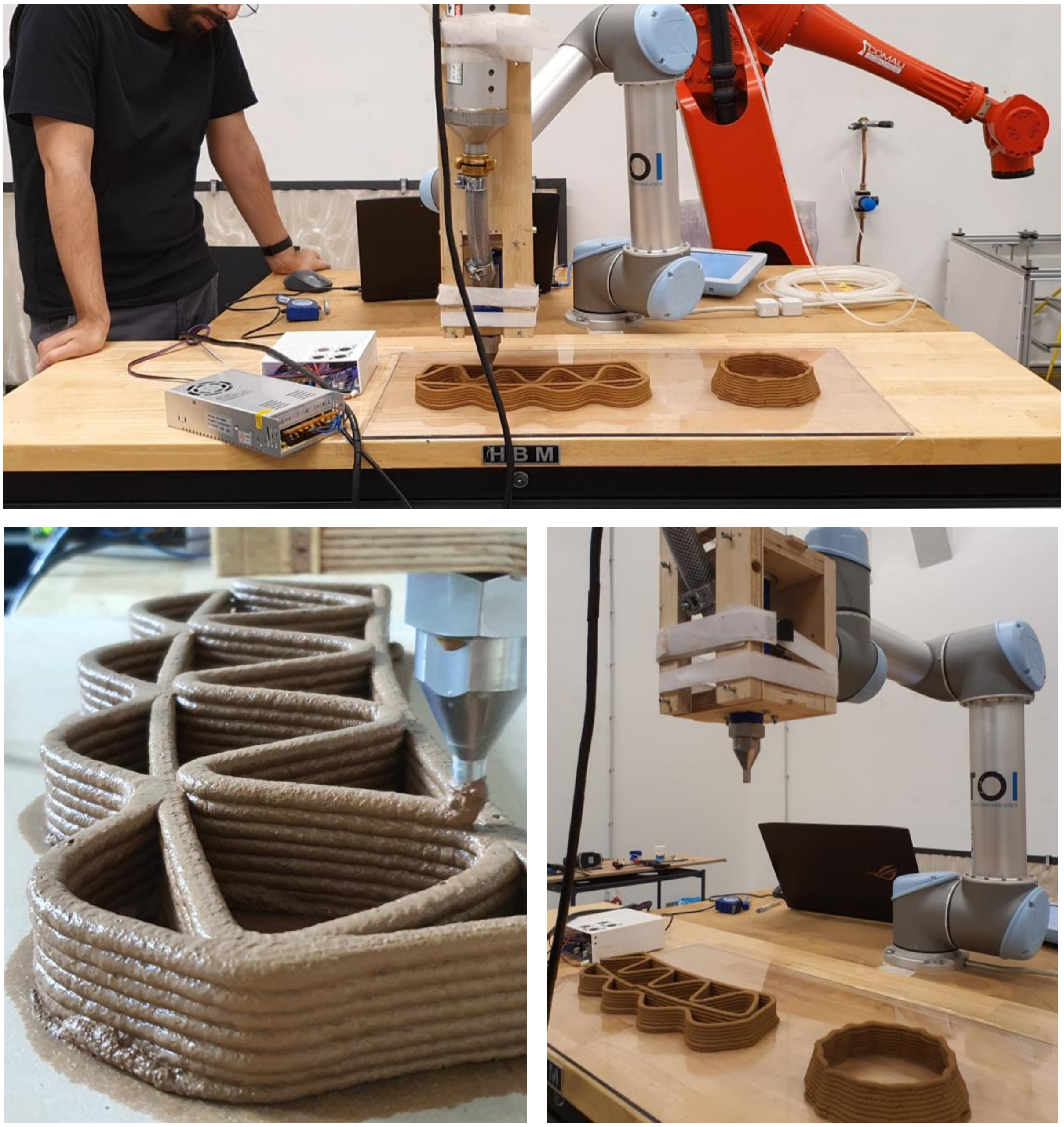


Figure 68 Clay Prototype Printing
Source: Author

Discussion

Several Prints were produced using material collected from the refugee camp sites along with additives as highlighted in the final mixture in the material chapter of this research. This demonstrates the printability of the material found on site as well as a proof-of-concept for the material extraction to design to robotic production workflow.

Due to the UR5 being rather small with a payload of only 5kg, the scale of achieved prints is rather small. Furthermore, and since the extruder is controlled separately, it is difficult to refill the cartridge and have the robot start again from where it stopped since both the robot and extruder would need to be manually stopped at the exact same moment. This leads to the amount of layers and model size to be restricted to one cartridge of material.

Viscosity is also a very important factor, and since the available nozzle sizes are rather small, no large fibers could be added to the mix. Where in a 1:1 scale, larger fibers that increase the tensile strength of the mixture can potentially be added. The limited motor powers also meant that the mixture had to be made more wet for the motor to be able to push out the material, which also led to more shrinkage and cracking in the final prints after drying. This was overcome by covering the prints as they dry.

6. Conclusions

This chapter contains research conclusions, reflections, limitations, and suggestions for future research possibilities that could be a continuation of this research.

6.1 Conclusions

This research aimed to answer the main question of “How can additive manufacturing be employed in creating mass-customized refugee shelters using on-site earthen materials? “which was further divided into the three subcomponents of material, design, and robotic fabrication.

A review of relevant literature assisted in understanding the properties of earth as a construction material, along with potential additives and their expected effects on earthen material mixtures. This was followed by a study of historical precedents which further elaborated on the potentials of using of earth as a construction material. More recent precedents regarding 3d printing earth constructions aided in understand the process of creating a design tool for 3d printed structures. Furthermore, an understanding of the current situation of refugee camps and shelters, along with refugee needs assisted in deriving a set of shelter design requirements.

After testing multiple earth mixtures, a final mixture was developed and is composed of clay (42%), sand (28%), ash (20%), and fine sawdust (10%), with the ratios of sand and clay based on the ratios found in the composition of soil samples collected from the sites of Azraq and Zaatari refugee camps. Although the sand and clay mixture surprisingly resulted in a slightly higher compression strength, the added benefits of using ash and sawdust in the mixture are what influenced outweighed the small difference in compressive strength. It was also chosen in favor of lime as ash is widely available as a waste material that is easily produced and is usually disposed of with limited other uses for the material giving it a second life. In comparison to using clay on its own, the resulting mixture is shown to improve the qualities of extrusions in terms of shrinkage, compressive strength, tensile strength, drying speed, deformation, cracking, insulation qualities, lightness, and interlayer bonding.

Afterwards, a computational tool and user interface were developed, allowing refugees to customize their shelter designs for 3d printing with earth. A set of simple inputs and sliders allow them to generate bespoke solutions that cater to their individual needs and preferences. The user inputs can control variables such as wall profiles, opening shapes, privacy, layout, roof type, wall height, wall patterns, and more. The versatile computational design tool can generate a wide range of up to thousands of different design options resulting in an expansive library of potential alternatives for users to choose from.

Finally a set of 1:10 3d printed design iterations are produced showcasing the wide variety of design options followed by a 1:5 printed prototype using the developed earth mixture as a proof of concept.

6.2 Reflection

Relationship Between Graduation Topic and Studio Theme

The graduation topic ‘Digital Earthen Shelters’ falls within the intersection of the studios choices of Design Informatics and Material Sciences and within the larger theme of the sustainable graduation studio. This research utilizes methods from the fields of design informatics and material science in order to develop a tool and workflow for mass-customizing additively manufactured refugee shelters using earthen materials found on site. Both realms of architecture and engineering are combined in using robotics, material mixtures, and computational tools in order to design, prototype, and construct functional refugee dwellings which is very much at the core of what building technology is about. This in turn also fits into the broader fields of architecture, urbanism, and building sciences as it concerns the spatial design and fabrication of dwellings in the context of refugees and refugee camps which themselves are becoming urban settings.

The research is posed as is a continuation and builds upon previous research topics revolving around robotic 3d printing with clay for building components that have taken place in recent years within the Building Technology program at TU Delft. Namely, these are the Master’s theses works of Ammar Taher Ibrahim, Maximilian Mandat, Athanasios Rodiftsis, and Tommaso Venturini.

Methods and Processes – Relationship Between Research and Design

The main objective of this research was to identify a method to create a tool for mass-customized 3D printed shelters for refugee families catering to their longer-term needs, and by using earthen materials that are found on-site. This was done through dividing the research into three subcomponents of material, shelter design, and fabrication process. Methods of design by research and research by design were implemented in these three subcategories.

Researching the properties and behavior of earth as a building material and potential additives was done through reviewing the relevant literature and precedents. This in turn informed the development of multiple mixture experiments that were evaluated leading to a final mixture to be used as a printing medium along with a guide for creating the mixture as soil compositions vary from one site to another.

Following the research and analysis of varying refugee needs shelter requirements, a digital workflow for mass-customized refugee shelter designs was created. Design parameters influenced by user inputs generate the final bespoke shelter design to be printed on-site.

A study of available and feasible robotic production methods is then carried out informing the logistics and construction sequence of realizing these shelter designs within a refugee camp context. The generated design iterations are then prototyped as a proof-of-concept. This is achieved first through robot simulation software, followed by 3D printing multiple scale models using a PLA printer, and finally a scaled prototype using the UR5 robot in the LAMA Lab utilizing the developed soil mixture as a printing medium.

SWOT Analysis of Methods;

Strengths	Weaknesses	Opportunities	Threats
• Developing Computational Workflow Skills • Material Exploration • Learning Fabrication Methods	• Emerging Field with Limited Precedents • Procurement of Additives/Materials • Limited Access to Sites	• lab resources and tool utilization • Industry Partnerships • Sustainable and Innovative Solutions	• Inconsistent Material Behavior • Complex Robotic Processes • Time Constraints and Scope Limitations

Impact

Social Relevance and Sustainability:

The social component is central to this research as it concerns the current state of refugee sheltering and livelihood. Refugee numbers are unfortunately rapidly increasing in recent years due to continued global humanitarian crises with a need for adequate and less temporary sheltering solutions that meet their individual needs.

Optimizing the use of 3D printing earth for refugee shelters can have an immensely positive effect on the livelihood of said refugees by creating bespoke long-term dwellings that they can belong to fostering social sustainability. This also comes along with great benefits for the environment as earth is shown to be a widely available, reusable, biodegradable material with extremely low environmental impact. Innovations in the field of large scale additive manufacturing are constantly evolving and will continue to improve and are increasingly becoming more affordable and mainstream. The application of innovative technologies such as large scale additive manufacturing could also assist in creating new skills and job opportunities for marginalized refugee groups within emerging economies in developing countries.

Scientific Relevance:

Additive manufacturing in the field of construction is an emerging technology with new advancements being constantly made as we transition into more digital workflows to create our built environment. A main attribute of additive manufacturing is that the end product can be infinitely customized for each iteration of production, meaning that mass customization is inherent to the process of additive manufacturing, which in combination with using earth found on site as a medium for printing, could make it a viable and innovative approach to constructing shelters.

This research contributes to both fields of material science and design informatics by identifying a viable material mixture consisting of earth found on site, and a developing computational workflow to create mass customized 3d printed earth shelters informed by individual user needs.

Ethical Considerations

The context of refugee camps can be sensitive and politically unstable. When visiting the camps for the soil collection, extra care was taken in communicating with the authorities present on-site about the purposes of the research and the intentions of collecting the samples. Further attention was given to the documentation process, where no refugees or individual refugee dwellings are depicted in any of the collected imagery without consent.

Furthermore, the use of robots for construction can be seen by some as a cause for increasing unemployment rates by replacing traditional construction labor. It can however be argued that through the deployment of robots and training people to use them, their skillsets will be elevated and new work opportunities will arise in creating more efficient and bespoke solutions.

6.3 Further Research

Some aspects that fall outside the scope of this research could be developed in future research projects as a continuation to the findings of this research as follows;

Dwellings: The design tool could be developed into a more universal application that works for a wider range of 3d printed dwelling in all settings, and perhaps for materials such as concrete as well.

Structure: Further research can be done to incorporate structural calculations and optimization with the computational design tool and user interface.

Building Performance: The integration of building performance indicators such as climatic conditions, thermal performance, acoustics, lighting, and more could be beneficial in realizing a more holistic solution.

Carbon Footprint: The design tool can also be developed to integrate an impact analysis informing the user of potential environmental benefits of the designs they generate and aid them in making an informed decision.

Full Scale: Developing a 1:1 prototype will give more insight into a more realistic application of the shelter designs. This will also help in developing wall infill patterns, mechanical components, electrical components, plumbing, skill training, and more.

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Appendix

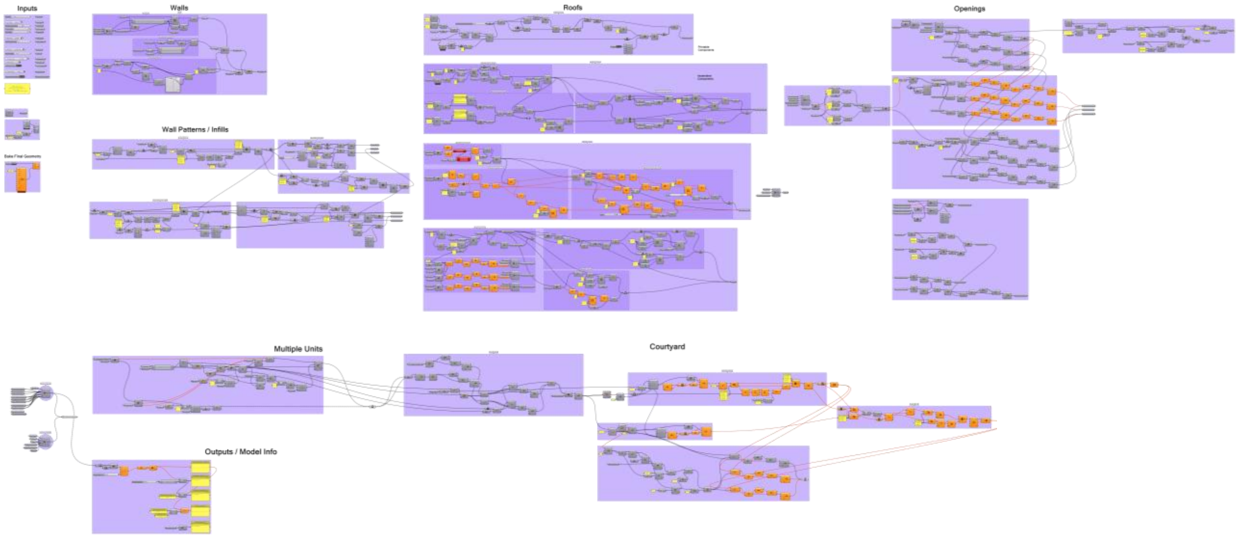

Figure 69 Design Script Overview
Source: Author


No. Units 3

Base Shape Circle

Max Radius 3.3

Corner Radius 1.2

Wall Height 4.0

Wall Profile Straight

Wall Inclination Deg 21

Roof Type Hybrid

Roof Tilt Angle 12

Opening Shape Teardrop

Privacy Level 2

Closed Courtyard False

Facade Pattern Wave 2

Figure 70 Computational Script Inputs

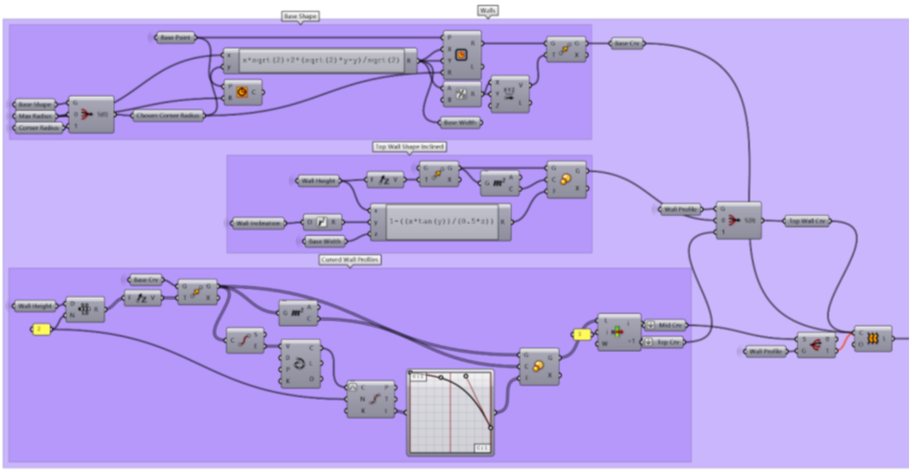

Figure 71 Wall Profiles Script

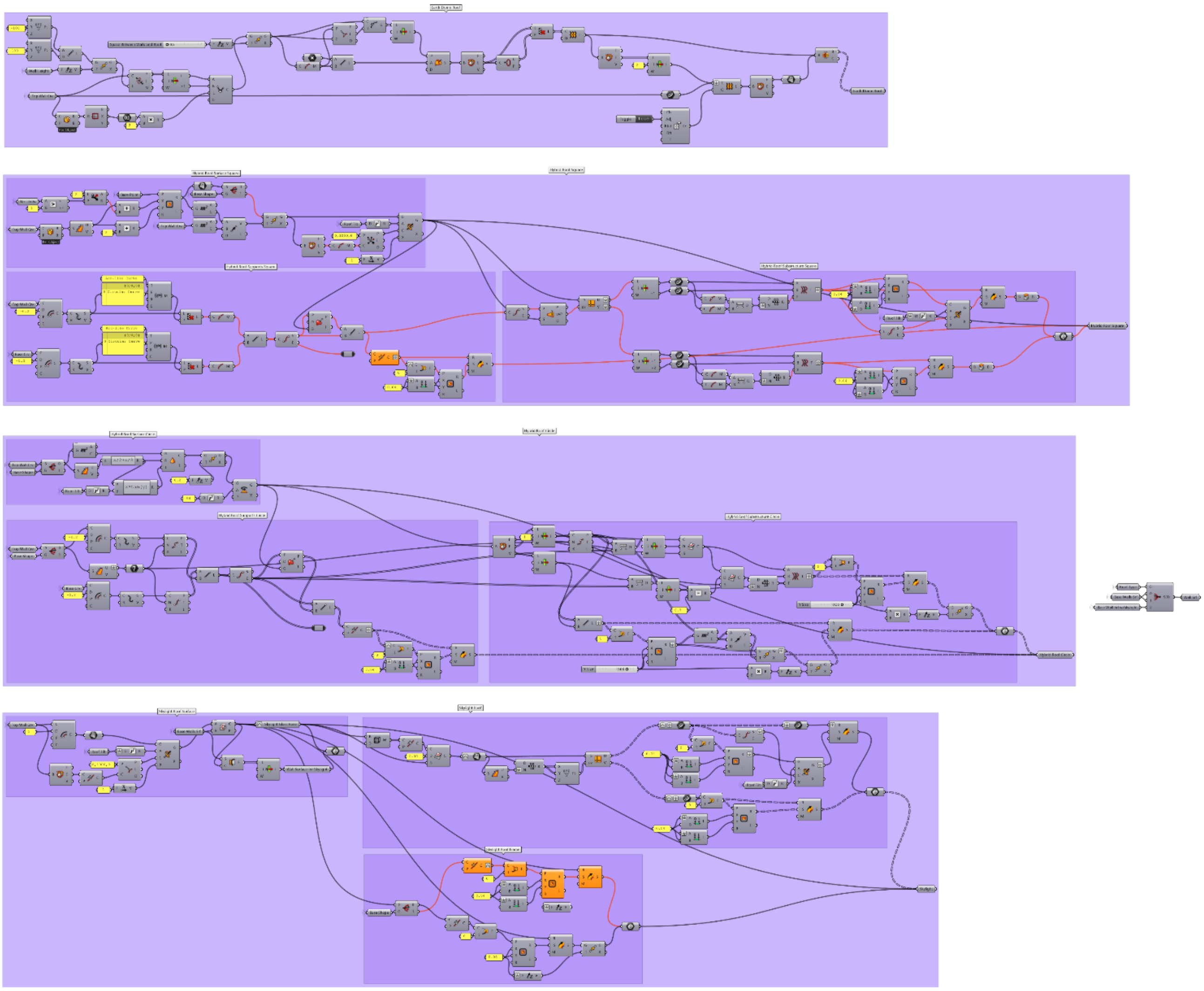

Figure 72 Roof Types Script

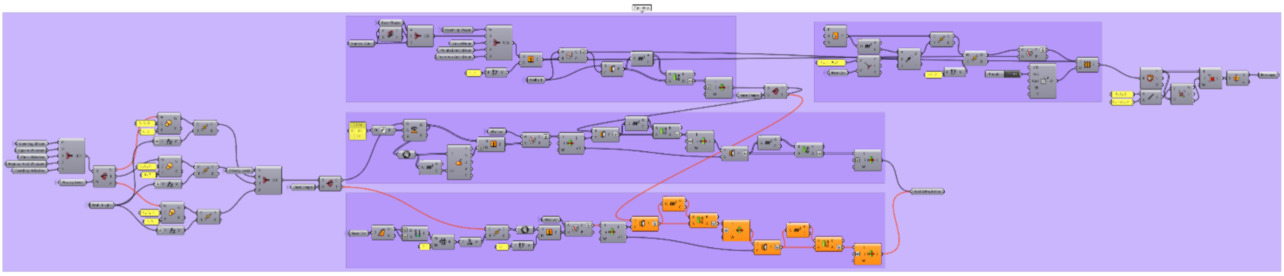

Figure 73 Openings Script

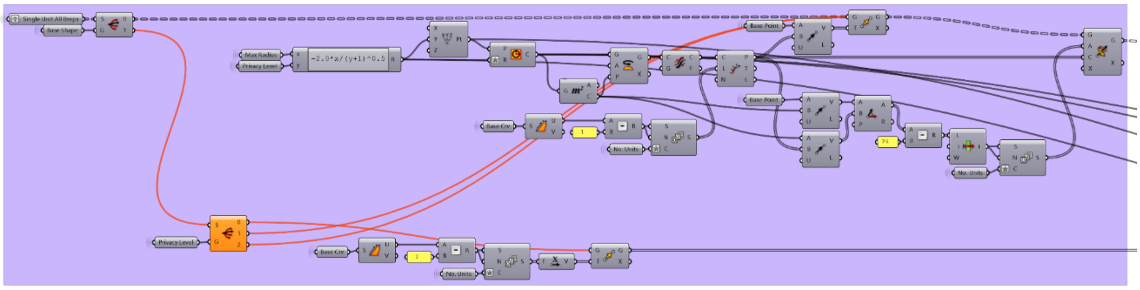

Figure 74 Unit Distribution Script

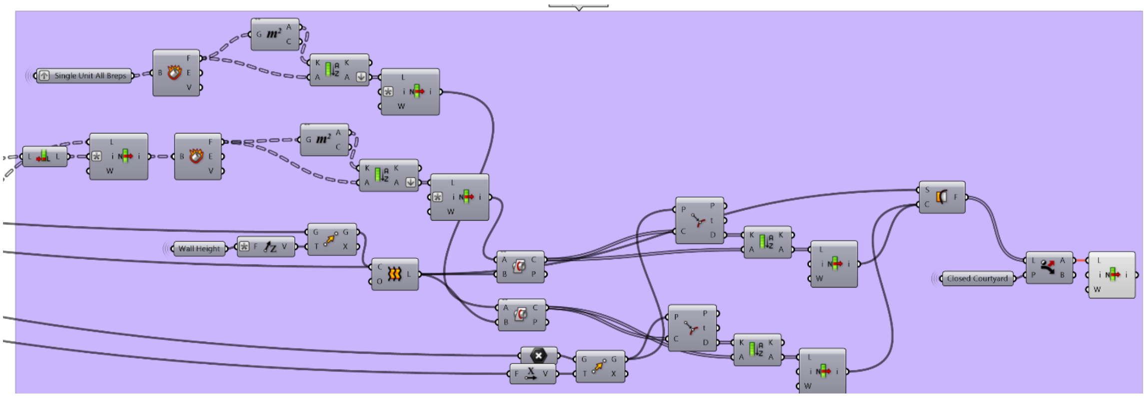

Figure 75 Layout Privacy and Courtyard Wall Script

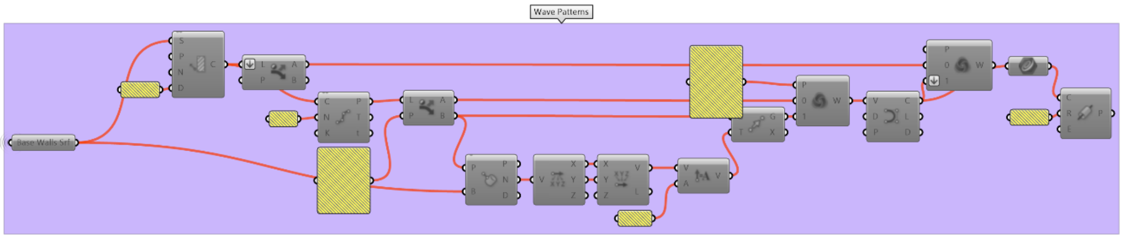

Figure 76 Wall Patterns and Printing Paths Script