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MSc Architecture, Urbanism & Building Sciences
Building Technology Track

3D PRINTING CLAY FACADE WALLS

Integrating Ventilation Systems Into Printing Process

Thesis report

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Abstract

Since 3D printing is relatively new in the architecture applications, exploring how it could be integrated with environment-friendly materials as clay could lead to a more sustainable approach for materialising complex building components. This research is investigating the answer to the research question “What are the printing techniques and tools that can help integrate the clay as an environment-friendly material, into the 3d printing of building components, while maintaining the required indoor and outdoor performance quality?”.

The research was divided into four aspects of exploration and design. Clay as a printing material, ventilation system as a wall component to be prototyped, Robotic fabrication as the process to be considered while designing and Extrusion system for the printing to realise and materialise the prototype design. Four of them abbreviated as CREW.

Firstly, material research lead to choosing stoneware clay as a suitable clay type for architecture and building components due to its thermal properties, shrinkage and plasticity behaviour in addition to its availability and cost. Later material experiments were conducted on small scale prototypes for seven different organic additives to the clay body; to improve its performance in terms of shrinkage, cracking, extrudability, and printing time. The final mixture was found to be clay in addition to Chammote 0-0.2 mm grain size, Gypsum and Water as a binding substance.

Secondly, the displacement ventilation system was designed according to the HVAC ventilation system requirements and the design criteria derived from literature review. Eventually, multiple variations for the duct complex geometry were evaluated and verified for their performance according to the concluded design criteria. These Morphological variations were introduced into CFD simulation by Ansys Fluent software to validate the results in terms of the pressure drop and outlet air velocity values. Air streamlines and flow over the different branches of the morphology to assure better air distribution over the case study room was considered as well.

Thirdly, out of the final morphology of the ventilation system, a proportion of 90 cm height and a base of 70*30 cm was chosen as a prototype for the printing process exploration. This prototype was sliced in by a designed Grasshopper script in Rhino software. Sliced geometry was then further developed and designed in terms of the infilling of the prototype wall. The infilling consisted of four elements, layer boundary, overhangs from the duct, structural supports for the layers and the thermal buffer for thermal performance. The thermal performance was evaluated using Therm in Ladybug tools for Grasshopper.
Eventually, a particular design for the infilling or the tool path for the robot program was found. The robot program was generated using RoboDk offline programming tool for robots. The generated tool path was linked from Grasshopper design to RoboDK directly, which eased adjusting and sampling the prototype.

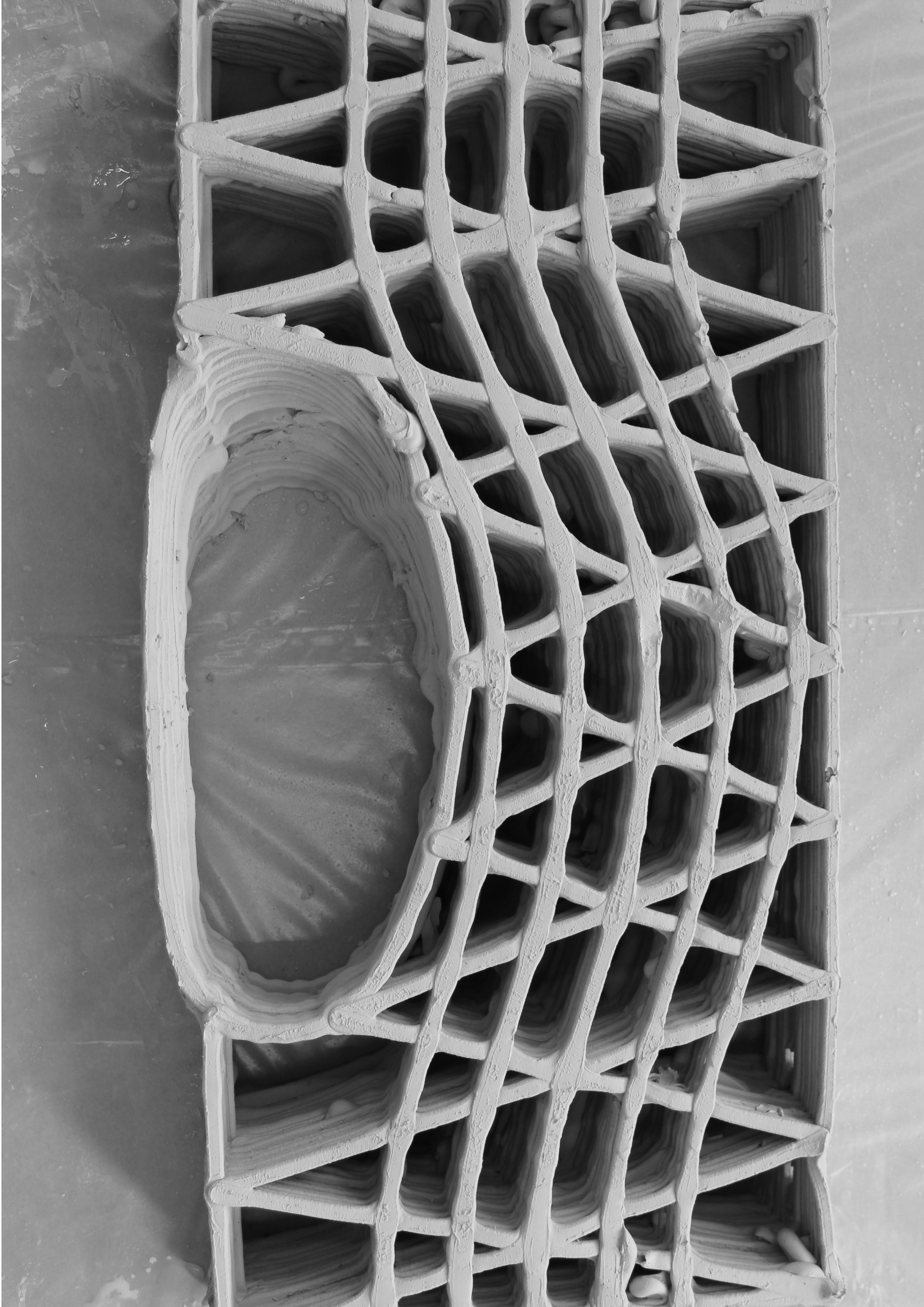
Finally, in parallel to generating and designing for the prototype printing, the hardware and tools were prepared. These tools included extrusion system of an extruder motor and its control board. A cartridge system of air pressurised PVC cartridge and the filling of the material into it while feeding it also to the extruder. Eventually, the robot and calibrating it with the printing bed height, nozzle height and the movement speed with the motor extrusion speed and air pressure.

Out of this process, a final prototype was created during the exploration of the clay in this large scale of 3d printed building components. So eventually, a design guide was created and a recommended process developments were illustrated. Lastly the aspects that require further development and the limitations were concluded.

Content

1 INTRODUCTION

This chapter introduces the research frame work. After narrating reserch background, the problems, objectives, questions, methodology and design assignments are elaborated.



1. Introduction

1.1 Background | Narrative

Due to the raising awareness about our environmental impacts as human beings on our planet and its climate change, we as architects became more aware now of how our architecture and the built environment has a significant role in climate change and sustainability approaches. According to the US Energy Information Administration annual report, the Building industry resembles more than 40 % of the energy consumption in the US, just as similar it is in most of the world (2012, P. 106). This energy consumption is not only for the construction process of the buildings, but also it represents the operational period of the building life span. During the operation phase of a building the energy consumed in cooling, heating or lights and all user comfort related devices, this energy consumption is highly controllable by the architect's design decisions that affect the thermal comfort or the building physics-related aspects. These aspects as for natural lighting or ventilation. Moreover, the choice of materials used in the building or its structure also affects the foot-print and the embodied energy of the whole building industry. Hence, seeking sustainable architecture -that has less footprint and ecological effect -has emerged in the latest decades as a design approach that is a must more than a luxury.

Consequently, performative design approaches have gained much attention, as it helped in creating an architecture that achieves high-performance criteria in terms of spatial quality, energy consumption, or structure behaviour. These performances are mostly created to reduce the footprint of the building industry by optimising the building's architecture, technology, and production.

CAD tools (Computer Aided Design) emerged and eased the process of the performative design by simulations and analysis possibilities that guided the form generating process. As a result, building geometries became more complex in its mass, form and morphology. This approach is because different buildings in different context and constraints generated different geometries. Hence, new innovative fabrication and production techniques were required to materialise the generated designs and their intricate details that might even have never been made before.

CAM tools (Computer Aided Manufacturing) as 3d printing, CNC milling, and moulding had high potentials in realising this complexity which demanded mass customisation in a considerable scale of quantity and precision.

Although these techniques had high Potentials, on one hand, they also had significant disadvantages and constraints on the other hand. For instance, moulding produces many waste materials, because one mould could be used only for one element; and the researched techniques to make the mould more flexible and adjustable is not yet fully applicable or verified in building industry. This waste questions the main intention for the sustainability of the design. Similarly is milling and CNC which even has the limitation of certain materials that can be used in the process and still produces wasted material. However, additive manufacturing -known as 3D printing- produces less or almost none wasted material and also has a wide range and possibility of materials; which favours it over the aforementioned techniques. Notably, it consumes much more time and not fully explored yet in the large scale of the construction and building industry.

To achieve these new fabrication techniques, industrial robots found its way into the architecture and building industry. It became more familiar nowadays to find an architect who is specialised in robotic manufacturing or trying to develop new building components dependent on the robot's end effector. This integration is due to the high potentials and possibilities that these robot arms offer in terms of the manufacturing scale, precision or interaction.

It is necessary to push the boundaries and limitations over 3D printing as a production technique in architecture; this will help create and materialise our optimised performative designs; Which will reduce the effect and the footprint of our built environment.

1.2 Problem Statement

Main Problem

- Printing Material | Environment friendly

Since the interest in additive manufacturing in the architecture and building fields has recently increased, the material scope exploration has consequently increased. Mostly, the used material in the large scale 3d Printing for facade walls being researched nowadays is concrete, which has many disadvantages. Concrete has a disastrous effect on climate change and the environment, not just in terms of deploying resources as gravel used in its industry, but also the amount of the greenhouse gas emissions it produces. Concrete and Cement industry according to Chatham house report represents alone 8% of the carbon dioxide emissions in the world by producing almost 4 billion tons/year (Lehne & Preston, 2018). Almost 1 ton of concrete to be produced, eventually produces 1 ton of CO_2; and this same 1 ton of concrete is produced for every person in the world per year (Huntzinger & Eatmon, 2009) which is a considerable amount to imagine for its consequences.

That being the case, an environment-friendly material is demanded, which has to be affordable, suitable for extrudability -printability- and performative in architectural and building components.

Fortunately, clay and earth are recently incrementally being used in 3d printing in general. Although it is an affordable, sustainable, and extrudable material, it is still not much explored to its full capacity. More research is required in order to push it is boundaries within this promising new technique to be applicable in building components.

Briefly, the main problems that this research addresses are firstly, the demand for an environmentally friendly alternative material in large 3d printing in architecture. Secondly, the need for more exploration of printability and performance as for clay in this new technology.

Highlighted in Fig.1 the problem position as proposed within the realisation process of a sustainable architecture product.

Sub-Problem

- Integrative process | Ventilation Systems

3d printing, on one hand, has many advantages as a production technique, including less waste material, highly complex geometries production, and a wide range of possible materials.

On the other hand, **Due to the amount of time consumed in the printing Process -especially in large scale- this innovative production technique has not been implemented within the building industry quite much. Therefore, as architects and designers, we need to design the process in such a way that is more integrative rather than linear.**

This might compensate the time of printing, in creating another scheduled building phase or product in the linear system that will be happening afterwards. Thus, the process's efficiency in terms of time and cost are more valued and reliable.

In order to narrow down the research frame, one building component in the building industry was chosen as an objective to integrate within the printing process. Ventilation systems as a secondary function mostly come after the facade walls were installed and then be integrated into the building. However, usually, the conventional designs of the outlets or the radiators - as in hydronic radiators- for the HVAC do not fit aesthetically with the facade walls to the interior as well as consuming space in the room. Therefore, ventilation systems were chosen as a case study of a building component that needs to be designed to fit within the 3d printing process in architecture.

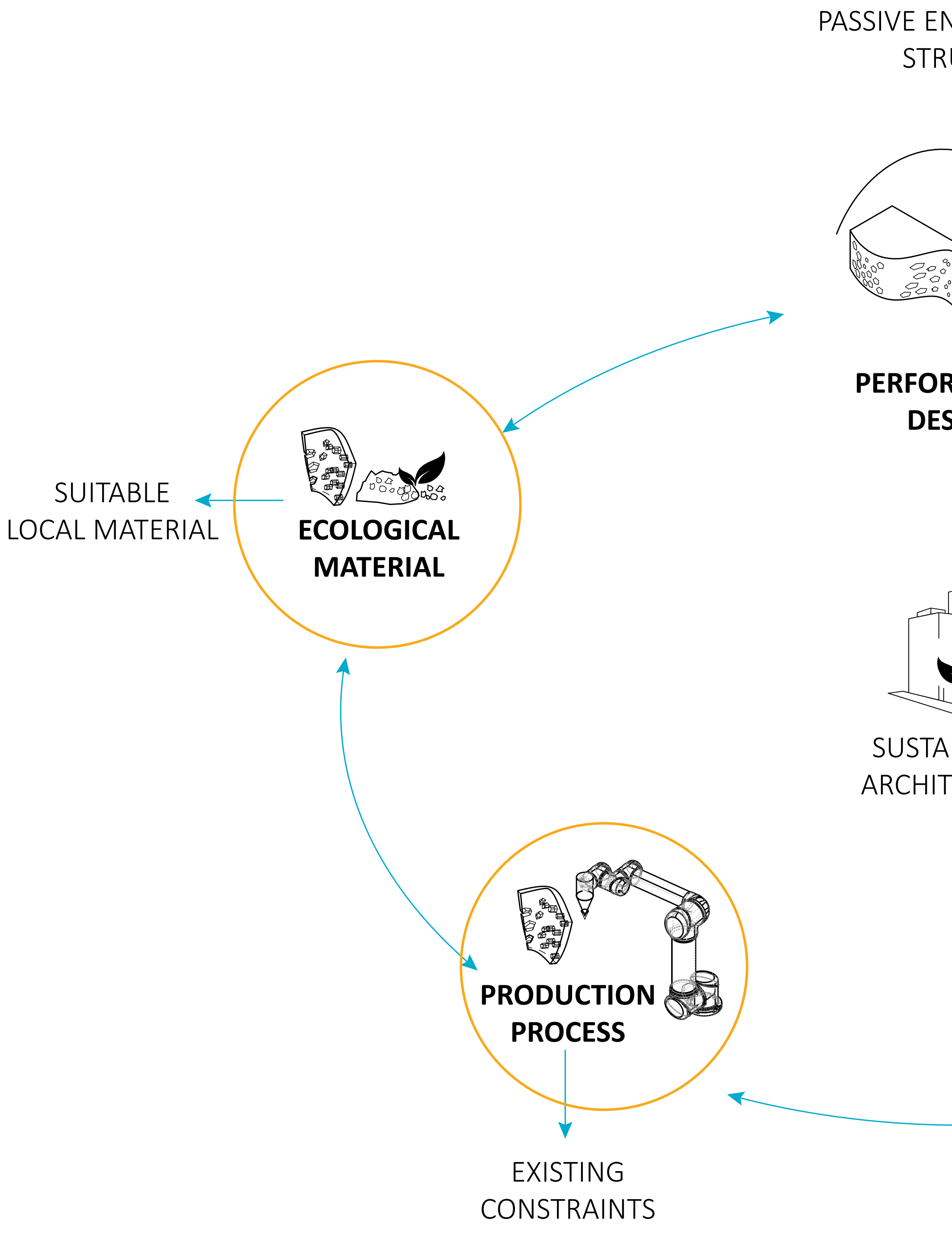


Fig.1. The problem position within the su
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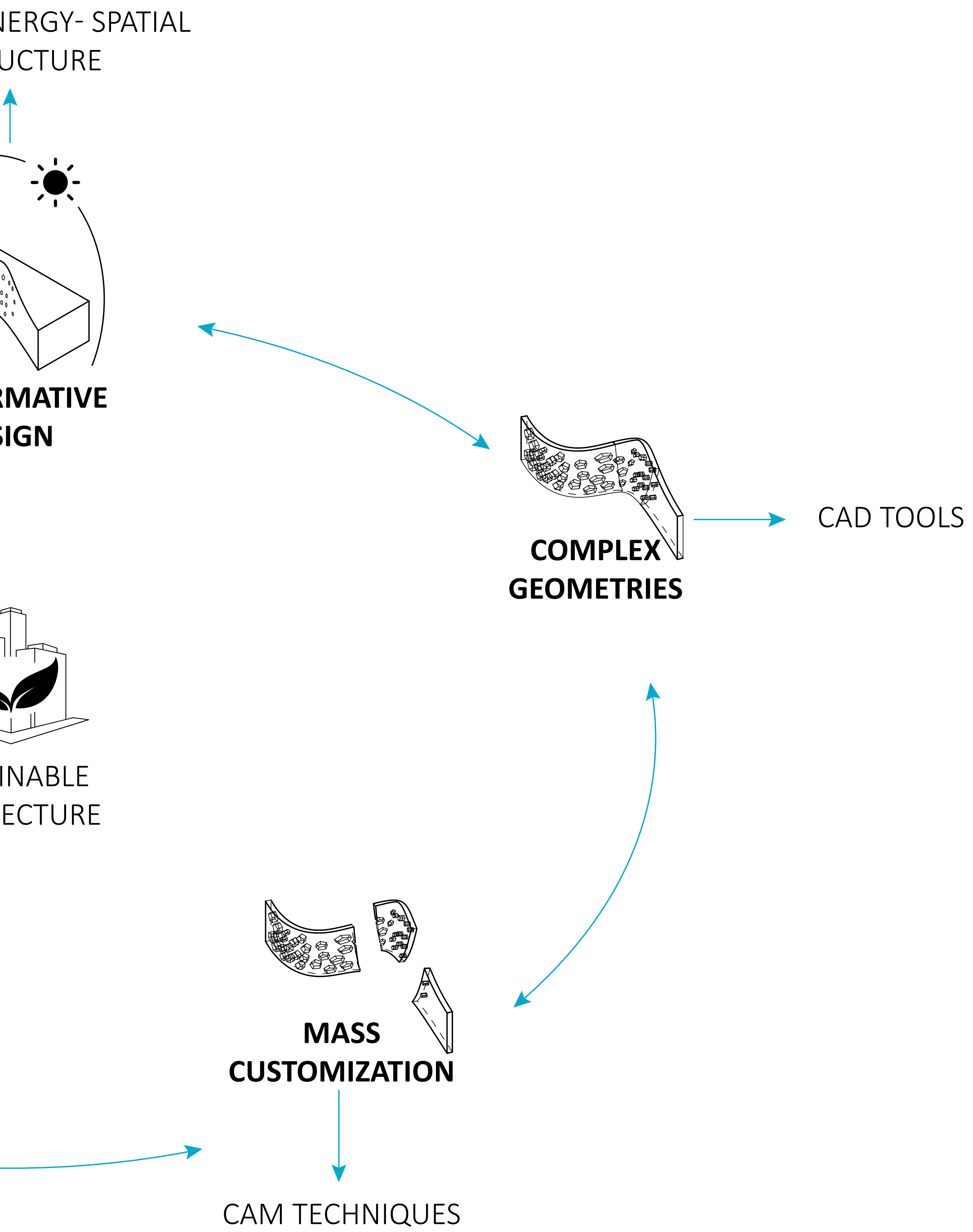


stainable architecture realization process.
Author)

1.3 Research Question

Main Question

According to the problems previously stated, there is a need for an integrative process in 3d printing to integrate the ventilation systems within the printed facade walls, while using clay as an environment-friendly printing material. These conditions lead to formulating the main research question to be:

What are the printing techniques and tools that can help integrate the clay as an environmentally friendly material, into the 3d printing of building components, while maintaining the required indoor and outdoor performance quality?

Sub-Questions

This main question leads to dividing the research and design process into four main categories. These will be referred to as **CREW**. An abbreviation for **Clay** as the printing material to be explored, **Robots** as the digital manufacturing process that will be designed for, **Extrusion** as the printing technique or tool for prototyping, and **Wall** component as a final product that integrates ventilation system within the printed object. For each of the CREW members or aspects, the main sub-question is stated below, and later mentioned the subdivided categories' questions -shown in Table 1- which by answering leads to completing the design assignments sorted in Table 2.

Clay: What is the best clay type in terms of printability and thermal performance in an architectural context? And what is the best mixture for extrudability in 3d printing process?

Robot: What are the different layering and infilling techniques that help achieve the required performance as an internal ventilation duct system, and an exterior facade envelope?

Extruder: How can clay be implemented in the 3d printing process, and what are the tools and techniques that help materialise the final designed product?

Wall: What are the performance criteria to design and verify the ventilation system in terms of indoor quality, and what are the design criteria for a facade envelope to be considered in the design for 3d printing?

C	R	E	W
CLAY	**ROBOT**	**EXTRUDER**	**WALL**
MATERIAL	PROCESS	TOOL	PRODUCT

Sub-Questions in 4 categories

1.4 Methodology

Process approaches

Depending on the research categorisation mentioned before, the process was divided to be achieved through four different approaches, Honors Program research integration, Research by design, literature review in parallel, and at latest the assessment process. **Fig 2** shows how the Process in total will be.

- Honours Program integration

During the honours program research, under the supervision of Dr. Michela Turrin, exploring how the material mix for clay can be developed to be suitable for 3d printing process in architecture components. In the research, the interest is for the organic additives to maintain the sustainability and recyclability of the printed product. Hence, the final recipe for clay mixture recommended as a result of the honours research will be used as the printing material during this thesis research.

- Research by Design

Once the material recipe is ready, a prototype facade will first be designed as a case study. Ventilation system morphology will be generated for this facade wall. Notably, the ventilation system design which requires necessary calculations and standards will be solved to be as a starting point for the morphology generation. The latest two mentioned design tasks -the ventilation calculations and morphology- will not be the main focus of the research, thus, in the time planning this will also give fewer time slots than other tasks.

Once the design of the prototype is ready as a facade wall, the printing process controllers will be explored. Divided into two aspects, the printing infill of the wall which contains the cavities and ducts of the ventilation system, and the layering as outdoor and indoor surface finishing. These two aspects will be the main focus in order to achieve the integration of the shafts within the printing process while meeting the criteria for thermal performance as a facade envelop.

- Literature review

Next to the design and testing, the literature review will be always as a reference primarily for clay types and behaviour as well as ventilation system design and background. The robot control and extrusion tool integration also will require to stand on state of the art in this field from different disciplines. Summing up the literature review will lead to verification criteria for the printed prototype as a facade envelop and as a ventilation system.

- Performance verification

Overall, the designed wall and the printed prototype will be assessed within the criteria resulted from the literature review. Digital simulation will be conducted to prove the liability of the designed morphology as ventilation shafts system. This will be done using CFD software. Moreover, Therm analysis for the thermal performance of the wall as an envelope, within the design for the printing process, will be one of the design guides.

The following **Table 1** shows the formulated research point and its equivalent question to be explored using the latest three different research approaches. This was the base for time planning of the graduation plan and had to be adjustable during the research process.

		Clay		Extruder
Approach	**Research Point**	**Material**	**Research Point**	**Tool**
		order materials - honours tests		
Literature	Clay types	what are the different Clay types? what are the major differences and properties? which are being integrated in the architecture field?	Surface finish	what are the possible tools/ techniques for the final (outdoo indoor) surface quality
	Thermal properties | Heating:Cooling	what is the thermal behaviour for clay types as building materials or as daily products? what are the U and R values for clay	Secondary functions	how to add secondary materia required for water insulation ar control? what tools?
	Thermal properties | insualtion:conductivity	how do you conduct heat from wall to interior? how to insulate heat from outdoor to walls or interior? what are the precedent/current techniques that used clay as an		
	Mix | Recyclability	how to recycle and reuse clay products? what is the end of life potentials for clay products? how to assure all the mix is sustainable?		
Experiment | Early	Mix | Water Resistance	what additives will help insulate the cavities from moisture? what additives will help insulate from the outdoor rain?	Mounting device	how to mount the extruder and setup to the robot arm?
	Mix | Extrudability	what is the best mixture to maintain extrudability? is using premixed clay better than powder? why?	Nozzle size	how can nozle size affect the fi product performance
	Mix | Shrinkage	what is the best mixture to maintain less shrinkage? what criteria should be considered in printing process for shrinkage control?	Nozzle shape	how can nozle shape affect th final product performance?
Experiment | Assesment	Finshings | Glazing : Firing	what are the pros & cons of glazing and firing? what are the side effects on other properties?		

Table 1. Formulated sub-questic
proach for each categ

		Robot		HVAC
	Research Point	Printing Process	Research Point	Building Physics
				decide case study (climate - building function - room size)
or -	Layring | Techniques	what are the precedent techniques in layring the material? what can be the reason for different layering?	HVAC systems types	what are the different types of HVAC systems used?
al nd	Layring | control	how to controll layer height? shape? and diameter? how is it related to the robot arm control?	Pros & cons of current systems	what can be improved in current systems by additive manufacturing integrative approach? what are the potential systems to be developed?
	Infill | technqiues	how to controll layer height? shape? and diameter? how is it related to the robot arm control?	System requirements | numerical	how to calculate heating - cooling-ventilation capacities for a choosen space function? how to calculate cavities min & max diameters?
	Infill | control	how to control the infill shape?	System requirements | physical	what are the conventional basic technical requirements for the choosen system?
the	Layring | effect	what are the functions of these layering shapes? how to integrate Air ventilation shafts within layering? how to control water resistance? self shading	Generative design base	what is the starting point to generate the wall cavity?
nal	infill | effect	how infill affects/control thermal behaviour for interior and exterior?		
ne	secondary function	how to maintain two different materials/ process within the printing process?		
			Performance assesment | criteria	what are the perfromance assesment criteria? what are the interior performance as HVAC? what are the exterior perfromance as envelope?
			Pefromance assesment | tools	how to asses the final product perfromance as a wall? what are the tools required?

ons, research points, and ap-
ory. (Source: Author)

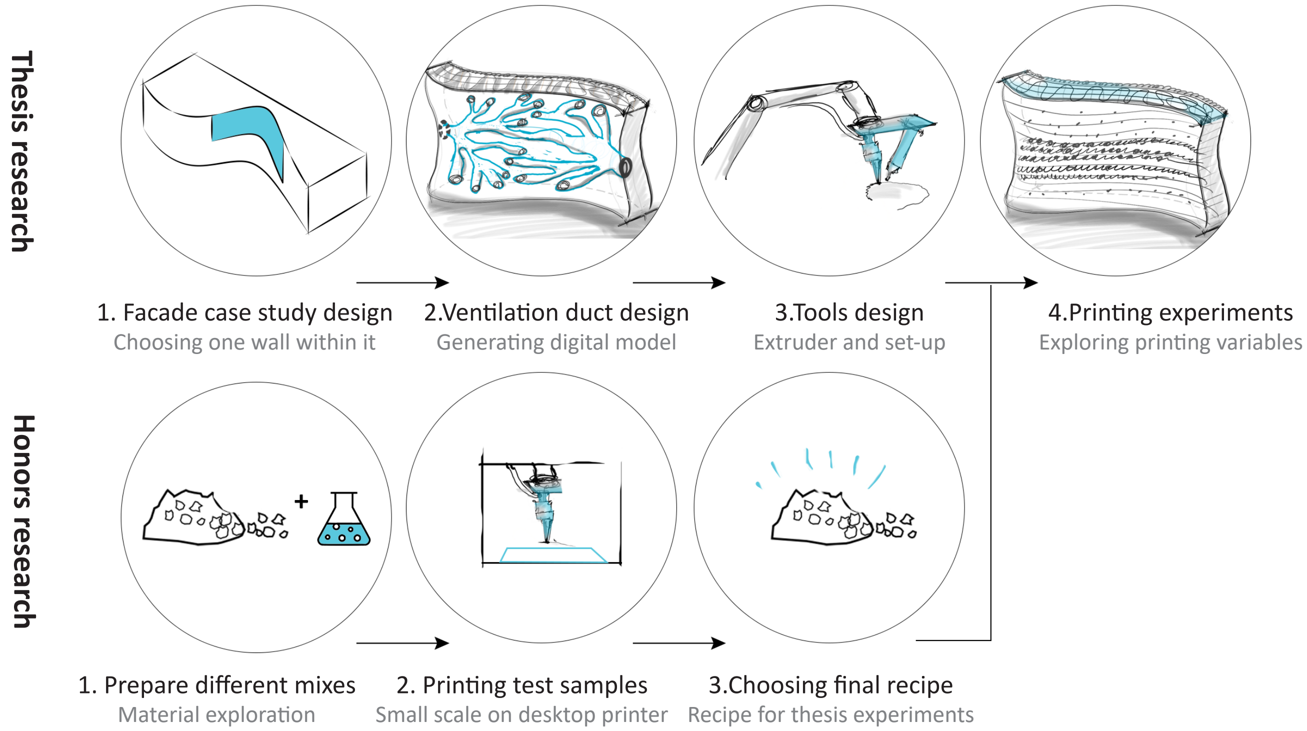


Fig.2. Research methodology and process, showing the parallel work of honors and thesis researche and their integration (Source: Author)

1.5 Design Assignment

The general design assignment is:

Facade wall printed out of clay where ventilation ducts are integrated as within its printed infilling.

A list of design sub-assignments to achieve this wall is created in **Table 2** and sorted according to the process priorities that need to be accomplished. The list was created based on the literature review and state of the art in each category's review. The time frame for each of the assignments differs according to the amount of work required, as well as the prior knowledge and background.

Category	Assignment	Task
Extruder	Nozzle | shape	Design
	Nozzle | size	Design
	Mounting Device	Design
	Setup preparation	Hardware
Wall	Case study | Room	Design
	Ventilation system | design principles	Design
	Ventilation system | Calculations	Design
	Morphology	Design | Variations
	Verification	Design | Variations
Robot	Slicing	Design
	Infilling design	Design
	Robot control | digital work flow	Exploration

Table 2. Design assignment as sub-assignments. (Source: Author)

2 MATERIAL EXPLORATION

This chapter defines what is meant by clay used in this research. Next, decides the best clay type for 3d printing architecture components. The main body of this chapter is the material experiments for a suitable clay mixture for large scale 3d printing. Out of the experiments a final clay recipe is decided and was used for the prototyping.

2. Material Exploration

2.1 Terminology & Definitions

Following, introduced and summarised the most important terminologies used in this research about the clay as a material. The most important term to define for the research is what is meant by Clay? Some researchers mistakenly do not differ between earth as a material and clay as a substance material; Adobe which contains a high percentage of sand is not the material used in this research.

According to the soil classification by the USDA (United States Department of agriculture) and its soil survey manual - shown in the Classification graph inFig.3- There twelve classifications for soil types. The soil is called sand if it contains more than 80% sand next to the other substitutes, while its called loam if it has a clay percentage of about 7-27 % clay and almost 50% for each of sand and silt. So importantly what is called Clay is what contains 40% or more of clay and less of the other two substances. in that respect the material used in this research is not meant to be Soil which is very general term, or Loam which has a different composition and not sands of course. [SOIL SURVEY MANUAL USDA]

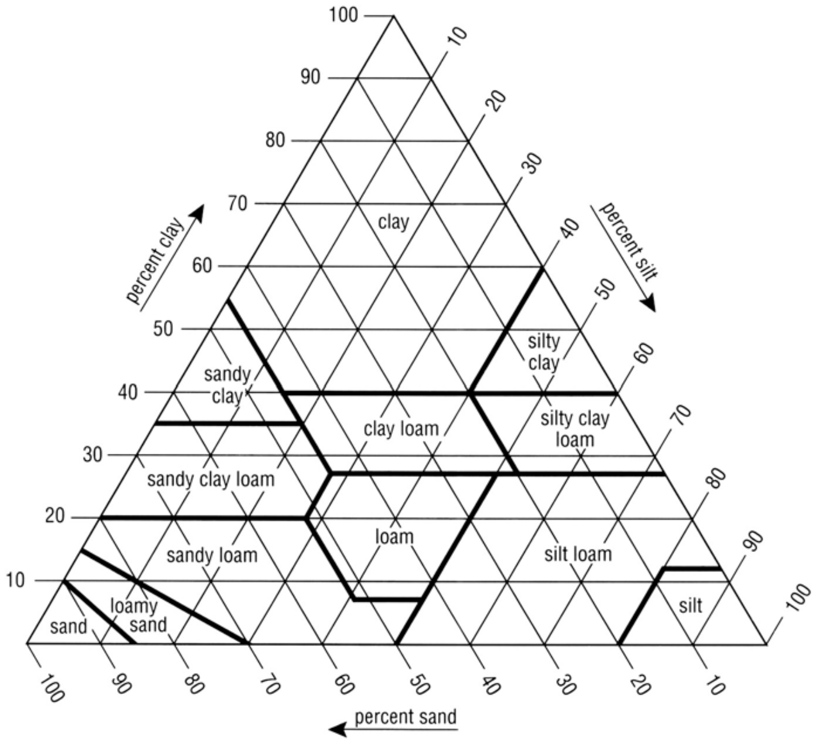


Fig.3. Basic Textural classification for soil according to the USDA survey.
(Source: Soil survey manual. United States Department of Agriculture, 1993)

TTo be more detailed about what clay is. According to [Rhodes,1958] this is the more detailed definition considered for the clay in this research.

CLAY is considered as the earth crust surface that consists of silica and alumina components and might have occasionally and depending on the source some oxides and minerals. This composition has a plastic state when wet and a hard stone-like state when dried and fired. However, Earth as material might consist more of sand, silt and different minerals, which is not the case we are handling in this research (P.11).

The following definitions are derived from D.Rhodes,(1958) book -as a scientific reference for clay - or otherwise would be mentioned. These definitions are meant to describe the material properties of the clay that might be affecting its printability behaviour.

PLASTICITY of clay describes the ability of the material to be shaped easily with the right amount of water added to its mixture. Due to the thin grains of the clay molecules which are plate-like shaped they tend to stick to each other while allowing sliding over to take shape applied by an external force(P.9).

Organic matter and minerals found in the clay has also a significant role in the plasticity by creating a bacterial action that produces a colloidal gel which acts as a glue. The older the clay mixture prepared, the better it is in shaping and work, that also illustrates why the old Chinese potters mixed and prepared clay for their grandchildren and used their grandparent's mixtures (P.8).

Although Clay has this ability to be shaped, it is also hard to maintain the right amount o water to clay that maintains the cohesion of the molecules without turning into liquid or being so hard to be shaped easily. Different degrees of plasticity determines different usages for the clay; for example being used for casting if it is more liquid, or used for throwing if it is more viscous. And so is it for the 3d printing which is the focus of this research. To Find the right clay to water ratio to achieve viscosity and plasticity to be extruded in a controllable matter.

IMPURITIES in clay occurs in the process of its formation. As the earth crust is affected by weathering or erosion and the clay is created if it is carried away by water into rivers or lands; then it tends to have in its composition some impurities that might affect the clay behaviour in shaping and firing.

Organic matter is the main impurity that might be present and causes a carbonaceous matter which is created by bacterial effects due to the longtime damping. Inorganic matter as minerals are also some impurities that affect the colouring and the firing of the clay, including the iron oxide as most common for causing the red colour in earthenware clays. (P.8)

CLAY BODY is the mixture of clays and additives that form the final recipe or mixture to be used. Including what gives it the required amount of plasticity for work; its properties of colouring, shrinkage, or firing temperature. (P.21) this term is used in the material experiments to be followed in the next pages to announce each sample produced in relation to the material composition it has.

2.2 Choosing the suitable Clay type

Step 1. Clay Types

Clay can be divided into two general categories, depending on the site of the formation and consequently the impurities in the mixture. These two are Primary Clay and Secondary Clay which differs in the physical and the firing properties eventually (Rhodes,1958).

PRIMARY CLAY, which is mostly found on the site where it was formed, and it had not faced any kind of transportation form it is original formation location by water, wind or glaciers. Kaolins are the most common ones we can recognise of this category. Since this clay has not moved away it mostly does not have any impurities as minerals or organic matter which gives it also its white colour after it has been fired, as it lakes mostly the mineral oxides that affect the colouring. This type of clay needs some expertise to work with as it is not so easy to find the best plasticity for work without any other clay types added to it.

SECONDARY CLAY, on the other hand, is the clay that has transported and moved from its original formation site. Wind, water or glaciers might take it to a different location where it collects in its way some impurities. Eventually, the colouring of these is caused due to the iron oxide that gives it its red and brownish colours. Stoneware and earthenware are mostly among this category (Fig.4).

However, for the clay overall, there are many and different sub-categories for clay types, and to put it briefly three main most common types -Fig2- are explained and considered in this research; Kaolin, stoneware and earthenware. Lastly summarised in Table 2 and compared.

- Kaolin | Porcelain

Considered as a primary clay, it usually has coarse grains and low plasticity in return. Addition of secondary plastic clay is required to increase it is plasticity. The firing temperature is high up to 1800° c, thus requires additive secondary clay again. The colours before and after firing ranges within the white-ish colours. It is the very commonly used clay for most of the old historic tableware and famous Chinese pottery.

- Stoneware

As a secondary clay, stoneware differs in grain size and contains some minerals and organic matter which makes it more plastic than kaolin. The plasticity ranges between high and medium. The firing temperature is mid to high temperature as well between 1100-1200° c. The fired colours range between very light grey and brownish colours. Notably, this type acquires high dense, stone-like state after firing. This stone-like state gives it the merit of being stiffer and has higher surface hardness than the other two types, which also introduce it as a potential solution for the architectural non-structural applications.

- Earthenware

A Secondary clay also whose plasticity differs much depending on the mining location as a very plastic and even sticky that needs additives as sand and coarse-grained clays. However, it is also available as almost non-plastic material and up to the user to define for what kind of work he needs it. With a low firing temperature between 950-1000°, it is prevalent to work with. It contains a considerable amount of iron and oxides that acquire it the red and brown -even sometimes black- colours before and after firing.

- Other types

Ball clay: relating to its name, it is used to be collected from its mining place, and then it would be formed in ball shapes to be easily transported or dragged to anywhere, that is undoubtedly due to it high plasticity that helps in creating these balls. This type is used to add plasticity to other clays and cannot be used alone due to its high shrinkage percentage of up to almost 20 %.

Fire clay: Another type of stoneware clay which is added to the clay body to increase its firing temperature up to 1500° (Rhodes, 1958).

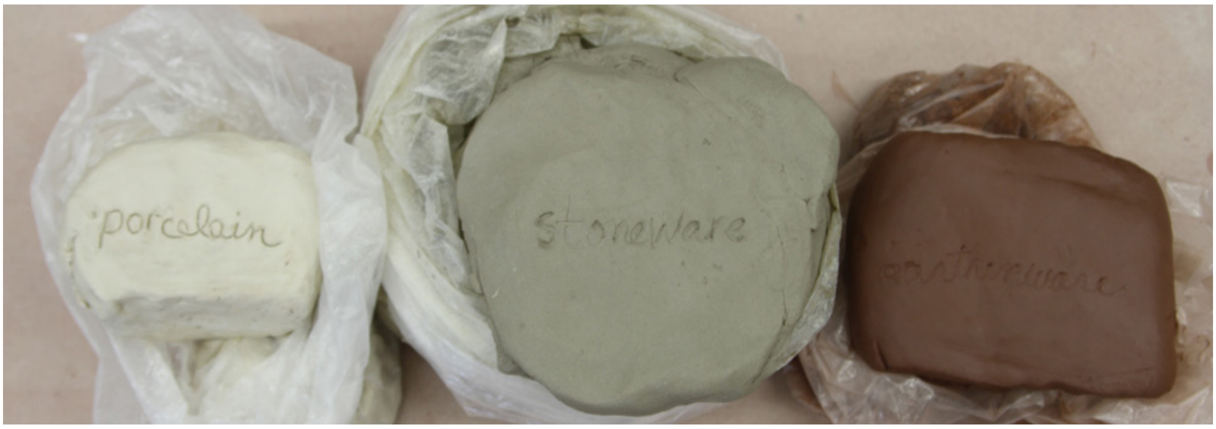


Fig.4. Three main types of clay differ in thermal performance and color.
(Source: http://chhsarts.weebly.com/ceramics-1/types-of-clay)

Step 2. Thermal Properties

For a Clay wall that will serve as an envelope, it will be essential to know the thermal behaviour and properties of the Clay as a building material. However, the available data and research about clay's thermal performance are relatively scarce to the data available about earth as a construction material in the forms of rammed earth, compressed earth blocks or adobe blocks.

Fortunately, a research experiment conducted by AKPABIO, ETUK, & UDOH they explored the clay as a building surface material and calculated and documented the thermal properties of the different clay types (2003).

According to Akpabio, three main aspects affect the thermal conductivity of the Clay. Firstly, the amount of solar radiation on the wall, as well as the colour of the clay used and finally the thickness of the wall and it is temperature variation during the day.

Colour controls the amount of absorbed and reflected energy and thus the amount of the temperature transmitted to the air surrounding the wall due to the absorbent energy, which finally affects the interior of the wall. The darker the colour, the more absorption it will has and less reflectivity, and vice versa, therefore a balance between the dark colour and the bright colours achieves better results.

Additionally, the thickness of the wall as noticed from the study run by (Dong, Soebarto, & Griffith, 2014) if doubled it cuts the heating and cooling loads by half, which indicates the significant role the material thickness plays as well. The more material there is, the more resistivity the heat will pass through before getting from one side of the wall to the other.

Eventually, the experiment run by (AKPABIO et al., 2003) concluded that the clay types have much lower heat conductivity than the non-wood building materials -shown in Table 4- and that kaolin is the least conductive among clay types and also the least thermal absorptive, which is probably due to its reflective white-ish colours.

However, since Kaolin is hard to work with and less available than the other clay types next to it is a higher price, the next least conductive and absorptive among stoneware and earthenware is the former one; which merits it another advantage as an architecture suitable clay.

Building Material	Density Kg/m^3	Thermal Conductivity Wm^{-1}K^{-1}	Thermal Resistivity W^{-1}mK
Kaolin	1190	0.370	2.70
Stoneware	1800	0.388	2.58
Earthenware	1960	0.463	2.16
Glass	2350	0.701	1.42
Cement plaster	1762	0.620	1.61
Brick	1820	0.697	1.43
Plywood	530	0.140	7.14

Table 3. Clay types comparison. (Source: AKPABIO et al., 2003)

Step 3. Drying | Firing process

"Clay, until it is fired and made durable, is a material of little or no practical value" (Rhodes, 1958, P.12)
Hence for the final prototype of the research, it is planned that there might be a chance of using a firing kiln. Thus understanding the process of firing and drying is essential for the final product.

Almost 25% of any clay mass is water according to Rhodes (1958, P.12) and as the clay is drying the surface loses it is water and then starts to lose the interior surface's water as well by the capillary effect. When the clay is fired it passes through different phases according to the temperature it reaches in the kiln. Most interesting in this case are Shrinkage and Vitrification.

SHRINKAGE *tends to happen as clay loses its water and the molecules start to gather nearby each other as a result of losing the water content between them.*

VITRIFICATION *is the last phase of the firing where the clay almost melts, and the molecules start to fuse in nearly a glass liquid-state. By cooling, as a result, the inner bonds are much stronger, and the clay is stiffer with higher compression strength and more water and chemicals resistant, which allows it to survive for centuries in harsh conditions (Rhodes, 1958).*

Practicals | To be considered

- A dense mass of clay risks higher cracking and shrinkage due to the uneven drying and shrinkage.
- Dense mass should be fired slowly and carefully to avoid an explosion of the mass due to the trapped evaporated steam inside the mass.
- Dense mass should also be cooled down slowly to avoid cracks caused by the change of the quartz state in the molecular body from a beta state to alpha state.
- Blackening might be caused by the carbon existing in the clay body when fired rapidly.
- The drying should be equal and even on the object surface to avoid warping and cracking.
- Grog (chammote), as well as Sand, may be added to clay to reduce shrinkage.
- Grain size from fine to coarse affects both the shrinkage and the plasticity of the body.

Step 4. Comparison & choosing

Noted from Table 5 for the comparison of the different properties of clay; derives us to the selected clay type used in this research. Although Kaolin has the highest thermal resistivity, its availability is lower than the other two types. Also, Kaolin's plasticity is lower and requires a composition of different secondary clay to acquire it the best workability properties.

On the other side, stoneware has the next higher thermal resistivity after kaolin, Yet it is mostly highly available. Moreover, Stoneware, unlike earthenware, Has a high surface stiffness and hardness especially after firing, which is very potential for outdoor non-structural applications as Facade panels or walls as in this research case. Moreover, since stoneware has less organic matter than earthenware, its shrinkage is also more predictable than earthenware.

Considering these aspects about the thermal properties, availability and surface stiffness, stoneware -with its appealing grey colour in a facade application- it is considered as the most suitable type to be used in this research as an architectural application of a facade wall.

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

Table 4. Clay types comparison. (Source: Author)

Summary

- The used material in this research is Clay which is the crust of the earth without sand or other coarse impurities that might be found in adobe or earth material.
- The used type of clay is stoneware clay due to its high availability, good shrinkage ratio, desirable plasticity, low thermal conductivity, as well as it is the grey colour which is more aesthetically preferred.
- Shrinkage ratio and plasticity consistency are two major factors to be considered for material behaviour and mixture in this research case.

2.3 Material experiments | Honours Programme research

2.3.1 Experiment Objective

On one hand, the objective of the thesis research is to explore the potentials of clay in robotic 3d printing, while considering the integration of ventilation duct systems within the printed facade wall's infilling as a case study for prototyping.

While on the other hand, the main scope of the honours research was finding the best material mixture for printability. this meant investigating the effects of different natural additives on the material behaviour within the process of 3d printing. Then this mixture was used for the thesis research prototyping.

2.3.2 Experiment Questions

The formulated two main research questions for this experiment are:

- What is the best Clay type in terms of printability and performance in architectural context?
- What is the best mixture of natural additives for a clay body that helps improving the printing process?

While the first question is already answered in the previous section of this part - Choosing the most suitable clay type- the second question experiments are elaborated in the following pages.

2.3.3 Experiments Design | Methodology

The research methodology is relying on an experiment design methodology where there are inputs and outputs. While there are constant inputs as material ratios, tools, or room conditions, there are also variables that are controlable and which are of a more interest for the researcher.

Next, for the outputs there are observations for the experiment and its execution's notes, problems or tips. Lastly, comes the results which out of their discussion a recommended material mixture is introduced.

Considered inputs and outputs in the process are:

Inputs:
- Tools: extruder - electronic controllers - air compressor.
- Surroundings: room conditions - printing bed material.
- Materials: Clay - Additives - water.

Outputs:
- Documented observations
- Physical prototypes
- Recommended material mixture

In the following Pages these inputs and outputs will be further elaborated in their definition and effects on the experiment design, and finally the conclusion is provided.

2.3.4 Experiment design

Inputs

Tools

All of these tools are marked in Fig.5 showing the setup used for the experimenting. and below they are further described.

- 1.Controller board: The motor is connected and controlled by a 3d printer board. this board is connected through an integrated WiFi chip to the internet network. Accessing the IP address of the board gives full control of the motor speed and the steps it can take to extrude the material. The on/off of the motor is not fully figured out and the emergency stop command was an alternative enough for the current prototypes.
- 2.Extruder: The used extruder in the experiments is a motor driven one. This motor is a gear headed stepper motor that is attached to an 11 mm drilling pit. The drilling pit and the motor both control and determine the extrusion of the material out of the printing nozzle. A metal nozzle was used with a circular cross section of 5 mm diameter.
- 3.Cartridge: The extruder is feed by material through a pressurized cartridge. which is connected to an air compressor and accepts a maximum pressure of 6 bars.
- 4.Air compressor: An air compressor was used to pressurize the air in the cartridge which allows the material to be feed to the extruder.
- 5.Analogue printing frame: Since the use of a digital 3d printer was logistically limited, a wooden frame was designed and assembled to act as a printing frame for the prototypes. the frame is topped by a rail for the printing head to move in the XY direction while the printing bed can be adjusted in the Z direction manually for each layer.

Environment conditions

- Printing bed: the used printing bed is made out of 3mm MDF wood plates. the bed was used in a dry state without adding any adhesive or wetting for the surface.
- Room climate: the room temperature ranged between 23-26 C. the prototypes were mixed and prototyped during the second week of January which might be considered when taking into account the amount of time the prototypes spent during the cold nights without air control in the room.

Materials

- Clay

The chosen clay type to work with is stoneware clay which was concluded from the literature review. this literature review is presented in the next two pages as a further elaboration on the suitability of stoneware than the other types for being used both in architectural scale and as for printability.

Used clay was a powder clay which gave the opportunity to explore the effect of the clay to water ratio on the viscosity and the fluid of the clay body as for printing.

- Additives

A very important aspect in the research was to decide the experimented additives. used additives were conclude from an intensive literature review during the first year of the honors programme. this literature review was in the beginning focusing on the additives that might help the earth as a building material to be stabilized and face less shrinkage levels. Another main aspect was to investigate the used additives on earth or soil to consume less drying time which would help in the printing process to create stronger successive layers for the build-up of the printed objects.

Although the reviewed additives ranged between organic and synthetic, the experimented ones were the organic natural ones in order to maintain the sustainability and the circularity of the printing material.

Shown in Table 6 the different additives explored and their expected effect on the final material mixture as derived from the literature review mainly form Stulz, R., & Mukerji, K. (1988) book " Appropriate building materials" where it is mentioned most of the additives that were proved over time to be efficient in terms of stabilization for soil and clay.

Material category	Additive	Expected Effect
Organic	Chammote 0 - 0.2 mm	Less shrinkage - less cracks - surface hardness
	Chammote 0 - 1 mm	Less shrinkage - less cracks - surface hardness
	Wheat	Less shrinkage - less cracks - better binding
	Gypsum	Less shrinkage - less drying time
	Lime	less shrinkage - less drying time - better strength
	Saw dust	Better density - less cracks
	Gelatin	Better strength (Binding) - Better viscosity
	Sand	less shrinkage - less drying time - better strength
	Vegetable oil	Water resistance- less drying time
	Straw fibers / Hay	Quick hardening, light weight
Synthetic	Water glass (Sodium Silicate)	Better mixing(dispersant) - less shrinkage - better viscosity
	Soda	Dispersant - better viscosity
	Portland Cement	Water proofing - stabilization best for sandy clayes
	Acrylic Resin	Water proofing - less drying time
	Plastics(PLA)	Water proofing - less drying time
	Aniline-Furfural	less shrinkage - better binding

Table 5. Clay additives and their expected effect on the clay body (Source: Concluded by the author)

Chart: Constants

The constants of the process are documented in the experiments final chart together with the variables, and shortly described as below and shown in Table 7.

- Layer height: set to be 4 mm height, it is meant to be the height of the printed layer and not referring to the height of the extruder from the built layer. this is because the printing in this research was analog and it would be almost impossible to make sure that the extruder height is the same for all the prototypes and for all the layers per each prototype.
- Nozzle size: set to a 5 mm circular nozzle diameter it was used for all the prototypes.
- Extruder speed: set to 400 mm/s the speed of the extruder motor controlled the amount of the material pushed out of the nozzle. for some of the mixtures the speed was doubled to allow similar flow speed to the other mixtures.
- Clay weight: the used clay weight was set to 500 gm per sample for only the clay body test, 300 gm for the solo-additive tests, and 250 gm for the mixed additives. this variation from the different types of tests was to maintain similar total weight for each sample.
- Air pressure: the air pressure is set to the range of 5-6 bar as a recommended value by the extruder provider.
- Observations time: all the samples were observed and noted twice with equal intervals of 24 hours.

Constants						
Layer Height mm	Nozzle size mm	Flow | Extruder speed mm/s	Observation time H	Number of layers	Air Pressure bar	Clay weight gm

Table 6. Chart constants (Source: Author)

Chart: Variables

The variables are the controlled percentages and weights of the additives to the clay powder, whether it is water or the organic material.

- Water percentage to clay: The water percentage of 25-30 % was the recommended one by the extruder provider, this gave the weight of water required in the first tests for only clay body. later it was adjusted according to the desired consistency.
- Water percentage to the total body: Represents the amount of water required to bind all the additives together. this would make it easier to estimate the required weight of water in all the prototypes to be almost similar.
- Additive percentage: The resultant additive percentage that was adjusted during the process to achieve the desired consistency and then noted to be the best for each of them.

Outputs

Chart: Observations

Documenting the process notes and creating results out of it requires defining the objectives to be investigated and recorded. Each one of these objectives is described as how it was derived during the process and later in the results of the experiment its mentioned what it was for each of the tests.(Table 8)

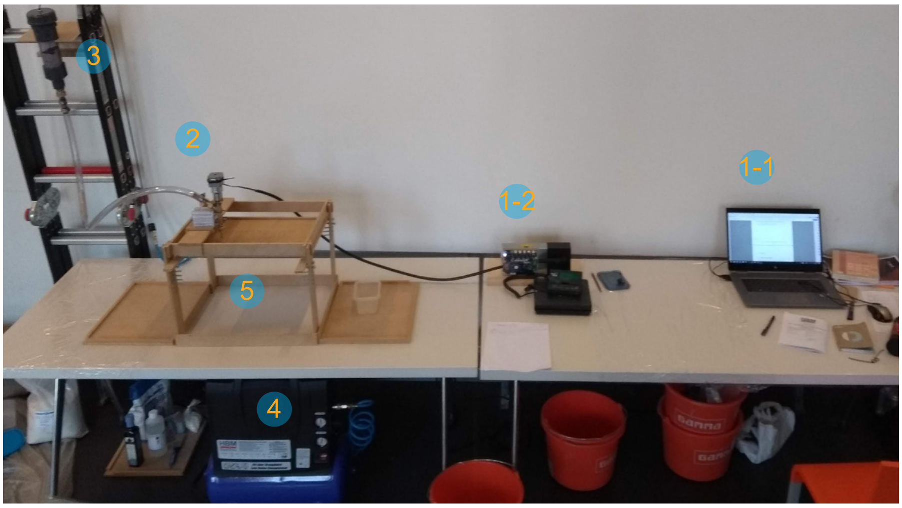
- Weight loss Average percentage: the amount of weight the sample lost after 24 hours and after 48 hours of the printing date. this majorly resembles the water loss percentage from the clay body. this might help in estimating the final weight of the printed objects in any later applications.
- Flow rate: the amount of printed material measured by the weight of the sample right after printing was divided by the Time consumed during printing. this is represented by the unit of gm/s.
- Printing speed: the amount of time consumed to print a layer it gives an indication together with the flow rate about how the material consistency and viscosity affect the printing time as a total and this helps to choose the right additive.
- Shrinkage Percentage: the amount of shrinkage in clay caused by the loss of the water content and the molecules getting closer to each other. this is very important to consider while choosing the suitable mixture for printing; specially in a large-scale product where more shrinkage might cause cracks. If not considered this will also affect the tolerances in the facade components or any other assembled products.
- Cracking: cracking due to shrinkage or due to the used additive effect is observed without measurements as its not easily quantified. Hence, a grading of 0 to 4 was assigned to each sample by visual estimation.
- Plasticity: represented by a grade of 1 to 5 since its not measurable, the plasticity refers to the consistency of the material and its possibility to be shaped as described in the terminology section.
- Line continuity: this differentiate between the plasticity as a shaping possibility and flowing on one side, and its sticky adhesive property on the other side. The more adhesive and sticky the mixture is, the more it is able to have a continuous layer line without curling. This is also Graded a grade of 1 to 5 as a non-quantifiable element.

Variables																			
Controled						Observation													
Water gm	Additive	Additive %	Water % of clay	Water % of total body	Additive rec. %	before (sample + plate weight)	after (sample + plate weight)	sample weight	sample weight loss %	Ball weight loss %	average weight loss	Flow rate gm/s	Shrinkage % 24 H	Plasticity 1:5	Cracking 0-4	Line continuity 1:5	Building Speed Layer/minute

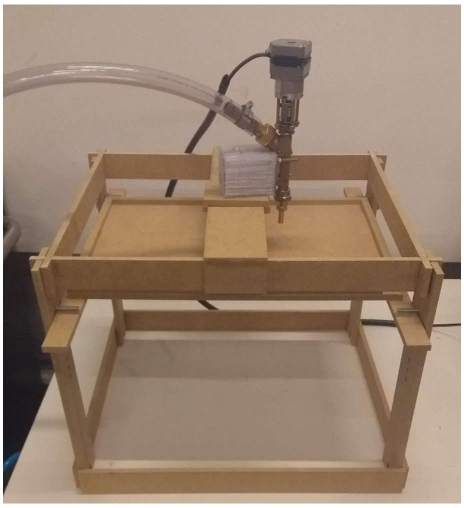
Table 7. Chart variables as controlled inputs, and output observations (Source: Author)

2.3.5 Experiment Procedure

Once the setup shown in Fig.5 was ready the experimentation of the material mixtures started. Before starting the mixing of the materials and the different prototypes, the samples were divided into three phases of experimenting.



(a) Setup showing the electronic connections made to controll the motor and the air compressor



(b) The analog printing frame used

Fig.5. Showing the setup for the experiment and the used printing frame (Source:Author)

Starting by figuring out the right percentage of water to clay body and testing the different consistencies that are suitable for the extruder and the air pressure system. In that phase 4 different water ratios where investigated starting by the recommended ratio by the extruder provider as to be 25-30% after which the water percentage was increased to 36% and 40% so as to be aware of the effects of the over increment of water.

Secondly, the solo-additive body where each additive from the materials list mentioned previously was tested individually within the clay and water mixture. Seven materials were chosen to be investigated. these materials are starting by Chammote of 0.2 mm and followed by 1mm grain size powder. Chammote which is basically a grinded fired clay powder is expected to reduce the shrinkage and the cracks while also adding surface hardness to the model. Next came the Gypsum powder which reduces the shrinkage and the drying time. Wheat flour, which is mentioned to be not only reducing the cracks and shrinkage but also it creates stronger binding effect for the grains together, it was the fourth tested mixture. afterwards, came the saw dust collected from the wood cutting machines and then sieved to be only the powder without any large grains, this dust is expected to reduce the shrinkage and craks as it would absorb some of the water content without losing it quickly in the drying process. followed by the gelatine sheets which were melted in the water used for the mixture in hot water, as the last organic material tested it was assumed to afford better binding and density while improving the viscosity. However, Water glass -or named as Sodium silicate- as synthetic material was used after being recommended by different potters and clay specialized practices as a dispersant for the clay that help in its viscosity with less water.

Lastly, after evaluating the different solo-additives samples, three different materials where combined in two different mixtures of maximum three components including the clay powder. Briefly, in total 13 mixture for the clay body were created.

Working on the mixtures included several steps in the process that were replicated for all the samples in principle. these are in total almost eleven steps.

Firstly, the Clay preparation is conducted by weighting the clay powder, the additive -if assigned- and the water using an electronic weight scale. after which they are all mixed together manually by hand in a plastic bucket. in that process checking the consistency of the body is initially evaluated.

After this, the cartridge is filled with the clay. at that point it's very important to make sure that the clay is well compacted and compressed together without any air bubbles within it. this assures the consistent flow of the material and prevents the risk of having air shots out of the extruder nozzle -due to the air pressure in the cartridge- which might damage the model.

Once the cartridge is filled and closed, the air compressor is connected to the top of the cartridge and it allows the material to move out of the cartridge to the extruder motorized pit. at that point the compressor outlet pressure is set to 5-6 bar as recommended by the extruder provider.

When the cartridge is connected to the extruder pit, the motor receives the number of steps to move and the speed of it is assigned too through the WiFi chip. this is when the printing starts, and this is where the extruder is rested on the printing frame shown in Fig.5(b).

The printing is done manually as moving the printing head on the wooden frame in the XY directions to create the prototype. First layer was drawn on the printing bed to be followed to make sure all the samples have almost the same size. the successive layers were printed until the material in the cartridge is almost finished. continuous printing till the last piece of material comes out of the cartridge risks the possibility of having air shots due to the air pressure as mentioned before.

Not before long, the leftover material from the cartridge is formed into a compressed ball and is weighted as well as the sample Fig.7. The ball is to record and investigate the weight loss of the material. Also, a clay line is formed and marked on the printing bed next to the sample left to dry, so as to measure the shrinkage percentage.

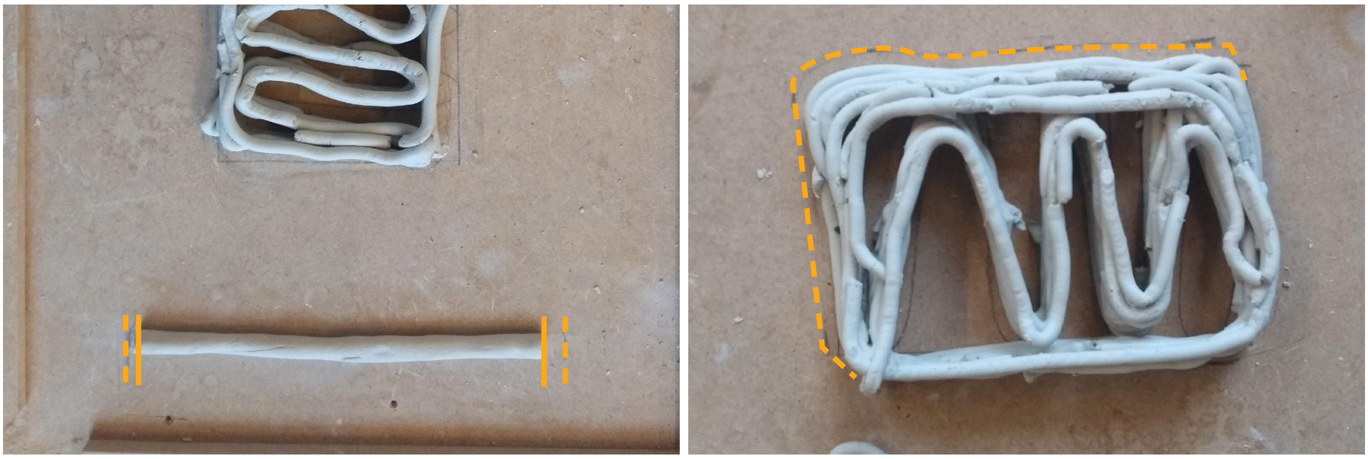


Fig.6. Shrinkage of the sample was noted on the samples but was hard to estimate. therefore lines were created to make it easier to measure as a percentage of the length (Source:Author)

Fig.7. Clay balls were formed to weight before and after drying to estimate the weight loss (Source:Author)

Lastly the sample is documented as photographed from all four sides to notice the shrinkage and the cracks in the next 48 hours (Fig.6). The sample data is recorded in the experiment chart as for its variables are also concluded in terms of the percentages used and the observations during the printing.

The experiments were documented in an Excel chart -Table 4 described in the experiment design section- that is divided into three main sections. Firstly, the constants which are dependent on the inputs as tools and materials. Secondly, the variables which are controlling the inputs of the experiment and that is where the testing is mostly taking place. Lastly, the observations of the process which lead to the results of the experiment to be used for creating a conclusion about the effect of each additive and its percentage.

2.3.6 Experiment results

The results of the experiments were recorded in the chart shown in table 4 and could be seen in appendix 1. Results were then divided into two main categories. Firstly, the printing process of clay using an air pressurized system and an electronic driven motor. Secondly, the material behaviour and the effects of the different additives on the performance of the printable clay, which finally lead to choosing the best clay body.

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

Table 4. The resultant chart out of the experiments conducted and shows all the constants, variables and observations of the process (Source:Author)

Results 1. Printing Process

As observed from the printing process, General practical notes were recorded starting by the printing bed and its material. This should have been something that absorbs less water than the wooden bed used, in this way it assures uniform drying behaviour for the mixture. Using a fired rough clay bed would maybe be better in that case.

Secondly, the clay in the cartridge should be fully compressed without any air bubbles to prevent air shots out of the nozzle as in Fig.8(a).

Also by the motor properties, the printing speed at the corners would be better if slowed down to allow the material to stick without being pulled in a curved path in the 90 degrees corners. Putting in mind that the corners tend to have a fillet radius if the printing didn't slow down more at the corners.

Moreover, the printing nozzle shape -Fig.8(b)- affects the compression of the layers as the circular nozzle requires lower printing height to allow more surface area on the top of the layer to accept the later layer above. While using rectangular nozzle might help in creating this surface easily and the layers will be more compacted together. A diameter of 5mm for the nozzle in a larger scale than the printed prototype is highly recommended, as this assures more stable layers that can prevent the build-up from falling.

Finally, the infilling design of the layers does affects the stability and the strength of the model in general, and it was observed that an overlapping for the infilling on the longer edges of the layer and a tangent on the shorter edges, does provide better support for the layers and the build-up ability Fig.8(c).

(b) Air shots caused by the air voids in the clay body

(b) 5mm diameter nozzle used in the experiments

(c) Overlapping the infill on the long edges assures more stability

Fig.8. Clay balls were formed to weight before and after drying to estimate the weight loss (Source:Author)

Results 2. **Material Mixture**

- **Solo-Clay**

Material: Stoneware Clay
Firing Temprature: 1180 -1280 °C
Color: Offwhite
Percentage: Main body

Since the whole process was relatively new the first tests which were only using the clay as solo with water to explore the consistency, it was concluded that the clay if not well compressed in the cartridge might cause critical damage to the printed model. as the air bubbles get trapped inside the clay body, while extruding at the same time of the air pressure existing in the cartridge to push the material, it creates air shots out of the nozzle Fig.8(a). these air shots can be avoided by creating a well compressed ball of the clay before feeding it in the micro-cartridge. also in bigger quantities a compressing wooden device that push the material all together in the cartridge was used. Noticeably the material in the micro cartridge should not be less than 200 gm to create a consistnet distribution of the air pressure on the material and prevent the air shots.

The clay body is clearly affected by the water percentage, as 25% water to clay weight results a body that is very hard to be extruded out by air pressure. Noticeably, maintaining a percentage between 27% as an initial ratio up to 35% provides a good viscosity -Fig.9- and plasticity for the clay to be printable and gets a shrinkage percentage around 11% Fig.10(a). If the water increases more than 35% the clay body becomes more creamy and easily flows out of the nozzle without even using the extruder motor, this means that it will not be controllable and the air pressure will always leak it out of the extruder.

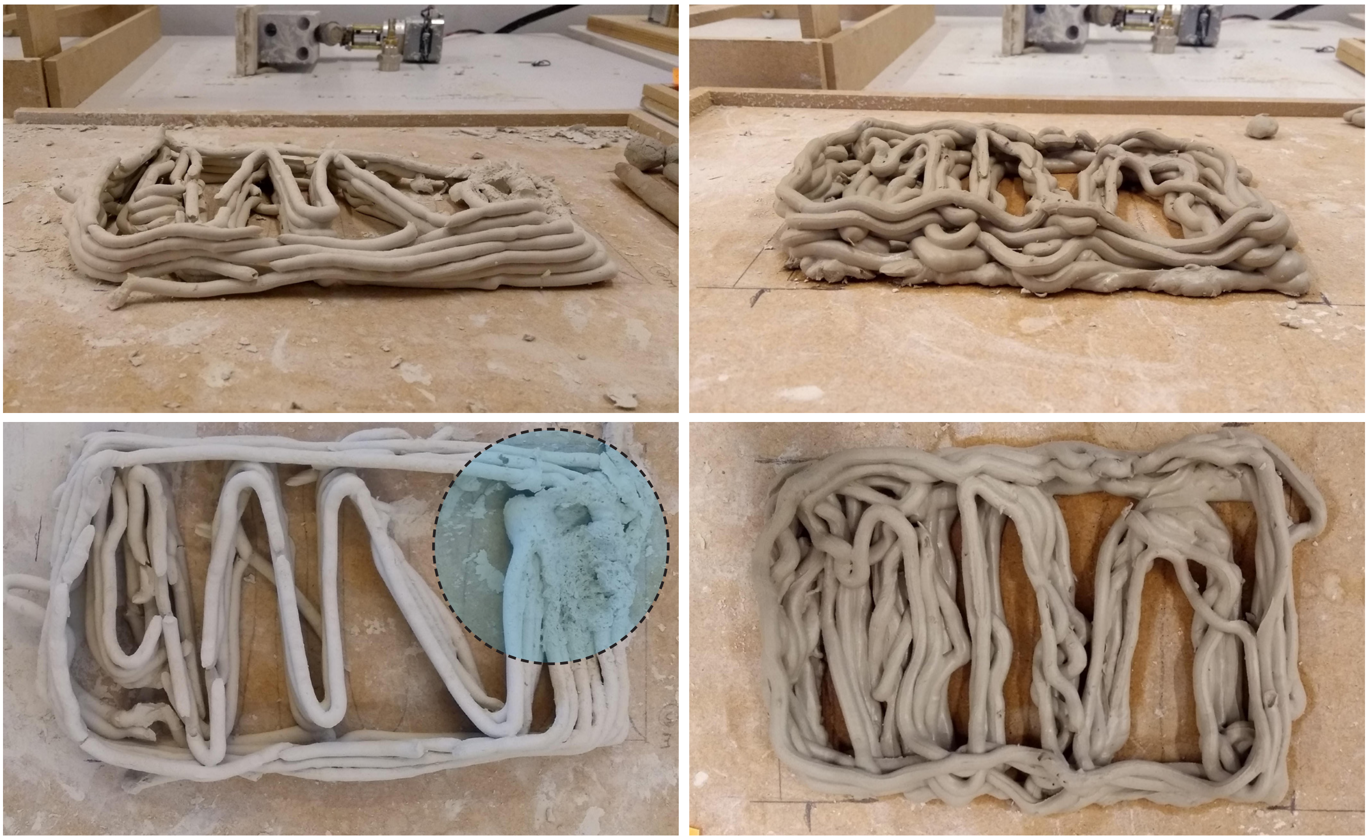
Fig.9. Plastic yet viscous material is better than the dry plastic one, this allows it to be sticky on the printing bed as well. iimage shows the inital extrudable consistency. (Source:Author)

- **Water glass /Sodium silicate**

Material: Sodium silicate
Expected effect: Dispersant-less shrinkage - better viscosity
State: Liquid
Percentage to clay: 0.25 cap

Starting the phase of adding solo-additive to the clay body was by water glass Fig.10(b).. Although, the mixture was more homogenous than the solo-clay one, it was more liquid and creamy that made it not strong enough to handle successive layers as the printing speed was 0.84 layer/minute. Moreover, controlling the ratio of the additive is very hard as it should be in about milli-grams and just adding a bit more of it would make the body very creamy. lastly if it is mixed for a while before extruding it creates a hard crumby effect, which prevents the clay from extruding.

After first 24 hours of drying the clay body didn't show cracks and gave it a grade of 0 out of 4 for cracks which is the best. on the other hand, the shrinkage which stopped after 24 hours was already a large percentage of 8.4%.



(a) Clay 35% water mixture & air shots (b) Water glass mixture

Fig.10. Showing the first experiment results for clay and for water glass as dispersant were not very successful.
(Source:Author)

- **Chamotte 0-0.2mm**

Material: Chamotte 0-0.2 mm
Expected effect: Less shrinkage-less cracks-surface hardness
State: Fine grains
Percentage to clay: 34%

First organic material tested -Fig.11(a) - as an additive showed more plasticity and a homogenous body. the building speed for the chammote mixture was 0.21 layer/minute. However, the extrusion was continous and controllable which gave it a grade of 4 out of 5 for both line continuity and plasticity. The clay body which was more stronger in compare to the water glass situation, allowed more successive layers. Also, it maintained a lower shrinkage percentage -in compare to the water glass- of only 4.6%, which is considered the least among all the mixtures. The cracking grading was 1 out of 5 due to very small air bubbles on the surface due to the air loss after drying. In addition, the average weight loss was very low at almost 16%.

- **Chamotte 0-1mm**

Material: Chamotte 0-1mm
Expected effect: Less shrinkage-less cracks-surface hardness
State: coarse grains
Percentage to clay: 34%

Chammote with a bigger grain size of 0-1mm -Fig.11(b)- was coarse enough to prevent the extruder motor from Pivoting or moving. Even more, just as a trial to observe how it behaves in a linear manner, it was hard to shape the clay manually by hand into a line. Thus, no results were recorded for this mixture.

- **Wheat flour**

Material: Wheat flour
Expected effect: Less shrinkage - less cracks - better binding
State: very fine powder
Percentage to clay: 10%

The wheat mixture seemed to be plastic enough, yet very dry and less sticky or viscous even after adding more than 42% water. This dry body doesn't stick to the printing bed which causes the printed lines to curl around itself and creating uncontinous lines -Fig.11(c)- which graded it 2 out of 5 for the line continuity and the plasticity. the extruder speed had to be doubled to 800 mm/s , yet the flow was very slow in comparison to the other mixtures, This meant eliminating this mixture's record for the layer building speed. Moreover, shrinkage percentage was almost double that of the chammote 0-0.2mm mixture to reach 8.1% in that case, with a weight loss average of 24.55%.

- **Gypsum**

Material: Gypsum
Expected effect: Less shrinkage - less drying time
State:very fine powder
Percentage to clay: 10%

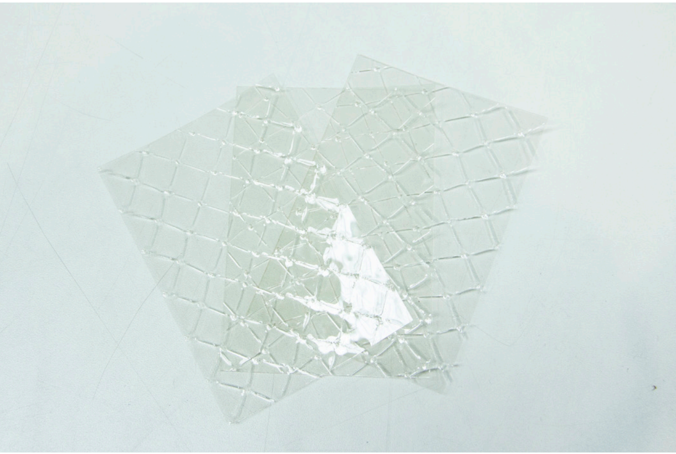
With a respective due of consideration for the amount of water added to the mixture, if the water content is less, it affects the continuity of the lines in gypsum mixture. However the grade was 4 out of 5 similar to chammote 0-0.2mm, and the plasticity was less than the later by one to reach 3 out of 5 on the grading. Noticeably the shrinkage and the average weight loss percentages were 18.2% and 7.2 respectively, which are not so far from the results for the chammote mixture as well. However the gypsum -Fig.11(d)- causes a noticeable early hardening for the clay which is still within the time possible for printing and extruding out of the cartridge. this last mentioned characteristic gives it a high potential in creating faster layer building more stable and strong with a recorded speed of 0.27 layer/ minute. Lastly, the cracking grading was 0 out of 4 as there was no noticable cracks in the sample for the first 24 hours and the later 24 hours as well.

- **Saw dust**

Material: Wood saw dust
Expected effect: Better density - less cracks
State: Sieved fine fibers
Percentage to clay: 5%

The fine grains of the saw dust after being sieved, helped it in not getting stuck in the extruder. however the mixture -Fig.11(e)- required more water content than the gypsum or chammote to reach up to 32% of the mixture body to make it more viscous. Due to the less viscousity than the chammote or gypsum the line continuity and plasticity were graded to 3 out of 5 and 4 out of 5 respectively. Since more water was added, the weight loss reached 20.45% on average which is more than the chamotte or gypsum. Shrinkage percentage was 6.3%, while the layer building speed was 0.25 layer/minute which is almost similar to the gypsum.

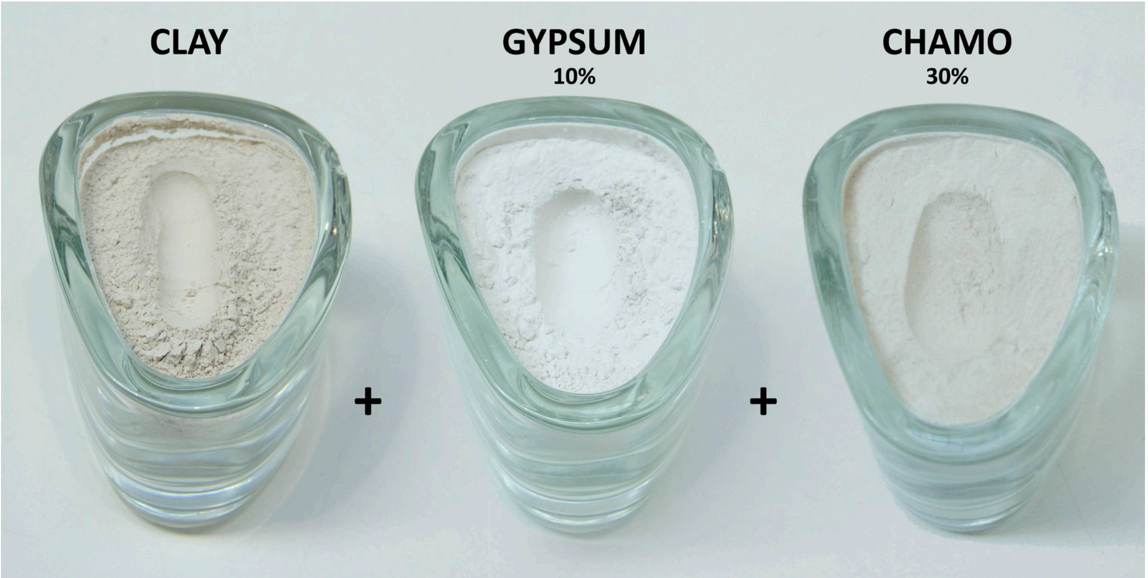
- **Gelatine**



Material: Food Gelatine
Expected effect: Better Binding - Better viscosity
State: Melted fine slices
Percentage to clay: 5%

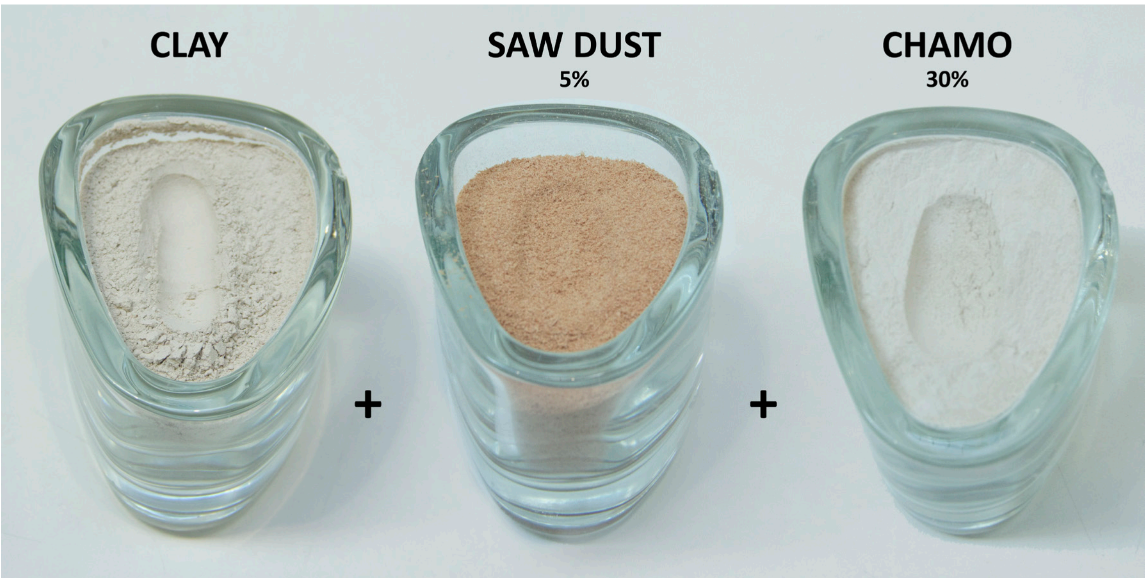
Gelatine behaved in a different manner than all the other additives, as it turned the mixture body to be more foamy and the clay body was crumbling in small pieces -Fig.11(f)- which didn't allow it to be extruded form the extruder in a continous manner. The mixture extruded as small separate lines equal to the diameter of the extruder driller which means its not able to be viscous to behave as a whole one body. Even more, neither adding more chammote or clay did change the behaviour or bind together the particles.

- **Mix 1 | Clay + chamotte 0.2 + Gypsum**



After adding the chammote and gypsum together in one clay body, the resultant mixture -Fig.11(g)- showed low average weight loss and reasonable shrinkage percentage of 15.5% and 7.3 respectively. Although the crack grading was 0 out of 5, the line continuity and plasticity were both graded 3 out of 5 due to the less content of water added. Consequently, due to the low viscosity some of the layers required manually sticking the first deposition of its line which noted the need for more water to make it more sticky and binded. Noticeably the printing building speed was almost double the other solo-mixtures recorded at 0.4 layer/minute.

- **Mix 2 | Clay + chamotte 0.2 + Saw dust**



Because the saw dust used was very fine to be almost a powder it absorbed more water and required more content as a percentage of almost 35% and yet it wasn't sticky or viscous enough. the mixture -Fig.11(h)- which had a zero cracking grade, showed less line continuity and plasticity than the first mixture to be graded 3 and 2 out of 5 in order. Still, the shrinkage percentage was less than mix 1 at a 4.6% and almost similar average weight loss at almost 15%. Due to the low viscosity slower printing speed was required to allow the layers stick and compress over each other, and this resulted in a lower building speed -than mix1- of 0.35 layer/ minute.

(a) Chammote 0-0.2 mm mixture

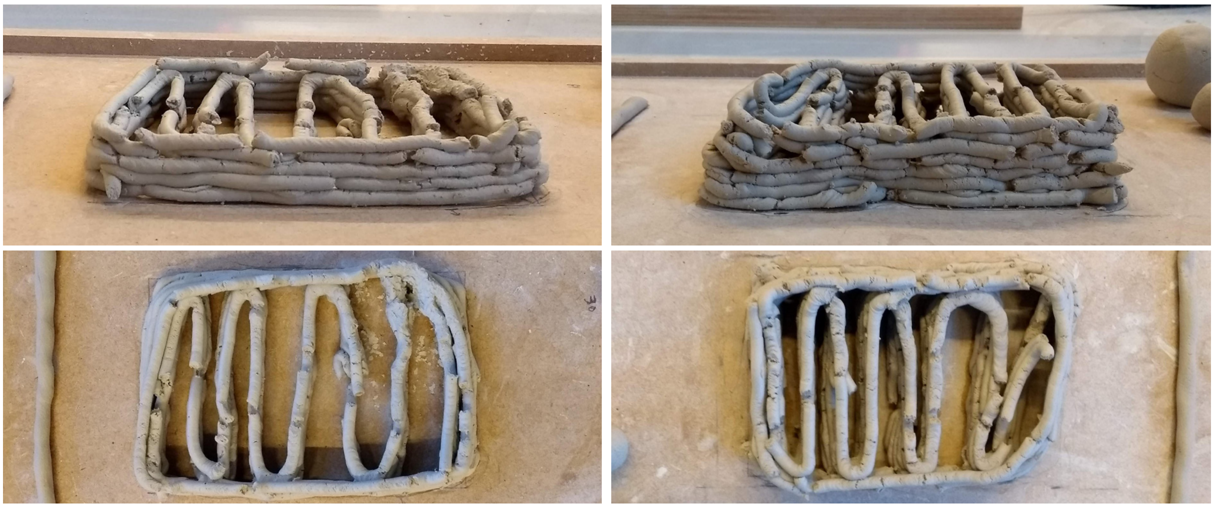
(b) Chammote 0-1 mm unextrudable consistency

(c) Wheat flour mixture

(d) Gypsum mixture

(e) Saw dust mixture

(f) Gelatin crumbling consistency



(g) Mix1 which has clay+chamotte 0-0.2 mm+ gypsum
Chosen mixture

(h) Mix2 which has clay+chamotte 0-0.2 mm+ saw dust

Fig.11. (a:f) shows the solo-additives of natural materials. (g:h) shows The final mixtures of which the chosen recipe was selected (Source:Author)

2.3.7 Deviations & Limitations

The experiment had some limitations that might affect the results and was not taken into account for the results of these experiments. These are related to two main aspects.

Firstly, the room conditions which might change in temperature and other climate aspects during the day and night. And this might affect the drying conditions for the prototypes.

Secondly, the Printing Process which was manual might have had been affected in terms of three aspects mainly — starting with the printing speed which is not very well controlled manually. Followed by the layer height which might as well have a bit of differentiation over a single layer. And lastly, the printed model size which was manually estimated to be almost the same for all the samples.

2.3.8 Discussion & Conclusion

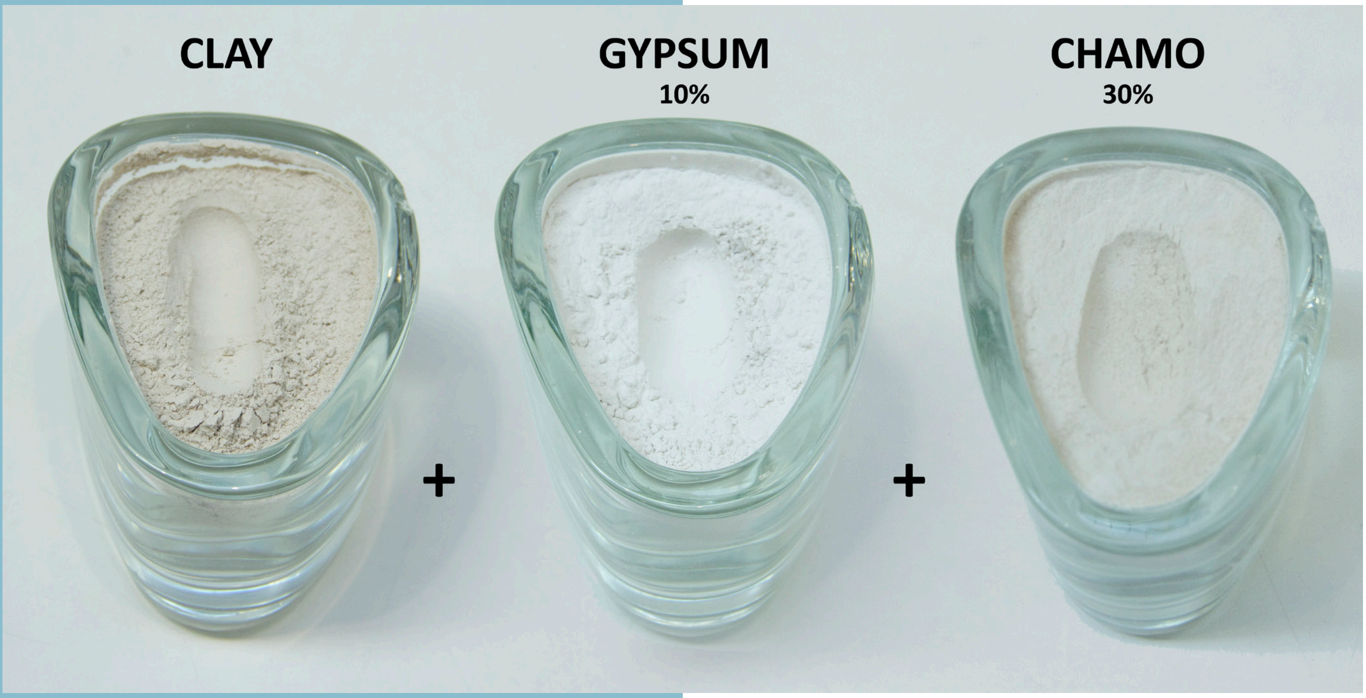
Exploring the printing process as an overall can be summarised in three main points to be considered for that they affect the product and the process majorly. Firstly, the clay body in the cartridge should be inevitably compressed without any air bubbles in between. Secondly, water content as a percentage in relation to the total weight of the mixture affects the viscosity and the line continuity of the mixture and should be carefully considered. Lastly, the design of the infilling and how it overlaps with the out-walls or shell of the layer affects the supporting and stability of the whole printed part. Hence, the longer sides of the wall should have overlapping supporting points from the infill, while the shorter width sides should have a tangent supporting infilling lines.

Material wise, concluded from the results of the experiments which are recorded in the experiment chart -Table 4.- as shown in detail in appendix1, it was concluded that out of the 4 different water percentages tested, the water percentage to the total clay body was recommended to be between 27.5% as minimum and 35% as a maximum. Additionally, out of the seven different additives used, only Chammote 0-0.2 mm, gypsum and saw dust were successfully printed and showed potential in terms of printability. While the other four additives, chammote 0-1mm, gelatine, wheat flour and, Water glass, were concluded as not printable as the first two mentioned, or badly behaving in printability as for the latest two.

If used as a solo, the clay body with only water in the mixture might have a high percentage of shrinkage to around 11%. While adding some additives that might develop and improve the printability and the material behaviour might decrease the shrinkage ratio to around 4.6% minimum as the case in Chammote 0-0.2mm, and around 8% maximum as for Wheat flour.

Layer building speed increased in the last mixed bodies, as mix1 of chammote 0-0.2mm and gypsum had the highest building speed at 0.4 layers/ minute. This might be reasoned to the fast hardening of the gypsum and the better densification and binding of the chammote. Although the saw dust mix2 showed less percentage of shrinkage, it is mostly hard to get the well-sieved saw dust in large quantities for more extensive prototyping, as well as it consumes more water content and as a result loses more of its weight on average.

In conclusion, the mixture of clay added to 30% chammote 0-0.2 mm grain size as well as gypsum of 10%, should all be mixed with 30% water as a percentage to the total body weight. This mixture showed the highest potential in terms of printability and material behaviour.

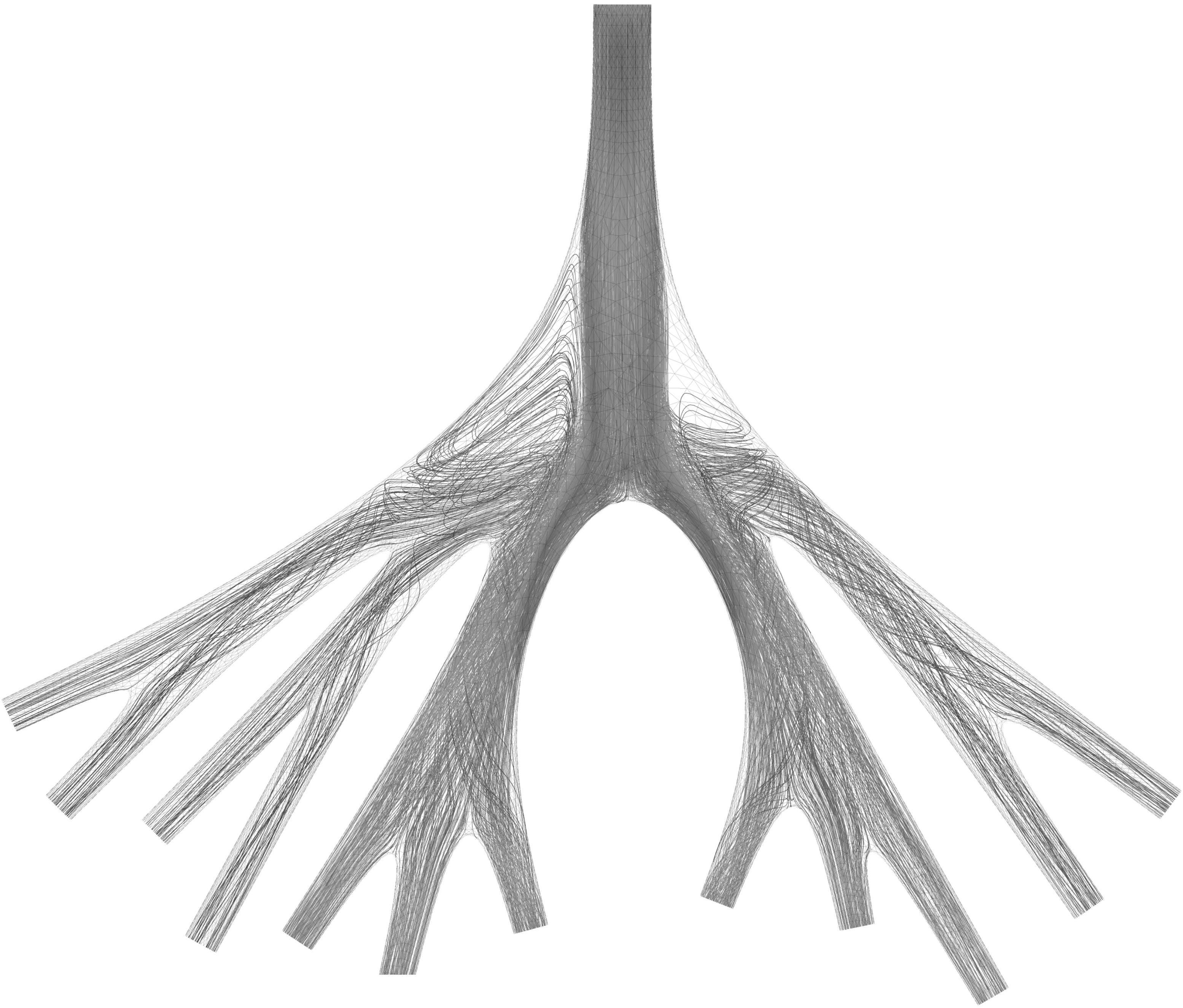


Final Clay mixture

3 WALL MORPHOLOGY

VENTILATION DESIGN

This chapter starts by introducing the integrated ventilation system in the design process, displacement ventilation. Next, presenting the case study location, requirements and dimensions as a base for the research design and verification. the duct design and morphology generation is following the calculations to determine these verification criteria. Lastsly, CFD analysis results run to evaluate the variant duct designs to come up with a final design used for prototyping.



3. Wall Morphology & Ventilation design

3.1 Chosen system | Displacement Ventilation

As carbon dioxide, water vapour, odours or any other contaminations in the building's air environment must be exhausted, newly fresh or conditioned air should replace it (Lechner, 2001). Ventilation systems might work in two major ways, conventional Mixing ventilation system or as a Displacement ventilation system. Both of the systems has its advantages and disadvantages, and in this research, the case is focused on the displacement ventilation system.

Displacement Ventilation was chosen as the system to be integrated within the research prototype. To further explain what is meant by displacement ventilation it could be described as when you add some new water to a full water cup that has some contaminations in it already. If the addition of water is added from the top, then the new and existing water will get mixed, and it gets harder to get rid of the contaminations. While if the water is added from the below -i.e. using a pipe - then the new water will start to replace the contaminated layers and push them out of the cup till the cup is freshly replaced without contaminations (Lechner, 2001).

The same principle applies in the air ventilation systems. By integrating lower air supply outlets near the floors, rather than ceilings as in the mixing systems, if these outlets have low air velocity, it will allow the space to be ventilated in a better manner and provide higher quality than in the mixing ventilation system.Fig.12 explains the difference between the displacement and mixing systems.

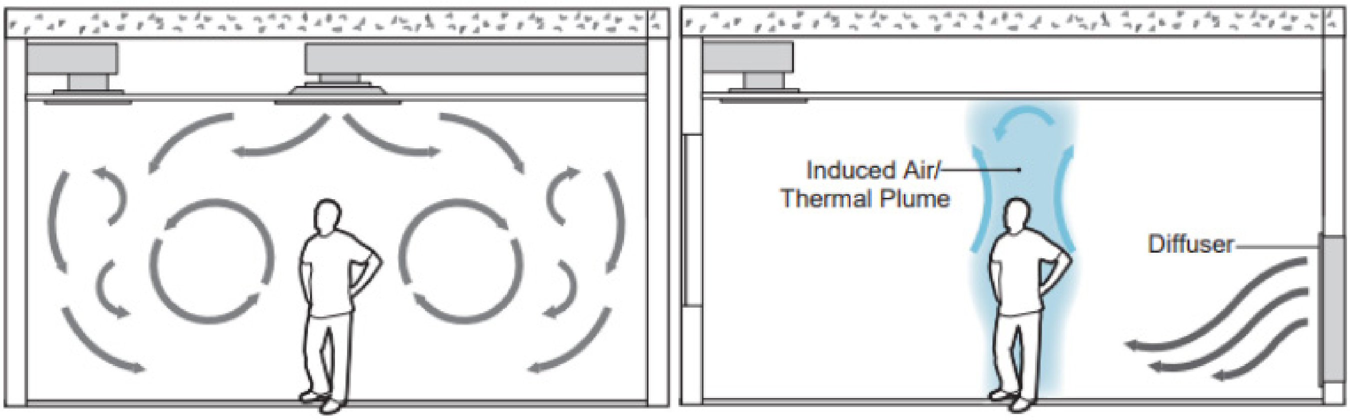


Fig.12. Difference between mixing ventilation system on the left where air is supplied from the top ceiling, and displacement ventilation on the right where air is supplied from walls or floors.
(Source: Price engineering guide book, 2011)

3.1.1 Advantages:

The displacement ventilation does have its advantages as it has its limitations as well. Regarding the advantages could be summarised in four points. Firstly, Better IAQ (Indoor Air Quality) is assured that the other conventional mixing systems. Due to the buoyancy forces of the air supply, it assures that the contaminated air will be exhausted from the higher returns easily (Fig.12(b)). Notably, the thermal plume of the existing bodies and heat sources in the space affect the temperature rise in the air introduced. Moreover, the warmer the air gets, it starts to rise higher in the room from the floor to the returning and exhausting outlets in the ceiling. Thus, contaminations existed in the room are derived out by the buoyancy effect, and better air quality is provided.
On the other hand, mixing ventilation system would provide cold air from the top ceiling, and by default, once it supplied and moved lower and lower, it gets mixed with all the contaminations in the room. Reducing the air quality introduced. As mentioned before in the example of the water glass by Lechner.

Secondly, this system requires lower air velocities which means that the fan speed used to move the air is consuming less energy. The requirement for low air velocity is because the air supplied from the wall in low heights near the floor if in high velocities might cause drafts which are not comfortable nor desirable. The low velocities also assure that the air will be distributed without the drought area in the adjacent area to the diffuser outlet (REHVA,2017).

Thirdly, Higher Chiller efficiency is achieved by the higher temperature of the return air and less supply temperature requirement. This is most useful when the outdoor air needs to be conditioned and dehumidified which means it will be less costly than in the conventional and typical mixing systems.

Finally, Lower air velocity means in return lower noise levels in the room ventilated, as the fan speed, in general, will also be less. This low velocity also achieves more indoor comfort because of the fewer air drafts which might happen when the induced air is in high velocity as in mixing systems (Price, 2011).

3.1.2 Limitations:

Although Displacement ventilation does provide many advantages, Yet it still has its limitations and considerations to be efficient enough and more preferable than mixing ventilation systems. Starting from the room and the space characteristics. As the required space for the ducts might be limited by the amount of solid or opaque area in the room, if it is not provided from the floors. Moreover, the ceiling height would be required to reach higher than 2.75 m to allow the air to be extracted by thermal plumes effect easily and maintain an even temperature distribution in the space. While considering that returns are placed not more than 30 cm from the maximum ceiling height to assure full extraction of the contaminated stratification zone. According to the design guide provided by some of the suppliers for displacement ventilation systems, the room depth should not exceed more than 8-9 m so that the induced air can reach all of the space areas.

Eventually, the limitations introduced were considered while designing for the ducts system in the final prototype and were considered as design criteria that helped to shape the final geometry as well.

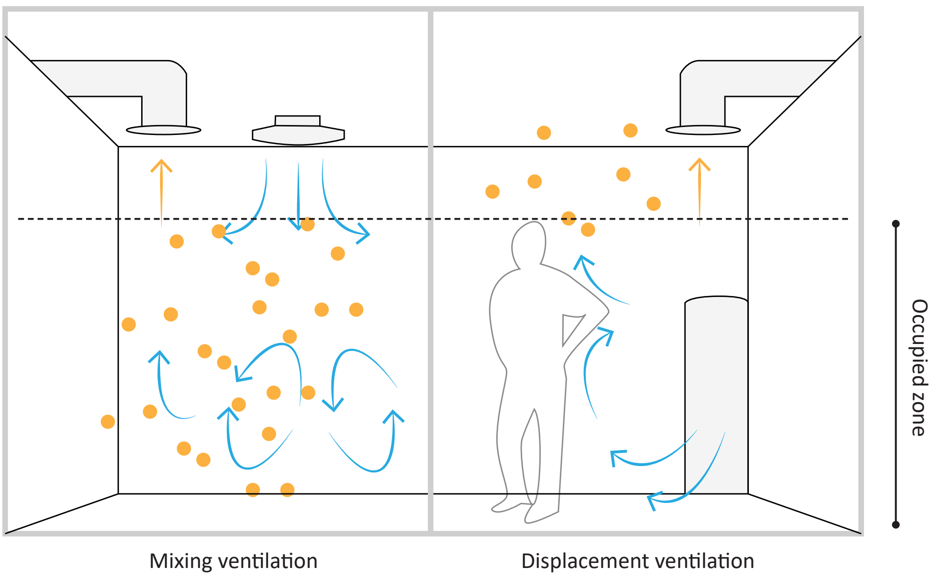


Fig.12(b) Difference between mixing ventilation system on the left, and displacement ventilation on the right in terms of indoor quality . (Source: Price engineering guide book, 2011)

3.2 Initial Design concept

The concept introduced for the wall to be prototyped is, in brief, an integrated displacement ventilation system into a facade wall. The designed wall is non-structural facade unit; these facade units on the building scale integrate a connected system of ventilation ducts. The ducts are interconnected from one facade unit to the other, where the air is supplied from one starting point in the first unit and flows to the endpoint which represents the starting for the next facade unit -Fig13- to continue the airflow over the whole building facade. However, This initial concept has been changed, as will be mentioned later in the design principles.

As a coral reef morphology the air ducts were imagined to be starting by the main trunk and then branches into multiple smaller branches; some of which gather and intersect again in a node to be directed in one big trunk at the adjacent side of the wall towards the next facade unit. While on the other hand, some of the branches are ending with an opening to release and supply the air to the room as shown in Fig.13.

The wall ducts are assumed to be moving within and inside the wall printing infill. but then it also bumps out to the interior side of the wall until it reaches the surface with the supply and releasing openings and other branches continue to the next unit as mentioned before. the openings are distributed on the top and the bottom of the wall to act as suppliers for the warm air from the bottom to allow it to raise up for heating purposes; while the other openings are from the top supplying cold air that goes down for cooling.

This wall facade by integrating the air ducts within it, it introduces more qualities to the space it envelopes. Firstly, it helps to reduce the amount of space consumed by the air ducts in the conventional air systems. by integrating the air ducts within the wall area that is already occupied, it offers higher ceiling height which is not occupied anymore. Moreover, by supplying the air from the walls or the side of the room instead of the ceiling -as in the mixing ventilation systems- it introduces the ability to create, instead, a displacement ventilation air supply system. Displacement ventilation as mentioned before offers variant qualities to the air within the room and hence, improves the user indoor comfort experience.

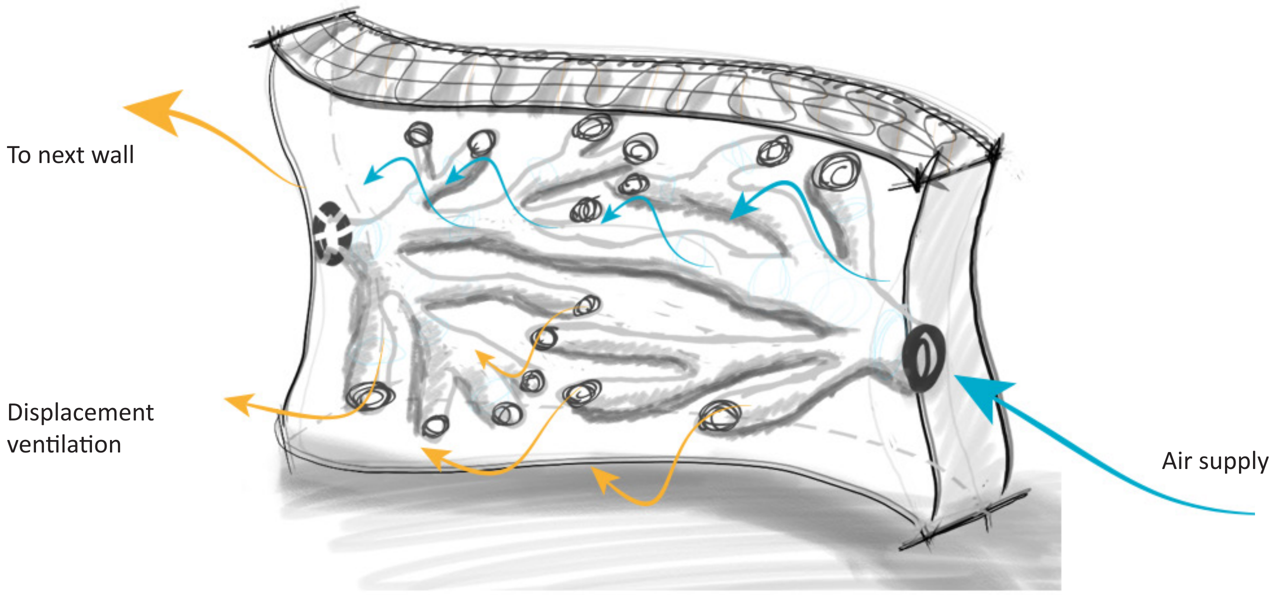


Fig.13. Initial design concept for continous duct system over the facade units through the coral reefs morphology to supply air over the wall from one inlet to the next. (Source: Author)

3.3 Case study design

3.3.1 Location

Deciding a case study for the research allows the research to be based on real-life values and limitations. the chosen location was considered to be the city of Seville in Spain. This City has a Mediterranean hot summer climate according to the Köppen climate classification system Fig.14. Which is assigned “Csa” in the same classification system, referring to (C) as temperate, (s) as dry summer, and (a) as hot summer. in such climate, the summer is hot and dry while it might be rainy and has moderate fluctuating temperatures in winter. (Beck, H. E., 2018)

Seville’s weather data was used in the calculations and simulation for the cooling loads required for the designed room in such a climate, and consequently calculating the required U-values for the wall to be designed within the research.

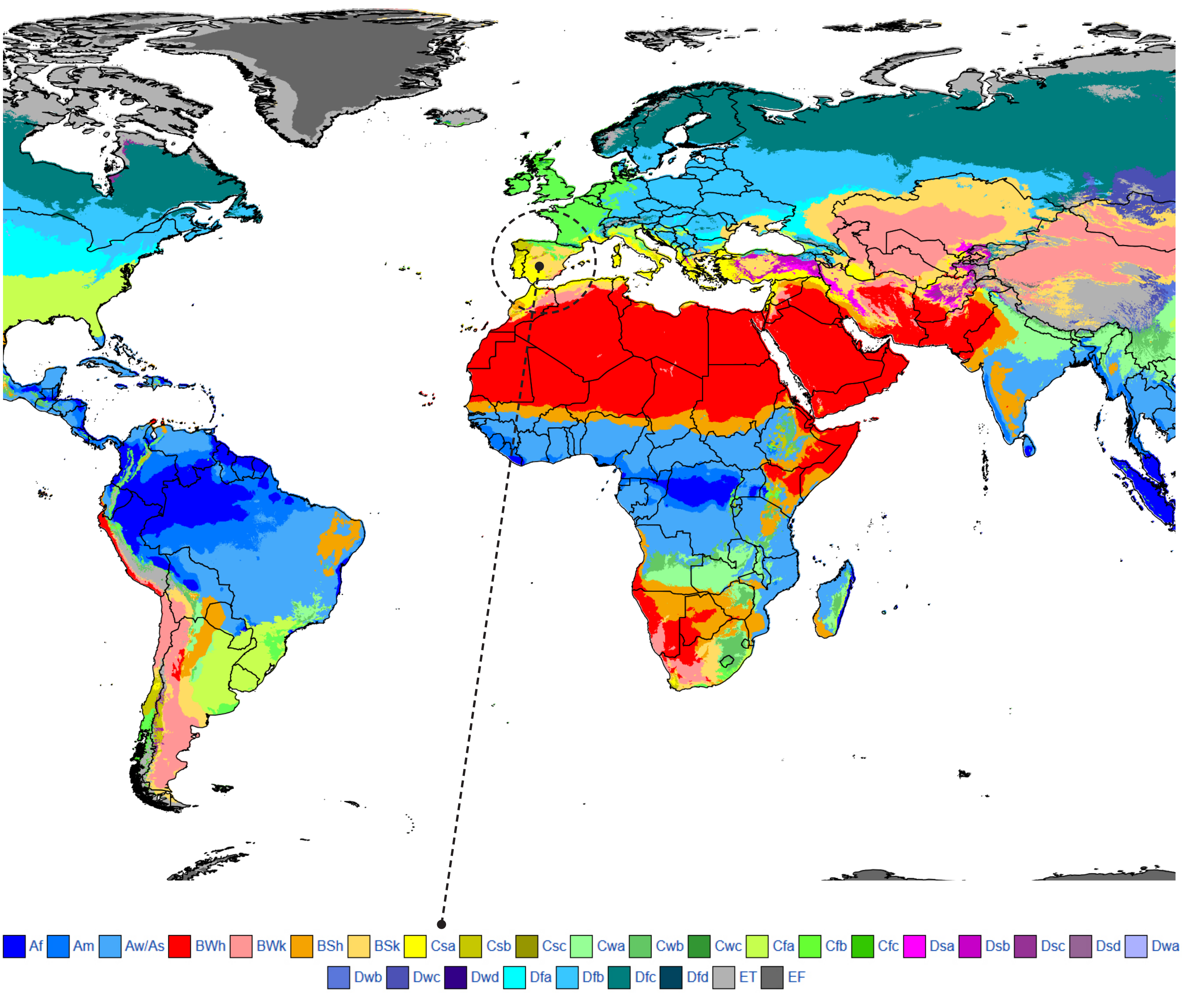


Fig.14. Chosen climate location on Köppen Geiger Climate Classification Map as a Mediterranean climate of Seville in Spain.
(Source: Beck, H. E., 2018)

3.3.2 Room Dimensioning

An office building is considered as the function or the typology for the case study. As shown in Fig.16, the open floor plan of an office building is assumed to have a core where all the service and machining is located. Out from the core, the air ventilation duct system is distributed over the office rooms, and it reaches each room with a branch which supplies the air to the room. This branch is assumed to be the designed supply duct that could be replaced with the proposed wall design.

Choosing the corner room of the floor plan, it was dimensioned according to the U.S. (United States) and the U.K. (United Kingdom) office design standards average. An office space that is accommodating three persons as a manager and two other employees with a table in between. According to the Uk typical standards a professional room for a group room in an office building, it would assume 9 m^2 per person (van Meel, 2000). This means that the room size for three persons is 27 m^2. While according to the U.S. standards, same space decreases to be 8.6 m^2 (International Facility Management Association, 1997), giving a room area of 25.8 m^2, which is not a huge difference. On the other side, the European standards assume more than double this space and vary from London to Frankfurt or Amsterdam which has 16.8, 25.5 and 24 m^2 per person, respectively. Since the UK and the US standards are more close to each other on average, and the European standards are a bit deviating from them. As an approximation, the room is dimensioned to be 30 m2 for three persons, with a length of 6 m and a width of 5 m as shown in Fig.16.

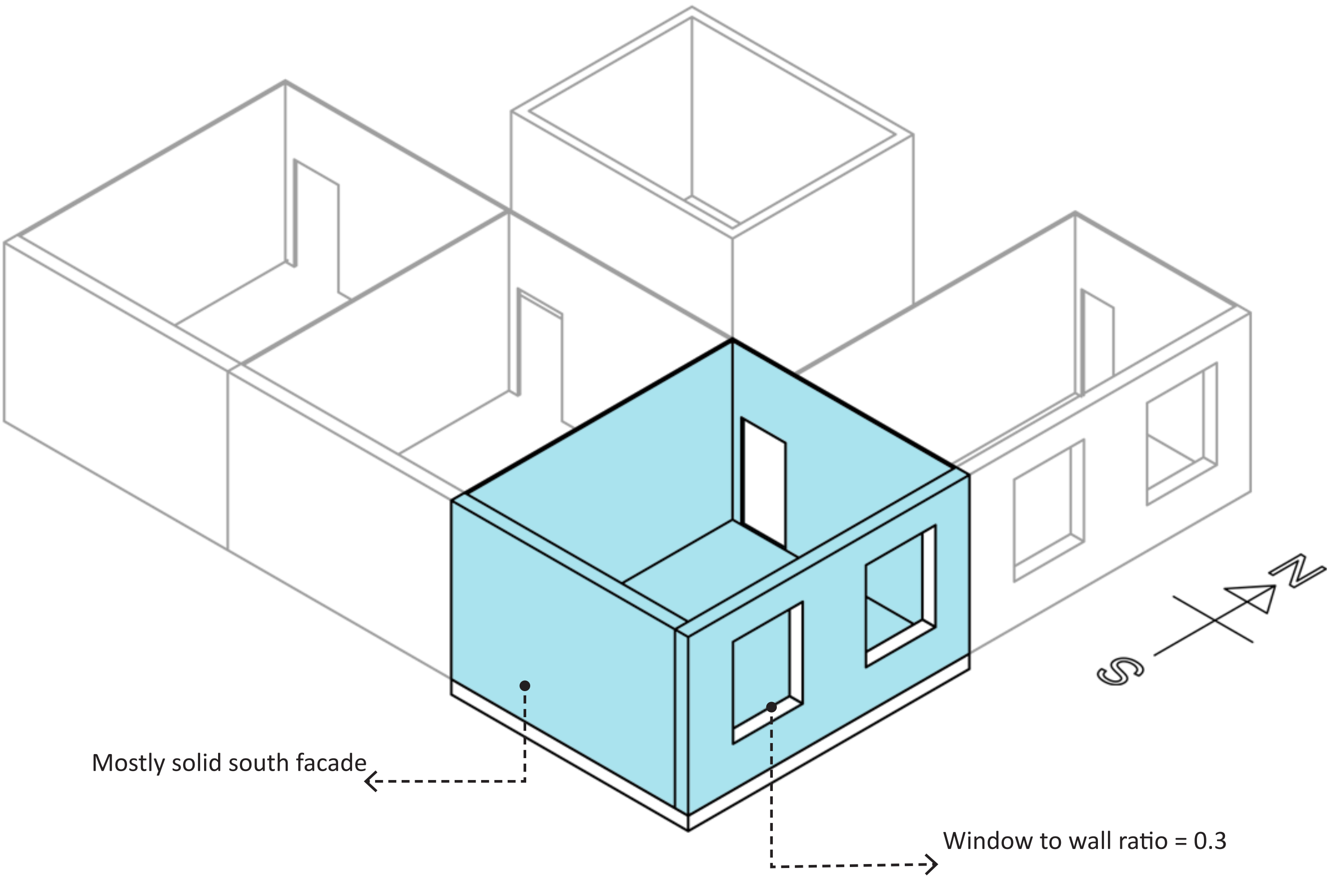


Fig.15. The room is oriented to the south which is mostly in that context a solid wall. This is the wall that could be printed out of clay as an opaque material. (Source: ASHRAE,2013)

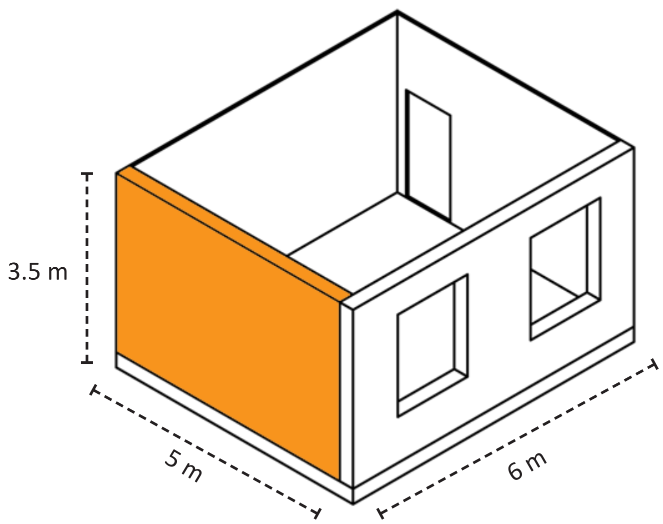
The room is on the corner facing south facade from one side which is the designed wall and mostly would be opaque to prevent most of the solar gain through the windows and glazing. While the perpendicular corner side is facing east and has two windows. WWR (Window to wall ratio) is assumed to be 30% for the east corner side which is 6 m in length (Fig.15).

The ceiling height is assumed to be 3.5 m because, as mentioned before, ceilings that are higher than 2.75 m are required for the displacement ventilation to be more efficient. Hence the height is considered to be 3.5 m including the required service false ceiling above the 2.75 m. This means that the windows are designed according to the following:

Wall area = 6 m * 3.5 m= 21 m^2
Windows area = 30% * 21 = **6.3 m^2**

Assuming two windows:
One Window area= 6.3/2 = **3.15 m^2**

The dimensioned room is digitally modelled as shown in Fig.16, and a Design Builder analysis was conducted to find out the required cooling load for it which is further explained in the following section.



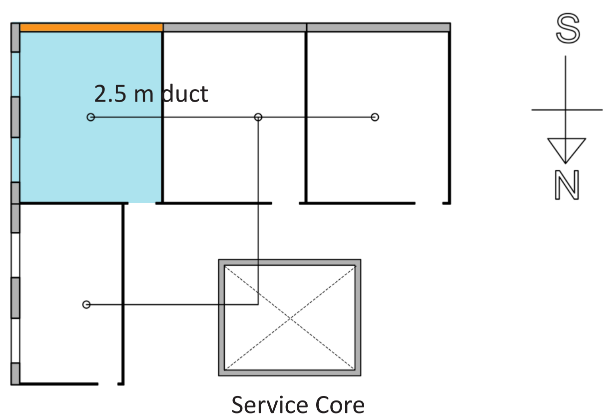


Fig.16. Left: The room is dimensioned according to the Office design standards, and the ceiling height was according to the diplacement ventilation requirements. Right: The corner room in an office plan as a case study, The ducts reach from the service core to the room in a conventional design of 2.5m supply duct in the room. (Source: Author)

3.3.3 Duct Design | Verification criteria

The ASHRAE Handbook of Fundamentals 2017, in par. 21.6.3.3 mentions the Equal Friction Method and the Static Regain Method for designing duct systems. For low-pressure systems, the Equal Friction Method is advised. In this method the pressure drop per meter length is the same in all branches. The resultant duct diameter out of this calculation and the pressure drop value per unit length will be considered as the criteria for deciding whether or not the proposed morphology is working and verify its applicability.

"Friction losses are due to fluid viscosity and result from a momentum exchange between molecules (in laminar flow) or between individual particles of adjacent fluid layers moving at different velocities (in turbulent flow). Friction losses occur along the entire duct length." (ASHRAE,2013,Ch 21.6). Although the flow will predominantly be turbulent in this design, low pressure drops will be observed.

Step 1: Total Cooling load

For the equal friction method, the cooling load should be determined in the beginning. This was done using DesignBuilder software analysis for the modelled case study shown previously.

Wall layers for the two exterior walls in the case study model were assumed to be a conventional wall layers design. Considered typical wall with layers of 100 mm Brickwork to the exterior, followed by 10 mm air cavity, 30mm of XPS (Extruded polystyrene), and finally, 13 mm gypsum plastering to the interior. These Layers gives a U-value of 0.73 $W/m^2.K$, this is within the recommended range of 0.94 $W/m^2.K$ for new buildings in the Spanish code for Malaga region and even the average of Spain overall of 0.83 $W/m^2.K$ (Ministero de Fomento, 2009). The other two interior walls, as well as the floor and the ceiling, were set as adiabatic for more straightforward calculations.

Results were gained from the analysis, and the total annual cooling load was -995.7 kWh. Considering that the cooling loads will only be required during the annual hours at which the temperature is reaching 26°C, this gave total hours of 978.5 hours. Therefore, the total cooling load is 1.017 kW, following is its brief:

U-value = 0.73 $W/m^2.K$
Total annual cooling load= 995.7 kWh
Total hours at or above 26° = 978.5 h

Total average cooling load = 995.7/978.5 = **1.017 kW**

Step 2: Volume flow rate

Next step was calculating the volume flow rate, which depends on calculating the mass flow rate. Mass flow rate is determined using the equation in equ.1:

$$m = \frac{Q}{C_p * \Delta T} \qquad \textit{Equ.1}$$

where:

m = mass flow rate *kg/s*
Q= Total cooling load *kW*
C_p= Specific heat capacity of air *kJ/kgK*
ΔT= Temprature difference between supply air and return air *°C*

$$m = \frac{1.017}{1.026 * (26-18)} = \mathbf{0.123\ kg/s}$$

Where the air supply temperature was set at 18°C and the return air temperature set to be 26°C, according to the typical design parameters (Price engineering guide book, 2011), this gives a temperature difference of 8°C. The specific heat capacity for air is a typical well value as 1.026 KJ/KgK.

Volume flow rate is determined by the equation equ.2:

$$V = m * v \qquad \textit{Equ.2}$$

Where:

V= Volume flow rate *m^3/s*
m = mass flow rate *kg/s*
v= specific volume *m^3/kg*

Specific volume =

$$v = \frac{1}{\rho} = \frac{1}{1.2} = \mathbf{0.833\ m^3/kg}$$

Where:

ρ = Density of the air *m^3*/kg

Therefore volume flow rate is:

$$V = 0.123 * 0.833 = \mathbf{0.103\ m^3/s}$$

Step 3: Duct diameter

Once the volume flow rate is calculated a characteristic duct diameter and the pressure drop value are obtained from the graph shown in Fig.17.

Assuming an air velocity of 3 m/s for the branch designed, a length of the duct of about 2.5 m which reaches to the middle of the room as shown in Fig.16. The duct diameter used in such conditions is found from the chart in Fig.17 to be 200 mm in diameter. And the equivalent pressure drop value is 0.6 Pa/m as a pressure drop over the unit length.

Reynolds number is calculated as well to estimate the analysis process for the morphology later as if it was laminar fluid or turbulent. Therefore at a temperature for the air of 18°C and a duct length of 2.5 m the following equation -equ.3- is used to determine the Reynolds number.

$$Re = \frac{\rho V L}{\mu} \qquad \textit{Equ.3}$$

where:

Re = Reynolds number
ρ = Density of the air *m^3*/kg
L = Diameter of the duct *m*
μ = Dynamic viscosity of air *kg/m-s*

$$Re = \frac{1.2 * 3 * 0.2}{1.825 * 10^{-5}} = \mathbf{39,452}$$

Since Re is more than 2300, it is considered to be turbulent flow.

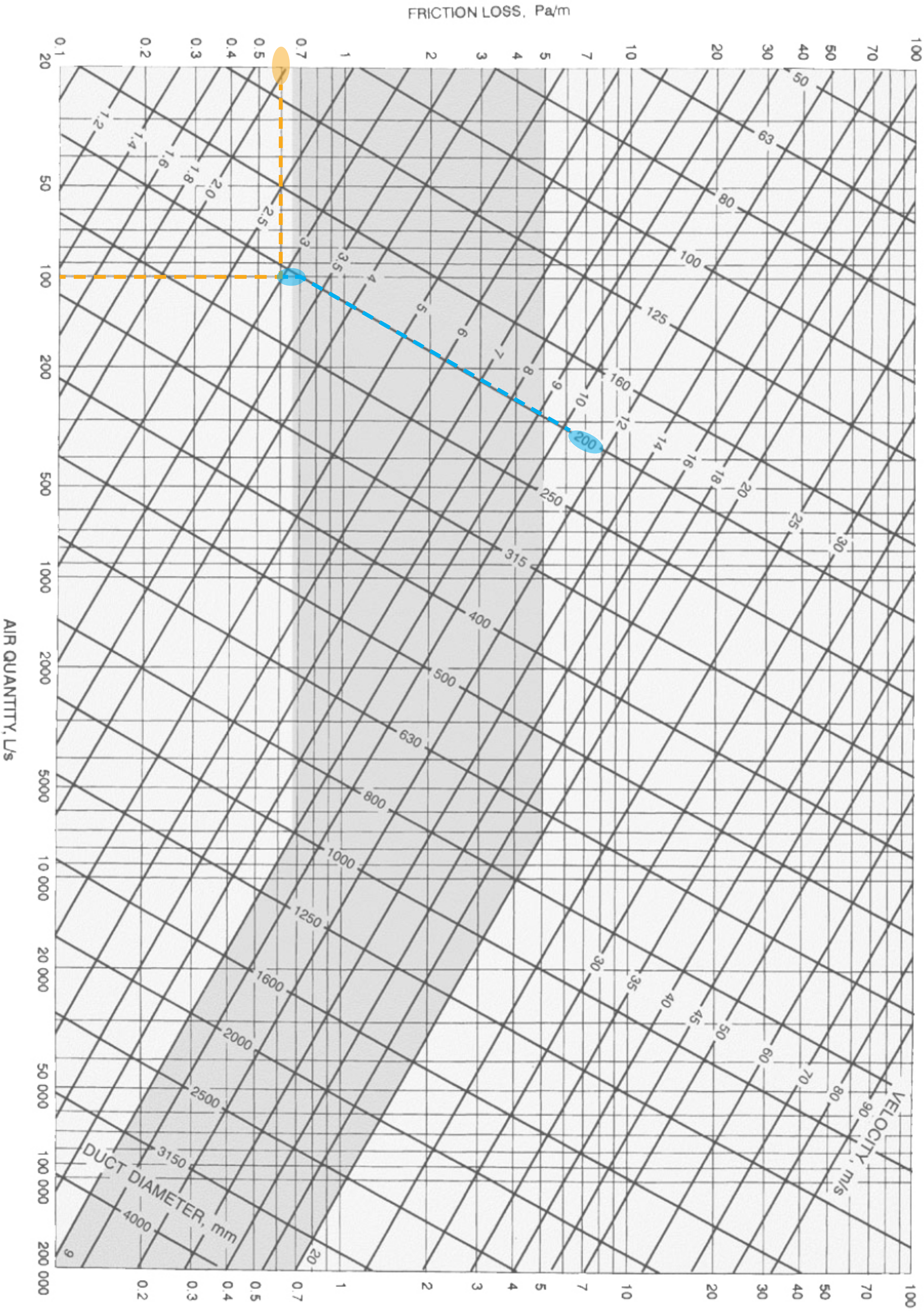


Fig.17. Friction loss chart used to determine the duct diameter and equivalent pressure drop. (Source: ASHRAE,2013)

These values are considered as the design criteria that were followed to verify the designed morphology for the facade unit later. The duct diameter was used as a base and a starting point to generate the morphology that sprang off into smaller branches. While the pressure drop value was used to verify each variation generated for the morphology using the CFD analysis software as will be mentioned later.

Table 7 summarize the values calculated and used to come up with these design criteria.

Design Builder anlysis

Literature review calculation requirements

Designed case study

Literature review

Friction loss chart

Function	Value	Unit
Total cooling load (Design Builder)	995.7	KWh
Total hours at or above 26	978.5	h
U-Value	0.73	$W/m^2.K$
Total cooling load	1.017577925	kW
Cp (specific heat capacity of air)	1.026	KkJ/kgK
supply air temprature	18	°C
room air temperature	26	°C
ΔT	8	°C
m (mass flow rate)	0.1239739188	kg/s
Air dynamic Viscosity	1.83E-05	kg/m-s
Reynolds number	39,452	
ρ (Density of the air)	1.2	kg/m^3
Specific Volume	0.8333333333	m^3/kg
V (Volume flow rate)	0.103311599	m^3/s
L (length of duct)	2.5	m
Air Supply Velocity	3	m/s
P (Pressure Drop)	**0.06**	**mm water/m**
	0.6	**Pa/m**
D (Duct Diameter)	**0.2**	**m**

Table 8. Summary for the calcualted and used values to determine the initial design and verification criteria for the morphology of the facade to be designed. (Source: Author)

3.4 Design Morphology Principles

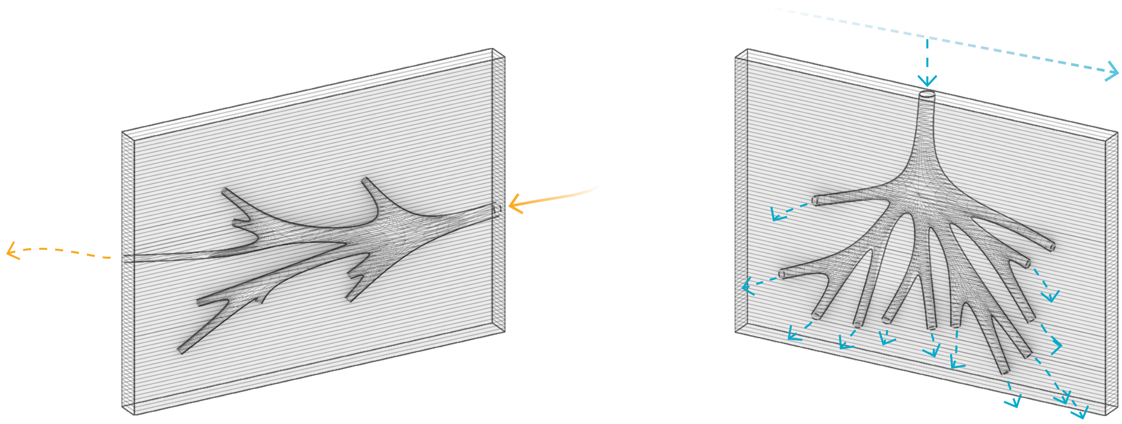
In the initial design concept, the air is supplied from the vertical side of the wall to the adjacent vertical side in a horizontal manner. However, reconsidering this aspect, it was assumed that the air pressure might drop drastically from one unit to the other. Hence, the overall pressure drop of the facade will be high and it will lead to different supply rates for each wall section. The high-pressure drop will reduce the wall sustainability considerations -maintained by the material used and the technology- that it tries to promote, as it will be less energy efficient.

Therefore, the wall is considered to be not a fully connected network from one unit to the other, but instead, it's proposed to be connected by one main duct that runs over the facade horizontally in each floor. This main duct supplies the air to the facade units from one supply point. From this supply point, the air is distributed downwards to the openings on the surface (Fig.18). The ducts are not reaching from one side to the other directly anymore; instead, it just supplies -from lower level heights- the air to the room.

Design principles:

3.4.1 Distribution direction:

The orientation of the distribution depends on the orientation of the supply openings. If the duct branches are as in the developed design it will assure smooth air flows from the ducts to the floor. From the floor it can distribute over the room space. While the sided orientation as in the initial design causes the air to be moving in a horizontal direction before it falls down to the floor (Fig.18). Sided orientation would not have supplied equal distribution for the air over the floor and the room space.



Initial design
High pressure drop expected

Developed design
Lower pressure drop expected

Fig.18. Due to the continuous supply over the inner ducts through facade, pressure losses will be high in initial design (left). (Source: Author)

3.4.2 Printing orientation:

This new orientation of the ducts from upwards to downwards introduces additional advantages. Firstly it is more suitable for the printing process. By building up the printing of the wall over the short height of the elevation, as in Fig.19, it helps to reduce the risk of collapsing while printing. As less material is accumulating over each other in the successive layers, the layers will be facing less compression strength from the above built-up layers, and the risk of buckling for the structure is less.

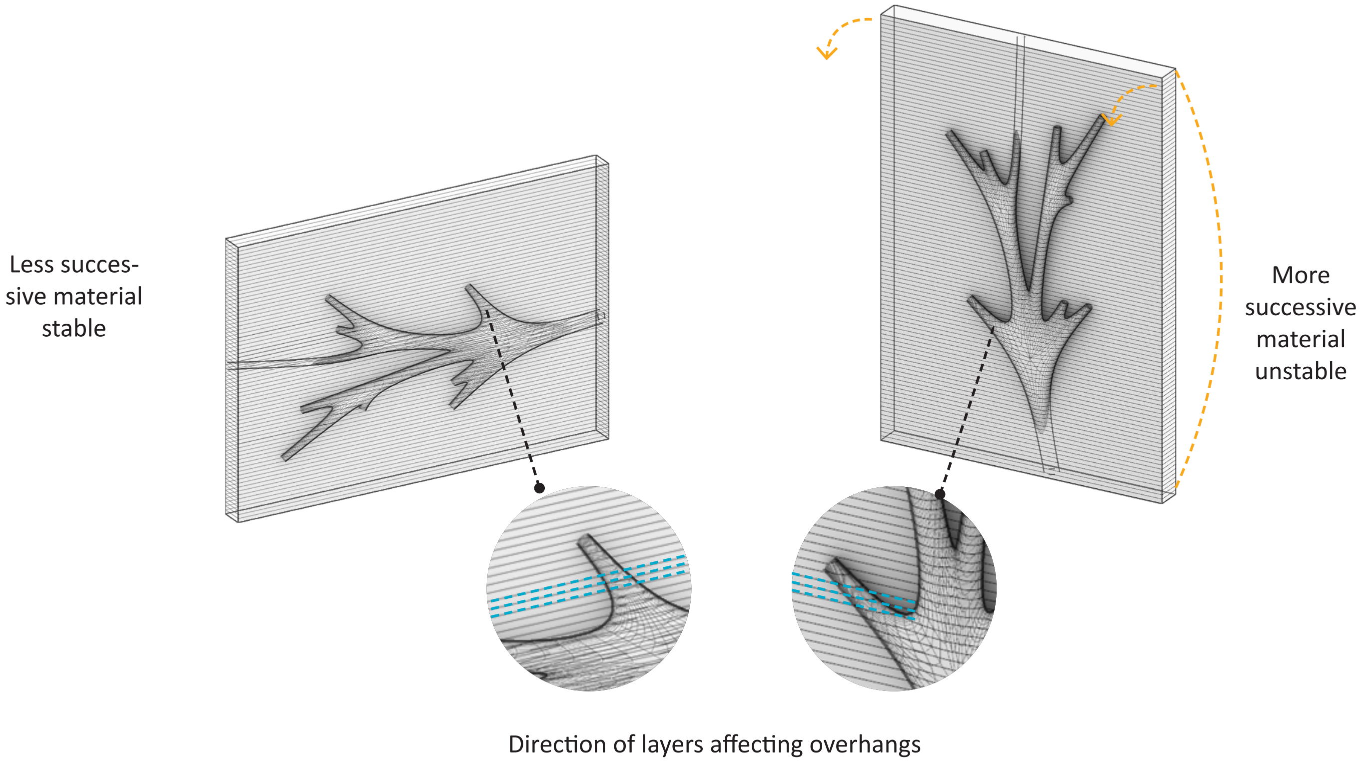


Fig.19. Printing direction affects the stability behaviour while building up the print. it also affects the support for the overhangs to be printed. (Source: Author)

Morphology Parametric Script

The rest of the design principles for the morphology are applied through a Grasshopper script for generating tapered coral reef morphology. This parametric script is based mainly on the C# script created by Laurent Delrieu and available as an open source file on Grasshopper online community. The script was adjusted for the ducts design where the required principles were possible to control. Shown in App.2 in the appendix the full script used to generate different ducts design before CFD analysis.

Inputs for the script shown in Fig.20 start by a center distribution node for the ducts. This center node represent the divergence node for the branches from the inlet to the outlets as in Fig.22. Multiple control points are linked to the center node and resembling two groups. Firstly the outlet and inlet openings and secondly the in between nodes to link the outlets/inlet to the center node. as shown in Fig.22. Three values are controlling the diameters of the ducts. Initially the grouping amount which is used to manipulate the link between the in-between nodes and the rest of the points. Briefly, it changes the density of the lines network shown in Fig.22. The last two inputs are the inlet radius in meters and the ratio controller for the outlets radius.

Outputs are simply the ducts as a smoothened mesh and the inlet and outlets as a Brep (Boundary representation) for a total area ratio evaluation and presentation.

Shown in Fig.21 are different possible variations as a result of changing the inputs in the Grasshopper script. Either by changing the numeric sliders or the amount and location of the inserted points to the script.

Each of the following design principles is represented in reference to the grasshopper script and how it works to achieve the ventilation design requirements.

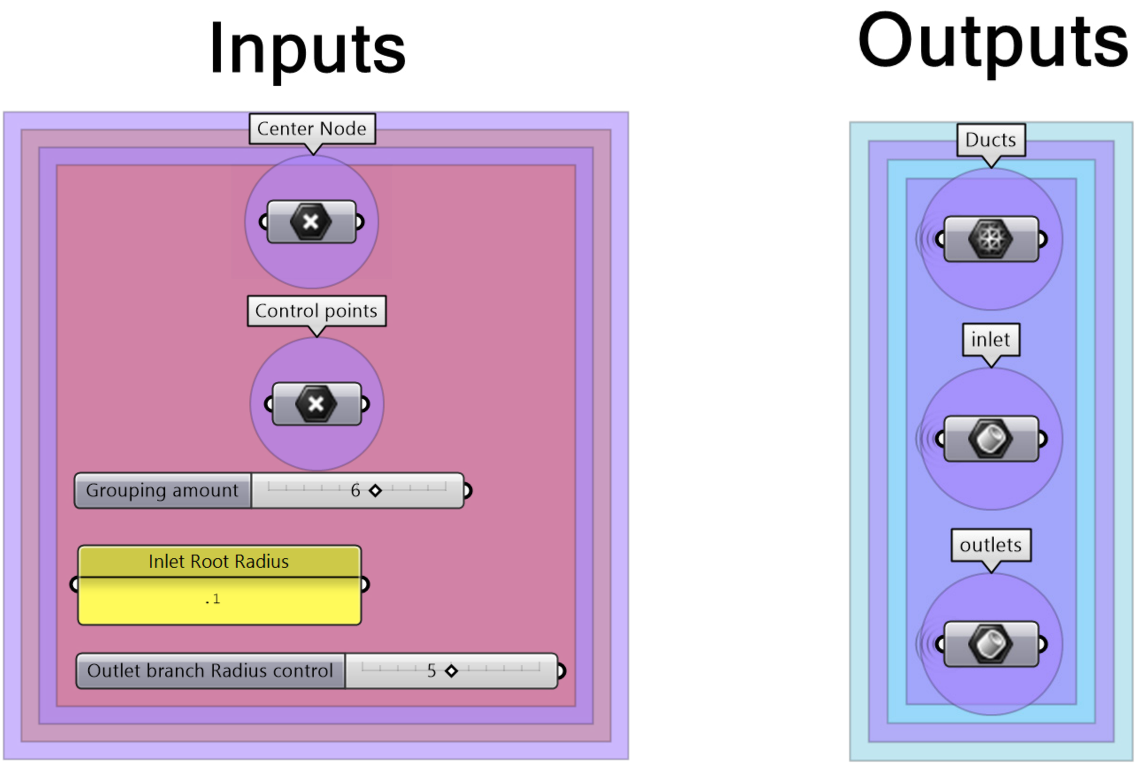
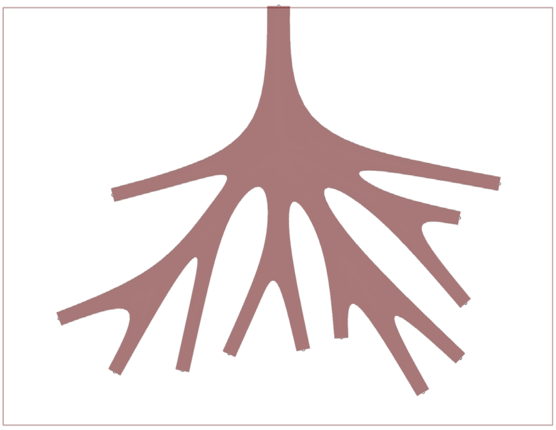
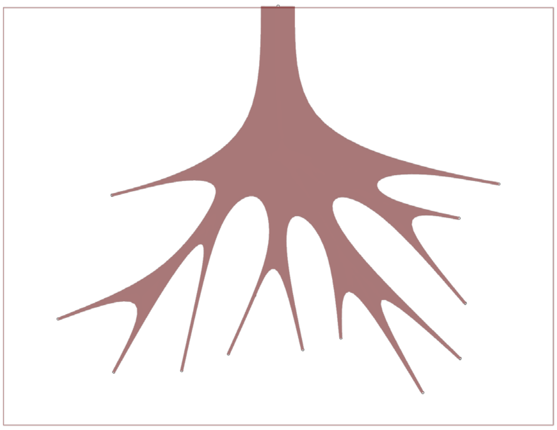


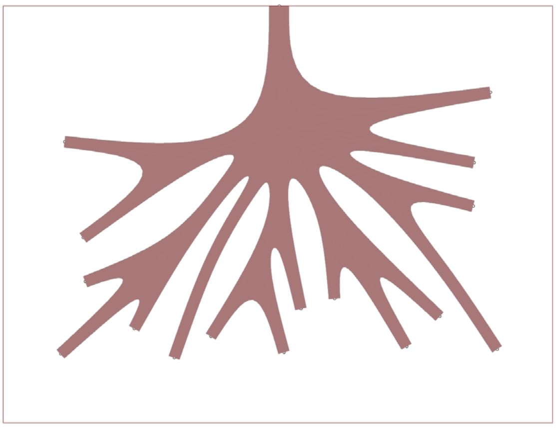
Fig.20. Inputs and outputs for generating the duct morphology through a grasshopper script that eases the generation of variants easily and quickly to be assessed in CFD. (Source: Author)



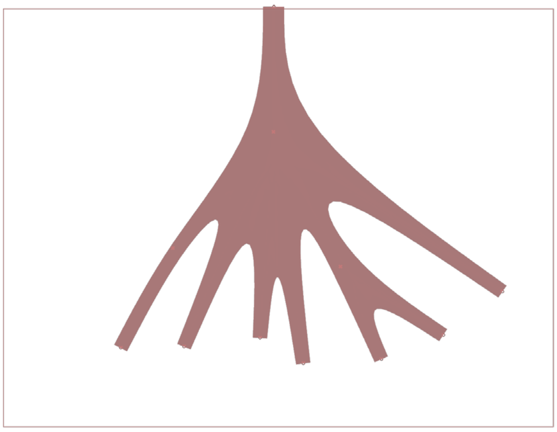
inlet radius: 0.1 m
Outlet radius: 0.05 m



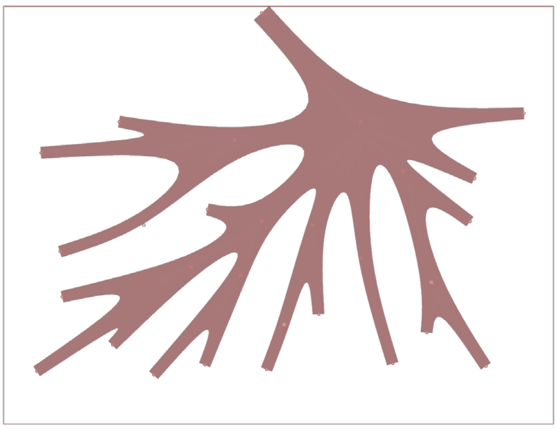
inlet radius: 0.15 m
Outlet radius: 0.015 m



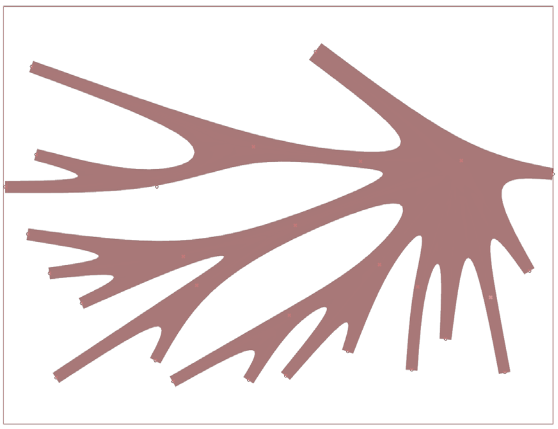
Control points: 30



Control points: 10



Inlet to outlet link: Top - Down



Inlet to outlet link: Side-Side

Fig.21. Variant options generated by the Grasshopper script eases the process of the design and its adjustment to fit for different climate requirements and further optimization research. (Source: Author)

3.4.3 Shortest walk & Opening height:

Conventionally, in duct designs, the shorter distance between the supply and the outlet is considered better. This is because it reduces the power required to move the air from one point to the other, as well as reducing the material used for the ducts while possibly saving the space occupied.

Similarly, the design principle in the morphology for the facade unit is considering the shortest walk between the inlet opening from the top to the outlet distribution openings over the wall interior surface.

For the morphology design, certain points that are adjustable and controllable are assigned to the outlets. Another point was assigned to the inlet which is also controllable. Moreover, another set of points were assigned to be the links between the inlet and the outlet to control the resultant morphology and make it looks more interesting as a coral or tree system. Shown in Fig.22 is such a set of points, which are afterwards connected with a network of lines by a controllable approximation. The approximation generates network lines between each point and a controllable amount of the other closest points. Once the approximation network is generated, the shortest walk between each outlet point and the node point is found among the approximated network. This Shortest walk line found is considered the first step to generate the morphology.

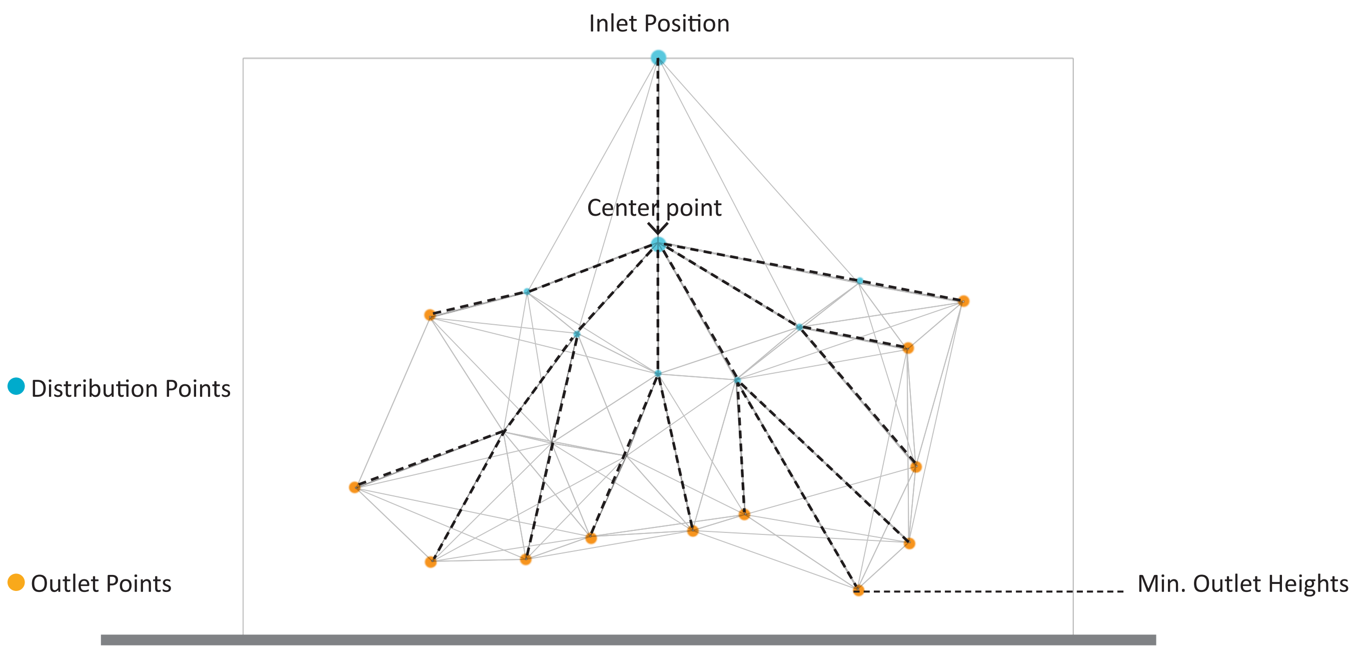


Fig.22. Shortest walk among network of Proximity links between inlet and outlet points created, assure less friction losses and pressure drop. (Source: Author)

3.4.4 The inlet to outlet area ratio:

To attain the 3d morphology, a radius is assigned to the inlet and the outlets. The inlet radius is derived from the conventional duct design techniques as mentioned in the sub-section of the case study design of this chapter of the research. It was assigned for the inlet diameter to be 10 cm in radius. The outlets are assigned a radius as a proportion of the main radius. This creates a difference in the area of the inlet to the outlet as a ratio. The inlet to outlet ratio affects the evenly distribution of air over all the outlet. For small outlets, the flow rate over each will be the same. However, such a geometry will induce a high pressure drop. An optimum is sought between a good distribution of air while maintaining a low pressure drop. (Fig.23).

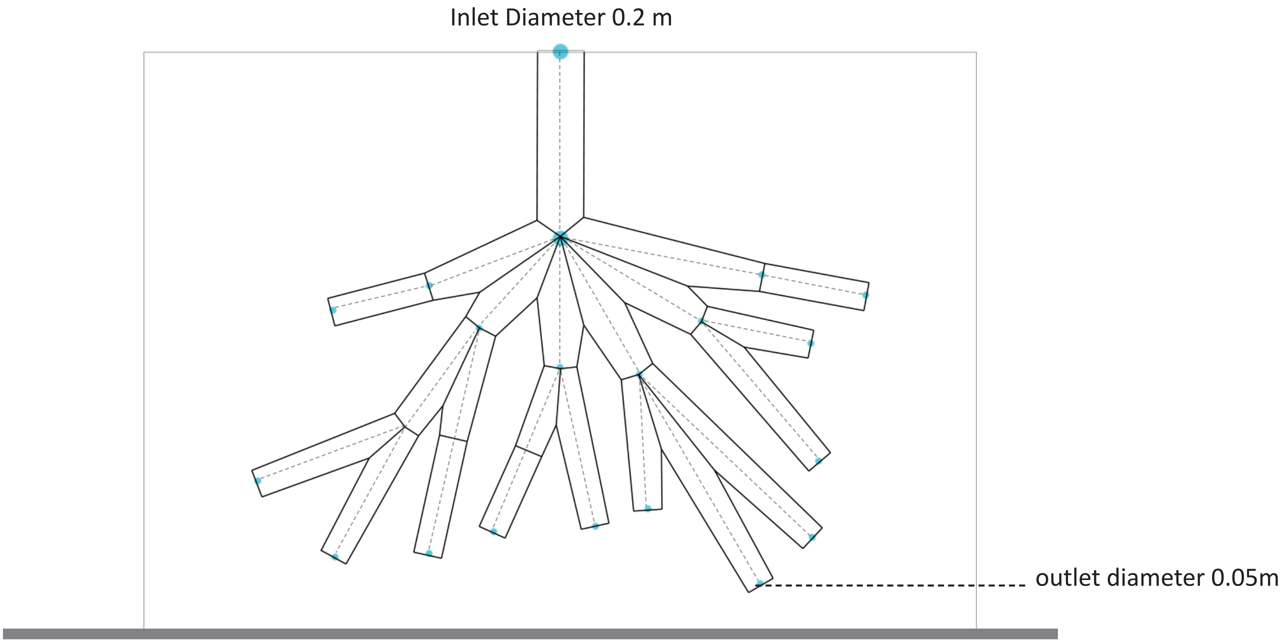


Fig.23. Inlet diameter derived from the inital calculations for the duct design, the outlet diameters are smaller to assure better air distribution by pressure. (Source: Author)

3.4.5 Smooth edges:

After the 3d geometry is generated around the centerline of the generated network, the edges of this geometry are smoothened to eliminate the sudden changes. This assures that the air will be flowing easily inside the ducts and reduce the frictional losses or losing its speed (Fig.24).

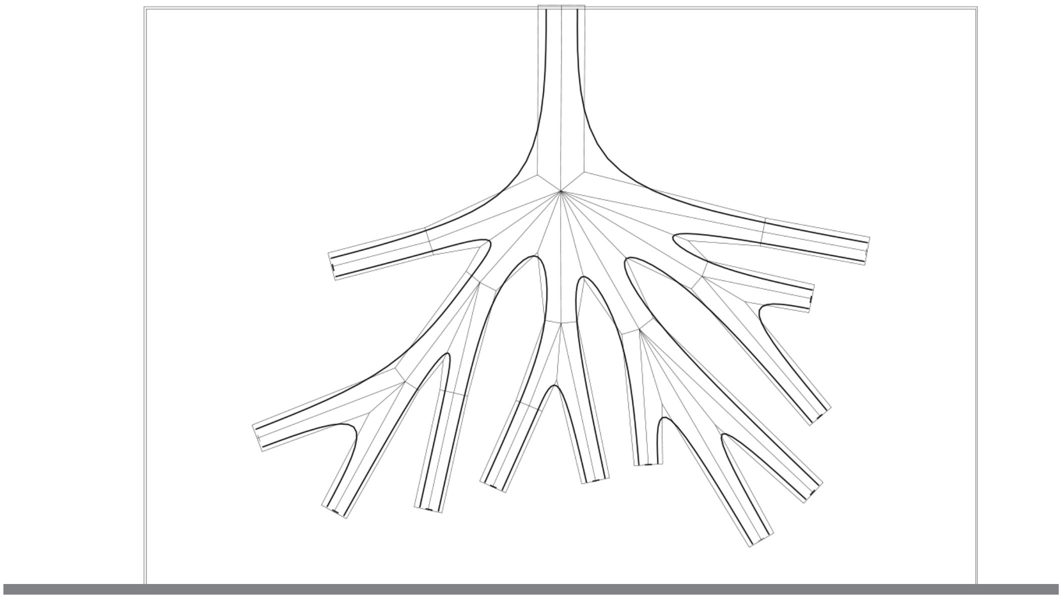


Fig.24. Smooth corners and avoiding sudden corners or turns to reduce the turbulent effect and pressure losses. (Source: Author)

3.4.6 Outlets overhang:

Eventually, the outlet openings are overhung from the wall interior surface to the room. This assures a better distribution of the air directly to the room. Unlike the flat faced openings over the wall surface which doesn't assure a certain direction for the air. The small overhangs do give the air its direction or orientation through the room which affects the way the air is flowing over the floor of the room.
Moreover, the Overhangs cause the ducts to be bumped out which adds an aesthetic value to the wall in the space and do expose the potentials and possibilities of 3d printing to produce complex geometries easily (Fig.25).

Once, all previously mentioned design principles are applied, different geometries and morphologies were obtained and verified in CFD analysis as will be mentioned in the following pages.

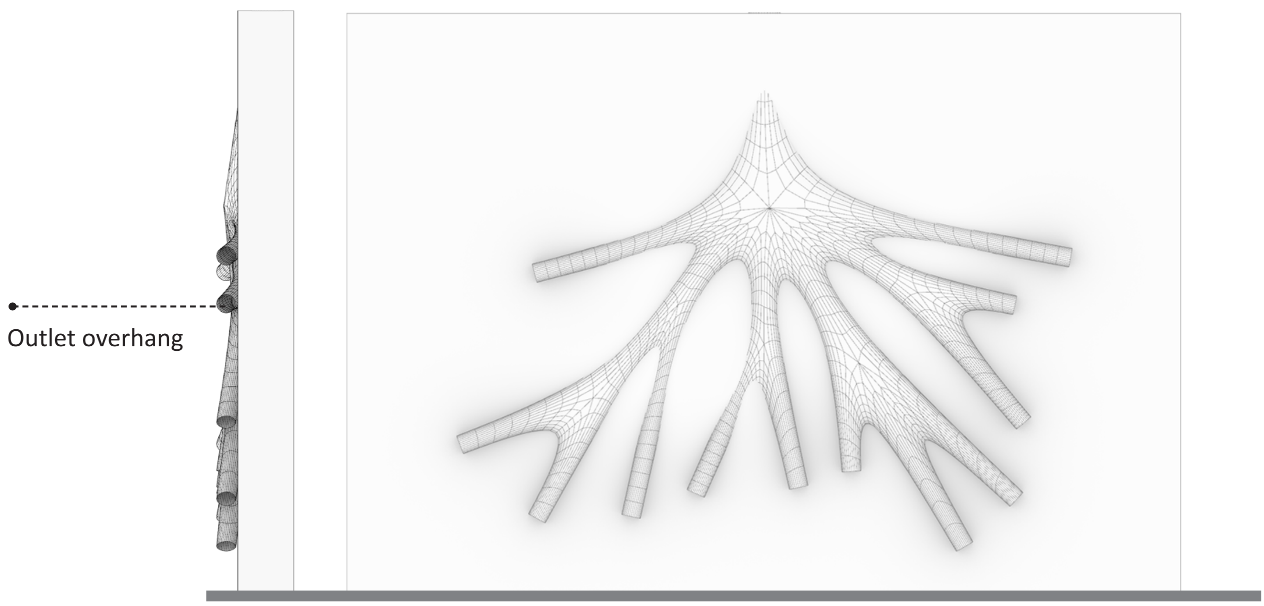


Fig.25. Overhang outlets create the bump effect over the interior surface. (Source: Author)

3.5 Variations & Verification analysis

3.5.1 Method | CFD Analysis

The initial design generated from the previously mentioned principles, had to be verified that it complies with the criteria concluded in the duct design phase of this research. This assures that the geometry will be working correctly in its unconventional morphology which later will be printed and prototyped.

This verification is done using CFD analysis (Computational Fluid Dynamics). Starting by using Butterfly, a plugin for Grasshopper interface, it was not so practical or easy to operate the software and assure it works properly due to the many constraints and issues with installing the related operating software to it as OpenFoam software. Moreover, as the plugin was working, it is considerably used for an outdoor CFD analysis and wind tunnel similar cases, than to be used for an internal air flow through complex geometry. However, Rhino CFD plugin as well was explored, although it is much easier to operate and run, it had the same problem as Butterfly that it does not support the analysis of internal flow in complex geometry, rather, more suitable for simple geometries.

Eventually, Ansys Fluent software was used to run the analysis. Ansys Fluent which is widely used in the aerospace industry offered the possibility for CFD analysis for the turbulent flow of the air within the geometry generated from Grasshopper & Rhino. Fluent is accepting the geometry from Rhino models and runs the analysis as for a mesh model.

The meshing of the geometry considerably affects the precision of the results. This is due to the amount of the mesh faces generated, and for which the analysis is run. The more faces there are, the higher precision and more reliable the results are. For that, the mesh independent values that could be generated and become reliable, require reducing the size of the mesh face to half. That meant to run the analysis multiple times with a different number of faces. However, the academic license used in this research has a limited amount of mesh faces, a maximum 512,000 mesh face to be analysed. This number of mesh faces was nearly reached, and the analysis for each of the geometries generated from Rhino was analysed only once using the maximum allowable number of mesh faces it can reach. This is considered as one of the limitations of the study which should be mentioned and might be improved for further research in terms of optimising the morphology of the design.

3.5.2 Analysis setup

Used setup for the analysis starts by the General solver which was a pressure-based solver. For a standard initialisation solution method, a turbulent flow condition was considered. Secondly, The inlet boundary conditions used for the initialisation of the analysis were defined by a magnitude of 3 m/s for the inlet air velocity.

The material used for the fluid is the standard air material with a density of 1.225 Kg/m3 and viscosity of 1.7894e-05 Kg/m-s. While the wall or the duct, in that case, was considered as a standard fluent aluminium material for more straightforward analysis process; and because the roughness or the properties of the 3d printed clay material is not yet known or documented since its a work in progress and still research in development. To define the material properties in that aspect could be another focus of another research.

The results were extracted as numerical values and also as graphical representations. Numerically, total pressure was an output result. Calculated as the difference between the average total pressure at the inlet, and the total pressure average at the outlets. This gives the value of the total pressure as a value of Pascal. Dividing this value by the total length of the duct from the inlet to the lowest outlet, as an estimated height for the duct, gives a characteristic value of the pressure drop per meter length. It is compared to the design criteria calculated previously in the duct design phase.

Graphical results generated were, firstly the streamlines of velocity which shows the turbulent flow of the air from the inlet to the outlet and through the overall designed geometry. This helped to notice the unnecessarily generated outlet branches, as well as, noticing where the air would be moving backwards due to the sudden changes or the direct connections from inlet to the outlets. Secondly, the contours or vertical sections parallel to the elevation of the wall, these contours had two representations separately. Total pressure value to notice where the most losses of pressure are happening along with the flow, and the velocity as well to be noticed along the flow direction and also over the outlet section.

3.5.3 Simulation Results

Initial Analysis | Geometry 1

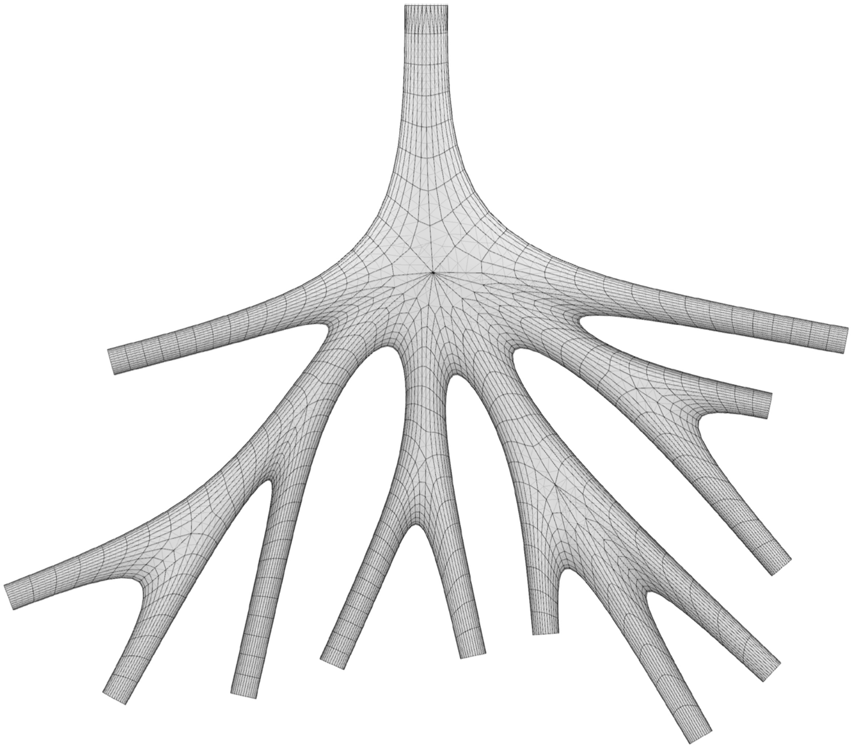


Fig.26. Initial geometry G1 introduced for CFD analysis for validation. (Source: Author)

The initial design generated, shown in Fig.26 and referred to as G1, was introduced in Ansys for CFD simulation analysis. Using mesh faces count of 311,986 faces or element. The resultant Total pressure drop had a value of 2.79 Pa, which along the length of the duct is 0.91 Pa/m considering 3 m the height of the duct. Although this value is higher than the calculated value for the design criteria of 0.6 Pa/m, Yet it is still efficient and an acceptable value for a low pressure system. And the average outlet velocity was 0.72 m/s.

Noticed from the Streamline representation in Fig.27, the branches that are in an angle of 10-25 degrees from the horizontal axis has almost zero air flow, and the outlets as shown in Fig.28 have almost zero velocity. therefore for the other variations, it was recommended to cull these branches of such an angle. This is also due to the height of these branches outlet openings which might be affected with the temperature of the cold air that might not go up easily but rather down.

This derived the conclusion that some of the branches might be a waste of material to be produced and are inefficient or neglectable in terms of the air distribution system performance.

Also, from the Total pressure contour in Fig.29 it is clear that at the branches distribution node, when the air is directed towards it, the high-pressure losses tend to happen at these points. Hence, it reduces the velocity of the air coming through. Furthermore, the outlets that are on a direct line with the inlet tend to have higher air velocity than the others and for sure more air flow rate as in Fig.30.

Thus, the indirect links between inlet and outlets are preferred while also reducing the distribution junctions that are facing the inlet or the high-velocity airflow.

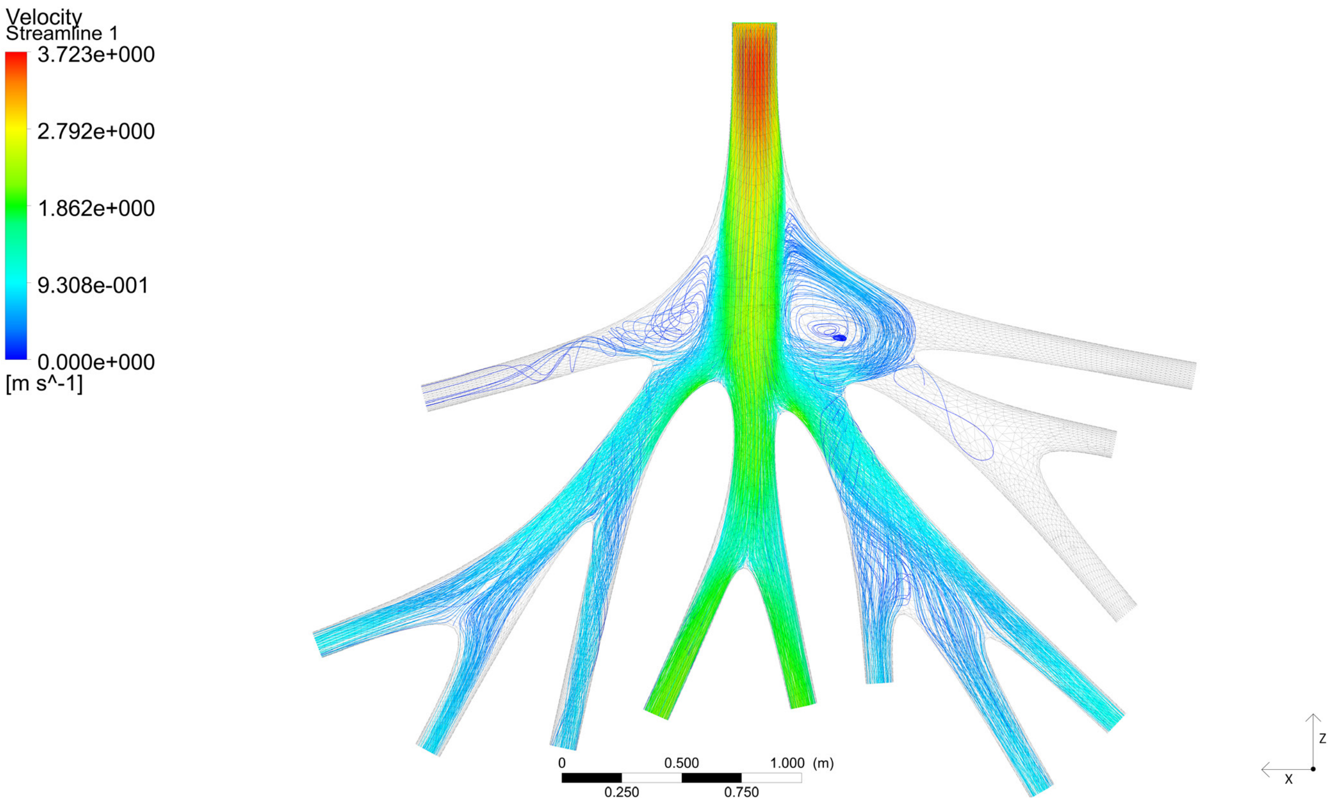


Fig.27. Velocity stream lines results shows the inefficient or neglect-able branches in G1. (Source: Author)

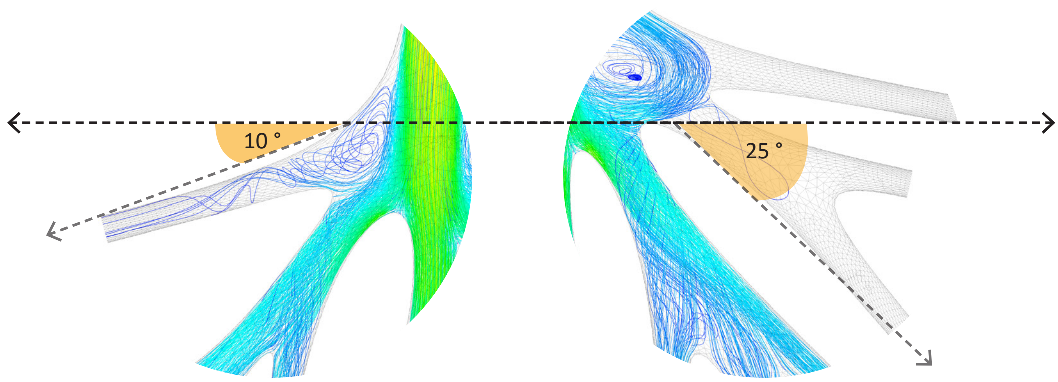


Fig.28. Branches that are between 10-25 degrees of inclination from the horizontal axis are the least efficient, as the air does not flow through it (Source: Author)

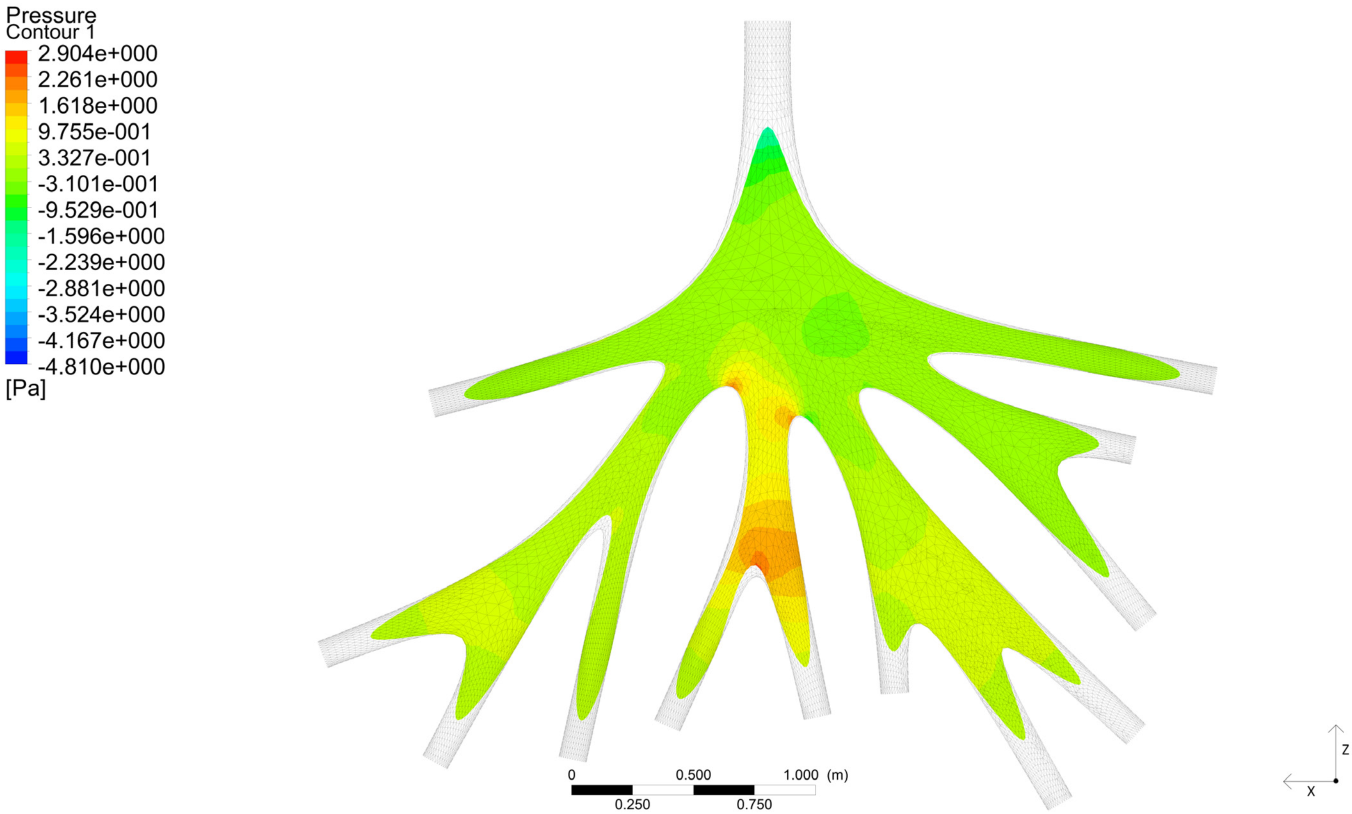


Fig.29. Total Pressure contour shows the velocity losses at the distribution nodes for the branches. (Source: Author)

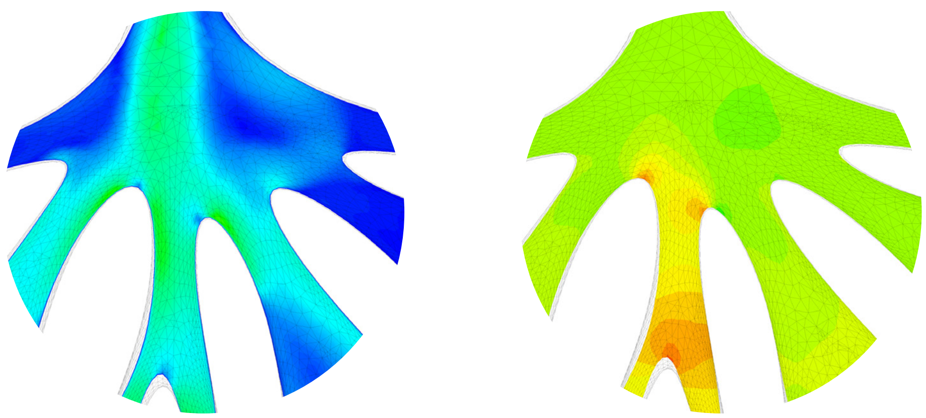


Fig.30. Pressure losses at the nodes caused by the velocity decrement as shown on the left side contour for velocity . (Source: Author)

Variations | Geometry 2

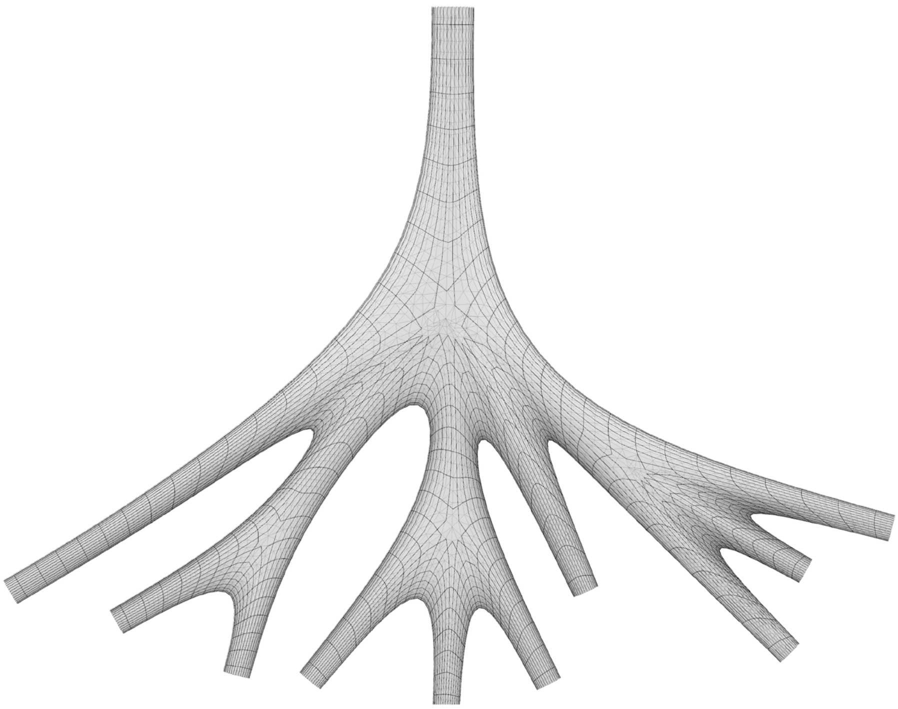


Fig.31. G2 second variation with less branches of 10-25 °. (Source: Author)

These notes from G1 helped in generating the next geometries to be analysed. Starting by Geometry 2 shown in Fig.31 referred to as G2. The unnecessary branches were eliminated, and only the branches that are on the angle of more than 25 degrees from the horizontal axis, were kept. Besides, the nodes or the points where the branches are growing or diverging from were reduced from 11 nodes to 9 nodes.

The analysed mesh had total elements of 248570 mesh face. The resultant total pressure value was 2.26 Pa which counts for 0.75 Pa/m. This is 20% less pressure drop than the first initial geometry. Still, the average outlet velocity increased from 0.72 to 0.76 m/s.

Clearly, from Fig.32, the air flow within the geometry G2 became more efficient than G1 in relation to the air streamline distribution over the branches. However, it still had some inefficient branches that had an almost zero flow as observed in the streamline representation.

Considerably, the same principle that resulted from G1, that the direct nodes that are facing the air flow are the main points where the pressure losses are happening, this same note was in G2 as shown in Fig.33. As a result, it affects also the velocity of the air before coming out of the outlets as well as the distribution of the air-flow over the sub-branches.

Briefly, the resultant geometry needed more refinement to be more efficient in terms of air distribution and flow. Also in terms of the outlet average velocity which the less it is, the better. Moreover, finally to explore if the pressure drop value can be reduced even more.

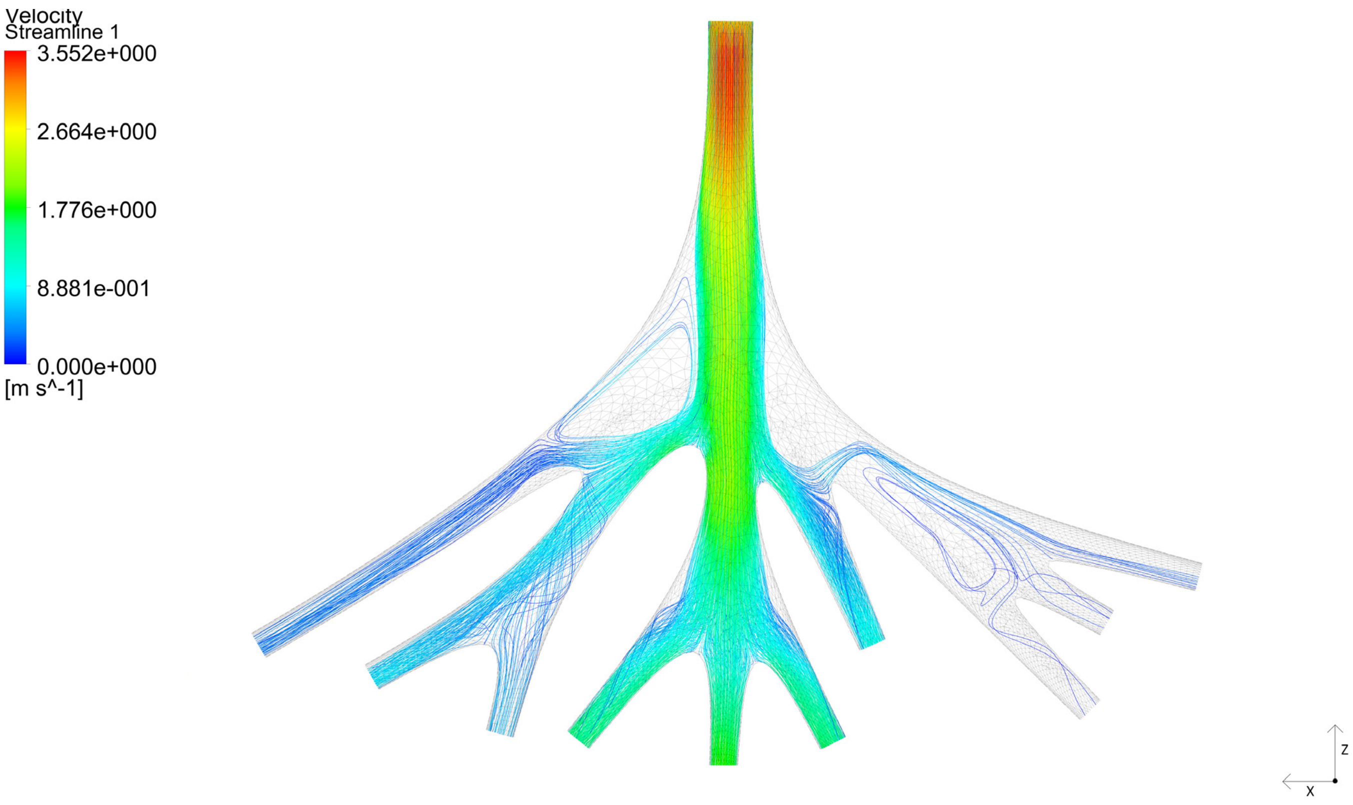


Fig.32. Velocity stream lines results shows the inefficient or neglect-able branches in G2. (Source: Author)

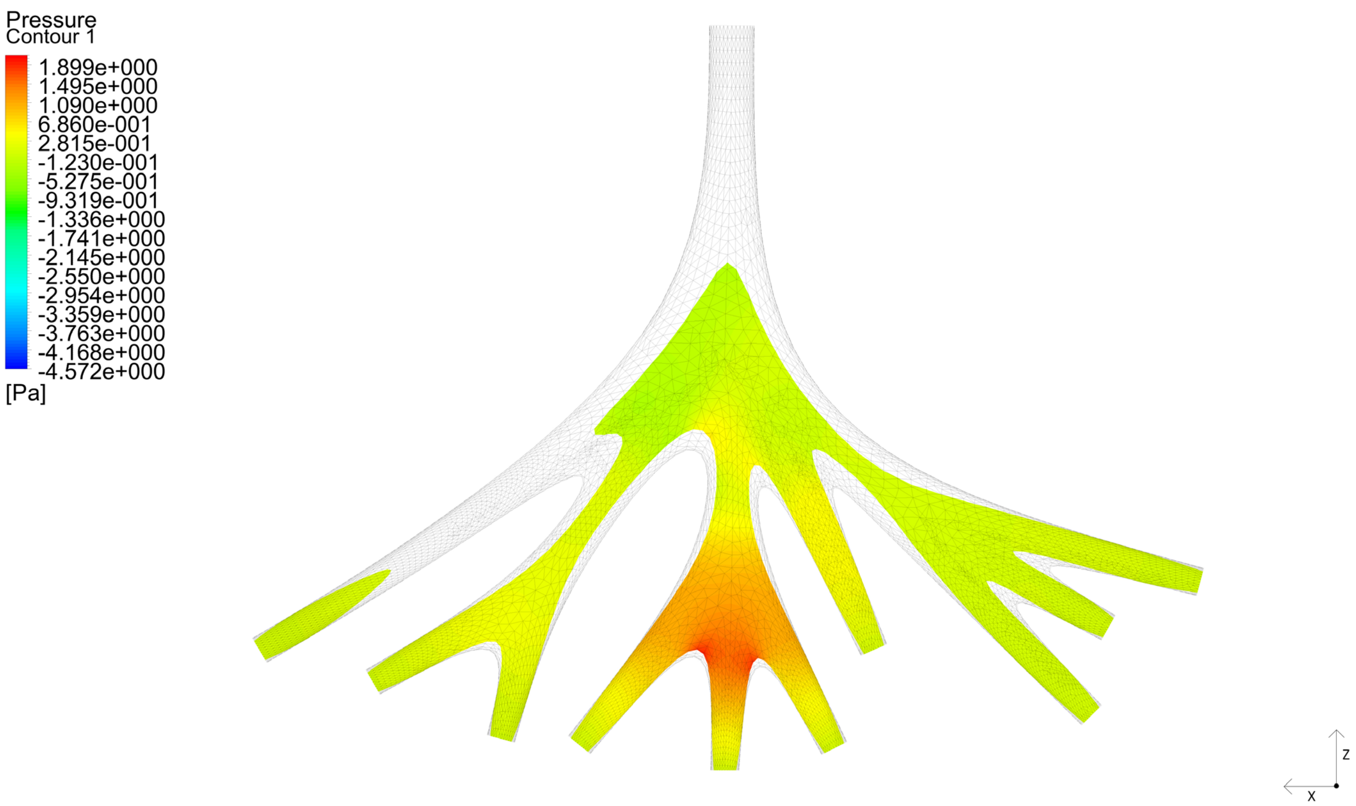


Fig.33. Total Pressure contour shows the velocity losses at the distribution nodes for the branches. (Source: Author)

Variations | Geometry 3

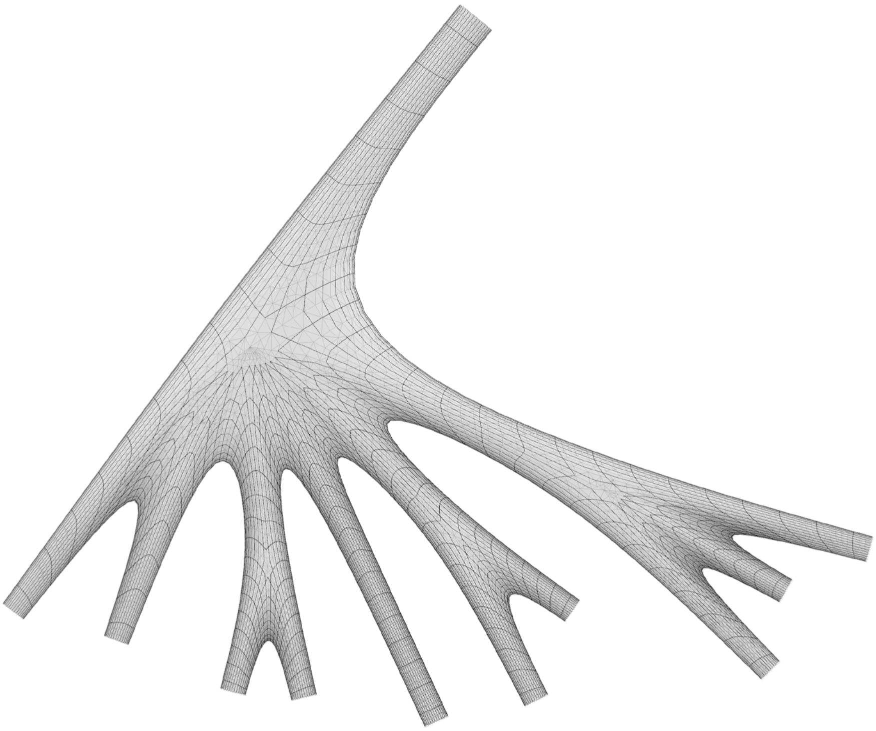


Fig.34. G3 third variation with different inlet direction for further exploration. (Source: Author)

For further exploration of the effect of the geometry shape on the air flow, a variation with a different inlet-outlet relation is generated. This geometry referred to as G3, has a main branch or trunk of a 50 degrees angle from the horizontal axis as in Fig.34. While also it has other branches distributed from one side of the main trunk, instead of two as in the previous geometries. The mesh model had 269197 mesh faces for the analysis.

Remarkably, the branches with an angle of 20 degrees still had some air flow through it, contrary to the initial G1 branches with a 20 degrees angle. Although the pressure dropped less than G1, it was not a huge difference to decrease from 0.91 Pa/m in G1 to 0.89 Pa/m in G3. The average outlet velocity still increased from G1 and was similar to G2 to have a value of 0.76 m/s.

Due to the relatively wide distribution node in the geometry, noticed in Fig.35, the air flow is affected and creates a backwards movement within this node as turbulent flow. The far right branch which had the angle of 20 degrees had a relatively wide diameter as well which resulted in directing the air in on of its sub-branches and caused the distribution to be less uniform than the other branches.

From The pressure contouring, Fig.36, it was obvious then and clear how the direct inlet to outlet relation does affect the flow of the air and also how the distribution nodes are always a point of high-pressure losses.

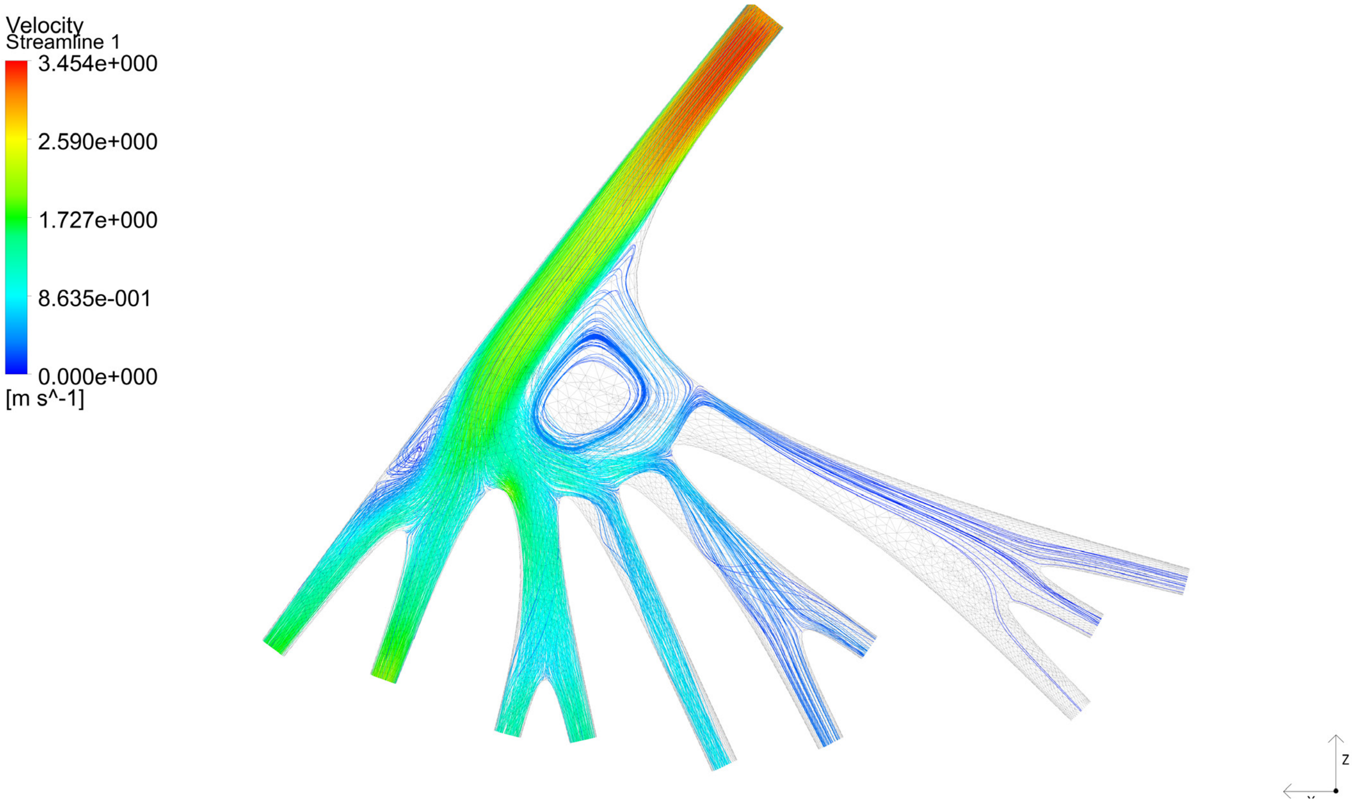


Fig.35. Backward movement in the huge main node cause much of the in efficient air distribution over the branches. (Source: Author)

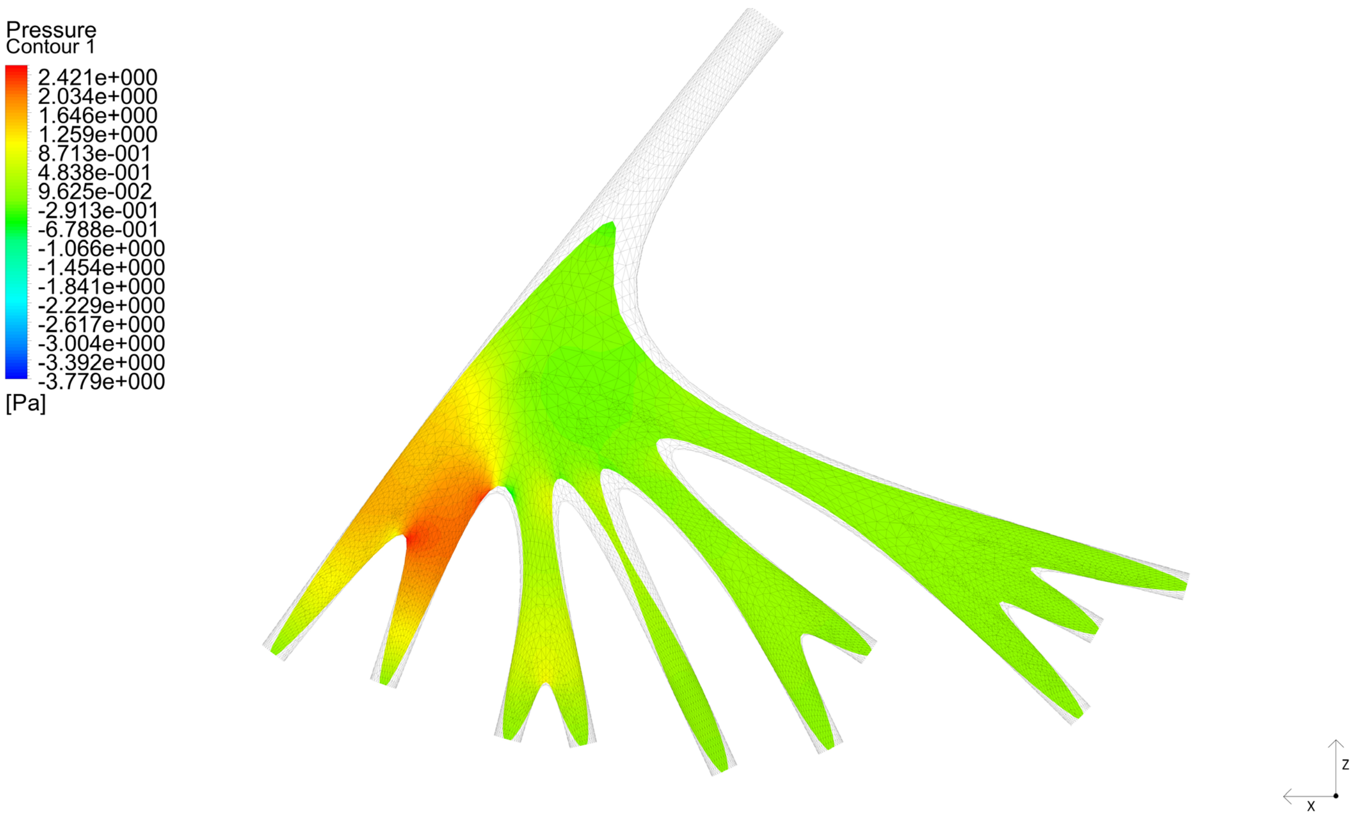
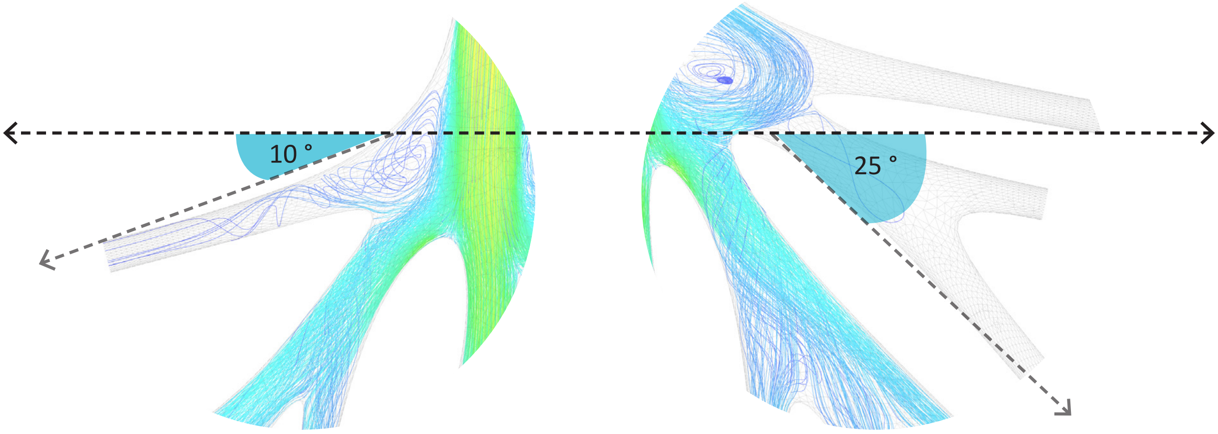


Fig.36. Total Pressure contour shows the velocity and pressure loss at the direct nodes to the inlet still as in G1. (Source: Author)

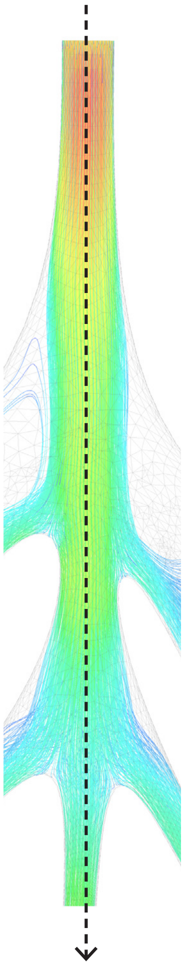
Design consideraions:

Concluding the aspects that should be met in the design of the final geometry from the previously simulated geometries:

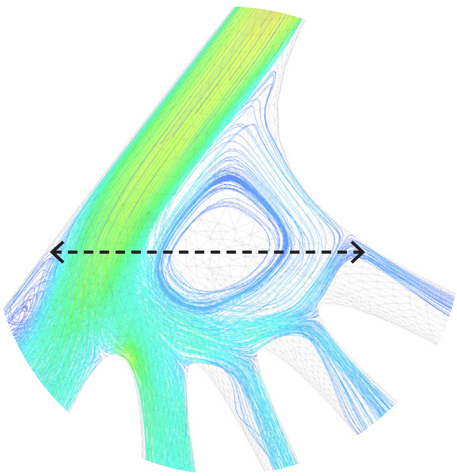
- Reduce the direct inlet to outlet relation, and make it more indirect to assure better distribution of the air along with all the branches and the outlets over the wall.
- Eliminate the branches that have an angle of fewer than 10-25 degrees. Because branches within that range are inefficient and have no air distribution along them.
- Avoid creating many distribution nodes in the main branches. This reduces the pressure losses along with the air flow.
- Avoid wide distribution main node to reduce the backwards flow and hence reduce the pressure losses and turbulent effect.



1. more than 10 -25° branch inclination angles



2. Avoid Direct inlet to outlet connections



3. Avoid wide distribution main nodes

Final Analysis | Geometry 4

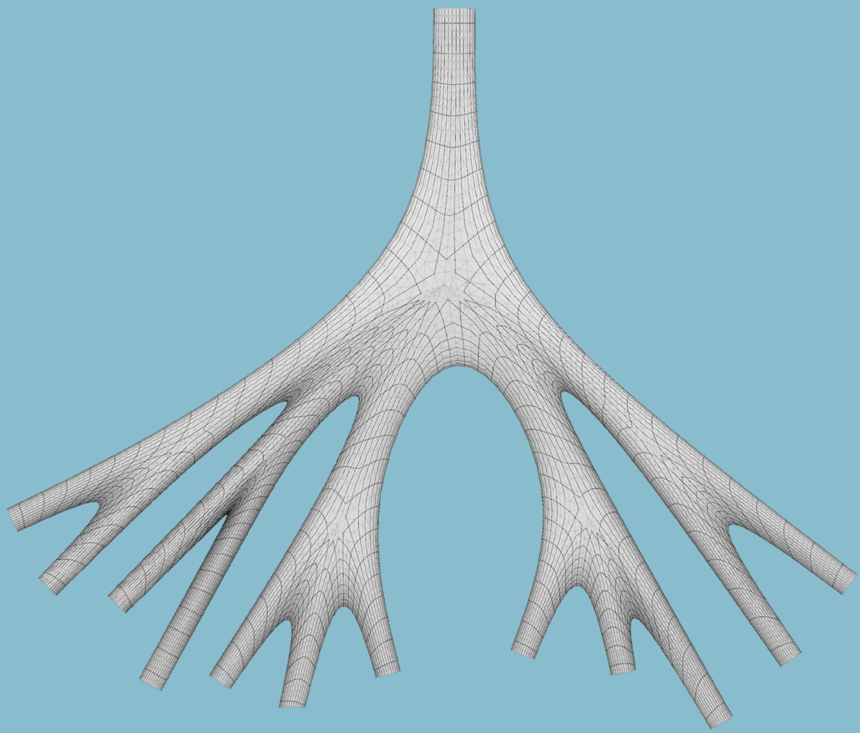


Fig.37. G4 final geometry introduced for CFD analysis for validation, it includes all of the noticed aspects to be considered from the previous variations. (Source: Author)

The final analysis went after the previously mentioned conclusions or criteria. This Geometry referred to as G4 in Fig.37, had the smallest distribution node among the four variations analysed. Remarkably, the direct flow from the inlet to the outlet was avoided in that geometry, and the inlet faced a distribution node instead of an outlet as in the previous variants. Again, the branches less than 20-25 degrees were neglected, and the least angle was 35 degrees. The mesh for the Ansys fluent analysis had a total of 328324 mesh faces.

The resultant, Pressure drop went down from 0.91 Pa/m in the initial geometry to 2.58 Pa which accounted for 0.85 Pa/m. This value is still considered verified and efficient enough for a distribution ventilation system. In addition, the velocity average for the outlets went down to 0.69 m/s which is the least among the variants.

Eventually, the air distribution over the geometry as in Fig.38. Is considered the best resultant in relation to the other variants. Therefore, the efficiency of the outlets created is more guaranteed as a requirement to distribute air over the wall surface to the room more efficiently.

From the pressure and velocity contours, it is seen that the pressure losses are happening mainly at the facing node to the inlet and it is almost eliminated on the other distribution nodes (Fig.39). Which might be one of the main reasons for the reduced pressure drop value.

Finally, This last geometry was considered the best option among the four variants analysed due to firstly, its efficient air distribution over the wall surface and the designed branches within the system. Secondly, its low-pressure drop value along with the low outlet average velocity value which assures the energy efficiency of the system next to the comfort supply of air to the room without drafts or noise generated by the face velocity (Fig.40, Fig.41).

Table 10 summarises the results and the values inherited from the analysis for the four geometries analysed.

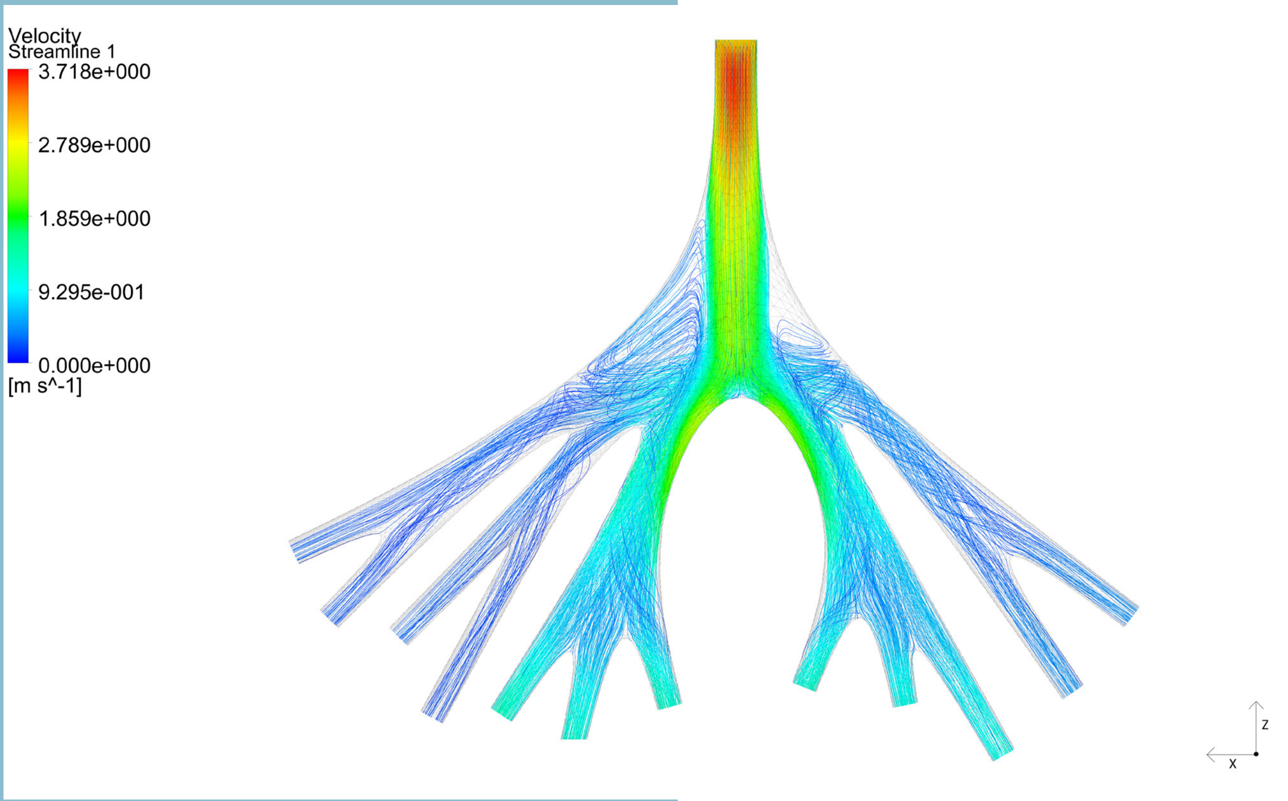


Fig.38. Distribution over the branches is better than all of the other variations and all the branches are working instead of neglect-able as in G1. (Source: Author)

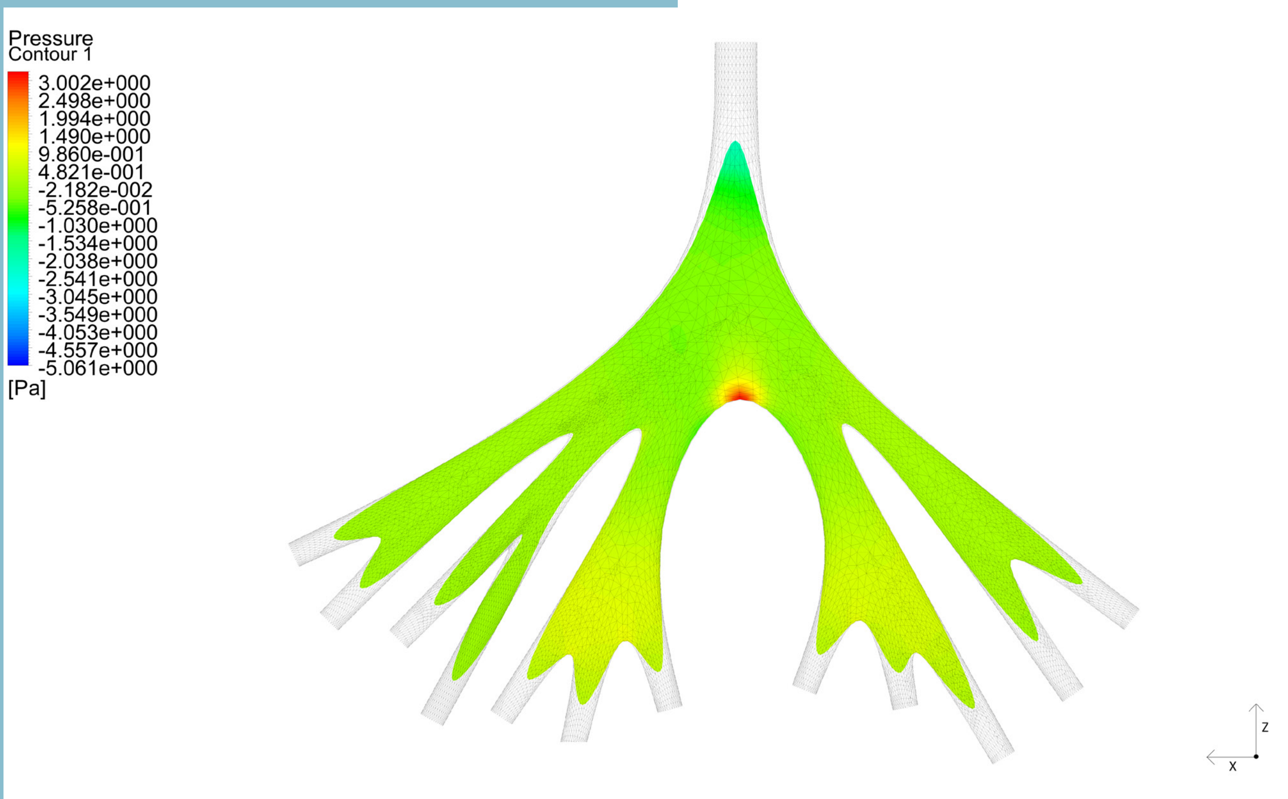


Fig.39. Least amount of pressure losses at the intersection nodes and better pressure distribution over the geometry. (Source: Author)

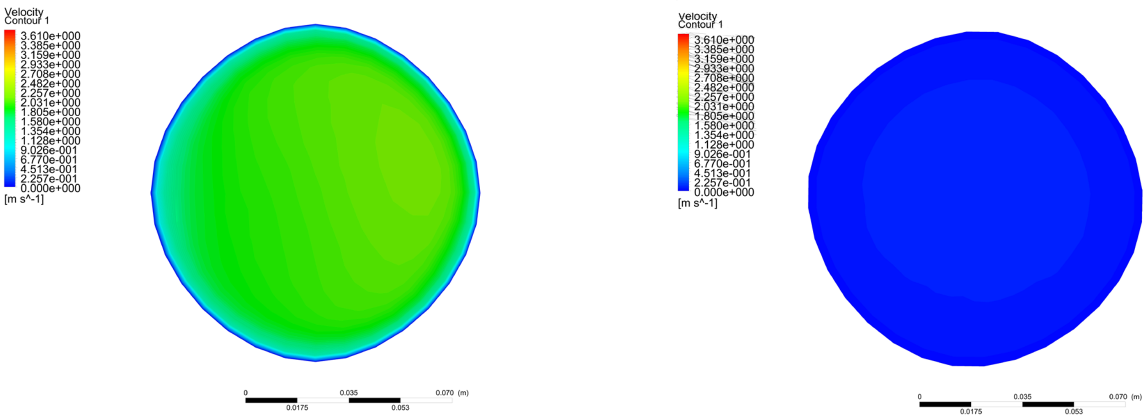


Fig.40. Left: branch outlet velocity contour for G1, shows higher velocity values compared to the right side contour, almost zero velocity values for the other neglect-able branches (Source: Author)

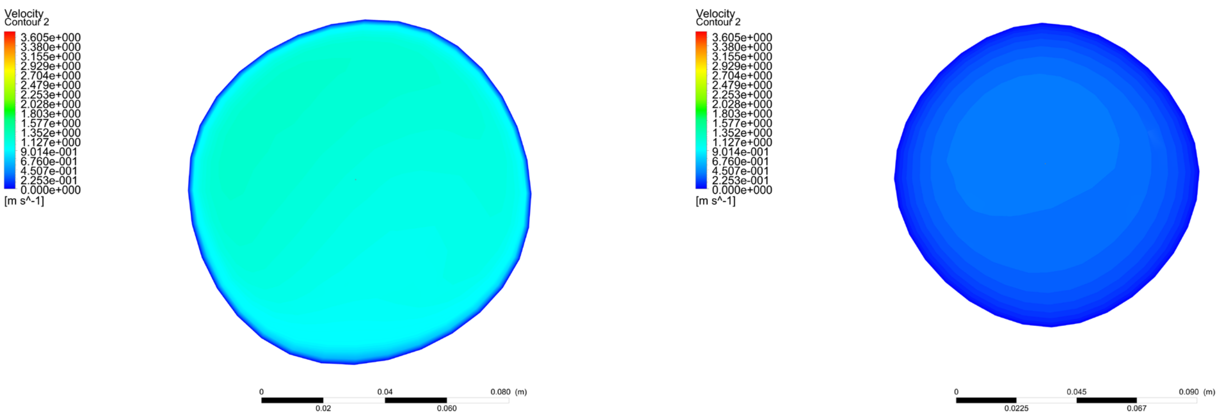


Fig.41. Left: branch outlet velocity contour for G4, shows low velocity values compared to G1 the. Right: Velocity contour in other branches has low velocities, but always more than zero. (Source: Author)

Geometry	G1	G2	G3	G4
Mesh Faces	311986	248570	269197	328324
Area In/out ratio	4.4	4	4	4.4
Avg. Outlets' Velocity	0.72 [m/s]	0.76 [m/s]	0.76 [m/s]	0.69 [m/s]
Total Pressure	2.73 [Pa]	2.26 [Pa]	2.67 [Pa]	2.58 [Pa]
Pressure drop	0.91 [Pa/m]	0.75 [Pa/m]	0.89 [Pa/m]	0.85 [Pa/m]

Table 9. CFD analysis results for the four morphology variants (Source: The author)

Visualization for the final wall morphology
Implemented in an interior design of an office building.


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

Visualization for variant wall morphology
Design differs according to space function and climate.

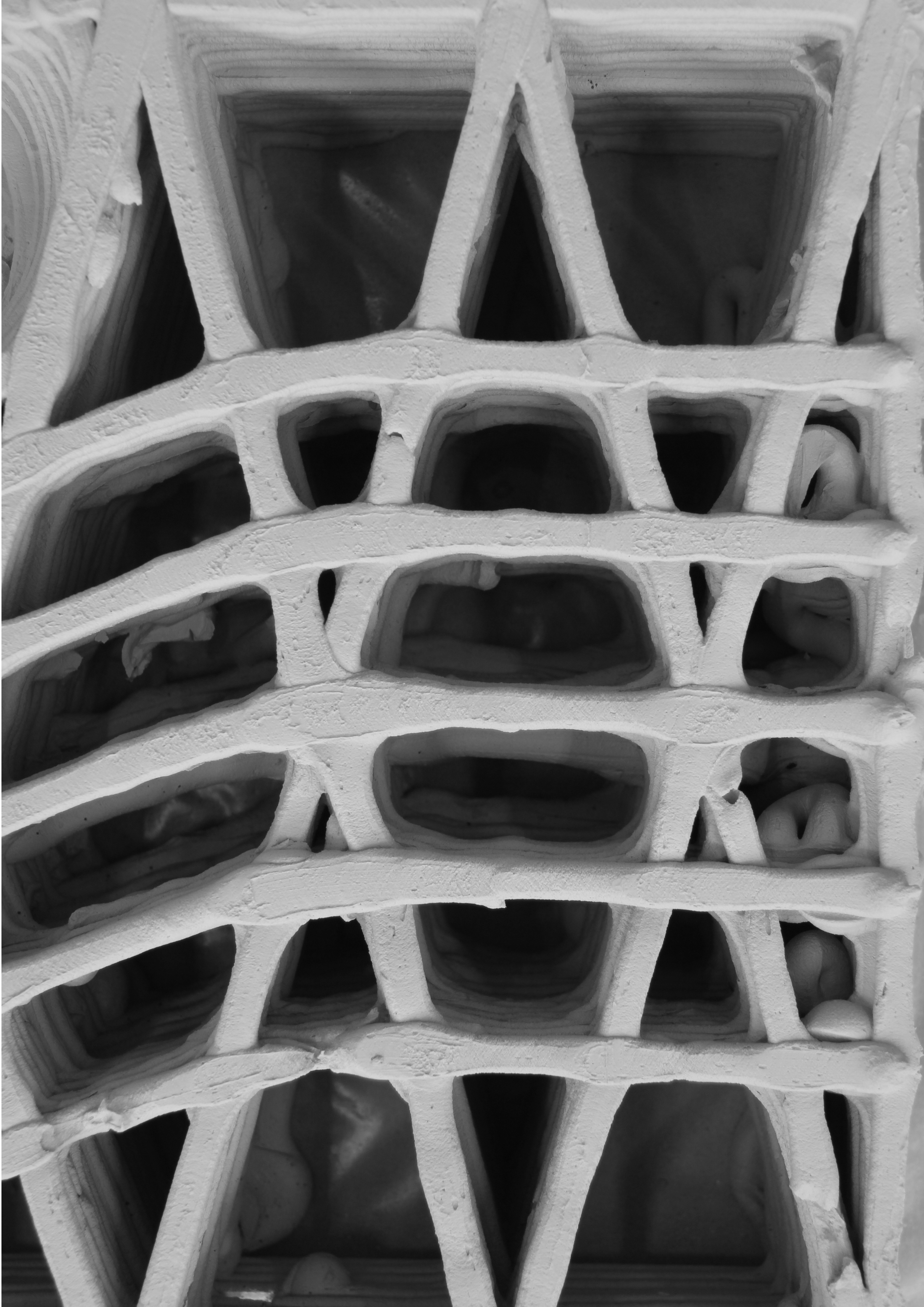

3D PRINTED CLAY FACADE WALLS
Integrating Ventilation system into printing process

Visualization looking up to ceiling
Showing the ventilation openings supplying air to the room.

4 DESIGN FOR 3D-PRINTING

PROTOTYPE

This chapter promotes the prototype to be printed out of the final wall morphology design. Afterwards, the infilling and layer design is described in terms of its design principles. Firstly, the structure stability to assure the safe build-up without collapsing. Secondly, thermal performance in relation to the U-value required for the chosen location for the case study. Eventually, the parametric model created to adjust the layer design is explained.



4. Design for 3D printing | Prototype

4.1 Prototype Decision

A chosen proportion, out of the final morphology design, was considered for 3d printing as a proof of concept and a case study to explore the 3d printing process challenges. The prototype, shown in Fig.42 & Fig.43, was decided to be printed on a scale of 1:1 to explore the challenges that might face the printing process on a large scale. The bigger the scale, the more challenges that tend to appear than a smaller reduced scale. The challenges that were expected are mainly the shrinkage and cracks in a large printed object, as well as the overhangs from the ducts of the designed ventilation system to the outside of the wall interior surface. Putting into consideration also the exploration of how the ducts inside the wall cavity would be printed and grow without collapsing while printing.

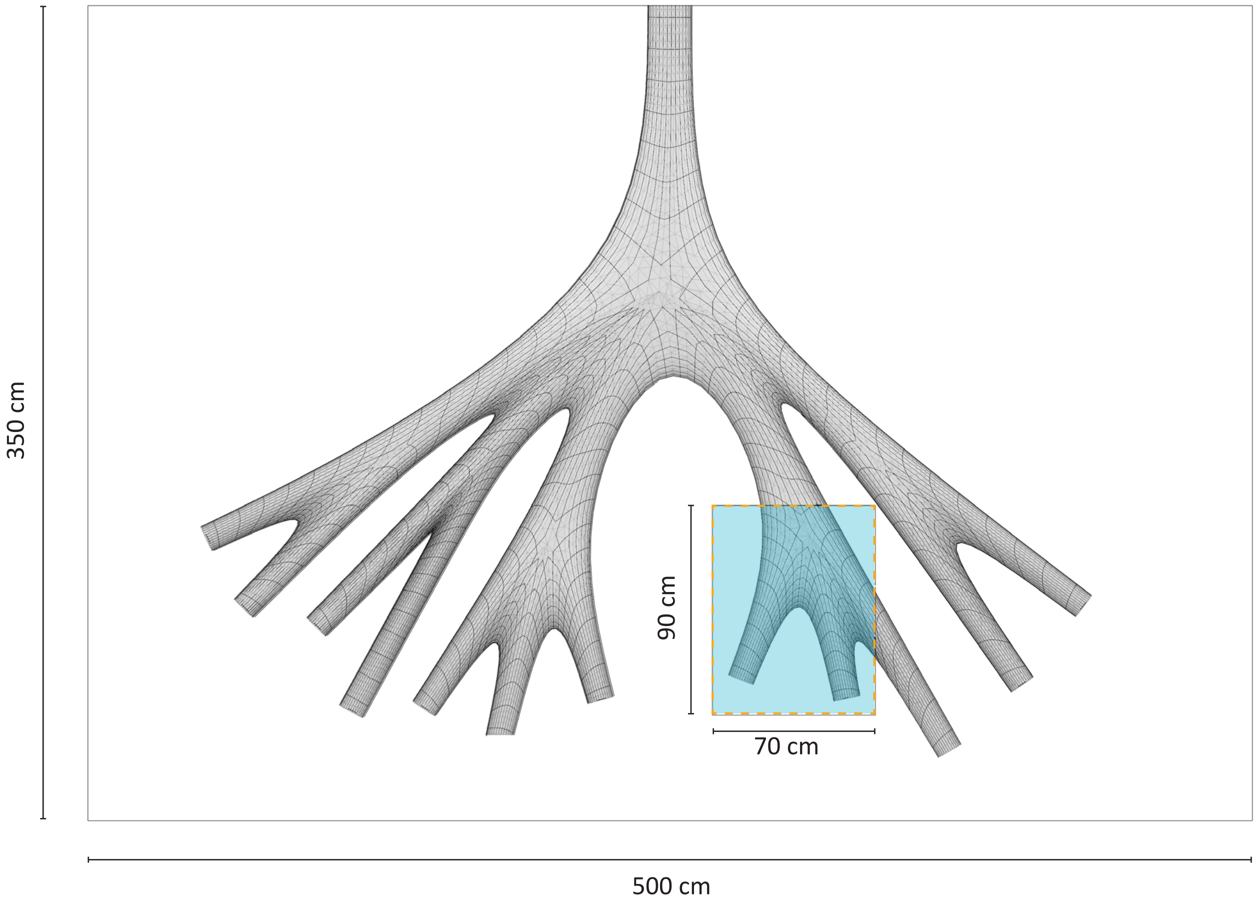


Fig.42. The final prototype position within the wall and its designed morphology of the ventilation system. (Source: Author)

As shown in Fig.43, the prototype portion was chosen so that it contains three main elements; the air ducts inside the wall cavity, the air ducts' overhangs from the wall interior surface, and the end openings of the air ducts to the interior. The prototype bounding box had a length of 70 cm, a width of 45 cm, and a height of 90 cm.

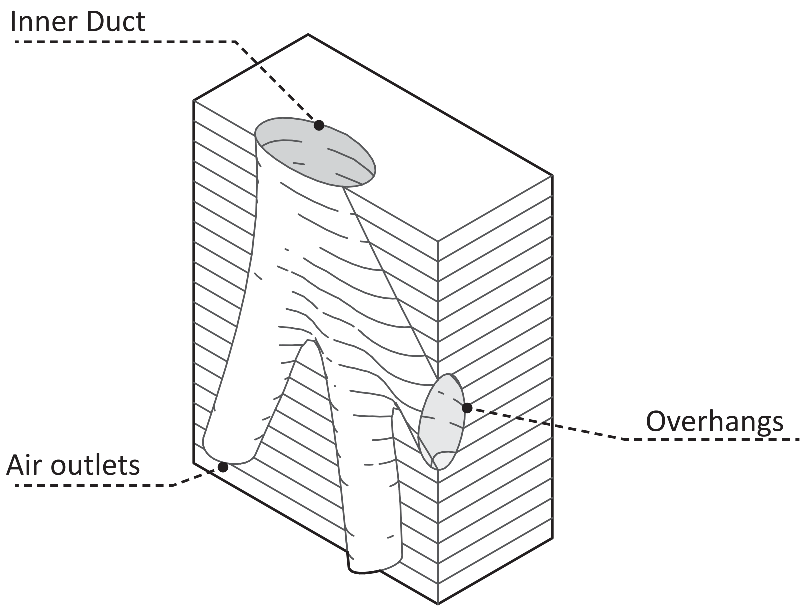
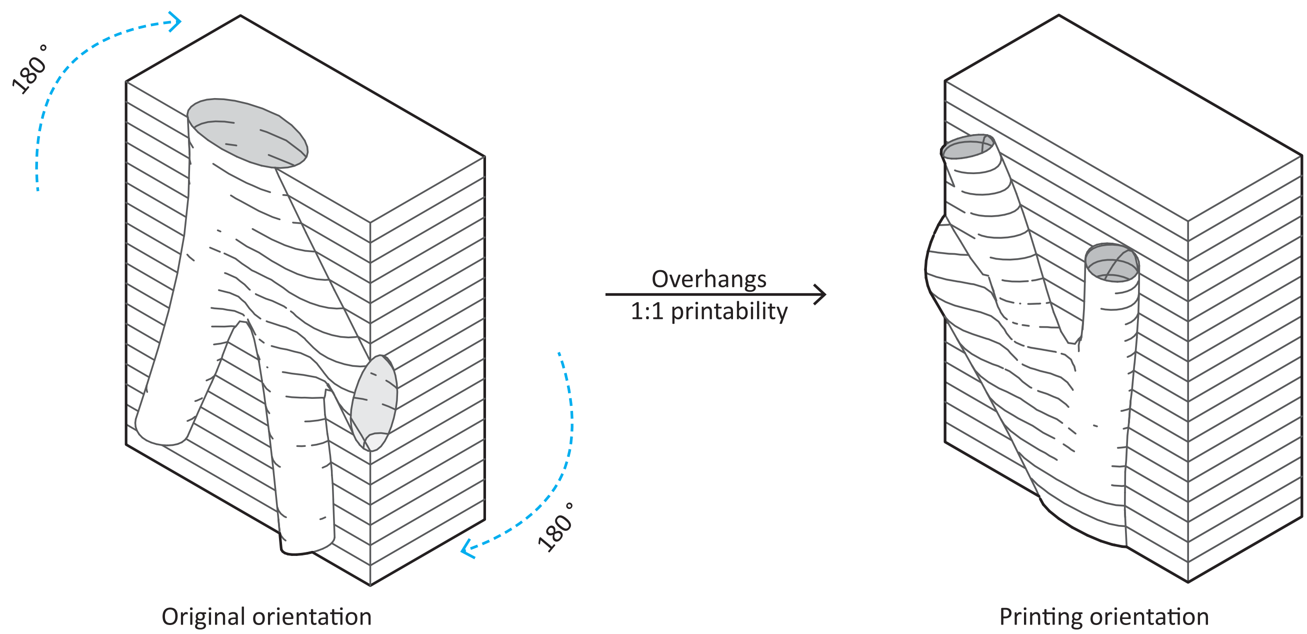


Fig.43. Chosen prototype exhibit the three challenging points of the printing to achieve without collapsing. (Source: Author)

The orientation for the printing of the prototype was to rotate the original direction 180 degrees. This would assure easier layering of the overhangs and more stability for the openings of the ducts, as each layer provides support for the successive one while building up.



4.2 Infilling design

4.2.1 Design principles

Infilling is meant to be the middle cavity space of the wall thickness or the printed surface shell. that infilling needs to be there for various reasons, and in that case, needs to be designed according to defined principles. Controlling the design of the cavity and infilling could be for structural stability during and after printing, thermal performance of the wall and for openings design requirements (IAAC, 2017).

Each of these reasons was considered as a principle that needs to be designed and more elaborated instead of using the conventional available slicing software. In that case, the thermal requirements of the wall are easier to be achieved and analysed as well. Moreover, once this infilling is designed, the prototype will be ready to be printed and sent to the robot in its program language.

Principle 1: Structure stability

Due to the lateral forces over the wall, i.e. wind and earthquakes, it should be considered how to prevent the failure of the structure as a whole facade system. Also during printing, supporting the overhangs or cantilevered printed parts so that it can accept a successive layer above, requires a designed infilling. This assures the build-up possibility of the wall as it gets higher during printing without collapsing due to its self-weight.

The designed structure infilling should be able to support three main points or forces. Firstly, the self-weight forces that might cause the whole printed part to collapse over itself. This might happen also due to the buckling of the thin wall boundary. Secondly, the outdoor forces caused by wind in the normal direction over the length of the wall section or the earthquakes in the normal direction over the width. This means it needs to support the weight on both directions of the wall section plan as shown in Fig.44. Lastly, The points where the air ducts inside the wall cavity are might have a cantilever or an overhang angle, creating supports in the below layers will help it to build up stable.

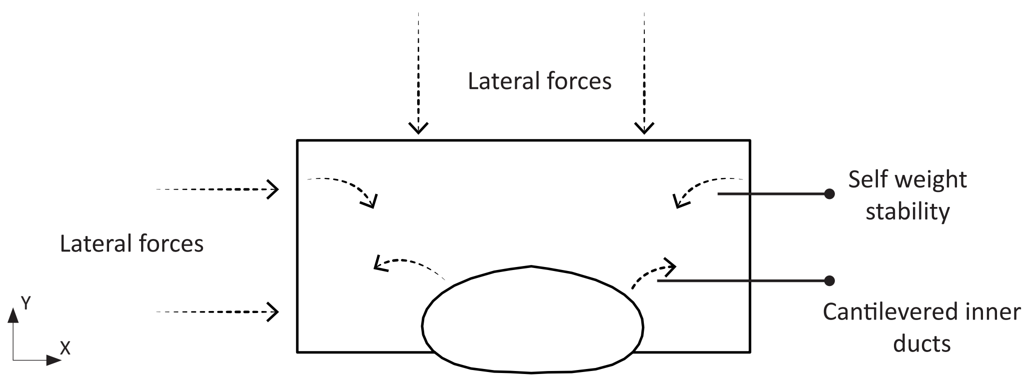


Fig.44. Three main forces that requires support by the infilling design of the wall section. (Source: Author)

Each of these three main points of support could be achieved separately using the variants in Fig.45 (b) and (c) as will be further explained. While the support in variant (d) achieves better performance in all of the required aspects together.

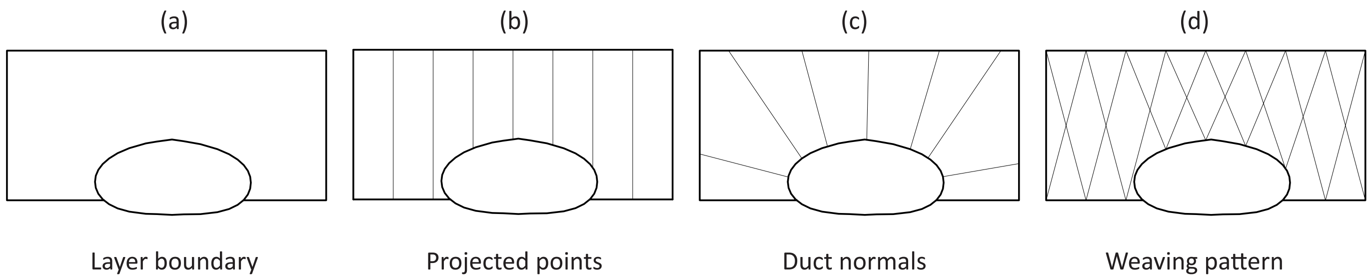


Fig.45. Possible solutions for structure supports explored. (Source: Author)

Creating normal lines that go through in the Y direction as shown in Fig.46, these lines do support the forces from the outdoor like the wind. However, it does not take into account the other lateral forces affected by the earth-quakes or the failure of the layering self-weight over the width side. Moreover, it does not support the interior overhangs.

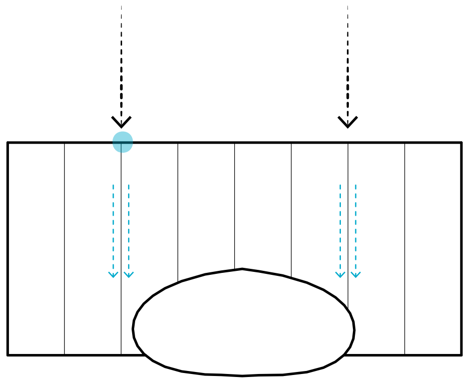


Fig.46. Forces points supported by variant (b) which are normal to the length of the wall. (Source: Author)

In another way, Creating lines in the normal direction to the interior cavity as in Fig.47 supports its build-up ability. However, in the same time, it would reduce the number of support points to the outdoor surface, and also to the forces along the width side.

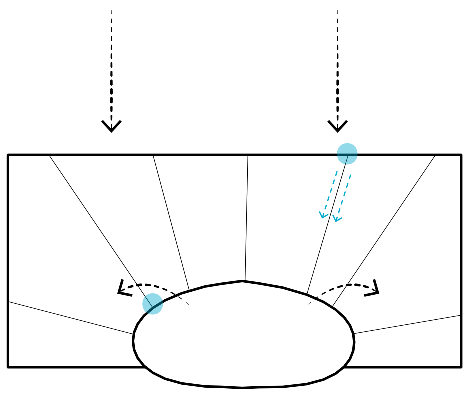


Fig.47. Forces points supported by variant (c) which are normal to the length of the wall and also the inner cavity overhangs. (Source: Author)

Finally, an option that would opt for all of the required supporting points was the zigzag pattern or the weaving pattern shown in Fig.48. In that weaving pattern, the structure is supported from both length and width directions. Also, it supports the overhangs of the inner ducts as it inclines around where the cantilevering is happening. Even more, the points created by the intersection of the weaving pattern in two directions, these points assures better distribution of the lateral forces and the self-weight and helps the geometry to act as a whole one body.

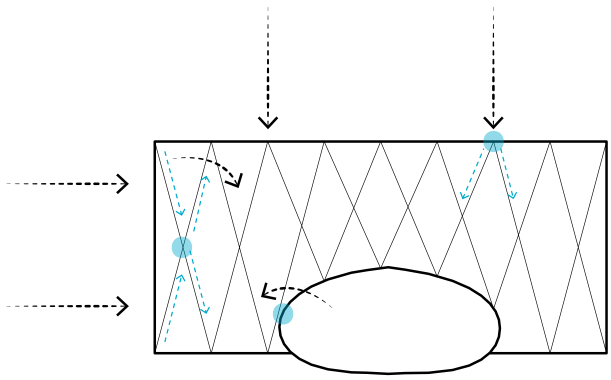


Fig.48. All the Force points considered are supported by variant (d) which qualifies it to be the chosen structure support variant. (Source: Author)

Although Having this pattern consumes more material, the more intensified the infilling, the more structural stability it guarantees. Another reason that is further elaborated in the following thermal performance section is that this pattern creates smaller cavities than the other two variants. This helps in terms of the thermal resistivity or R-value. Therefore, weaving pattern was chosen for the infilling structure support functions.

This weaving pattern was developed in a Grasshopper script as a parametric model that could be intensified and the number of supporting points increased. This helps in adjusting the wall section design prototype according to the feedback from the printing process, as if it collapses or not. Which informs the validity of the number of supporting points.

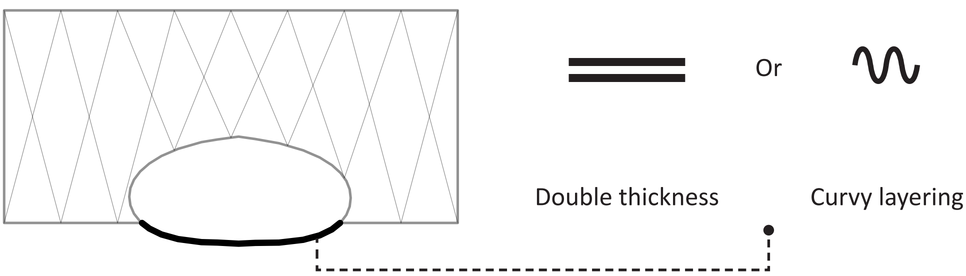


Fig.49. Double thickness or curvy deposition would reduce the buckling of the overhangs while building up the print. (Source: Author)

to support the duct overhangs and to prevent the buckling while building up the prototype, two options might be viable. Either by creating a double layer thickness to enhance the stiffness of the overhangs and increase the cross section stability. Or the second option would be to create a curvy deposition for layers as in Fig.49 which will increase the thickness and the load distribution instead of a single straight line. This is because adding structure supports inside the duct will disturb the air flow. However, During this research the structure mechanics is not within the scope of the study, Therefore no structure analysis was made to assure this assumption. Eventually, Only single layer thickness was deposited in prototyping to test wither or not it was necessary to increase the thickness.

Principle 2: Thermal performance

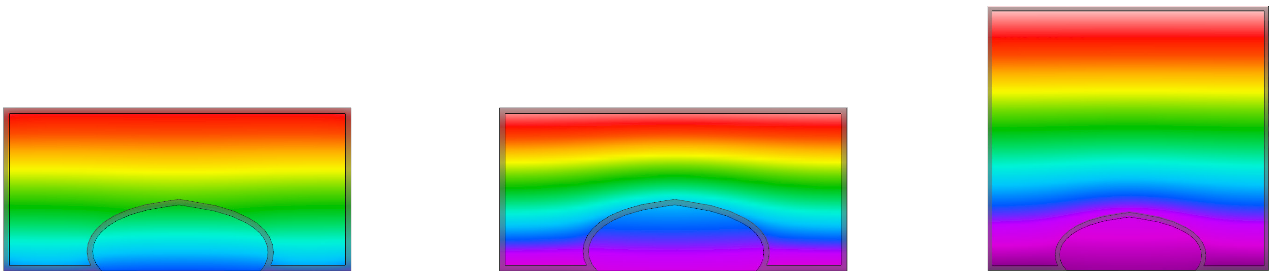
Second aspect in the design of the infilling was the thermal performance as a facade wall. This meant that the infilling should also have the ability to reduce the heat transfer on both of the wall sides. Also, it should be able to achieve the U-value of 0.73 W/m2K as used in the calculation for the cooling loads explained previously in the design criteria from the conventional duct design in chapter 3. Alternatively, at least it should be able to reach a value closer to the required and recommended U-value for the case study location of Seville, which is 0.94 W/m^{2}K for new buildings in Malaga region (Ministero de Fomento, 2009). Ladybug tools for Grasshopper were used to run Thermal analysis by constructing an Energyplus material component that had the following properties. Out of Therm analysis, U-value and R-value were compared for each variation.

Digital Material	Energy plus opaque material | Stoneware clay
Density	1800 Kg/m^3
Conductivity	0.388 W/m-K
Specific heat	2940 J/Kg-K
Roughness	Medium

- **Solid-Thickness performance:**

Achieving low U-value or high thermal resistivity R-value could happen by designing to reduce heat transfer by the three main types of heat transfer, Conduction, convection and radiation.

Conduction happens due to the energy transmission within the material molecules to each other from the warmer side to the cooler side. This means that the higher the thickness of the material the less conduction there will be. Hence, the design of the wall considers a higher thickness of the layer and also the amount of material that the heat will have to flow through from one side to the other. (Moore F., 1993)



Air/ void infill
U-Value: 2.15 W/m^{2}K
R-Value: 0.47 m^{2}K/W

Solid infill
U-Value: 1.13 W/m^{2}K
R-Value: 0.89 m^{2}K/W

Double thickness Solid
U-Value: 0.58 W/m^{2}K
R-Value: 1.74 m^{2}K/W

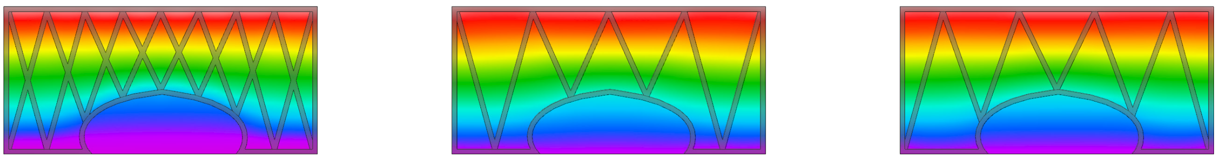
Fig.50. Solid infill tends to be more insulate than the large air cavities, while increasing the thickness would increase the thermal resistivity and reduce the transmittance. (Source: Author)

Shown in Fig.50, therm analysis was conducted over the wall boundary for one layer as a case study. Analysis results show how the thickness of the wall if doubled, would double the value of the thermal resistivity and hence reduces the U-value to almost half. Also, the air cavity or the void if larger than needed, it would not behave as required for the thermal insulation. This is due to the other types of heat transfer as convection mostly and radia-tion.

- **Weaving pattern performance:**

Radiation tends to happen differently not by the movement of the molecules but rather by the electromagnetic waves emitted from the heated material. This means that it can also be transferred through the air cavities. Reducing its effect requires to have more barriers from the heated or the source surface to the last interior surface. This means the amount of the heat transferred from the initial source until it reaches the last surface will be much less if it got reduced by the resistivity of the material barriers in between. Therefore, more barriers were considered to be added in the parallel direction to the length of the wall. (Moore F., 1993)

Initially, the structural support for the infilling, designed previously as a weaving pattern, was put into Therm analysis again using Honeybee in Ladybug tools plugin for Grasshopper. Starting by one Weaving line, it is realised - as in Fig.51- the effect of the increased amount of material in reducing the U-value but not as much as in the void infilling in Fig.50. That is because although the air voids are smaller, yet they were still large enough to create convection effect. On the other hand, the double weaving lines or the mainly designed structure support creates smaller cavities due to the intersections, which reduces the effect of the convection heat transfer.

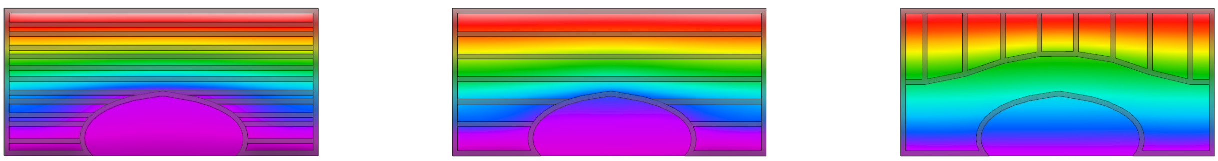


Structure support	Halved structure infill	Halved structure infill 2
U-Value: 1.14 W/m²K	U-Value: 1.47 W/m²K	U-Value: 1.46 W/m²K
R-Value: 0.87 m²K/W	R-Value: 0.68 m²K/W	R-Value: 0.68 m²K/W

Fig.51. Designed structure support infilling already has low U-value due to the smaller cavity size created by the intersections and the material area provided. (Source: Author)

- **Horizontal barriers performance:**

To reduce the effect of the convection and also the radiation heat transfer, It requires the air cavity to be smaller than 30 cm which is the case in here but also to be duplicated many times. Therefore, the air does not move and transfers the heat from one side to the other by convection, but rather acts as insulation which has a good thermal resistivity. As could be seen in Fig.53 the air layer thickness increment could reduce the conduction effect, but after a certain threshold thickness which is almost 40 mm, it could also increase the natural convection which increases the total heat transfer by consequence. While radiation does not get affected by the air layer thickness, it could be affected by the material of barriers provided to create these cavities and the number of the barriers provided. (Bekkouche & others, 2013)



2 cm, 12 cavities	4 cm, 6 cavities	Two parallel cavities
U-Value: 0.63 W/m²K	U-Value: 0.86 W/m²K	U-Value: 1.40 W/m²K
R-Value: 1.59 m²K/W	R-Value: 1.17 m²K/W	R-Value: 0.72 m²K/W

Fig.52. Parallel barriers with smaller and more air cavities tends to meet the design criteria for U-value. (Source: Author)

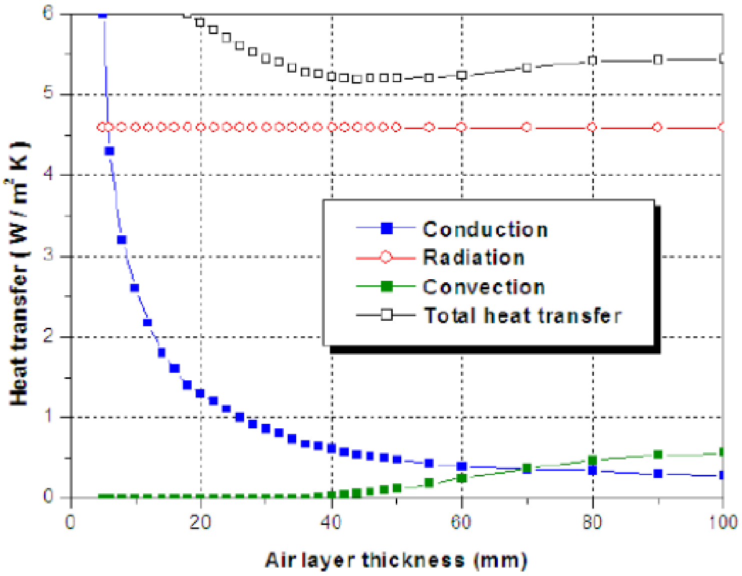


Fig.53. Effect of air thickness on the heat tranfer. (Source: Bekkouche & others, 2013)

Therm analysis for the effect of the air cavity size and the number of parallel barriers was conducted. Shown in Fig.52, it starts by two parallel barriers and normal direction divisions which reduced the U-value but was not enough to meet the design criteria. Another analysis run for more barriers with a cavity in between 4 cm each, resulted in a U-value that meets the design requirement already. Moreover, by reducing the size of the air cavity to the half and doubling their number to 12 instead of 6, the U-value reduced to almost half as well.

Therefore, it could be concluded from Equ.4, that the more width the cavity has and the less thickness of the clay barriers in between them, the more resistivity and less conduction created.

$$R = \frac{L_1 + L_2}{\frac{\lambda_1 * L_1}{d} + \frac{L_2}{R_2}} \qquad \textit{Equ.4}$$

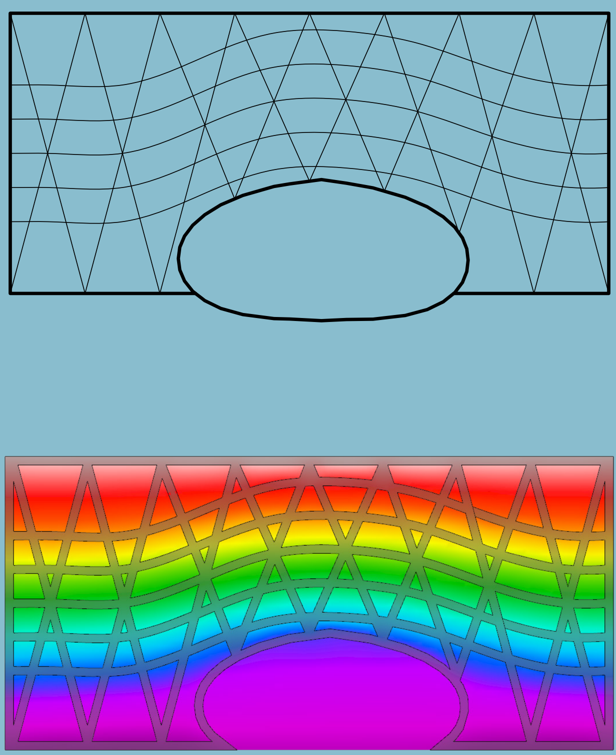
where:

R = Thermal resistivity of one cavity & clay unit m^2K/W
L_1= Clay layer width m
L_2= Air cavity width m
λ_1= Heat conduction coefficient for clay W/mK
d= length of the cavity m
R_2= Thermal resistivity of air cavity m^2K/W

4.2.2 Final Infilling design

Final infilling had into consideration these techniques previously mentioned, Solid and air cavity thicknesses. Firstly, parallel barriers to the length of the wall with a distance in-between less than 4 cm were created. Next, due to the intersections of the structure support, it even reduced the cavities size and created more of it. This was considered enough to reduce the U-value of the wall to the required design criteria. As it reduced the heat transfer by convection of the air, while also it reduced the radiation effect due to the many barriers that resist the heat consecutively. Shown in Fig.54 & Fig.55 the final design of the wall infilling that was the starting point for the printing process to test its build-ability. This design could be later further modified since it was designed as a parametric model.

Therm analysis in Fig.54, showed a U-value of 0.73 W/m^{2}K and R-Value of 1.36 m^{2}K/W. These values are exactly the same values used in calculating the cooling load as mentioned before in Table 9 in chapter 3. Which is also still within the range between 0.94 W/m^2.K For new buildings in the Spanish code for Malaga region and even the average for Spain overall of 0.83 W/m^2.K (Ministero de Fomento, 2009).



U-Value: 0.73 W/m^{2}K
R-Value: 1.36 m^{2}K/W

Fig.54. Top: Final designed infilling to be as a starting point for prototyping and test its build-ability. Bottom: Therm results for U-value of 0.73 W/m^{2}K which is within the requirements for the chosen location case study. (Source: Author)

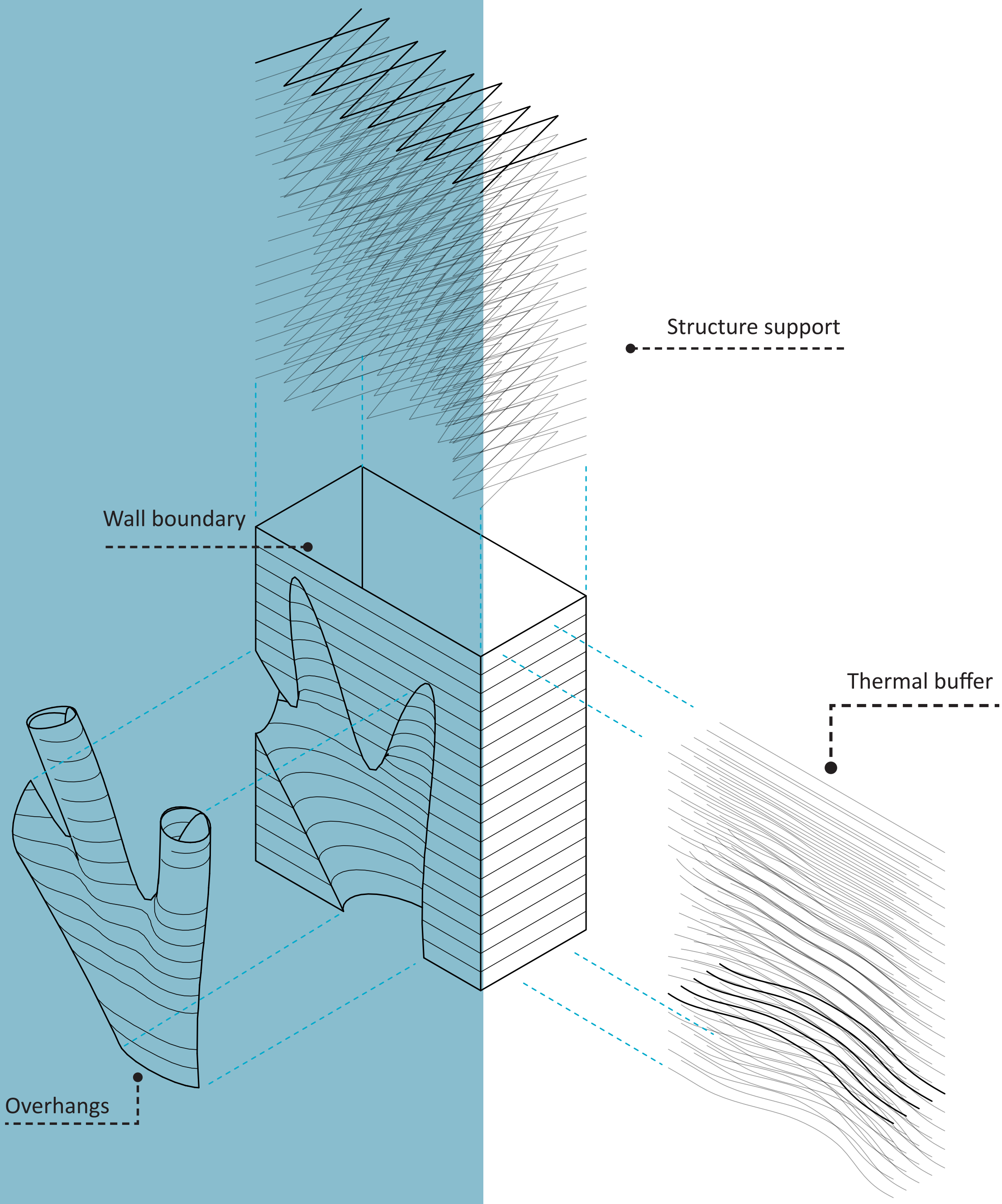


Fig.55. Final four components that form any of the prototype layers . (Source: Author)

4.2.3 Infilling parametric script

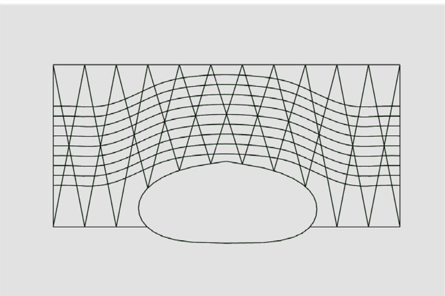
To generate the infilling and make it easily adjustable according to the needs of the print, a Grasshopper script was created. By controlling the layer design, it would be easy to respond to the requirements in different climates where the facade would eventually be.

As shown in Fig.57, Inputs for the script are the mesh of the prototype as part 1, the mesh of the over hangs separetly as part 2. Both of these meshes as layer boundaries are merged at the end with thermal and structural elements. The first controller defines the layer height which started by 30 mm and was adjusted later to 5mm to be suitable enough for better adhesion of the layers as will be mentioned later in the printing results chapter 5.

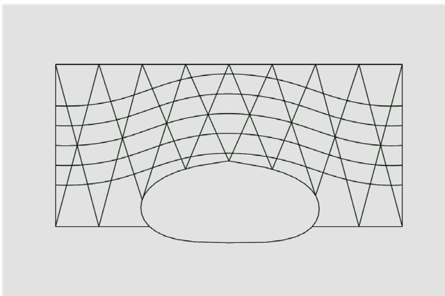
Second parameter is the number of structure supporting nodes. This defines the density of the weaving pattern necessary for the stability during the print and the build-up of the prototype. The following two parameters are the thermal buffer controllers. Controlling the number of the horizontal barriers is necessary for adjusting the wall design for the thermal performance requirements for different climates and locations. Same importance and function is for the parameter of the cavity width. Shown in Fig.56 The different variables that could be generated by adjusting the controllers of the inputs.

The script also orients the sliced layers to the printing bed in Rhino model. This orientation is necessary for generating the robot program later in RoboDK. The position of the layers within the bed is also adjustable in the X,Y and Z direction by the latest three sliders in Fig.57.

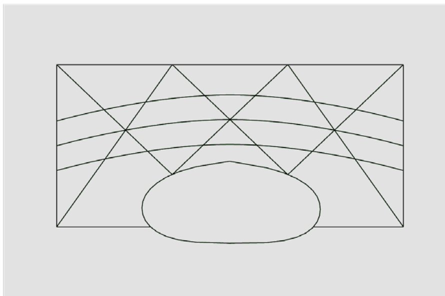
The outputs as shown in Fig.59 are the layers curves as a list to be transfered to RoboDK for program generation. It could be either all the layers or a sample of them. Generating a sublist could be examined firstly layer by layer as in Fig.58, for any undesirable intersections or overlaps. This could be done using the last slider of the one layer view. Attached in the Appendices, App.3 is the full script used.



Thermal buffer: 9 barriers
Cavity width: 20 mm
Structure support: 10 nodes



Thermal buffer: 5 barriers
Cavity width: 40 mm
Structure support: 7 nodes



Thermal buffer: 3 barriers
Cavity width: 50 mm
Structure support: 2 nodes

Fig.56. Variant layer designs generated by the Grasshopper script, it could be adjusted for different climate thermal requirements as well as the printing build-up demands. (Source: Author)

Inputs

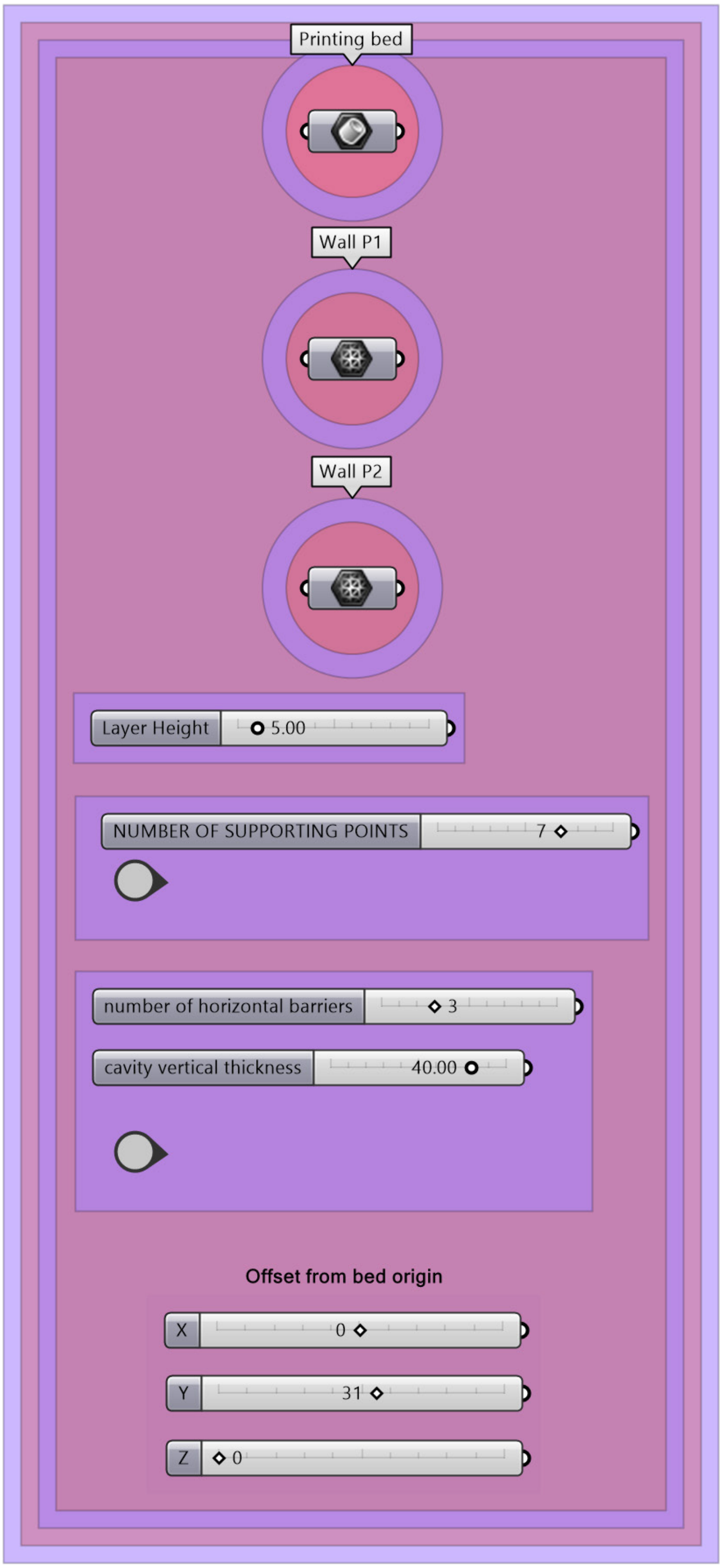


Fig.57. Inputs for the Slicing and layer design script in Grasshopper. Each of them is described in the side text.
(Source: Author)

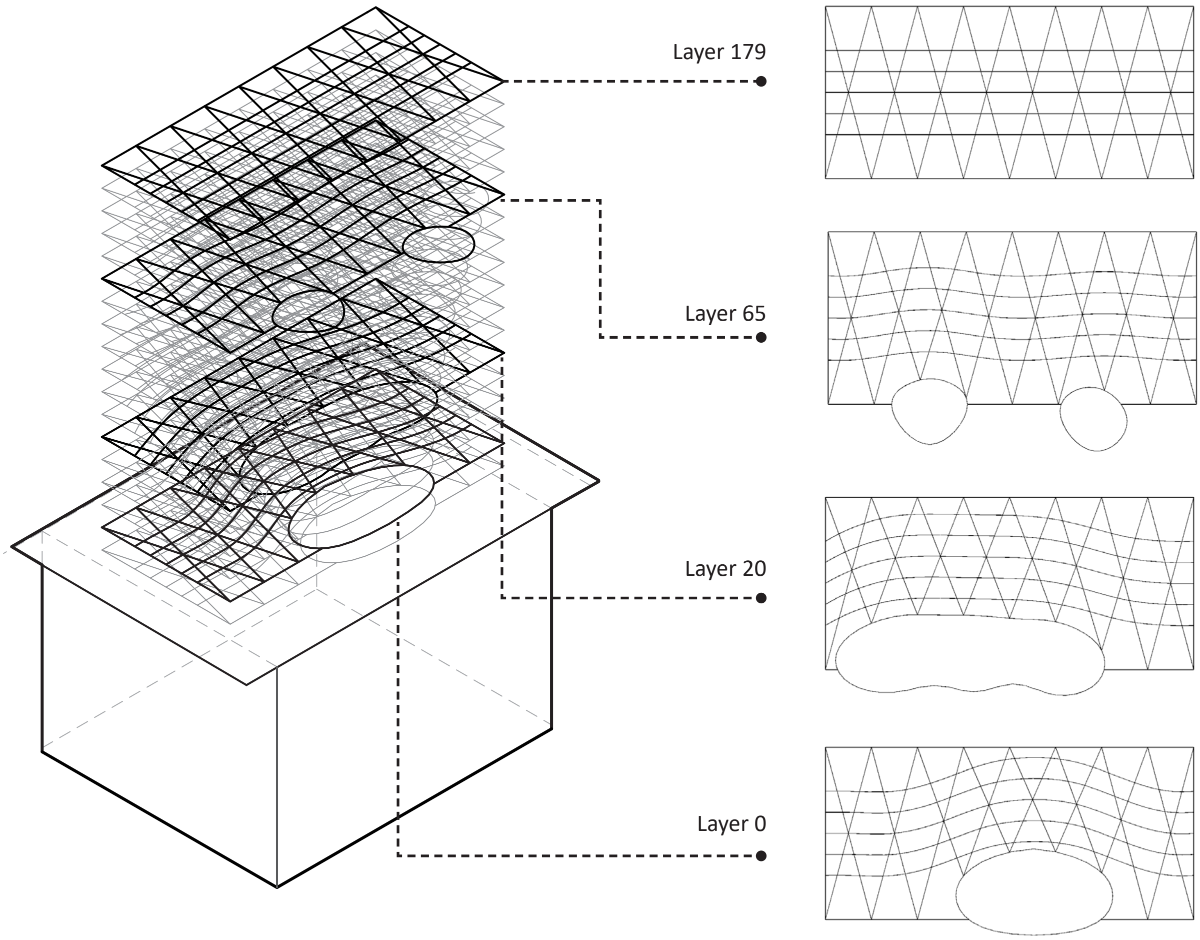


Fig.58. Layers are generated all over the height of the prototype, each layer could be checked separately and by controlling layer height it controls their adhesion together. (Source: Author)

Outputs

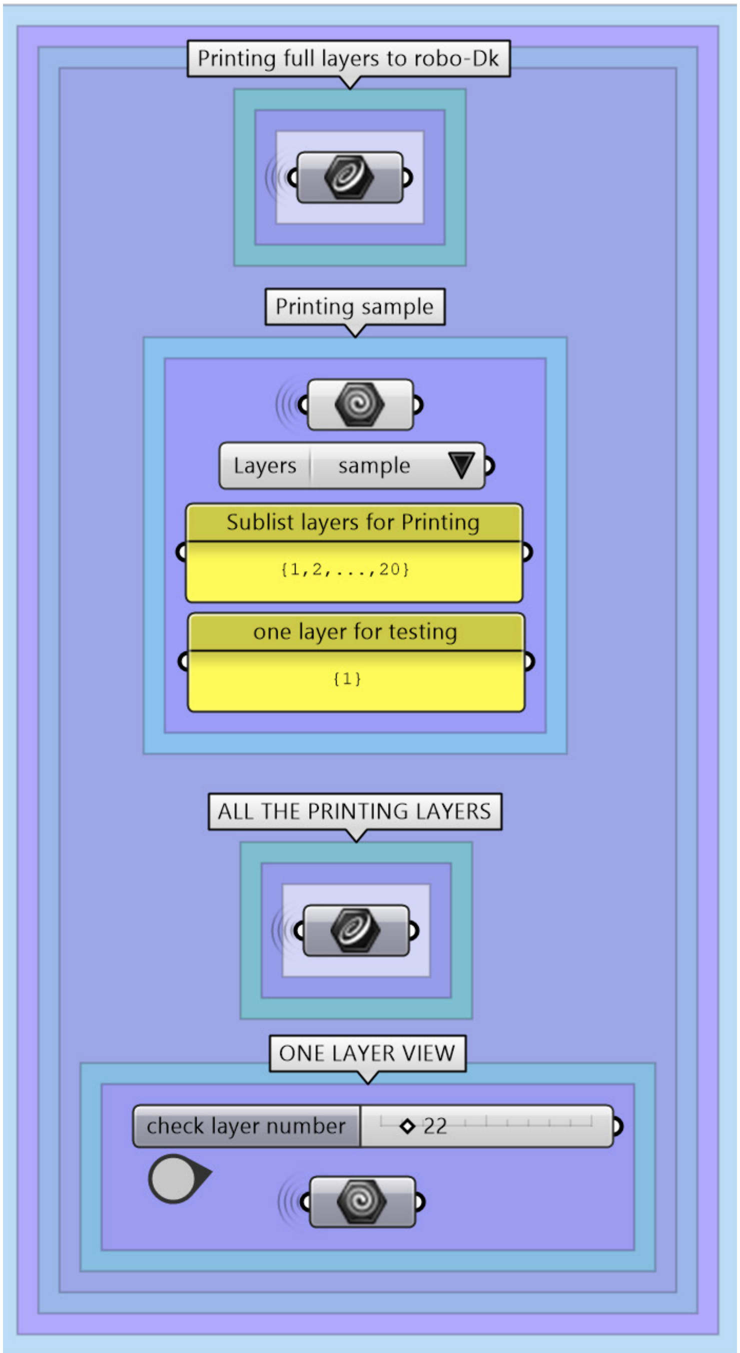
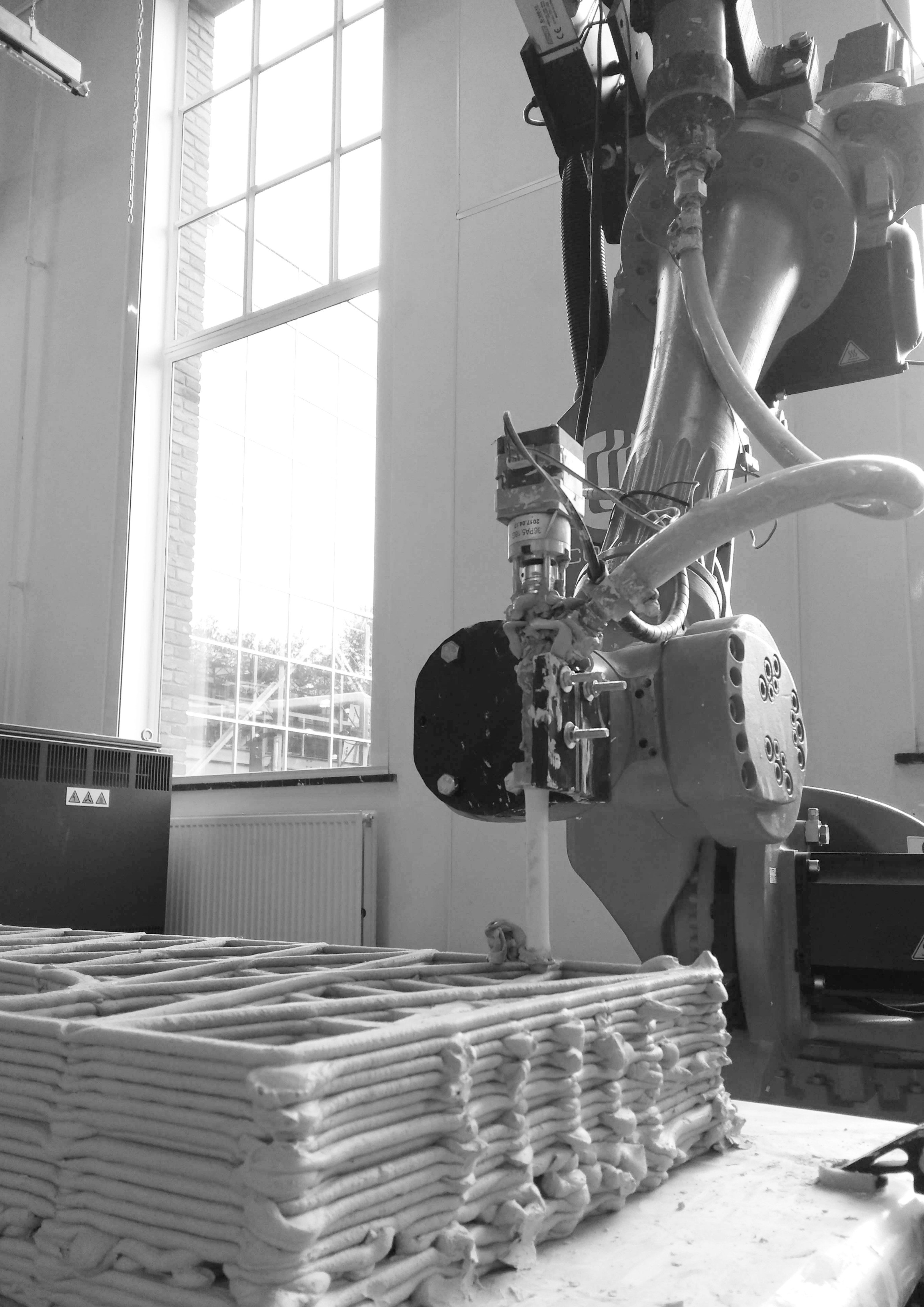


Fig.59. Outputs of the parametric script to be transfered to RoboDK for robot program generation.
(Source: Author)

5 3-D PRINTING PROCESS

PRODUCTION

This chapter elaborates on the printing process in three aspects. Firstly, describing the used hardware tools and setup while mentioning their specification that enables a replication of the same process in other researche. Secondly, The robot programming process as a digital work flow. Further, the calibration between the digital, the hardware tools and the robot. Lastly, The results from the prototype 3d printing in terms of material, Setup and prototype design.



5. 3-D Printing Process | Production

The printing process involved from one side the software aspects. That included the design for the ventilation wall, its prototype and the design for the infilling. Most of these aspects are mentioned previously in the other section of the research. On the other hand, the Printing and prototyping process involved a loop of informative design, Between the hardware that is controlling the physical materialisation of the design, and the software control. Each aspect of these two elements of the process had its requirements and resulted in different observations and considerations for the process to be successful.

In this section of the thesis, each aspect of the process elements is further elaborated, and the interactive loop between them is more explained in terms of the analysis and observations of the results. How each aspect is affected by the other, and how it affects the process overall. Starting by describing the hardware, tools and setup created for the prototyping. Followed by the software control and programming of the robot arm used. Finally, the resultant observations are analysed and illustrated to produce a list of considerations and recommendations for the clay as a material for large scale 3d printing in architecture applications.

5.1 Tools & Setup

The tools used in this research could be categorized into two main categories. Firstly, the material related tools, starting from the mixing of the material and its preparation, until how it gets through to the printing extrusion. Secondly, The tools related to the control of the process, as for the extrusion rate and behaviour until the robot control and programming. Putting together all these tools and connecting them in one process setup was a major part of the research but it was eased by the Honours programme research where most of the tools operating were figured out. Following, each of these tools is further elaborated and explained.

5.1.1 Material & Extrusion

- **Clay mixer**

Tool	Electrical material mixer
Volt	230 Volt
Watts	1110 W
Function	Preparing clay mixture for printing

Starting by mixing the material as the very first step of the process, many aspects were considered while mixing. The material mixture used was the same mixture concluded from the material experiments previously mentioned in chapter 2. It consisted of clay, chammote, and gypsum as the powder body creating the mixture mixed by water.

The initial mixtures started from a total body of 1876 gm of material. Where clay is 1000 gm, and the rest are according to the recommended mixture ratio from the material mixture experiments. Next, the clay powder was tripled to be 3000 gm and had a total body of 5628 gm. These mixtures will be further elaborated in the printing properties section.

Noticeably, the amount of material around 5000 gm was almost fine to be mixed by hand. Mixing the powder and water by hand was easy to figure out the right consistency for the material and also assuring that the air bubbles are the least by having a homogeneous mixture. Making sure that the mixture does not have any clogging of material assures the continuous extrusion of the material, as well as, the homogeneous behaviour for drying after printing.

However, once the amount of material had to be mixed increased, it was harder to control and assure the homogeneity of the mixture. This is since using hand will require a major labour work, which sometimes gets to be mixing with feet on the ground as in the soil mixing for adobe bricks in the traditional techniques.

Since this research is investigating the process of large scale printing, it was wiser to figure out a more automated process for the mixing than using hands or feet. Therefore, within the possible and available tools, an electric concrete hand mixer, as shown in Fig.60, was used.

The concrete mixer enabled the mixing of more than double the quantity mixed by hand. Mixing 6000 gm of clay created a total body of 11256 gm of material. This quantity is enough to fill in more than four cartridges of the used cartridge size which will be mentioned later. Although mixing increases the quantity, it is still hard to maintain a homogenous mixture.

Mixing the material in large quantities allowed faster printing process. As the mixed material could be preserved in a wet condition for almost a week, as long as it is covered with a plastic sheet as in Fig.60. It also should maintain almost airtightness to keep the moisture content that preserves the material in its extrudable state.

Fig.60. Left: Electric concrete mixer used for material preparation for printing, Right: covering mixture with plastic sheet keeps the mixture moist enough for printing over the week. (Source: Author)

- **Cartridge System**

Tool	Cartreidge & Air compressor
Material	PVC-U
Cartridge Capacity	2.5 m^3
Function	Feeding clay mixture to the extruder

Once the material mixture is ready, the material is fed to the extruder through a filled cartridge that is air pressurized afterwards. The cartridge is made out of PVC with special high-pressure PVC glues (Fig.61). It has a size capacity of 2.5 m^3 and can contain up to 3000 gm of the material body. This cartridge is bigger than the one used in the material experiments which had a total capacity size of 650 CC.

The cartridge is feeding material through a hose -22 mm polyflex transparent Tube with two threaded ends- attached to the extruder where material extrusion and flow is controlled. However, the cartridge has to be air pressurized to push the material out of the hose to the extruder. It can contain a maximum pressure of 8 Bar at a temperature of 21 °C, and a maximum of 5 Bar at a temperature of 31 °C. The pressure usually used in that case was around 6-8 Bar which differs due to the different material consistencies feed into the cartridge.

Finally, the air is supplied by a noiseless air compressor that is connected to the cartridge through an air pressure control valve shown in Fig.61.

Assuring the airtightness of the cartridge to allow the air pressure to push the material consumed much of the printing process time. Therefore, if the system was enlarged and more automated it would have been easier, in terms of labour work as well as the time consumption, it would have been easier to use bigger material tanks to allow the process to be continuous.

Filling the cartridge does require a careful, practice work. If the material is filled into the cartridge without compression, it traps air bubbles within the mixture, which later causes fatal problems for the printed object. If the material had air bubbles due to the un-compressed filling, it causes air shots out of the extruder, which does destroy the object being printed. This, along with other observations for the air bubble effects, will later be explained in the observations.

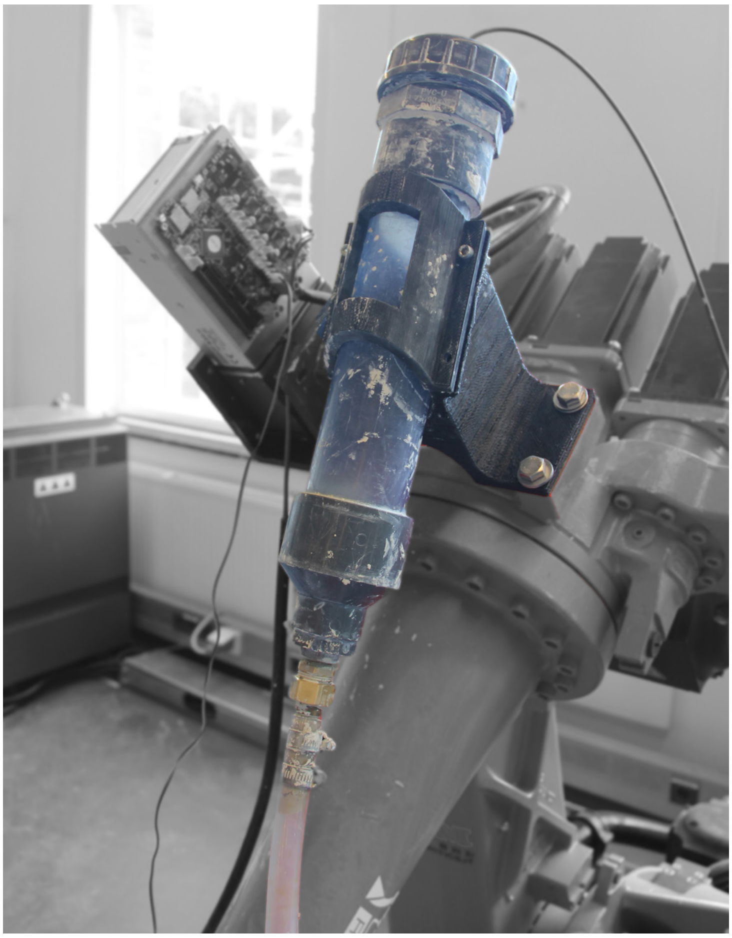


Fig.61. Top: PVC Pressurized cartridge used for feeding material through plastic hose, Bottom: Air compressor used to providing air to the cartridge. (Source: Author)

- **Extruder**

Tool	Clay extruder
Material	Casted metal
Parts	Stepper-motor, screw pit, threaded metal part
Function	Control the material extrusion

Tool	Bipolar Stepper motor
Voltage	2 V
Rated Current	1.3 A
Holding Torque(without torque)	260 mN.m
Screw Diameter	10 mm

The second stage of the process is extrusion. This is done through the clay extruder which is a metal cast part with three threaded openings as shown in Fig.62. Starting from the side where the material is fed from the hose of the cartridge. The end is threaded to accept nozzles to be attached to it and is customised accordingly. Lastly, the upper opening which fits with the extrusion metal screw pit through it with a diameter of 10mm.

The extruder screw pit as in Fig.62 is a metal drilling pit of a diameter 10 mm. It is connected to a gear-box-stepper motor. Controlling the stepper motor allows controlling the extrusion. Instead of the air pressure control which might be not as accurate. This gives the ability to control the on/off for the extrusion. While also it Provides better control over the flow rate or the amount of the material extruded by controlling the speed of the motor. Hence, it affects the printing speed for the overall process.

The casted metal part also have three holes of 4 mm to allow its mounting. This is where it is mounted to the designed mounting devices which will be mentioned later.

Brush-less 12 V fan was mounted on the top of the Stepper motor; this is used to cool down the motor if it gets warm due to the continuous extrusion in its maximum speed.

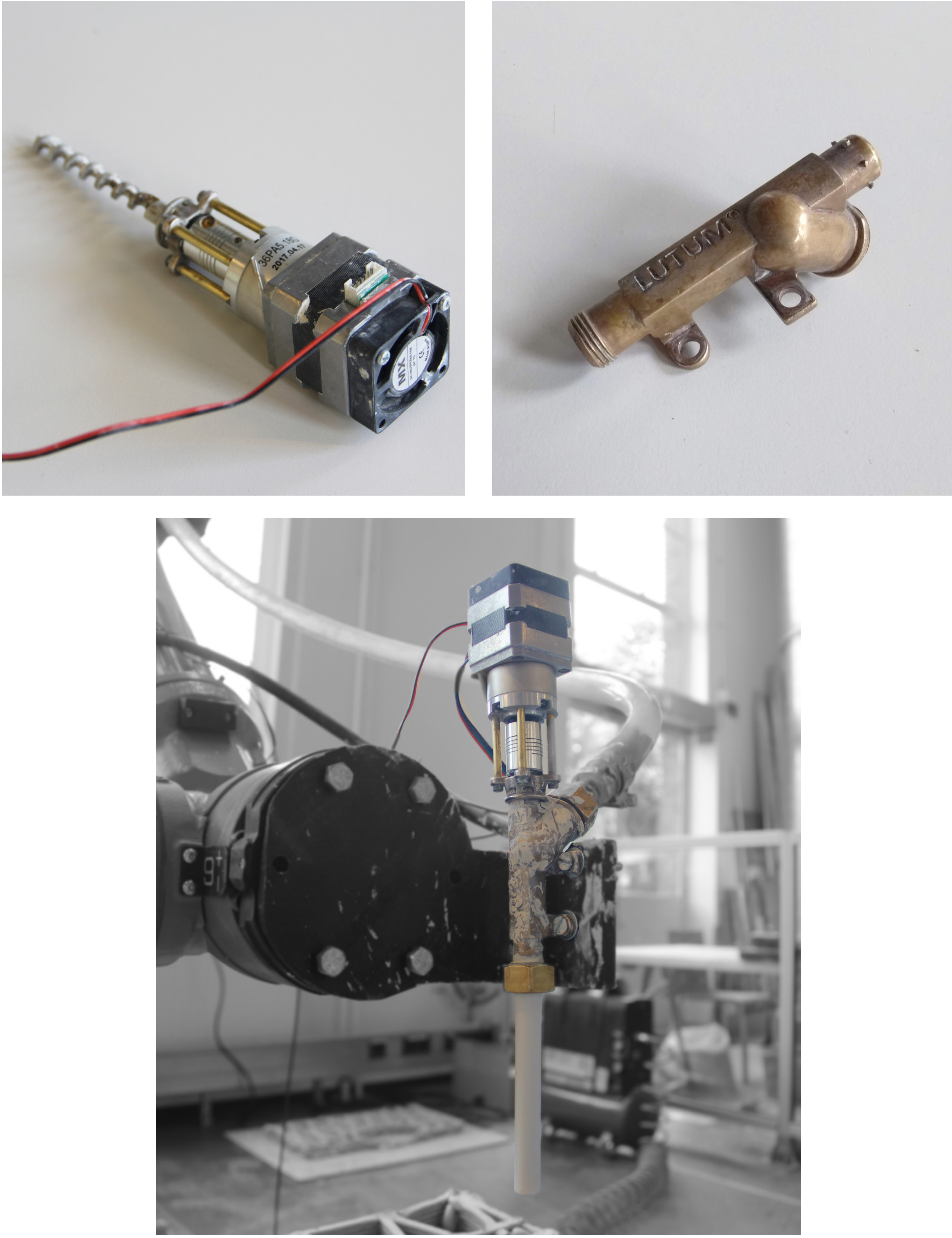


Fig.62. Top left: extruder screw pit used to control the extrusion, Top right: the metal casted threaded part, Bottom: fully assembled extruder. (Source: Author)

- **Printing Nozzle**

Tool	Extrusion nozzle
Material	3D printed - PETG
Diameter	11mm
Cross-section	Circular- 1mm thickness

The printing nozzle was customised by designing it digitally as shown in Fig.63. Then it was 3d printed out of PETG plastic material. Attached through a metal thread to the extruder. The nozzle was initially printed out of PLA plastic, but it could not handle the pressure of the clay and was weak enough to break. PETG does have higher tensile strength and was stronger enough to handle the pressure by the accumulation of the clay being directed towards the extrusion.

The cross-section is circular with a layer thickness of 1mm for an internal diameter of 11mm, which is quite big to allow thicker walls, but also does have a higher flow rate compared to the regular clay nozzle sizes (5-7mm maximum). Elongating the nozzle height out of the extruder prevented the robot wrist from colliding with the printed parts and gave a better compression for a homogenous extruded material.

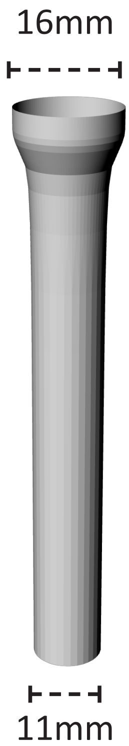


Fig.63. Top: digital model for the nozzle to fit within the metal thread, Bottom: PETG 3d printed nozzle used for extrusion , (Source: Author)

5.1.2 Hardware & control

- **Motor controller board**

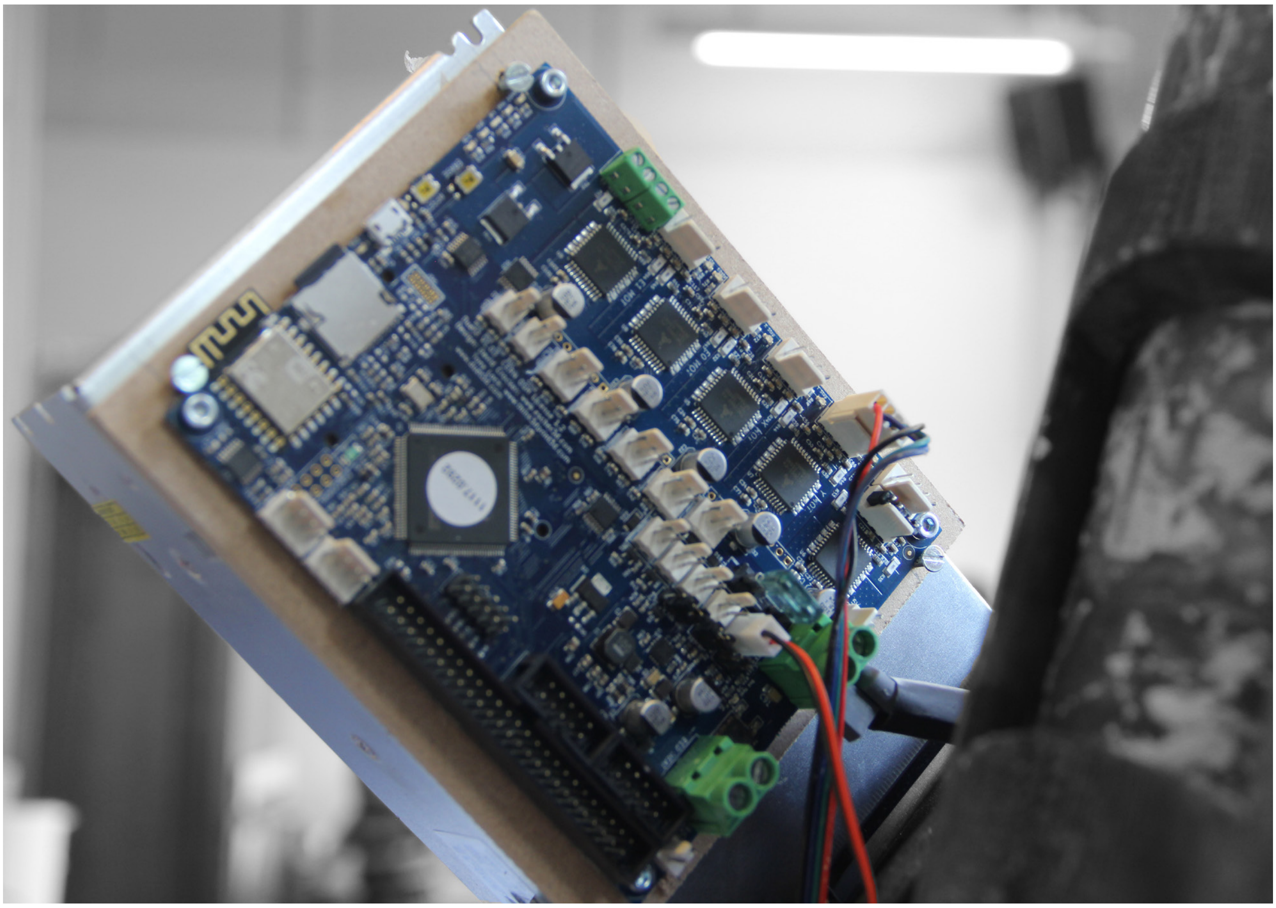
Tool	Duet3D WiFi controller board
Firmware	RepRap firmware
Communication	WiFi control - IP address communication
Function	Contorl Stepper motor - Cooling Fan power supply

3D printer control board was used to control the extrusion stepper motor. Connected through WiFi to the Laptop computer, it was possible to communicate to the board through its IP address using G-code language. The stepper motor was connected to the Y-motor digital output on the board as if it was used for a Y-axis motor in a 3d printer machine. Of course, the board is connected to the power current plug received from a power supply for 24V.

The firmware uploaded to the board was generated by “RepRap firmware Configuration Tool v2”. in the config G-code, it is assigned to be given relative coordinates. This means that the stepper motor can keep rotating or be switched on as long as a G-code of the number of steps required is sent to it. This made the control easier by sending a controlled amount of steps as required for the print individually, instead of having absolute coordinates which would limit the rotation or the steps to the Y-axis limit assigned in the configuration.

Moreover, The fan cooling the motor is connected to the continuous power supply for the fan. It allows the motor to be cooled down during the whole printing process, as long as the power is connected to the board.

The obvious Problem in using the G-code to control the motor is that controlling the on/off for the motor or interrupting the steps sent already for the motor to rotate, is not possible. This is because in the G-code language; the steps have to be completed before receiving the next line of programming for pausing or stopping the motor. This meant that the emergency stop had to be used frequently to stop the motor for example for material infill or pausing the printing in general. This could have been avoided if the motor was controlled using an Arduino board and an input/output signals or a power button connected. But due to the time limitations, this Duet 3d print controller was sufficient to proceed with the research.



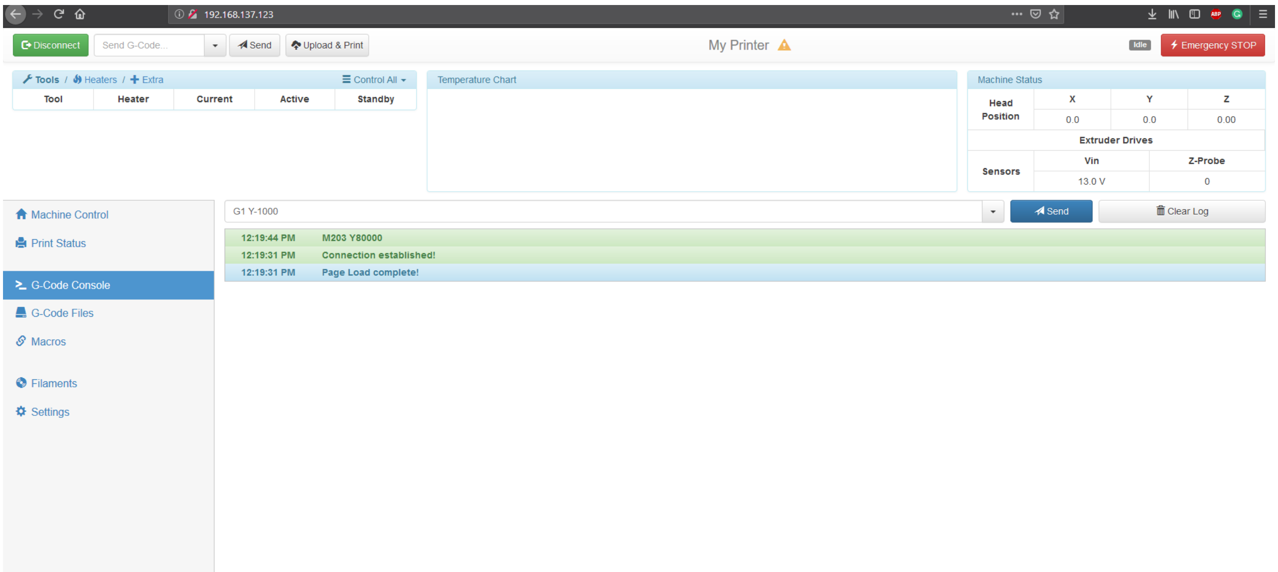


Fig.64. Top: The control board for the extrusion motor , Bottom: Online interface sending G-code to the board through WiFi communication. (Source: Author)

- **Printing bed**

Tool	Printing bed
Material	MDF 6mm
Dimensions	90 * 60 Cm
Additions	Plastic Sheet cover

The Printing bed was initially decided to have a clay surface. This was recommended by most of the clay printers providers, and according to the research conducted by (Revelo & others, 2018), using unglazed clay as the printing bed or substrate is concluded to be most suitable in terms of the material shrinkage and the behaviour while drying to avoid cracks. Also, it helps the first printed layer to stick well to receive the successive layers, which is achieved by the rough surface of the clay.

However, a panel was cast out of earthenware clay, but after drying without being fired, it had too many cracks as in Fig.65. It was hard to maintain the flat surface for the panel which together with the cracks would affect the precision and the cumulative error in the successive layers of the printed geometry.

Eventually, a wooden surface of MDF 6mm panel was used on an elevated wooden box (Fig.65). The wooden surface is dimensioned as 90 * 60 cm. This fits the designed geometry which has a footprint in total 30*70 cm. This also had to be tested as part of the research, and according to the resultant observations, it had to be covered by a plastic cover as will e mentioned in the upcoming results section.

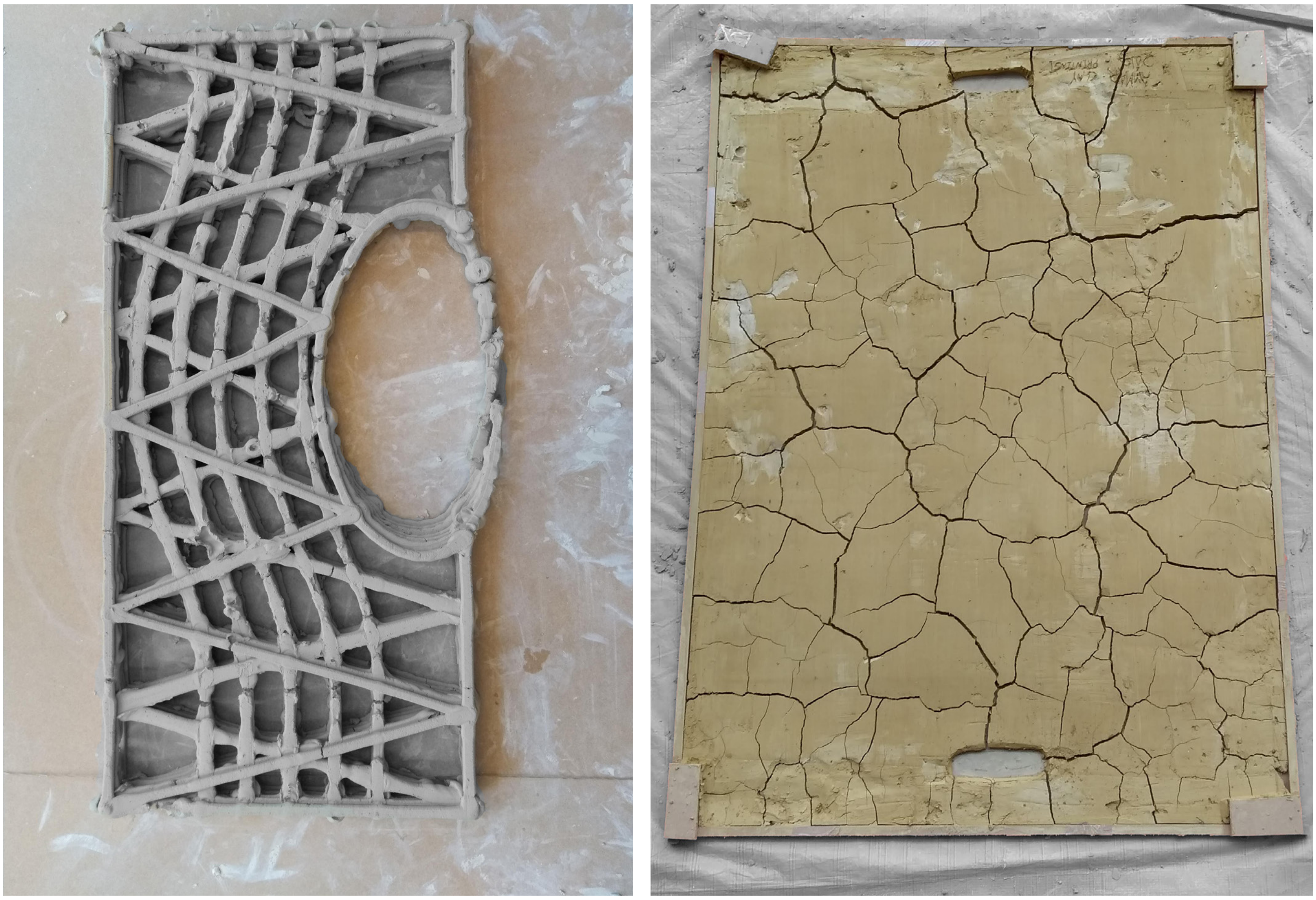


Fig.65. Left: Printing bed out of MDF Raised on a wooden platform, Right: Clay Plate casted as a trial for printing bed
(Source: Author)

- **Robotic Arm**

Tool	Comau NJ6022
Number of Axes	6 axes
Maximum Horizontal Reach	2.258 m
Maximum Wrist payload	60 Kg
Maximum Forearm payload	20 Kg

Used as the leading printing machine that all of the setup components are mounted over, the used robotic arm in this research is a Comau NJ6022 robot with six axes (Fig.66). This robot has a horizontal reach of 2258 mm, and with its 60Kg wrist payload, it is most suitable to be used for the research of the large scale printing. The six axes would give the possibility to later discover the print over double curved or non-linear layered objects. The robot is programmed using .PDL2 language files which are then translated into .code files for the robot to execute within its control pad. This whole controlling process and its calibration will be further elaborated in the following section of this chapter.

Fig.66. Used 6 axis Robotic arm Comau NJ6022 with a maximum reach of 2.2m.
(Source: Author)

- **Mounting devices**

Tool	Mounting devices
Material	3D printed PLA
Function	Prevent tools movement or breakage during printing
Additions	Extruder - Cartridge - Power supply & Controller

To mount the previously mentioned tools on the robot and prepare the setup for the printing, mounting devices were designed. Three main parts were designed according to the robot dimensioned drawings and shown in Fig.67. Firstly, the extruder holder, which fits over the Wrist of the robot and holds the extruder in a position that allows the material to be feed to it through the hose from the cartridge Fig.68. Secondly, Cartridge holder was designed out of two parts. Lower part mounts on the robot forearm as on four fixing points or screws, and an upper part which fixes the cartridge in its place using two bolts. The cartridge holder was sized to fit the medium sized cartridge of 2.5L, while also it fits the micro-cartridge of 600 CC using the bolts in a different position. Noticeably from Fig.68, it positions the cartridge in an inclined angle of 35° which allows the material to flow out easily through the hose even if the robot position is in a horizontal axis for the forearm. Last Part was the controller holder, which holds the power supply device attached to the Duet control board. This part is also mounted on the forearm and fixed through the cartridge holder down to the forearm fixing points. It was connected then to the power plug from a high ceiling cable to avoid clashing with the robot movement.

All these parts were 3D printed out of PLA plastic with different infilling percentage. The extruder holder had to handle much of the torsion assigned while fixing the hose and the motor to the metal body of the extruder. Even more, it had to be stable with less movement or buckling during robot movement to assure the precision of the printed material flow. Therefore it had an infilling of 100%. While on the other hand the cartridge holder did not have to handle much of torsion and neither had to be stable, as it does not affect the material flow out to the printing directly as the extruder, so it had an infilling of 50% as well as the power supply holder.

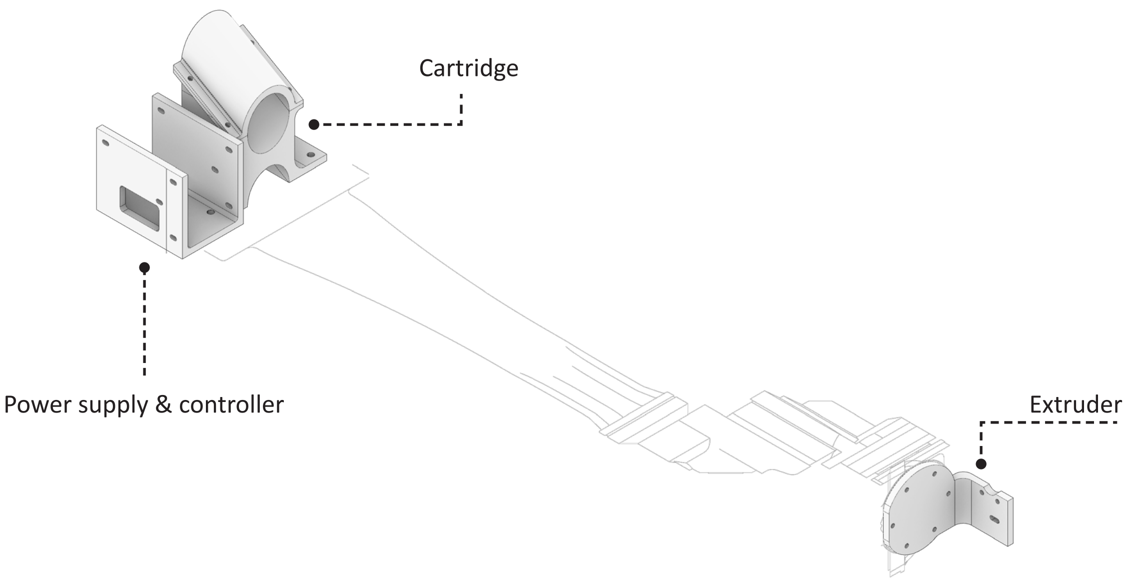


Fig.67. Designed mounting on the robot arm are 3d printed later to fit on the robot and fix the tools mounted over it
(Source: Author)

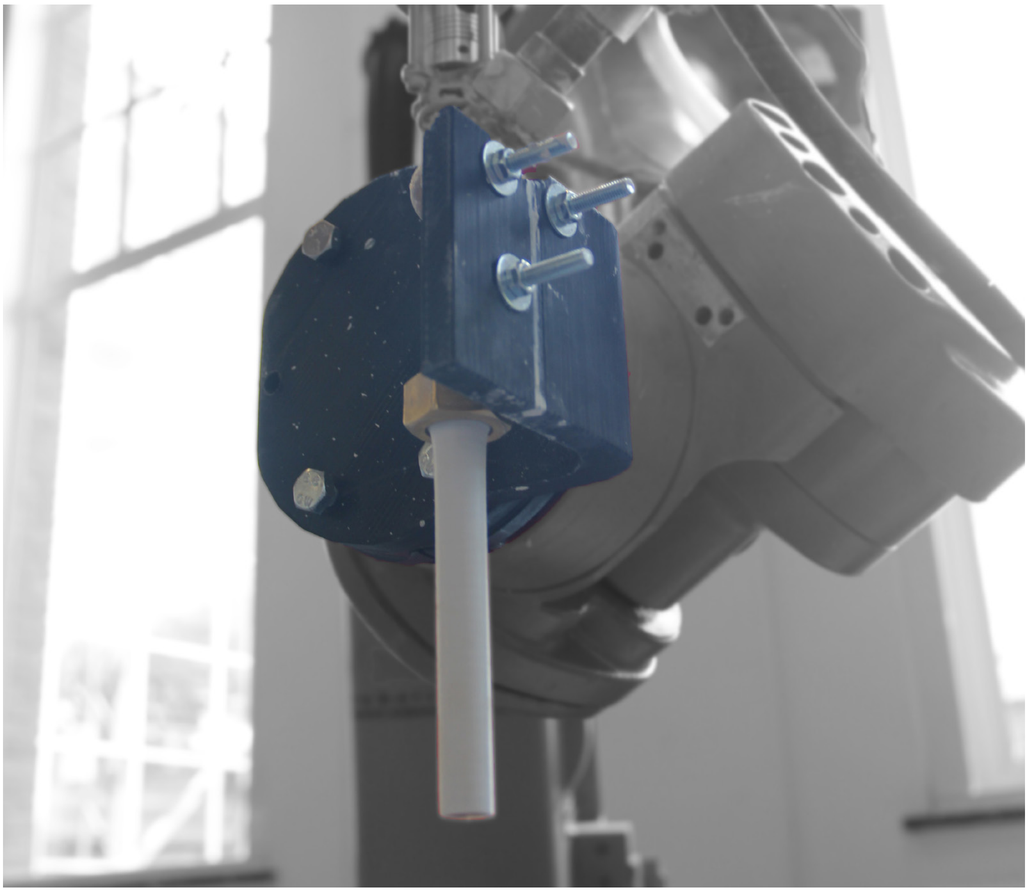


Fig.68. Top: 3d printed Extruder mounting on the wrist, Bottom: Cartridge adjustable mounting accepts two sizes of cartridges. (Source: Author)

5.1.3 Final setup

Shown in Fig.69 the final setup and tools prepared for the printing process.

Starting by the Clay mixing phase, where the material is weighted and mixed as previously mentioned in the process of the material experiment. Secondly, The air compressor connected to the cartridge as a controlled parameter that affects the amount of material fed to the extruder. Followed by the extruder's motor control through wifi connection to the laptop computer where the on/off of the motor and the speed are assigned through G-code online interface. Next, the extrusion and the nozzle fixed to the metal body of the extruder where the material is finally pushed through to flow over the printing bed which is the final phase.

These Phases are representing the printing process in terms of the hardware and their controllers. The robot programming and the designed prototype are differently described in the following section of this chapter. Where the resultant created setup is translated into digital input for the robot programming and also an influence on the quality of the final prototype which will be mentioned later in the results and observations section.

Fig.69. Fully assembled and mounted tools over the robot arm used for the printign process.(Source: Author)

5.2 Robot programming

5.2.1 Digital Work flow

- **Grasshopper to RoboDK**

Programming the robot was the parallel process that was happening next to the hardware setup preparations, and later, both were continuously being calibrated together until it was fine-tuned and the workflow was settled and verified to be suitable for the process within the time range available for the research.

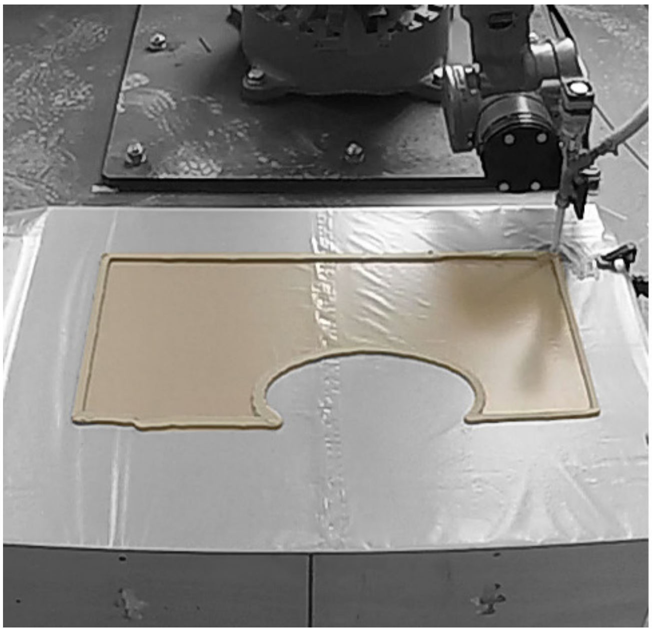
The first step in the digital workflow was to turn the generated curves geometry in grasshopper into a toolpath language that the robot can read as a programming language. Therefore a link between Grasshopper and the used robot programming software, RoboDK, was necessary and essential to ease the workflow. Fortunately, The RoboDK plugin for Rhino and Grasshopper allowed the geometry to be transferred quickly. The setup was transferred directly from Rhino geometry to RoboDK. While the toolpath curves were transferred by integrating the Grasshopper plugin for grasshopper into the slicing script mentioned previously in the design for Prototyping chapter 4.

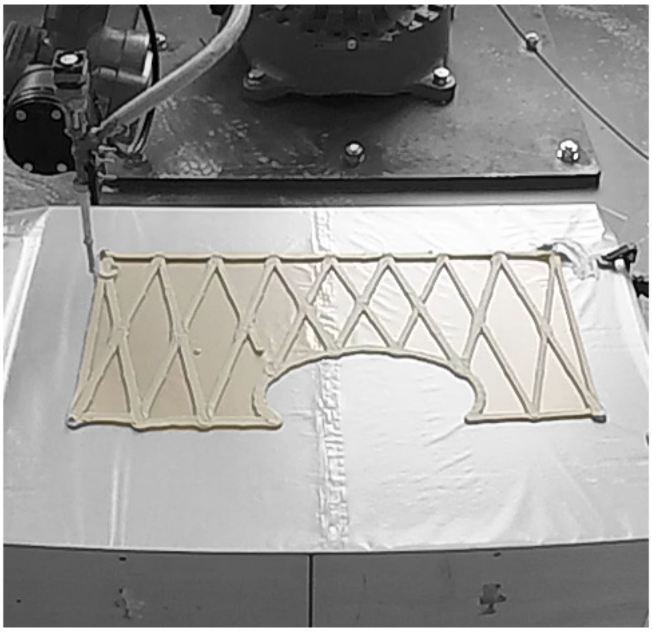
Firstly, the Curves in Grasshopper out of the slicing algorithm were sorted as inFig.70 in order as for the priority in the printing process for stability. By sorting the layer boundary to be the first to be printed per each layer, it defines the shape of the layer first and its outer boundary to be supported by the structure supports.

Followed by the structure supports, which intersect with the layer boundary and overlaps to prevent the layers from falling apart or collapsing due to its self-weight or the material viscous consistency. Overlapping the structure supports after the layer boundary would provide desired and required stability for the printed object.

Next, was the thermal buffer horizontal curves. These curves were not mainly structural and therefore were possible to be printed later after the structure support. While on the other hand it also has its separate starting and end points from the layer boundaries. Unlike the structure supports which always started from and ended at layer boundary start and end points. This assured less retraction and approaching time or movement during the printing process. Which is more efficient in terms of material saving as well as time-saving and printing overall speed.

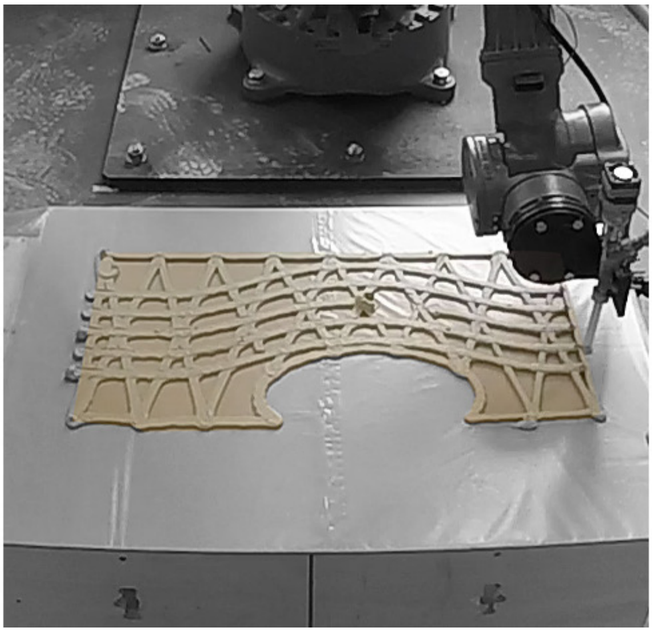
Lastly, the overhangs were listed as the last curve to be printed in the tool path list order. This allows the printed geometry to be structurally stable and also provides support for the overhangs to be resting over.

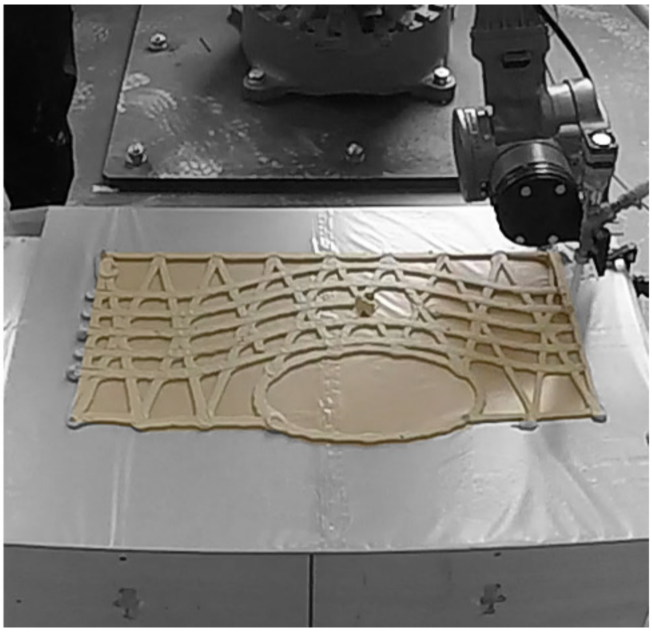




1. Layer boundary

2. Structure supports





3. Thermal buffer

4. Over hangs

Fig.70. The curves sorted in grasshopper and prioritized in the order of printing to assure the stability of the print while building up (Source: Author)

- **Program generation | RoboDK**

Once the curves list was ready and ordered in the desired sequence for the printing, It was then transferred to RoboDK as a station project. In grasshopper it was possible to decide the number of layers to be sent as toolpath and to generate robot program for. Also in the grasshopper script, it was possible to view the starting and end points for each curve to check the continuity of the printing. Shown inFig.71 the output view possibilities from the Grasshopper script for easy workflow to RoboDK to verify the sample scale to be printed and its starting position in order to reduce the tool path length.

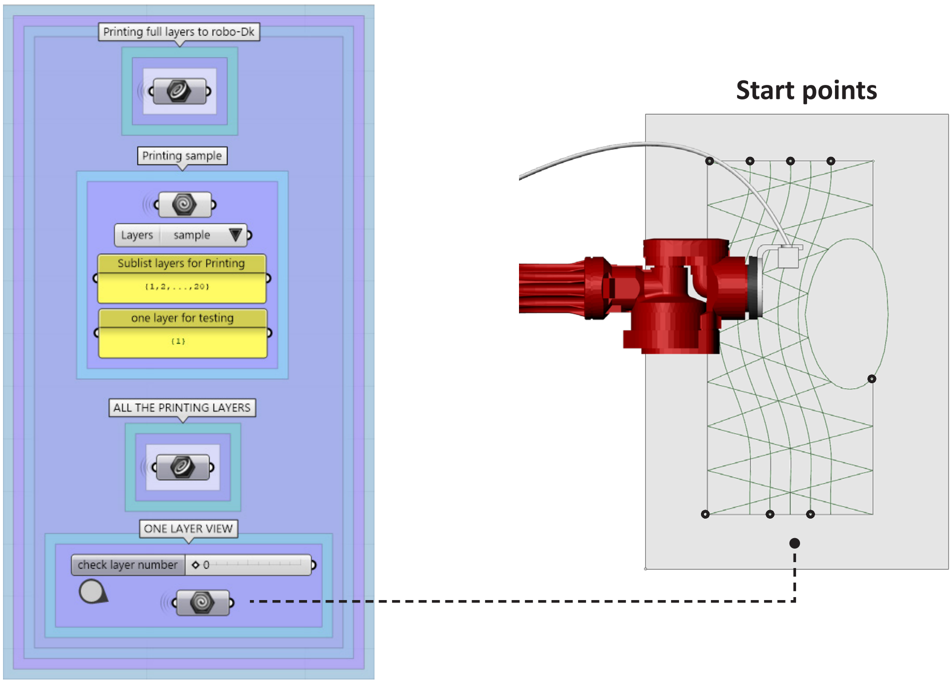


Fig.71. Out of the full sample to be printed, each layer can be examined separetly for the start and end points in Grasshopper for easier calibration. (Source: Author)

On the other hand, The setup was digitally modelled in Rhino, And then it was transferred to RoboDK using its plugin for Rhino. Shown in Fig.72 the digital setup used to simulate the printed object and have an imagination about how the scale of the object to be printed is and its orientation. The Sliced geometry is then oriented to be over the digital setup as a step before exporting it to RoboDK environment. The orientated geometry placed over the printing bed and in the right distance to the robot base, assures its right import in RoboDK programme generation.

In RoboDK the robot program is generated for the imported curves from grasshopper as a tool path. The movement type is defined by default as a Linear movement which is suitable in that case. However, also could be adjusted to be joint movement later. It could be simulated in RoboDK how the tool is oriented in that case the extruder nozzle pointing towards the Z-axis of the robot base which is the X-axis of the flange. Moreover, The TCP (Tool Center Point) is assigned from the training of the robot after the extruder is mounted on it which will be mentioned later.

The movement speed is assigned as 50 mm/s, and the override speed could be controlled by the robot control pad manually. Moreover The approach and retract at each curve end and start could be controlled as if it should happen or not in addition to the amount of the retraction and approach in mm. This allows the excessive material extruded by the motor to be easily removed before moving to the next curve starting point in the programme. Although the I/O digital input and output for the motor during the printing path was possible to be implemented, it was not feasible in the available time for the research, but would be an important point for further research. Also, the retraction and approach amount prevents the collision between the tool and the printed paths which makes it important to be integrated within the program.

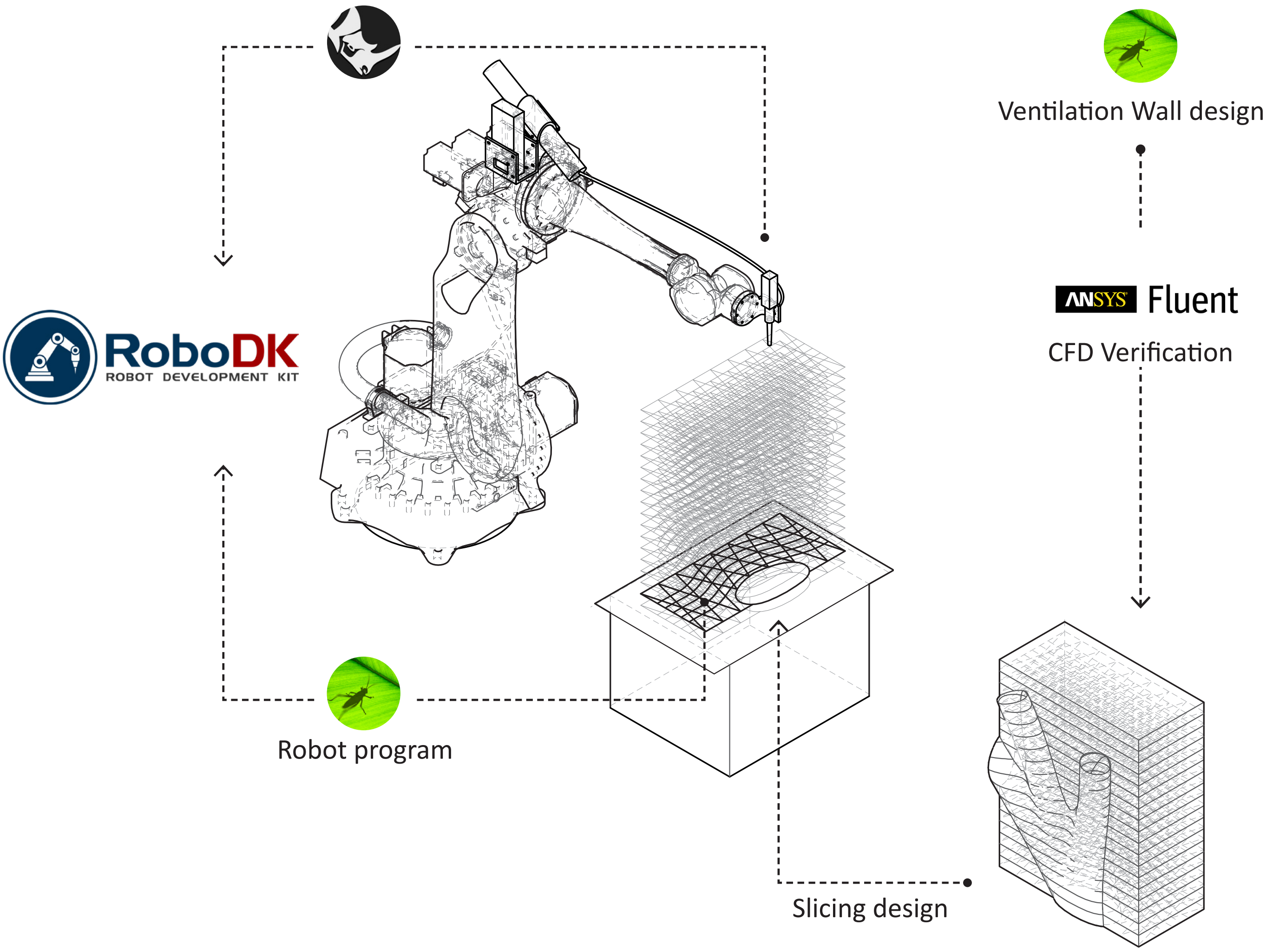


Fig.72. Digital work flow from the generated geometry in rhino and grasshopper, to the robot program generation in RoboDK (Source: Author)

Finally, an approach point at the beginning of the programme was added together with a retract point at the end of the program as seen in Fig.72-b. These two approaches and retract points gives a period to prepare the motor for extrusion and assure that the tool orientation is proper and matches with the simulated program in RoboDK.

Noticeably, a reference frame point was considered for the program coordinates generated. This reference frame point was programmed or trained to the robot firstly, and then was assigned in RoboDK as a reference to align most of the printing coordinates. As by assigning this point to the corner of the printing bed, it was easier afterwards to align all the setup as the printing bed and the position of the printing over it.

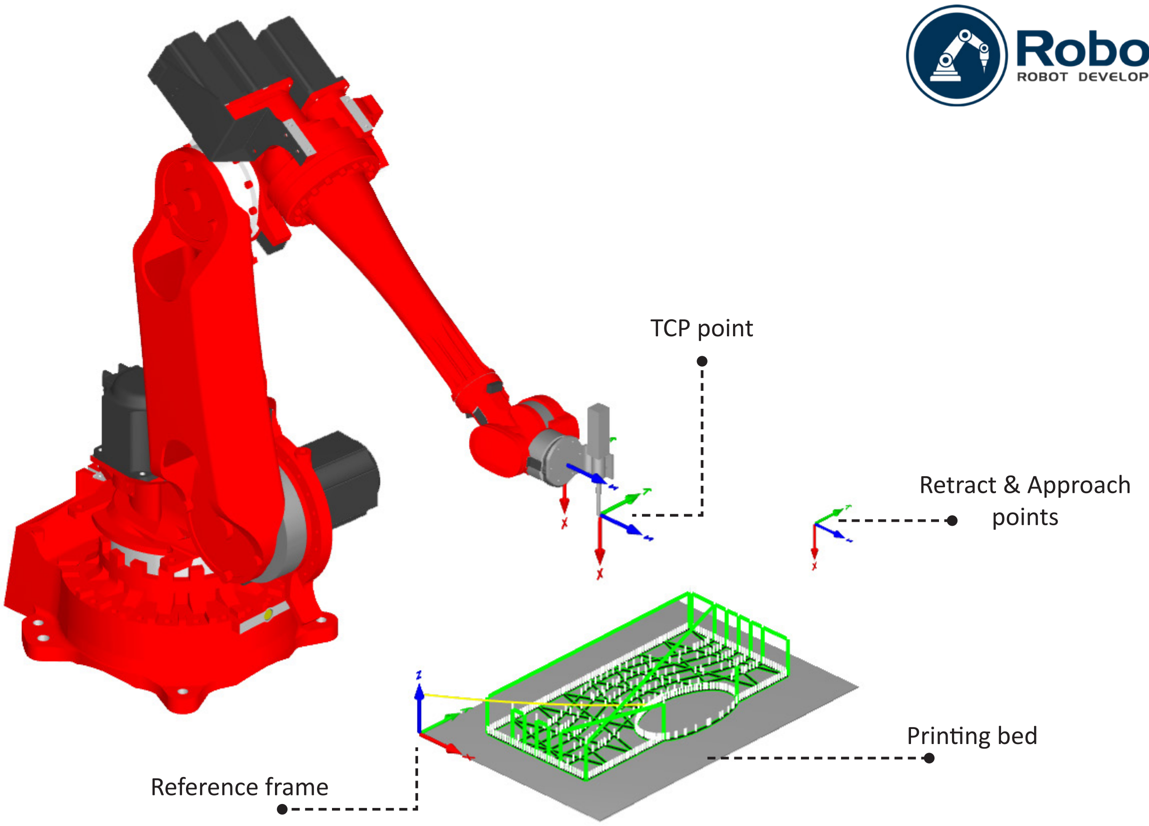


Fig72-b. Defining the TCP, Reference frame, and the printing setup in RoboDK generates the right tool path for the robot program eventually. (Source: Author)

5.2.2 Calibration

Eventually, the robot program could be generated as a .PDL2 file format, which is readable in the control pad of the robot when transferred using a USB drive. It could then be translated into a .Code file format to be executed.

To be able to generate the right program for the robot, the physical setup and program had to be calibrated well with the digital setup and generated a program in RoboDK. This calibration had two main phases. Initially the set-up of the printing bed and the TCP teaching, as well as the reference frame. Secondly, the speed tuning between the three of the controlled tools, the motor speed, the robot speed and the air pressure, putting the material consistency effect aside as it could be solved with the speed override in the robot movement manually.

- **Setup Calibration | Digital & Physical**

The first step in the calibration for the setup was to define the TCP of the extruder mounted on the wrist. This is done through the Robot 3 points teaching. This allows defining the TCP coordinates in relation to the wrist flange. Reading these coordinates from the robot control pad, it was then translated into the digital model in RoboDK. By inserting the TCP coordinates, it was then easy to simulate the program generated for collision detection as well.

Secondly, the reference frame of the bed was necessary to define the position of the printing bed in relation to the robot base center point. This was defined by teaching the robot the Reference frame by defining the corner of the positioned bed to be the reference frame and then defining the planarity of the bed in X, Y direction in relation to the robot base center point. And since the coordinates are defined in the control pad, it was then also defined in RoboDK. By assigning the reference frame as the reference for all the generated program points coordinates, the program was calibrated with the printing bed which was fixed in its position using clipping devices to prevent its position change.

As far as the TCP and the reference frame were defined and their coordinates were known, in Rhino environment the printing bed was modeled and placed in relation to the robot base center point as shown inFig.72. Later it was transferred to Robo DK for the simulation requirements and the collision detections.

- **Speed calibration | Extrusion & Movement**

Not only does the robot speed has a significant effect on the printing time but also the quality and the precision of the printed object. Robot operation movement which was assigned in the RoboDK program was 50 mm/s and allowed speed override during program execution. Therefore the 100% speed in the control pad means that the speed was used as 50 mm/s, while a 50% override meant the speed was 25 mm/s.

Another speed that had to be working along with the robot speed was the extruder's motor speed. This speed of the stepper motor was limited in the first tests due to the firmware configuration for the controller board. Where the maximum steps per mm were assigned 80.00, the motor speed was not fast enough to extruder the material in its designed mixture consistency through the bigger nozzle size in comparison to the small-sized nozzle used in the material experiments (Fig.73). Therefore, it was adjusted to be 420,00, and in that case, the maximum speed was possible to jump up from 400 mm/s up to 1333 mm/s which is more than triple the initial limitation. This motor speed was set as the standard motor speed all along the prototyping process.

Lastly, the air pressure in relation to material consistency had to be matched and adjusted according to the previously mentioned two speeds. As the cartridge had a maximum pressure of 8 Bar, The range of the pressure suitable for the material was between the range of 5-6 Bar, depending on the material mixture consistency.

The three of these speeds or rates -Fig.74 - when all adjusted together played an essential role in assuring that the material will be extruded in the desired matter that provides a better consistent flow through all over the printing procedure.

Fig.73. Used Nozzle size in material experiments had different requirements for the air pressure and the motor speed than the used nozzle size in the prototyping. (Source: Author)

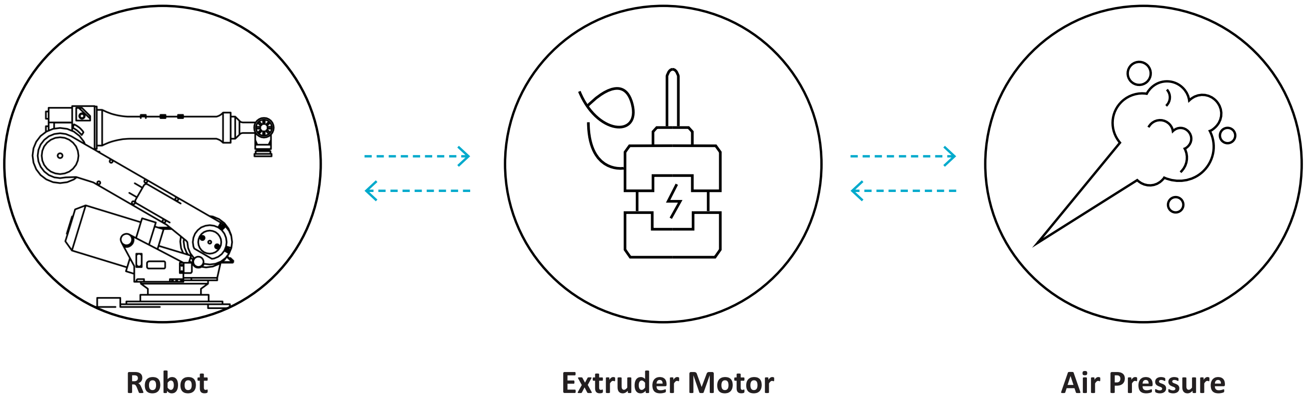


Fig.74. Three speeds and rates had to be calibrated, the extruder motor, the robot speed and the air pressure. (Source: Author)

5.3 Printing Results | Analysis

The printing process had three elements or aspects that are being affected and affecting the resultant final product. These elements are described as how they are influencing the process each one separately in that section of the printing results. It will be mentioned and elaborated more in the conclusion chapter how they all are interlinked. Even more, how that changing one aspect in one of these elements would change and affect the other elements, and consequently the final product's quality as well as the time and material consumed in the printing process.

These elements are briefly:

1-Material 2- Setup 3- Design

5.3.1 Material

Starting by the material as the first step in the printing process, in general, is to mix the clay and prepare it to be fed into the extruder. The material has a significant effect on the resultant quality. Alongside its effect on the time consumed in the printing by affecting the robot override speed. Also, it would affect the amount of air pressure used and in return the amount of energy consumed in air compression. Therefore it is essential to mention the resultant observations and considerations to assure a better workflow.

Three main aspects are again considered within the material element. Namely, material properties, consistency out of mixing and lastly, filling or feeding technique to the extruder. These three aspects each affects the final product differently.

Material Properties

Clay as a natural material, and as mentioned before, has its characteristics and properties which should be considered while designing and its behaviour should be expected relatively. The exact behaviour of the material is not easily predictable, but still could be estimated and then further developed.

The material Properties that are mainly considered in here and had a considerable effect of being noted are Shrinkage and water absorption.

- **Shrinkage & water absorption**

Clay tendency to shrink after it has dried makes it much harder to control the final product. As the material is drying it loses its water content, causing the space between the clay molecules to be reduced and hence the final product shrink. This shrinkage as noticed inFig.76 causes not only a change in the designed weight and the size of the printed object but also it creates cracks. As the shrinkage is happening, it causes the object to be colliding with itself and hence cause the cracks to appear due to the tension forces created all over the printed layers as one body.

Noticeably, The cracks are found to be concentrated at the nodes of material accumulation. This is where firstly, the intersections are, as in the design its in the infilling where every line meeting the other lines. As observed inFig.77 the intersection nodes tend to have the most of the material concentrated and this is due to the lack of I/O control for the motor, which causes the motor to keep extruding all along the tool path of the program generated.

However, Clay with its tendency to absorb water helped in keeping the printing material ready over many day. This is mainly by sprinkling water over the printed objects at the end of the print keeps the surface and the material wet which allows the print to continue in the next day. it reduced the shrinkage rate at that moment and hence allows the precision of the printed object to be higher than if it was left to dry over the night. Moreover, the wet layers allow the print in the next day to stick well over and continue building up without curling.

The material is kept wet by covering it with a plastic sheet, and the airtightness is as much as possible assured as shown in Fig.75. Covering the print is not enough if it is not matching with the material of the printing bed as well which affects the shrinkage rapidly. This will further be elaborated in the next results about the setup effects especially the printing bed on the material and the printing quality.

Lastly, as it is mentioned before, “Clay, until it is fired and made durable, is a material of little or no practical value” (Rhodes, 1958, P.12). As the first test print was not fired, it was noticed that it had major shrinkage and cracks and almost broke into small parts. All in addition to the printing bed effect which absorbed much water and accelerated the drying process. Therefore, it is noted that it is better if there is a direct firing once the printing is done.

Briefly: Keep printed object wet by covering it if the printing is happening over different days. Expect cracks if the material is not fired or if it had a rapid uncontrolled drying.

For further development: Automation of material filling and hence Printing, assure homogenous drying for the printed object. Firing directly after the print might reduce the chances of having cracks or broken material.

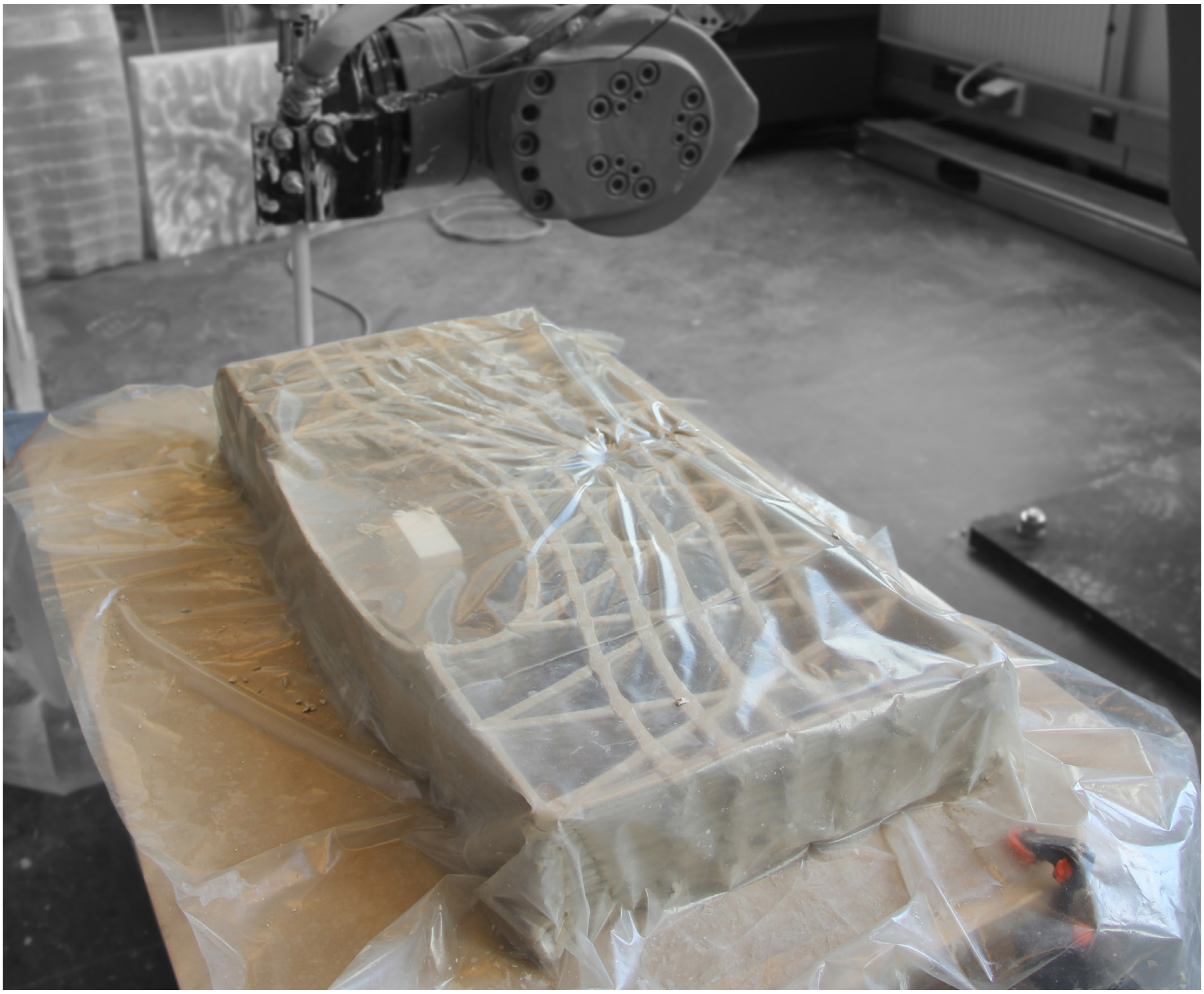


Fig.75. Covering the printed object with plastic sheet keeps it wet for the next printing days. (Source: Author)

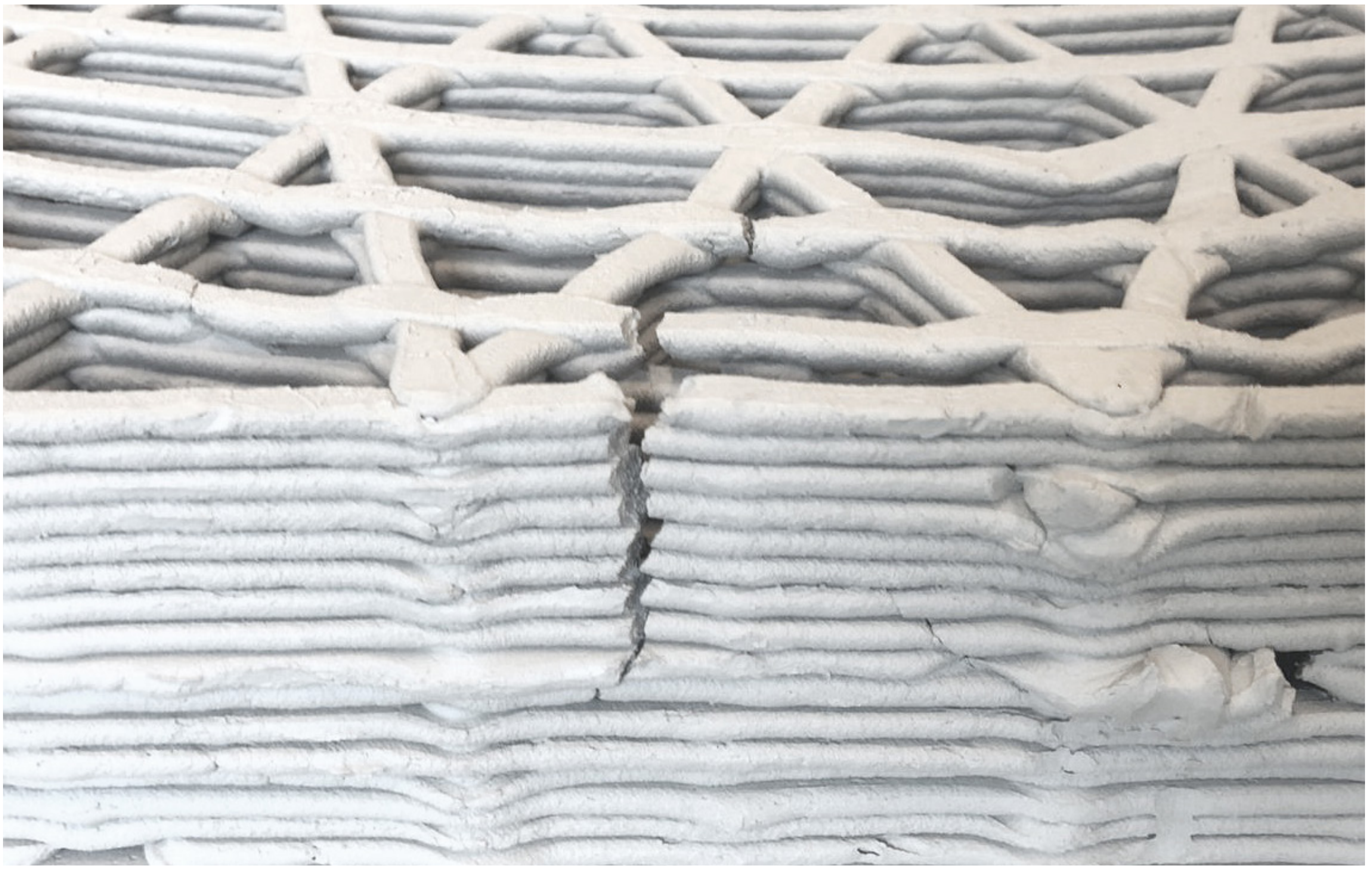
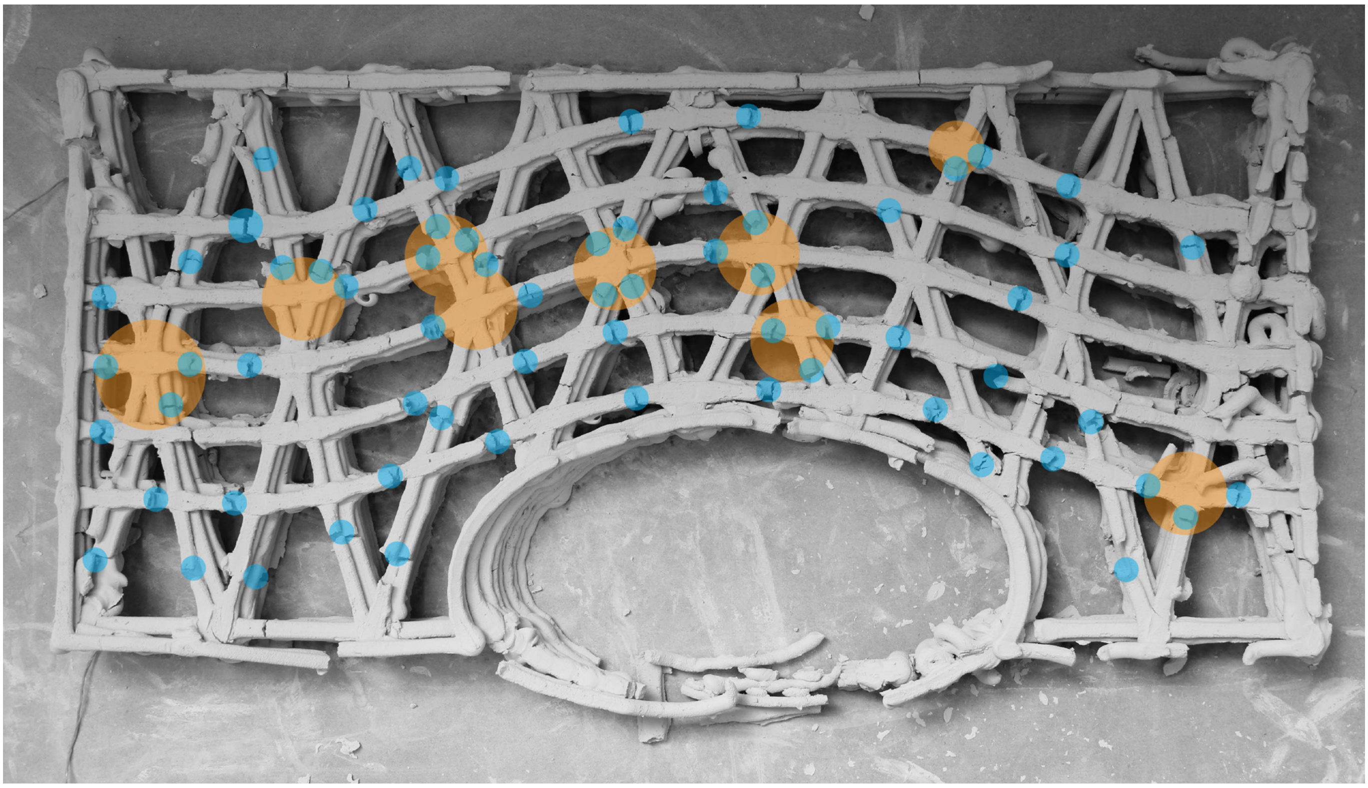


Fig.76. Top: Cracks happening around the material accumulation nodes due to shock-dry without cover at all. Bottom: if the print is un covered earlier than two weeks, the cracks tend to happen in the exposed nodes. (Source: Author)



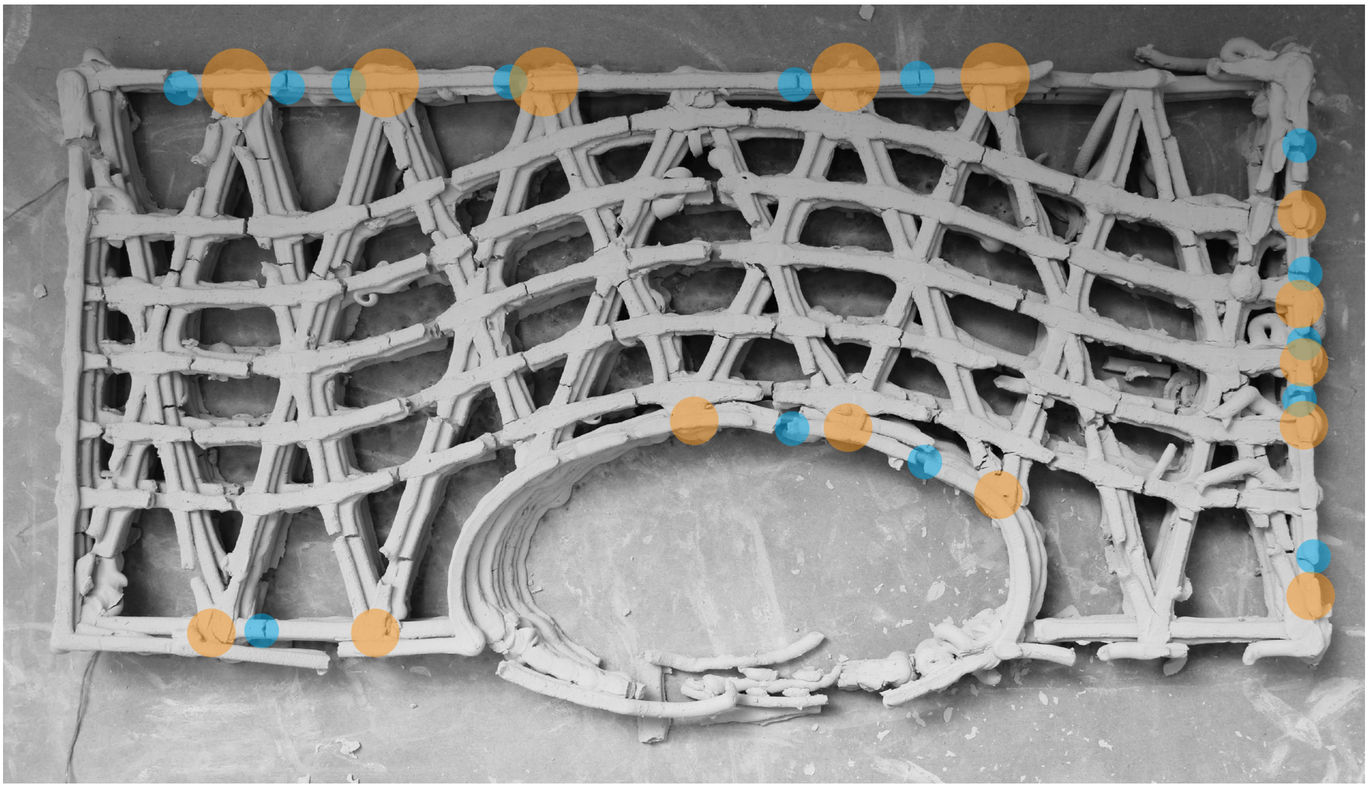


Fig.77. Upper: Cracks in Cyan nodes accumulating around the intersection nodes in Yellow of structure support and the thermal buffer lines. Lower: Same happens on the layer boundary where it is overlapping with the structure supports. (Source: Author)

Material Consistency

The material consistency is dependent on the amount of water added to the mixture and its viscosity. Additionaly, it depends on the material mixing process and its quantity, which determines a clogged or a smooth consistency of the final clay body.

- **Water Percentage:**

The amount of water added to change the mixture from its Powder body into a viscous material that can be deposited and extruded is always tricky and not as easy as expected to achieve. The initial amount of material considered and derived from the material experiments was 30%. This ratio or percentage although it worked fine for the small scale printed samples in the material experiments, it was not compatible with the large scale due to the different nozzle sizes. Since the nozzle size in the material experiments was smaller, and the cartridge was connected directly to the extruder metal body, it was easier for the material to flow out and being extruded. While in the large scale printed prototype, the nozzle size was more than double the one in the material experiments, and the material is transferred through a hose from the cartridge to the extruder. Hence changing the amount of water percentage to 34% and even up to 36% assured a better flow of the material.

Using a water percentage of 34% matched with the robot speed to be overridden at 25% of the operation speed in the program. Noticeably and remarkably, increasing the water percentage by 2% to reach 36% out of the total powder body, it was possible to increase the speed of the robot by almost double the speed in the initial mix of 34%. This meant that the override speed reached up to 45-50%, which is more efficent in terms of the printing speed and time.

The effect of the water percentage on the material consistency could be noticed inFig.78 where the initial printing experiments had very curly and discontinuous lines. The less water quantity caused the dry mixture body to be hard to flow relatively well with the robot speed, and also to stick to the printing bed or the layers beneath.

On the other hand, Excessive amount of water added to the mixture is not recommended and led to bad results as well. An excessive amount of water turns the mixture into a more liquid consistency. Which is hard to control by the extruder motor, and the air pressure alone would be enough to push it through the nozzle at a very high rate. Sometimes this required an override speed for the robot to reach up to 100%. Shown in Fig.79 the effect of the overwatering on the printed layer line thickness and consistency. As it sticks very well to the bed or the underneath layers, yet it does have a much higher layer thickness.

Briefly: Maintain a proper consistency of clay and water ratio to reach up to 36%, in order to avoid the discontinuous layering or excessive layering. Calibrate the water ratio with the nozzle size and the amount of the material flowing out.

For further development: Standardized mixing for the clay body assures a homogeneous consistency for the extrusion and hence the quality of the layering and the final product.

Fig.78. Left, the Dry consistency of the material caused discontinous lines in relation to the robot speed. Right: curly lines resulted from the lack of viscousity and the water content in the mixture. (Source: Author)

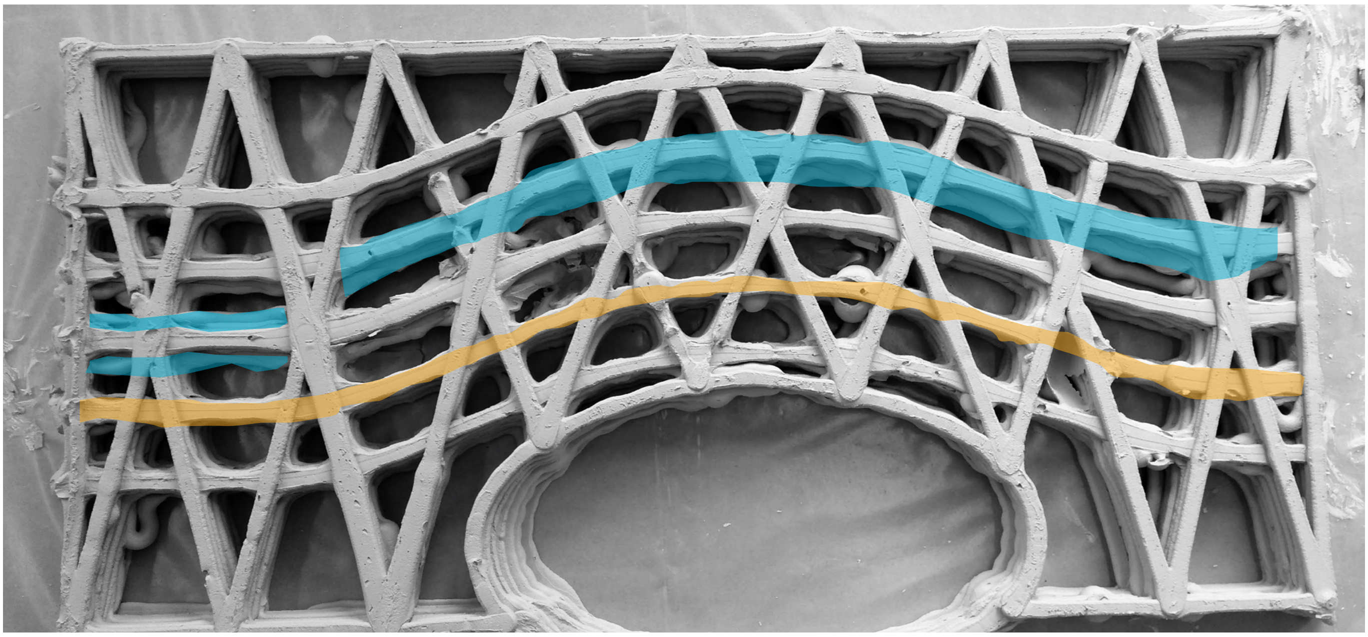


Fig.79. Cyan colored lines had an excessive water percentages due to the unconsistent and unproper mixing of the material, differently the yellow lines had a better conistency and extrusion rate in relation to the robot speed. (Source: Author)

- **Clogging:**

Obviously, as the material used was powder, it had to be mixed with water. Clay is affected by the amount of water added and how its consistency will be. As the material is mixed, the clay tends to be formed into Small balls or gets clogged as the space between the powder is filled with water and then the grains are sticking to each other as mentioned previously and described in the material research chapter 2. This clogging affects the final consistency as if not well mixed, small clogged pieces does stop the material flow out of the motor or at least delay the extrusion rate, and hence the printed layers tend to have small gaps or discontinuous layer paths as the material is not fully calibrated at that moment with the robot speed. Shown in Fig.80 and Fig.81 the effect of this clogging on the continuity of the layer.

Mixing the material by hand as in the first test prints did produce good and desirable consistency, since the material quantity was manageable and possible to be mixed very well. Small quantity is meant to be around 1000 gm and up to 3000 gm of clay without considering the additives which will help raise it up to almost 6000 gm. While mixing by hands, it could be felt and sensed how far is it clogged or not. However, once the material is in large quantities, more than 3000 gm of clay it started to be much harder to control the mixing quality.

As in this research case, the largest amount in one mixed sample was around 6000 gm of clay and a total clay body of 11256 gm. This required using an electric concrete mixer as shown in Fig.60. Using the electric mixer reduced the amount of clogging than if it was by hands. Still, It was not enough to be entirely smooth and consistent.

Hence after the material is mixed in a large quantity, it is then had to be processed in a second phase of mixing by hand before filling it into the cartridge, and by adding a bit of water to make it possible to get smoother and more consistent.

Briefly: Mix material properly and have no cloggings to assure a continuous flow of material during the extrusion process. Two mixing processing stages for the material in large quantities are much more recommended than one process by hand or electric mixing.

For further development: Automated large scale mixing of the material as in concrete, would assure its continuous and consistent flow.

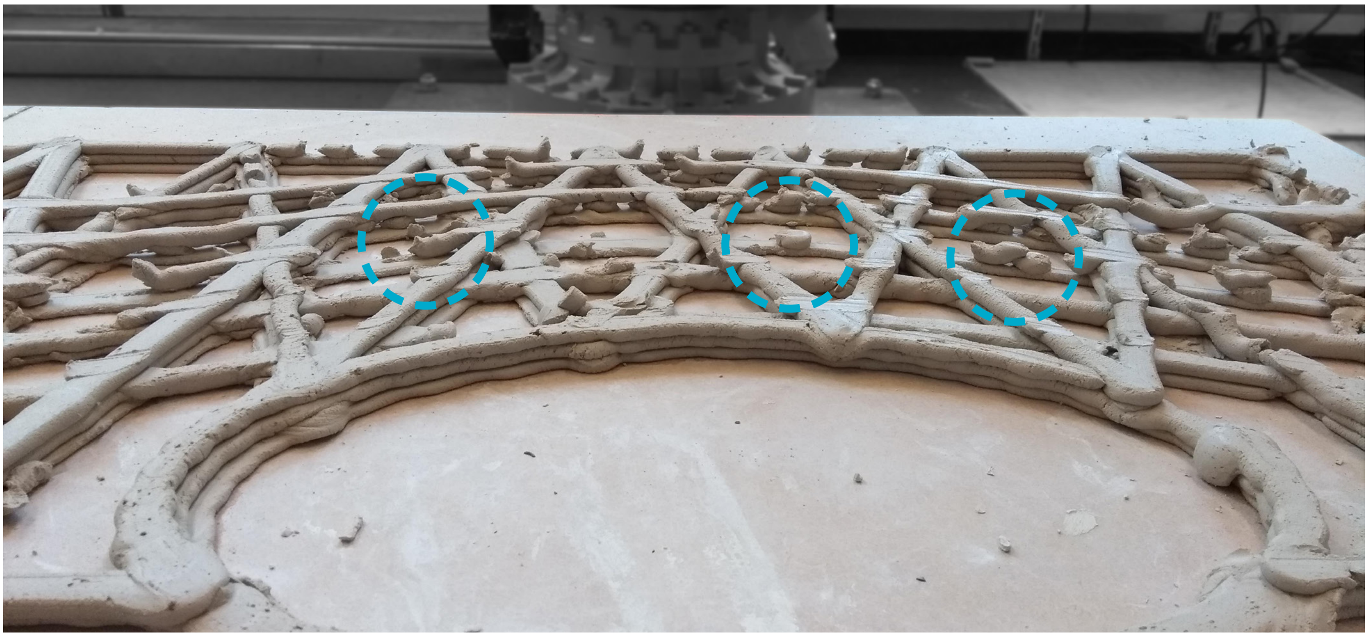


Fig.80. Clogged clay body not only causes discontinuous lines but also causes the motor to stop and gets locked due to the inability to push the material stuck within it. (Source: Author)

Fig.81. Discontinuous layer lines because of the clogging, the water percentage and the bed material. (Source: Author)

Material Filling

Last material related aspect is the material filling or feeding into the cartridge system. Once the material is mixed and prepared, it is now one step far from being extruded, which is to be filled into the cartridges. Unfortunately, filling the cartridges is not as easy and fast as it could be expected from a viscous material. This is because the material is feed into the extruder through an air pressure system, which has the risk of causing pressurised side effects.

As noted before in the material experiments chapter 2, as the clay is mixed, there will always be air cavities and bubbles in the mixture body. Also, while filling the cartridge air cavities and bubbles are created inside the cartridge. Therefore, If these bubbles did not get out, it would cause what was called “Air shots”. These air shots tend to happen as the material is being pushed out of the cartridge down to the extruder and come out of the nozzle while the printing process is happening. These air shots cause the print to be discontinuous and consequently less precise as in Fig.82. Moreover, the last part or quantity of the cartridge’s material fed through does has a worse effect than just a discontinuous extrusion. It causes a strong air shot that the air flows in high pressure out of the nozzle and damages the printed layers beneath directly as seen in Fig.83.

To avoid air shots, the material filling into the cartridge had to be compressed very well. After many trial and error, eventually, two ways for filling the material were considered, depending on the size of the cartridge used. Although the same technique for the bigger cartridge fits for the micro-cartridge, it is still more time consuming than the previously used technique during the material experiments.

Firstly, for the micro cartridge, a small wooden circular piece in the same diameter of the cartridge inner diameter, was created and attached to a wooden stick — this Wooden device allowed to compress the material once the cartridge is fed with material quickly. Compressing the material in that way released the air bubbles and spaces within the material and avoided air shots very efficiently.

Secondly, for the bigger cartridge used in the printing, the wooden device was much harder to use in large quantities of material, harder to be compressed manually. Therefore, The used technique was the spatula filled in technique. Using a spatula to compress the material before feeding it into the cartridge and filling in layer by layer while the other end of the cartridge is almost closed. The spatula and layers feeding assure that the air bubbles are released. However, this technique consumes much of the process time.

Due to the importance of the consistency and continuity, while also avoiding air shots to prevent printed model damage, filling in the cartridges did consume quite much of the printing process time. This is almost more than the time consumed in the extrusion itself. However, Automating the process in large scale might be more feasible if the material is hydraulically compressed in the feeding cartridges. The effect of the cartridge system will be mentioned later apart from the material behaviour within it.

Briefly: Assure the least amount of air bubbles and cavities within the mixture while and after it is fed into the cartridge. This prevents the air shots which might damage the printed objects or at least cause discontinuous flow for the material.

For further development: Mechanically compressed clay large quantities in large cartridges might not be a problem if the process is automated instead of the human labour.

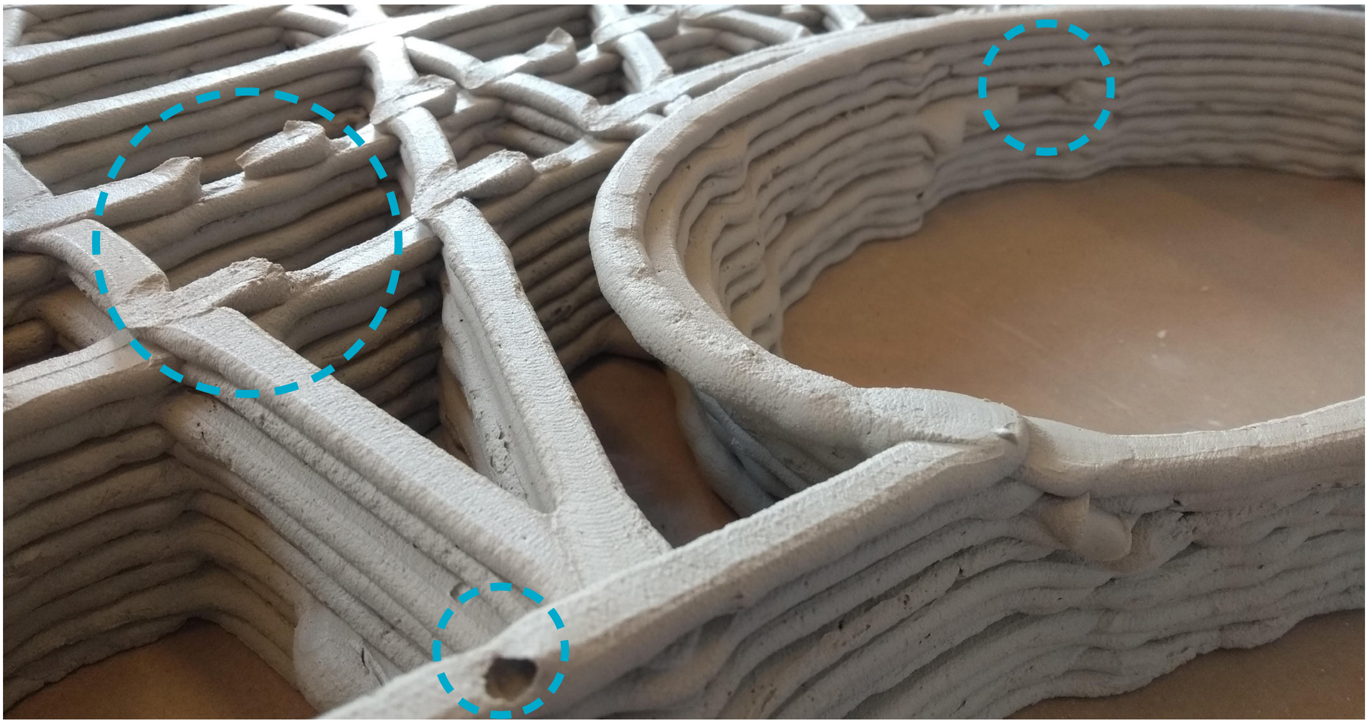


Fig.82. The discontinuity caused by the air bubbles within the mixture and due to the lack of good compression into the cartridge. (Source: Author)

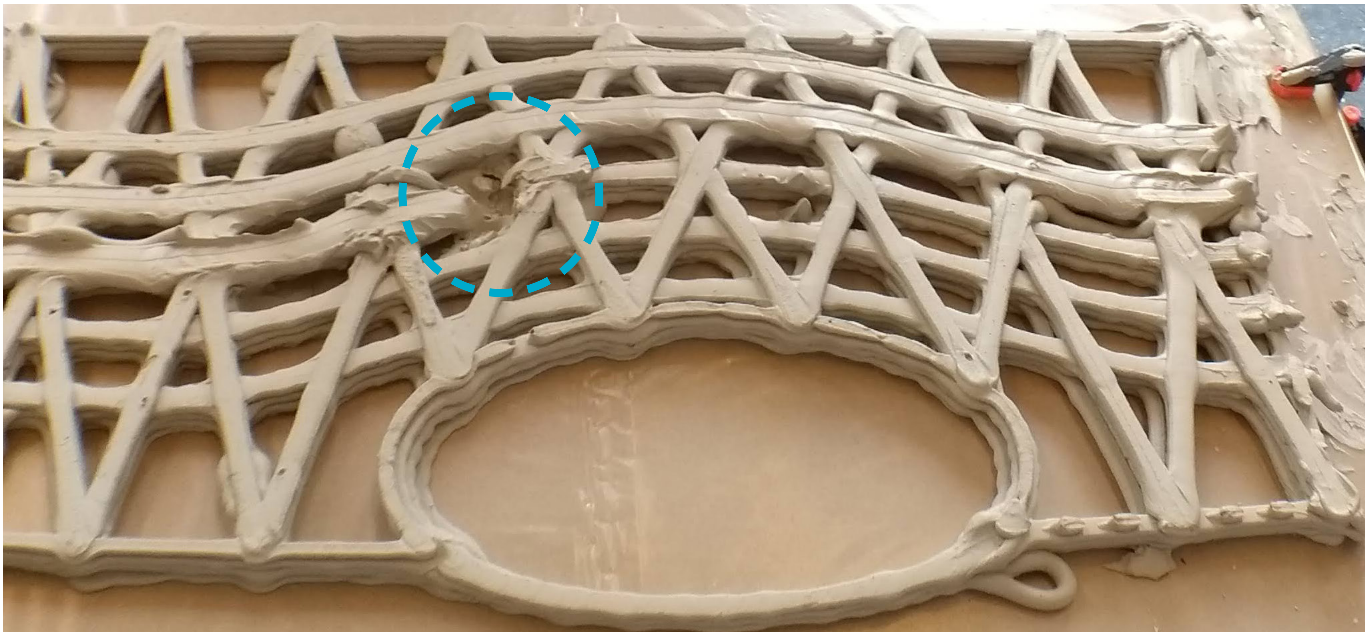


Fig.83. Air shots caused by the last part of the cartridge if not well compressed, which damages the printed model. (Source: Author)

5.3.2 Setup

The second element that influences the printing process is the setup. As the material is prepared and ready for extrusion, the setup and its materials also do affect the final product. In these results, it will be mentioned how three major aspects had this influence. Starting by Printing bed relation to the printing quality and even possibility, followed by the I/O of the extruder motor, and eventually, the cartridge system relation to the printing time and speed. Each of these elements had a noticeable effect to be considered and adjusted in the current research or to be considered for further research.

Printing Bed

The printing bed material has major consequences on the printing process and the final product as well. This is because the first layer which is the base for the buildability of the whole model does have direct contact with the bed, and therefore is affected by its material and its behaviour with the clay properties. The two main observations about the printing bed or substantiate were concluded in the following layer adhesion description and the Shrinkage and water absorption effect.

It is important to mention though that the recommended printing material to be clay bed as found from literature review and other smaller scale clay printing projects mentioned previously in the tools description section of this chapter. However, Due to the large scale of the printed object, making a bed that is out of clay was not feasible mainly due to the lack of a firing kiln to suit the size of the bed. Hence, the unfired bed cracked -Fig.65- and had a non-planar surface which did not suit the printing process precision. Eventually, the used printing bed in the first test was MDF 6mm wooden Plate with the dimension of 90*60 cm. Which later was covered by a plastic sheet. The reasons behind that plastic cover will be mentioned later.

- **Layer adhesion**

Clay is a viscous material which tends to stick over each other, yet if the water content is not too much for it to stick over other materials, then it is always hard to maintain the first layer of printing. The initially used bed as MDF wooden sheet did not have a rough surface enough to stick the material in the first layers as shown in Fig.81. Which resulted in curly and discontinuous printed layers. Even though the material had enough water content and was viscous enough to stick over the bed, it did not and caused even some parts of the printed layer to move along with the extruder in the turn over at corner points.

Therefore, The second trial was to continue printing over the clay layers created initially, and it had better adhesion over each other. It was not precise enough due to the fact that the first layer -printed over MDF- was very chaotic and imprecise. It reassures again the fact that printing over clay bed or fired clay was an option that should be considered.

Eventually, The printing bed in the next printed trials was covered by a Plastic sheet as a cover over the MDF plate. This is tried over a small foil sheet and for short lines of clay printed as a test, which worked efficiently. Therefore it was decided afterwards to cover all the MDF sheet with the plastic thick cover. The plastic tends to be adhesive to the clay as the material is deposited over it, and the plastic had to be insured to be very tight over the MDF so that it does not slip or move, due to the viscosity of the clay.

- **Shrinkage & water absorption**

Not only, did the material of the bed affect the adhesion of the first layer and its precision, but also it affected the final printed object greatly. Due to the fact that the wood absorbs water, The clay water content necessary for it to cure and which requires slow drying if not fired or until it is fired. The wood when it absorbed the water content of the clay, caused the clay to have a shock dry and therefore the shrinkage was very high and caused many cracks in the printed object as seen in Fig.84. By reducing the water absorption, the shrinkage could be controlled for a while until the next layers could be printed in another day or after some time without losing the precision of the print.

Remarkably, also due to the water absorption property of the wood, the water absorbed from the clay was enough to cause the bed to deform and bend. This led to a non-planar surface for the printing. Which meant that the definition for the reference frame and its plane is almost useless and the printing planarity is questioned of its effect on the precision of the final product.

Briefly: Printing bed material affects the adhesion of the first layer. Its material property as the water absorption might cause shrinkage, cracks and Non-planar print. Using plastic sheet is more efficient and suitable.

For further development: Using fired clay bed would make it easier to be moved directly into the kiln for firing, instead of the plastic sheet cover or the wooden plate underneath.

Fig.84. Top: Wooden MDF sheet caused crack, rapid shrinkage, un-planar printing and weak adhesion for the first layer. Bottom: Plastic cover sheet over the wood prevented the shrinkage and cracks while providing good adhesion for the first layer. (Source: Author)

I/O Motor control

The extruder motor was controlled using a 3d printer controller board which meant that the control was using a G-code, not an Arduino or IDE programming language. Hence, sending an On signal to the motor meant sending a certain amount of steps for the motor to spin. The Off signal then cannot be sent until the steps sent are over. In the meanwhile, the control of the motor rotation is not possible. Consequentially, Using the emergency code to stop the motor and its control board is the only option in case of errors in the print. However, it takes a few seconds to get back to the motor control online, which means it is not efficient enough to be used as on/off technique.

The motor Control by an Arduino board would have made the possibility to control the motor by an I/O signal easier. Also it could have been integrated within the program of the robot. As the robot does has an I/O plug which might be programmed as well for such cases.

The reason that the I/O is essential to control the motor and turn it on or off while printing is mainly due to the material property of shrinkage and cracks. This could be noticed as mentioned before in the material results of the cracks and how it concentrates on the material accumulation nodes Fig.77. Thus stopping the motor from extrusion at these intersection nodes or overlapping points, not only would reduce the amount of material used in the printing but also would help prevent the shrinkage and cracks caused by the material accumulation.

During the travel path of the robot, from one endpoint of a curve to the start point of another, also the material keeps flowing out of the nozzle. Which sometimes fall over the printed object, and causes imprecision as well as waste material. Shown in Fig.85 how the continuous flow of material affects also the outer surface of the print as it creates excessive material on the start points of each curve after the robot traveled from the previous end point for another curve.

Almost 30% of the mixed material to be used in the printing and fed to the cartridge are wasted because the motor is running On during all over the printing phase and not just over the programmed tool path. The amount of clay body for the last printed prototype was 17000 gm out of which 5000 gm was waste collected material. This is caused by the I/O absence at the intersections, robot travel path, and motor errors as the motor had to be working all over the process continuously.

Briefly: The lack of I/O control over the motor led to material accumulation in the intersection nodes, cracks concentration in these nodes, excessive material on the outer surface at each line start point, and finally almost 30% material waste.

For further development: I/O signal using an Arduino board or direct connection to the robot I/O digital plugs would integrate the motor control within the robot program.

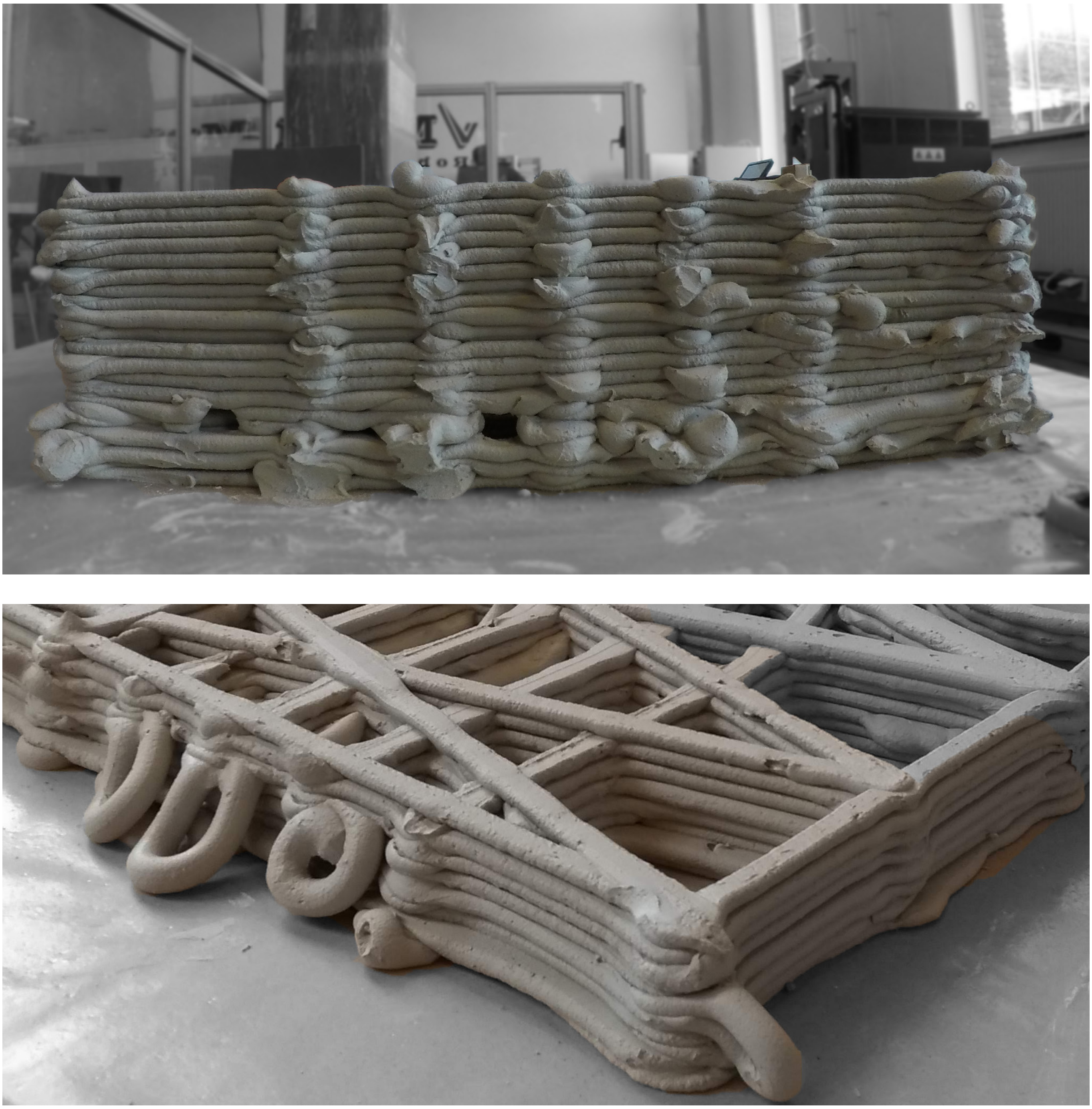


Fig.85. Excessive material on the outer surface and in the intersection nodes cause d by the lack of I/O control to turn the motor on/off while printing. (Source: Author)

Cartridge System

The used cartridge system seemed to be consuming most of the process time. The system is time-consuming because of its size limitations firstly. As the cartridge diameter used is hard to be cleaned easily by hand, it was always not easy to replace the clay mixture if the used consistency was found to be harder than required to be extruded for example. Also, The two available and used cartridge sizes were limited to extrude only two layers of the designed infilling, and they both accounted for a material initially of more than 3500 gm in total. This meant the cartridge had to be replaced off the robot and refilled again after every two layers of printing, which preoccupied most of the process time. Instead, it would have been efficient if the cartridge sizes are big enough to suit the material needed for each printed object, and hence it will be filled and refill at a reasonable pace.

Moreover, Since the used system was air pressure based, It required ensuring the airtightness of the cartridge lid. Which by default made it almost labor hard work to close and re-open it before and after each printed patch for refilling.

Considerably, also using a hose that delivers the material, from the cartridge on the robot forearm to the extruder at the wrist of the robot, it had its disadvantages. If the material is not well mixed to be vicious and fluid enough to be extruded, getting the material out of the hose was always hectic. It even led to cut it into shorter length to get rid of the stuck material within after it dried as in Fig.86. Thus it should be considered to provide a cleaning system for the hose and clearing it up once the material is replaced or after the printing is over.

Briefly: Cartridge system consumed most of the printing time in filling it, Closing & opening the airtight lid and replacing it in multiple patches because of its limited size in relation to the printed object scale.

For further development: Considering the scale of the print, the cartridge should be big enough to reduce the amount of material patches preparation.

Fig.86. Top: the hose when gets stuck with dry material is almost useless and had to be cut shorter. Bottom: The two cartridge sizes used in the material feeding which were enough only for three layers in total to print. (Source: Author)

5.3.3 Design

The design of the printed object as well affects the process in terms of its efficiency other than its possibility. This could be observed in three aspects, the material consumed, the Printing speed or time spent, and finally the cracks and its frequency. Each one of these effects is described later in terms of the infilling design and its inclined angled overhangs, as in that case, the duct inside the wall. Moreover, how the inclination angle would behave relatively to the material behaviour.

Infilling design

The infilling of the wall was described previously in chapter 4, has two specific functions, structural supports and achieving a certain U-value for the wall overall. However, this infilling also affects printing in different ways. Firstly, the amount of material consumed. The longer the tool path and the curves within the infilling, the more material required to be printed. Hence, optimising the tool path to be the least needed while achieving all the desired functionality is what should be targeted during the design process.

Additionally, the time of the printing is profoundly affected by the design of the infilling and the tool path length. As the speed of the robot and the motor extrusion will always be constant as much as possible, the longer the tool path, the more time consumed in just one layer and the overall product production. If the start and end points for the curves in order to be printed are sorted in a sequence to reduce the robot travel from the endpoint to the next start, this would be more efficient, especially in the case that the infilling is highly dense.

Lastly, as described and observed in the shrinkage results, the nodes where the infilling curves are intersecting, is mostly the nodes where the material would accumulate Fig.87. That means that these nodes will always have a high potential to be cracking nodes. As the whole body gets to dry, these nodes tend to cause cracks in the lines diverging from it. Thus, reducing these intersections will consequently, reduce the chances of cracks to happen in the final product.

Considering the material thickness would also change the way the design could be finalised. As designing the infilling in single lines does not necessarily take into account the overlapping percentage of the infilling to the layer boundaries. This boundary overlapping could be shifted, so it is reduced to be only tangent to the layer boundary. Or not fully overlapped and seen from the outer surface as seen in Fig.87.

Briefly: The infilling design affected the time and speed of the printing process due to the long tool-path consumed by the robot. Avoiding the intersection nodes as much as possible would reduce the chances of cracks. Considering the design of the overlapping to the layer outer boundary would also reduce cracks and offer better surface quality.

For further development: Developing the program and tool path to be as short as possible while achieving the required thermal and structural desired functionalities. Optimising the tool path and the robot travel points would reduce the time consumed in the process overall as well as the material wasted if the I/O is missing.

Fig.87. Top: Intersection nodes are recommended to be reduced to avoid material accumulation and cracks. Bottom: Overlapping the infilling with the layer boundary accumulates material as well and affects the outer surface quality. (Source: Author)

Overhangs

The second element of the design that might be highly affected by the material behaviour and properties is the overhangs of the designed duct. This duct have an inclination angle which shown in Fig.88. Inclination angle, in that case, was enough for the layers to build up upon each other without collapsing. The printed 20 layers did not show any intention or signs of failure and were stable enough until the structure support -as shown inFig.89- provided extra support for it to continue growing. This proved that the designed infilling had an added value in the structure and providing stability.

However, the overhangs from the outer surface in the designed prototype had an inclination angle without supports. These overhangs were not possible to be fully observed within the time of the research. Therefore it will be an interesting point for research for further research. Although the inclination angle of the inner duct, before the structure support touch or overlap with it, was higher than the angle of the outer overhangs it was stable enough to continue building up the prototype. This gives an insight of the material behaviour as a consistency that could support its self weight without collapsing.

Briefly: The overhangs angle was enough for the stability and buildup of the inner duct. While providing structure supports in the infilling design also offers a higher degree of stability.

For further development: Exploring the overhangs in different angles to get to the maximum possible angle within the used clay mixture and the water to powder percentage.

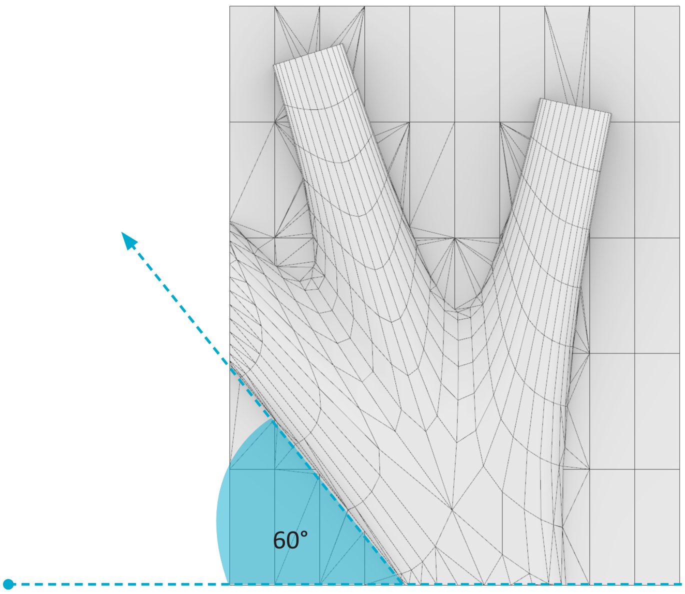


Fig.88. The angle used in the overhangs, 60°, is enough to be stable with and without structure supports.
(Source: Author)

Fig.89. Top: The overhang of the duct has an angle which is enough to be supported without any structure supports. Bottom: Overlapping structure supports meets the duct at certain point and provide extra supports for it to be stable. (Source: Author)

5.3.4 Final Print

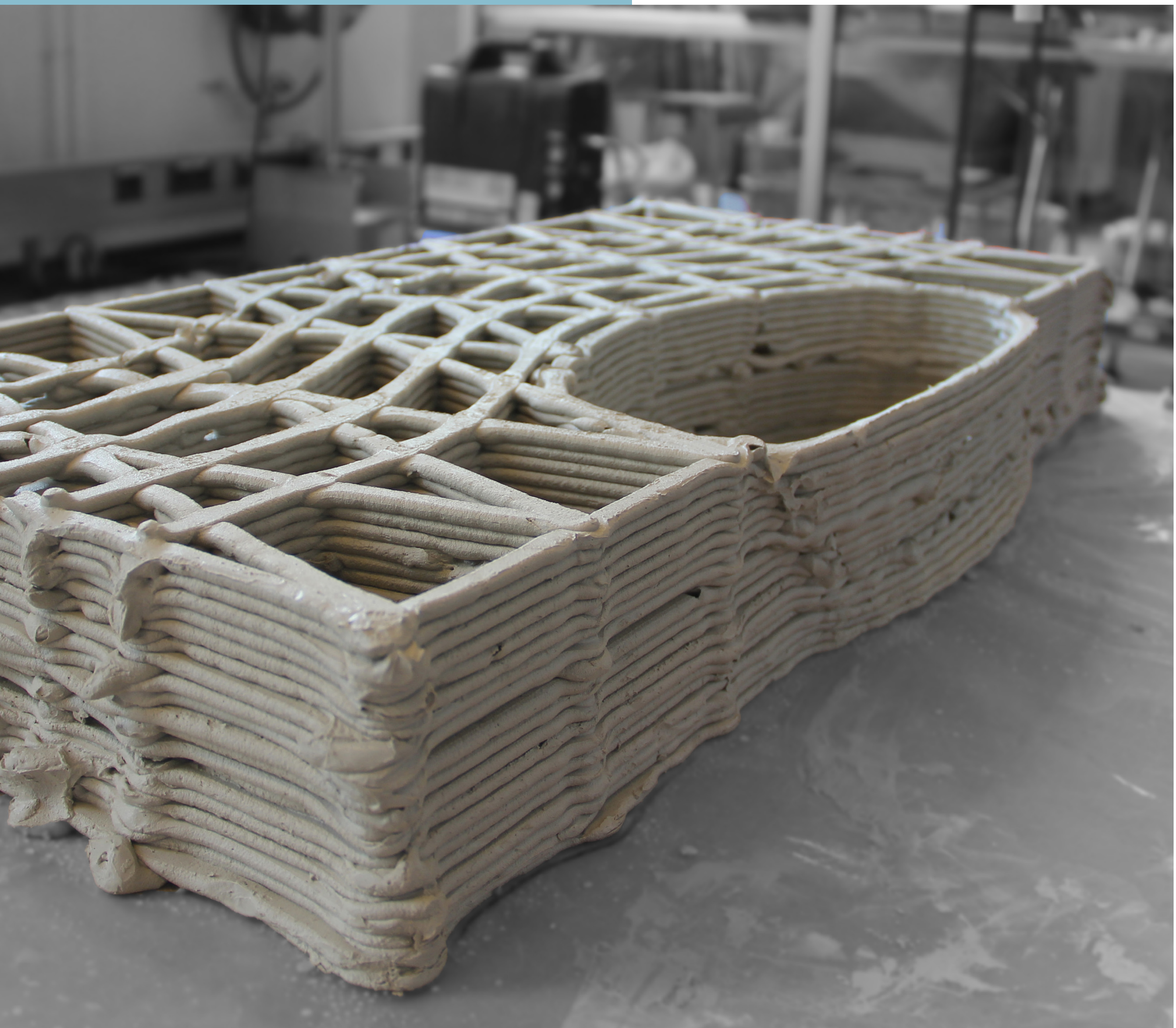
The final print was:

- Number of layers: 20 successive layers.
- Dimensions of the linear sides : 70 cm length, 30 cm width and 10 cm height.
- Total tool path length: 246 m

- Total material mixed: 17 Kg
- Model weight: 12 Kg
- Waste material: 5 Kg
- Waste ratio: 30%

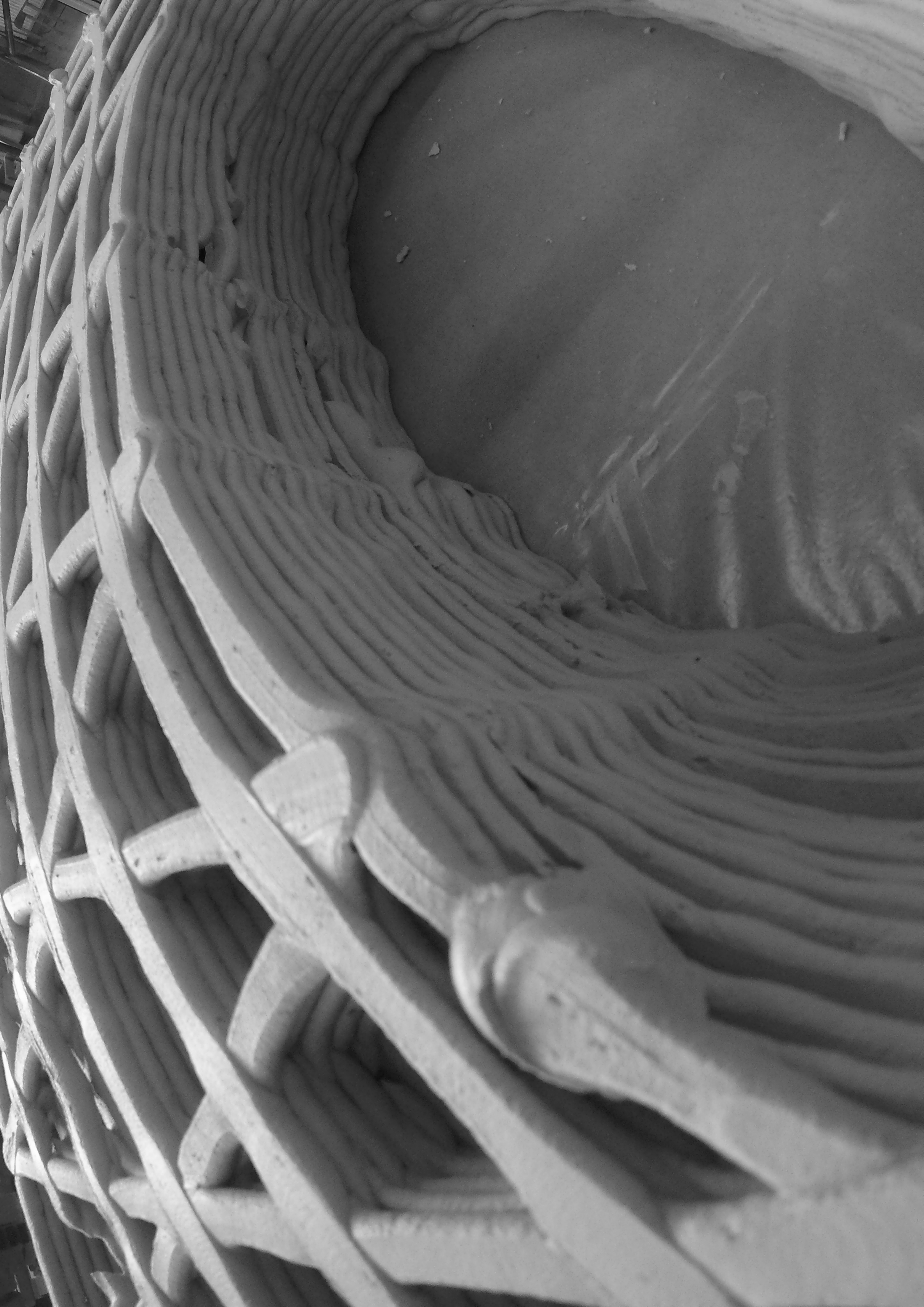
Material consumed over the printing research:

- 47 Kg Total material
- 25 Kg Stoneware clay
- 3 Kg Earthenware clay
- 7.5 Kg Chammote 0-0.2 mm
- 2.5 Kg Gypsum
- 12 Kg Water



6 CONCLUSIONS

This chapter not only cocnludes the research results and frame work, but also it introduces a design guide for easier and more concise replication of the 3d printing process. It also introduces the recommended automation of the process before narrating the limitations faced the research and what could to be further developed and studied.



6.1 Design Guide

To Sum up and link all the aforementioned process results in the previous chapter, a design guide is proposed in Fig.90 & 91. This design guide shows the process that already existed and used in this research as in Fig.90. Each element of the process is summarized in terms of the requirements for better quality, as well as in terms of its effects on the process. Following, in Fig.91 a proposed automated process that could further develop the printing at large scale. This automation is reasoned in Fig.92 in the conclusion while describing the interlinking and integration of the different input and objectives elements.

It is essential to mention that this design guide and its recommendations are from the perspective of this research objective and requirements. Hence, all the recommendations might be efficient enough for some purposes and not for others outside the scope of this research.

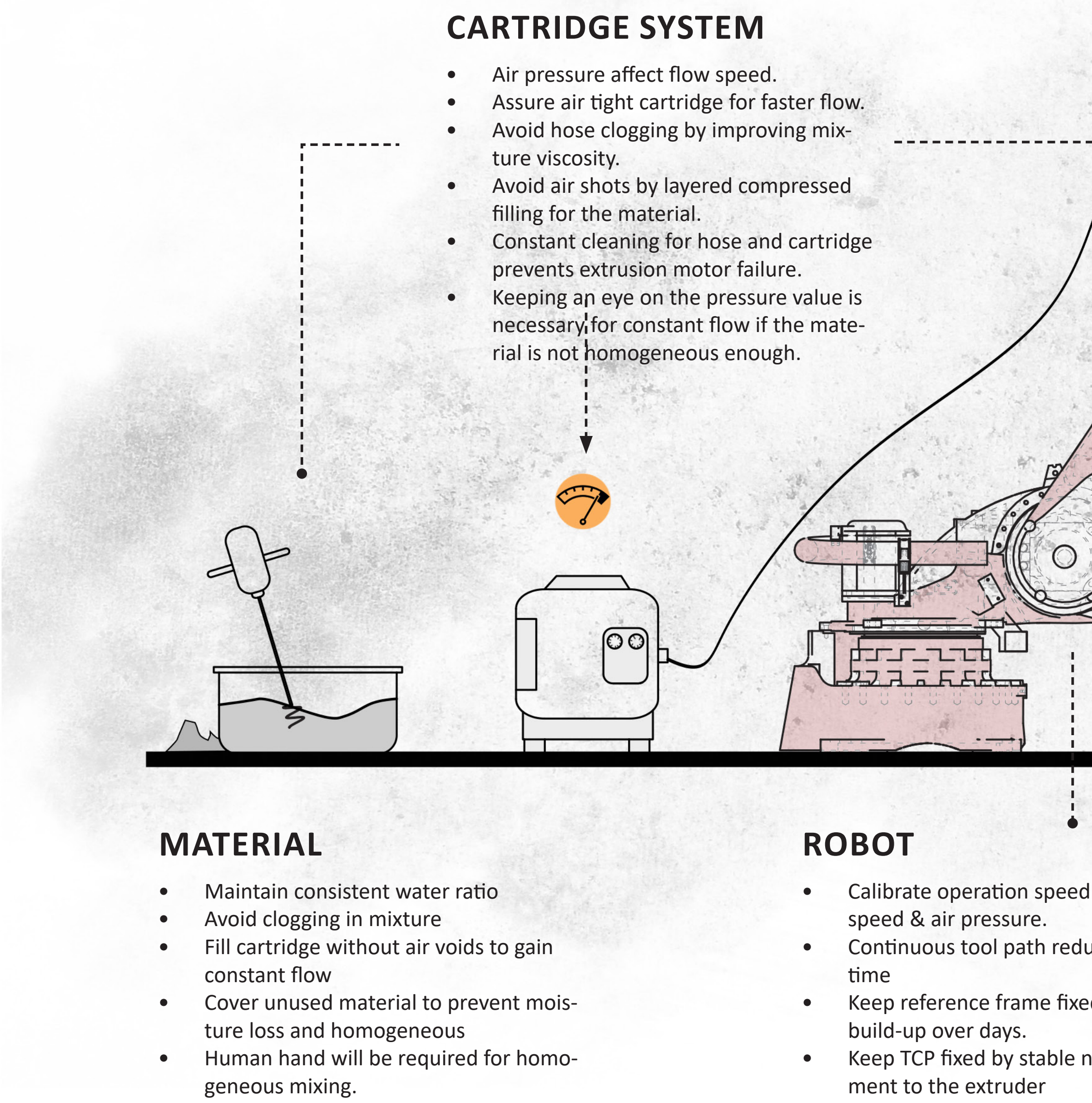
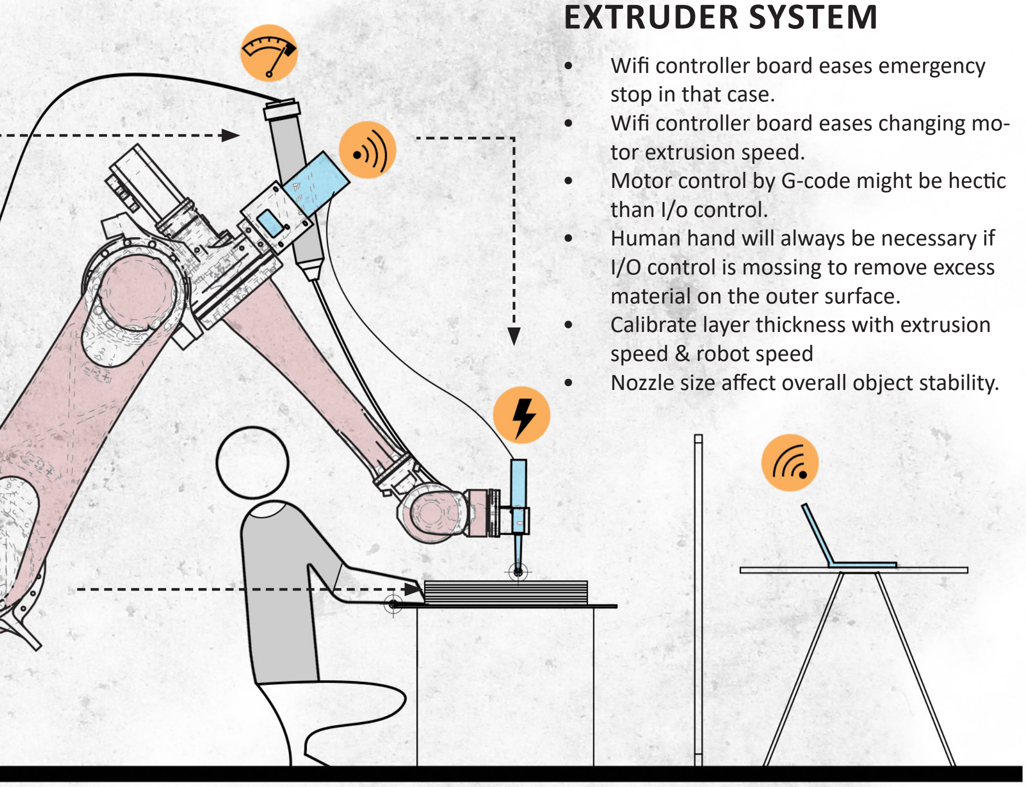


Fig.90. A summary for the clay printing process and th



EXTRUDER SYSTEM

- Wifi controller board eases emergency stop in that case.
- Wifi controller board eases changing motor extrusion speed.
- Motor control by G-code might be hectic than I/o control.
- Human hand will always be necessary if I/O control is mossing to remove excess material on the outer surface.
- Calibrate layer thickness with extrusion speed & robot speed
- Nozzle size affect overall object stability.

to Extrusion

ces travel

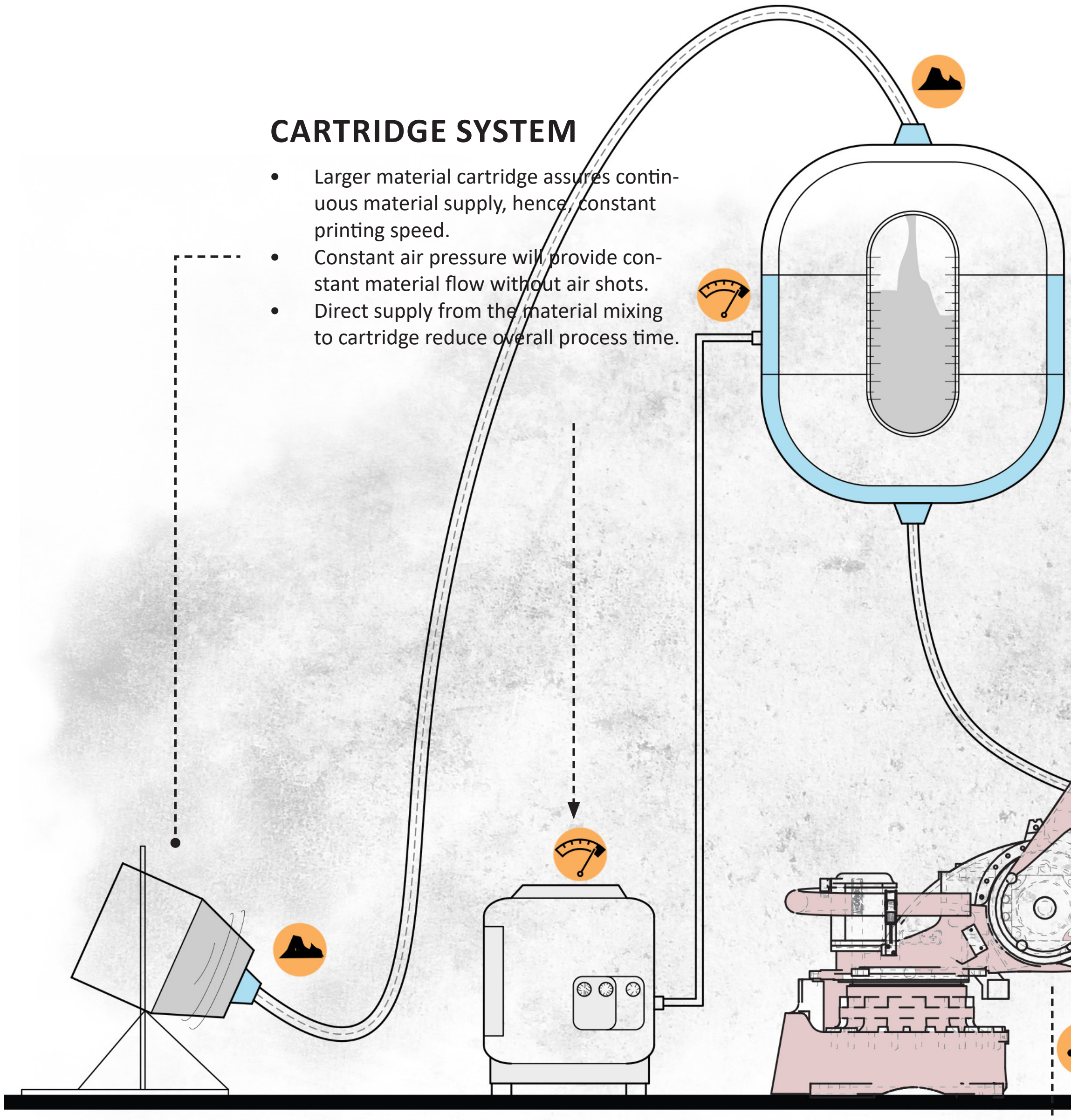
d for precise

ozzle attach-

DESIGN

- Avoid overlaps & intersections for infilling to reduce cracks & shrinkage.
- Tangent or half overlapped infill over the outer surface, gives better surface quality.
- Overhangs should be supported by infilling.
- Expect imprecision due to shrinkage, if not printed once.

e important notes to be considered. (Source: Author)



CARTRIDGE SYSTEM

- Larger material cartridge assures contin-uous material supply, hence, constant printing speed.
- Constant air pressure will provide con-stant material flow without air shots.
- Direct supply from the material mixing to cartridge reduce overall process time.

MATERIAL

- Automated mixing for the material pro-vides homogeneous consistency.
- Standardized mixture rates in accor-dance with the supply rate will create better flow and printing quality.

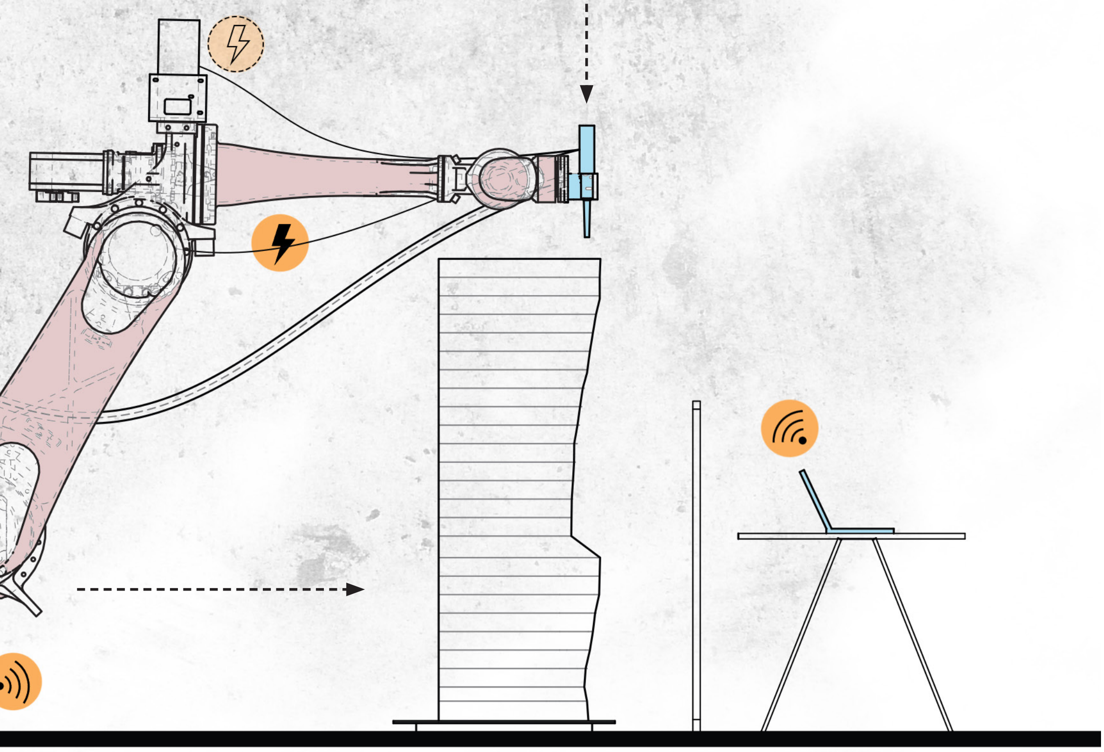
ROBOT

- Wifi control to ease progra
and overriding.
- Utilization of the 6 axis po
exploring the printing of d
surfaces.

Fig.91. Proposed Automated process in an exagge

EXTRUDER SYSTEM

- I/O connection from robot to extruder motor for better tool path and design coordination.
- Separate power supply could still be present for emergency stop.
- Higher torque motor will allow bigger nozzle sizes and hence bigger scale printing.



DESIGN

- Optimized tool path in relation to infill and layer design reduces cracks, material consumption and printing time.

am loading

ssibilities by
ouble curved

rated illustration for clarification. (Source: Author)

6.2 Conclusion

This research aimed at answering the main question of “What are the printing techniques and tools that can help integrate the clay as an environmentally friendly material, into the 3d printing of building components, while maintaining the required indoor and outdoor performance quality?” Therefore, the research had four main aspects that were explored to further develop this printing process. . These are symbolized in the acronym CREW, representing Clay as the material explored, Robot as the programmed and digital workflow, Extruder system as hardware setup, and eventually, Wall component as a case study for the prototyping of complex geometry.

Firstly, finding the suitable clay type was decided based on a literature review. Stoneware clay was chosen as the main powder in the research due to its suitable architectural properties. Once the material was chosen, material experiments were conducted to find the best material mixture suitable for the building component. Seven organic and natural materials were tested as additives to clay and observed for their suitability for extrusion and pre-printing behaviour. Finally, the mixture of clay, gypsum and chammote was considered the best in its performance. Not only in terms of shrinkage and fewer cracks but also for its printability speed and low weight loss. Hence this mixture was introduced into the printing process as the clay body for the large scale prototyping.

Secondly, the design of the wall component was based on research about the HVAC system and especially, displacement ventilation. It was found that a displacement ventilation duct system could be rather naturally integrated into building components as facade walls. Thus, a ventilation system was designed according to the conventional design techniques firstly and evaluation criteria was decided for verification of the final design. Afterwards, a complex shaped ventilation system was generated based on the design criteria. CFD simulations were conducted using Ansys Fluent software to verify the flow resistance of duct system geometry. The final geometry generated showed very satisfying values in terms of pressure drop and the distribution of outlet flow rate.

Thirdly, the generated geometry from Grasshopper and verified by CFD analysis, was the base for the digital workflow for prototyping. A portion of the designed wall ventilation system was considered for 1:1 scale prototyping and exploration. For that, the digital workflow to prototype consisted of three phases. Starting by the slicing and infill design. The infilling integrated structural supports for the successive layers, as well as the ducts overhangs. It also bears the thermal design performance required for the wall component within the selected climate context (Seville, Spain). Multiple options were explored, and eventually, one design technique was decided to fit within the infilling prototyped.

Subsequently, once the infilling was designed, the robot program was generated using RoboDK offline programming tool. Linking the Grasshopper & Rhino environment eased the workflow for sorting the tool path curves and layers for in order for program generation.

Lastly, the hardware and setup for 3d printing using the robotic arm were in parallel being prepared. The combined setup of the robotic arm the extrusion system required much calibration in order to acquire the desired final product quality. The extruder system included an extrusion motor whose speed was adjusted to match the robot arm movement speed. Additionally, the right value for the air pressure system to feed the material from the cartridge system to the extrusion was adjusted. Other elements that affected the printed products such as the printing bed and the absence of a microcontroller for the motor were considered as points that requires more research than feasible within the limited time available for this project.

It can be concluded that clay as a printing material for building components at large scale does have potentials to be further developed. However, the process setup and preparation require a huge amount of automation to assure better quality than what could be generated within the limits of this research and its available tools. Clay 3d printing is a very integrative process, as it is the case for other digital fabrication and CAM tools, illustrated by the interlinking between process requirements and design considerations in Fig.92.

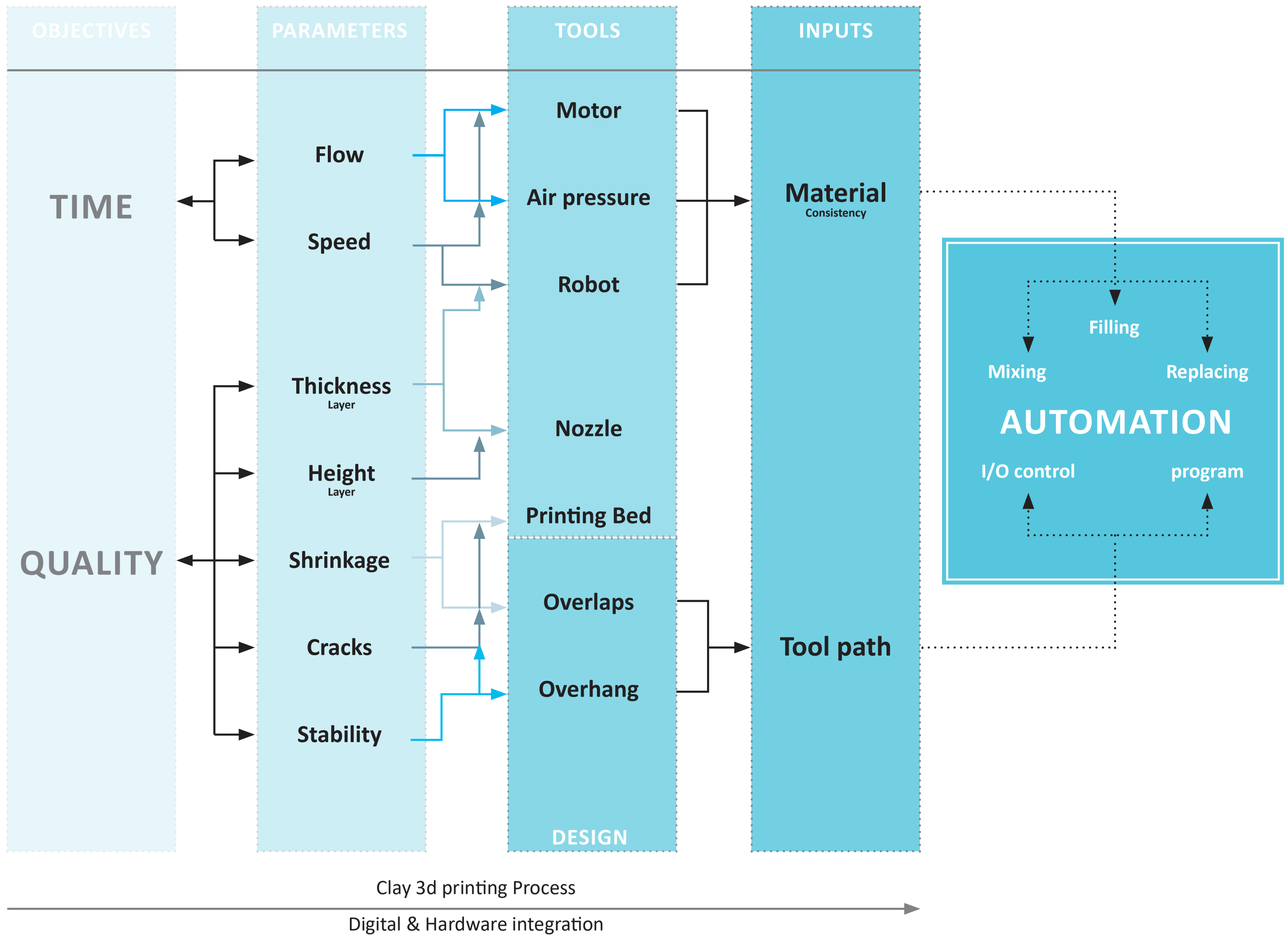


Fig.92. Integrative digital fabrication process by clay, where the objectives are dependent on tools & design simultaneously. Automation as a recommendation is proposed. (Source: Author)

6.3 Limitations

This research context had some limitation factors, both software-wise and hardware-wise. These limitations might affect the results of the research if met in another context, and most of the proposed and recommended aspects might differ accordingly.

Firstly, the digital aspects were affected in the CFD simulation in the beginning. Since Ansys Fluent has a limited amount of elements to be analysed for the academic software license which was up to 512,000 elements in maximum. A larger number of elements might have provided higher accuracy in the calculations for the flow field and pressure drop. Hence, this might affect the resultant final geometry.

Additionally, a software limitation is observed in the extruder motor control. Due to the lack of I/O control to the motor in the process, the final product is affected by unnecessary accumulation of the material in the nodes. Only the starting points for solving this and achieving the I/O could be investigated.

Secondly, in terms of the tools and hardware. The material aspect was one significant and essential element that might affect the resultant product remarkably. This might be in the material mixing procedure, where the mixing had to be manually done, even after using the electric mixer as mentioned before. This resulted in a non-fully homogenous consistency for the material used. This consistency also differed from one patch of the mixed body to the other. Automating this process might lead to much better and more accurate results.

Also, regarding the material, filling or feeding the cartridge is affected by the manual filling and compression using a spatula. Replacing this by a pre-pressurized material body that is fed equally in each patch to the cartridge, would result in better quality as well. However, the material experiment's limitations are explicitly mentioned as elaborated in the material experiments chapter.

Moreover, the cartridge sizes available for feeding the material limited the printing time and speed. As filling the material and mixing it consumed much time from the extrusion process overall. It was not entirely possible to estimate the time consumed for the printing due to variable clay body mixture patches.

Finally, the drying conditions for the printed object might also affect the resultant prototype. The room temperature and humidity level might have varied during the printing days. This should be part of more precise material research about such a printing process with such a material.

6.4 Further research

Since the objective of the research and its context are relatively new, many aspects and factors could be explored and implemented in a further research and development process.

Starting by the Ventilation system as a building product, its unconventional way of distributing the air by asymmetrical and complex geometry requires further development. The optimisation of the morphology could be investigated to get the least pressure drop and the highest energy efficiency. Keeping in mind that the resultant geometry will be 3d printed, which overcomes its complexity in terms of production. Moreover, the geometry could be studied not as a single unit but as a network of air supply and ventilation system over the building's facade. This might be more interesting for facade and mechanical engineers.

Secondly, automating the printing process in terms of the hardware and tools related to the material. This might lead to better mixing quality for the clay mixture to prevent clogging and crumbling behaviour. Also, if the refilling of the cartridge is automated, it will assure better flow and continuous layer extrusion. Hence, better printing quality is achieved. Last, but not least, replacing the empty cartridges and having an extra material supply will assure the continuity of the printing process. This continuity might reduce the time consumed and increase the amount of production per day or per material patch as well.

Lastly, integrating an I/O signals to the robot program to control the extrusion motor at specific points and nodes of the design. By controlling the extrusion motor, it would reduce the amount of wasted material, reduce the shrinkage and cracks as mentioned before, and also will help creating better outer surface quality.

Similarly, optimising the tool path in terms of its length and lines printing order would also reduce the amount of material and time consumption.

Other interesting points for research in terms of the printing control also might be related to the effect of the speed of the motor and robot on the printed layers. Researching the speed effect on the layer width as well as the structural stability of the product. Even more, the influence of the water amount in the clay body on the shrinkage and cracks. Therefore, optimising the material mixture for the least shrinkage and cracks.

6.5 Reflection

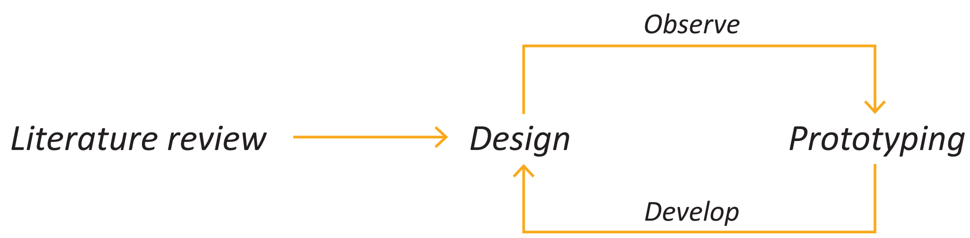
6.5.1 Relationship between Research & design

The main objective of this research was to answer the question of:
"What are the printing techniques and tools that can help integrate the clay as an environmentally friendly material, into the 3d printing of building components,while maintaining the required indoor and outdoor performance quality?". This required dividing the research into four main aspects, firstly the explored material, clay. Secondly, ventilation systems and their effect on the indoor quality. Then, the design and generation of a facade wall that integrates the ventilation system. And lastly, the robotic printing where prototyping is exploring the effects of the process limitations on the design process.

Hence, the research had three major approaches where two of them were sequential in the first period of the project. Starting with literature review which was providing the base for each aspect of the previously mentioned research aspects. Then, the digital design where the literature concluded results were used to generate the design and verify it. Lastly, the prototyping and making iteratively informing and informed by the design requirements that are based on the literature review.

To be more specific, literature review informed the material choice of what type of clay suits the architecture applications and its properties. That choice affected the calculations for designing the ventilation system according to the thermal resistivity and conductivity of the material as the thermal performance in a facade. While, in the same time literature review was conducted for the ventilation system calculations and their verifications. This designed ventilations system generated the wall morphology which then was detailed in respect to the requirements of the prototyping and building process.

In brief, the research by design and design by research where both implemented in this project and differentiated from the first period of the project to the last ones. This showed how relevant each step of an architectural product is to the available production techniques.



6.5.2 Relationship between graduation topic & studio theme.

Named "Sustainable graduation studio" the main theme of the graduation studio in building technology program is the sustainability and its integration within the architecture applications. Sustainability was integrated and could be observed in this research in the three main points of the material, production technique and integrated ventilation system. Firstly, the base for the research is exploring a sustainable and environment friendly alternative material within the architectural new fabrication technologies. This material is bio-degradable and the resultant product can has an end of life back to the same place where it was extracted from as a primary material. In addition, additive manufacturing or 3d printing as an explored technology and fabrication technique, it was promoted in this research as a better sustainable solution for the complex geometries production. As 3d printing has less wasted material than in -for example- molding or CNC cutting techniques. Lastly, the chosen designed and integrated function within the printed product is the displacement ventilation system. This kind of ventilation consumes less energy than the conventional mixing ventilation while also insures better indoor air quality.

To summarize, the sustainability aspect was the main drive or the core of this research project and achieving it was the real challenge.

6.5.3 Relationship between graduation methodology & graduation studio method

According to the requirements of the graduation studio and the building technology track for a master thesis to be integrating two at least of the chairs of structure design , facade design, building physics or design informatics. The latest two chairs were integrated in this project in which design informatics is designing and verifying the building physics requirements. While prototyping it and exploring the effect of the production limitations on the design requirements.

However, this research goes also further to explore the sustainable material clay, which is less researched or explored in the architecture new fabrication context yet. The honors master program research was integrated to represent a main part of the thesis project where the material is being explored and material experiments were conducted to conclude a final recipe for clay to be used in the thesis research prototyping. Integrating material science, design informatics, and building physics enhances the interdisciplinary approach recommended by the graduation studio.

6.5.4 Relationship to the wider social framework

Societal Relevance

Being an affordable material and low cost, clay represents a promising building material that suits the current economical approaches where there is a need for more affordable housing for more people in need. Pushing the limits of this material by research and continuous innovation, introduces the community to a better sustainable affordable material. Moreover, the research emerges from the sense of the social responsibility for architects towards the sustainability of the built environment. As architect's decision on a certain material or system to be used in his design has an effect on the environment, not only as a building operation performance but even more on the embodied energy within these materials and systems. Consequently, by promoting the clay as an environmentally friendly and affordable material helps to reduce the footprint of the buildings. Not to mention also that pushing the boundaries of the large-scale 3d printing - especially with such a sustainable material- helps the continuous development of environment-oriented performative designs and more sustainable architecture.

On the other hand, designing a displacement ventilation system provides more exposure for that kind of ventilation which assures more indoor quality to the users of the buildings. In addition, it consumes less energy which reduces the operation costs, energy and footprint of the building over its lifetime.

This investigation of clay and displacement ventilation helps in changing the way we observe these less exposed and used materials or systems even though they have high potential for the community and the environment in parallel.

For that social responsibility for architects lies not only in building interaction with society, but rather more the integration with the whole environment.

Scientific Relevance

Further development in the growing field of digital fabrication in architecture is considered one of this research's objectives. Since the field of digital fabrication in architecture is still relatively new, introducing sustainable materials into it enhances the possibilities of future developments that are more sustainability oriented. The research might introduce a reference for those who are interested in the sustainable materials -clay specifically- in additive manufacturing. Unfortunately, resources about clay as a printing material or even as an architectural material and its thermal properties or performance, these resources were very few to be found. Therefore, this research might help in giving insights on its performance in terms of printability and properties while adding to its referenced knowledge and documented data.

TU Delft Relevance

Due to the growing interest in clay and earth materials in the design informatics chair, a new extruder for clay was provided recently. Previous research on earth extrusion was conducted by Tommaso Venturini, and a new masters course "Earthy" for digital optimization of the clay and earth related building designs is introduced. Thus, this research by using and operating the clay extruder for the first time will provide a good base reference and data for the possible future clay printing related research projects. This also assures that this will help to continue developing clay as an environment friendly material. Even further innovate more on the alternative materials to concrete to help shape a better sustainable built environment.

6.5.5 Ethical relationships to the graduation topic

The main ethical dilemma in every project that implements or using robots in architecture scale or production industry is always how is it expected to affect the human labor in the future? This integration of robots according to some opinions- on one hand- will create more un-employment not only in the building production industry but in general. On the other hand, different perspective argues that the development of technology always shifts the jobs into another level of instead of removing it in general too. This means that as for every machine that always had been made, workers had to move to a different level of jobs within the same field or even within a different related field. Also, by replacing humans tasks which requires repetition or hard labor work, replacing by robots or machines has always helped in the development of the civilization. This is by integrating more minds in the process of innovating and creating instead of hard laboring.

Lastly, the dilemma of whether we should replace concrete by clay or other materials or should we only reduce it? This argument is based on the fact that concrete has a very strong potential structurally, and so far there is no other material that can replace it, hence, ignoring clay or not would not make a difference. This can be argued against by clarifying that we didn't find a sustainable alternative till now because there is less action or interest to actually find it. Moreover, if concrete is highly performative in structure, it would be wise to not use it in all architecture applications that might not require this high structural properties and rather explore the other sustainable materials as clay and how to implement them in these non structural products.

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APPENDICES

Appendices

App.1

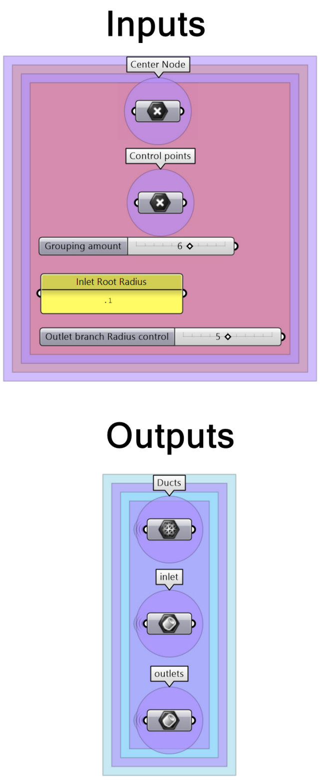
Phase	Material	Function	Constants								
			Layer Height mm	Nozzle size mm	Flow | Extruder speed mm/s	Observation time H	Number of layers	Air Pressure bar	Clay weight gm	Water gm	Add
Clay Body	Stoneware - KP101	Main clay body	-	5	400	-	-	6	500	125	
			-	5	400	-	-	6	500	150	
			5	5	400	24 -48 H	6	6	500	175	
			-	5	400	-	-	6	500	200	
Solo - Additives	Chammote 0 - 0.2 mm	less shrinkage - less cracks - surface hardness	5	5	400	24 -48 H	7	5-6 bar	300	110	1
	Gypsum	less shrinkage - less drying time	4	5	800	24 -48 H	4	5-6 bar	300	95.7	3
	Saw dust	Better density - less cracks	4	5	400	24 -48 H	5	5-6 bar	300	100	1
	Wheat	less shrinkage - less cracks - better binding	4	5	800	24 -48 H	3	5-6 bar	300	140	3
	Water glass(Sodium Silicate)	dispersant - less shrinkage - better viscosity	4	5	400	24 -48 H	5	5-6 bar	410	127.1	.25
	Chammote 0 - 1 mm	less shrinkage - less cracks - surface hardness	-	5	400	24 -48 H	-	5-6 bar	300	110	1
	Gelatin	better strength (Binding) - better viscosity	-	5	400	24 -48 H	-	5-6 bar	300	86.5	1
Mix - Additives	cham0.2+gypsum	chamotte 0.2 mm	4	5	400	24 -48 H	4	5-6 bar	250	105	7
		gypsum									2
	cham0.2+saw dust	chamotte 0.2 mm	4	5	400	24 -48 H	7	5-6 bar	250	114	7
		Saw dust									12

Fig.93. Material experiments results, blue shaded cells ar
resultant values.

Variables																
Controled					Observation											
itive	Additive %	Water % of clay	Water % of total body	Additive rec. %	before (sample + plate weight)	after (sample + plate weight)	sample weight	sample weight loss %	Ball weight loss %	average weight loss	Flow rate gm/s	Shrinkage % 24 H	Plasticity 1:5	Cracking 0-4	Line continuity 1:5	Building Speed Layer/minute
-	-	25%	25%	25-30%				-	-	-		-	1	-	-	-
-	-	30%	30%	25-30%				-	-	-	-	-	1	-	-	-
-	-	35%	35%	25-30%				-	220	-	-	11%	3	0	4	
-	-	40%	40%	25-30%	-	-	-	-	-	-	-	-	5	-	-	-
00	33.4	37%	27.50%	20 - 40	1000	952	270	17.8	14.3	16.05	8	4.6	4	1	4	0.21
30	10	32%	29.00%	10 W	928	892	198	18.2	18.2	18.2	10.5	7.2	3	0	4	0.27
15	5	33%	32.00%	N/A	926	888	196	19.4	21.5	20.45	9.8	6.3	4	1	3	0.25
30	10	46.50%	42.50%	6 - 20 W	860	832	130	21.6	27.5	24.55	3.9	8.1	2	3	2	-
cap	-	31%	31%	5%	-	-	-	-	16.7	-	-	8.4	3	0	5	0.84
00	33.4	37%	27.50%	20 - 40	-	-	-	-	18.5	-	-	4.6	-	-	-	-
15	5	29.00%	27.50%	3 - 5	-	-	-				-	-	1	-	1	-
75	30%	42%	30%	-	934	890	204	21.6	9.4	15.5	18.6	7.3	3	0	3	0.4
25	10%			-												
75	30%	46.50%	34%	-	1014	952	284	21.9	8.2	15.05	14.2	4.6	2	0	3	0.35
2.5	5%			-												

re the constants, Yellow shaded are the variables and the
(Source: Author)

App.2



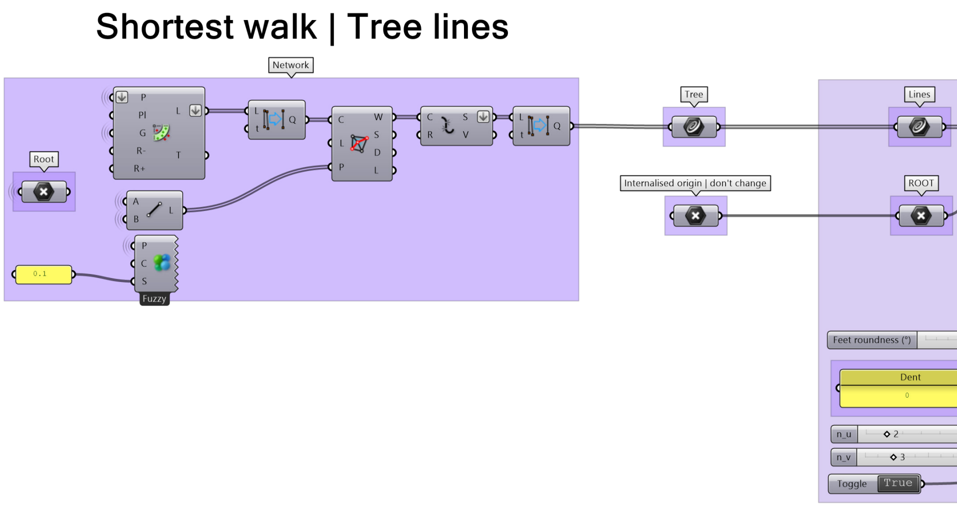
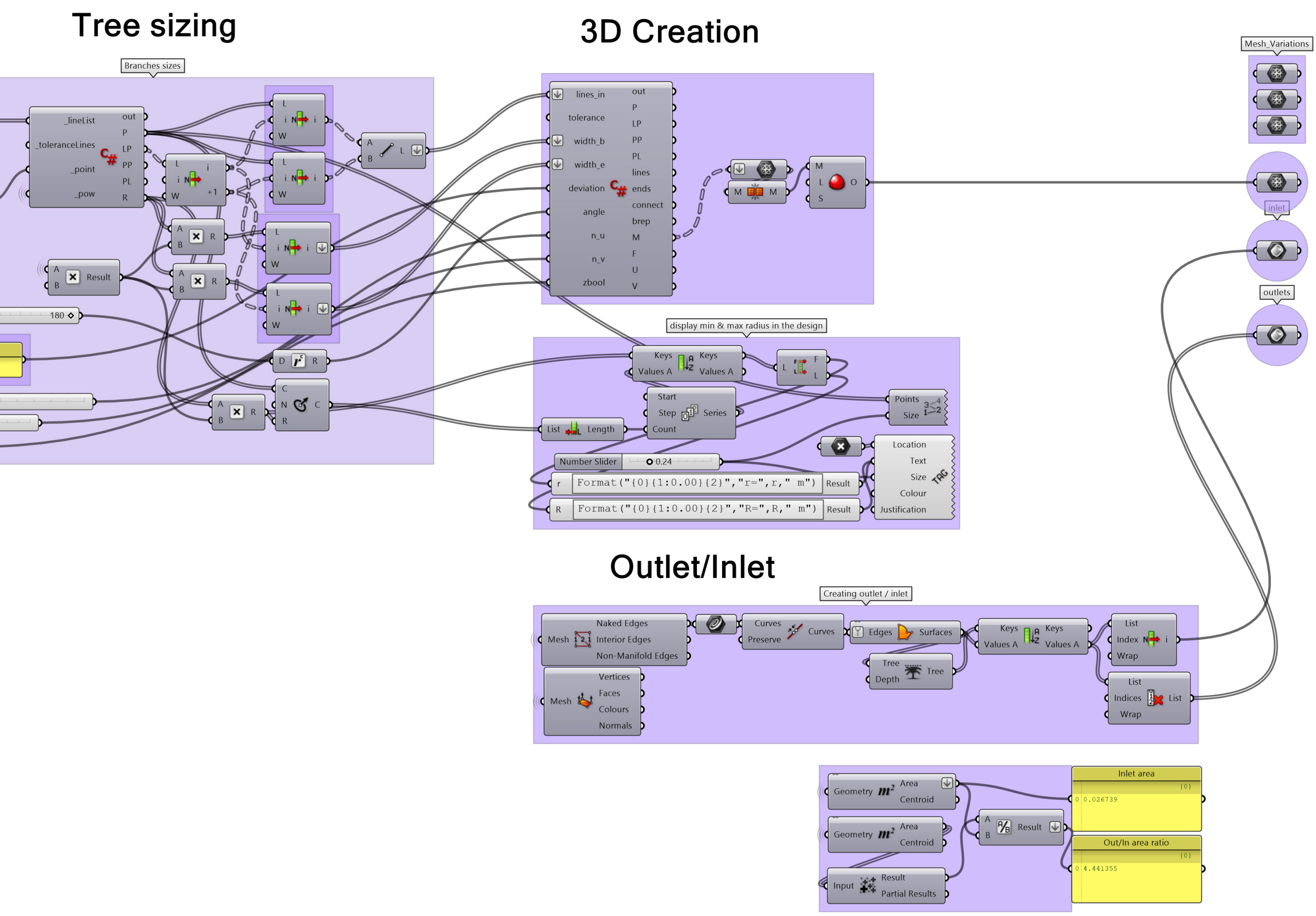


Fig.94. Grasshopper script for generating the v



entilation ducts morphology. (Source: Author)

App.3

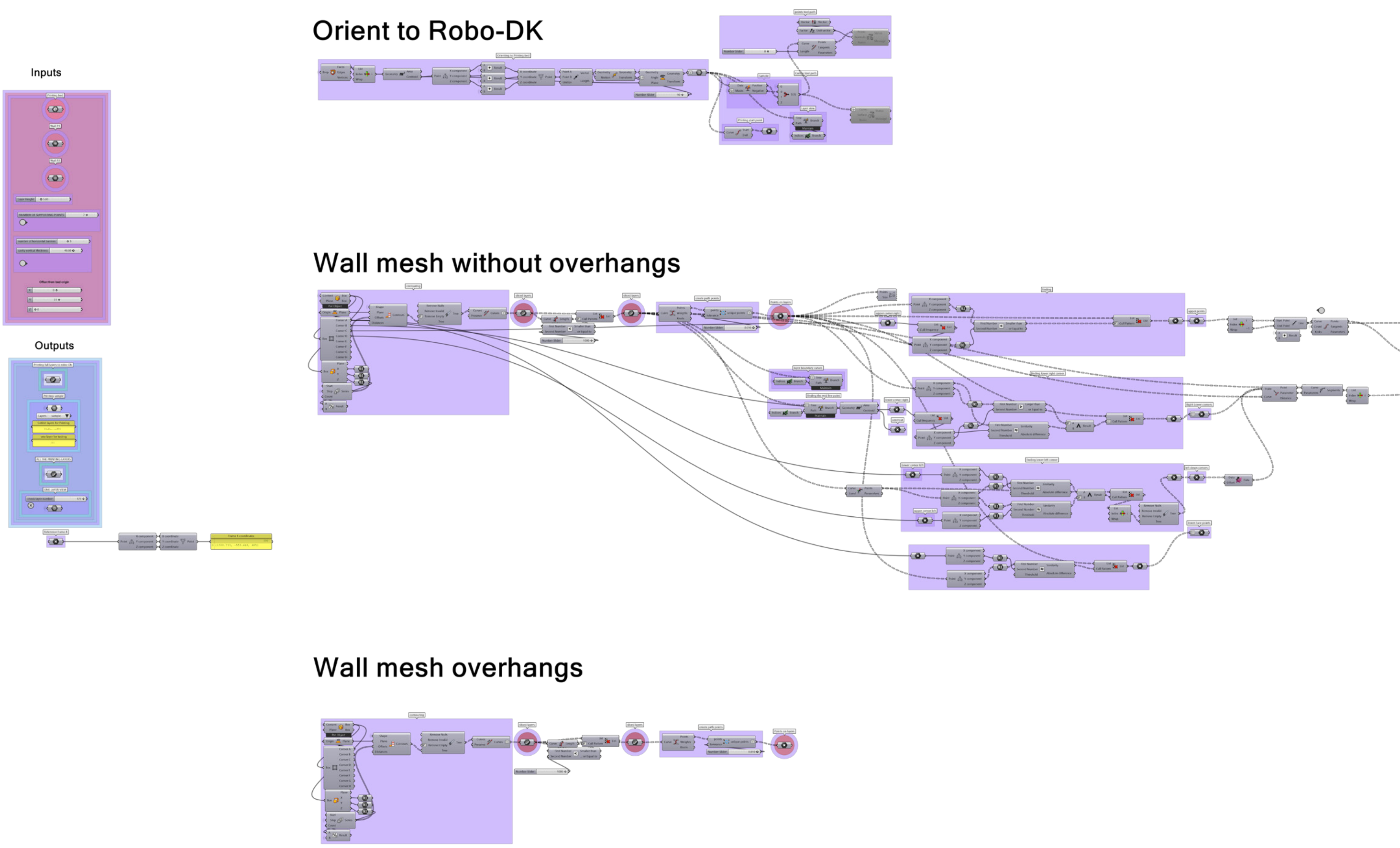
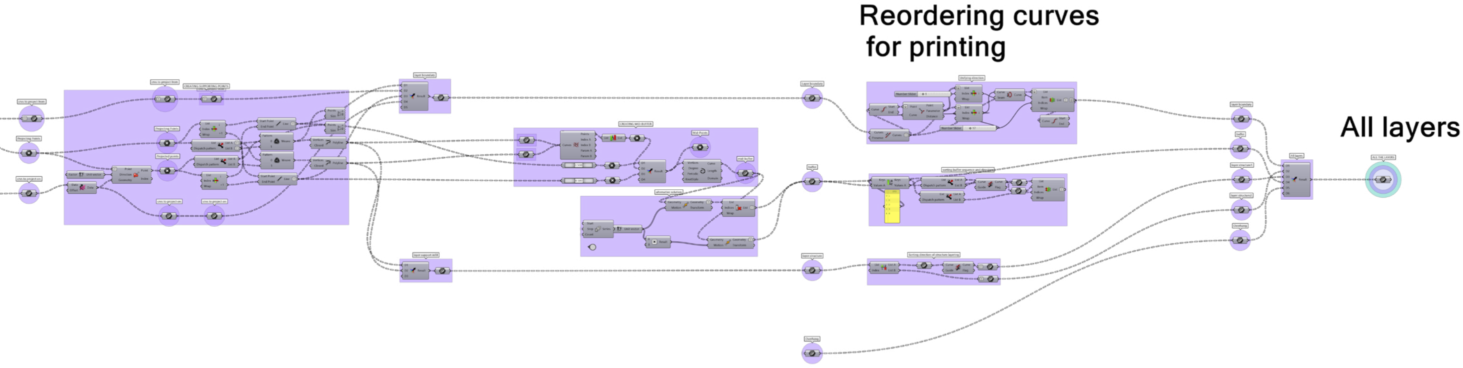


Fig.95. Grasshopper script for generating the layers, its i
robot program. (



nfilling desing, and the link to RoboDK for generating the
(Source: Author)