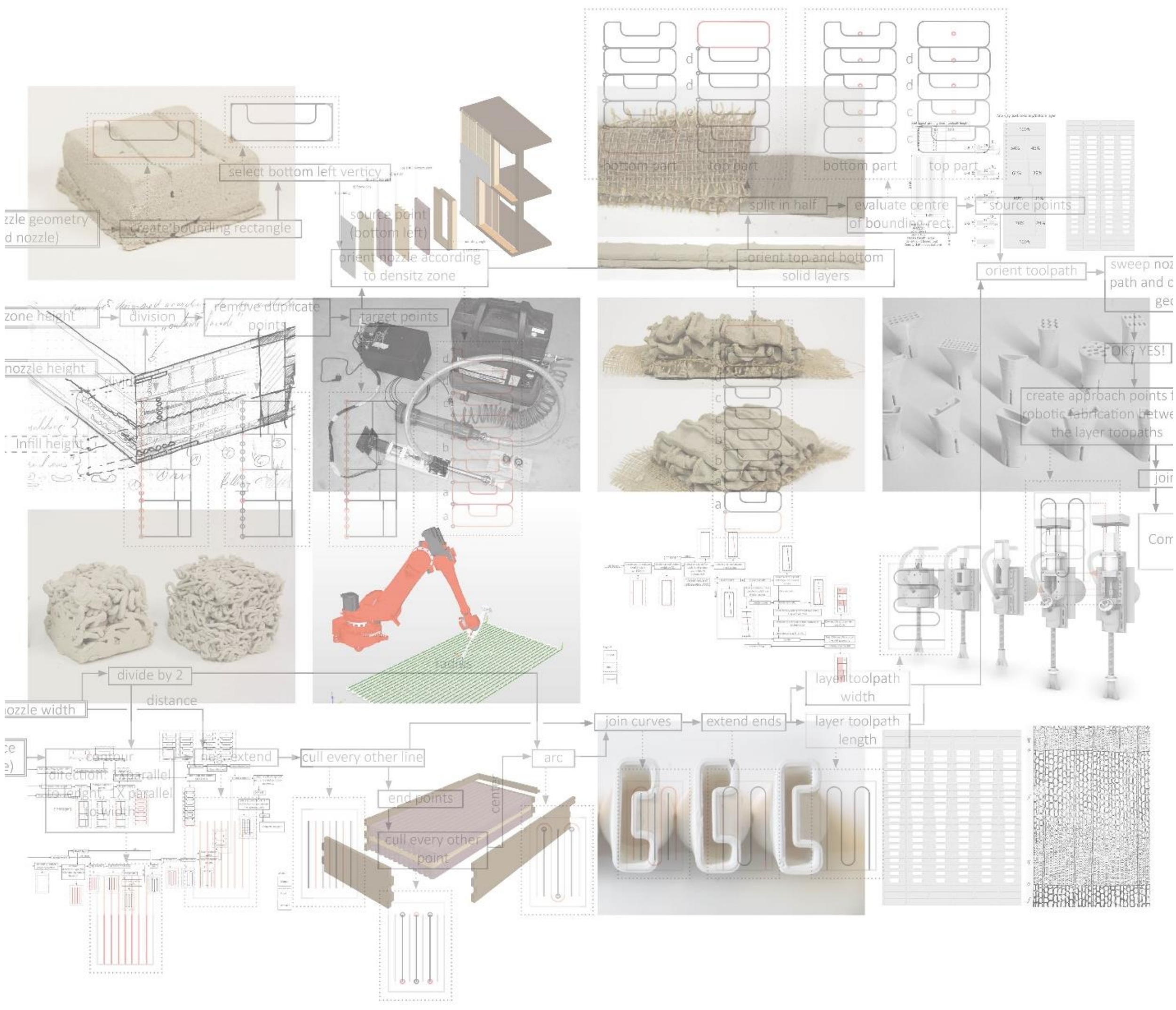
MSc Architecture, Urbanism & Building Sciences
Building Technology Track

Robotic 3DPrinting Earth

Earthen additive manufacturing with customized nozzles to create a gradient material for on-demand performance.



P2 Graduation Plan by Maximilian Mandat 2020

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Robotic **3DP**rinting **E**arth

Earthen additive manufacturing with customized nozzles to create a gradient material for on-demand performance.

Delft, 15.01.20

Graduation Plan Report

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Terms and definitions

AM - additive manufacturing
3DP - 3-dimensional printing
3DPE - 3-dimensional printing earth
LAMA- Laboratory for additive manufacturing, faculty of architecture, TU Delft
FGT- functionally graded material

Digital tools:

RN- 3D CAD software: Rhinoceros
GH - Grasshopper, a Plugin for rhinoceros
AR- Arduino: Software for the extruder control
RDK- RoboDK: Software for robot control , connected with Arduino

Measurements:

r = radius
t = wall thickness

1) Research framework

1.1. Background

Circularity

Due to a limited Planet and an increasing use of resources we face the necessity of a circular economy. That requires fundamental changes in all industries and leads to new approaches in design and production. Rising awareness for the environment helped the so-called sustainable architecture shift from a former niche to a establishes form of design. But what defines sustainable architecture? Is it, its integrated design, the used materials, location and orientation of the building or its energy performance? There are many more factors that influence the co2 equivalent footprint of a building. The used materials influence the footprint of a new construction largely. The embodied energy, the reusability and recyclability of materials and building components is determining the overall carbon emissions and the circularity of a future build project. The chosen construction material can change the footprint from large to negative by almost similar appearance. Especially if the used materials can be easily recycled or reused, we come closer to the goal of creating a circular material flow. Although the paradox of using an almost infinitely available material, as earth is, does not implicit require a circular material flow – but allows it certainly.

Digitalisation and production techniques

Conventional production methods in the building industry are changing. The digitalisation or industry 4.0 is a societal and political reality that will have a huge impact on all existing branches as well as the building sector. It enables informative workflows in which design and production are an integrated process. Compared to conventional production techniques where those are separated phases the digitalisation offers high potential for material reduction, shape and design optimisation. All this helps to achieve an overall integrated design. One promising emerging technology of the industrial revolution 4.0 is additive manufacturing, commonly known as 3D-printing (3DP). Elements with complex geometries to increase their performance can be produced without any formwork. Shape optimisation, form finding, or functional gradation leads to strong and relative light-weight building components. Especially for prefabrication robotic 3DP offers many opportunities and unleashes multiple new potentials while reducing the amount of required labour.

Reviving traditional construction techniques with digital fabrication

The optimization of production and planning methods that the digitalisation offers is mostly wrongly considered as the enemy of traditional construction and craftmanship. But every emerging technology is just another tool which usage is determined by the user. Digital fabrication offers the chance of using a construction material that humankind uses for thousands of years, long before we developed the wheel. Although its low material cost its high demand of manual labour made clay too expensive to be used as a mainstream construction material in industrialized countries. 3DP earth to prefab building components could help reviving a largely underestimated material. Traditional materials and modern production methods are not always a contractionary. Robotic 3d printing clay offers the chance to use a low-tech material without losing the large potential of a digital fabrication.

1.2. Problem statement

Clay is a sustainable, highly available and cheap material. Although its benefits, the labour-intensive production is a major cost factor for clay building components. Large-scale 3DP in combination with robotic fabrication offers a possibility to increase the production efficiency of clay building components. [1]

Increasing the efficiency earthen building components could help to re-establish this sustainable and circular construction material on the market. Besides the occasional misprint and jammed extruder, the major problems that are holding back large-scale additive manufacturing from transforming the market revolutionary are the amount of required time, the quality or discontinuity of the printed layers and the non-informative workflow between the building component, the printing tools and the material.

Sub-problems

Printing quality and discontinuity of the Material

- Material mixture
- Material properties (wet/dry)
- Interlayer bonding
- Cracks caused by tension within the printed Object due to uncontrolled, too fast drying process. Also known as “shock drying”.

The printing quality is a result of the material mixture, printing process and its speed. Especially the inter-layer-bonding is largely influenced by the cycle time. The rule of thumb is the avoid a cold or dry joining of overlaying layers [2]. This problem is mainly witnessed during concrete 3DP, where accelerators let the concrete harden faster as the cycle time. The cycle time is the required time to print one layer. Since clay is not chemically hardening like concrete but physically due to evaporation of water[3], it is to investigate if this problem is also applying for clay 3dp since the drying time is much slower then accelerated concrete.
The quality of a 3D printed object depends on the print environment and the extruded material. It is influenced by temperature, humidity, weather (wind, rain, sun radiation). A controlled environment offers the best conditions to print in a repeatable quality. The environment is not only influencing the process of additive manufacturing (AM) itself but also the post production. Especially the condition under which the wet clay is drying are important.
When the applied clay mixture is drying out to fast it will cause cracks that can influence the structure and appearance of the design building component. This will be investigated by experiments and is described in *5.5. Printing environment and post production treatment.* It might be beneficial to have a climate chamber that allows the control of the humidity.

It is important to mention that organic material such as straw or rice grain husks might go mouldy if the drying process takes too long. But since the organic fibres functions as a sort of reinforcement they could also prevent cracking during faster drying process.

Production techniques

- The nozzle design is barely influenced by the printable building component.
- Components are designed for single-nozzle print and optimized on material efficiency and tool-pathing. Contour crafting by Khoshnevis [4] and following publications offers a good insight into this fabrication process. Also, the possible surface manipulation by rotating brooms different spatulas.

The tool path design depends on the wet and dry material properties, the size and characteristics of the nozzle and the geometry of the produced element. [5] One fact that occurred during the research repeatedly was the single nozzle design. Large objects that have thicker outlines and thinner infills for stability or to increase the thermal behaviour. Printing those infills with only one nozzle seems not very efficient. There is a lag of correspondence between the component design and the nozzle design. This could be solved by an informative workflow. Manipulating the extruded material (contour crafting) is another option to broaden the possibilities and have a larger component design variation. [4]

The necessary time to print a building component depends on many parameters. The print speed and the extrusion flow influence the cycle time largely. The cycle time results from the extrusion path length and the speed that the material mixture can be extruded along this path [2] The shorter the cycle time the faster one layer can be printed. Reducing the necessary printable layers by increasing the layer thickness reduces the amount of required cycles and possibly the production time. But only if the travel speeds off the nozzle decreases too much. It is important to understand that changes on one parameter influence the others as well. The process should not be optimized only according to one parameter. Nevertheless, small changes can have a big influence on the overall printing time. Changes on one parameter, might increase the print speed but elongate the drying time and increase the deformation under self-weight. [5]

Some of the influencing and adjustable parameters are:

- The Layer height and width (the geometry of the nozzle in general)
- The extrusion flow
- The print speeds
- Orientation of the component (vertical or horizontal)
- Material (inertia, deformation under self-weight)
- Cycle time (influenced by the geometry of the component, the apparatus).

- Batch sizes: It would be beneficial to allow a constant production without the need of refilling the extruders. Snail extruders have the huge benefit that they allow a constant material flow compared with compressed air extruders, that need to be refilled after thy are empty.

Specially to produce clay building components, not only the printing time but also the drying time is important. The Drying time, and the storage of the components during it will be important for a production line to become economically feasible.

Component design and case study

- **Finding a niche**/case study where prefab clay building components could be competitive on the market
- **structural performance** of clay results in its use as space building infill for a loadbearing frame, or a massive monolithic structure
- **Infill design** designed to increase the efficiency.

To re-establish 3DPEarth as a construction material, it is necessary to find a niche where it can be competitive. Increasing the efficiency will help doing that. Unfired clay performs poorly compared to other building materials regarding its structural strength. To allow the clay component to be used in multi-story buildings a load bearing structure needs to be developed. 3DP offers a large variation of shapes and complex geometries that could usually only be achieved due to complex formwork or large manual labour. The design of the building component should include a challenges of clay manufacturing that could be solved with 3DP printing. In this case, it would be the goal of achieving a gradient material and realising irregular and variable infills for a structural frame. Both challenges will influence the design and production of the clay component.

1.3. Objective

Optimizing the printing progress to make it faster, have a more continuous material quality. Establish and informative workflow between the building component, the material and the nozzle to create a functional gradated material (FGT).
This should increase the overall efficiency of the material and the production process.

Regarding the fast development in the construction sector, 3d-rpinting could be an option that allows the transition of this traditional building material towards a high-tech fabrication. Without new production methods clay buildings could unfortunately become unaffordable due to its labour intense construction in industrialized countries.

Sub-objectives

Necessary material properties for large scale additive manufacturing and the qualities of earth as a building material.

Creating an informative workflow between the nozzle and the building component

Functional gradated Material a functional gradation increases the efficiency of the material usage by adding another function.

Final products

A 3d printed **pre-fabricated building component for a wall system.**
A set of **various customized nozzles and tools** to produce the component.
A **clay mixture** suitable for large scale additive manufacturing, strong enough to withstand compression due to self-weight during production.
This should increase the efficiency of 3DPE.
The printed building component will be probably used as a non-structural infill for a timber skeleton construction. Its mass distribution should help regulate the indoor climate and reduce the thermal conductivity. A visualisation of this idea can be seen *Fig. 1*

Hypotheses about the direction

Designing a gradient material that is dense on the inside and get increasingly light to the outside could fulfil the requirements. The created cavities reduce the density and should reduce the thermal conductivity. To reduce the cycle time each density class of this stepwise gradated wall system has its customized nozzle.

The efficiency of the production could be increased by establishing an informative workflow between the building component and the nozzle. The nozzles will be customized to reduce the cycle time and the number of cycles by creating a gradient material at the same time. This Gradient material can be used as in infill for a hybrid wall structure or as a massive monolithic wall.

Boundary conditions

The main approach is to research by design and design by research. This should lead to a prototype of a prefab exterior wall that will be assembled on site. The wall will consist out of two parts, a structural frame and a 3D printed clay infill.
The load bearing timber skeleton is out of scope of this research. The skeleton will be used to create irregular shapes for the gradient clay infills, design joints between the structure and the infill.
The component will be printed with a earthen mixture and used as an non-structural infill.
The printing process should lead to a gradient material, that is dense on the inside and light on the outside. This allows the usage of its thermal mass for the indoor climate regulation. Cavities and hollow parts on the outside should decrease the thermal conductivity of the component. The gradient structure of the cross section should decrease the risk of condensation inside the component.
The current attempt is a mono material mixture print. There might be an option to combine multiple material mixtures if there is enough time to evaluate this in dept. In this case Materials such as straw or grain husks are increasing the insulating performance. These additional materials could be printed as well or just filled within the cavities and hollow segments of the gradient pattern.
The thermal conductivity of the wall is not the scope of this research. A finite element analysis (FEM) based on a computational model to evaluate the thermal behaviour is not the scope of this research. The increasing thermal insulation will be achieved due to a density shift. The lighter the relative weight per volume the higher the insulation properties.

The scope will be the design and production of the mentioned 3D printed clay infill. On site assembly, transportation, mobility will influence the component design. The design of the gradient material and the necessary tolls (nozzles and possible additional tooling for contour crafting) will be done computationally.

Research by design and design by research results in an coordinated design between the building component and the nozzle/tools.

1.4. Research Question

How can the efficiency of 3D Printing a Clay prefab wall component with a 6-axis robotic arm be increased by coordinating and customising the nozzle design together with the building component and material properties?

Sub questions

The Sub question will be answered due to the literature study and the evaluations of the experiments mentioned under the chapter “experiment design”. First results from the material experiments lead to educated guesses in the field of production and possible extrusion processes, as well as wet and dry material properties.

- Material

Why is clay a sustainable and circular material?

What are the requirements for a clay mixture to be suitable for an additive extrusion process?

How can a stepwise gradient material be achieved by developing a geometric design for an extrusion process?

How can the functional shift within the gradient material be achieved – what properties are increasing, decreasing?

- Production

Production requirements for a draft nozzle design according to the material properties?

Can a gradient material be produced out of a single earthen by customizing the nozzle geometry?

How does to material and nozzle limitations influence the draft component design and the “infill” geometry?

How does the results of the active experimentation influence the design of the printed component and nozzles?

What is the optimal printing environment and orientation of the object?

What printing set ups exist and how do they influence the efficiency of the printing process?

What variables influence the printing process?

What is the toolpath limitation of each nozzle to create a gradient material through the geometry of the cross section?

- Building component

What kind of clay prefab elements exist, what are their limitations, how can they be assembled?

How can the wall system be cladded and/or protected from inside and outside?

What appearance could this wall system have?

What load bearing construction does not increase the embodied energy of the façade?

How can a secondary structure for transportation and assembly be integrated within the component?

1.5. Approach and methodology

The general approach to this research is to define limitations due to literature research and active experimentation. Those limitations will be used to create a building component and customized nozzles to increase the production efficiency. The optimization will be achieved by customizing the tools. In general, the practicality and feasibility of the production will be explored by a "hands on" design as described in the points below.
The research is based on three columns of investigation: Materials, Production and tools, Building Component.

Literature review and **active experimentation** about the three columns of this research: Material, production and tools and building component will give the initial ideas for the draft component, nozzle design and material mixtures.

Manual material and nozzle experiments with a hand-held clay extruder (Fig x) should result in limitation for the component and nozzle design.

Experiment-Toolpath and draft nozzle design will be done like described under chapter "experiment design"

Robotic material and nozzle test will be executed with the robotic arm to define further limitation for the production like toolpath limitations. The material mixture will be set according to the requirements of the extruder and component design.

Draft component/Nozzle design of an exterior wall system according to limitation from the material test and the literature. According to this component design one or multiple different extruder nozzles will be designed. The aim is to develop a functional gradient material.

Digital workflow for the nozzles/component design and toolpath. will be made with *Rhinoceros* and *Grasshopper*.

Production workflow for the robot and extrusion control. The toolpath will be exported to *RoboDK (RDK)* to control the Robot, its travel and production speed. The extrusion control will be controlled with *Arduino* over *RDK.*

Nozzle customization according to density requirement of the gradient material. The building component and the nozzles will be further design according to the experiment results.

Informative workflow to have a production optimized design and tooling. This requires thinking design and production as one continuous process instead of two separated phases. The limitations of the production are influencing the tool design. The results of the literature study and experiments will help defining those limitations
(printable size, storage of elements, the nozzle, the movement, speed, extrusion speed, material mixture, pressure, self-weight, layer Hight and number of layers before self-compression occurs)

Influence of the production on the building component. After the limitations of the printing process are defined it is important to look at the influence those limitations have on the design of the building component (geometry, curvature, thickness, orientation while printing (horizontal or vertical), density shift)

The finale component and nozzle design will be created. The customized nozzle should allow an efficient production of a gradient material with a single mixture.

Scheme of the approach and methodology, can be found on Page 10

Timetable is in the Appendix

1.6. Planning and organisation

Timeline: can be found in the appendix.
Research team:
Student: Maximilian Mandat 4931068
1st Mentor: Dr. Serdar Aşut
2nd Mentor: Dr. Marcel Bilow
Delegate examiner: Dr. Andrej Radman

Company to produce the final prototype: Studio RAP (not confirmed yet)

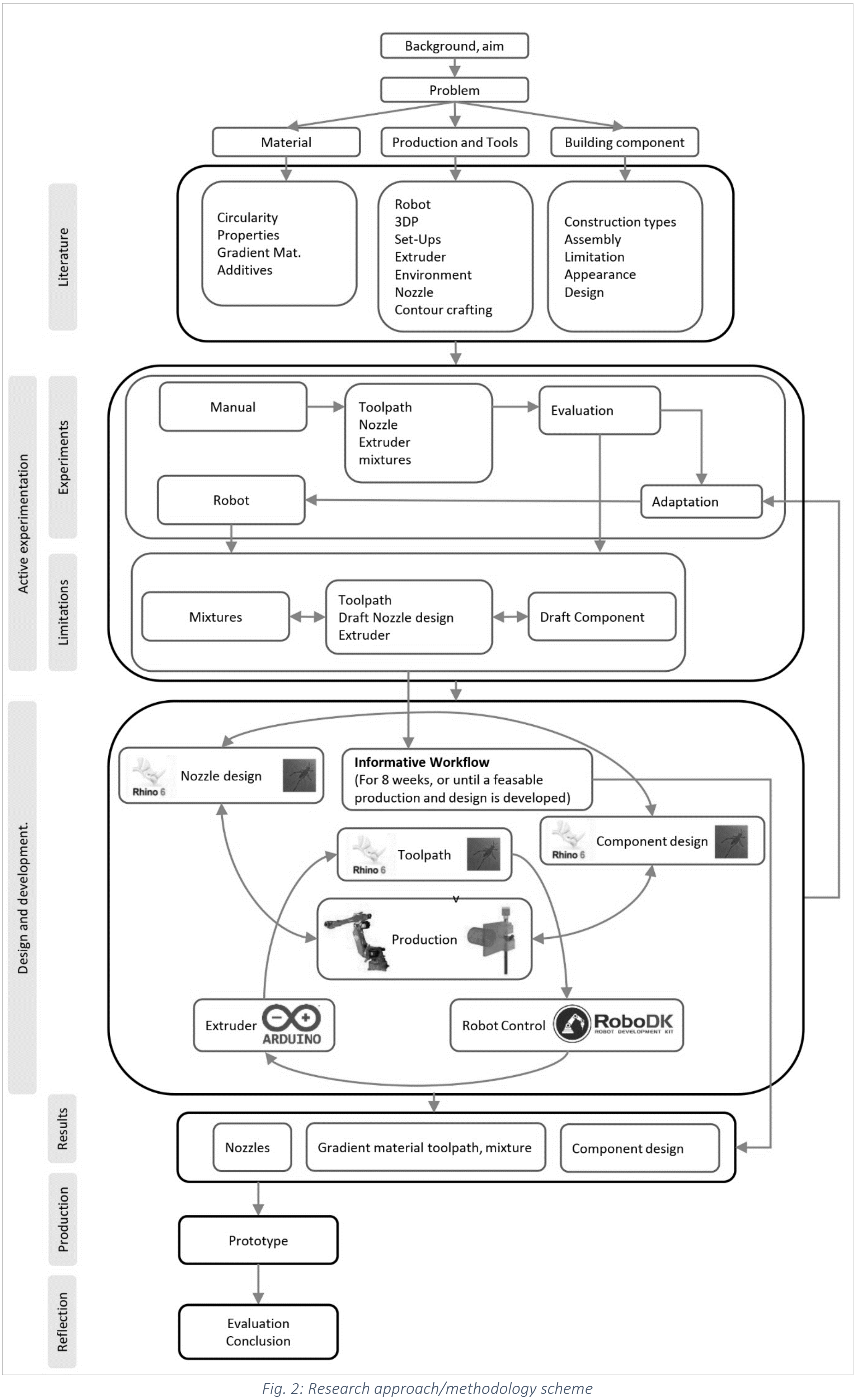

Fig. 2: Research approach/methodology scheme

2) Material

2.1. Introduction of the Material Earth

In the moment our building culture is facing an amnesia regarding Earth as a construction material. Otherwise it is hard to explain why thousands of years old techniques and cultural aspects of earth and clay construction are being forgotten. It is paradox since contemporary architecture claims more than ever to aim for harmony between humans, the build environment and nature. But when it is about earth as a building material, we fall back in paternalistic behaviours and suggest this material often as a solution for poor rural areas and refugee camps. Instead we should aim to use it in urban environments.[6] This chapter Materials, is the elaboration on the properties of pure, unbaked, earth. This material is familiar to all of us, since it is found in large occurrences around the globe and is one of the most available resources on Earth. It is so omnipresent that we named our planet after it. In addition to its almost infinite availability, it is one of the most sustainable materials we can use in building. [7] It requires almost no energy, can be gained locally and is almost free when the building site is already owned. In this scenario, clay could help to establish a local circular economy, where the added value of a building stays within its region.

The price of materials is currently not reflecting its impact on the environment. A Co2 taxation is currently discussed in many governments to fulfil the recommendations of the *Intergovernmental Panel on Climate Change*. Lester R. Brown states that we need to develop a new material awareness, one which reflects the environmental impact of a material. This would lead to a so-called eco-capitalism, that values natural recourses. “Communism failed because the prices did not reflect the economic truth and capitalism will fail as well if prices will not reflect the ecological value” he says. [8] Earth as a construction material would become much more attractive if construction prices would reflect their environmental impacts.

It could help to reduce the industrial pollution, is ecological harmless and cheap. The extraction from the ground requires no chemicals or complicate industrial processes. In short: Earth does neither harm the planet nor the user. Or as the *Financial Times* named it: We could use the most primitive material to build to most sophisticated houses. [6] [1].

Although there are many benefits, there specific challenges for this material in industrialized countries. Many regulation tests are designed for industrial conventional construction material. Earth has troubles to fulfil some of those. Especially structural behaviour and erosion tests. Furthermore, the production is labour intensive and requires skilled craftmanship as guidance. This leads to higher construction costs and longer construction time [9] – a state that could be changed with pre-fabricated building components.

Of course, earth, like every other material, has its limitations. It can barely take tensile forces and need to be used under compression. In regions with a moderated climate, earthen walls should be protected from weather influences with a so called “wellington and hat” strategy. This requires solid foundation against capillary water from the ground and a cantilevering roof construction that protects it from rain. To allow higher construction or span widths earth can be applied in hybrid construction. A structure made of timber, steel or concrete could support infills made from earth [10]. This topic will be elaborated in *4.1. Hybrid constructions*

2.2. Circularity

Using Earth as a construction material is not a concurrent for agriculture. Agriculture needs the top layer of the ground that is rich of organic matter to grow food. [10] Earth suitable for construction is found under this fertile layer and is mostly a mixture of sand clay and silt as seen in Fig. 3

Cities and large metropoles are trying to implement circular concepts to become less depending from the surrounding areas. One resource that cities can provide in large amounts is excavated earth from inner city construction sites.

Every year, millions of tons of this less regarded resource are getting extracted and brought to landfills outside the city. The huge potential of these excavations, especially for earthen constructions, got less attention until now. For example, the metropole region of Paris is currently changing this. The approximated 40 million tons of material that need to be moved to make space for the new regional connection “Grand Paris Express” between 2016 and 2030 should be brought to special sorting landfills. A new emerging field of earth moving companies is separating the reusable, clay containing layers. This allows it to be used as a sustainable, reusable construction material an reduces the negative ecological impact of landfills. Another positive side effect is the reduced dependency of Paris for sand and gravel. Hugo Gasnier says that many initiatives show that there is currently an ecological, political and technological transformation happening. This leads us to a new perspective using the huge potential of inner-city excavation materials. It is a sign for the change in urban resource management and establishes using “waste” as construction materials. [11]

2.3. Properties of Earth as a construction material

Earth is a material that consists of many different particles and granules that vary in size and type. It consists out of sand, silt and clay, as it can be seen in *Fig. 4, Fig. 5*

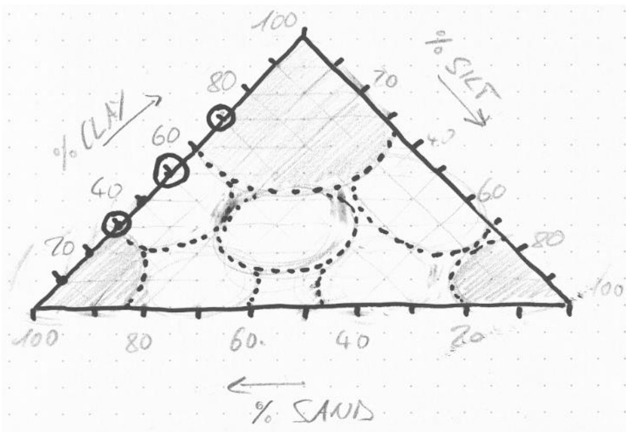

Fig. 6: Sand, Silt, Clay diagram. The Illustration shows what different types of soil can be found. Locally available earth can be remixed to fulfil certain mixture requirements.

The distribution of the grain size of each group should be according to a sift curve and can be optimized. It is important that the size of the grain is distributed according to the sift curve in order to minimize possible cavities. It allows smaller particles to fill the gaps between larger ones. *Fig. 7*

Two main mechanisms are responsible for the strength of an earthen wall: friction and cohesion. Friction is cause by the rough surfaces of the particles and granules. The stronger the particles are pressed together results in more friction.

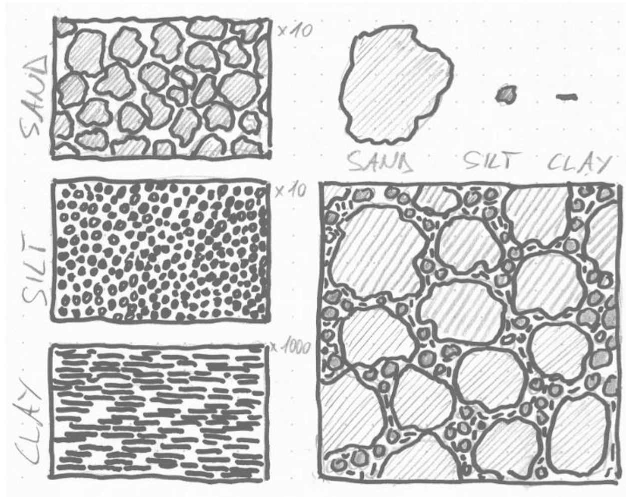

Fig. 8: Size difference illustration of Sand, Silt and Clay. The Silt particles fill up the voids between the sand, the clay “flakes” fill up the remaining voids.

This friction is responsible for the maximum angle of repose if no other binders are added. The cohesion is the force with which the granules and grains are attracting to each other. In this case it is a combination between gravity and electrostatic charges. The electrostatic charges are even between very small particles which is remarkable, since positive charges particles are attracted to negative ones. If water is added to the mixture, we will be capillary cohesion. This cohesion allows the surface tension to increase the cohesion even more. The capillary cohesion is the reason why we can form a ball with wet sand but not with dry sand. But this applies only if there is not too much water in the mixture. In this case, it increases the rheology and makes a mixture that is pump-able and extrude-able so long as the water does not get pressed out of the mixture.

The smaller the particles of a mixture the more capillary bridges are present. As a result, the grains are more attracted to each other and form a stronger bond. Clay and its thin and flaky morphology of particles increase the electrical cohesion of a mixture. This is due to the large surface area of the clay particles. Because their flaky morphology the area of contact and the possibility of contact within the mixture increases. Clay makes the mixture smooth and plastic.

If the water in the capillary bridges is evaporating the clay particles slide into its place. Without water, the distance between every particle gets smaller until they are touching each other. When the mixture is dry the direct electrostatic cohesion forces and the friction create a strong bond.

The process of evaporating water results in the distance reduction between the particles, which can be described as shrinkage. The higher the water content the more shrinkage will happen. The tension forces created due to the volumetric change causes cracks.

The structural strength of a dried material depends largely on the water content – a phenomenon that occurs as well in concrete. When the mixture is too wet, the evaporating water causes large pores, that cannot be filled with other particles. These pores decrease the structural properties but at the same time increase the ability to regulate the humidity and absorb odours. [9] The mechanical properties of a raw, unbaked earthen mixture without additives therefore depends largely on the water content. [4]

The structural properties of clay can be increased by adding additional material such as lime or cement. Also, synthetic polymer binders are in development. It is important to mention that most of these additives don't allow for reuse of the Earth as a circular material. The reusability is not possible anymore, since the clay flakes are permanently bonded together and cannot fill the voids caused by the evaporating water. Terracotta or "cooked earth" increases some of the structural properties of unbaked earth. But the baking requires energy intensive production. This increases the carbon footprint tremendously. [6] Since the clay flakes in terracotta are melted together the material is not reusable anymore. The reason is the same as for the additive binders.
Since the circularity of the material is one of the major benefits, I will not use any additional non bio degradable binders

2.4. Gradient Materials

A gradient material is a functionally graded (functionally graded material, FGM). It allows to build light weight components and helps reducing the recourse consumption. The properties of the material can be aligned due to specific desired requirements. [12] This results in a material or component that has a continuous parameter change within its cross section. A good visualisation of a gradient material is the microstructure of wood, or the structure of bones. Every year ring of wood consists out of denser and lighter parts. The denser parts are darker and stronger ring of wood. There is a gradient shift from light to dense as it can be seen in *Fig. 9.*

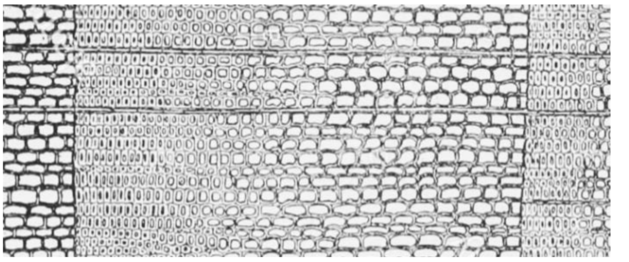

Fig. 10: microscopic view of a wooden year ring. A seamless density shift can be seen within one year. Source: Ref.

By decreasing the density of an material, due to the creation of porosity the thermal insulation properties are improved. Increasing the density by reducing the porosity enhances the structural characteristics. A Visualisation of this shift can be seen in *Fig. 11* on the left. Ideally a gradient material has a seamless property shift. However, the production of a seamless pattern shift is challenging. A "Stepwise gradation" of the material is a practical simplification that makes the implementation into a production process easier [12]. This stepwise gradation along a declining curve can be seen in *Fig. 12* on the left.

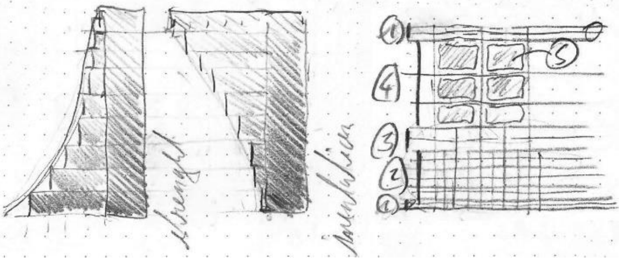

Fig. 13: stepwise gradation of strength and insulation, translation into a concept cross section of an functional graded exterior wall.

The principal of a FGM can be applied well at an exterior wall. It allows to produce walls that are strong while light weight and have an improved thermal efficiency. Developing an FGM from a single material mixture, like earth, would allow a very efficient production and recycling. Depending on the production efficiency the component might be able to supply the bulk market within its niche.
To achieve the gradation two option will be further designed, experimented and evaluated.

Gradation due to nozzle design: For each stepwise gradation a customized nozzle and toolpath will be developed. This process is explained more detailed under *3.4. Machines and tools, Nozzle.*

Gradation du to misprint on purpose. Under-filling the extrusion during the printing process creates voids. This is a problem when the goal is to create a geometry with a density requirement "as good as casted". [13] Under-filling the layer on purpose could be a way to get a gradient material or to create a density shift inside a stepwise gradation[5]. Maybe purposely underfilling could help creating a more seamless property shift between the stepwise gradation created by the nozzle customization. A special toolpath design with many directional changes could be a starting point for an active experimentation.

2.5. Additive materials

Additive materials have been used ever since humans used Earth to create shelters. Traditional additives such as straw, thin branches or cow dung are still in use and increase the performance of the material. Although, the performance is still below the value that modern industrial building materials can achieve. Today, many chemical additives and binders are added to earth mixtures. These "modern" additives such as cement or superplasticisers are increasing the carbon footprint largely [9]. Reusing the material at its EOL is not possible anymore. The low carbon footprint and the circular aspect are key properties of the material in which I don't want to lose, so I have decided to not look any further into this research. Instead, I researched two groups of additives: Fibres and Granules.

Fibres

Fibres are "reinforcing" the earthen mixture. As steel does in concrete, the fibres in straw are taking tension forces, but in a much smaller scale. On top of this, they reduce the density of the material mixture. The most commonly used fibres are **grasses**, **straws** and **thin branches**. Furthermore, they are agricultural waste and therefore a relatively cheap resource. **Horse/cow dung** as an additive contains fibres as well and can reduce the risk of surface cracks. Fibres in dung contain mostly non rotting fibres and could reduce the risk of mould during the drying process. Dried clay that contains horse or cow dung has no bad smell, while unfortunately, the wet mixture does. **Flax and Hemp** have thin and long fibres. But such materials are specifically grown on arable land, which makes them a direct concurrence of food production. To allow a good extrudability, the fibre length for AM (additive manufacturing) should be limited. The fibre length should be as long as possible to have the biggest benefit. Production limitations of 3DPE will require shorter fibres – a topic that will be evaluated in the experiments. [14]

Granules

As straw, granules can be used to reduce the density of the material mixture. A few possible granules are: **clay, wood chips/flakes, wood pellets, and baked clay granules.** Clay granules used a substratum are baked. They **expand** during the baking process and turn porous inside while maintaining a closed surface. The embodied energy of clay granules is higher than that of clay, due to the need for baking.
The production limitation for granules is their size. To reduce the risk of a clogged nozzle, the granules need to be below a certain size. Clay granules are a mineral additive. Therefore, it could reduce the risk of moulding during the drying process and increase the insulation properties of the building component. The extrusion ability of a mixture containing granules is depending on the grain size and the machines size used for the process. To limit the risk of a clogged extruder, adding the granules in a secondary process is recommended. This process is described under *3.4. Machines and tools, Contour Crafting*. There is a risk of moulding during the drying process for non-mineral, bio degradable granules, especially for larger building components that require an extended drying process. A faster, artificial drying process would reduce this risk but increase the risk for drying cracks. [15]

3) Production and tools

In most industrialized countries clay or earth and the related techniques has been repressed by industrial building components. Along with that the education of skilled craftsman's that can work with this natural material is declining. The digitalisation is promoting a revival of that traditional building material. [6]

3.1. Introduction of 3D printing Earth (3DPE)

Regarding traditional construction techniques for Earth, we could witness a huge development in the past decades. Hubert Guillard states two of the major innovation drivers. The first goal is to process the material to make the production more suitable for and industrialised mass production. The second one is to increase the social status and the appearance of earthen construction. [11] In most industrialized countries clay or earth and the related techniques has been repressed by industrial building components. Along with that the education of skilled craftsman's that can work with this natural material is declining. The digitalisation is promoting a revival of that traditional building material. [6]
3DPE is a new emerging field of earthen construction and aims to fulfil both. Increasing the efficiency and the social appearance. Via an extruder the viscous earthen mixture is applied in layers via a nozzle. 3DPE is not a proposed option for rural areas or developing countries. But it offers a potential for industrialized countries where labour is a large cost driving factor for construction. The introduction of 3DP could, if developed further, increase the productivity, quality and safety. [4]

3.2. Production set ups

The production speed efficiency of a building component is largely depending on the available printing set up. There are "finite" and "infinite" set ups. The difference is how the material mixture gets transported to the extruder. A small-scale finite extruder is more convenient for pottery. For large scale 3DP instead, an infinite set up allows a more efficient production. The introduced set-ups are both suitable for a 6-axis robotic fabrication and a conventional 3-axis AM. Both set ups require to create a material mixture before the printing process. For earth a pan-mill is ideal, many companies specialised on clay buildings us as well old bakery mixers. For an optimal homogeny of the material it is important to force the material together. [16]

Finite set-up:

The current set up at the LAMA is a finite set up. As it can be seen in *Fig. 14* the clay gets filled in a container or cartridge. The container is connected to a compressor that builds up a pressure of about 4-6 Bar. This pressure extrudes the material mixture through a hose to the extruder. The function of a paste extruder will be described detailed in *3.4. Machines and tools, Extruder.* The compressor and extruder are ideally both connected to a control panel that managed the required pressure according to the extrusion speed. [16]
The pressurized container can only contain a certain amount of material before its empty and needs to be refilled. Since the surface of the container needs to withstand the high pressure the size is usually limited. Another occurring problem is that the cartridge is under pressure, that includes the risk of an explosion. Although this risk is very low if all parts are maintained well, special care is recommended. The necessary refill every time the container is empty causes production stops and leads to irregularities in the printing pattern. Another problem is that the mixture should not contain any entrapped air when filled in the cartridge. Eliminating all air bubbles in a sticky mixture with high clay content would require a vacuum pump. And even this extra production step does not guarantee that air gets not trapped within the mixture while refilling the cartridge. This problem can be reduced by having multiple containers that get exchanged once they are empty. Nevertheless, a short production stop will be unavoidable.
The container can be either placed next to the robot or mounted on it. By mounting the material cartridge on the robot, is it important to keep the weight below the maximal additional weight. The benefit of mounting it on the Robot is a higher degree of toolpath freedom since the possibility of collision is reduced.
The finite set up is suitable to achieve the proposed experiments for the robotic fabrication. The prototype production would be possible as well, although the production time will be elongated.

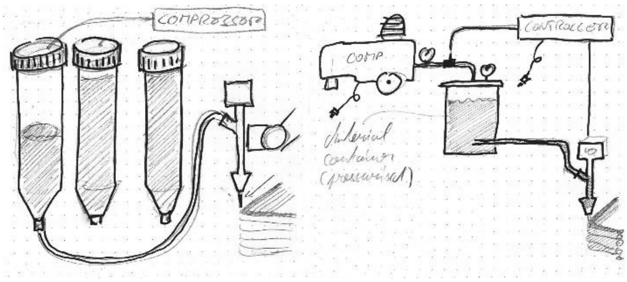

Fig. 15: Finite production set-up for paste 3DP. The material mixture gets filled in a container or cartridge and pressed towards the extruder.

Infinite set-up:

For mass fabrication or large-scale 3DP an infinite set up has one big benefit. It allows continuous printing and requires no production stops due to refilling a container. The created mixture is filled in a plaster pump from where it gets pressed through a hose to the extruder. Ideally the compression process with and auger, required to press the mixture through the hose, will eliminate any air bubbles trapped within the mixture. Specialised pumps for this purpose are available on the market. The plaster pump is an open system that can be refilled continuously. If there is enough material to pump, a nonstop production is possible. The hose between the pump and the extruder can be mounted on the robot or on a scaffolding and allows a high freedom of movement for the robotic arm.

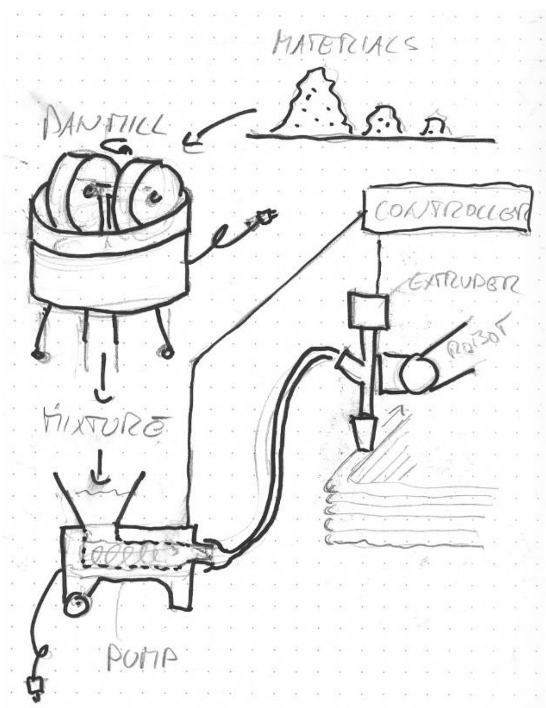

Fig. 16: Infinite Production set-up. The material gets mixed in a pan mill and afterward filled in a pump. The pump extrudes the mixture towards the extruder. The material mixture can be continuously being filled in the pump

1:1 Prototype production:

To produce a 1:1 prototype I would recommend an infinite set up. This will allow to record the production time and evaluate the efficiency of the process. A clear statement about industrial large scale 3DP could be given since the set up would be state of the art. Unfortunately, we currently don’t have such a set up at the LAMA.

The company for Robotic Architecture Production - *Studio RAP*, has an infinite set up for clay 3DP and is willing to help me producing my final prototype at their location, RDM Rotterdam. After the P2 we will further discuss a possible collaboration and timeframe for the prototype production.

Different printing Environments

AM is strongly influencing by the production environment. Especially the quality and continuity of the printed object is influenced by it. Uncontrolled condition, such as found when printing on site, lead to several quality reduction. Some are: uneven draying due to wind and sun radiation what causes drying and settling cracks, the viscosity of the mixture is harder to control since the humidity influences tit, In-situ printing usually aims to produce large object without dilatation gaps, that causes tension and cracks during the drying process, setting up the production on site takes a lot of time and requires a roof construction for the plot- expensive and logistic hard to archive.

A production in a controlled environment allow an excellent calibrated set up, continuous viscosity of the printed material, a controlled slow drying process to reduce the risk of cracks. The produced objects are limited in their size due to transportation and handling – this reduces the risk of shrinkage cracking. Temperature and humidity control are not only beneficial to produce the building component, but as well for the worker. A year-round construction is possible.

3.3. Material requirements for 3DPE

To allow excavated regional material to be usable for 3DPE it is important to sort and sift the dried earthen mixture. Otherwise it cannot be used in an extrusion process. Critical for a successful extrusion is the maximum grain size. Too huge granules will clock the extruder and causes interruptions of the production and

a decrease of the efficiency. A phenomenon that occurred during our first material test, before the sand was sifted.
The so configurated but unprocessed soil can be mixed with water, be extruded and reused at the end of life (EOL). The content of different grain sizes for an earthen mixture is largely influencing the stability of the mixture. The grain size needs to be adapted according to the extruder and the nozzle design to avoid clocked machines. Therefore, the mixture must be soft, but not so soft that it cannot support itself anymore (self-weight compression). The degree of viscosity should allow an easy shaping and a stable plastic state. This will largely depend on the water and clay content of the mixture. The mixture will be adapted to the indoor climate of the LAMA further evaluated during the experiments.

3.4. Machines and tools (physical/digital)

Extruder

The current clay extruder at the LAMA, has a nozzle diameter of 5 mm. That allows a cross section surface of the extrusion of about 20mm2. Too small to modify and shape the geometry of the nozzle. To allow more realistic 1:1 scale experiment with the nozzles and mixtures we require an larger extruder. The LAMA has most of the parts that are necessary to build a "do it yourself" (DIY) large scale clay extruder (FIGX). To allow the nozzle shapes and sizes to be as realistic as possible Rodiftsis, T. and I decided to develop with Paul Ruiter and the help of Marcel Bilow our own extruder for the LAMA. The large scale is important to have valid results about the ability to shape the mixture. To that the self-compression and possible contour crafting can be easier evaluated in a larger scale.
The earthen paste gets pressed into a (9. feeding pipe r=11mm, t=2mm), from there on its gets transported with a (16. snail extruder) towards the nozzle. The extruder is a conventional 18mm
diameter wood drill. The extruder will be connected over a (11. transformation nut, 5. Connection Bit, 4. Coupling and connectors, 3. Gearbox) with the (2. Motor).
The extrusion flow of the mixture will be controlled by adjusting the rotational speed of the motor. The motor will be controlled over an Arduino board that relates to the robot control over a relay. A continuous extrusion flow can be achieved when a constant rotational speed is maintained. At the bottom of the (13, steel pipe extruder) the nozzle will be mounted. The extruder can be taken apart from the (8. Pipe connector) downwards. This ensures that the sensible electronics and mechanic (motor, gearbox) don't get wet and dirty when cleaning the extruder after the use. The whole set up is 3D modelled in RH and will be imported into RDK. We already purchased or collected all necessary parts for the DIY extruder, they will be assembled in the week after the P2 presentation.

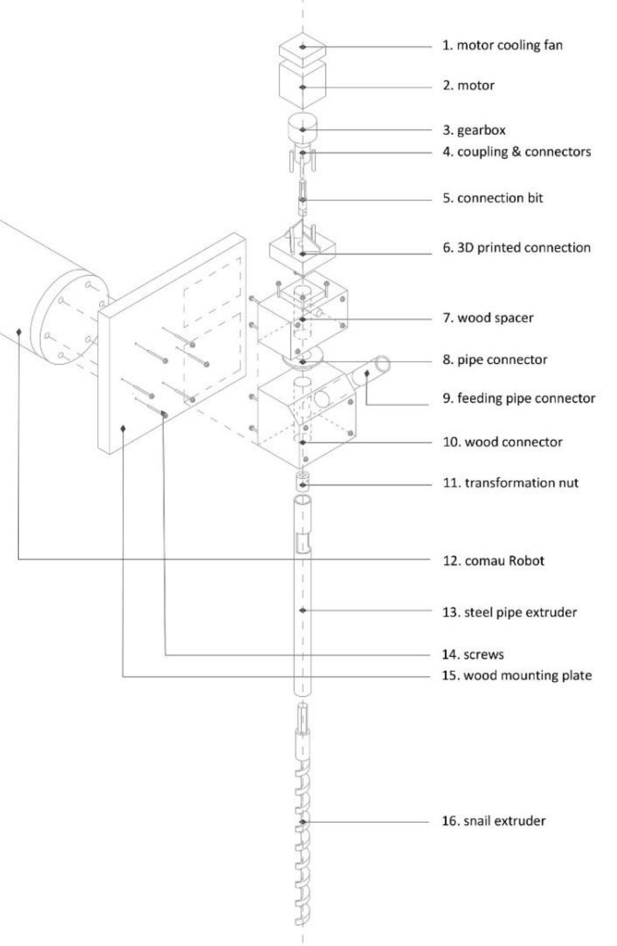

Fig. 17: Autor's: Rodiftsis,A., Mandat,M., isometric drawing of the planned paste extruder.

Nozzles

The optimization of the production will be achieved through the customized nozzle design. The nozzle should modify the extruded geometry. The design of the building component and the nozzles will be done computationally and depending on each other requirements. The optimization of the production will be done within the nozzle design. The design of the nozzle itself is developed within RN and GH and linked to the component design file. Both files will be updated according to the experiment results and pattern development.
The main function of the nozzle is shaping the extrusion geometry to reduce the density per volume. In addition, different toolpaths will be developed to create void and cavities when the extrusions are stacked.
A first draft of possible nozzles can be seen below in

Fig. 18. The shape options for the nozzle is limited by the viscosity of the material and possible additives. As described under experiments, added fibres increase the risk of a clocked extruder.

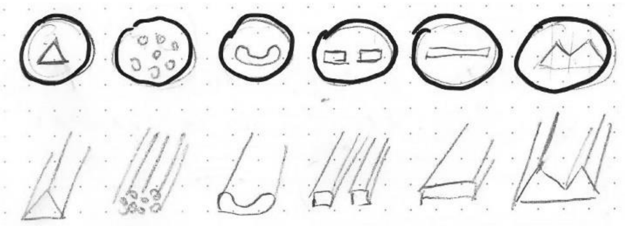

Fig. 19: Nozzle ideas. From left to right: triangular, "spaghetti", U-Shape, double nozzle, long rectangular nozzle, M-shape nozzle.

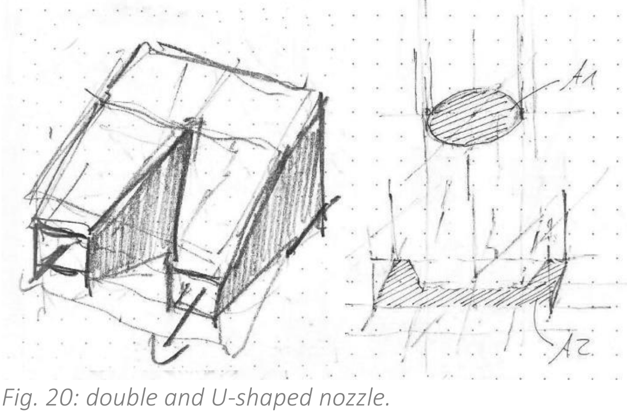

Fig. 20: double and U-shaped nozzle.

To reduce the density per volume of the component the outlet surface of the nozzle (A2) will be modified. To have a pressured material mixture within in the nozzle the outlet surface must be smaller than the inlet surface (A1) *Fig. 21.* Each nozzle will be designed for a specific “density class” of the building component. By creating bigger voids within an increasing relative surface of the outlet nozzle the density per volume of the printed object will decrease. The different nozzles will be 3D-printed with a thermoplastic printer at the LAMA. This a cheap fast rapid prototyping solution.

Requirements from the components design

The production requirements from the building component are based on a draft component design. This will mainly influence the nozzle design. And further explored during the informative design process. The component design will also define the size of the prototype and include the necessity of secondary structures for transportation, assembly and handling.

Contour crafting

Contour crafting (CC) is a method to post process or model the extrusion geometry of a layered manufacturing technique. [17] It allows printing large scale objects out of polymers, ceramics, Cementous mixtures and more. It allows a fast production speed and the placing of other internal structures via gripers. CC manipulates the extrusion with trowels to achieve a smooth surface. The extruded material gets constraint along or between the trowels. The accumulation of the extruded material leads to a thicker material deposition and results in an increased layer height. The higher the layer-thickness the faster the component can be produced. A higher layer thickness requires less cycles to print the object. This reduces usually the production time. The possible layer height is a direct result of the trowel height and the viscosity of the material mixture.
For CC with earthen mixtures or clay the paste needs to be viscous and formable [4]. If the mixture contains too much water, is too liquid, it will not stay in the crafted shape and will be deformed under self-weight or simple gravity.
The exact material mixture will be developed via active experimentation as described under the *5.2. Material Experiments*
CC requires an extrusion unit, as seen in Fig. 22 and a trowel control mechanism. Such a control unit can be seen in *Fig. 23*

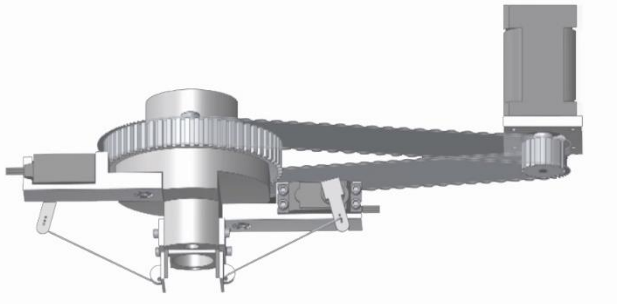

Fig. 24: trowel control unit to modify the extruded paste.

CC enables to created hollow deposition by crafting the extruded paste or modifying the nozzle.

It could also allow adding granules or fibres in a post extrusion process as suggested in *Fig. 25*. Therefore, a customized nozzle could create a U-shaped extrusion. The void could be filled in a secondary process with granules or fibres and pressed into the still plastic paste. To avoid horizontal deformation, trowels as mentioned previously would constrain the material and maintain a clean boarder. [4]
Applying CC in the production process requires additional tooling and machines as seen in *Fig. 26.* Since we do not have those at the LAMA, post extrusion CC

options will be investigated with manual experiments. This counts as well for adding additional reinforcements or secondary structures necessary for transporting the prefab component. Automating this in the production of the planned building component would require to much time and is out of the research scope.

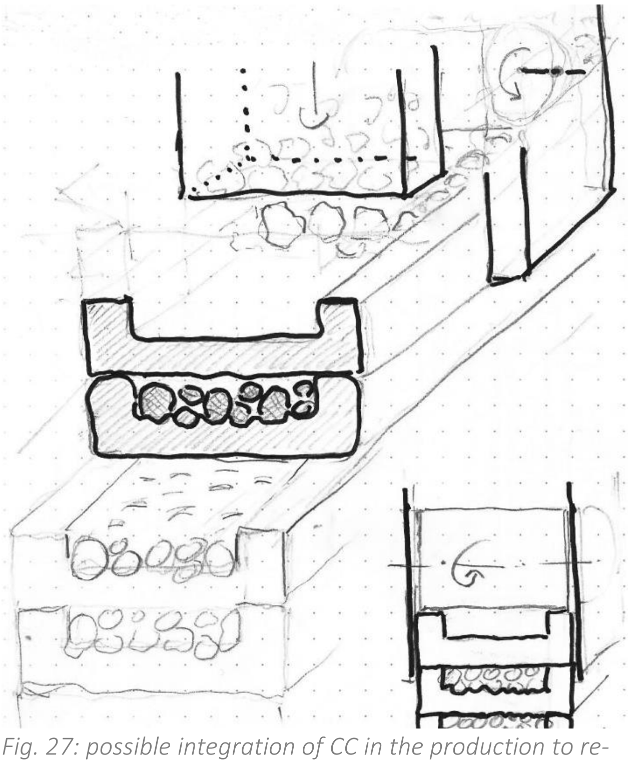

Fig. 27: possible integration of CC in the production to reduce the density while not decreasing he compressional strength of the still plastic material.

6 axis robotic production benefits:

The 6 axis robots arm allows to reach every point within its workspace from a specific orientation. This freedom of movement allows to create toolpath design that result in a weaving deposition of the extruded material, like patisserie. The 6axis allow the tangential orientation of the nozzle along the toolpath and the non-perpendicular extrusion on the printing surface. Besides the extruder, different aggregates can be mounted on the robot. This would allow to automate the integration of secondary structures. If the component will be an infill for a hybrid construction, the shape of each component will be different. This task good manageable by robotic fabrication if there is a proper applied file to factory workflow.

In an industrial set up, each production step would be done by a different nozzle. The produced Object would move from one to another production step. This would eliminate the time required for changing the nozzle.

Efficiency:

Christoph Achammer states that the automotive or manufacturing industry could never afford launching such unready products to the market as the construction industry does. [22]

According to a study by McKinsey the productivity of the construction sector is today at the level of the 1950s [24] Building are usually prototypes and barely produce in series. That could explain the low production efficiency. Robotic 3DP offers the possibility to have an efficient non serial production of building components

For the planned building component, I intend to measure the production efficiency by reducing the cycle time and number of cycles that are necessary. A standard STL slicing with a single nozzle will be simulated within RDK to evaluate the time difference.

Digital tools and workflow

The design of the building component will be developed within the 3D CAD software *Rhinoceros* and the Plugin *Grasshopper.* The same software will be used to create the design for the nozzle and the toolpath design. There is a broad variety of additional grasshopper plugins that can be useful to generate the computational model.

There will be no computational geometry optimization of the building component to increase the production efficiency, since the scope of this research is the optimisation through the nozzle design.

However, the design of the nozzle and the component will be linked together to achieve an informative workflow.

To allow a better coordination a RoboDK (RD) Plugin will be installed on the Software RN. The position of the component (toolpath) in Rhino on a cartesian coordinate system should be the same in RD – this simplifies the adjustment.

The generated toolpath will be exported as a STL file and imported into RoboDK (RD). For 3DP a Tool Coordinate System (TCP) is more useful for the orientation and positioning of the Robot. Therefor the constructed extruder needs to be imported as a STL file into RD as well. The centre of gravity should be calculated to allow the robot a more precise joint control. The tangent nozzle position along he toolpath will be set in RD. [18]

4) Building Component

As described in *3.2. Printing Environment* the building component will be produced in a controlled environment. The transportation, assembly and handling include many limitations for the building components. The previous research about material production and tools will be used to design a prefab building component of an exterior wall. Generally, I deferred two types of construction methods suitable to produce this wall: Hybrid and monolithic. Both are detailed described below.

4.1. Hybrid construction

Hybrid constructions of earth and a structural skeleton have a long tradition of use. One of the most common in Europe is the half-timbered house. Many century-old examples that are in excellent condition can be found in France and Germany. Fig. 28 [6] A structural skeleton carries the load of the earthen infill. The skeleton can consist out of any conventional construction material. The traditional skeleton material is timber; it has also the lowest embodied energy and could help in developing a carbon negative wall system. This is possible due the fact that timber can sequester carbon. If we don't burn the timber, the carbon that was extracted from the air during the wood's growth stays stored in it. Especially for the urban environment, a hybrid construction offers the large benefit that we can build up to 6 levels. [19]

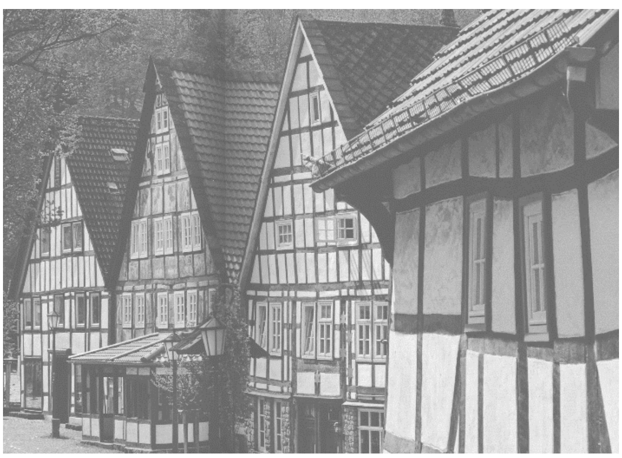

Fig. 29: traditional German half-timbered house. The timber skeleton carries the weight of the light earth infills. The infills are a mixture that contain high amounts of straw and other fibres to reduce the weight and increase the insulation properties. Source [6]

Skeleton:

Should be made from a conventional building material such as concrete, steel and timber. They are well known, and the calculation can be referencing all standards, without the need of long and expensive structural test. This simplifies the use of regional soil since its only requirement is being strong enough to carry its own weight. [20]

Infill design:

It is to mention that the weight of the infill should be as low as possible without losing the benefit of a thermal mass. The infill will be designed according to the requirements of a functionally, stepwise gradated material. Each step should have a defined density. Nozzles, customized for each density, will be used to produce the component. As seen below, each density part of the component has a corelating nozzle. The outer and inner surface of the component should be denser to withstand impact forces.

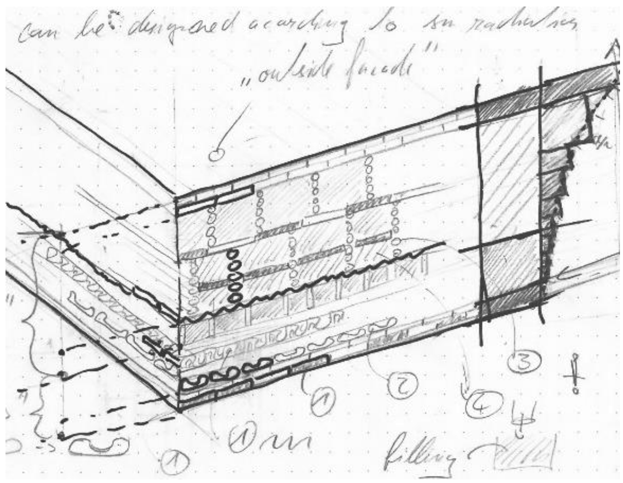

Fig. 30: possible infill for a hybrid construction. A similar geometry would be used for the monolithic structure as well, but with a much thicker "solid" section to allow the wall to carry more weight.

Possible Assembling

The infills will be slid into the structural frame and connected with it. The joints between the structure and the infills require a strong bond and should ideally be able to disassemble.
To allow that, it might be necessary to have a secondary material at the joints. Wood could be a good option due to its low heat conductivity as it reduces the risk of cold bridges and condensation associated with it. [20]

Example prefab earth hybrid constructions.

A building that is currently under construction in Schlins, Austria by Martin Rauch is the ERDEN production Hall as seen under construction in *Fig. 31* The Timber construction, as well as the prefab rammed earth components are assembled on site. [21]

Fig. 32: ERDEN, production Hall for prefab rammed earth components, Schlins, Austria, 2019, Source: [21]

Possible design options:

A possible option of a draft hybrid component design can be seen below. The timber skeleton carries the weight of the infills. A cladding is mounted with a sub-construction on the outside to protect the component and the timber from weather influences. The design is an attempt to reinterpret the traditional German half-timbered houses.

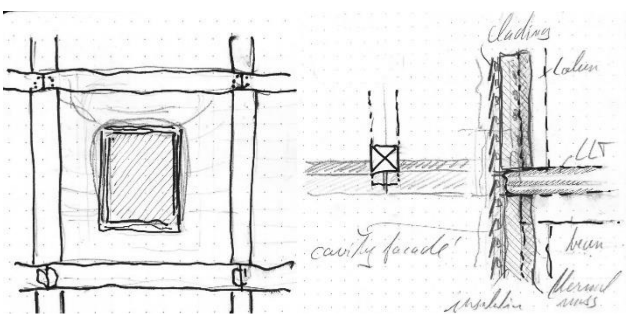

Fig. 33: modern reinterpretation of a timber-earth hybrid construction with a possible cladding against erosion.

4.2. Monolithic construction

The wall construction consists mostly out of clay and only includes additional materials for transportation, handling and joining. The earthen mixture itself is the load bearing material. This requires a enough strength to carry not only its own weight, but all loads that occur in a building. Fulfilling the current regulation (made for industrial building materials) will be one of the biggest challenges for earthen load bearing structures. This leads in many cases in very thick walls. Most of the monolithic prefab structures are rammed earth walls. The thick and dense components can be used as structural elements and be stacked up the 11 meters [9]. Using earth as s structural material for houses higher than 3 stories in an urban environment will be very hard to achieve in Europe due to strict regulation for the material. Although there are examples of 6 story high adobe building in the city Schibam, Yemen. [6]

Function of dense and light part

The previously mentioned idea to create a gradient material will be applied for the monolithic walls system as well. The dense part will be responsible for the thermal mass and load bearing. The less dense parts will be used as previously mentioned to reduce the thermal convection.

Possible Assembly

A possible assembly for a monolithic load bearing structure would be like a brick wall. The components will be staggered over each other and joint with a clay mixture between them. The joints can be out of earth and notched. The components need a certain wall thickness to have the required strength. This makes the elements quite heavy and reduced the possible height. As seen in the picture below the rammed earth prefab component is massive and not to handle without a crane. The high weight and the handling are a limitation for the component design. [21]

Fig. 34: Assembly of a prefab, monolithic rammed earth wall. Schlins, Austria, 2019. Source: [21]

Examples of prefab earth monolithic constructions.

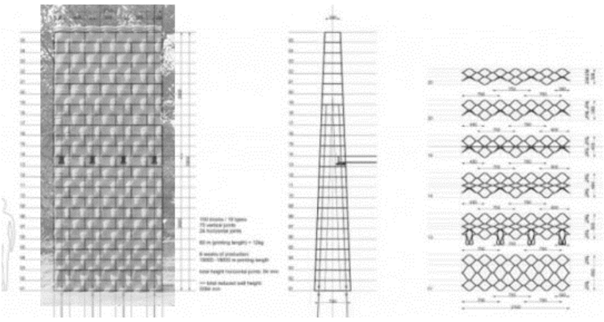

Fig. 35: Digital adobe, IAAC. Source : [25]

The monolithic prefab wall system from IAAC, has a cellular cross section, that is filled with earth when assembled on site. The 3DP structure function as a sort of lost formwork, the low weight of the unfilled segments allows a much easier transportation and assembly. The section of the wall is conical and according to the stress distribution. The façade has a pattern that can be useful against erosion. The Wall is assembled like a large-scale brick wall. [25]

Possible design option:

The design option will be a gradient material as introduces earlier. The dense part will be used structurally. The lighter part will be used to increase the insulating property of the wall system. The thickness of the dense part can decrease each level since the load reduces as well.

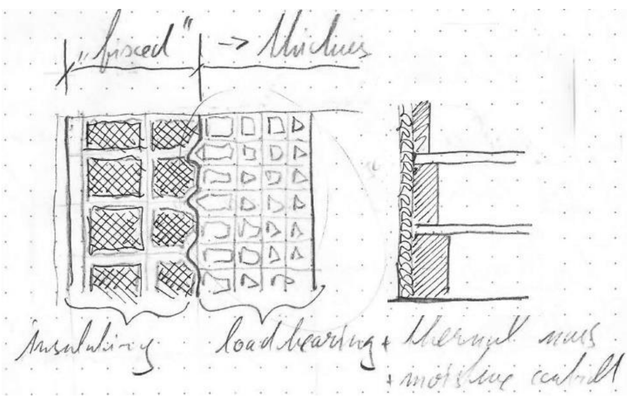

Fig. 36:draft design idea of a gradient material, load bearing monolithic building component with insulating properties.

4.3. Appearance of the wall system

The architectonic appearance of the building component is not the scope of this research. However, the component should allow different design options to allow constructions for multiple purposes without being limited by its appearance. This counts for both the inside and the outside skin of the wall.
For a functioning wall system, the design of the outside skin is more important since the weather resistance of a clay façade is one of the main maintenance fields.
Two possible option to allow this design variety and protection is by cladding the component and creating a ventilated façade, or by modifying the surface to make it more resistant against erosion. Both surface options can be applied on the hybrid and the monolithic façade. [20]

Claddings:

Claddings offer an almost infinite possibilities to design a façade. At the same time, a cladding protects the wall behind it against outside influences. Especially for earthen walls, which are prone to erosion, claddings offer a good solution. The weight of the cladding must be regarded during the design of the building component. Possible joint between the cladding and the component should be integrated in the design and the production as well. A simple sub-construction, embedded into the printed component, would allow to mount a green façade, solar panels or any desired cladding that is not too heavy. If the architectural appearance is designed within the limitations of a cladding system, the design should be applicable on the printed building component.
Another interesting question is the assembly – will the cladding be mounted to the component on site or in a controlled environment? The mounting on site includes an easier handling of the building component, since small damages due to transportation or the assembling process can be covered with the cladding. If the façade is completely assembled at the factory, the transport and assembly on site must be done with special care. Damages will be later visible on the façade surface. [20]

Modifying the surface:

Unlike the cladding system that covers the whole façade, the method of modifying the surface allows the visibility of the material earth.
The main problem in this case is the risk of erosion of the material. This problem is well known in traditional

and modern earth architecture. To reduce this risk, cantilevering plates can be integrated horizontally in a fixed distance. The plates should be composed of a water-resistant material. This technique is applied in many different regions and used as an architectural appearance as well.
Another approach is modifying the surface to canalise the rainwater to limit the erosion to a specific area. A remarkable example of this might be the houses of the Musgum Tribe in Cameroon. The created pattern can be used as ladder for maintenance.
Modifying the surface allows a huge variety for surface shape design. Computational design and robotic fabrication offer a large variety of possible designs.

5) Experiment design and results

The second column of my research will be the active experimentation. The Material and production limitation of additive manufacturing can be experienced with some basic manual test. For more detailed information the experiments will be repeated with extruders and the robot.

The experiments will be performed in collaboration with my college Athanasios Rodiftsis. He is graduation within the same field but focusing on the structural optimization of 3DPE. The results of the experiments will give both of us a better understanding of the material properties and production techniques.

5.1. Used tools

Required tools:
Kitchen-scale, measuring cup, ruler, buckets, sift, plastic sheets, tape, pen and sticky-notes, tools, mixer …

Manual Clay extruder:

To test multiple different material mixtures, extrusion angles, nozzles and distances of the nozzle and the printing surface as well as movements to achieve certain patterns, a manual extruder is ideal. It allows to work intuitive according to the mixtures that is currently used and gives direct feedback. Specific movement to create wave like structures can be tested easily manually and be later translated into a detailed too path for the robotic arm. The manual extruder as seen in *Fig. 20* can be filled with about 800 ml of material mixtures. It pressurized the mixtures through a stamp as commonly know from silicone syringe.

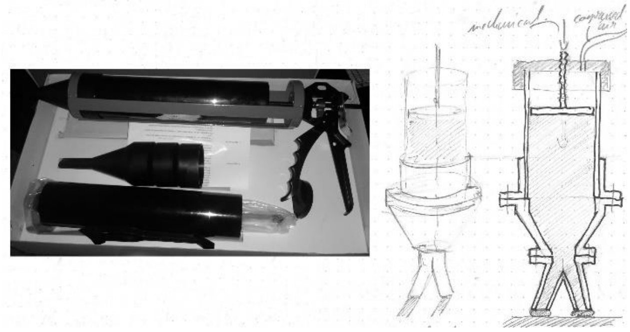

Fig. 20: Manuel extruder used for basic material and extrusion experiments. Nozzles with different form and size can be applied.

Self-designed clay extruder:

The Extruder as described in Fig. 8 will be mounted on the 6- Axis robotic arm and connected with the pressurized clay container. The extrusion flow can be adjusted precisely over a control board. This allows adjusting the extrusion flow according to the travel speed of the robotic arm.

6 axis Robot:

The robot used for the experiments will be the *Comau NJ60 2.2.* It is a 6-axis welding robot that allows fast and precise travel. It can carry 60kg on its 4th joint and 20 kg on the 6th joint. That results in a set up where the clay container will be mounted on the 6th join. The material mixture will be pressed through a hose from the cartridge to the extruder. The clay extruder will be mounted on the end of 6-Axis robotic arm. With a maximum horizontal span width of 2250 mm this robot allows to produce a 1:1 scale prototype. The Robot allow to test in dept the relation of the distance and angle between the nozzle and the printing surface.
It allows to test travel speed and specific movement. The described translation of a weaving movement from the manual extrusion test can be precisely and repeatably created with this arm. The robotic arm in combination with the *Arduino* control panel allows a fine tuning of all possible parameters and should result in a high print quality.

5.2. Materials experiments

The performed experiments will be done at a storage room of the LAMA under room temperature and uncontrolled humidity.

Soil types:

The Basic material for the tested mixtures is Soil. The composition of the soil varies depending on the location. We create 3 types of soil with different clay and sand content.

My research lead me to the following mixtures, which are referred as “Soil A,B,C”. [3]

Material	*Soil A (adobe Mix)*	*Soil B (50/50 Mix)*	*Soil C (Wasp Mix)*
Clay	30	50	35 35 Silt
Coarse Sand	40	25	-
Fine Sand	30	25	30

Tab. 1: different ratios between clay and sand, all values in % of the volume

All created soils will be dry mixed first to assure a homogenous mass. Later water will be added to the mixture. I will start with 10% water content. Since the viscosity and extrudability of the wet mixture is hard to predict the exact water content will be evaluated by weight. As suggested in the literature, feeling the material and observing how its viscosity changes is the easiest way to find the right water content. The proportion of the mixtures can be change after the evaluation of the first results.

Additive Materials:

The additive Materials should increase or decrease some of the Material properties. For example, the more straw is added to the soil the lower the density and heat transmission coefficient of the mixture gets. At the same time its compressive strength should decrease. Adding fibres to the Earthen mixture should increase the tensile strength.
I differed the additive materials in two groups: Fibres and Granules.

Fibres	*Granules*
Straw	Clay Granules (chrushed)
Cellulose (Newspa-per)	Wood chips (Saw dust)
Horse dung	Wood pellets
Flax	Grain Husks

Tab. 2: additive materials

Tested Material mixtures:

The goal of the experiment is the development of material mixtures that are suitable to print a gradient material. To achieve that, the mixtures should have different densities, and be highly plastic. The high plasticity allows the mixture to be crafted by the nozzle without losing the shape. In the experiments we also test if added fibres are changing the extrusion ability. The initial tested mixtures will be changed, extended and modified after the first tests.

The criteria for the mixtures are evaluated for are: good extrudability, good layer adhesion, plasticity, shrinkage while drying, cracking while drying, to bridging ability.

Mixtures of soils and additive materials

	Material/Mixture	1	2	3	4	5	6	7	8	9	10	11	12	13
	Soil Type	A	B	A	A	A	A-B	C	A	A	A	A	A	A
Earth	Clay	30	50	30	30	30	40	70	30	30	30	30	30	30
	Sand	70	50	70	70	70	60	30	70	70	70	70	70	70
Additives	H_20+ Cellulose	-	-	-	-	-	-	-	-	30	-	-	-	-
	Straw	10	-	-	10	-	-	-	30	-	-	40	30	-
	Milled grain	-	-	-	-	-	-	-	-	-	20	-	-	20
	Water	25	20	30	25	20	20	20	25	-	45	35	35	60

Tab.3: different mixtures of soils and additive materials, all values in % of the volume

5.3. Toolpath and Nozzle experiments

After the initial manual material tests three mixtures will be selected for the more detailed nozzle and toolpath tests with the robot and the extrusion set up. If all the mixtures will be tested in depth it would consume too much time. Mixtures that failed already in an early stage at the manual extrusion test are considered not suitable for further testing.

Nozzle design

6 Nozzles will be initially tested during the first experiments see *Fig. 9.* The goal of the different nozzles is to achieve a reduction of the density per volume to create a gradient material. The different nozzles create cavities and hollow parts due to certain print paths and patterns. In addition, the nozzle shape should preferably increase the interlayer bonding and allow contour crafting as it can be seen in *Fig. 12*. The exact density per Volume will be evaluated due to printed cubes *Fig. 20a*. One cube of 100/100mm will be the reference density of each mixture and casted. The density will be evaluated through the weight divided through the volume.

$d=w/V$, $V=a*a*a$. The weight will be taken with a kitchen scale in g =Gramm and display in kg.

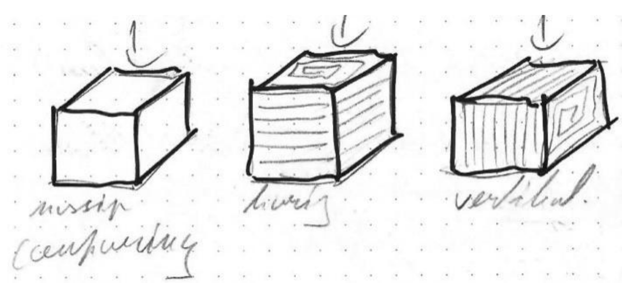

Fig. 37a: Solid cube and printed cubes. This test should show the density shift per volume when different nozzles and toolpaths are being used.

Experiment-toolpath design

To define the limitation for the toolpath certain experiment tool paths will be created. They will be divided into three major groups:

a) single layer extrusion *Fig.21*

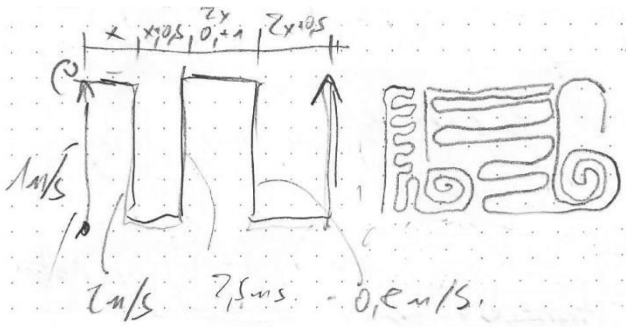

Fig.21: Solid cube and printed cubes. This test should show the density shift per volume when different nozzles and toolpaths are being used.

The experiments with the single layer toolpath will show the relation between the travel and extrusion speed. The same path will be travelled with different speed and extrusion flow. The evaluation of this experiment will lead to an optimal travel speed and the correlating extrusion flow. In addition, this experiment leads to the toolpath limitations of the different nozzles. Therefore, this experiment toolpath will contain different extrusion angles, radiuses as well as distances to the printing surface.

b) stacked layer extrusion – bridging *Fig. 22*

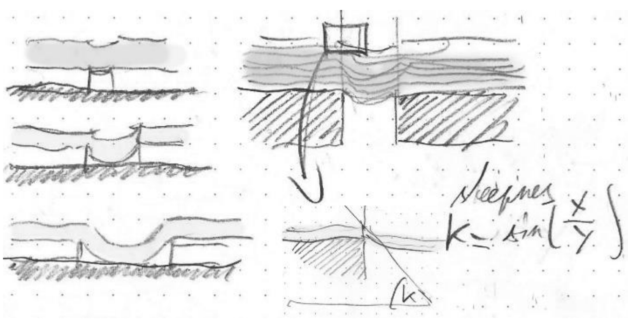

Fig. 22: How far can the extrusion bridge gaps? The bridging ability of the material mix will influence the toolpath design and density per Volume largely.

The stacked layer extrusion will analyse the bridging ability of the tested material mixtures. The wider an extrusion can bridge gaps over the bottom layer the better. A good bridging ability is important for the approach of creating a gradient material by designing the infill geometry. For this test multiple parallel lines with an increasing distance will be overprinted perpendicularly. Evaluated will be the deformation of the bridging extrusion and the angle k, as seen in Fig. 22. Another important result will be if the bridging extrusion is touching the printing surface below or not.

c) stacked layer extrusion – interlayer-bonding Fig. 23

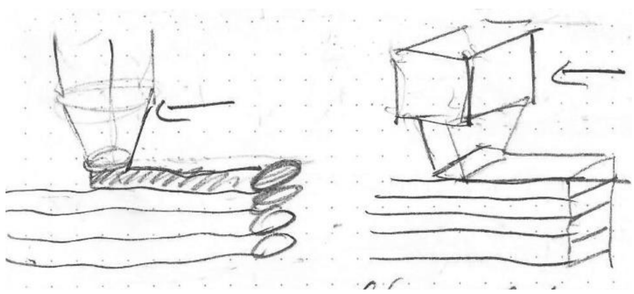

Fig. 23: Difference of interlayer bonding depending on nozzle form and extrusion angle. Will the material be extruded on the surface or lying on it?

The nozzle form and extrusion angle influence the interlayer-bonding largely. The difference between a “layed down” extrusion and an extrusion that presses the new material on top if the existing layers will be tested in this experiment. As it can be seen in Fig. 23 the shape of the nozzle can increase the contact surface between two layers. All 6 nozzles will be tested on various toolpaths to evaluate the optimal interlayer bonding. Especially interesting will be the combination of different nozzles and the influence on the toolpath design.

5.4. Printing environment and post production treatment

The temperature and humidity of the LAMA can be adjusted. However, a constant environment during the printing is more important than a certain temperature or humidity. The printing process will be adjusted according to the existing standard room temperature.
The drying process of the component should be as slow as possible to avoid shrinkage cracks. A cool and humid environment should allow a continuous slow drying. We will try creating this by covering the large printed objects with a plastic heat and store them in the basement. By removing the sheet several times a day, the excessive water can escape and the component should dry. To allow a statement about the

efficiency of this drying process we will "shock dry" the second specimen at the LAMA. The third specimen of a larger object will be dried next to the firs in the basement but not covert by a plastic sheet.

5.5. Expected outcomes of the experiments

The experiments lead to a better understanding of the effects different mixtures and nozzles have on the printing process. Small changes like water content or fibres can change he usability of a mixtures tremendously.
I will evaluate the plasticity and the extrudability of the mixtures. In addition, overhanging layers and toolpath limitation such as curve radius and speed will be on the scope. The ability of shaping the mixture with the extrusion nozzle is one of the mains scopes.

The expected results are listed below. Their cross relation should give enough information to answers the expected outcome above.

- Shrinkage
- Density
- Compression under self-weight
- Tool path limitations
- Surface cracking during production
- Cracking during the drying process
- Interlayer bonding
- Nozzle influence on the extrusion geometry
- Extrusion angle and flow
- Material mixture
- Possible contour crafting
- Limitations of the production set up for a 1:1 prototype
- Productivity in relation to a conventional single nozzle production

5.6. Result evaluation

The most promising results were already evaluated and are listed below. According to the research timeframe the experiment evaluation is scheduled after the P2. The shrinkage was measured with a ruler. Two marks, a distance of 100 mm were made into the wet clay and measured after the drying process.

Mixture: 7**, Soil:** A, **Nozzle**: Rectangular, 10*8mm

Fig. 38: rectangular nozzle, linear and S-shape single layer, stacked layer extrusion.

Extruder:	Manual
Shrinkage:	1%
Production cracks:	Barely
Drying cracks:	No
Deformation under self-weight:	Barely

Production evaluation: Easy to handle and extrude. The rectangular nozzle needs to be tangential to the extrusion path it the mixture gets extruded non-perpendicular to the printing surface. The rectangular nozzle allows a good interlayer bonding when the extrusion is "laid down" instead of extruded on the printing surface. The extrusion stayed good in shape of the nozzle.

Comment: Soil A is a promising mixture, and suitable for paste extrusion. The mixture will be further investigated after Silt is added to the mixture.

Mixture: 6**, Soil:** A-B, **Nozzle**: round d=12mm

Fig. 39: Mixture 6 extruded on the print surface. single layer, stacked layer linear. stacked layer S-Shape.

Extruder:	Manual
Shrinkage:	1%
Production cracks:	Yes
Drying cracks:	No
Deformation under self-weight:	Barely

Production evaluation: Good to handle and extrude. Perpendicular extrusion on the printing surface allows curvy toolpath without the necessity of rotating the nozzle and good interlayer bonding.

Comment : Soil A-B is a promising mixture, and suitable for paste extrusion. The mixture will be further investigated after Silt is added to the mixture. The production cracks were surprising since we assumed that more clay will reduce cracks during the production. We expected an increase of crack due to fast drying.

Mixture: 7**, Soil:** C, **Nozzle**: round d=12mm

Fig. 40: S-Shaped laid down single layer, stacked linear layers extruded on the printing surface, stacked laid down extrusion, tower extruded on print surface.

Extruder:	Manual
Shrinkage:	1%
Production cracks:	No
Drying cracks:	No
Deformation under self-weight:	Barely

Production evaluation: see mixture 6, in addition: very plastic mixture. Good interlay bonding even when the round extrusion is laid down on the printing surface.

Comment : Soil B is very promising and will be further investigated after Silt is added to the mixture. Due to the good extrusion ability and plasticity a mixture between Soil A-B and B will be tested

Mixture: 7, **Soil:** C, **Nozzle**: round d=12mm

Fig. 41: stacked layers with laid down extrusion and 60+° overhang.

Extruder:	Manual
Shrinkage:	1%
Production cracks:	No
Drying cracks:	No
Deformation under self-weight:	Barely

Production evaluation: very sticky and plastic mixture, high risk of entrapped air, harder to extrude then the other mixture. Very good interlayer bonding allows extrusion on non-horizontal printing surface and over 60° overhangs.

Comment: Maybe not suitable for standard extrusion. Interesting for overhang printing or printing domes with customized nozzles for cycle time reduction.

General experiment statement

The first manual experiments were above our expectations. The tested soils where all easy to extrude. Modification of the extruded geometry should be possible for all soils. This however needs to be further evaluated with manual and robotic experiments. The mixtures where fibres where added were hard to extrude. The required high compressional force pressed the water out of the mixture. Fibres could be possibly added with CC. For further experiment we try to purchase Sand and Silt that are already sifted and have a certain grain size distribution.

6) Reflection, Relevance

6.1. Reflection

After the first literature studies and experiments, I feel confident in achieving a feasible component and nozzle design. Additional test and experiments will be necessary. In particular, the calibration of the extruder and the robot will be challenging. Adjusting the extrusion flow according to the print speed and specific movements will include additional experiments. Collaborating with Rodiftsis, A. for the experiment was very helpful and will be continued. The different approaches regarding a similar topic is inspiring. The material earth is very intuitive. To develop the right viscosity or a mixture the manual experiments helped a lot.

6.2. Societal, economic and ecological relevance:

Enabling a traditional, sustainable and low-tech building material that is also cheap but requires a lot of labour costs to become a mainstream building material again. Reinterpreting old techniques and traditional materials and combining them with digital fabrication could help decarbonising the construction sector. Especially for industrialised countries, robotic fabrication by 3dpriting earth offers an option to produce economically with high efficiency. Simultaneously, a huge ecological benefit is created.
However, the societal impact of digital/robotic fabrication is currently broadly discussed. Some say that we will face a huge crisis of unemployment since many workers will lose their jobs. Others see a bright und flourishing utopian future where machines create the wealth.
As the Philosopher Richard David Precht states “the future is not happening, we create it” [23] In this sense, technological innovation will always have an impact on society, economy and the environment, but it is up to us, as a society, to determine whether it leads us towards a utopian or dystopian path. 3DPE is of course not the overall solution but could be in several cases a possible low carbon alternative.

6.2 Projected innovation:

Since 3DP with clay or other ceramics does not require any heat during extrusion, the customisation of the nozzle is much easier than for thermoplastics nozzles. Multi-outlet extruders can print two or more layers next, or on top of each other. Customizing the nozzle could be easily produced with a conventional thermoplastic printer. This would increase the efficiency of printing a mono gradient material. Including multiple nozzle designs already in an early design stage into the component design could influence the whole production (printing process). Additional contour crafting would allow producing a gradient material from two different materials, increasing the performance even more. The customized tooling for a gradient material should result in faster print speeds, reduced tool paths, and a better thermal performance.

The practical feasibility of 3DPE will largely depend on further developments, such as regulation and materials taxations. Although, I expect that there will be niche for additive manufactured gradient earthen building components.

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Figures and Tables:

All sketches, pictures, tables, schemes are done by Autor, except a source is mentioned.

Fig. 42.: microscopic view of a wooden year ring, alamy.com
https://www.alamy.com/fig-94-querschnittsansicht-des-holzes-der-weitanne-abtes-pectinata

Fig. 43: trowel control unit to modify the extruded paste
Youtube screenshot, Alto University Finland
https://www.youtube.com/watch?v=1Pq4YVi_Q-M&t=34s

Fig. 44: traditional German half-timbered house. Dethier J. (2019). Lehmbaukultur 262-263

Fig. 45: ERDEN, production Hall
http://www.lehmtonerde.at/de/aktuell/#news226

Fig. 46: Digital adobe
https://iaac.net/project/digital-adobe/

10) Appendix

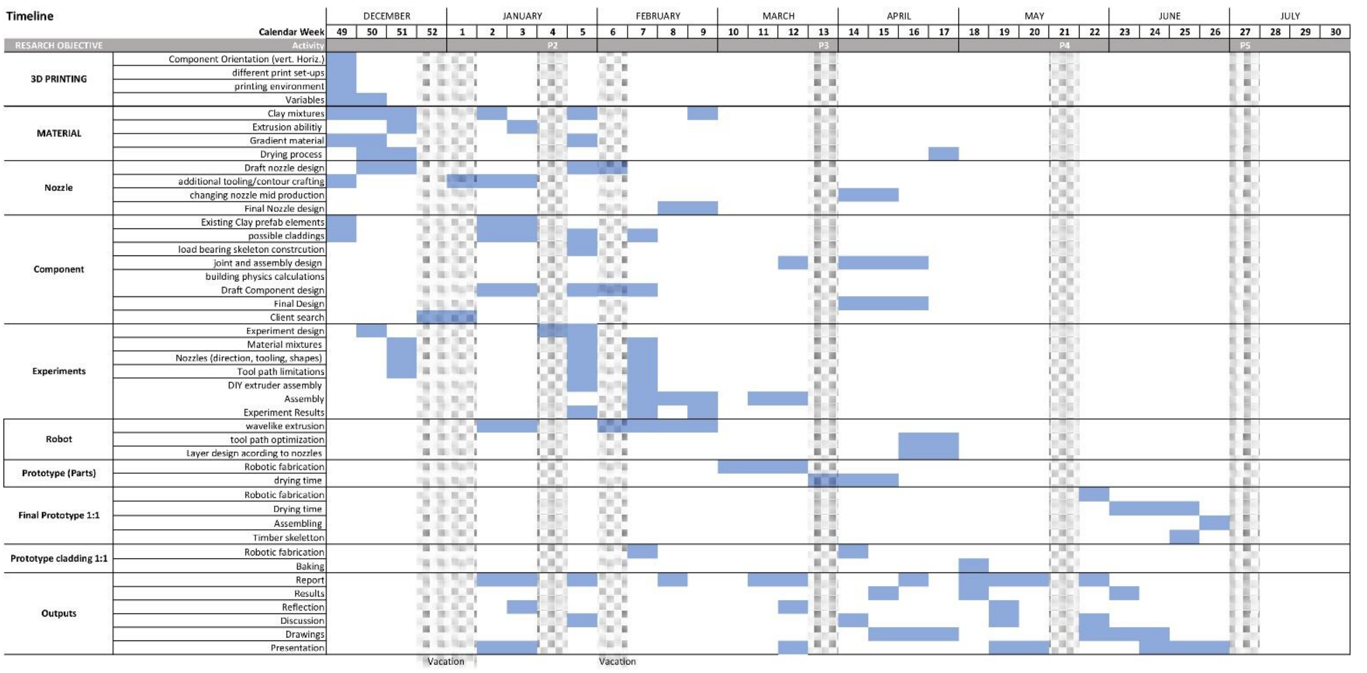

Fig. 47: Schedule