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.

Master Thesis by Maximilian Mandat 2020

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Master Thesis

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Abbreviations

AM - Additive Manufacturing
3DP - 3-Dimensional Printing
3DPE - 3-Dimensional Printing Earth
LAMA- Laboratory for Additive Manufacturing, Faculty of Architecture, TU Delft
FGM- Functionally Graded Material
CLT- Cross Laminated Timber
CDT- Cross Doweled Timber
EOL- End of Life
DIY- Do It Yourself
TCP- Tool Centre Point
PU- Poly Urethan
CC- Contour Crafting
CNC- Computerized Numerical Control
IAAC- Institute for Advanced Architecture in Catalonia
VPB- Vertically Perforated Brick

Software:

RN- 3D CAD software: Rhinoceros
GH - Grasshopper, a Plugin for Rhinoceros
AR- Arduino: Software for the extruder control
RDK- RoboDK: Software for robot control
S3D- Slicing software: Simplify 3D

1) Abstract

To cope with the climate crisis, sustainable and eco-friendly buildings are a necessity. To achieve this, we need to change the way we build, this accounts as well for construction materials. For thousands of years, humans have lived in clay and timber hybrid constructions. These hybrids are made of sustainable, possibly circular, highly available and renewable materials with low embodied energy. However, the labour-intensive production makes these hybrid constructions expensive. This was, among others, one reason why modern architecture and construction looked to other, industrial and artificial building materials to satisfy our need for cheap, fast and prefabricated construction methods. The promising, traditional combination of earth and timber has barley been used for prefabricated wall components and façades, despite their huge ecological benefits. On the contrary, questionable and polluting building technologies and materials are used to increase the efficiency within the construction sector. These materials have a large carbon footprint compared with clay or timber.
As designers and engineers we should start looking back into clay/timber hybrids as one solution architecture can offer as an answer to the climate crisis, despite the high labour cost of this construction type. Digitalisation might be a solution to tackle these high costs. Customized computational design, large-scale 3D-printing and file-to-factory robotic fabrication allow the automatization of certain labour-intensive production steps. It offers new perspectives on production techniques and material usage. The fourth industrial revolution could, in combination with changing legislation and CO^2 taxation, lead to a revival of clay/timber hybrid buildings. These hybrids could be made of timber with a density decreased gradient material infill, such as 3D printed with clay.

Exploring material mixtures, production techniques and building components results in a computational, informative workflow for customized nozzles and the building component. This allows to coordinate and customise the nozzle design according to the limitations of the material properties, the building component and the 3D printing process.

But how can the density of a 3D Printed clay prefab wall component with a 6-axis robotic arm be gradually decreased? Designing a gradient material that is dense on the inside and gets increasingly lighter towards the outside could increase the efficiency by adding another function to the earthen building element. The created cavities reduce the density, the thermal conductivity and the material usage compared to a traditional solid earthen infill. To simplify the toolpath and reduce the cycle time each density class of this stepwise gradated wall system has its customized nozzle. The customization of the nozzle allows to print a complex cross-section geometry with a simplified, otherwise complex toolpath.

Establishing an informative workflow between the building component design, the production tools and the material mixture should lead to a design that is considering the limitations of each input category. Ideally, this approach reduces the necessary amount of adaptations before the earthen component infill can be printed. The nozzles will be customized to reduce the cycle time and shorten the toolpath by creating a gradient material at the same time. This material can be used as an infill for a hybrid wall structure.

To evaluate the density decrease of the extruded mixtures and used nozzles, manual experiments were performed, since the robotic arm was not available due to the lockdown of the faculty. These experiments offered detailed information about the 3D printing extrusion process and showed that a density decrease is possible due to the customized nozzles.

This research by design approach resulted in the design and prototype of a prefabricated wall component from two of the oldest construction materials of humankind with state-of-the-art digital robotic fabrication. The final product aims to do no harm to the user and the environment from cradle to cradle. In addition, it should contribute to mainstream clay as a construction material for multi storey buildings.

2) Introduction

2.1. Background

We need to develop circular construction systems that do no harm to the environment nor the user.
A possibility to achieve this, is using natural materials with low embodied energy in a digital fabrication process.

Circularity

Due to limited resources on our Planet and an increasing use of energy 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 and construction. 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. (Adams, 2017)

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 flow with natural materials. 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. (De los Rios et al., 2017)

Reviving traditional construction techniques with digital fabrication

The optimization of production and planning methods that the digitalisation offers are mostly wrongly considered as the enemy of traditional construction and craftmanship. But every emerging technology offers new ways of production, the usage is determined by the user or designer. Digital fabrication offers the chance of using a construction material that humankind uses for millennia, 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 conflicting.
Robotic 3d printing clay offers the chance to use a low-tech material without losing the large potential of a digital fabrication.

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). This Technology enables to design and produce elements with complex geometries. This increases their performance and allows a production without the necessity of formwork. Shape optimisation, form finding, or functional gradation leads to strong and relative lightweight building components. Especially for prefabrication robotic 3DP offers many opportunities and unleashes multiple new potentials while reducing the amount of required labour. (Neligan, 2018)

Societal, ecological and economic relevance:

The research aims to enable a traditional, sustainable and low-tech building material that is also cheap. However, traditional clay constructions are often labour intensive; through digital fabrication such as 3D printing these costs can be reduced. Reinterpreting old techniques and traditional materials and combining them with digital fabrication could additionally help decarbonise the construction sector. Currently technologies such as additive manufacturing (AM) have an high embodied energy. This is caused by the relatively long toolpath length compared to conventional CNC milling. This increases the amount of electricity that is required for the production. On the other hand, AM, especially liquid deposition modelling (FDM) creates less waste and can reduce the footprint compared to a subtractive manufacturing process. **(Faludi et al, 2015)**
The footprint of the electricity depends largely on the source of the energy. If the electricity is produced from renewable sources, the CO^2 footprint

decreases largely. The embodied energy depends on the material for its production, the machines and the energy mix of the power grid. This research does not focus on the CO^2 footprint of the machines or the energy production. It can be stated that the footprint of regional earthen material mixtures is rather low. Especially for industrialised countries, robotic fabrication and 3dpriting offers an option to produce economically, highly efficient earthen building components.

However, the societal impact of digital/robotic fabrication is currently broadly discussed. We at a fork in the road with two directions, a optimistic and a pessimistic direction. Pessimists might state that we will face a huge crisis of unemployment since many workers will lose their jobs. Optimists 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". (Precht, 2018)
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 production alternative.

The economic downfall due to the corona virus causes many countries to set impulses to strengthen the economy. Those actions should lead towards a sustainable future. The reasons of climate damaging constructions are known for half a century now but till now nothing much has changed. But the trend is luckily changing, timber and clay construction are getting more and more popular. The time where clay-timber construction solutions were not being taken seriously is over. To reduce greenhouse gas emissions, clay constructions have the potential to become a major part of future building systems and construction technique, resulting in an ecological built environment. (Anger, 2019). This project aims to contribute a small part to help mainstreaming this sustainable construction material. Of course, politicians, architects, engineers and many more must collaborate strongly together to achieve a shift towards a circular build environment.

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 a thermoplastic nozzle. Extruders with Multi-outlet nozzles could print two or more layers next, or on top of each other. This could allow the deposition of several layers at once. However, this limits possible toolpath options largely, since this method works well for straight lines but has multiple problems while printing curves. Producing customized nozzles could be easily achieved with a conventional thermoplastic desktop 3d printer. This would increase the efficiency of printing a material with a customized performance profile or functionally graded material (FGM). This function profile can be according to specific demands like insulation or structural properties. Customized nozzles offer to print cross section patterns that are almost impossible to print with non-customized nozzles. 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 due to a reduced density of the 3DPE element. The financial and practical feasibility of 3DPE will largely depend on further developments such as construction regulations and materials taxations according to their Co2 footprint. This might open a niche to establish 3DPE on the market.

2.2. Problem statement

Clay is a sustainable, widely available material with low embodied energy compared to industrial building material such as concrete or steel. (Houben et al., 2019) Despite its benefits, the labour-intensive, small scale industrial production is a major cost factor for clay buildings and components. The material costs of a standard timber framing construction with a clay infill can be estimated below 10% of the total costs of the construction. (Schroeder, 2013). Of course, the value is changing depending on the location, quantity and used material. It is to mention that these costs are only estimated for the finished construction and do not include maintenance and operative costs. Unfortunately, the costs for primary energy balance, recyclability and positive effects on health and wellbeing are not taken into consideration. (Schroeder, 2013)

Large-scale 3DP in combination with robotic fabrication offers a possibility to increase the production efficiency of clay building components. An automated production reduces the cost and 3DPE offers new applications for clay.

Increasing the efficiency of earthen building components, by reducing the density and therefore adding a insulation function to the materials, could help to re-establish this sustainable and circular construction material on the market. Several problems are holding back large-scale additive manufacturing from transforming the market revolutionary. 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.

To target those, the problems can be divided into three major groups

1) Material

2) Component design and application

3) 3D printing and production

1) 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 cycle time is the required time to print one layer. The rule of thumb is to avoid a dry joining of overlaying layers (Wangler et al., 2016). This problem is mainly witnessed during concrete 3DP, where accelerators let the concrete harden faster than the cycle time. Since clay is not chemically hardening like concrete but physically due to evaporation (Reeves et al., 2006) of water the risk of dry joining is neglectable for 3DPE.

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 postproduction. Especially the conditions under which the clay is drying are important.

When the applied clay mixture is drying too fast it will cause cracks that can influence the structure and appearance of the designed building component. This will be investigated by experiments and is described in "*4.2. - Printing environment and postproduction*". It might be beneficial to have a climate chamber that allows to control the humidity.

It is important to mention that organic material such as straw or rice grain husks might mould 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.

2) Building component design

- **Finding a niche** developing case study to possibly implement the component on the market.
- **Structural performance** of clay results in its use as infill for a loadbearing frame, or a massive monolithic structure
- **Infill design** designed to achieve a gradient density shift.

To re-establish Earth as a construction material, it is necessary to find a niche where it can be applied. Adding another function 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. Developing a gradient clay infill is a challenge for conventional clay manufacturing. This could be solved with customized nozzle for 3DPE. In this case, it would be the goal of achieving a gradient material design that allows irregular and variable sizes for a structural frame infill. Both challenges will influence the design and production of the clay component.

3) 3D printing and production

- **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 et al., 2006) and following publications offers a good insight into this fabrication process.

The toolpath design depends on the wet and dry material properties, the size and characteristics of the nozzle and the geometry of the produced element. (Buswell et al., 2018) One fact that occurred during the research repeatedly was that most 3DP processes are designed for one single nozzle. Printing complex elements with only one nozzle seems not very efficient. A single nozzle print requires is time consuming for complex cross section patterns, since the toolpath length increases dramatically. 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 more options for the digital fabrication process. (Khoshnevis et al., 2006)

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. (Wangler et al., 2016) The shorter the cycle time the faster one layer can be printed. Reducing the necessary printable layers by increasing the layer height reduces the amount of required cycles and possibly the production time. It is important to understand that changes on one parameter influence many others as well. A clear separation in different topics is not always possible or desired. The process should not be optimized only according to one parameter. Nevertheless, small changes can have a big influence on the overall printing time. Changing one parameter, might increase the print speed but elongate the drying time and increase the deformation under self-weight. (Buswell et al., 2018)

Some of the influencing and adjustable parameters are:

- The Layer height and width (the geometry of the nozzle in general)
- The extrusion speeds
- The print speeds
- Orientation of the component (“lying” or “standing”
- Material (inertia, deformation under self-weight)
- Cycle time
- Batch sizes or max. print volume

Hypothesis

Designing a gradient material that is dense on the inside and get increasingly light to the outside could increase the efficiency by adding another function to the material. The created cavities reduce the density and should reduce the thermal conductivity. To simplify the toolpath and reduce the cycle time each density class of this stepwise gradated wall system has its customized nozzle. The customization of the nozzle allows a simplification of an otherwise complex toolpath.

Establishing an informative workflow between the building component design, the production and the nozzle should lead to an design that is considering the limitations of each input category. Ideally this approach reduces the necessary amount of adaptations before the component can printed. 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.

2.3. Objective

1) Material

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

2) Component design and case study

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

Designing a building component for the 3DPE infill.

What component design 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.

3) 3D printing and production

Creating an informative workflow between the nozzle design, the building component design and the robotic fabrication.

The workflow is based on findings from research by design and active experimentation

Developing various customized nozzles to create a 3d printed infill. The different nozzles should create a density shift within the 3DP element.

<u>Boundary conditions</u>

The main approach is to research by design and design by research. This should lead to the design of a prefab exterior wall component. The wall will consist out of two main parts, a structural, protective frame and a 3D printed earthen infill.

The dimensions and calculations for load bearing timber skeleton is out of scope of this research.

The 3DPe infill will be printed with an 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 voids on the outside should increase the thermal insulation.
The current attempt is a mono material mixture print. The thermal insulation of the wall is not the scope of this research. The increasing thermal insulation will be achieved due to a density reduction. It is assumed that the lighter the relative weight per volume the higher the insulation properties.

The scope will be on the design and production of the gradient 3DPE infill and the necessary nozzles and toolpath to produce this element. A computational design process will establish the informative workflow between the material, building component and production limitations. The inputs for the informative workflow are based on the literature research as well as the results of the research by design manual experiments.

2.4. Research Question

How can a gradient 3d printed clay wall be produced by customizing the nozzles within the limitations of the production process and the material?

<u>Sub questions</u>

The sub questions are divided into the three major group regarding the material, the production and the building component.

The Sub question will be answered in the literature study “state of the art”, the evaluations of the experiments mentioned under the chapter “experiment design and results” and in the “design” chapter.

- ### 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 an extrusion process?

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

- ### Building component

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

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

How can the building component be designed by only using natural materials?

How can the component be designed to withstand the forces during the transportation and assembly?

- ### 3D printing and production

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

How does the 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 would be the optimal printing set up for a production with customized nozzles?

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

2.5. Research methods

The general approach to this research is to define limitations for the design and production due to literature research and active experimentation. Those limitations will be used to create a functionally gradient material, customized nozzles for its production and a building component where the 3DPE infill is implemented. This should result in an increased efficiency, since another function is added to the clay element.
In general, the practicality and feasibility of the production will be explored by a "hands on" design as described in the points below.

Literature review and **active experimentation** about the three columns of this research: Material, production and tools, 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 seen in Fig.26 should result in limitation for the component and nozzle design.

Experiment-Toolpath and draft nozzle design will be done like described under chapter "4.3. Toolpath and Nozzle experiments"

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.

Due to the closing of the architecture faculty, caused by the Covid-19 Pandemic, it was unfortunately not possible to use the *Comau NJ60 2.2* robot for the above-mentioned experiments. Instead all experiments where held with the manual extruder, as described under *"4.1 manual clay extruder".* Hopefully this experiment could still be

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

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.

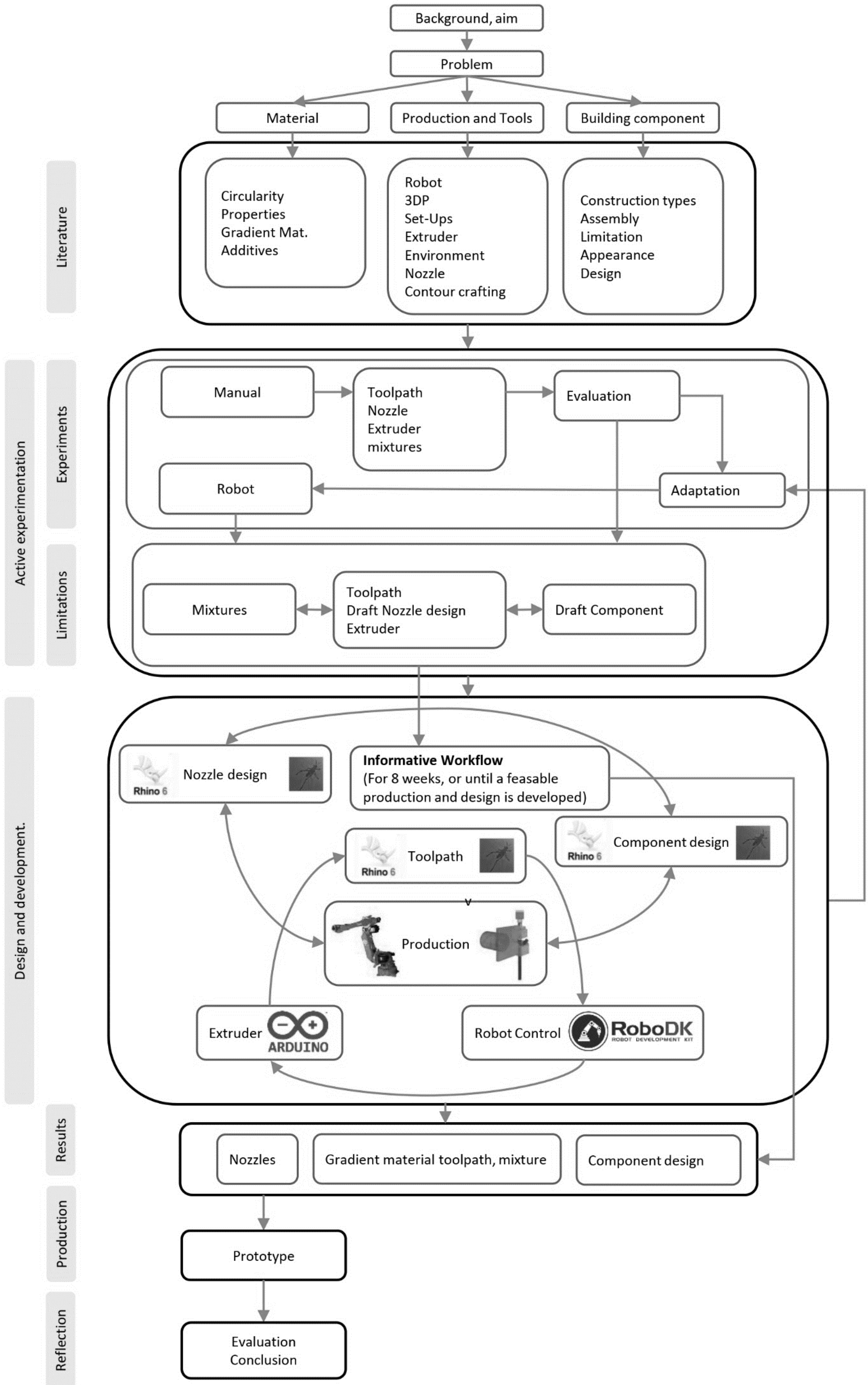
Production workflow for the robot and extrusion control. The toolpath will be exported to *RoboDK (RDK)* to control the Robot, its travel and extrusion speed. The extrusion will be controlled with *Arduino* over the g-code created by *RDK.*

Nozzle customization according to density requirement of the gradient material. The building component and the nozzles will be further designed 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, vertical or horizontal orientation during the printing process, density shift)

Scheme of the approach and methodology, can be found on Page 11



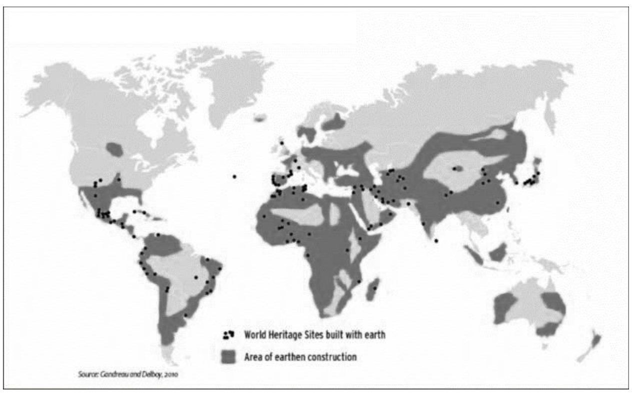
Research approach/methodology scheme

3) State of the Art

3.1. Material Earth

3.1.1. 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 millennia 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 dense urban environments of industrialized countries. (Dethier, 2019)
This chapter the material earth is the elaboration on the properties of pure, unfired earth in dry and wet state. This material is found in large occurrences around the globe and is one of the most available resources on Earth. In addition to its almost infinite availability *Fig. 1*, it is one of the most sustainable materials we can use for constructions. (Lévi-Strauss, 1990) It requires almost no energy for its extraction, can be gained locally and is therefore 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.



Fig,: 1, Source: (Gandreau et al., 2010). Zones in which traditional clay constructions exist + earthen world heritage sites

The price of building materials is currently not reflecting its impact on the environment. A Co2 taxation is currently discussed in many countries in order to fulfil the recommendations of the *Intergovernmental Panel on Climate Change*.
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". (Brown, 2001) Earth as a construction material would become much more attractive if construction material prices would reflect their environmental impacts.
Earth could help to reduce the industrial pollution, is ecological harmless and cheap. The extraction from the ground requires no chemicals or complex industrial processes. In short: Earth does neither harm the planet nor the user. We could use the most primitive material to build to most sophisticated houses (Dethier, 2019).
Although there are many benefits, there are specific challenges for this material in industrialized countries. Especially structural behaviour and erosion tests are hard to pass for earthen structures. Furthermore, the production is labour intensive and requires skilled craftmanship as guidance. This leads to higher construction costs and longer construction time (Houben et al., 2019). This could be changed with prefabricated building components that are assembled on site.
Of course, earth, like every other material, has its limitations. It can barely take tensile forces and needs to be used under compression. (Reeves et al., 2006) 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. This accounts as well for timber constructions and is known as constructive timber protection. To allow higher constructions or span widths earth can be used as an infill into hybrid construction. A structural system made of timber, steel or concrete could support infills made from earth. (Gauzin-Müller, Dethier, 2019) This topic will be further elaborated in "*3.2.1. Hybrid construction"*

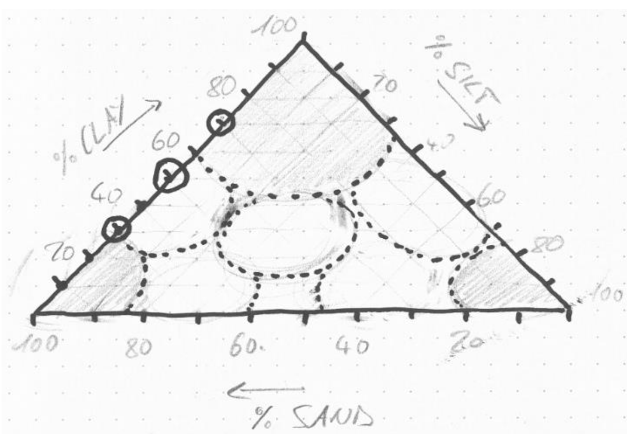
3.1.2. Circularity

Using Earth as a construction material is not a concurrent for agriculture. (Gauzin-Müller, Dethier, 2019) Agriculture needs the top layer of the ground that is rich of organic matter to grow crops. Earth which is suitable for constructions is found under this fertile layer and is mostly a mixture of sand clay and silt as seen in *Fig. 2.*

Cities and large metropoles are trying to implement circular concepts to become less depending from their 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 potential of these excavations got less attention until now although it can be used for earthen constructions. The metropole region of Paris is currently changing this. The excavated material that need to be moved to make space for the new regional connection "Grand Paris Express" between 2016 and 2030 could be brought to special sorting landfills. A new emerging field of earth moving companies is separating and sifting the reusable, clay containing layers and checks them for undesired contaminations. This allows it to be used as a sustainable, upcycled construction material an reduces the negative ecological impact of landfills. Another positive side effect is the reduced dependency of Paris for sand and gravel. It shows that there is an ecological, political and technological transformation happening. This leads 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 excavation material as construction materials. (Gasnier, Dethier, 2019)

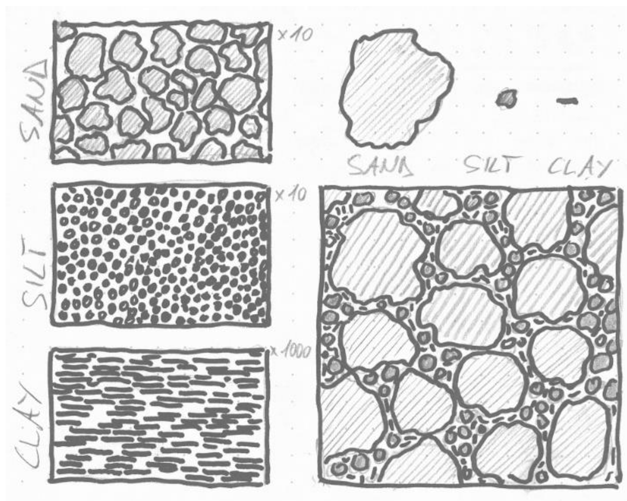
<u>*3.1.3. Properties of Earth as a construction material*</u>

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 the diagram *Fig. 2, Fig. 3.*



Fig,: 2, 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. It is important that the size of the grain is distributed according to a sift curve in order to minimize possible cavities. It allows smaller particles to fill the voids between larger ones as visible in *Fig. 3.* The fine adjustments of the sift curves need to be developed by a material scientist especially for and additive extrusion process.
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. This is one reason why rammed earth walls are the strongest earthen constructions.



Fig,: 3, 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.

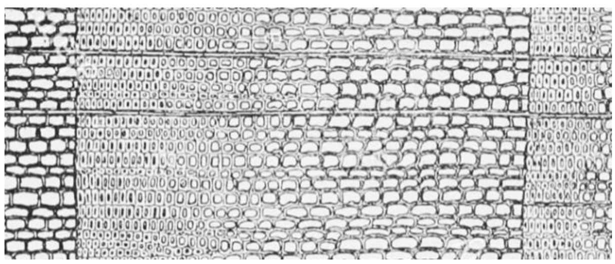
This friction is responsible for the maximum angle of repose if no other binders are added. The cohesion is the force with which the granules and grains are attracting to each other. In this case it is a combination between gravity and electrostatic charges. The electrostatic charges are even between very small particles which is remarkable, since positive charged particles are attracted to negative ones. If water is added to the mixture, there 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. The importance of this additional tensile strength will be elaborated later under the chapter. *"4.4. Result evaluation"* But this applies only if there is not too much water in the mixture. In this case, it increases the rheology and creates a material mixture that is pump-able and extrude-able so long as the water does not get pressed out of the mixture. (Reeves et al., 2006)

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 particle morphology 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. These properties of clay are what 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 force 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 and clay content the more shrinkage will happen. The tensile forces created due to the volumetric change causes cracks. The structural strength of a dried material depends largely on the water content of the wet mixture – a phenomenon that occurs as well in concrete. When the mixture is too wet, the evaporating excessive water causes large pores, that cannot be filled with clay or silt particles. These pores decrease the structural properties but at the same time increase the ability to regulate the humidity and absorb odours. (Houben et al., 2019)
The mechanical properties of a raw, unbaked earthen mixture without additives therefore depends largely on the water content of the mixture before the drying process. (Reeves et al., 2006)

The structural properties of clay can be increased by adding additional materials 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 the reuse of the earthen mixture as a circular material anymore. If additional binders are added the reusability is not possible anymore, since the clay flakes are permanently bonded together.
Terracotta or "cooked earth" increases most of the structural properties of unbaked earth by sintering the clay and sand particles together. But the baking process is an energy intensive production. This increases the carbon footprint tremendously. (Dethier, 2019)
Since the clay flakes in terracotta are melted together the material is not reusable anymore.
Since the circularity of the material is one of its major benefits, no additional non-biodegradable or artificial binders will be used during this research.

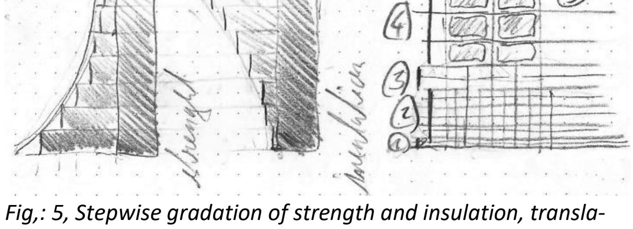
3.1.4. Gradient Materials

A gradient material is a 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. (Herrmann, Sobek, 2017) This results in a material or building component that has a continuous parameter change within its cross section. The desired parameter change for the research is the density. A good visualisation of a natural gradient material is the microstructure of wood, or the structure of bones. Every year-ring of wood consists of a denser and a lighter part. The denser part is the darker and stronger part of the year-ring. There is a gradient shift from light to dense as it can be seen in *Fig. 4.* The cell wall thickness increases as well.



Fig,: 4, Source: (Alamy) Microscopic view of a wooden year-ring. A seamless density shift can be seen within one year.

By decreasing the density of a 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. 5*. 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. (Herrmann, Sobek, 2017) This stepwise gradation along a declining curve can be seen in *Fig. 5 on the left.*



Fig,: 5, Stepwise gradation of strength and insulation, translation into a concept cross section of an functional graded exterior wall.

The principal of an 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 insulation. At the same time the wall is dense on the inside for thermal mass. Developing an FGM from a single earthen material mixture, would allow a very efficient production and recycling process. There are two options to achieve the gradation:

Gradation due to nozzle design: For each stepwise gradation a customized nozzle and toolpath will be developed. This process is explained more detailed in *"3.3.4. Machines and tools – Nozzles".* The extrusion geometry of customized nozzles is depending on a constant material flow through the nozzle.

Gradation due 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". (Le et al., 2012) 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. (Buswell et al., 2018) 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. The gradation due to misprinting is best suitable for not customized nozzles.

3.1.5. 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 can increase the performance of the material. Although, the performance is still below the value that modern industrial building materials, such as concrete, steel and timber products 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 (Houben et al., 2019) As described above, reusing the material at its end of life (EOL) is not possible anymore when synthetic additives are applied. The low carbon footprint and the circular aspects are key properties of the material. To keep these properties, chemical binders were not further investigated in this research. Instead fibres and granules where investigated.

Fibres

Fibres are "reinforcing" the earthen mixture. As steel does in concrete, the fibres in straw are taking tensile 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**, **straw** and **thin branches**. Furthermore, they are agricultural waste and therefore a relatively cheap and available 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, Hemp and Jute** have thin and long fibres. This allows it to weave them into meshes or fabrics and apply them between printed layers. But such materials are specifically grown on arable land, which makes them a direct concurrence of food production. However, if the cultivation of these material is according to environmental standards biodiverse the use of these material can be considered as sustainable. As so often, the footprint of a material depends large on its source.

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 increase the contact surface between the fibres and the clay mixture. (Volhard, Röhlen, 2009) Production limitations of 3DPE will require shorter fibres– a topic that will be evaluated in the material mixture experiments. Straw fibres with a length between 4-8cm are often used for straw clay and to increase the structural properties of adobe bricks. Fibres with a length of max. 1cm are usually used in plasters. Since biobased fibres have a lower density than clay, the density of the material mixture decreases the more fibres are added.

Granules

As fibres, 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 usually used as substratum are baked. They expand during the baking process and turn porous inside while maintaining a closed surface. Due to the burning process 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 grain size. Clay granules are a mineral additive. The extrusion ability of a mixture containing granules is depending on the grain size and the machines size used for the process. If the grains are too big, the extruder or the nozzle will clog. 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, biodegradable granules. Especially for larger building components that require an extended drying process. A faster artificial drying process, in a dying chamber, would reduce this risk but increase the risk for drying cracks. (Schroeder, 2013). A accelerated drying process in a drying chamber increases the footprint of the production as well and should ideally be avoided.

3.2. Building Components with Earth

This chapter define limitations for a building component that includes 3DPE parts. Generally, I deferred two types of construction methods suitable to produce this component: Hybrid and monolithic. Both are detailed described below. Each construction type has certain benefits and downsides. The goal is to find limitations for a serial building system that allows to mainstream 3DPE. As previously mentioned, the designed building component should enable clay as a construction material for low and midrise buildings.

3.2.1. Hybrid construction

As mentioned previously this thesis aims to translate traditional constructions into digital fabrication methods. Hybrid clay construction are a well know construction technique. *(Volhard, 2016)* Some of the used techniques may help to develop a 3DPE containing building component that is produced digitally-
One of the most common clay timber hybrid constructions in Europe is the half-timbered house. Many, century-old examples that are in excellent condition can be found in France and Germany, *Fig. 6.* In a hybrid construction a structural skeleton carries the load of the earthen infill. The skeleton can consist out of any conventional construction material that allows to build a skeleton construction. The traditional skeleton material for earthen constructions is timber. It has the lowest embodied energy compared with steel, or concrete. Timber 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. Timber is in addition the only natural material that allows to construct a skeleton construction.
Especially for the urban environment, a hybrid construction offers the large benefit of building more than 6 Storey, while having a feasible wall thickness. (Kaufmann et al., 2018)

Fig,: 6, Source: (Dethier, 2019) 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.

Fig,: 7, Source: (Laimer, 2020) Traditional sub construction for the straw clay infill of a half-timbered house.

Due to no maintenance, the sub construction of the infill is visible in *Fig. 7.* This shows the importance to protect a clay façade surface from erosion. Either a water-resistant plaster e.g. lime plaster, or a cladding need to be applied. Traditionally branches or non-uniform timber was used to form a grid. Thinner branches where weaved horizontally in between bigger vertical element to form simple but stable grid. This grid is placed into the skeleton and the straw-clay mixture (light clay) was applied in multiple layers. The applied clay mixture has a good adhesion on the uneven grid of branches. In addition, the grid reinforces the infill an prevents that bigger parts of the infill are falling off.

Requirements for the Skeleton:

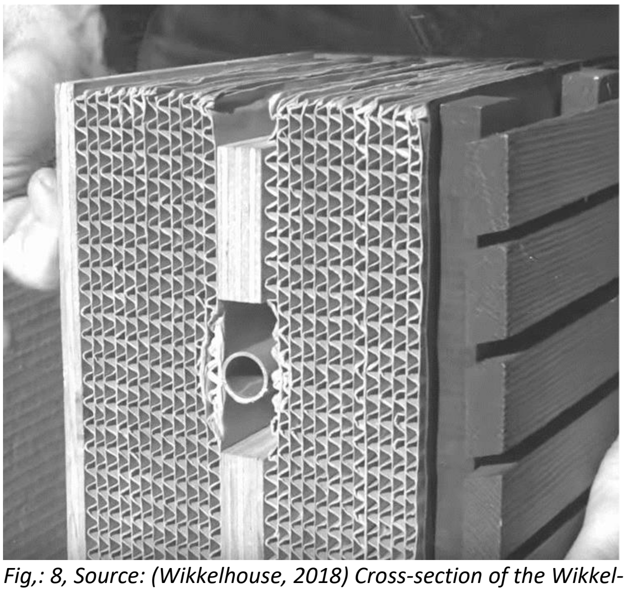
The load bearing structure of the building should be made from a conventional building material such as timber, steel or reinforced concrete. Preferably the structure is built from a natural material. The conventional construction materials are well known, the calculation can be referencing all standards. This means that the structure can be realised without the need of long and expensive structural test, that would be necessary if clay is the load bearing structure.
This simplifies the use of regional soil since its only requirement is being strong enough to carry its own weight. (Herzog, 2017) The skeleton needs to be strong enough to carry all loads of the building. The design should take advantage of the high load that is applied in form of the exterior wall component. Using the weight to pretension the floor slaps would be an option. Prefabrication requires a certain tolerance, to allow a problem free assembly on site. Timber constructions allow low tolerances and are limiting the risk of cold bridges in the façade. (Kaufmann et al., 2018)

Requirements for the 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.
The possible integration of the mentioned traditional sub construction would be useful. The sub construction could function as a thermal spacer between the inner and outer 3DPE element. The 3DPE infill is fragile due to its porosity, transportation and mounting might damage the element and could cause large cracks. To allow a good handling the infill should be protected by a casing or frame.

Spacer between infill

The planned infill could as well be separated into two parts. One denser part inside that functions as a thermal mass to regulate the indoor climate. A second less dense part outside, that increases the insulation properties of the wall component. As visible in *Fig. 8* the "Wikkelhouse" is separating the cardboard infill as well with a spacer. The spacer is used to create a gap for possible installations and cable management. Such a spacer could as well be used as a thermal break to decrease the thermal transmission through the wall. (Latka, 2018) In addition, the spacer could be used to create a new printing surface for the top 3DPE part, this reduces the compression under self-weight for the bottom 3DPE part.



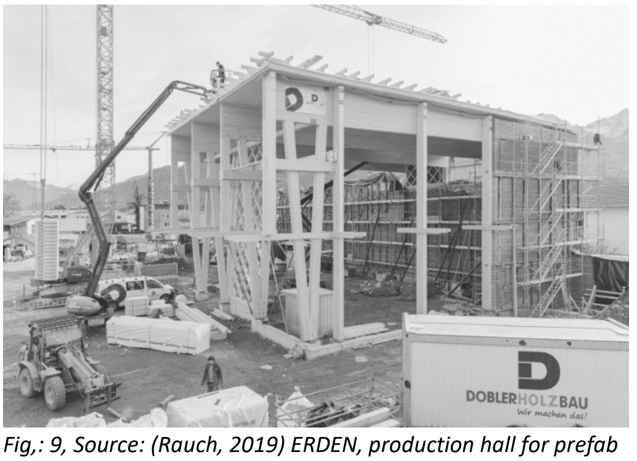
Fig,: 8, Source: (Wikkelhouse, 2018) Cross-section of the Wikkelhouse.

Possible Assembling

The infills will be mounted onto the skeleton and connected with it. The joints between the structure and the infills require a strong bond and should ideally be able to disassemble. As just mentioned under "requirements for the Infill design" the infill should be protected by a frame or casing. This would allow a much easier and faster mounting process on site. The tolerances of the frame and the skeleton should be respecting the different scales. For timber construction these tolerances are well established, and the assembling of large and small building components is well known and tested.
The building component should be designed to disassemble. This allows an easier reuse of the applied materials and is an essential part of a circular design. (Herzog, 2017)

Example prefab earth-timber 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. 9.*
The Timber construction, as well as the prefab rammed earth components are assembled on site. (Rauch, 2019)



Fig,: 9, Source: (Rauch, 2019) ERDEN, production hall for prefab rammed earth components, Schlins, Austria

3.2.2. Monolithic construction

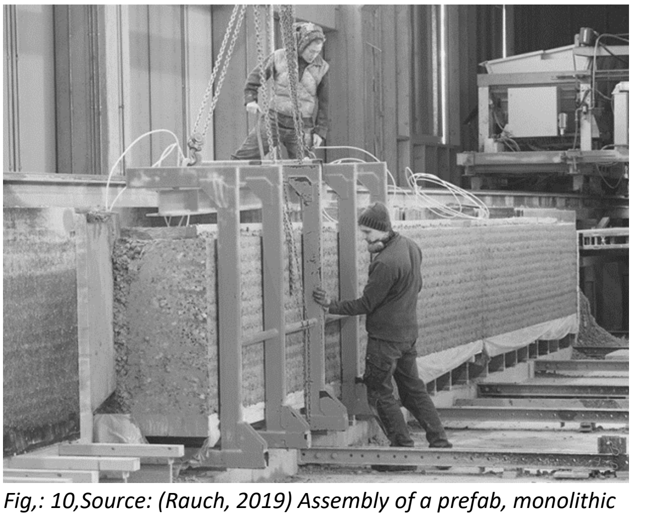
The wall construction consists mostly out of clay and only includes additional materials for transportation, handling and joining. The earthen mixture itself is the load bearing material. The component needs to be strong enough to carry not only its own weight, but all loads that occur in a building. Fulfilling the current regulation will be one of the biggest challenges for earthen load bearing structures the are 3d printed. Especially if a multi-story building is the goals of the design. Thick walls will be the result. Most of the monolithic prefab structures are rammed earth walls due to their structural strength. The thick and dense components can be used as structural elements and be stacked up the 11 meters. (Houben et al., 2019) Using earth as s structural material for houses higher than 3 stories in an urban environment will be very hard to achieve due to the strict regulation for the material. Although there are examples of 6 story high adobe and rammed earth buildings in the city Schibam in Yemen (Dethier, 2019), or as well in moderate climate like in Weilburg, Germany (Volhard, Röhlen, 2009).

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. A draft design idea of this can be found in the chapter *"design".*

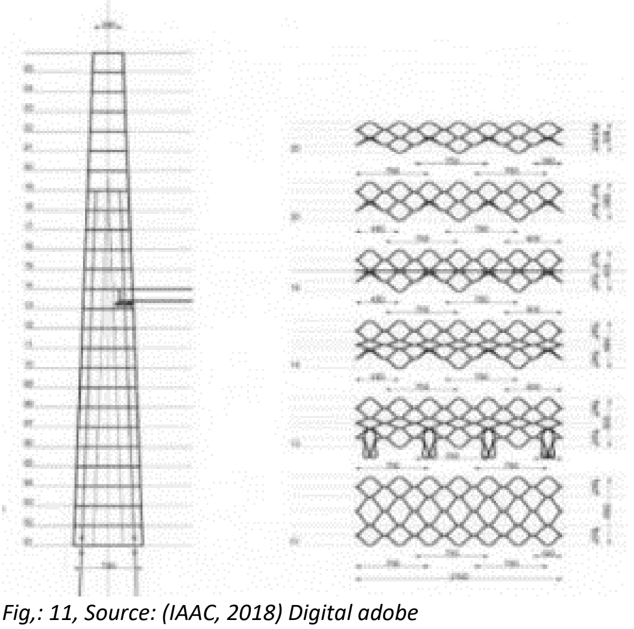
Possible Assembly

A possible assembly for a monolithic load bearing structure would be like a brick wall. The heavy components will be staggered over each other and joint with a clay mixture between them. To join the elements a clay mixture gets applied in between them. The components need a certain wall thickness to have the required strength, see *Fig. 10*. This makes the elements heavy. As seen in the picture below the rammed earth prefab component is massive, adding an lighter part for insulation would increase the wall thickness even more. The thickness of the denser structural part of the component needs to be increased since 3DPE has lower structural properties than rammed earth. This is caused by the moisture of the material mixture that is required for the extrusion. Rammed earth requires only a minimum of moisture and the mixture is compressed in a formwork to gain its form. The high weight and the handling are a limitation for the component design. (Rauch, 2019)



Fig,: 10,Source: (Rauch, 2019) Assembly of a prefab, monolithic rammed earth wall. Schlins, Austria

Examples of prefab 3DPE monolithic constructions

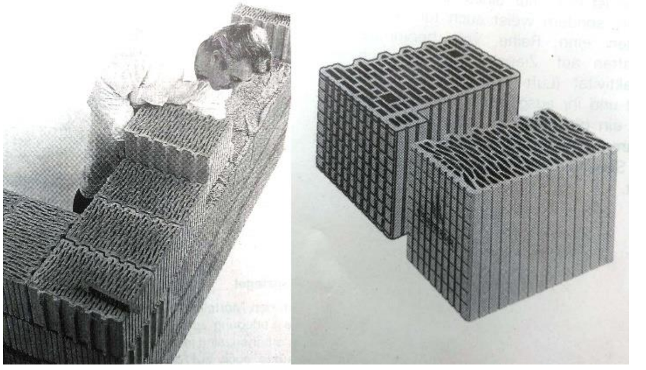


Fig,: 11, Source: (IAAC, 2018) Digital adobe

The monolithic prefab wall system from IAAC, *Fig. 11*, 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. (IAAC, 2018)

Conventional vertically perforated brick (VPB)

A conventional building system for insulated fired clay are VPB. The hollow chambers decrease the density and increase the insulation of the bricks, *Fig. 12*. However, the firing process increases the co2 footprint of the bricks largely. In some cases, sawdust is added to the clay mixture, when the bricks are fired the saw dust burn away and a hollow void remains at their place. This increases the porosity and the insulation. The bricks get produced with an extrusion process. The very dry material mixture gets pressed through a stencil under high pressure. The low moisture content reduces shrinkage while drying to a minimum. The bricks can be walled up on site or assembled to large prefab wall components that get assembled on site. These bricks can be used structurally, but only because of the firing process. This thesis aim to reproduce the hollow pattern of the bricks by manipulating the extrusion with different nozzles. By changing the pattern of the voids, a gradient material could be created. (Riccabona, 2004)



Fig,: 12, Source: (Riccabona, 2004) Top view of a VPB and assembly.

The density of a chosen VPB, by the company "Wiener Berger" was 650kg/m³.

3.2.3. 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 and appearances. 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. (Herzog, 2017)

Claddings:

Claddings offer almost infinite possibilities to design a façade. At the same time, a cladding protects the wall construction behind it. 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 joints 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. The sub construction for the cladding can as well be directly connected to the frame of the 3DPE component to reduce the forces onto the 3DPE element. If the architectural appearance is designed within the limitations of a cladding system, the design should be applicable and constructible as the exterior wall 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, repairing those takes time and costs money. (Herzog, 2017) Mounting the cladding on site allows to use panels that are bigger than one building component. The façade grid does not necessarily have to be the same grid as used to construct the component. (Kaufmann et al., 2018)

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. This problem is well known in traditional and modern earthen 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. The high maintenance cost for this kind of facades might decrease the financial feasibility of the building component. A not cladded façade is not recommended.

However, both surface modifying methods require a yearly maintenance. The washed off earth must be replaced yearly, especially in a moderate climate where rain is nothing unusual. This increases the operational cost of the building and might scare off possible users and investors.

3.3. 3D printing earth (3DPE)

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 digital fabrication is promoting a revival of this traditional building material besides conventional methods. (Dethier, 2019)

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

Regarding traditional construction techniques for Earth, we could witness a huge societal and technological development in the past decades.
There are two major innovation drivers for earthen construction. 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. (Gasnier, Dethier, 2019) In most industrialized countries clay or earth and the related techniques has been repressed by industrial building materials. 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 this traditional building material. (Dethier, 2019)
3DPE is a new emerging field of earthen construction and aims to fulfil both. Increasing the efficiency and the social appearance and acceptance. Via an extruder the viscous earthen mixture is applied in layers along a toolpath via a nozzle. The principal is the same as for conventional thermoplastic desktop 3d printers that use fused deposition modelling (FDM), only in a larger scale and without a hot extruder.
Since no heat is needed and the earthen mixture needs to be viscous/ liquid the deposition method used for this research is called "Liquid Deposition Modelling" (LDM). (Cuevas, Pugliese, 2020)
R3DPE 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 constructions. The introduction of 3DP could, if developed further, increase the productivity, quality and safety. (Khoshnevis et al., 2006) Since structural components need to fulfil all kind of safety requirements, many regulations and laws need to be passed by municipalities. Although there are many similarities between concrete 3DP and 3DPE it is not always possible to compare them. While the concrete mixture needs to be quite liquid of an additive production

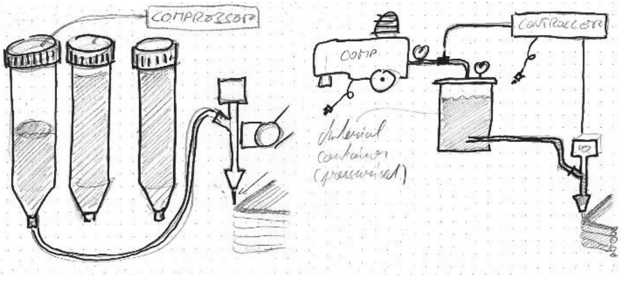
process an earthen mixture can be drier. That is a result of the different rheology of the wet mixtures. Compression under self-weight is more crucial for concrete 3DP. To prevent a too high compression under self-weight accelerators are added to the mixture shortly before the extrusion. A faster hardening concrete increases its strength against self-compression and allows a printing height of more than 2 meters. (Buswell et al., 2018) Even with added accelerator clay cannot harden out that fast to allow such a printing height. The printing height of 3DPE is largely depending on the moisture of the material mixture and the nozzle geometry. To avoid the problem of a low possible print height of earth, it is recommended that the gradient material infill is printed in horizontal position. (Cuevas, Pugliese, 2020)

3.3.2. Production set ups

The production speed 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 from the mixer 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 that avoid lumps of sand or clay. For an optimal homogeny of the material it is important to force the material together. (Rael, 2017)

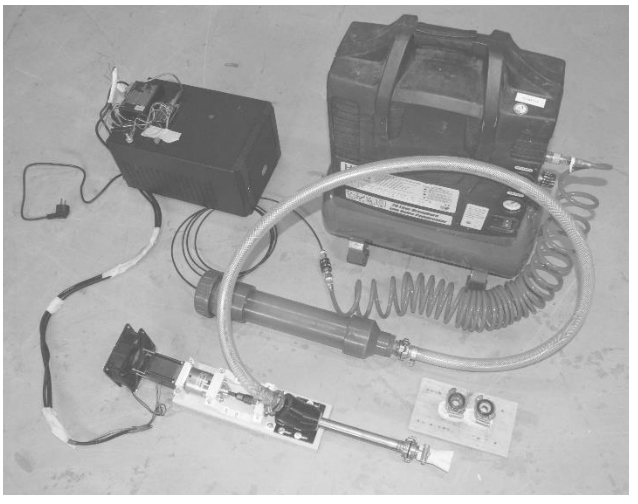
"Finite" set-up:

The current set up at the LAMA is a "finite" or closed system 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 "*3.3.4. 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. (Rael, 2017)
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 if the cartridge is damaged or misused. 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.



Fig,: 13, Finite production set-up for paste 3DP. The material mixture gets filled in a container or cartridge and pressed towards the extruder.

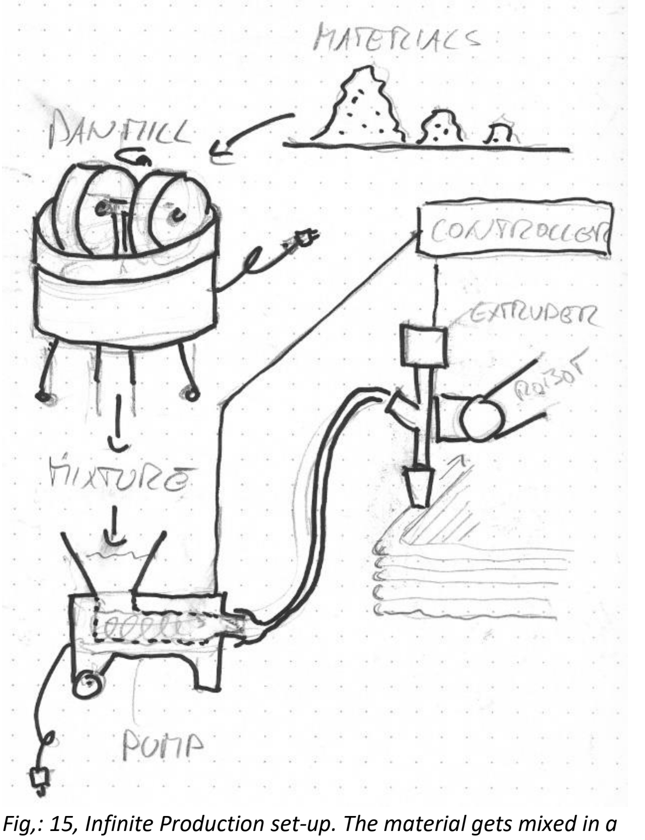
The container can be either placed next to the robot or mounted on it. By mounting the material cartridge on the robot, is it important to keep the weight below the maximal additional weight. For the Comau at the LAMA the max. additional weight at the third joint is 60 kg and would not be exceeded with the biggest cartridge. 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 and extruder calibration. The prototype production would be possible as well, although the production time will be elongated, the prototype should be lighter than 20kg.



Fig,: 14, The current "finite" set-up of the LAMA. Compressor, Cartridge, Extruder, Extruder control unit, self-changing nozzle holder.

Infinite set-up:

For mass fabrication or large-scale 3DP an "infinite" or open system set up has one big benefit. It allows continuous printing and requires no production stops to refill a cartridge. The desired mixture is filled in a special plaster pump from where it gets pressed through a hose to the extruder. Ideally the compression process with and auger will eliminate the 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 non-stop 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. 15*



Fig,: 15, 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 in full size I would recommend an infinite set up. This will allow to record the production time and evaluate the printing time and problems during the production. 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.
For a smaller portable 1:1 scaled part of the prototype a finite set up should work as well.

Different printing Environments

AM is strongly influenced 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, decrease the overall material quality of the printed object. Some are: uneven drying due to wind and sun radiation what causes drying and settling cracks. The viscosity of the wet mixture is harder to control since the humidity influences it. In-situ printing usually aims to produce large object without dilatation gaps, that causes tension and can lead to cracks during the drying and production process. Setting up the production on site takes time. A roof is required if the production should be continuously. 3DPE is not possible during rain. This additional step increases the construction cost.

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 a large-scale object, such as a building component, but as well for the workers. A year-round construction under similar conditions is possible and desirable.

3.3.3. 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 and later because sand and clay formed small slumps. During the sifting process the clay content of the soil should be evaluated to allow a repeatable material mixture.
The so configurated but unprocessed soil can be mixed with water, be extruded and reused at the EOL of the building component. 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 viscos. If the mixture is too viscos it cannot support itself anymore. The self-weight compression depends on the viscosity of the mixture and the number of applied layers. 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.

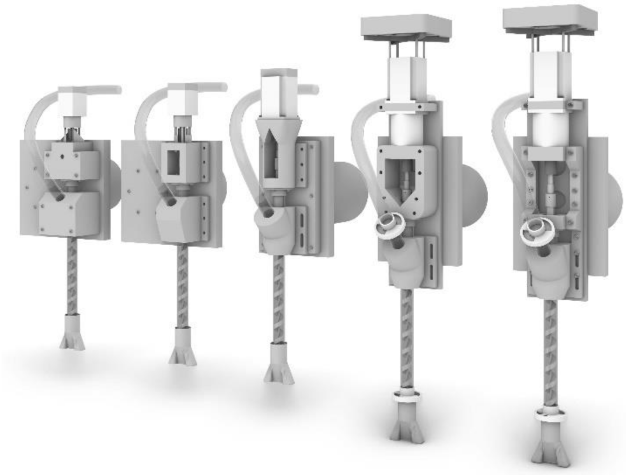
3.3.4. Machines and tools (physical/digital)

Motorized 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. This is too small to modify and shape the geometry of the nozzle. To allow more realistic 1:1 scale experiment with customized nozzles and mixtures a larger extruder is required. The larger scale is important since extrusion geometries cannot simply be upscaled. The 1:1 scale is therefore necessary to allow valid experiments, realistic prototype productions and valid results.
To that the self-compression and possible contour crafting can be easier evaluated in a larger scale. The LAMA has most of the parts that are required to build a “do it yourself” (DIY) large scale clay extruder *Fig. 17.* To allow the nozzle shapes and sizes to be as realistic as possible Rodiftsis, T. and I decided to develop with Serdar Aşut, Marcel Bilow and Paul de Ruiter our own extruder for the LAMA.
Building a DIY clay extruder led to a better understanding of the extrusion process. This better understanding was especially useful for the development of nozzles and a suitable production process. After an initial design and several redesigns after failed tests the extruder was working.

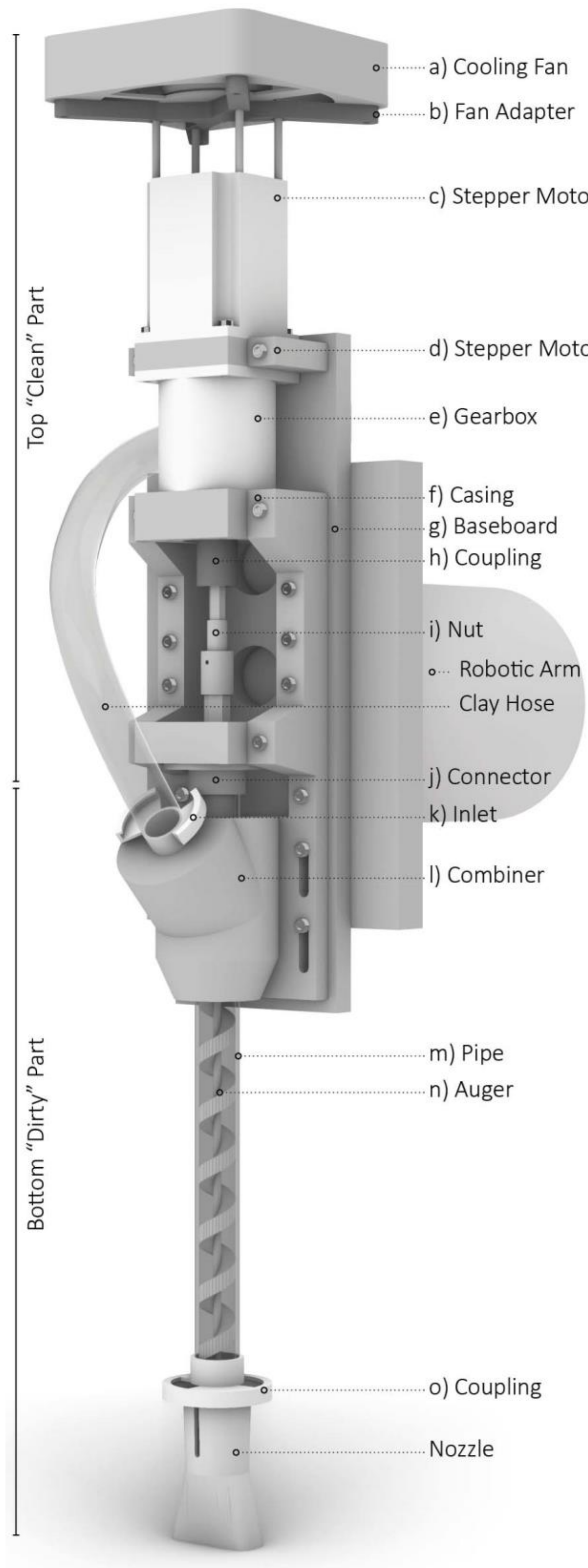
The principal of a clay extruder is simply and can be compared with an Archimedes screw that moves a material through a pipe. However, implementing an easy principal can become quite complex when certain boundary conditions are applied. In this case the earthen paste gets pressed into a feeding pipe. Afterwards the mixture gets transported with a snail extruder (auger) towards the nozzle. The auger is a conventional 18mm diameter wood drill. It will be connected over a transformation nut, Coupling with the Gearbox and the 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 end of the steel pipe extruder the nozzle will be mounted. The whole set up is 3D modelled in RH and will be imported into RDK as a STL to have a correct dimension for the collision detection. The tool centre point (TCP) will be entered in RDK for the production simulation.

The design process can be seen in *Fig. 16.* The initial design was improved several times according to new findings and failed test runs. On the left is the initial design, on the right the final design. The latest designs are mounted centric on the robotic arm. The centre of gravity of the extruder is therefore closer to the flanch of the robotic arm. This allows faster traveling and a more accurate positioning of the extruder and leads to a better printing quality.



Fig,: 16, Design evolution of the DIY clay extruder

Each component, its relation and function within the extruder will be described in detail below. The extruder can be separated in two major parts, the clean (top) part and the dirty (bottom) part as visible in *Fig. 18*. The "clean part" includes all the electronics, the gearbox and the transformation nut. The "dirty part" contains all elements that will have direct contact with the earthen mixture. To allow a convenient cleaning process, the clean and dirty part should be easy to disconnect from each other. This allows to pressure wash the clay of from the bottom part while the electronics and mechanics containing top part stays dry and clean. The "clean part" might even stay mounted onto the robotic arm during the cleaning process.



Fig,: 17, Isometric drawing of the planned paste extruder.

Top Part (Clean)

a) Cooling Fan.

Stepper motors tend to become hot, especially when high torque is required. The reason is that we observed that the motor is running hot even when it is not rotating since the current is heating is up. Since the extruder should be able to be in use for several hours. To prevent overheating of the motor and a self shout down the extruder is equipped with a large cooling fan. The fan is directly connected with the power inlet of the main control board and therefor always running if the extruder is plugged into the power socket. To allow an optimal airflow the fan is mounted within 30mm from the top of the motor. The fan is mounted with nuts and bolts to the adapter.

b) Fan Adapter

The used fan was initially not designed to be mounted on a stepper motor. To connect both elements an X-shaped adapter was designed. The X-shape should avoid blocking the air stream downwards to the motor. The Adapter is 3d printed from PLA. Three top, bottom and outline Layers, an infill of 50%, printed with a 1,2mm nozzle results in a strong element. It gets mounted with nuts and bolts to the motor.

c) Stepper Motor

While developing the extruder we hoped that the Nema alone is strong enough to extrude the earthen mixture. The height rotational speed of 600rpm at low torque would have allowed a very high extrusion speed and volume per minute. The rotational speed of the motor depends on the torque and the micro steps. Unfortunately, initial test showed that the torque was not enough. The friction caused by the sand between the auger and the steel pipe is too high as that the Nema 23 could generate enough torque to rotate the auger. A connected potentiometer allowed to tune the motor from slow to fast, but it was not possible to increase its torque anymore by changing the Arduino script. To increase the torque a gearbox was added between the motor and the auger. I was possible to order this gearbox from Europe to reduce the long shipping time from china caused by the Covid19 pandemic.

d) Spacer and connector

The existing axis of the motor was too long and needed to be modified to allow a connection to the gearbox. To bridge the gap, the spacer was developed. To reduce the torque on the connection between the gearbox and the upper casing, the spacer will be mounted directly on the baseboard of the extruder with nuts and bolts. The Spacer is 3d printed from PLA. Three top, bottom and outline Layers and an infill of 50%, printed with a 1,2mm nozzle results in a strong piece. The Motor, the spacer and the gearbox are screwed together with 4 bolts that fit within the wrench on the gearbox.

e) Gearbox 1:15

A gearbox translates a fast rotation with low torque into a slow rotation with high torque. The ratio describes the translation. To not decrease the speed too much a 1:15 gearbox was added. Increasing the torque 15 times is strong enough to extrude the sand and clay mixture. Unfortunately, the desired high extrusion flow was not possible anymore, since the rotational speed was reduced by 15 times as well. Nevertheless, the extruder was finally working after installing the gearbox. Slow but steady the nozzles could be tested. Further improvements are of course possible by changing the gearbox. A 1:10, or 1:5 gearbox might already be strong enough to assure a constant extrusion and would increase the speed by the same ratio.

f) Upper casing, Lower casing

The casing is designed to surround the open rotating parts of the extruder. To readjust, connect/disconnect or to see the rotation direction and speed, it is very important to have access to this part. Such as the coupling, the bit including the holding pin and the top of the auger. The Casing was separated into the top and bottom part to allow more possible adaptations and modifications for future development of the extruder. In addition to that, separating the large casing into two parts eased the 3d printing. While the upper casing relates to the baser plate with 6 nuts and bolts, the bottom casing is mounted with 8. The upper casing is fixed to the gearbox with 4 bolts. The bottom casing is fixes to the pipe connector with 3 bolts. Both parts are 3d printed from PLA. Three top, bottom and outline Layers and an infill of 50%, Nozzle width 1,2mm, Layer height 0.5mm

g) Baseboard

The baseboard is the backbone of the extruder. It connects all mayor parts with each other and is made of 19mm plywood. The baseboard will also function as a connection between the robotic arm and the extruder. Two holes with a diameter of 30mm will be drilled into the base plate to allow an access to the rotating parts mentioned under “Upper casing, Lower casing “.

h) Coupling

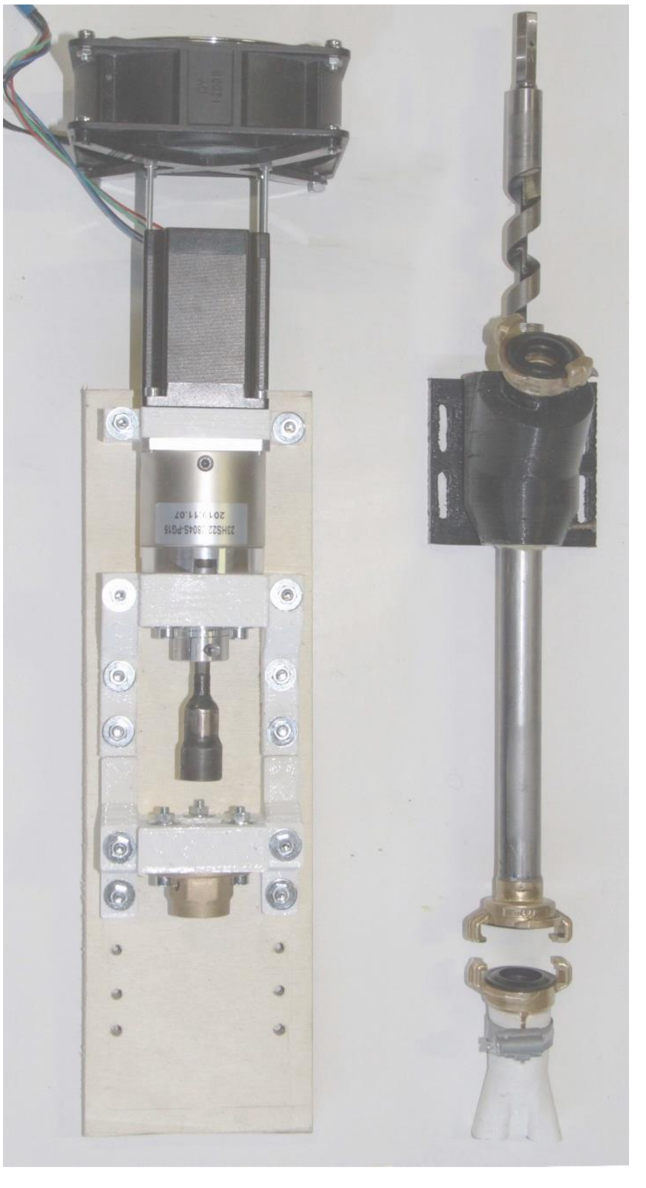
The coupling connects two shafts to transmit torque. In our case the pin, coming from the gearbox, with the bit that holds the auger. Flexible couplings are used in application when there is a possible misalignment of the shafts and inaccuracies, such as parallel, angular or axial misalignments. The chosen coupling is made from aluminium and gains its flexibility from the spiral cut in its centre. Although all parts were fabricated digital, some inaccuracies where expected. These might cause additional friction between the auger and the steel pipe. To avoid that and to reduce possible vibrations a flexible coupling was applied. In addition, the settling time gets diminished, that reduces load peaks for the motor, especially when starting and stopping the extruder. In an 3d printing process, starting and stopping the extrusion occurs frequently. By choosing a flexible coupling the lifetime of the motor and the gearbox should be elongated. The Coupling has two openings 12mm and 8mm. The 12mm is for the connection with the gearbox and the 8mm for the bit. Both shafts get fixed with two grub screws (M3) to the coupling.

i) Transformation Nut

To connect the auger with the flexible coupling, a transformation nut was necessary. The transformation nut must withstand the required torque and hold the auger in vertical position with a pin. The top of the auger fits inside a hexagonal 14mm bit (hex bit) and is too big to be connected directly with a flexible coupling. A conventional hex bit and a bit socket were welded together with a stainless-steel ring. Since the chrome vanadium hex bit was too hard to be drilled trough for the holding pin, the steel ring was drilled through. The steel ring is therefore responsible for holding the auger in vertical position with the pin. The hex bit is responsible for translating the torque on the auger. The transformation nut allows a fast and easy assemble and disassemble for cleaning a storage. To remove the auger, only the pin must be pulled, after that the auger can be removed from the hex bit. The Transformation nut was developed and produced with the help of Marcel Bilow in his workshop.

j) Connector

To reduce friction as much as possible we aimed to have all moving parts and the steel pipe around the auger in the axis of the motor. To assure a correct alignment of the bottom part we used a wall connector for water piping. With a lathe the wrench was removed so the steel pipe could fit inside. The pipe connector could be mounted with 3 bolts on the lower casing.



Fig,: 18, clean part (left), dirty part with auger and nozzle (right)

Bottom Part (Dirty)

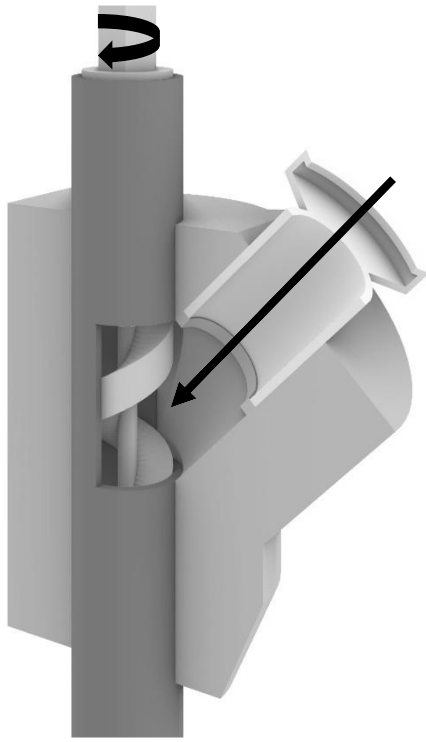
As mentioned, the bottom part of the extruder can be detached from the top part to allow a convenient cleaning process.

k) Inlet Connector (GEKA Coupling)

The clay is pressed through a hose into the combiner with about 4-5 bar. The connection between the hose and the combiner are two Identical GEKA quick couplings. These are usually used for industrial or garden hoses and are robust and long-lasting high-pressure couplings that can be operated up to 40 bar. The couplings are made of brass and are non-corrosive. The standardized joint between the couplings allows attachments for inside and outside imperial wrenches and hoses of various sizes. One big benefit compared with screw-on-couplings is the fast and easy-going connection. Any kind of dirt in the wrench usually leads to unnecessary complication during the set-up preparations, experiments, production and clean up. Tightening and disconnecting a wrench connection with sand is very hard going and can require lots of time and force. Since GEKA couplings don't have any wrench leaked earthen mixture between the coupling does not cause any problems. By using GEKA quick couplings this problem is not an issue anymore. However, the short and therefor unusual stiff hose disconnected sometimes during the initial test. The cause was that the coupling requires only 1/3 of a rotation and a small amount of axial pressure to connect and disconnect. The stiff hose was already enough to cause this. It could be said that the quick coupling was even too easy to disconnect. A simple welding rod slid between the U-shaped wings of the coupling and bended upwards at the ends solved that issue. The rod functions as a safety pin and prevents the coupling to disconnect unintentionally.

The GEKA couplings are used for all connections involving the earthen material mixture. From the Clay cartridge to the hose, from the hose to the combiner and from the extruder to the changeable nozzles.

l) Combiner



Fig,: 19, vertical section of the combiner

As its name states, the combiner unifies multiple elements. The inlet GEKA coupling, the steel pipe and the pressure chamber are glued together with the 3DP combiner. To assure a tight adhesive joint, foaming Poly Urethan (PU) glue was used. The glue is applied, and the different parts get assembled. A temporary security screw prevents movement due to the expanding and foaming PU glue. After 24h curing time the glue reaches its full strength.

Inside the combiner the Earthen mixture gets pressed into the extrusion canal, also referred as the steel pipe. From there on, the clay material mixture moves no longer due to the higher atmospheric pressure, but due to the rotation of the auger. Due to friction in the cartridge and the hose, the clay mixture reaches the combiner with less pressure than initially applied to the clay cartridge. To avoid the occurrence of air bubbles the mixtures needs to be pressed into the auger and the extrusion channel. The necessary pressure that needs to be applied on the cartridge is depending on the pressure within the combiner. Large scale clay extruders have a probe inside the combiners chamber to assure an optimal pressure. (Venturini, 2020) The applied pressure on the cartridge or the plaster pump is ideally depending on the pressure within the combiner and can be adjusted accordingly. The realized design does not include such a probe and the pressure regulation is solved by simply over pressuring the mixture into the combiner. The pressure inside the extrusion channel decreases towards the end of the auger. This is caused by the extended path that the material mixture must take around the auger. The extended path increases the friction and reduced the pressure towards the end of the auger. The combiner must withstand the pressure at the inlet of the mixture where it is the highest. To assure a safe design the combiner is designed to withstand approximately 4 bar. The round form is a result of the offset of the steel pipe and the inlet coupling. In addition, the round shape should minimize the occurrence of pressure peaks along sharp edges. As the other nonstandard parts, it is 3d printed from PLA with three top, bottom and outline Layers and an infill of 80%. Nozzle width 1,2mm, Layer height 0.5mm. To assure a good interlayer bonding the travel speed was set to 15mm/sec. The slow printing process and the high infill percentage should lead to a very robust and strong combiner that can handle the applied pressure. To assure a safe usage of the combiner the first test was held under special caution. The extruder was positioned within a wooden box and the pressure on the cartridge was slowly increased until we reached 5 bar. The auger clocked the top opening and bottom opening and assured the pressured mixture cannot escape the chamber of the combiner. After 15 min waiting time the pressure was decreased and the combiner was checked for any leaking material or cracks. After the optical check did not show any damage, the test was repeated with a rotating auger. As mentioned under "*c) Motor*", the torque was to low and the test failed. But the combiner was proved safe.

m) Steel pipe

The extrusion canal is a steel pipe with an inner diameter of 18mm (= the diameter of the auger) and has a wall thickness t=2mm. That results in an outer diameter of 22mm. The pipe has a rectangular hole on the top quarter as visible in *Fig. 19.* This opening lets the clay mixture enter the extrusion canal from the combiner. To reduce the friction between the auger and the pipe the inner surface was polished. The rough sand grains are roughening the surface up during the usage though. Other methods to avoid friction will me mentioned under "*n) auger*"

n) Auger

The auger is a conventional wood drill from the construction market for 20€. Wood drills are usually made from steel, that is not very hard. We expect that the auger will be worn off after a certain lifetime. It needs to be replaced after that. To transform a wood drill into an extruder, only the sharp tip must be removed with an angle grinder. And the rotation direction is not right anymore but left. Of course, a drill is not an optimal auger, but it is a cheap and robust alternative that can easily be renewed if necessary. After the design of the extruder with a drill as auger, an auger made of Teflon was found, especially designed for clay extruders. Unfortunately, the diameter did not fit into the steel pipe. Changing the steel pipe diameter would have required changing many other, already finished parts of the extruder. Due to time pressure and because the extruder is only a side project of the graduation, the decision was to not change the design anymore. Changing the auger was not necessary anymore after we performed an extrusion test with a hand drill instead of the Nema motor. The performance was very satisfying. This test also proved that our design is feasible, if we have a motor that produced enough torque.

The previously mentioned Teflon screw has only a helix height a 2mm whereas the converted wooden drill has a height of 12mm. This increase of the possibly grinding surface on the inner wall of the steel pipe leads to more friction and results in a higher required torque. To reduce this friction there are two possible options: minimizing the difference or purposely creating a gap.

Minimizing the gap: The difference between the inner diameter of the steel pipe and the diameter of the auger should be almost zero. If there is no distance between the auger and the inner wall of the extrusion canal no grains from the material mixture can slide in between and cause any additional friction. One option to enable this is to insert a second lubricant synthetic pipe inside the steel pipe. The synthetic pipe is much softer than the steel pipe and allows that the auger can be pressed into it. The distance between the auger and the synthetic pipe is neglectable. In this case the auger is friction fitted into the synthetic pipe. To rotate the auger now, a high torque and therefore strong and heavy motor is required. The general design of the extruder must withstand these high forces. In addition, hydraulic presses are necessary to insert and eject the auger for cleaning and maintenance. The friction caused by grains between the auger and the pipe get reduced, but the friction fit increases the it again. The benefits are that this method enables the usage of very dry material mixtures. Since the low water content reduces the shrinkage the mixture can have a much higher clay content and will be stronger after the drying process. This method of extrusion requires many specialized tools to produce the extruder as well as for the usage and maintenance. Not to mention the generally higher cost for the motor and the several parts that could probably not be 3dprinted with a conventional desktop 3d printer.

Purposely creating a gap: The diameter of the auger should be around 2,5 times smaller than the biggest possible sand grain in the material mixture. This way the grains that slide in between the auger and the pipe don't get grinded up and therefore create less friction. The necessary torque gets reduces dramatically. This allows the use of smaller motors and a generally less bulky design of the extruder. The result is a smaller, lighter and cheaper extruder that can be produced with a conventional desktop 3d printer. Possible downsides of this method are that the extruder might start leaking. The bigger this gap becomes the more inefficient the rotational force get translated into moving the material mixture through the pipe. If the distance gets too big the material mixture does not need to follow the extended path around the auger, as described under *l) combiner*. The mixture would simply be pressed through the too big gap.

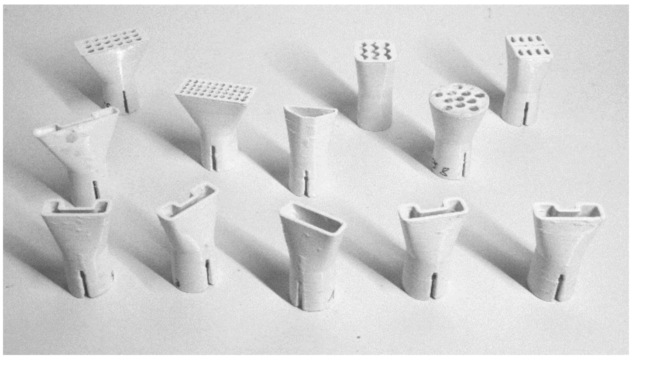
The current design of the extruder is a compromised of the two introduced options. The Auger and the steel pipe have almost no distance, but it is not a friction fit and small sand grains can slide in between them and get grinded up. This causes a higher torque. But since the auger is made of soft steel it wears of and becomes slightly smaller by the time. Due to this shrinkage, the optimal gap between pipe and auger should be established after a certain life span. Ideally a 17.9mm wood drill could be used to shorten this process.

o) Coupling

A ¾ inch GEKA lock, that had the inner wrench removed on a lathe, is glued on the bottom end of the steel pipe with epoxide resin. This allows a fast change of customized nozzles. For round nozzles a simple GEKA coupling for hoses can be applied in various sized. The fast coupling allows to automate the nozzle change. The robotic arm only must travel to the nozzle holder, approach it within the right rotation. Perform a 1/3 rotation and the current nozzle would be removed. The same procedure can be repeated, and new nozzle would be mounted onto the extruder.

Nozzles

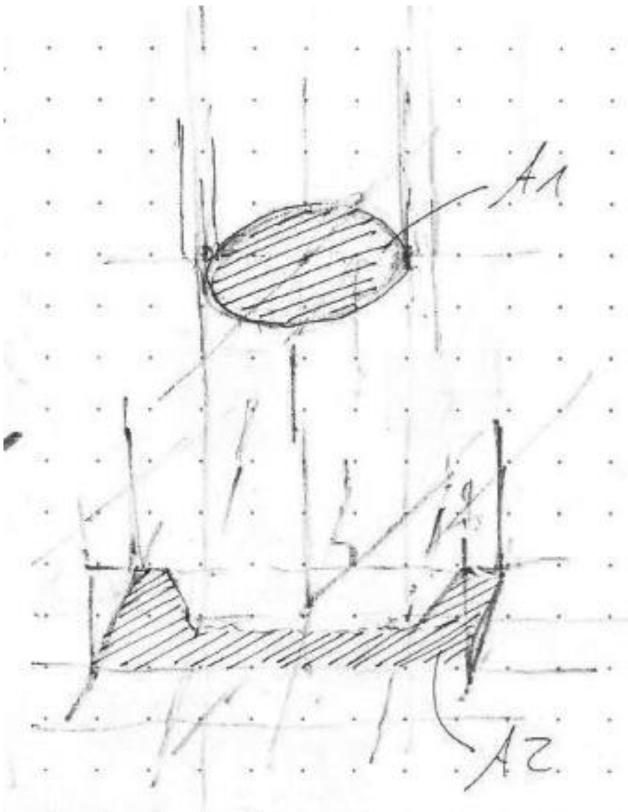
The nozzle should modify the extruded geometry to achieve a density shift within the cross section of the 3DPE element. The design of the building component and the nozzles will be done computationally and consider the respective needs. The complex nozzle design results in a simplified toolpath compared to standard slicing methods. 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. Different toolpath options will be evaluated to improve the 3DPE process and reduce the compression under self-weight. The set of tested nozzles can be seen in *Fig. 20.* The shape options for the nozzle is limited by the viscosity of the material and possible additives. As described under "*research by design*", added fibres increase the risk of a clocked extruder. It is possible that not all the proposed Nozzle are feasible. A detailed evaluation can be found under *"4.4 result evaluation"*



Fig,: 20, tested Nozzles

To reduce the density per volume of the component the outlet surface of the nozzle (A2) will be modified.

To have an equal material distribution within the nozzle its outlet surface (A2) must be smaller than the inlet surface (A1) *Fig. 21.* Each nozzle will be designed for a specific “density class” of the building component. The design process is detailed explained under “6 Design”. The different nozzles will be 3D-printed with a thermoplastic desktop printer at the LAMA. This a cheap fast rapid prototyping solution.



Fig,: 21, Outlet surface of the nozzle needs to be smaller as the inlet surface to have an equal material deposition.

The nozzles were printed with PLA on a Delta 3D desktop printer, the detailed printing setting can be found in the Appendix 14,15.

Automized nozzle change

Each nozzle is designed for a specific density zone. If a new density zone gets printed the nozzle needs to be changed. This can be done manually, or it can be automated. Inspired by a CNC-Mill tool carousel a non-moveable nozzle holder was designed, see *Fig. 22*. The required nozzles are all equipped with a GEKA coupling and stacked into the nozzle holder. The holder is part of the environment file that is inserted into RDK. That allows the robot to precisely approach the nozzles and connect or disconnect automated. The nozzle than needs to travel over a bucket and extrude material till the nozzle is fully filed with the mixture. After that the printing process the filled nozzles get put back in the holder. It must be further evaluated if the nozzles need to be cleaned in between the use. If the material mixture is still viscous enough to be extruded over the bucket, it can be used to print a new density zone of a separate 3DPe component.

Fig,: 22, Nozzle battery for automized nozzle change

If automating the nozzle change is desired the traveling of the robotic arm to the nozzle holder will be a part of the toolpath design. With an infinite set-up as described earlier and an automated nozzle changing process the 3DPE component could be printed without a production stop.

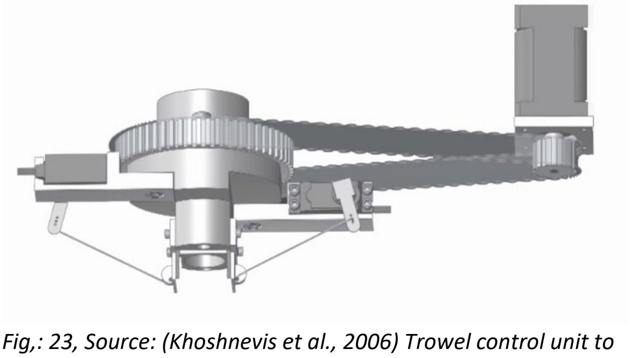
Requirements from the components design

The production requirements for the nozzles from the building component are mainly regarding the desired density shift and height of the 3DPE element. Those will influence the nozzle Width, Hight and outlet geometry.

Contour crafting

Contour crafting (CC) is a method to post process or model the extrusion geometry of a layered manufacturing technique. (Khoshnevis et al., 2006) 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 plastic formable. (Khoshnevis et al., 2006) 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 "*4.4. Material Experiments* results"
CC requires an extrusion unit and a trowel control mechanism. Such a control and extrusion unit can be seen in *Fig. 23.*

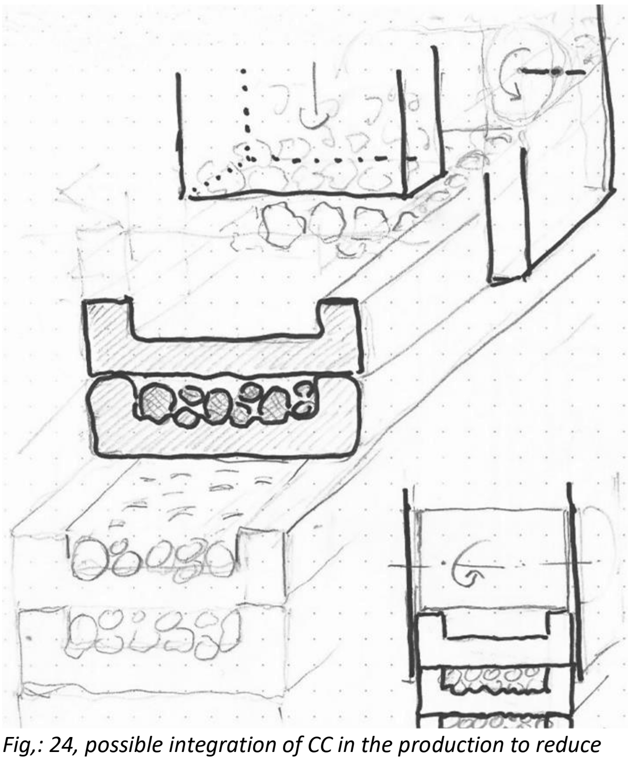


Fig,: 23, Source: (Khoshnevis et al., 2006) Trowel control unit to modify the extruded paste.

CC enables to created hollow deposition by crafting the extruded paste or modifying the nozzle. In contrast to the shaped nozzle deposition the extruded geometry gets shaped after the material deposition in CC. This allows a better surface quality but increases the risk of collapsing layers if the extruded geometry is fragile.

CC could allow adding granules or fibres in a post extrusion process as suggested in *Fig. 24.* The combination of a customized nozzle and CC post extrusion step allows higher porosities of the FGM.
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. (Khoshnevis et al., 2006) The filled voids could reduce the compression under self-weight and result in a more stable extruded geometry.

Applying CC in the production process requires additional tooling and machines as mentioned. Since we do not have those at the LAMA, post extrusion CC will not be experimented. 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 too much time and is out of the research scope.



Fig,: 24, 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:

A 6 axis robotic 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. This enables a laid down extrusion along a curved toolpath. The digital fabrication process allows to produce 3DPE elements that are all different in shape but have the same density shift.
In an industrial set up, each density zone would be printed with a different Root. The printed Object would move from one robot to another This would reduce downtimes, allow the usage of customized material mixtures and eases to integrate drying processes between the printing.

The automotive or manufacturing industry could never afford launching such unready products to the market as the construction industry does. (Wojciech, 2015)

Building are usually prototyping and barely produce in series. That could explain the low production efficiency. Architecture however has more task then just be very efficient. Social and cultural aspects are influencing the design as well or even more than he production. The public nowadays is more interested in an individualized architecture as in “off shelf” modernistic architecture. A possible compromise could be an individualistic architectural design, that can react on the users wishes but can be built with a serial construction system. This building system would be mass customized and could be produced in an industrial building system. Especially Robotic production and 3DPE offers the possibility to have an efficient serial production of building components that form a non-serial building. The designed building component aims to please those needs, by using natural building materials.

For the planned building component, I intend to reduce the cycle time and number of cycles that are necessary. This reduces the total toolpath that is necessary to print the component. A comparison of the toolpath length and time will be presented under the chapter “6 Design”.

Digital tools and workflow

The design of the building component will be developed within the 3D CAD software *Rhinoceros (RN)* and the Plugin *Grasshopper (GH).* The same software will be used to create the design for the nozzle and the toolpath. The computational flowcharts can be found under “6 Design”.

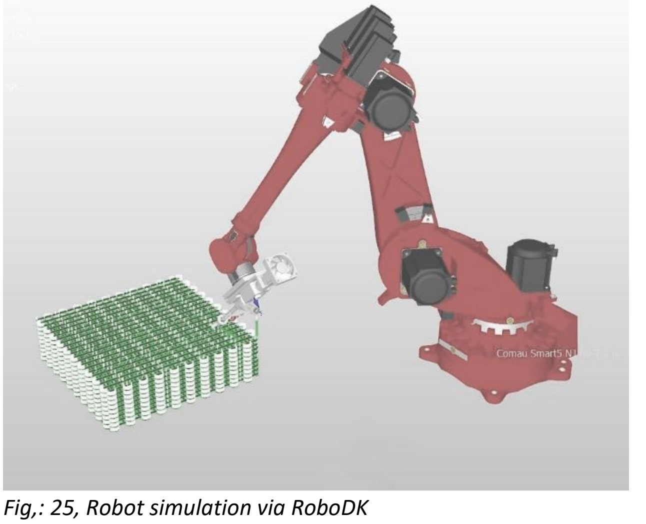
There will be no computational geometry optimization of the building component to increase the production efficiency since the scope of this research is the optimisation through the nozzle design and not the typical single nozzle toolpath.

The design of the nozzle and the component will be linked together to achieve an informative workflow between gradient material and nozzle design.

To allow a better coordination a RoboDK (RD) Plugin will be installed on the Software RN and GH. The position of the component’s toolpath and the nozzle holder on a cartesian coordinate system in RN will be synchronized with RD – this simplifies the adjustment and calibration before the printing process.

The generated toolpath will be exported from RN/GH with the GH component “Robo DK – Curve to Robot” directly into RDK. To calibrate and set-up the robot a Tool Coordinate System (TCP) is necessary for the orientation and positioning of the extruder in relation to the toolpath.

The constructed extruder needs to be imported as a STL file into RD. The Extruder gets attached to the flanch of the robotic arm to run the collision prevention simulation. The centre of gravity should be calculated to allow the robot a more precise joint control. The extruder design considers this and was designed to have the centre of gravity as close as possible to the flanch of the robotic arm. The short distance between the extruder and the flanch made the centre of gravities calculation unnecessary for the planned usage. The tangent nozzle position along the toolpath will be set in RD. As visible in *Fig. 25* the used robot *Comau NJ60 2.2* is equipped with the extruder and simulating a parallel Toolpath in Robo DK. The Angle of extrusion is 45°, the nozzle must follow the toolpath perpendicular. The vertical distance from the TCP to the toolpath is 20mm. The 45° angle in combination with the vertical distance results in a “laid down” extrusion. As desired a laid down extrusion does not deform the extruded geometry after exiting the nozzle. The shape of the applied layers does only change due to its self-weight and not due to the extrusion process.



Fig,: 25, Robot simulation via RoboDK

Toolpath

As mentioned, a complex nozzle design allows a simpler toolpath design to entrap air within the extrusion. Simple parallel, crossed toolpaths, or a random extrusion for special nozzles allow a clear statement of the nozzles influence on the density shift of the gradient material, see “4.3. *Experiment toolpath design”*

The deformation under self-weight has a big influence on the toolpath. Especially when a laid down extrusion is desired. To reach the desired printing height the self-compression must be compensated by printing more layers as initially designed to be necessary. This requires a precise evaluation of the compression, when the specimen is printed with the robotic arm and the motorized extruder. The evaluated compression can be translated into an “additional-layer-Factor”. This factor gets added to the designed number of layers. The result are the necessary number of layer to reach the desired height. Since the additional layer will be compressed as well and the desired height might not be achieved yet- the “additional-layer-factor” needs to be revaluated by experimentation until the desired height is possible. The orientation of the toolpath, interlayer meshes and other factors are influencing this process and need to be considered and included during the experiments.

After the development of the nozzles more complex toolpath should be developed and tested. Those can include multiple nozzles and automated nozzle changes per layer. The goal of more complex toolpath is to increase the strength of the 3DPE element while reducing its density. Since the focus of the research was the nozzle design, the toolpath optimization is recommended as the next step in the development process.

4) Research by design and experimentation

The second column of this research will be the hands on experimentation. The Material and production limitation of additive manufacturing can be experienced with some basic manual test. For more detailed information about the extrusion process these experiments should be repeated with the robotic arm. Since the Robot was unfortunately not available due to the closing of the faculty the experiments where only executed by hand.

The experiments will be performed in collaboration with my college Athanasios Rodiftsis. He is graduating within the same field but focusing on the structural optimization of 3DPE. We have separate experiment design and perform them individually. However, we assist each other by making the material mixture, refilling the clay extruder, preparing and cleaning up the warehouse. The results of the experiments will give both of us a better understanding of the material properties and production techniques.

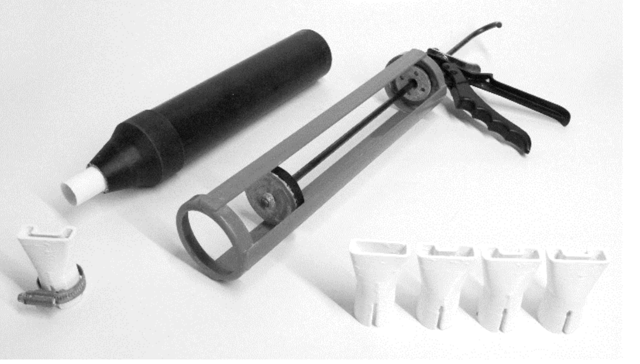
4.1. Used tools

Required tools and materials

Kitchen-scale, measuring cup, ruler, buckets, sift, plastic sheets, tape, pen and sticky-notes, tools, straw, sand, clay, Jute fibre mesh.

Manual Clay extruder:

To test multiple different material mixtures, extrusion angles, nozzles and distances between 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 toolpath for the robotic arm. The manual extruder as seen in *Fig. 26* can be filled with about 800 ml of material mixtures. It presses the mixtures with a stamp towards the nozzle. The same principle as commonly know from silicone syringe.



Fig,: 26, Manuel extruder used for basic material and extrusion experiments. Nozzle width different form and size can be applied

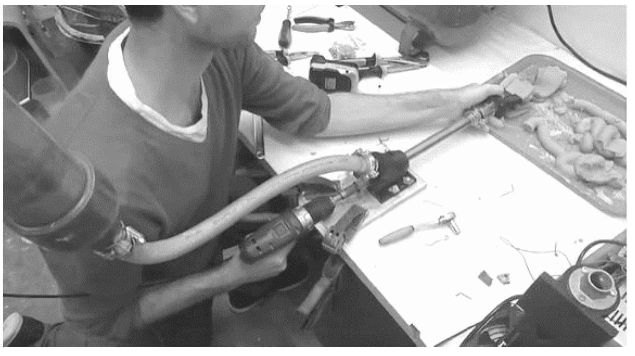
Self-designed motorized clay extruder:

The Extruder as described in *Fig. 17,* will be mounted on the 6- Axis robotic arm and connected with the pressurized clay container as described under *"3.3.2.-Finit set up".* 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.

Using the Self-designed extruder, the clay mixtures exiting the extruder was dryer than the mixture filled into the cartridge. This might be a result of the friction in the extruder itself. Sand grains get between the screw or auger and the steel pipe. This sand is increasing the necessary moment to turn the auger. Similar as sand in the gears. The motor of the extruder requires a height torque to continue rotating although sand grains are between the auger and the steel pipe. The auger functions like a mill and crushes the sand between the auger and the steel pipe. It might be possible that the fine remainders of the crushed sand might accumulate some of the water in the mixture. Comparable as adding more sand to the mixture.

The auger itself gets worn off as well. Sharp edges get smoother and the diameter of the auger will change slightly the longer the extruder has been in use. These sanded off metal particles become a part of the material mixtures as well. This was clearly visible after the first use, when the clay mixture started to show traces of rust. The influence of the metal traces in the material mixtures are neglectable. The auger wears away with long-term use and can be easily replaced. It is important that the steel grade of the steel pipe is higher than the auger' since it is more difficult to change the pipe.

The required toque for the extrusion was underestimated at first. The long auger created more friction than expected. To check if the design of the extruder is even feasible a common hand drill was used instead of the Nema23 stepper motor. The “dirty part” of the extruder was clamped to a table and the drill was used to rotating the auger, see *Fig. 27.* This test proved that the design of the extruder is working if the attached motor is strong enough.



Fig,: 27, Hand drill used as a high torque motor- proof of concept for the designed extruder and U-shaped nozzle

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 4th joint. 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 flanch of the 6th joint. 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.

Experiment adjustments due to inaccessibility of the robotic arm

Ideally the following experiments would be executed with the motorise extruder as described previously and the robotic arm *Comau NJ60 2.2.* Due the closing of the faculty building the robotic arm was not accessible anymore and the experiments could not be held with the desired precision. The toolpath and nozzle test where done with the manual extruder, as described in *“4.1. Used tools”.* The filigree shapes of the extruded material mixture require a precise deposition of material along a repeatable toolpath. The robotic arm and the motorized extruder are more suitable to fulfil these tasks. All following specimens are made by hand and the accuracy of the extrusion is lower than with a robot. The assumption is, that if the experiment was successful with the manual extruder it should be repeatable with the robotic arm in the same or a better quality.

4.2. Material experiments

The experiments lead to a better understanding of the effects different mixtures have on the printing process. Small changes like water content or fibres can change the usability of a mixtures tremendously. The experiments should evaluate the plasticity and the extrudability of the mixtures. The material experiment goal is to evaluate a mixture that is suitable to be shaped by a nozzle. The mixture should have the right viscosity to be extrudable but plastic enough to keep its shape after deposition.

The performed material experiments were done at a storage room of the LAMA with the manual clay extruder 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. Three soils types with different clay and sand ratios were created to simulate the usage of excavation material.

The literature research lead to the following mixtures "Soil A,B,C". (Reeves et al., 2006)

Material	*Soil A (adobe Mix)*	*Soil B (50/50 Mix)*	*Soil C (Wasp Mix)*
Clay	30	50	70
Fine Sand	70	50	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 mix. Later water will be added to the mixture. First only 10% water was added. Since the viscosity and extrudability of the wet mixture is hard to predict the desired water content of 20% was approach stepwise under continuous evaluation of the plasticity. As suggested in the literature, feeling the material and observing how its viscosity changes is the easiest way to find the right water content.

As mentioned, the sift curve of the chosen sand is important. Unfortunately, the sand we used for the experiments had an unknown grain size distribution since we could not get any sifted sands. This became an issue since the sand we used for the initial material mixture had smaller grains than the sand we used for later mixtures. Although both were sold as "fine sand". The usage of two different batches of sand made it necessary to readjust the mixture for the toolpath experiments. The smaller grains had the effect that the ideal mixtures contained more water than in the initial test and behaved slightly different.

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. The fibres function within the material mixtures as a reinforcement. The additive materials are listed in two groups: Fibres and Granules. In initial tests between 10 and 40% straw fibres where added to the mixture (Tab.3). The length of the fibres was between 10mm and 30 mm. The material experiment should evaluate if mixture containing fibres or granules are extrudable.

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

Tab. 2: additive materials

Printing environment, drying and postproduction treatment.

The temperature and humidity of the LAMA cannot be adjusted for the experiments. The printing process will be adjusted according to the existing standard room temperature and humidity.

All specimens will be "shock dried". Exposing the small specimens to a harsh drying environment should increase the risk for cracks. By creating optimal printing and drying condition the cracking risk should be reduced. The drying process for the prototype will be elongated by drying it first for four days in a cool basement so the humidity can even out within the element. Later the prototype will be dried under room temperature.

The drying process of the component should be as slow as necessary to avoid shrinkage-cracks and as fast as possible to be feasible. A cool and humid environment should allow a continuous slow drying. The drying environment will be created by covering the specimens with a plastic sheet. By removing the sheet multiple times daily, the excessive water can escape and the component should dry slowly. However, this method of drying takes long and is hard to implement as an industrial process. Dark, cool and ventilated basements would be a good alternative drying environment.

To decrease the risk of surface cracks, water can be misted onto the 3DPE Element. Since the surface is drying faster than the inside, the different humidity content and shrinkage ratios cause tension and causes cracks.

A controlled drying process is a necessary part of the 3DPE-elements' production and needs to be engineered to reduce shrinkage and cracking. The drying conditions and environmental influences were neither the focus of the research nor within this scope.

The goal of the experiment is the development of material mixtures that are suitable to print a gradient material due to customized nozzles. To achieve that, the mixture should be highly plastic, good to extrude and show a low number of cracks due to production and drying. 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. All tested material mixtures designed for extrusion can be found in *Tab.3*

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

Straw clay insulation

In addition to the material mixtures that should be extrudable one straw clay mixture was tested. The straw-clay functions as an additional insulation layer. The mixture was made of 15% Soil B and 85% straw with a fibre length of 4-8cm.

Tested Material mixtures

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	wet 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

4.3. Toolpath and Nozzle experiments

After the initial manual material tests one mixture is selected for nozzle and toolpath tests. Mixtures that failed already in an early stage at the manual extrusion test are considered not suitable for further testing.

After the closing of the faculty due to the covid-19 pandemic the experiments where continued in the warehouse of the Smit's design centre that was so kind to open its doors for Rodiftsis T. and myself during the partial lockdown in the Netherlands.

Nozzle design

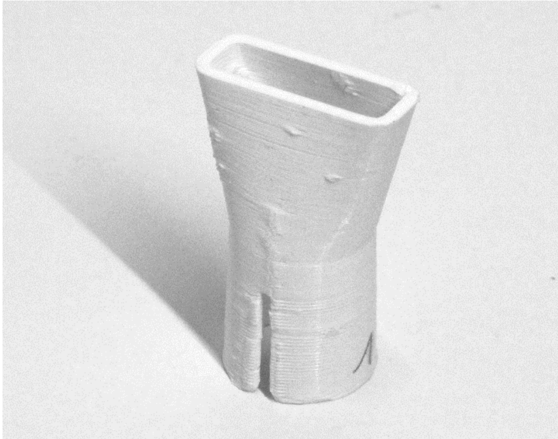
11 Nozzles were tested and evaluated

- Rectangular: 1, Fig. 28
- U-shaped: 4, Fig. 29
- Triangular: 1, Fig. 31
- "Spaghetti": 3, Fig. 32
- "Tagliatelle": 1, Fig. 33
- Stacked S-Shaped:1, Fig. 34

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 that will be explained in *"4.3.-* Experiment toolpath design". In addition, the nozzle shape should allow a good interlayer bonding and low compression under self-weight. A brief introduction of the tested nozzle can be found below.

- Rectangular Nozzle

The rectangular nozzle is designed for the outer and inner printed solid layers. These layers protect the fragile infill. The nozzle should have a density that is "as dense as casted".

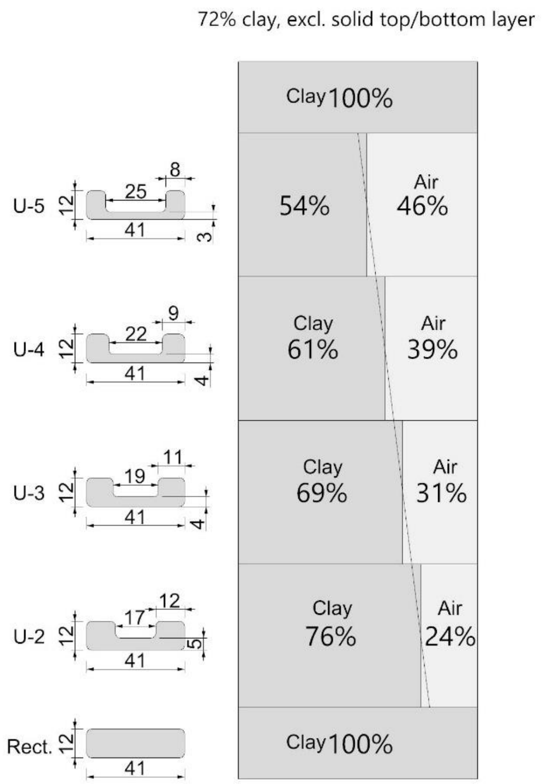


Fig,: 28, Rectangular Nozzle, h:12mm, w:40mm, fillet r=2mm

- *U-shaped Nozzle*

During the draft design four U-shaped nozzles where developed, like the one visible in *Fig. 29*. For the toolpath experiments the weakest nozzle with the smallest flanch width, the thinnest web and longest web span was chosen: Nozzle U-5. The most fragile nozzle should show the biggest deformations and allows a better evaluation of the extrusion geometry's behaviour. For the Density evaluation all four U-Shaped nozzles were tested. The detailed computational design flowchart of the density shift and nozzle design can be seen in *Fig. 80, 81.*

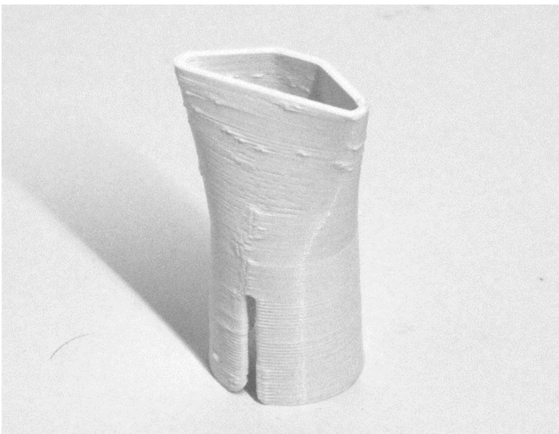
Fig,: 29, 3DP U-5 Nozzle



Fig,: 30, All U-shaped Nozzles, the corresponding density zone and the clay and air percentage. fillet r=2mm

- *Triangular (Trapezoid) Nozzle*

To make the triangular nozzle more stable the shape was slightly adapted what led to a more trapezoid shape of the extrusion geometry. To have a higher contact surface between stacked layers the top corner was flattened. The left and right corners where rounded up. This nozzle should prevent the unpredictable collapsing as described in *"Result evaluation- Stacked parallel extrusion of U-shaped Nozzle".*

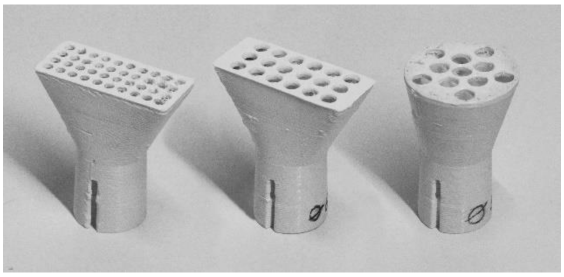


Fig,: 31, Triangular Nozzle, w: 40mm, H:12mm, fillet r=3mm

Since the main load bearing part of the extruded geometry of this nozzle is in the centre, the chances that this nozzle will collapse is much lower as compared with a u-shaped nozzle.

- **"Spaghetti" - multiple, round, small diameter extrusion Nozzles**

The small cross sections of the extrusions tend so "snake". This "snaking" helps enclosing air voids within the material mixture and decreasing the density compared to a casted solid cube.



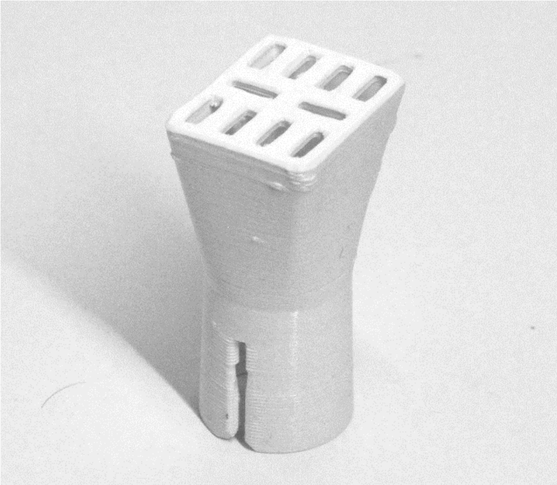
Fig,: 32, Spaghetti nozzle. 40x r=2mm,18x r=3mm,11x r=4mm

Different nozzle diameters were tested to investigate the relation between small and larger nozzle opening. The deposition of the extrusion geometry will be chaotic. The toolpath design needs to allow a certain tolerance to prevent complications such as double deposition of the material. The mixture was extruded randomly into the mentioned cubical form.

- **"Tagliatelle" - multiple, rectangular, small extrusions Nozzles**

The principal of theses extrusion is very similar as the "spaghetti" extrusion. Therefore, the title is as well Pasta inspired. The cross section of a single rectangular opening has about 33mm2 and would be size wise comparable with the 6mm diameter spaghetti nozzle. The small rectangular nozzles should be in an upright position during the extrusion process, what leads to two horizontal middle nozzles, see Fig.33.

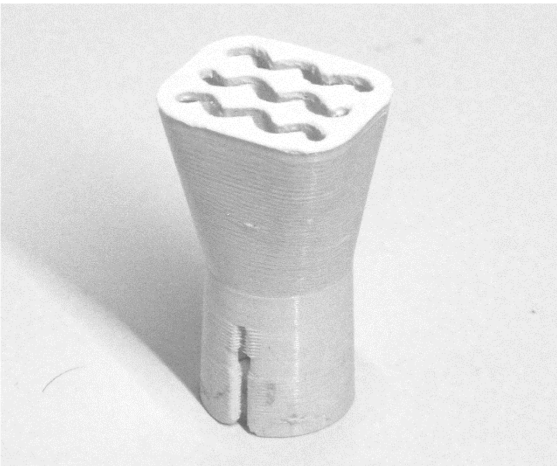
The two horizontal middle nozzles function as a spacer between the standing nozzle and should avoid that the top rectangles extrusion is sliding in between the bottom ones. This would increase the density and reduce the desired entrapped air voids.



Fig,: 33, "Tagliatelle" Nozzle- same principle as the "Spaghetti" Nozzle. 10x rectangular openings of 3x12mm

- ## S-shaped stacked nozzles.

Three S-shaped nozzles (two and a half S) were stacked over each other. The middle nozzle was mirrored to create voids during the extrusion process, see *Fig. 34*. The idea behind this nozzle design was to extrude the material in a wave-like pattern.



Fig,: 34, S-shaped stacked nozzle, 3x 3,5x40mm

Experiment-toolpath design

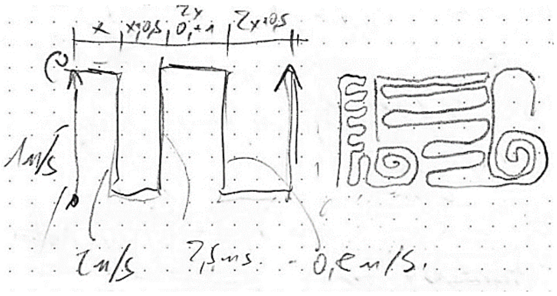
To define the limitation for the toolpath certain experiment tool paths will be created. They will be divided into five major groups

a) Single layer extrusion
b) Stacked layer extrusion- bridging
c) Stacked layer extrusion-interlayer bonding, web bridging and compression under self-weight
d) Chaotic snaking, waved extrusion
e) Stacked layers – interlayer mesh

Detailed description of the expected outcomes is listed below. The toolpath experiments are design to print the 3DPE component horizontally or "lying". This decreases the necessary height and reduced the compression under self-weight.

a) single layer extrusion

Tested Nozzles: Rectangular, U-Shaped



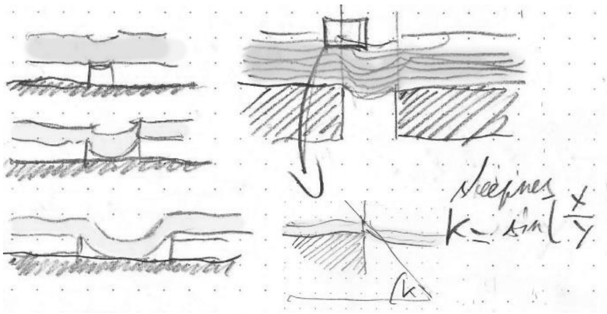
Fig,: 35, The singe layer toolpath should evaluate the impact of different travel and extrusion speeds, possible curve radiuses

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. (Wei, Tay et al. 2019)

This toolpath experiments could not be executed as planned. Since the robot could not be used, many of the desire results could not be generated. The manual extrusion is not precise and consistent enough to give proper information about the extrusion angel, the speed, the min. curve radius etc. Hopefully these experiments can be continued after the reopening of the faculty.

b) stacked layer extrusion – bridging

Tested Nozzles: Rectangular



Fig,: 36, How far can the extrusion bridge gaps? The bridging ability of the material mix will influence the toolpath design and density per Volume largely

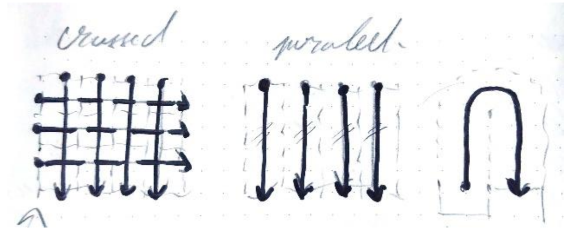
The stacked layer extrusion will analyse the bridging ability of the material mixture. The wider an extrusion can bridge gaps the better. For this test multiple parallel lines with an increasing distance will be overprinted perpendicularly. Evaluated will be the deformation of the bridging extrusion. Another important result will be if the bridging extrusion is touching the printing surface below or not. The specimens should show if the approach of bridging webs might be possible or not.

This toolpath experiments could not be executed as planned. Since the robot could not be used, many of the desire results could not be generated. The manual extrusion is not precise and consistent enough to give proper information about the extrusion angel, the speed, the min. curve radius etc. Hopefully these experiments can be continued after the reopening of the faculty.

c) stacked layer extrusion – interlayer-bonding, web bridging and compression under self-weight.

Tested Nozzles: Rectangular, U-shaped (U-5), Triangular

This is the largest group of toolpath and nozzle test. The nozzle shapes and extrusion angles influence the interlayer-bonding largely. To keep the extrusion geometry intact and possibly create voids within the extruded material, a laid-down material deposition gets tested. Parallel and crossed toolpath should evaluate the interlayer bounding between stacked and neighbouring layers. In addition, the influence of the toolpath on the compression under self-weight will be measured. The web bridging ability of U-shaped nozzles and the impact on the cross-section pattern will be evaluated as well.



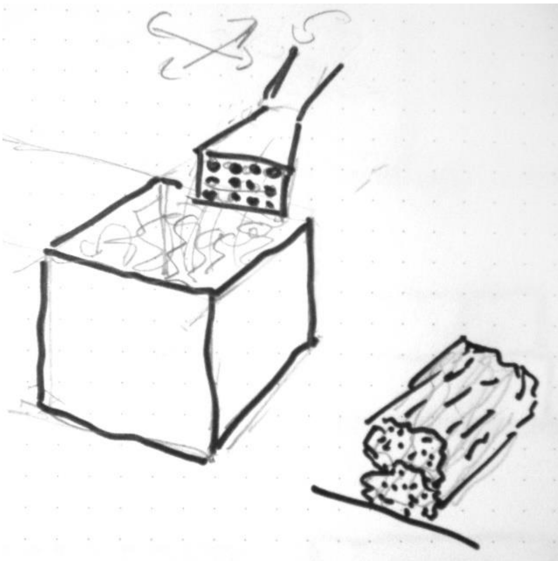
Fig,: 37, Stacked layer parallel or crossed toolpath. Stacked layer curved toolpath

d) Chaotic-snaking, waved extrusion

Tested Nozzles: "Spaghetti", "Tagliatelle", S-Shaped

The nozzles will extrude the material mixture into a hollow cube (100/100/100mm). The pattern in which the extrusion is filled into the cube is random. The extrusion angles is between 45° and 135°, the nozzle was rotated around the extrusion axis.

In addition, there will be a straight, stacked, parallel extrusion (two layers) to evaluate the stacking ability of the nozzles.



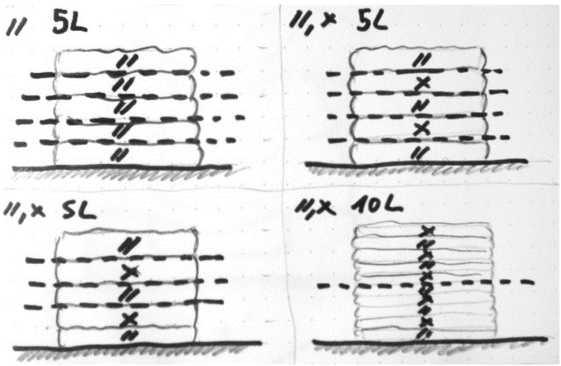
Fig,: 38, Filling the box with the extruded material mixture chaotically. Straight chaotically extrusion

e) Stacked layers – interlayer mesh

Tested Nozzles: Rectangular, U-Shaped (U-5)

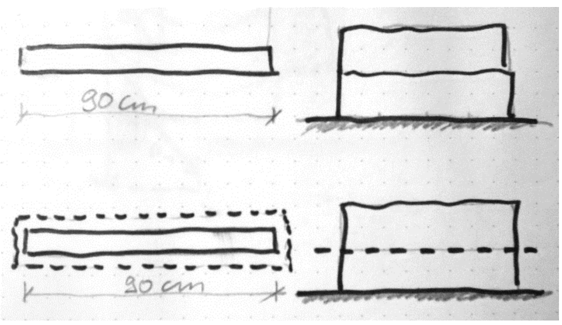
Meshes will be applied between certain layers to evaluate if the compression of the 3DPE element's cross section patter will change. The position of the mesh can be seen in *Fig. 39*. The applied mesh has a fibre width between 3-5mm. When the textile is placed on the already printed layers the fibres sink into the material mixture. The mesh will be gently brushed into the bottom layer to increase the bonding. It is important to not apply too much pressure on the textile to avoid deforming the already printed layers. The textile functions as a printing surface and leads to a better load distribution on the flanches of the U-shaped extrusion geometry. The fibres should reduce the tensile forces within the 3DPE component and reduce the risk of crack during transportation and mounting.

The meshes will be places in between parallel and crossed U-5 extrusion.



Fig,: 39, Interlayer mesh in between every layer (crossed and parallel toolpath), in between ever other layer (crossed toolpath), between two density zones (crossed toolpath)

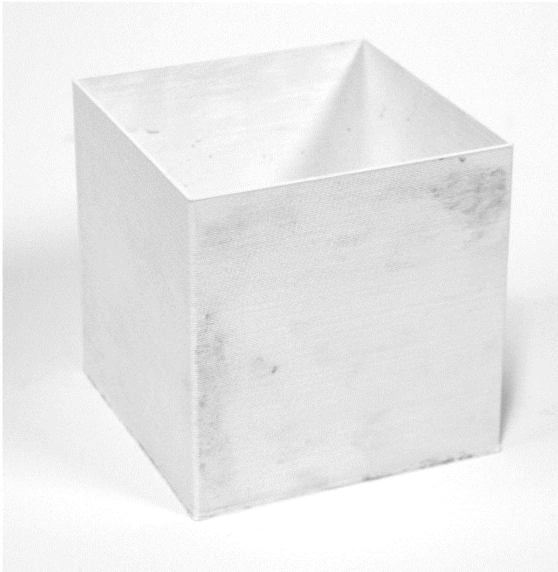
To test if the applied mesh will decrease cracks due to shrinckage it will be placed between one 90cm long, stacked parallel extrusion of two layers, *Fig. 40*



Fig,: 40, 90cm long extrusion with mesh reinforcement (left). Control extrusion, without fibres (right)

Density evaluation and comparison.

The density per Volume will be evaluated due to square prisms specimens. One cube with a side-length of 100mm will be casted of a solid material mixture. The density will be evaluated through the weight divided through the volume. The form as seen in *Fig. 41* will be used to cut out square samples, cast the solid cube and filled with the chaotic extrusions. Tested Nozzles: All 11 nozzles mentioned under "nozzle design". The square density samples will be printed with parallel, crossed, chaotic and waved toolpath depending on the nozzle.



Fig,: 41, Solid cube form. The cube is used as a stamp to create samples with a length and width of 100mm

Density= Weight/Volume

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

The density evaluation of the extruded material mixture nozzles will be based on the square cut outs of stacked, parallel or crossed toolpaths, the chaotic extrusions.

Layer compression under self-weight.

The height of the samples will be measured when dried. The specimens are expected to have different height at the edges, the height will be therefore evaluated in the middle of the specimens as good as possible. Their height will be compared with the designed height. The layer compression will be displayed in percentage of deformation.

4.4. Result evaluation

Materials experiments results

The criteria of which the mixtures are evaluated are extrudability, layer adhesion, plasticity, shrinkage while drying, cracking while production and drying, bridging ability.

The most promising results are listed below. The shrinkage was measured with a ruler. Two marks, 100 mm apart, were made into the wet clay and measured after the drying process.

Adding Fibres to the material mixtures resulted in a heavy decrease of the extrudability. The fibres where clocking the nozzle and made the extrusion impossible. The only mixtures that contained straw fibres and where partially extrudable were mixture 1 and 4. The fibre content was 10% and the length of the fibres was max. 10mm. Anyway, these mixtures caused still troubles in the extrusion process. The manual extrusion test showed that the pressure inside the cartridge is compressing the fibres. The pressure within the material mixture varies depending on the position. While the high pressure in the cartridge compresses the fibres and reduces their Volume the relative low pressure inside the nozzle lets the fibres expand. This Volume change leads, besides other factors to a clocked nozzle and an interrupted production. Another factor that might contribute to clocked nozzles might be that added fibres change the viscosity of the compound.

Since the first results of the material test failed to successfully integrate fibres or other additives within an earthen material mixture, the use of fibres was not further investigated. The observed problems outweigh the benefits for this method of 3D printing. This accounts as well for granules. They were not further tested. The grainsize of the granules was too big to be extruded by the manual or the motorized extruder. This results that the mixtures 1,4,8,9,10,11,12,13 failed the initial tests of the extrudability and were not further investigated and evaluated.

Mixture: 5, **Soil:** A (30% clay, 70% sand)
Nozzle: Rectangular, 10*8mm

Fig,: 42, 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 inter-layer bonding when the extrusion is “laid down” instead of extruded on the printing surface. The extrusion geometry stayed in shape of the nozzle.

Comment: Soil A is a promising mixture, and suitable for an extrusion process. The elasticity is low, that might cause problems when bridging is desired. The low production crack might be a result of the “laid-down” extrusion. If extruded perpendicular onto the printing surface production cracks are expected to appear.

Mixture 5 and 3 have the same sand and clay ration and differ only by the water content. The higher water content of mixture 5 (30%) as visible in *Tab.3* made the mixture less plastic, increases the drying time and the risk of cracks.

Mixture: 6, **Soil:** A-B (40% clay, 60% sand) **Nozzle**: round d=12mm

Fig,: 43, Mixture 6 perpendicular 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 inter-layer bonding.

Comment : Soil A-B is a promising mixture, and suitable for paste extrusion. The production cracks are probably a cause of low elasticity of the mixture. The sand content might be the cause for that.

Mixture: 2, **Soil:** B (50%clay, 50% sand) **Nozzle**: round d=12mm

Fig,: 44, 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 (two laid down round extrusion have a small bonding surface and cause bad interlayer bonding)

Comment: Mixture appears to be suitable for laid down extrusions with complex extrusion geometries. The mixture is elastic and should have a good bridging ability. Because the mixture is sticky as well it must be carefully filled into the cartridge to avoid entrapped air bubbles that can cause air shots.

Mixture: 7, **Soil:** C (30% sand, 70% clay)
Nozzle: round d=12mm

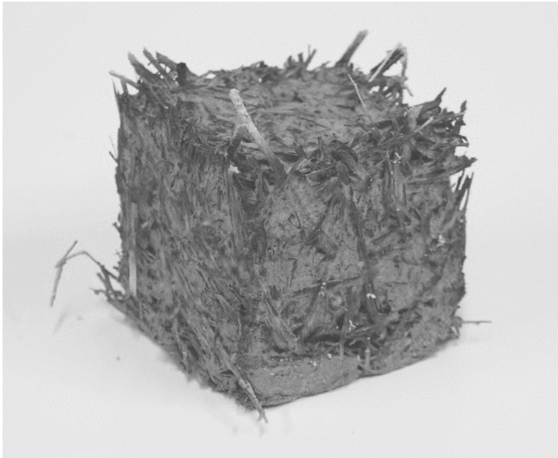
Fig,: 45, stacked layers with laid down extrusion and 60+° overhang

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 inter-layer 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. The high clay content could increase the cracking risk for larger objects. The more clay a mixture contains the higher the price will be.

Straw Clay (15% **Soil:** B, 85% straw)
Fibre length: 4-8cm



Fig,: 46, Straw clay, surface mould occurred during drying

Extruder:	Manual
Density:	Xy kg/m³
Drying cracks:	No

Production evaluation: To achieve a good bonding between the fibres and the clay the mixture needs to be compressed.

Comment: The mixture is not developed to be extrudable. The high straw content increases the insulation value and makes the mixture light. The high content of organic fibres makes the material prone to moulding during the drying process. It is recommended to dry the mixture fast in a chamber or have a constant air-flow around it to prevent moulding. It is possible to change the straw to clay ratio. The straw should be covert with clay to reduce the fire hazard.

Final Material mixture selection

Based on the results of the material mixture experiments one mixture was chosen for the "*Toolpath and Nozzle experiments"*

Mixture 2(50% Sand ,50% clay and 25% water.)

Mixture 6 consist of 40% clay and 60% sand. As visible in *Fig. 43* the wet mixture got production cracks when extruded perpendicular to the printing surface. This surface crack would influence a more complex extrusion geometry too much and decrease the overall quality of the 3d printed object. The low elasticity might cause ripped extrusion when bridged.

Mixture 7 was too viscose and sticky. This is a high risk for entrapped air. The high clay and lower sand ratio might reduce the friction in the extruder as described under *Extruder* and could allow a faster extrusion speed. Although the material experiments show only a shrinkage rate of about 1% the risk of crack during the drying process is higher due to the high clay content. This especially counts for larger object.

Mixtrue 2, Soil B is most promising for the upcoming nozzle and toolpath experiments. To increase the interlayer bonding, ease up he extrusion and allows a better handling of the mixture, the water content was increased by 5% to about 25%. This results in a more liquid mixture and reduces entrapped air and air-shots. The higher water content was also caused by the previously mentioned different sand grain size. As suggested for traditional clay construction the material mixture will optimally be kneaded one day before the production takes place. Overnight the mixture will be covert with a foil the avoid the surface to dry out. Before the 3DPE process the mixture will be kneaded again and the moisture will be checked and eventually adjusted. This assures a homogenous moisture distribution within the mixture. A clay mixture is like a dough and needs time to develop. During the material test we could see that the extrudability increases if the mixture has time to settle. A good example for the translation of traditional knowledge. (Volhard, Röhlen, 2009)

5.7. Results of the Toolpath and Nozzle experiments

The following specimens were made as described under *"Experiment-toolpath design"* The manual extrusion was done manually with as much care and precision as possible. Specimens made with the robotic arm and the motorized extruder should have a higher precision.

a) Single layer extrusion

Fig,: 47, Straight rectangular Nozzle extrusion. h: 12mm, w: 40mm, edge fillet r= 2mm, A=430mm²

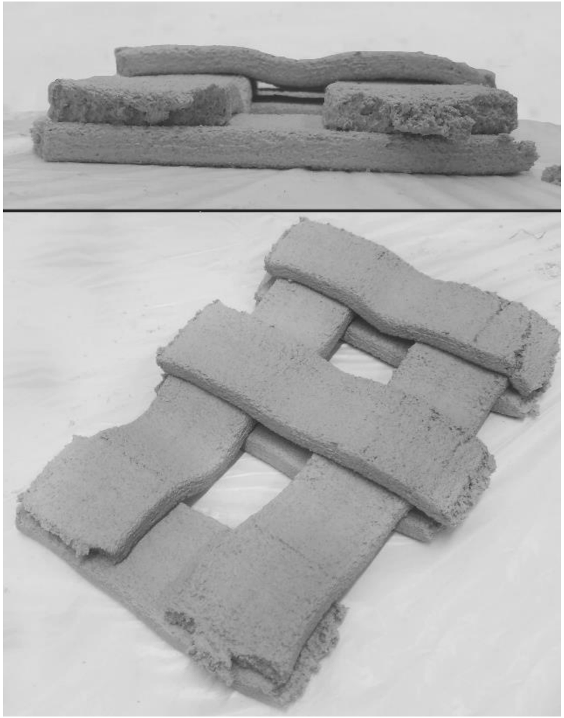
Fillet edges lead to a smoother extrusion geometry since the edges are less prone to cracking. The length of these cracks could increase during the drying process and weaken the 3d printed component. The surface of the extrusion was smooth and even with no visible crack after the extrusion or drying. The slightly bulkiness of the extrusion is cause by the manual, inconsistent extrusion.

The test of the U-shaped nozzle showed how important it is to sift the sand and allow no grain above a certain size to be in the material mixture. A single small stone was trapped in the web of the nozzle and caused a gap during the material deposition as visible on the left side and on top of the right side. The stone could only be removed by pushing it towards the flanch where it could exit the nozzle. During an automated production a trapped stone could destroy the result of the whole 3DPE object. Especially when the robotic arm is working unsupervised and the gap stays undetected. The middle extrusion showed that a U-shaped nozzle geometry is possible. The mixture got distributed well within the nozzle and got deposited in a full U-shape. At the bottom right of *Fig. 48* another crack is visible within the web. The crack was probably caused again by a small stone or another impurity in the earthen mixture. The foreign object was small enough to be removed by itself without any interference. The nozzle filled itself again completely with the material mixture and the extrusion geometry was U-shaped as desired.

Fig,: 48, Straight U-Shaped Nozzle

This test showed that a controlled grain size is not only important for the material mixture and its properties. It is as well crucial for the production process. A partially clocked nozzle can ruin a whole 3DPE component and cause delays in the production. To prevent this, the used sand must be sifted carefully before applied into the mixture. A simple sift with the max. allowable grain size could prevent this. Regarding the possible damage that a single screw could cause this sift is regarded as a necessity for all further experiments and the production of a prototype.

b) stacked layer extrusion, bridging ability



Fig,: 49, stacked orthogonal rectangular nozzle extrusion to evaluate the bridging ability of the wet material mixture. Nozzle: Rectangular, 12/40mm

This test was performed to test the bridging ability of the nozzle and the material mixture. The nozzle geometry influences the bridging ability largely. The moment of Inertia of the cross-section surface is important for the deflection. The thinner the cross section gets the more prone it is for a high deflection. The deflection according to the bridging distance can be seen below in Tab.1

Distance	20mm	40mm
Deflection	3-4mm	8-10

Tab.: 1, bridging deflection of a rectangular Nozzle extrusion

The test was successful and showed that bridging could be used to enclose air between two layers.

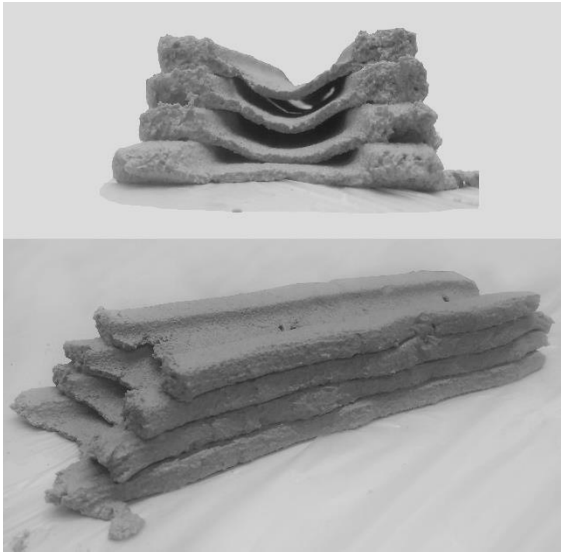
c) stacked layer extrusion – interlayer-bonding and web-bridging.

Stacked extrusion of rectangular Nozzle

The rectangular nozzle offers a large bonding surface between stacked layers. The precise material deposition is important for a good bonding between neighbouring layers. The rectangular extrusion geometry allows to print solid volumes with small voids in the filleted corners. The sample could be described as “almost as good as casted”. The density of the extruded solid is even higher hen the density of the casted specimen – see “density evaluation”

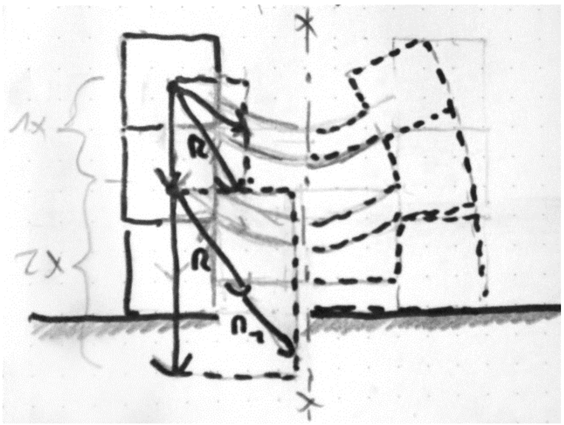
Fig,: 50. Straight, parallel, stacked rectangular nozzle

Stacked extrusion of U-shaped Nozzle



Fig,: 51, Straight, parallel, stacked U-Shaped Nozzle extrusion. Air gets enclosed within the layers. These voids lead du a reduction of density and should increase the insulation values of the material. Web length: 30mm, thickens: 3mm

As visible in *Fig. 51* the thin web of the U-shape is deflecting a lot under its own weight. The sticky, elastic material mixture withstands the tensile forces caused by the deflection and the resulting elongation. The size of the flanches is important to stack the extrusions. The tensile forces caused by the deflecting web can cause the flanches to bend inwards due to the high horizontal forces as seen in *Fig. 52*. The weight of the top layer applies a vertical force that helps the extrusion geometry to withstand the horizontal forces. The dimension of the flanches is therefore important for a stable extrusion cross section. Additional weight from top layers can function in this scenario like a pre-tension against the horizontal forces. This principal is like the applied weight off the pinnacle on a gothic dome, that increases the vertical force to withstand the horizontal forces caused by the roof construction and wind. The material mixture must be elastic enough to withstand the tensile forces within the web while in a wet state. The interlayer bonding between the layers is affected by the bonding surface of the flanches.



Fig,: 52, Sketch of the forces within a U-shaped Nozzle, benign along the main bending axis (toolpath)

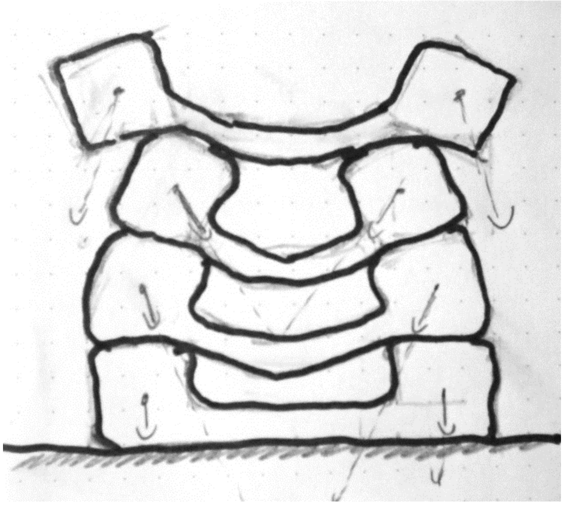
The span width of the web was: 30mm, and the deflection was about 5-6mm. In the top part of the picture it is visible that air gets enclosed within the layers. For a U-shaped design this bonding surface is largely reduced and results in a lower interlayer bonding compared to a rectangular extrusion. This is caused since the top surface of the flanches is only a fraction of the total nozzle width. Due to the material mixture and the right moisture ratio the interlayer bonding is nevertheless considered as satisfying. The goal of reducing the density and increasing the insulation properties of an 3DPE element could be achieved by using U-shaped nozzles.

Stacked, parallel extrusion of U-shaped Nozzle

This specimen was produced with the Nozzle U-5. This nozzle is produced for the zone with the lowest density. Therefore the flanch has the smallest width of all U-shaped nozzles and the extrusion geometry is the most fragile and prone to deformation

Fig,: 53, U-5 Nozzle,straight, parallel extrusion, five layers on top of each other. Collapsing layers

In *Fig. 53* a layer collapse is visible. The parallel extrusion led to a too high horizontal tensile force due to the small dimension of the flanch and the self-weight of the web. Since the extrusion is bending inwards, neighbouring layers get detached from each other. The deformation accumulated itself due to no change of the main bending/deflection axis. In this case the bending axis is the toolpath axis. This causes a further increase of the deformation until the layer collapses. This phenomenon was already witnessed after the second layer. The first layer gets extruded as desired, the second layer bends inwards since the bonding surface between the flanches is too small and the flanches too light. The third layer bends outwards since the contact surface between the bottom and top layer is not the flanch but the web. The fourth and fifth layer acted unpredictable due to already collapsing bottom layers, see *Fig. 54*



Fig,: 54, collapsing layers

The irregular collapsing extrusion causes a non-constant deflection in height. Since the distance from the TCP and the printing surface should be 20mm, an irregular height causes an unprecise material deposition of the next applied layer during an automated production process. Manually it was possible to react on this deformation, but the result was still undesirable. The next layer will increase the weight and the extrusion will further collapse and deform. The vicious circle of a collapsing extrusion geometry gets continued. The collapsing layers are not entrapping as much air as desired and the density decrease is smaller than expected. In addition, the overall height of the extrusion will decrease, and more layers than planned need to be printed. The necessity of more layers leads to a longer printing time. A parallel extrusion without any supporting or reinforcing materials is probably not suitable to produce a prototype.

Stacked, Parallel extrusion with Triangular nozzle.

If stacked, the left and right wings of the top extrusion cantilever from the top surface of the bottom layer. This cantilevering encloses an air void and reduces the density as seen below in *Fig. 55*. A possible density shift could be achieved by changing the width and height of the nozzle as well as the proportions of the "core" and the "wings" of the nozzle.

Fig,: 55, Triangular nozzle parallel toolpath

The parallel toolpath worked well and the compression due to self-weight was lower than the U-5 Nozzle. No big extrusion deformations where witnessed during the extrusion or after the drying process. Unlike the previously mention U-shaped nozzle, the triangular nozzle does not collapse along the extrusion axis. This is caused by the centred support. The Triangular nozzle is supported in the middle, and the wings are cantilevering from the centre to the side. This results in a more stable extrusion geometry. One issue with this is that gaps between neighbouring extrusion geometries might appear. The entrapped air is not trapped and can circulate through the 3DPE component. Non enclosed air pockets might draft thought the gaps and decrease the insulation properties of the 3DPE element. A precise toolpath could solve this issue.

Stacked, crossed extrusion U-shaped

Fig,: 56, U-5 Nozzle, cross extrusion, five layers on top of each other. The direction gets changed every other layer-lower risk of collapsing layers

By changing the extrusion direction every other layer another axis of deformation gets added. In addition to the previously mention axis of deformation along the toolpath a second axis perpendicular occurs. Since the whole top layer must bridge the gap between the bottom layers flanches the extrusion is deflecting in two perpendicular directions. The flanches of neighbouring layers that got detached from each other when parallel extruded stay better together now. The flanches of the bottom layer function as pillars, bridging the top layer in between them. By rotating the top layer 90° the inter layer adhesion is holding the bottom flanches together and prevents them from bending inwards. The elastic material mixture can be stretched carefully from flanch to flanch. A sticky and flexible material mixture allows small tensile forces in the material when it is still wet. This tension along the extrusion axis prevents a bending around the toolpath axis. To achieve this stretching or tension during material deposition the extrusion speed must be slightly lower than the printing speed. The stretching in combination with the second bending axis functions as a sort of pretention that reduces the deflection due to inwards bending as seen in *Fig. 53*. The settings must be evaluated in detail since a too low extrusion speed or a too high printing speed would result in a ripped extrusion geometry. Compiling these setting is unfortunately only possible with the motorised extruder and the robotic arm. As visible in *Fog. 56* there is still a visible deformation but compared with *Fig. 53* the applied layers can be still used as a printing surface. Of course, the bending along two axis causes more compression due to self-weight. This is a result of an even smaller contact surface between the stacked layers compared with the parallel extrusion. Only at the crossing of the flanches the load due to elf-weight can be distributed downwards. The transformation from a line load to a point load causes higher forces at the point load. A higher force leads to a higher compression. At the same time this has probably a positive side effect regarding the thermal transmission through the building component. The reduced contact surface results in a lower heat transmission and therefore a higher insulation property of the 3DPE element. The higher deflection caused by bending in two directions leads to smaller air pockets. This results in a higher density of the printed pattern and a lower insulation property. As mentioned, changing one parameter influences many other properties of the extrusion.

To resume: The crossed toolpath causes a higher layer compression due to self-weight and a reduction of entrapped air. But the compression and deflection are more even and predictable. Crossing every other layer allows a more continuous printing surface and results in a higher printing quality.

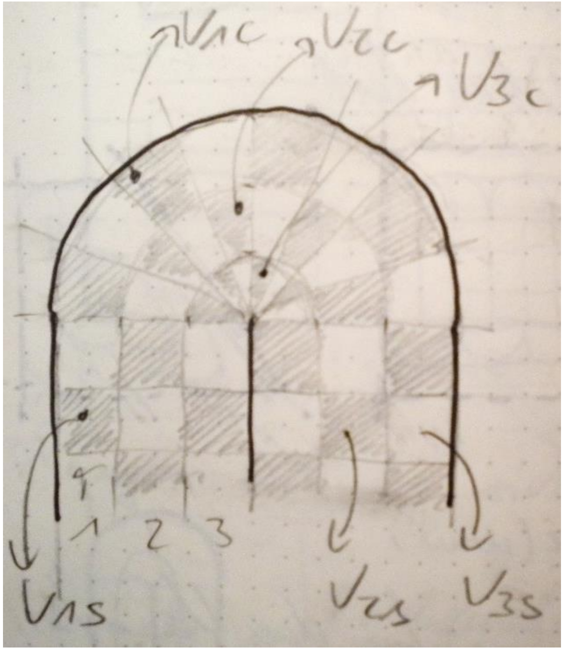
Crossed extrusion Triangular nozzle

While crossing out the toolpath for the U-5 nozzle increased the printing quality, the quality decreases when the toolpath for the triangular nozzle is crossed out. As visible in *Fig. 57* the extruded geometry bends between the bottom layers.

Fig,: 57, Triangular nozzle crossed toolpath

Curved extrusion, radius = nozzle width

The toolpath is longer on the outside radius then on the inside. More material gets extruded in the centre of the curve *Fig. 58*. This excessive material deposition is reduced by inclining the angle of the extruder. An extrusion on the printing surface and not a laid down extrusion could reduce the extra material. It was barely possible to evaluate this manually due to inaccuracies. The problem of excessive material deposition increases when the extrusion is parallel and not crossed *Fig. 59*. Interlayer meshes could even the extruded geometry out and reduce this problem. Although that will cause a higher compression at the centre. A curved toolpath can as well be avoided. The material gets therefor only extruded along a straight line. At the end of the line the extrusion stops. The Nozzle travels and rotate to the starting point of the new toolpath curve and start extruding there again. This "start-print-stop-travel" approach could as well lead so some irregularities thought.



Fig,: 58, Sketch of the necessary material deposition along curved toolpaths

Fig,: 59, U-5 Nozzle, Curved extrusion

d) Random/Chaotic extrusion

Multiple, round, small diameter extrusions "Spaghetti" nozzles

The nozzles were used to extrude the material mixture into a hollow cube (100/100/100mm). The extrusion process itself worked very well. Building up a 100mm high sample was possible without a too big compression for the nozzle diameter of 4mm. Increasing the nozzle diameter led to a higher compression due to self-weight and lesser entrapped air voids.

The compression can be easily seen in *Fig. 60.* While the thinner extrusion is still intact at the bottom of the cube and the single strings are visible, the other cubes have almost solid edges at the bottom. The higher these edges go the higher the compression. Since this compression happens already during the extrusion itself more material is necessary to reach the desired height of 100mm. More information is given in "*Density evaluation".*

Fig,: 60, Spaghetti nozzle. The thin nozzle openings create small clay strings. These strings enclose air. Right: r=2mm, Middle: r=3mm, Right: r=4mm

Although the extrusion works very well and a relative high volume can be deposited fast the dried samples are very fragile. Especially the smallest diameter is hard to handle. Lifting it up results in breaking off small part of the specimen. It is important to apply surface loads and no point load on the sample since the small clay strings cannot resist them. The drying process is fast due to the high relative surface to the volume and leads to small cracks within the strings and weakens them even more. The spaghetti technique offers a large potential due to the low density of the samples. Especially for the density zones that require a low density this technique could be applied. Only using them within the upper layers of a component would also decrease the applied load on them and result in more entrapper air voids. Another benefit of this technique could be the short drying time which results in a faster production. However, the deposited material needs to be stabilized to avoid crumbling due to vibrations and forces caused by transportation, mounting and usage. Enclosing the deposited material with a protecting frame as it is planned for the wall component might not be enough. Additional reinforcement in the form of fibres, fibres meshes or solid printed cells, like honeycomb structures that can be used as an enclosure would be a possible option and should be further investigated.

The toolpath of this nozzle would largely depend on the chosen stabilizing technique since the deposition is random anyway. Depositing the strings along a linear parallel or cross toolpath is as much possible as depositing the string into previously printed chambers.

Multiple, rectangular, small extrusions - "Tagliatelle" nozzles

The nozzle was used to extrude the material mixture into a hollow cube (100/100/100mm). The deposition into the cube was again executed randomly *Fig. 61*. The extrusion angles were between 45° and 135°, the nozzle was rotated around the extrusion axis. More information is given in "*Density evaluation".*

Fig,: 61, "Tagliatelle" Nozzle- same principle as the "Spaghetti „nozzle. 10x rectangular openings of 3x12mm

The rectangular cross sections have a better bonding between each other and enclose and enclose air. The cubical sample is still fragile but good to handle. The applied mixture nevertheless needs some sort of stabilizing like the previously mentioned "Spaghetti" nozzle.

The material mixture was as well extruded along a straight toolpath while most of the small rectangular nozzles were in an upright position. The specimen is visible in *Fig. 62.*

Although all nozzles openings usually have no angles that are not filleted the rectangular openings of this nozzle have 90° angles. To allow a faster printing time of the nozzle itself, it was designed to have an orthogonal printing path. This is a simplification of the quite complex printing path that was necessary for the "Spaghetti" nozzles and lead to undesired material deposition. To remove this excessive material a lot of post processing was necessary. The 90° angles did not lead to any cracks during the clay extrusion. A possible reason might be the small scale of the nozzles and the relative low pressure that needs to be applied to extrude the clay mixture.

Fig,: 62, "Tagliatelle" Nozzle- same principle as the "Spaghetti „nozzle

Multiple S-shaped stacked nozzles. Waved and straight extrusion.

Two sample where made to evaluate the density. One straight horizontal extrusion *Fig 64* and one wave-like extrusion as seen in *Fig 63*

Fig,: 63, S-shaped nozzle, woven extrusion

The extrusion worked well for both samples, however the multi-layer extrusion worked better for the horizontal sample. Applying multiple layers at the same time in a wave like pattern leads to some irregularities. These errors emerge because the extruded geometry can stick together before deposited on the final position. This can cause ripped extrusions. But the irregularities where manageable and the sample is not considered a fail. Depositing the material in waves might work better if the nozzle would only have one opening. But extruding only one layer at a time would decrease the production speed to 1/3. The minimal quality loss of a multi-layer extrusion compared to a single layer extrusion is acceptable considering the much faster production time.

Fig,: 64, S-shaped nozzle, straight extrusion

The toolpath for the wave-like extrusion can as well be orthogonal and does not necessary be curved to achieve a waved extrusion. (Alphen, 2017) However, the 6-axis robot offers many more possibilities for this kind a waving extrusion. A further investigation is highly recommended.

e) Stacked layers – interlayer mesh

The fibres where applied between each layer of a parallel *Fig 65* and cross extrusion *Fig 66* as described. The Applied mesh stabilized the flanches, causes a more even load distribution and functioned as a printing surface for new layers

Fig,: 65, U-5 Nozzle, parallel extrusion with jute mesh in between each layer. height: 5 layers, each 12mm

Fig,: 66, U-5 Nozzle, crossed extrusion with jute mesh in between each layer. height: 5 layers, each 12mm

Applying the mesh between every layer result in a high material usage. Let's assume a wall component has about 4 m², considering adding one mesh between every layer would lead to: 4*24=96m² of fabric for one single wall component. To reduce the necessary amount of cloth further test where done to evaluate the quality of the printed specimen if the mesh is only applied between every other or only between different density zones.

Due to the much better quality of the crossed extrusion the following interlay mesh tests where performed with a crossed toolpath.

- Mesh every other layer (reduction of mesh surface by 50%)

Fig,: 67, Mesh every other layer, cross extrusion

The specimen is made of 5 crossed layers on top of each other *Fig 67*. The mesh is applied between every other layer as visible in *Fig 39* The mesh stabilizes the extruded layers and evens the printing surface out. The mesh flattens minor height differences that are a result of the crossed-out extrusion. A plane printing surface results in an increased quality of the extruded geometry. Compared with the specimen that had meshes between every layer the result is almost the same. The layer compression is slightly higher as in specimen *Fig 65,66.*

- Mesh between each density zone (reduction of mesh surface by 85%)

Applying a mesh between the density zones results in a mesh every sixth layer. As described earlier. The layers collapse after about three to four layers in a parallel extrusion. To stack six layers without any reinforcement the crossed extrusion is better suited. For this specimen five layers for each density zone were assumed. The mesh was applied between layer five and six as visible in *Fig. 39.* The applied mesh flattened the bulky printing surface an formed a plane that functioned as an even printing surface for the new density zone. However, to even out the bulky surface caused by the crossed toolpath some gentle pressure needed to be applied onto the mesh. This pressure in combination with the self-weight of the layer let to a massive compression of the layers within the lower density zone as visible in *Fig. 68.*

Fig,: 68, Mesh between every density zone, cross extrusion

Fibre mesh reinforcement against shrinkage and cracking

Fig,: 69, Top: bonding between mesh and clay mixture Bottom: Two 90cm long, stacked rectangular (12x40mm) extrusions. Back: Without fibre reinforcement, front: one fibre mesh between the two layers

The bigger the 3DPE parts are, the more prone they are to shrinkage. To test if added meshes are reducing the risk of shrinkage cracks two 90cm long specimens were extruded, see *Fig 39.* The samples are made of two layers. One did not have any reinforcement, the other one had a mesh (fibre width 3-5mm) in between. Two marks, 900mm apart were made on the specimens. The shrinkage was about 3% for the unreinforced and 3% for the reinforces sample. Against the expectation the reinforced sample showed a large crack (width 3mm) in the top layer. The conventional one had no visible cracks. Since the extrusion was done manually this could be a random error due to inconsistencies during the production. Another option could be that the mesh soaked too much water out of the material mixture and lead to too fast drying. To reduce the risk of an error multiple samples should be produced with the motorized extruder and the robotic arm.

The bonding between the applied mesh and the material mixture was not very good. The top layer can be removed from the mesh, the mesh from the bottom layer. The mesh did even reduce the interlayer bonding instead of increasing it. This phenomenon was not witnessed at the previous specimens with a mesh reinforcement.

A possible option to increase the interlayer bonding could be to soak the mesh shortly before it is deposited into a clayish slurry. A wet cloth would not suck the moisture out of the material mixture and would probably increase the bonding between the layers. Possible options and the effect on shrinkage and interlayer bonding need to be further investigated.

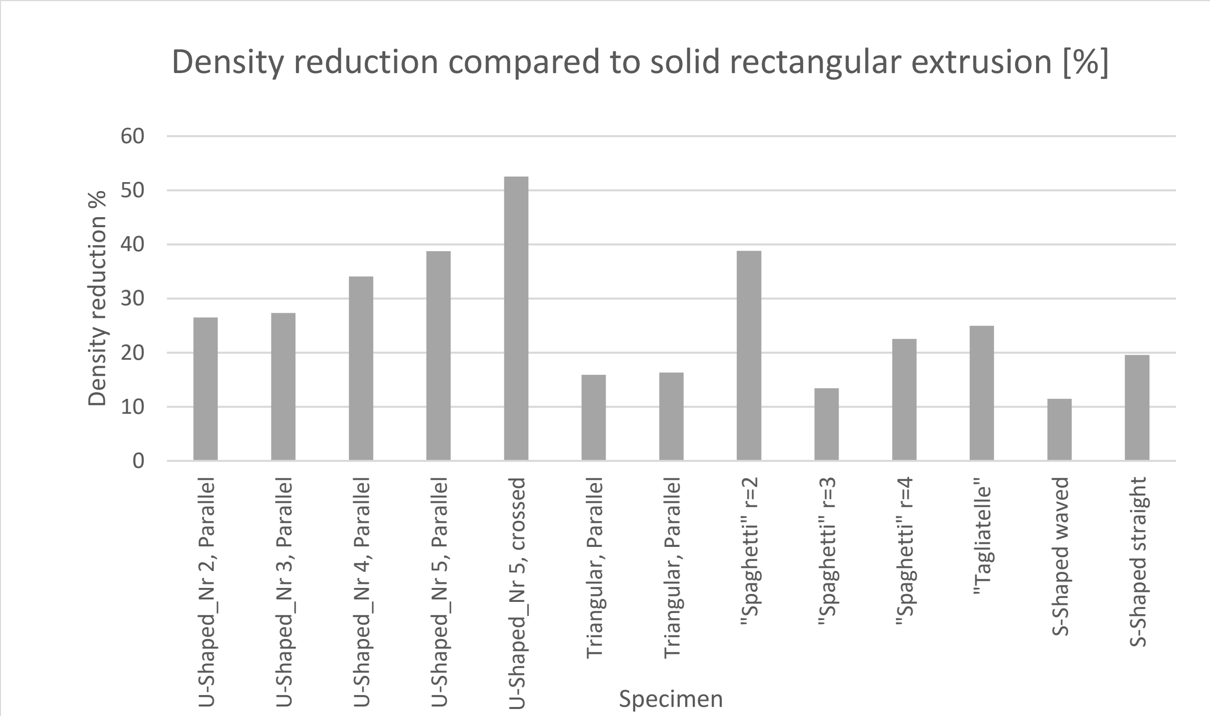
Density evaluation

The customized nozzles should create a density decrease within the cross section of the 3DPE element. This shift lads to a FGM. The created nozzles where printed along a toolpath that should result in the density decrease. The Specimens volume and weight was measured after drying, the density was calculated. To measure the decrease, each specimen’s density was compared to the “solid extrusion”, which was printed with a rectangular nozzle. The samples were compared to the solid extrusion because the whole 3DPE component will be printed. To evaluate the density, decrease of different extrusion geometries the results are more valid if compared with a solid extrusion, and not to a casted cube. The solid extrusion’s density is however higher than the casted cube. The weight of the “solid extrusion was about 7% higher than the casted sample.

NOZZLE / TOOLPATH	DENSITY[KG/M³]
VPB	650
STRAW CLAY (COMPRESSED)	970
STRAW CLAY (LOOSE)	600
CASTED CUBE	1629
RECTANGULAR, PARALLEL	1747
U-SHAPED_NR 2, PARALLEL	1197
U-SHAPED_NR 3, PARALLEL	1184
U-SHAPED_NR 4, PARALLEL	1073
U-SHAPED_NR 5, PARALLEL	997
U-SHAPED_NR 5, CROSSED	773
TRIANGULAR, PARALLEL	1369
TRIANGULAR, CROSSED	1362
"SPAGHETTI" R=2, RANDOM	996
"SPAGHETTI" R=3, RANDOM	1410
"SPAGHETTI" R=4, RANDOM	1262
"TAGLIATELLE", RANDOM	1222
S-SHAPED, WAVED	1441
S-SHAPED, STRAIGHT	1310

Tab.: 4, Density [kg/m³] of different nozzles and print patterns.

In *Tab. 4* below the density decrease between Nozzle U-Shaped Nr.2(26%), Nr.3(24), Nr.4 (34%) and Nr.5 (38%) is clearly visible for the parallel extrusion if compared to a rectangular extrusion. By crossing the toolpath of nozzle "U-Shaped Nr. 5" a density decreases of 54% was possible. This low density might be only possible since the crossed sample had only 3 layer and therefore a lower compression under self-weight happened. A promising density decrease is visible for the "Spaghetti" and "Tagliatelle" samples. Considering that these samples allowed to deposit material in a height between 80 and 90mm in one production step the decrease is higher as the one seen for the U-shaped samples. Although the reduction in density the chaotic extrusion leads to other problems as mentioned earlier.



Tab.: 5, Density reduction [%], the calculation spread sheet can be found in the Appendix 1

Compression under self-weight

Compression under self-weight with interlayer mesh

SPECIMEN	Hight	Layers	Designed Height	Compression [%]
U-5, PARALLE, MESH EVERY LAYER	58	5	60	2
U-5, CROSSED, MESH EVERY LAYER	45	5	60	15
U-5, CROSSED, MESH EVERY OTHER	45	5	60	15
U-5, CROSSED, MESH EVERY 5 LAYER	74	10	120	46
U-5, CROSSED, MESH EVERY OTHER	45	5	60	15

Tab.: 6, Compression under self-weight, the calculation spread sheet can be found in the Appendix 1

The compression under self-weight is one of the biggest problems for extrusions that are fragile to decrease the density. The more the extrusion gets compressed the higher the density gets. The more layers are applied the higher the compression. This was foreseeable and depends not only on the nozzle but as well of the material mixture and its water content. A dryer mixture causes less deformation. Applying a mesh between every layer resulted in the lowest compression if the toolpath is parallel. This highest compression could be seen if only one mesh gets applied between two density zones (every 5 layers) This led to a compression of 46%, see *Tab. 6.* Due to the inaccuracy of the manual material deposition the results of the experiments might differ from robotic produced samples. The calculated density of each sample can be seen in *Tab. 4.* By customizing the nozzle a density decrease was possible compare with solid extruded samples. However, the density of 3DPE elements is still higher compared to VPB or straw-clay.

Experiment statements

The compression under self-weight is higher on the edges of the specimens. Neighbouring layers are stabilizing themselves. Since there are no neighbouring layers on the border of the specimens the layers are more prone to collapse. This leads to a higher compression. The height is measured in the middle of the sample. Due to this effect every 3DPE object will have a lower thickness on the edges.

To allow a general conclusion all finding from the presented experiments are summarized according to Shrinkage, Density, Compression under self-weight, Toolpath limitations, Cracking during production, Cracking during drying, Interlayer bonding, Nozzle influence on the extrusion geometry, Extrusion angle and flow, material mixture, possible contour crafting, production set-up limitations for a 1:1 prototype, productivity compared with a conventional single nozzle extrusion. Each of these topics can be influenced when certain parameters get changed during the production. The design has a big impact on those as well. The results from the active experimentation and research by design were used as a input for the informative workflow.

The final design was based on the following production and material limitation:

- Shrinkage

As mentioned under "material" the shrinkage depends largely on the clay and water content of the material mixture. The higher the clay content the "fatter" the mixture. By adding sand, the mixture becomes less fat and the shrinkage is decreased. The evaluated material mixture samples showed a shrinkage of around 1%. This would accumulate of about 28mm for a 2800mm long façade panel. Multiple small cracks are predictable, they possibly will appear at some points. By reinforcing the applied material mixture with jute in between every other layer the 3d printed parts will stay compact and stable. However, the mesh will not stop the shrinkage, its purpose is more to hold cracked parts in place and bind them together. To increase the bonding between the clay mixture and the applied mesh further research must be done.

- Density

For detailed information about each extrusion density and the toolpath influence on the density see *Tab. 5* The nozzle and the toolpath influence the density of the 3DPE component. As visible in the table, a density reduction compared with the "solid" extrusion is possible and close to the design reduction. In some cases, the density reduction is even higher than designed. The usage of multiple nozzle types for different density zones might be an option to reduce the compression under self-weight.

- Compression under self-weight

The shape of the nozzle, as well as the toolpath and possible reinforcements as fibre meshes are influencing the compression under self-weight. In addition to that the moisture content and therefore the viscosity of the mixture is one of the major influences. The evaluated specimens showed that applying a fibre mesh between every layer, or every other layer reduces the self-compression for a parallel or crossed toolpath. This is cause by a more even material distribution. Applying interlayer meshes is improving the quality of extrusion positive. The negative influence on the interlayer bonding need to be further investigated. The lower the compression under self-weight the lower the density of the extrusion will be.

- Tool path limitations

The more complex the nozzle geometry gets the simpler the toolpath becomes. The limitations are largely depending on the hardware with which the component is going to be produced. The extruder cannot be rotated more than 360° due to the limitations of the robot. A max. rotation of about 180° seams feasible. The toolpath needs to be designed non-spiral, but instead 180° back and forth, as visible as *Fig. 25.* The focus of the research was the nozzle development and not the toolpath optimization. There is a big potential that more complex toolpath in combination with different nozzles allow a higher density reduction of the 3DPE element.

- Cracking during production

Is influenced by the nozzle shape and the material mixture. To prevent surface crack during the production a material mixture with enough clay and moisture content is recommended. The used Soil B, with a moisture of 20-25% did not show large production cracks. To allow a smooth extrusion the nozzles should not have any sharp edges. The fillet radius of 2mm for the edges of the nozzles lead to a good material deposition. It maintained the desired nozzle geometry without too many deformations.

- Cracking during the drying process

There was almost no cracking during the drying process for all smaller samples. This was according to the expectation since the clay mixture had a high sand content. However, the 90cm long samples showed some cracks. To reduce cracks during the drying process it is recommended to dry the component slowly. This can be done in a drying chamber where the humidity gets controlled.

- Interlayer bonding

Largely depends on the possible bounding surface and the material mixture. The extrusion angle and the nozzle are influencing the interlayer bonding as well. A good bonding between neighbouring layers is harder to achieve than a good bonding between stacked layers. The best results between stacked layers is achieved when the material mixture gets extruded onto the bottom layer in a 90° angle. To get the best bonding between neighbouring layers a 90° extrusion in combination with an overlap is desired. The overlap percentage of 20% should result in a good bonding without causing unwanted excessive material deposition during the extrusion. The perpendicular extrusion onto the printing surface does not allow a customized extrusion geometry and destroys the desired shape.

- Nozzle influence on the extrusion geometry

The inside surface of the nozzle should be smooth. Droplets of material cause by the 3d printed process on the inside surface of the nozzle influence the extrusion geometry more the closer they are towards the nozzle outlet. The printing settings for the nozzle is therefore influencing the general quality of the 3DPE component.

The smallest opening for a nozzle that should extrude a precise extrusion geometry should not be smaller than 3mm. Small lumps from an unprecise mixing process could clock the opening. Especially the web of a u-shaped extrusion is prone to clock due to its small diameter. For unprecise extrusion, with a desired chaotic extrusion geometry, such as “Spaghetti, Tagliatelle” can have smaller opening. The damage due to one small clocked nozzle is acceptable in this case.

The active experimentation showed that it is possible to the density of a 3DPE element by customizing the nozzle.

- Extrusion angle and flow

The extrusion angle is depending on the form of extrusion. If a maximum of interlayer bonding is desired the extrusion angle should perpendicular to the printing surface. If a complex extrusion geometry is desired the extrusion should be laid down. To achieve a laid down extrusion the angle should be between 30-60°. The distant of the TCP and the printing surface should be about 20mm. The angle in which the material is deposited can change depending on the toolpath. The manual experiments showed that narrow curves might be easier to achieve when the angle is about 60°. Straight lines can be printed faster if the angle is about 30°. The flat angle reduces the tension in the extruded geometry and reduced the risk of deformed extrusion. The extrusion flow must be adjusted accordingly to the printing speed. As described earlier the extrusion speed can be slight slower than the printing speed to achieve a higher bridging distance, the angle should be around 30° in this case.

Narrow curves require a slower movement, a higher extrusion angle and a slower extrusion speed. To achieve an even material deposition along curved toolpaths the distance between the TCP and the toolpath can be reduce. I addition the Nozzle can be tilted inwards to prevent an excessive material deposition along the centre of rotation. This can be roughly compared with a cyclist who leans into a narrow curve.

Straight curves allow a faster movement and extrusion speed. For higher speed the angle should be flatter.

The precise extrusion angle/flow needs to be evaluated with the motorised extruder and the robotic arm. Since the robotic arm was not available these settings could unfortunately not be determined.

- Material mixture

As described under “*4.4.- Material experiment results”* the material mixture is largely depending on the extrusion geometry. The chosen mixture for the nozzle and toolpath experiments was mixture 2, 50% clay, 50% sand. For further improvement silt can be added to the mixture. The addition of fibres is not recommended, since it highly increases the risk of a clocked extruder. This would cause large production delays and failed extrusions.

- Possible contour crafting

As described under “*3.3.4.- Contour Crafting”* the possible integration was explored only manually. Adding a jute textile between the layers allows a change of the printing direction. The application of meshes can be either automized or be done manually. Applying a large-scale mesh in between the layers would not be considered contour crafting anymore. This production step would not include the manipulation of the extruded geometry after its deposition, but only the deposition of a mesh. Brushed mounted to the extruder to apply a gentle for on the mesh to even the printing surface would be considered as contour crafting.

- Limitations of the production set up for a 1:1 prototype

Printing a 1:1 prototype of a wall panel would require about 270kg of dry material mixture per m^2 for the current design. The LAMA currently has a max cartridge capacity of 2.8 l=0.0028m^3. If the volume of the 1m^2 prototype is 0,21m^3 the cartridge would need to be refilled 75 times for a prototype of 1m^2. There are two option for possible 1:1 prototype production.

Option #1: scaling

Making a smaller prototype. 0,1m^2 could be a reasonable size. The cartridge would need to be refilled about 8 times. A small prototype would as well allow an easy transportation. The cost for the required framing would be decreased as well and could be done in the model hall of the architecture faculty.

Option #2: producing the 1:1 prototype at a company that has an industrial 3d printing set up.

A large 1:1 prototype (2.8x1.2m) would weight about 1000kg since it is considered as a massive construction. The transportation as well as storing would be unnecessary complicated. The required framing could not be produced in the model hall. Letting such a big frame be produced from a carpenter would be too expensive considering the current budget. A real 1:1 prototype would be required for further experiments regarding thermal insulation, fire resistance and is at the current point of research not recommended.

- Productivity in relation to a conventional single nozzle production.

The designed cross section geometry could not be produced with a non-customized nozzle. It would be possible to print a similar geometry with conventional round nozzles, but it would still require several nozzle diameters. If the designed gradient material would be produced with a single nozzle, the nozzle would need to be 3mm in diameter. This would increase the required toolpath tremendously and elongate the production process. In addition, the object would need to be printed standing upright, this would lead to a production pause every 20-30cm to allow the deposited material to dry and gain strength against self-compression. This would increase the production time tremendously.

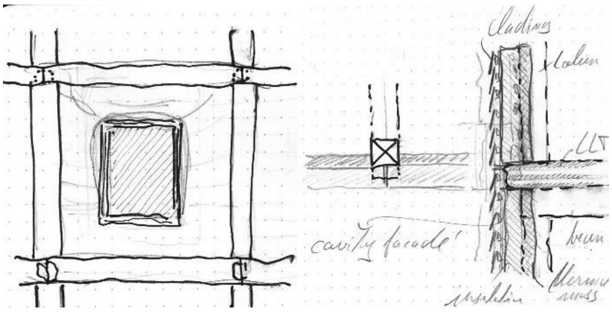
The printing process of the customized and conventional nozzles is quite different. So are the design options and limitation. What works well for one technique might not be possible for another method. Especially the design and the toolpath are largely influenced by the nozzle geometry. This does not implement that a similar design, with similar specifications could not be achieved with a conventional printing technique.

5) Design

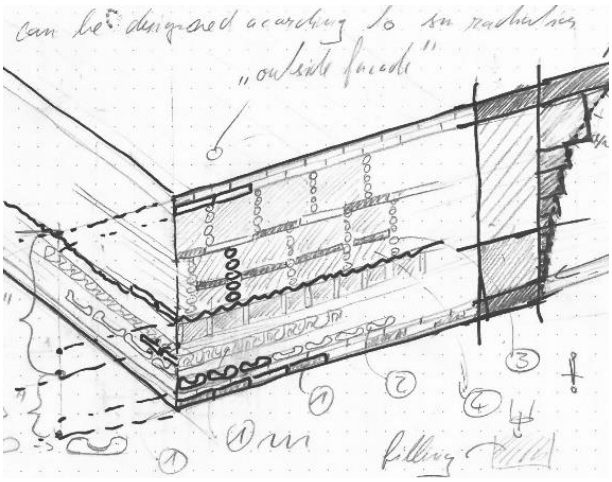
Design options

Hybrid construction

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.



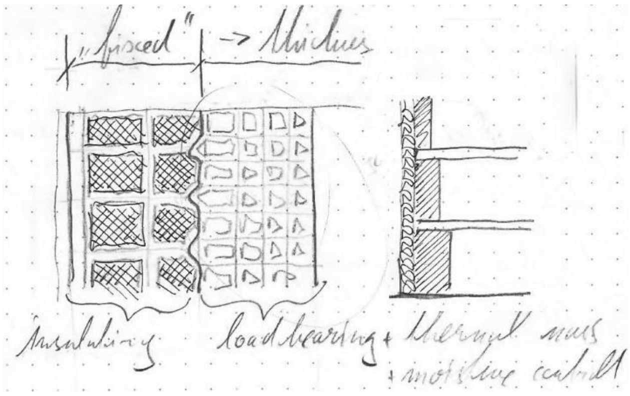
Fig,: 70, Reinterpretation of a timber-earth hybrid construction with a possible cladding against erosion



Fig,: 71, Possible infill for a hybrid construction. A similar geometry would be used for the monolithic

Monolithic construction

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,: 72, Draft design idea of a gradient material, load bearing monolithic building component with insulating properties

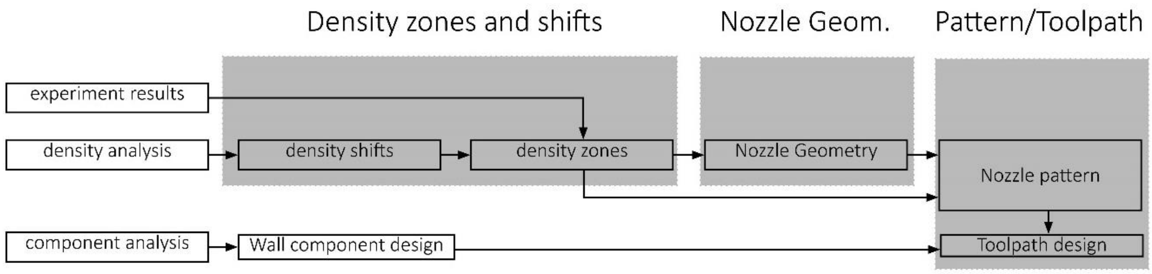
As mentioned, the structural properties of unfired, 3DP clay do temporarily not allow multi story buildings. To support the whole weight of the building the wall would need to be so thick that the project probably would not be finically feasible anymore.

Design process

To develop a component that could be established on the market a hybrid construction is more suitable. Especially for the urban environment this construction technique offers large benefits. A timber framework protects the 3DPE part from outside influences and allows a fast assembly with the structure of the building. The Structural system of the building is made of timber. The high degree of prefabrication for timber structures allows a fast assembly and small tolerances. Since the structure of the building and the component's frame are both made of timber, timber joining techniques can be applied and results in an easy and fast assembly on site. The regulations regarding timber joints and window mounting can be applied on this kind of construction. This eliminates the necessity of expensive testing on how to join a prefab earthen element with a timber construction to fulfil all construction regulations.

6.2. Computational design process

The design was made as described under *"3.3.4. - Digital tools and workflow"***.**
The computational design process is separated into 4 Parts. 1) Density zones and shifts, 2) Nozzle Geometry 3) FGM Pattern orientation and Toolpath 4) Wall component. For the relation between those parts see *Fig. 73.*
Then Parts 1,2 and 3 are the most important regarding the FGM material generation and will be elaborated in depth via flow charts *Fig. 80, 81, 82*. The 4th part, the wall component design is done computationally as well. Although the design of the wall component will be explained in depth, its computational design process will not.

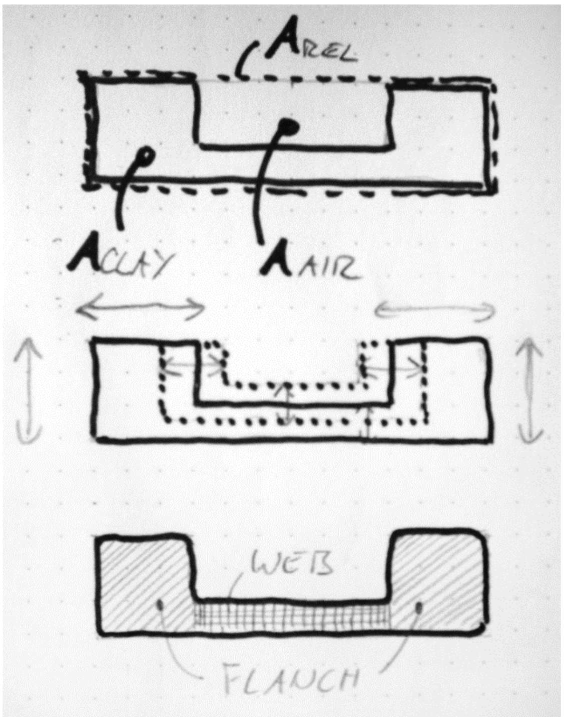


Fig,: 73, General computational design Flowchart

3d printed component - nozzle design and gradient material

The high density decreases of the U-shaped samples led to the decision to make the final design with this Nozzle Type. As stated under experiment results the triangular, "Spaghetti" and "Tagliatelle" nozzles could be promising nozzles types as well and should be further investigated. A combination of the evaluated nozzles would an option as well.

The Nozzle Design and the development of a functionally graded material are strongly related and depending on each other. There are certain parameters of A U-shaped Nozzle that can be changed to influence the print ability, as seen in *Fig. 74.* According to the experiments results the web thickness and the flanches where adjusted slightly for the final design.

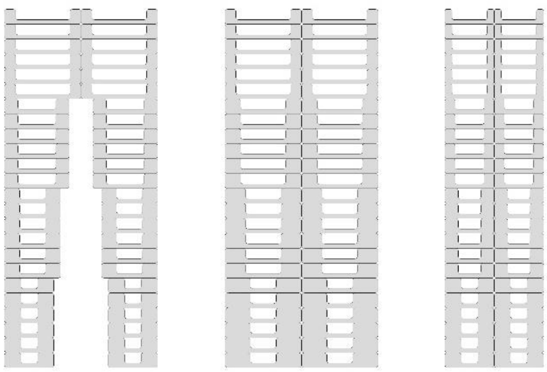


Fig,: 74, Sketch of a U-shaped Nozzle possible modifications. Web thickness: b, Flanch

The FGM should have a density degrease from the inside to the outside as seen in *Fig. 76.* This decrease is caused by different Nozzles for different density zones of the cross section of the wall component. For the first design the relative surface of the nozzles was increased but the material deposition was constant. The relative surface of a nozzle is the bounding rectangle of the extrusion geometry cross section. Both values, the relative surface, as well as the applied material are surface ratios, in mm². If the same amount of material is deposited on an increasing relative surface, voids are created. The difference between the relative surface and the applied material is the surface of the air voids. Or to state it as a Formula:

$$A_{relative} - A_{material} = A_{air}.$$

$A_{relative}$ is necessarily increasing, if $A_{material}$ stays constant and A_{air} requires more Surface to decrease the density of the extruded material mixture.



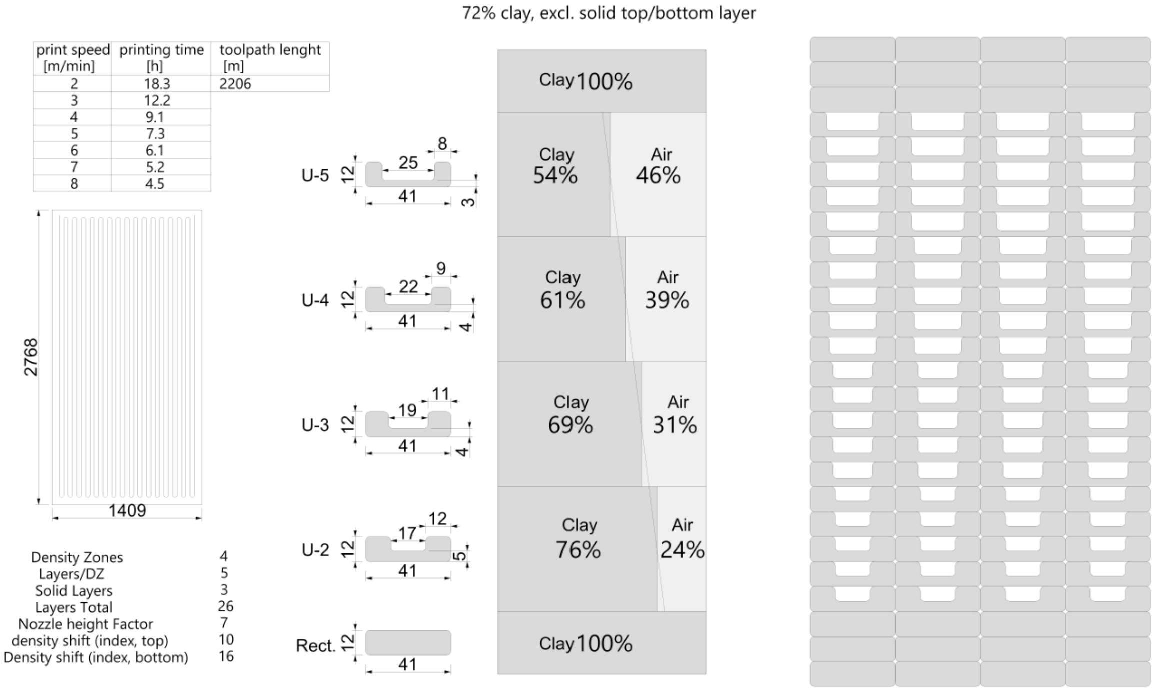
Fig,: 75, Nozzle Evolution. Left: unequal width, Middle: Equal width but too much material deposition, Right: Equal width and material deposition depending on the bottom Nozzle

This approach leads to an increase of the nozzle width if the height of the layers I kept constant. If the width is kept constant the height of the nozzle would change. Since the height per layer is about 10mm +- 3mm, the modification of this parameter is rather hard based on the relatively small modification possibilities. In addition, having a constant layer height is beneficial due to a similar layer compression. This results in a more predictable printing surface. Having a constant layer height as well eases the layer multiplication due to self-compression.

As visible in *Fig. 75(left),* the initial design lead to an unequal Nozzle width. This is caused by the constant material deposition as described previously. The different width of the Nozzles causes several problems regarding the constructability. The printing surface of the top layer is always the top surface of the flanch of the bottom layer. Due to the U-shape this surface is already smaller compared to a rectangular nozzle. Since the web is bridging between the flanches, it is bending downwards due to its self-weight as previously described. Within a density zone the flanches of each extrusion are always printed on top of each other. At every density zone shift the nozzle width is changing. This causes that the flanch of the top layer gets shifted to the side and the web is printed onto the top of the bottom flanch. Since the web is thin it cannot support the weight of one or multiple applied layers. To allow an even printing surface flanches must be printed over flanches. If the top layer's web is printed on the bottom layer's flanch the row will collapse. A collapse would destroy the extrusion geometry and the density shift within the material.

To assure that the flanches of the U-shaped extrusion are printed on top of each other the layer width must be equal for all density zones that are printed on top of each other. This can be achieved by either extending *Fig. 75(mid)* or compressing *Fig. 75(right)* the layer width to the Top or bottom density-zone layer width. Extending the width of the bottom layers, to the width of the top layer would unfortunately increase the required material deposition. This results in a decrease of the possible printing speed. Compressing the top layers to the width of the bottom layer reduces the necessary amount of material for the top layers. This allows an increase of the print speed for all density zones except the bottom one. Since each density zone's nozzle design has a different required material deposition the extrusion speed needs to be evaluated for each nozzle.

To allow a faster production the nozzle width of the top density zones was adapted to the width of the bottom density zone *Fig. 75(right)*.This increases the possible print speed of the top nozzles by the same ratio as the material is reduced. If the top Nozzle requires for example 30% less material the nozzle can be extruded 30% faster. As described under *"nozzle and toolpath experiments"* a parallel extrusion increases the risk of a collapse of the extruded geometry as well if there is no inter layer mesh. To allow an even printing surface the main printing direction of the toolpath gets rotated by 90°. This "crossed out" material deposition increases the quality of the extruded geometry.



Fig,: 76, Selected nozzles with the parallel extrusion toolpath, for all nozzle design groups see Appendix 2,3,4,5,6

The initial cross section pattern design was a result of the parallel extrusion toolpath as visible at *Fig. 76*. Since the experiments showed that the parallel extrusion has several issues that can lead to a collapse of the extruded geometry the pattern was redesigned. Instead of a parallel toolpath a crossed toolpath was chosen for the final design. The flow chart of the toolpath design process can be seen in *Fig. 81.*

The designed infill height is 240mm. To protect the infill from mechanical damages three solid layers where added on the top and the bottom of the infill. This results in a total height of the 3DPE component of 312mm. To reduce the layer compression under self-weight the 3DPE component will be printed in two parts. The "bottom" and "top part" as visible in *Fig. 86.* However, splitting the 3DPE component does not affect the design of the infill. The top part will simply be printed onto a spacer, which forms a new printing surface, see *Fig. 82.* The toolpath gets simply moved in Z-direction by the thickness of the spacer.

Fig,: 77, Crossed toolpath gradient material

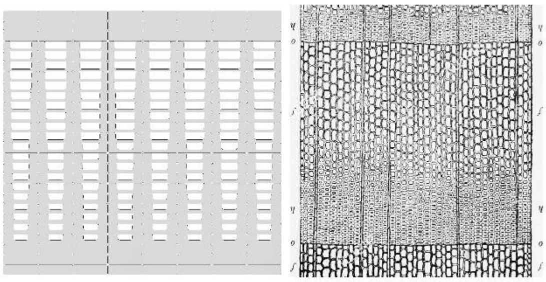
In addition, crossing the toolpath reduces the problem of underfilled edges due to the uneven material deposition along curved toolpaths. The top layer applies a weight on the bottom and evens-out the excessive material in the toolpath centre. The parallel extrusion led to an anisotropic 3DPE infill. By crossing the toolpath, the

3DPE component gains more isotropic properties compared to a parallel material deposition.

Fig,: 78, 3dprinted nozzles

Via the computational design process described in the flow chart several possible nozzles where created *Fig. 78.*

Based on the experience from the experiments the following nozzles group was selected to produce the final prototype. The Nozzle height is 12mm and the width 40mm. The 12mm nozzle height allowed to modify the thickness of the U-web to achieve a higher density for more thermal mass. Modifying the web thickness gradually, led in addition to a closer resemblance to the desired wooden cell structure. The gradually density shift within a wooden year ring was the inspiration of the gradient material. A comparison between the designed pattern and the wooden year ring can be seen in *Fig. 79.* To allow a comparison the toolpath is not crossed out in this picture.



Fig,: 79, left: Gradient material, right: wooden year ring, source (Alamy)

Toolpath

Due to the complexity of the nozzle and extrusion geometry the toolpath can be rather simple to achieve a similar decrease in density. The toolpath design is described in the flow chart *Fig. 82.*

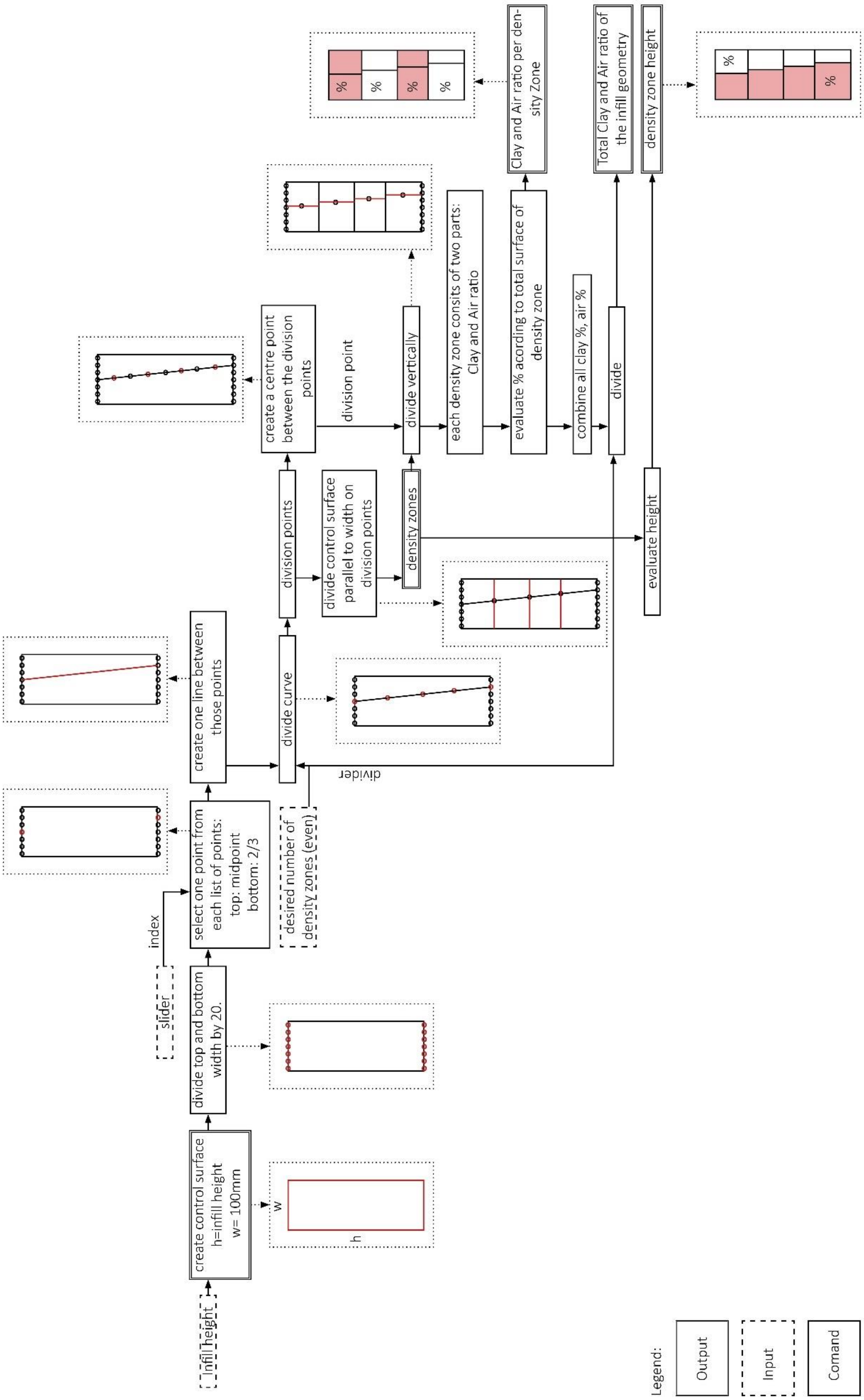
The printing time is depending on the print speed and the toolpath length. The shorter the toolpath the faster the 3DPE element can be printed. If the Nozzle width increase because the nozzle/layer height decreases the toolpath gets shorter. That happens although more layers need to be printed. A increasing width results in a denser extrusion geometry, since the narrower extrusions cannot entrap that much air anymore. A comparison of all analysed toolpath length ca be found in the Appendix 2,3,4,5,6.

To allow a good extrusion results the nozzle height should be not smaller than 10mm. This usually results in a width of over 40 mm.

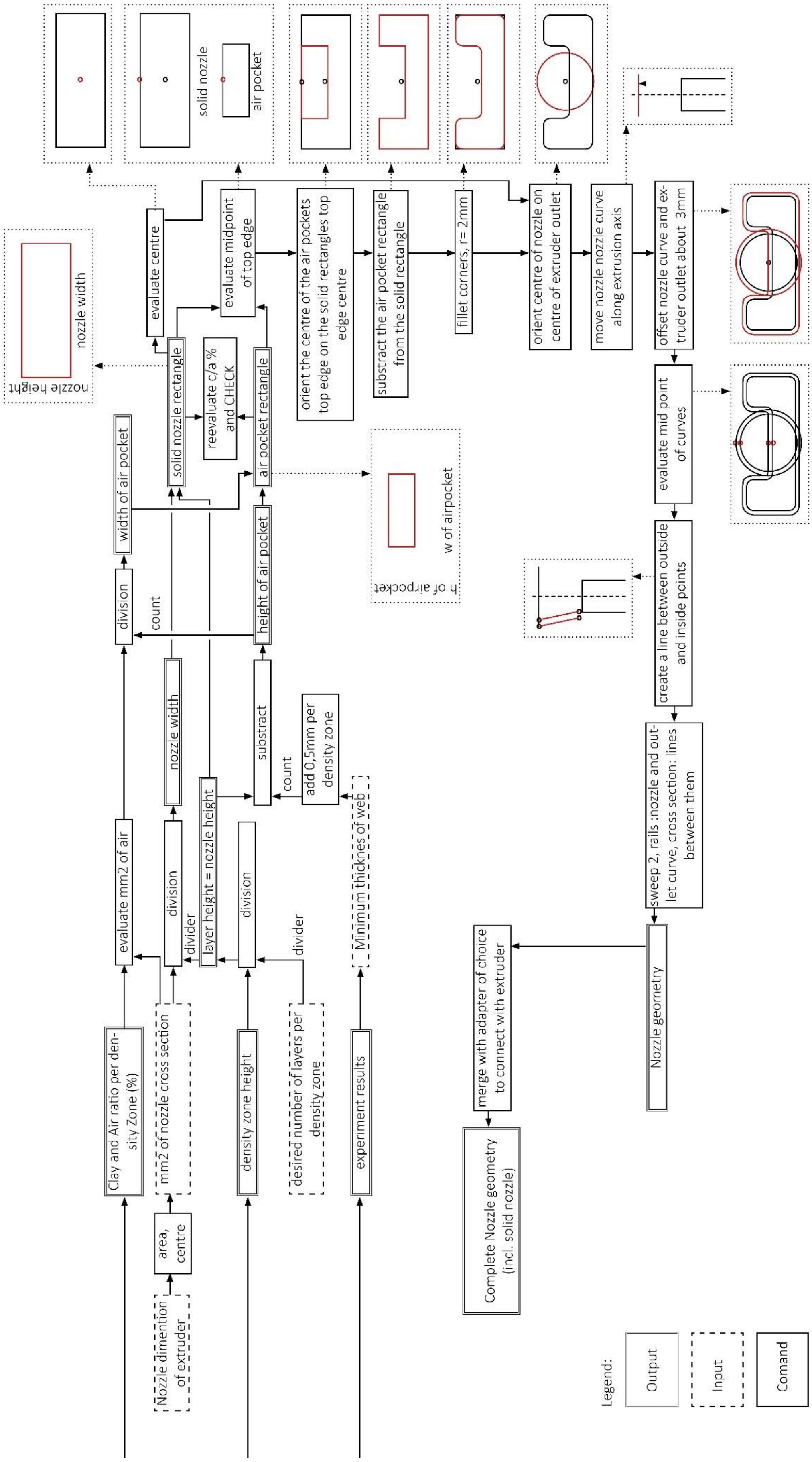
To increase the print speed, a hardware update, in form of a better extruder would be the best option.

Flowcharts

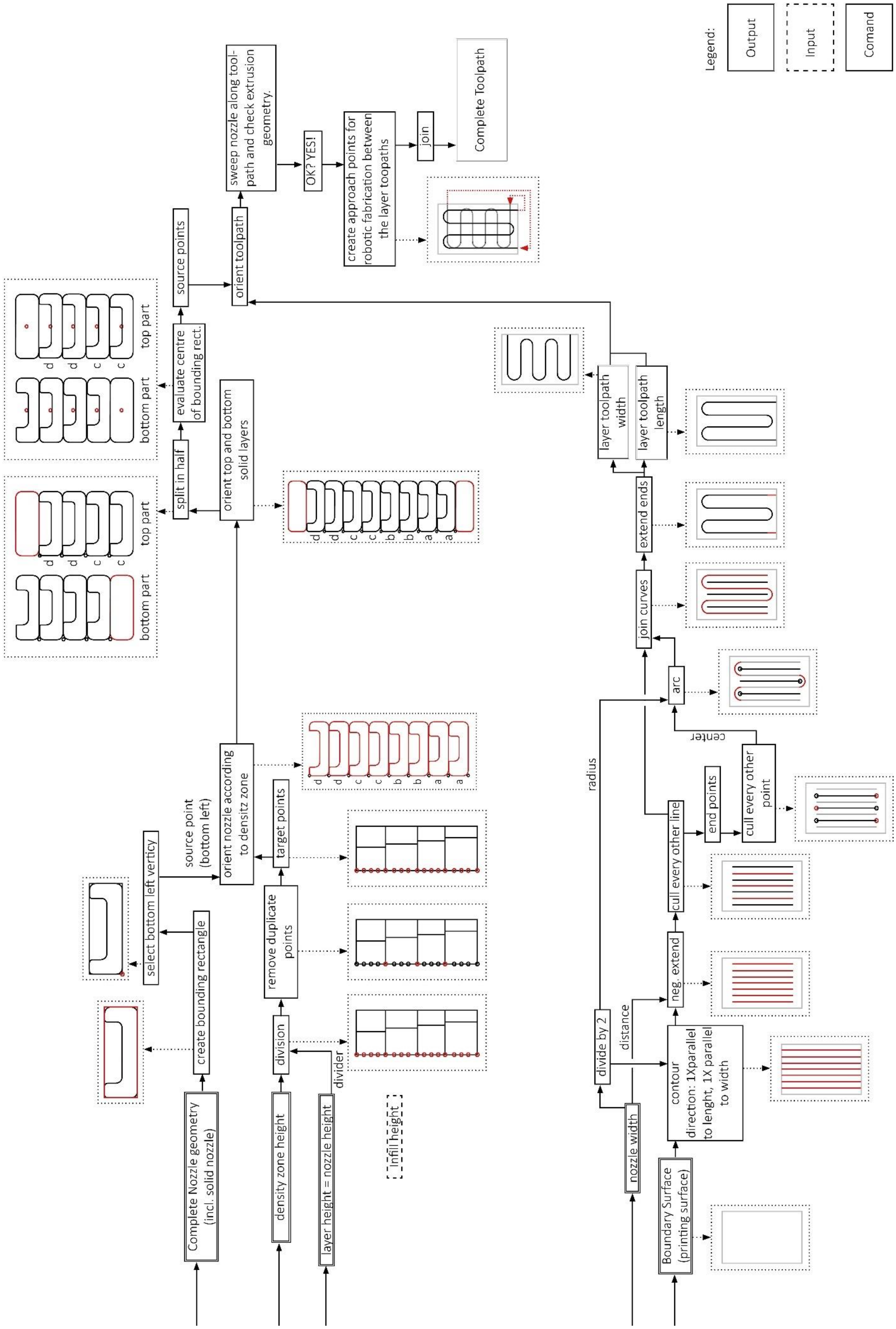
As seen in *Fig 73*, the design process is divided into four part. The following pages will elaborate the computational design of the 3DPE component, the customized nozzles and the toolpath in depth. To visualize the design the flowcharts were follow with the RH plugin GH to generate the necessary geometry for the nozzle production and the component design.



Fig,: 80, Computational Flow chart for Density zones and density shift



Fig,: 81, Computational Flowchart for the nozzle geometry



Fig,: 82, Computational Flowchart for the cross section pattern

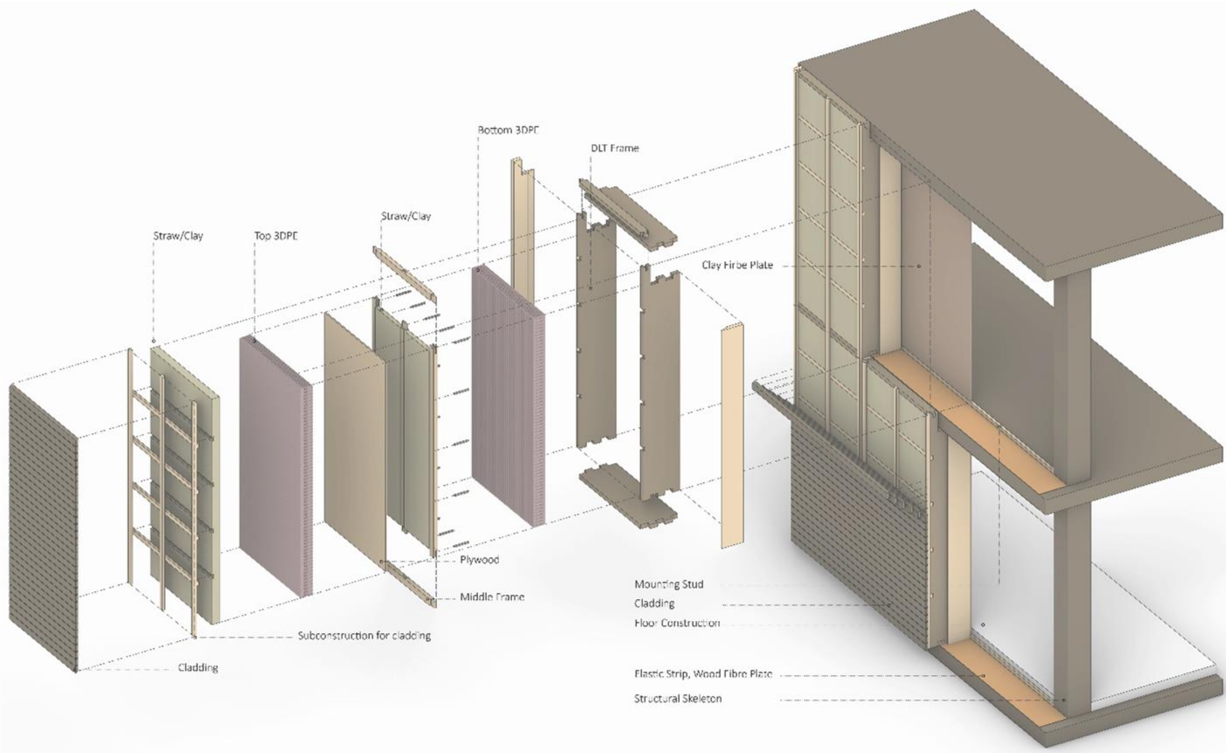
Wall building component introduction

The previously described 3DPE component functions as an infill for the wall component design. The function of the wall component is to protect the rather fragile 3DPE infill from any damage during the transportation, the mounting process and during the usage of the building. To fulfil this function, the wall component builds a frame around the 3DPE infill. The building component panels will be mounted on an structural skeleton. The proposed structure of the building is a timber skeleton. The structural system of the building is out of scope of this research and design process. The wall panels get joint together on site and form the exterior façade of a building. The main parts of the component can be seen in *Fig. 83.*

The design of this wall component tries to reduce the amount of synthetic building material as much as possible. In addition, materials with a high embodied energy such as steel, where reduced as much as possible. As previously mentioned, the goal is to design a component that does no harm to the environment or the user. The design is meant to be disassemble able to allow a circular material flow at the EOL.

The focus was to enable the usage of a functionally gradient 3dprinted clay material within an exterior façade system. To achieve the design was largely influenced by the limitation of the 3DPE part. Other very important parts like the thermal insulation of the wall component where considered as well although no insulation properties where calculated or simulated.

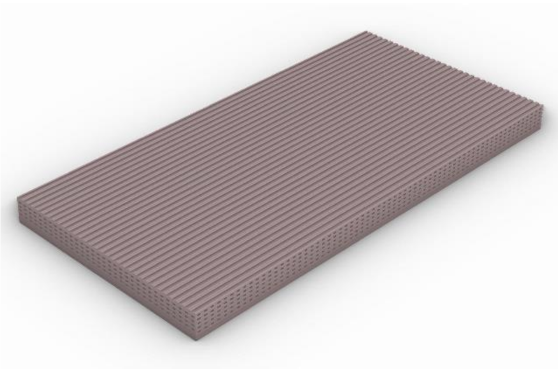
The main part of the components are a)CDT frame, b) 3DPE bottom part c) spacer d) 3DPE top part e) straw clay insulation f) claddings (inside, outside). The detailed description of these part will be done in the order of fabrication/assembly.



Fig,: 83, Overview of the design building component, a bigger drawing can be found in Appendix 7

Detailed description of the panel components and their production.

- Bottom 3DPE component



Fig,: 84, Bottom 3DPE element

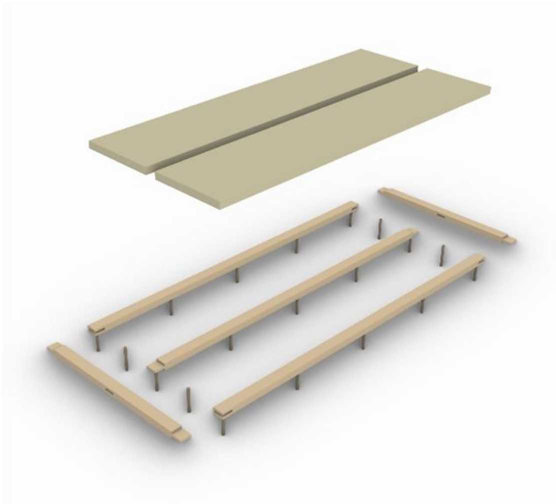
The bottom 3DPE part is the first element to be printed. As visible in *Fig. 84.* the printing pattern is crossed as mentioned before. The 3DPE element will be printed lying or horizontally. This reduces necessary production breaks to dry and reduce self-compression. The clay sand material mixture will be printed onto a temporary plate, that allows to move the 3DPE element during the several production phases. Necessary movement can be either to another robot or to into a drying chamber to pre-dry the component before further production steps can happen. The plate as well allows to erect the component without risking damaging the 3DPE infill.

The bottom 3DPE part, will be on the inside of the exterior wall. The density zone 1 and 2 will be within this part of the 3DPE, what makes it denser and less insulated. Due to its higher density this part will increase the thermal mass and help regulating the indoor climate. A high thermal mass reduces heat and cold peaks and decreases the necessary cooling and heating load.

Based on the computational design flow chart *Fig. 81* the nozzles U-2 and U-3 where designed to print this element. The Nozzle U-1 (solid nozzle) will create the three inner solid layers, to protect the gradient infill.

Between every other layer a jute fibre mesh (mesh width 3-5mm) will be applied. The mesh has cut-out on the spots where the legs of the spacer will penetrate the mixture. As previously mentioned, the shrinkage during the drying is one of the biggest challenges during the production process. To reduce large cracks that can go through the whole component and weaken the infill, the drying time should be elongated. The issue with an elongated drying time is that all biodegradable parts of the wall component are prone to get mouldy during that time. To reduce the moisture of the bottom 3DPE a pre drying process is recommended. The drying should reduce the moisture to the point that the mixture is still plastic deformable. The plastic deformation ability is important to allow the position of the spacer, as well as the bonding between the 3DPE part and the spacer.

- Spacer



Fig,: 85, Spacer without plywood cover, explosion drawing

The spacer is a central element of the 3DPE component and necessary for the printing process, as well as for the assembly and the stiffness of the complete building component. In addition, it increases the thermal insulation properties. *Fig. 85*

The spacer functions as a new printing surface for the top 3DPE part, which reduces the applied load on the bottom part. Lesser load results in a lower compression, lower density and higher insulation properties. In addition to that the spacer stiffens the panel out horizontally with its plywood-plate. The plywood gets coated with linseed oil to prevent that the plywood plate is soaking up a lot of water from the applied earthen mixture. The glue used to produce the plywood needs to be free from

Polyurethane and formaldehyde. The frame is made from 80x50mm massive timber studs with a tong and groove connection. Each connection gets secured with two beech wood dowels – making the connection metal free. The plywood gets doweled to the frame as well.

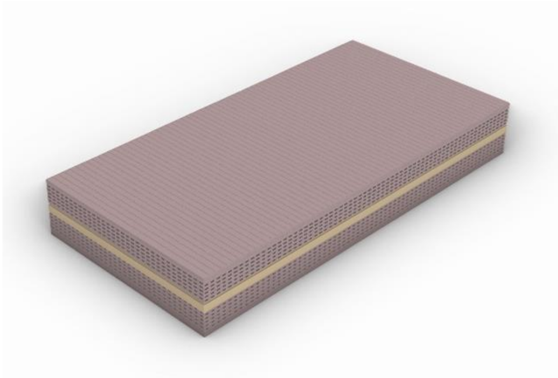
The timber studs have an average moisture of about 12%, the used dowels have a moisture content of about 5%. The dowels adapt to the higher humidity of the frame when pressed into it. The increasing humidity lets the dowels expand. The connection is friction fitted and the dowels cannot be removed anymore. This can be compared with "grown-in" branches. To disassemble the spacer, the dowels need to be drilled out of the structure. This method of doweled connection is also used for CDT (Cross Dowel Timber) and many others joints in this building component. By using the friction fitted dowels the necessary amount of metal for the connection could be reduced drastically.

To relieve the bottom 3DPE part from the load of the top part the spacer cannot rest onto the bottom part. Therefore, the spacer has legs, that are as long as the bottom 3DPE part is high. Theses distancers transferrer the load of the top 3DPE part into the previously mention temporary plate. It increases to possible print height and allows to print the 3DPE component faster.

The spacer also functions as a thermal break as described in *"3.2.1. Spacer between infill"* Clay has a higher thermal transmittance than wood. The spacer in between the two 3DPE elements prevents the direct transmittance between the two clay elements. To increase the thermal insulation the hollow part within the frame get filled with straw clay. To reduce the risk of moulding the straw clay insulated spacer should by dried inside a drying oven before it is applied. A straw clay mixture is more resistant to cracking, due to the reinforcing function of the fibres. The fibres make the surface of the mixture rough, which increases the connection between the bottom 3DPE part and the spacer.

The thermal break in an insulation glass (double or triple glazing) is called spacer. This element gained its name as well due to its function of separating the two 3DPE parts from each other.

- Top 3DPE component



Fig,: 86, Top 3DPE element printed onto the spacer

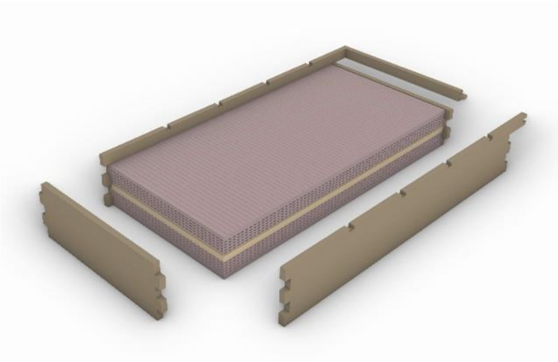
As the bottom part, this part gets as well cross printed and reinforced with a jute mesh between every other layer.

The top 3DPE will include the density zone 3 and 4, they are less dense than the bottom part and should increase the insulation value of the whole component. This element gains its low density due to the high amount of entrapper air voids as described earlier. These make the top part prone to damage, since the structure is quite fragile. The compressive strength will be low and any loads onto this 3DPE element should be avoided in this phase of production.

Based on the computational design flow chart *Fig. 81* the nozzles U-4 and U-5 where designed to print this component. The Nozzle U-1 (solid nozzle) will create the three outer solid layers, to protect the fragile infill. The experiments showed that there is a broad variety of other possible nozzle that could be used for these density zones. Especially the chaotic extrusion patterns of the "Spaghetti" and "Tagliatelle" seemed promising. However, they were not considered for this design due to their high fragility. This would increase the risk that the infill will crumble during transportation or mounting as described earlier under "*Spaghetti and tagliatelle nozzle"*

After the printing process the 3DPE elements get died as slow as necessary to prevent cracking, but as fast as possible to prevent moulding of the inter layer mesh.

- **CDT frame**



Fig,: 87, CDT frame with corner joints

The CDT (Dowel Laminated Timber) is very similar to a common CLT element. The panels are always composed out of an uneven number of layers. But instead of being glued together the timber boards are doweled together. The used timber for the frame is spruce, for the dowels beech is used. The dowels must withstand high shear stresses, beech is ideal for this application. As previously described the dowels have a lower humidity when pressed into the timber. The expended dowels are friction fitted and need to be drilled out to be removed. Unlike CLT panels, that cannot be delaminated, CDT can be recycled. Usually CLT panels get laminated with Polyurethane glue. Although the necessary amount of glue is small it contains solvents that evaporate and can influence the indoor climate. The thermal disposal at the end of life is as well more complex compared to massive timber. Special filters are required if polyurethane containing panels are burned (Kaufmann et al., 2018)

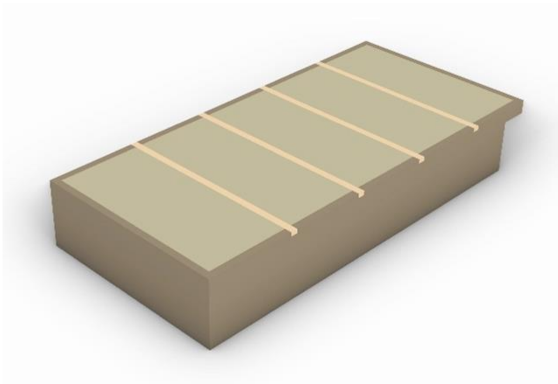
For CDT panels no chemicals are necessary for the production, the whole panel consist out of 100% timber. After drilling the Dowels out new panels can be made from the wooden boards. Using CDT, a company can run its production line forward to produce new panels and backwards to recycle old panels if necessary. (Thoma)

The frame of the wall component will be made of 3x19mm CDT panels, that have finger corner joint at the edges. Finger joints allow an automized production process via CNC machines and can be easily fitted together. To build the frame the milled CDT panels will be again doweled together.

The CDT frame will be assembled around the dried 3DPE elements and connected with the spacer. The connection between the frame and the spacer will be again doweled. The spacer and its plywood plate function as a bracing and make the whole component rigid. The doweled connection between the frame and the spacer prevents the frame from bending during transport and mounting. The high weight of the 3DPE infill will be distributed by the plate of the spacer onto the whole CDT frame.

Due to the shrinkage of the clay component there will be a small gap between the frame and the printed element. To assure a good connection this gap will be filled with the same clay and sand mixture used for the printing process. This process can be either automated with a robot or done manually. The automatization might cause several problems due to uneven shrinkage and a non-constant gap width. To prevent collisions between the nozzle and the 3DPE component a manual process might be easier to apply. This allows a quality control during this step and would not require too much time. The 3DPE component will be already fully dried during this production step. The additional moisture brought in by the wet mixture will be accumulated fast by the surrounding dry clay and partially by the DLT frame. To increase the adhesion between the clay mixture and the DLT the inner surface of the panels will be roughened up by a drum spike irrigator before the assembly of the frame.

- **Straw clay insulation**



Fig,: 88, additional straw clay insulation

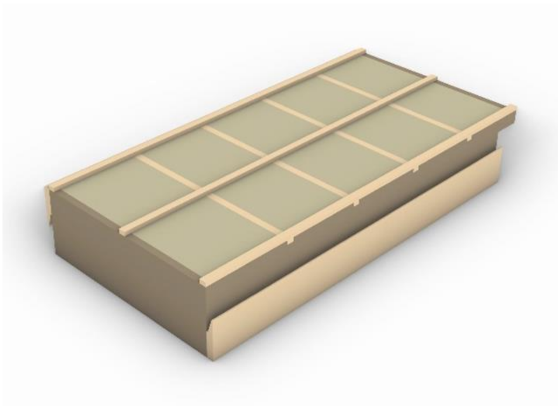
The density reduction of the 3DPE component is about 25% or lower, depending on the compression under self-weight. This is still 15% less than the analysed vertically perforated brick.

The brick had a density of 60% compared to a solid brick.

The higher density results in a lower thermal insulation property of the 3DPE element. To increase the insulation a straw clay layer is added onto the top 3DPE part. The thickness of the straw clay layer can vary depending on the desired U-value. For this design the thickness was 10cm. If the thickness increases 10cm the straw-clay layer must be applied in two phases and dried in-between them to avoid moulding. The straw-clay should dry in a drying chamber to reduce the risk of moulding. The mixture recipe is described under *"4.2.- Straw clay insulation"* As mentioned earlier the straw-clay mixture cannot be applied with the extruder. The mixture needs to be applied manually or with another mechanical production step. The CDT frame can be used as a measuring device for the necessary height. The excessive materials can be scraped off. To allow the mounting of the cladding's sub construction recesses for the studs need to be created. The studs get mounted before the final drying process.

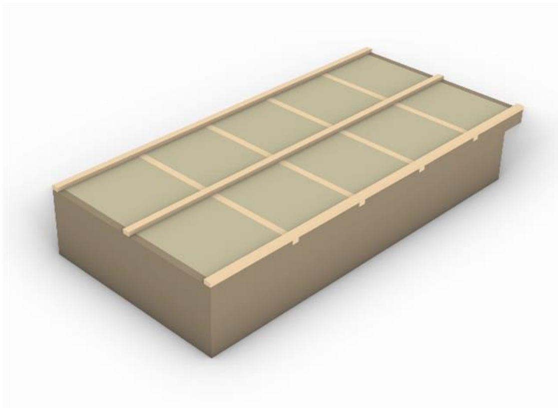
- Mounting angles

To assure a good connection between the prefabricated wall components two mounting angles are doweled onto the side of each CDT frame. The mounting angles are responsible to keep the separate wall components aligned and to assure a connection as tight as possible. The selection of possible joining profiles felt onto an inclined or angled butt joint as visible in *Fig. 89.* The next component slides into the angled butt joint and can be screwed together horizontally. When the screw is tightened the angled contact surfaces of the joints get pressed together. To increase the air tightness of this joint it is possible to apply a thin strip of wood fibre insulation, or hemp insulation in between them.



Fig,:89, Mounting angles

- Claddings and sub construction

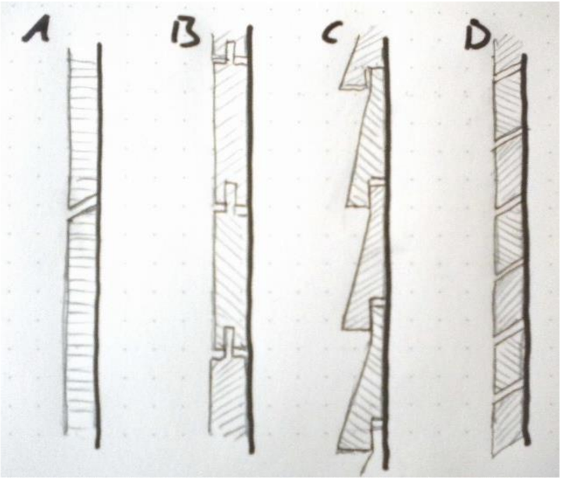


Fig,:90, Sub construction for claddings

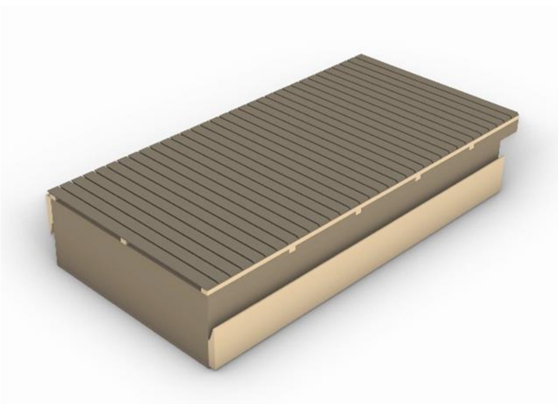
The cladding should not be the only weather protection for the prefabricated wall components. A well thought constructive timber protection, such as broad projected roof, balconies, cantilevering elements and so on are essential architectural elements.

The cladding protects the 3DPE and the straw-clay insulation from getting wet. To assure that the straw-clay can dry out in the case it gets wet the façade is planned as a ventilated façade. The studs for the sub construction of the cladding are made of spruce and are doweled onto the CDT frame. The vertical studs allow a vertical, unobstructed airflow behind the façade cladding. Possible variation of cladding can be found under "3.2.3.- Claddings*" and Fig. 91.* To protect the cladding, it should be mounted after the prefab wall components gets assemble on site. This allows a faster assemble. The same applies for the inner cladding.

Selection outer cladding: Tongue and groove boards, horizontally mounted onto the vertical sub construction studs. The boards are flamed, and the charcoal layer is brushed off. Afterwards the boards get coated with a hot linseed oil mixture. The hot oil penetrates deep inside the wood. The flaming darkened the surface and results in an even discolouring of the timber over time. Linseed oil is an ideal natural timber protection coating that allows that material to breathe. Microorganisms tend to avoid linseed oil, what makes it a good natural timber protection (Terziev, Panov 2011). The cladding and its joints are design to avoid any capillary gaps that suck up water and prevent a fast-drying process.



Fig,: 89, sketches of possible cladding



Fig,: 90, Claddings

Selection inner cladding:

There are two options for the inner cladding: a solid clay plaster that gets applied directly on the 3D printed inner surface after the wall assembly. Or a clay fibre boards that gets mounted onto an inner sub construction.

Applying a wet clay plaster is a labour-intensive process, since it usually is applied in multiple layers (Volhard, Röhlen, 2009). It increases the moisture that is brought into the building when it is already sealed by windows and exterior walls. This could increase the risk of moulding.

Applying the clay fibre boards allows a higher degree of freedom for cable management. The boards need to be covered with a thin layer of plaster as well. However, the level of necessary craftsmanship is lower, and the process is faster.

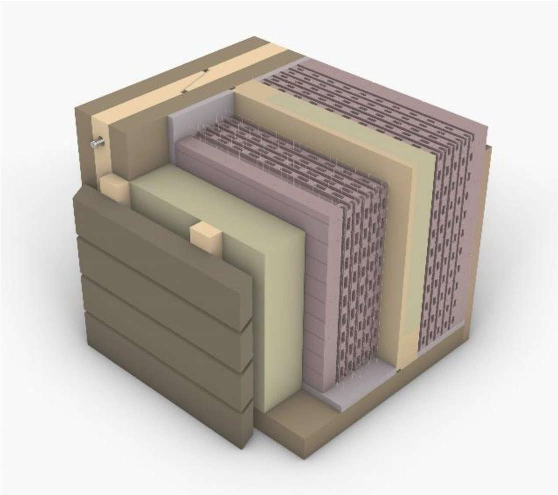
To allow a fast building to process the choice for the final design felt on the clay fibre boards. All drawings about the production of the façade panel can be found under the Appendix 9,10.

Prototype design and production

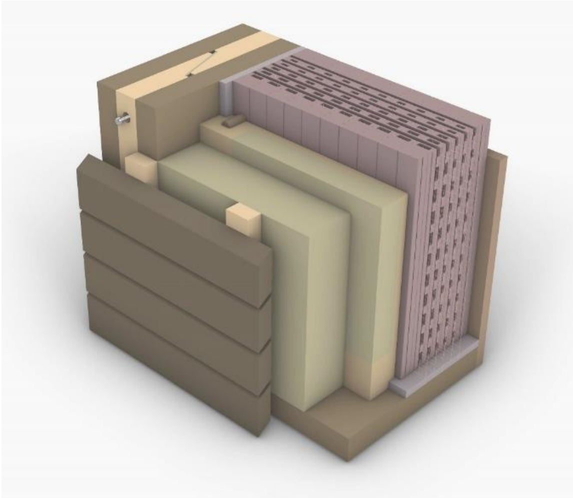
Single or split 3DPE infill

The current design is just one option of multiple different design variations. This accounts for the timber frame as well as for the 3DPE infill. The Infill can be a single gradient material or as suggested, divided by a spacer. The Infill can react on different parameters, like building physics or structural requirements. Such parameters include solar radiation and orientation, various insulation properties or wind load cases. These requirements could result in the usage of single or split 3DPE infills. In Fig. 92,93 two possible prototypes are presented. One with a continuous gradient material (Fig. 93.) and another with a divided gradient infill (Fig. 92.). The cross-section pattern and the density shift are more obvious when no spacer is dividing the infill. To allow a better understanding of the gradient material, the prototype will be produced as displayed in Fig. 93.

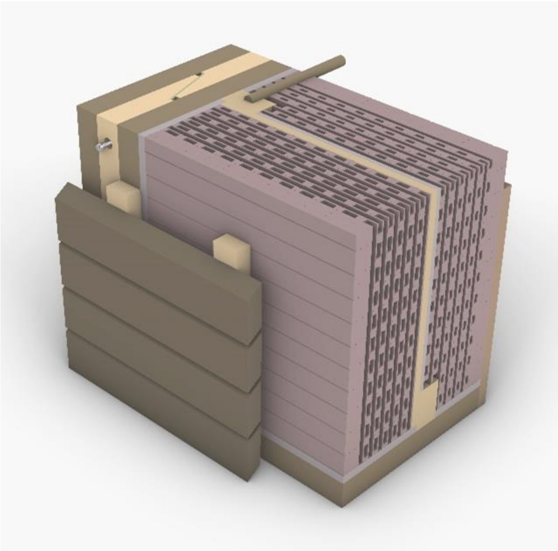
The presented prototype is a show model of the earthen 3D printed gradient infill and its protective timber frame. The prototype cannot be used to test thermal insulation or structural properties of the infill.



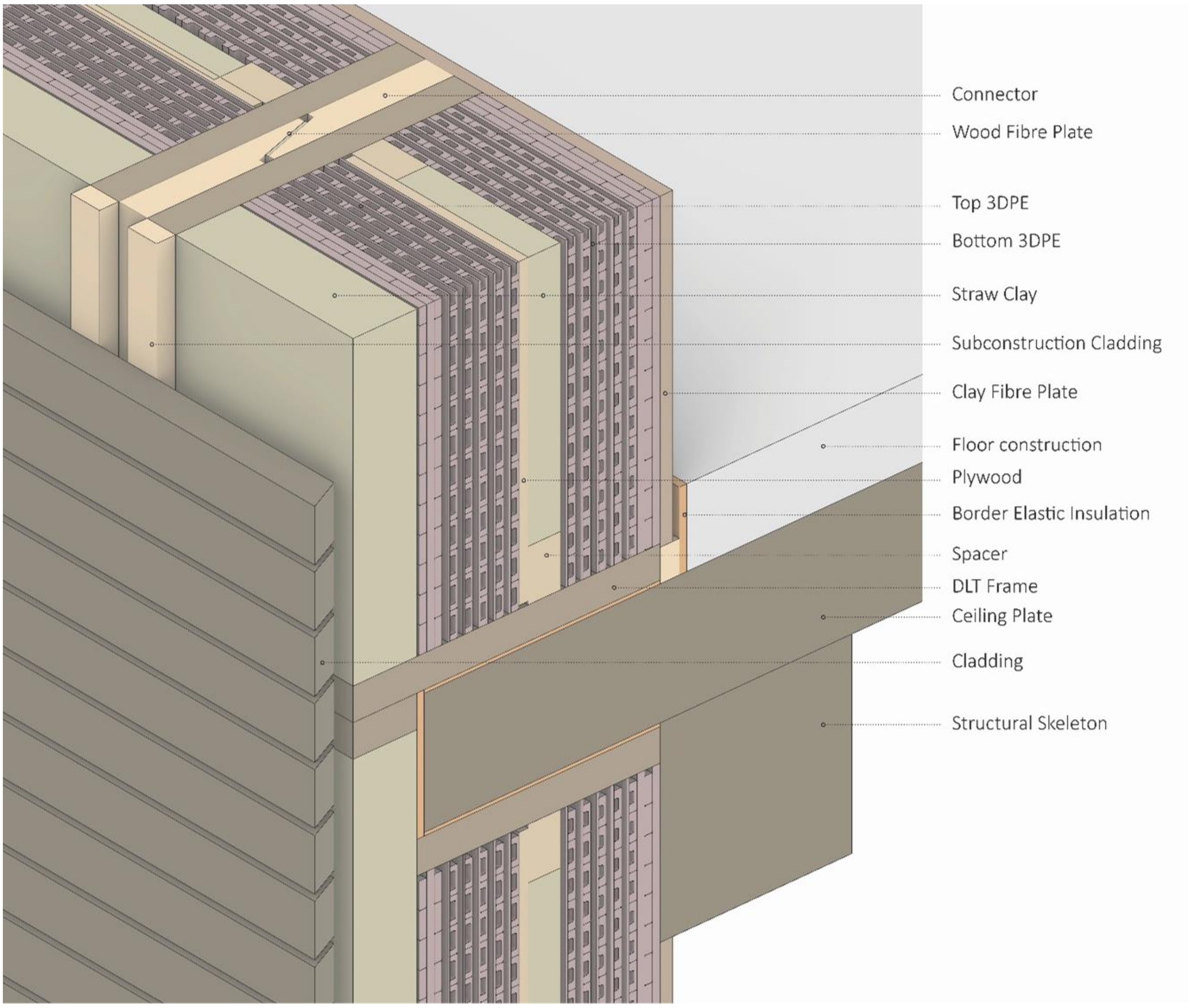
Fig,: 91, Dual Infill



Fig,: 933, Single Infill – realised prototype



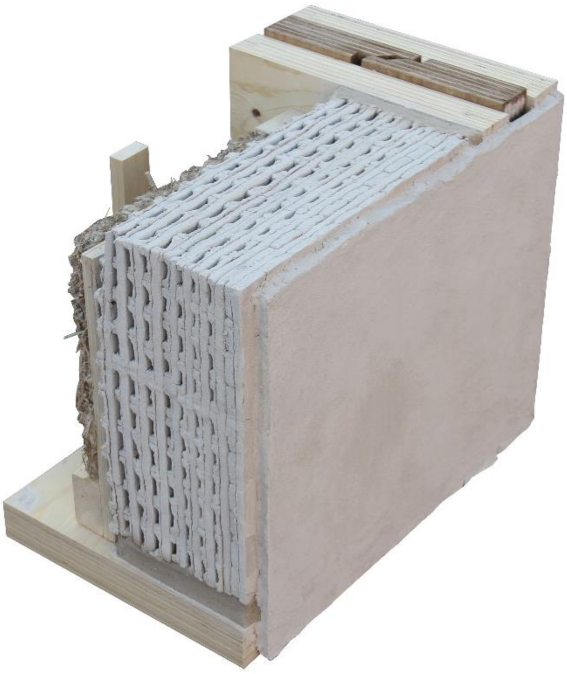
Fig,: 922, Infill without additional insulation



Fig,: 944, axonometry of vertical and horizontal section, a bigger drawing can be found in the Appendix 8

Fig,:95, Top view with all elevation around

Fig,: 956, Front view, charred cladding, clay covered straw insulation, spacer, 3DPE gradient infill.



Fig,: 967, Inside view – clay fibre board, clay plaster

6) Reflection

The aim was to develop a new production method for an old material that is highly sustainable - clay. This should allow to ease the mainstreaming of clay by offering a concept of a building system for multi storey construction.

Perforated earthen building material is used by the brick industry to increase the thermal insulation. This method is known from vertically perforated bricks or other porous bricks. However, these products are baked, therefore harder to recycle and have a high embodied energy compared to unbaked earthen products. In addition, the perforation is only in one direction. This is caused by their production through linear extrusion. Since 3D printing is a form of extrusion, the linear material deposition can be changed into a cross deposition for different layers, resulting in a new production method for earthen mixtures. 3DPE allows to produce customized performance-based gradient materials to create an individual building envelope. However, unbaked earth will never reach the structural strength of baked bricks.

To have an applicable production method the drying process is crucial. Since this drying process was not developed or solved during this thesis, further research in this field is necessary and suggested to allow a feasible production in the future. Without a fast-drying process, the production – in this case the drying time of the component, will require large amount of storage space. This increases the space that is necessary for the production and does not allow to produce close to the site in a mobile production hall. The idea of a decentralized mobile production set-up should be further investigated and might be the key for a regional circular economy in the future. Unfortunately, this regional production will not be possible without solving the drying issues. Using an industrial printing set-up and extruding very dry mixtures might be the key to reduce complications due to drying. Designing an industrial grade printing set-up for the application on an robotic arm is recommended.

The research was focusing on the robotic production of a non-structural prefab building component. The prefabrication is the key to apply this fabrication method since the designed gradient material is due to its reduced density not able to carry loads. A result of this low structural strength is that in-situ printing is besides the previously mentioned problems not possible for this cross-section geometry. Prefab does not necessarily mean centralized production. Prefabrication can be done decentralized and with local resources as well. A centralized production would further increase the footprint for transportation.

The 6-Axis robotic fabrication offers a very high degree of freedom for the production. The current designed component could as well be printed with a 4-Axis machine and therefore does not use the full potential of the robotic arm. By exploring the different combination of multiple nozzle types and more complex toolpaths, the 6-Axis robotic arm might be used to its full potential. To find the optimal production set-up for a gradient 3DPE material further research is recommended.

The designed gradient infill might as well become a set of various standardized blocks with different properties and different sizes. This blocks would be similar as vertically perforated bricks. Whereas the unbaked 3DPE blocks are used as non-structural infills due to the low structural performance of unbaked earth.

If I had the chance to continue this research further, I would explore the possibilities of the production set-up. Like previously mentioned, improvements on the set-up would have the biggest impact on the 3DPE object. Problems like the drying process, different material mixtures and possible nozzles would be much smaller and easier to solve if an “infinite” high-pressure extrusion set-up would be available. In addition, the component design should be further investigated, especially the joining between the clay infill and the timber frames. The infill could be developed toward the direction of a mono or duo-material block that does not need any additional insulation on the outside. This block could be printed with multiple different nozzle types as mentioned earlier.
Another possible research would be the legislative aspect regarding all kinds of building regulations. This would be especially important in the approval process for the building system.

7) Conclusion

Earth as a construction material has been used for millennia and offers a great potential to reduce the emissions of the construction sector. The combination of clay and timber could be part of a new environmentally friendly, bio based and regional architecture and construction culture. Translating traditional vernacular construction techniques within the framework of the fourth industrial revolution allows us to move forward, while acknowledging our historically developed building culture. There are many traditional applications such as rammed earth, or adobe that are currently witnessing a revival after unrightfully being ignored for several decades.

However, these construction methods are limited by their buildable height. Clay-Hybrid construction allow multi-level buildings in urban settings. Clay functions no more as heavy, massive structural material but as a non-structural and light infill that can increase the thermal mass, regulate the humidity and increase the insulation properties of an exterior wall. Traditional hybrid constructions offer a broad variety of possible implementations for future construction methods. However, the fabrication of these hybrid building components is labour intensive and therefore expensive in industrialized countries. Digital fabrication and 3D printing could be a solution for this problem. 3D printing earth combines a rural material with state-of-the-art digital fabrication. At first glance, these fields do not appear to be compatible, whereas additive manufacturing offers new strategies of how to build with earth. 3D printing enables the gradual reduction of the density compared to traditional, solid walls such as adobe or rammed earth - creating a gradient material. Robotic fabrication enables the automation of certain production steps and will reduce costs in the long run. This leads to the development of a serial construction system with all its benefits, that allows to be mass customized and performance based. Likely resulting in an individual, sustainable and circular built environment for a lower price. Not only the building component itself can be customized, but also the tools for its production. This leads to the research question mentioned previously in chapter 2.4:

How can a gradient 3d printed clay wall be produced by customizing the nozzles within the limitations of the production process and the material?

The thesis aimed to create a functionally gradient material by 3D-printing earth with customized nozzles. This gradient material is due to its low strength designed to be a non-structural infill for a timber frame façade. This timber frame protects the clay element and allows conventional timber joining methods on the construction site. Together, the timber frame and the clay infill form the prefabricated building component. This component can be applied on any desired structural, load-bearing skeleton. A timber skeleton is recommended to allow mono-material joining details between the façade panels and the structure, speed up the assembly process while reducing the carbon footprint. This construction method enables the usage of clay for multi storey buildings since the earthen infill is not load bearing. The high weight of the façade panel can be used to pretension the floor slabs and reduce the necessary amount of material.

The 3DPE infill is dense on the inside and increasingly light towards the outside. It functions as a thermal mass that helps regulating the indoor climate and humidity. This reduces heat and cold peaks in summer and winter. In addition, its reduced density increases the insulation properties compared to a solid clay wall. This principle is known from vertically perforated bricks, although these usually do not have a density shift along their cross section and are baked during production. To achieve the density decrease, air voids were embedded within the extrusion by the customized nozzles. The U-shaped nozzles were computationally designed based on the desired density shift and material limitations. In addition, several other nozzle concepts were designed to evaluate other possible strategies for density decreased 3DPE.
The nozzles were tested along different toolpaths to measure the density shift of the specimens. The experiments were conducted with a manual extruder, since the robotic arm was unavailable during the shutdown of the faculty

due to the Covid19 Pandemic. This impacts the repeatability. However, the manual extrusion lead to the following conclusions:

By customizing the nozzle, the extrusion geometry can be manipulated into shapes that enclose air when placed adjacently or stacked. The stability or plasticity of the extruded material mixture is largely dependent on the water content and clay to sand ratio. The specimens of the experiments show a density decrease between 11% and 52% of their mass. However, a high density decrease is causing a fragile 3DPE element and the specimens are prone to damage. When applied to a building component, the infill must be stable enough to not crumble during production, transportation or the mounting process. Applying interlayer meshes allows a cleaner cross section pattern, better distributes the self-weight and reduces the self-compression. The bonding between the meshes and the clay mixture, especially the influence on the interlayer bonding must be further investigated. The automated application of the mesh would be interesting for further research. If the clay-sand mixture is plastic and dry enough, the application of interlayer meshes is not necessary to achieve a stable 3DPE element. The production of the prototype proved this. A water content of about 15% with a clay-sand ratio of 50% resulted in a mixture that was plastic enough to entrap air voids without too much compression under self-weight.

Most of the encountered problems during the 3DPE process and the prototype production could be solved by having an industrial-grade printing set-up. The set-up would be able to handle higher pressure and to extrude drier material mixtures – this would reduce the compression under self-weight, the shrinkage and the necessary drying time. Interlayer meshes would become superfluous.

All tested nozzles (U-shapes, triangular, “Spaghetti” and “Tagliatelle”) showed a density decrease of the extruded samples, compared with a solid, rectangular nozzle extrusion, or a casted clay cube. It is possible to increase this density reduction even more by further developing these nozzles and their toolpaths. The usage of an industrial printing set up would decrease the material limitation further and possibly result in a higher density decrease. The solid extruded sample (rectangular nozzle) is denser than the cast cube sample, leading to the conclusion that the extrusion process is compressing the material mixture and minimizing its pores. A production process that tolerates small pores would be better for the thermal insulation and could be developed to further decrease the density of the 3DPE element. An extrusion method that allows the integration of small granules would achieve this.

To have a good interlayer bonding and avoid self-weight caused collapsing of the extrusion geometry, the flanch of the U-shaped extrusions should be wider than their height. The minimal height of the web should be adjusted to the maximum grain size of the sand used for the sand-clay mixture.

In the current design there is an additional insulation layer made of straw clay on the outside of the prefab façade panel. Ideally, the design of the 3DPE infill is insulating enough to make this insulation obsolete. This reduces necessary production steps and moulding risks during the drying process. It could be further investigated if this 3DPE infill could be made with one or multiple different material mixtures to further increase the insulation properties and reduce compression due to self-weight.

The implementation of the 3DPE element into the building component frame would be easier if the 3DPE elements were smaller. This reduces the shrinking and drying stresses. The subdivision of the 3DPE could be done with specially designed nozzles or material mixtures. Smaller infill dimensions might not require a space consuming drying process in a drying chamber. This increases the financial feasibility of the production. Since drying chambers are increasing the carbon footprint of the production, this would have a positive impact on the CO^2 balance of the product. The drying process of the infill is crucial for the feasibility, not only because of the costs, but as well for the stability of the 3DPE element. Without a manageable drying time, the production of the 3DPE element will not be possible at an industrial scale.

The focus of this research was on the customized nozzle design. The toolpaths were purposely kept simple to gain clear results about the nozzles' influence. A simple toolpath (parallel, crossed or chaotic) allows a better investigation of the nozzles' influence on the cross-section geometry and its density decrease. Developing more complex toolpaths and combining multiple nozzles could possibly increase the production efficiency of the 3DPE component, such as reducing the printing time and density, while increasing its stability. This should be further researched and would be the next step.

The held experiments should be repeated with the robotic arm and the designed motorized extruder to gain repeatable and more reliable results. This allows to create multiple, identical samples for each nozzle, reduces possible errors in their production and provides a precise density evaluation. The sand for the mixture should be according to a specific sift curve to have control of the grain size and allow the reproduction of the mixtures. After a possible redesign, the thermal properties of the gradient material and the whole building component should be calculated and tested. A "Finite Element Method" (FEM) simulation and analysis should provide valid results of the thermal insulation properties, as well as the thermal mass of the gradient material. Based on these results a further development of the cross-section pattern, nozzles and toolpaths would be ideal. To develop a functional and market-ready product multiple 1:1 scale wall panels must be built and tested to evaluate their fire safety, acoustic and thermal insulation properties, structural behaviour, tolerances, mounting processes, impact resistance and other parameters.

The automation of several production steps would be an interesting field of research on its own. The component needs to be adapted to fulfil the building regulations of the building site's location. In addition, cost calculation and production optimization need to be done and should lead to the development of a building component that can be established on the market. Non-structural, 3d-printed gradient infills could help to mainstream earth as a construction material.

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Figures and Tables:

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Fig. 4.: (Alamy)
Wooden cell structure, from: https://www.alamy.com/fig-94-querschnittsansicht-des-holzes-der-weitanne-abtes-pectinata

Fig. 6.: (Dethier, 2019)
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Fig. 79.:, right: Autor, left: (Alamy)
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9) Appendix

Appendix 1

Calculation Sheet (Density and Compression)

Specimen	lenght [m]	width [m]	hight [m]	Volume [m3]	weight [kg]	density [kg/m³]	number of layers [-]	layer height [mm]	designed height [mm]	compression under self-weight [%]	density increse compared to previous sample [%]	total density reduction compared with casted cube [%]	total density reduction compared with solid extrusion [%]
Solid cube	0,1	0,1	0,1	0,001	1,629	1629	-	-	-	-	0,00	0,00	0,00
Rectangular Nozzle, Parallel	0,1	0,1	0,04	0,0004	0,699	1748	4	0,012	0,048	8	-7,27	-7,27	-7,27
							4						
							4						
Rectangular Nozzle, Parallel	0,1	0,1	0,04	0,0004	0,699	1748	4	0,012	0,048	8	-7,27	-7,27	0,00
U-Shaped_Nr 2, Parallel	0,1	0,1	0,04	0,0004	0,479	1198	4	0,012	0,048	8	33,76	26,49	31,47
U-Shaped_Nr 3, Parallel	0,1	0,1	0,038	0,00038	0,45	1184	4	0,012	0,048	10	0,82	27,30	32,23
U-Shaped_Nr 4, Parallel	0,1	0,1	0,038	0,00038	0,408	1074	4	0,012	0,048	10	6,78	34,09	38,56
U-Shaped_Nr 5, Parallel	0,1	0,1	0,038	0,00038	0,379	997	4	0,012	0,048	10	4,68	38,77	42,93
U-Shaped_Nr 5, crossed	0,1	0,1	0,03	0,0003	0,232	773	3	0,012	0,036	6	13,75	52,53	55,75
Triangular, Parallel	0,1	0,1	0,043	0,00043	0,589	1370	4	0,012	0,048	5	0,00	15,91	21,62
Triangular, Parallel	0,1	0,1	0,043	0,00043	0,586	1363	4	0,012	0,048	5	0,43	16,34	22,01
"Spaghetti" r=2	0,1	0,1	0,09	0,0009	0,897	997	chaotic		0,1	10	22,48	38,82	42,97
"Spaghetti" r=3	0,1	0,1	0,08	0,0008	1,128	1410	chaotic		0,1	20	-25,37	13,44	19,31
"Spaghetti" r=4	0,1	0,1	0,085	0,00085	1,073	1262	chaotic		0,1	15	9,06	22,51	27,76
"Tagliatelle"	0,1	0,1	0,085	0,00085	1,039	1222	chaotic		0,1	15	2,46	24,96	30,05
S-Shaped waved	0,1	0,1	0,055	0,00055	0,793	1442	waved		0,055	0	-13,47	11,49	17,49
S-Shaped straight	0,1	0,1	0,038	0,00038	0,498	1311	waved		0,038	0	8,06	19,55	25,01

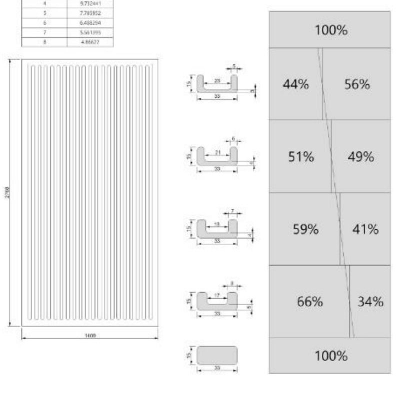
Specimen	hight [m]	number of layers [-]	layer height [m]	designed height [m]	compression under self-weight [%]
U-5, paralle, mesh every layer	0,058	5	0,012	0,06	3,33
U-5, crossed,mesh every layer	0,045	5	0,012	0,06	25,00
U-5, crossed, mesh every other	0,045	5	0,012	0,06	25,00
U-5, crossed, mesh every density zone	0,074	10	0,012	0,12	38,33
U-5, crossed, mesh every other	0,045	5	0,012	0,06	25,00
Draft U-Nozzle, Parallel, Dry mixture	0,132	18	0,009	0,162	18,52

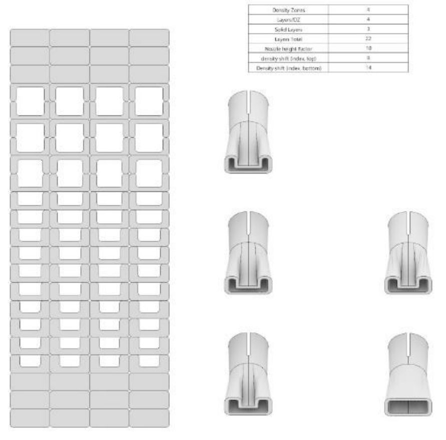
Appendix 2, Group A: Cross-section pattern, nozzles, toolpath

print speed	printing time	toolpath lenght
(m/min)	(h)	(m)
2	19.464881	2336
3	12.976587	
4	9.732441	
5	7.785952	
6	6.488294	
7	5.561395	
8	4.86627	

64% clay, excl. solid top/bottom layer

Density Zones	4
Layers/DZ	4
Solid Layers	3
Layers Total	22
Nozzle height factor	10
density shift (index, top)	8
Density shift (index, bottom)	14

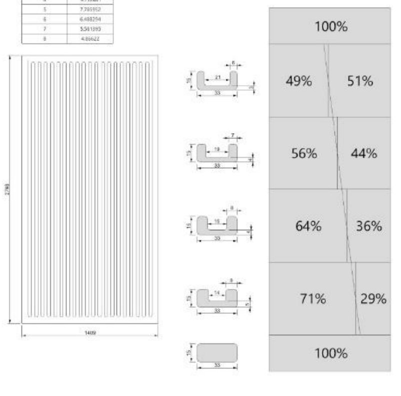


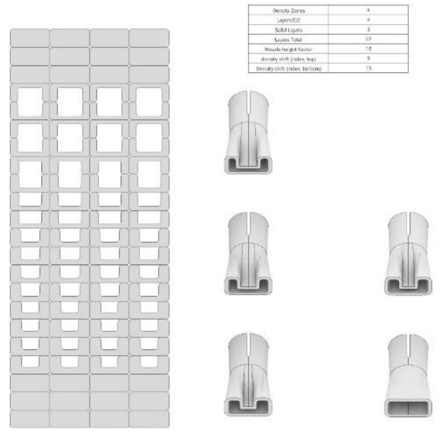


print speed	printing time	toolpath lenght
(m/min)	(h)	(m)
2	19.464881	2336
3	12.976587	
4	9.732441	
5	7.785952	
6	6.488294	
7	5.561395	
8	4.86627	

68% clay, excl. solid top/bottom layer

Density Zones	4
Layers/DZ	4
Solid Layers	3
Layers Total	22
Nozzle height factor	10
density shift (index, top)	9
Density shift (index, bottom)	15

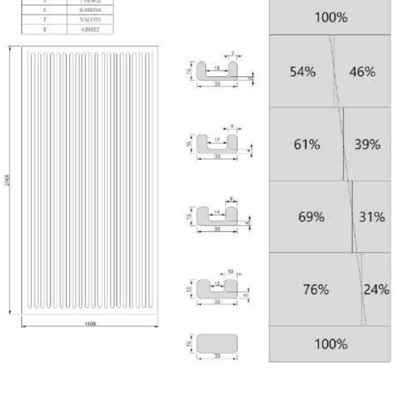


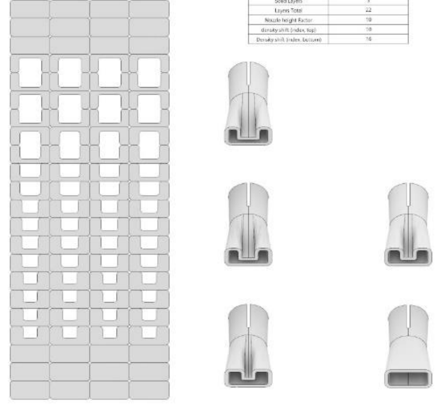


print speed	printing time	toolpath lenght
(m/min)	(h)	(m)
2	19.464881	2336
3	12.976587	
4	9.732441	
5	7.785952	
6	6.488294	
7	5.561395	
8	4.86627	

72% clay, excl. solid top/bottom layer

Density Zones	4
Layers/DZ	4
Solid Layers	3
Layers Total	22
Nozzle height Factor	10
density shift (index, top)	10
Density shift (index, bottom)	16





Appendix 3, Group B: Cross-section pattern, nozzles, toolpath

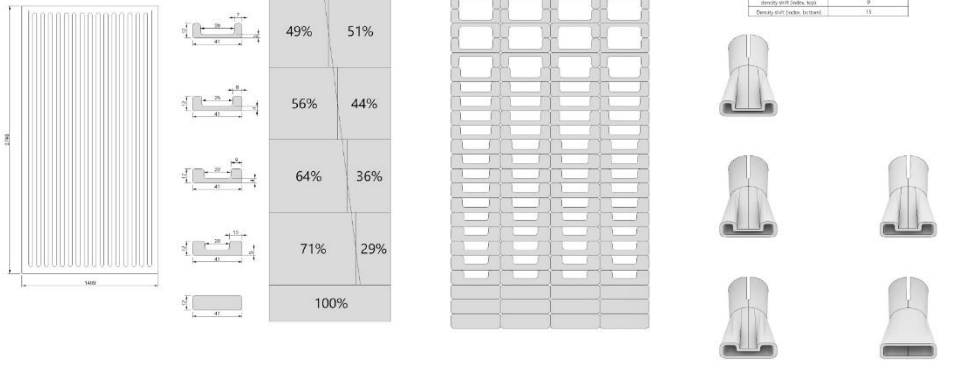
print speed	printing time	toolpath lenght
(m/min)	(h)	(m)
2	18.380178	2206
3	12.253452	
4	9.190089	
5	7.352071	
6	6.126726	
7	5.251479	
8	4.595045	

64% clay, excl. solid top/bottom layer

Density Zones	4
Layers/DZ	5
Solid Layers	3
Layers Total	26
Nozzle height Factor	7
density shift (index, top)	8
Density shift (index, bottom)	14

print speed	printing time	toolpath lenght
(m/min)	(h)	(m)
2	18.380178	2206
3	12.253452	
4	9.190089	
5	7.352071	
6	6.126726	
7	5.251479	
8	4.595045	

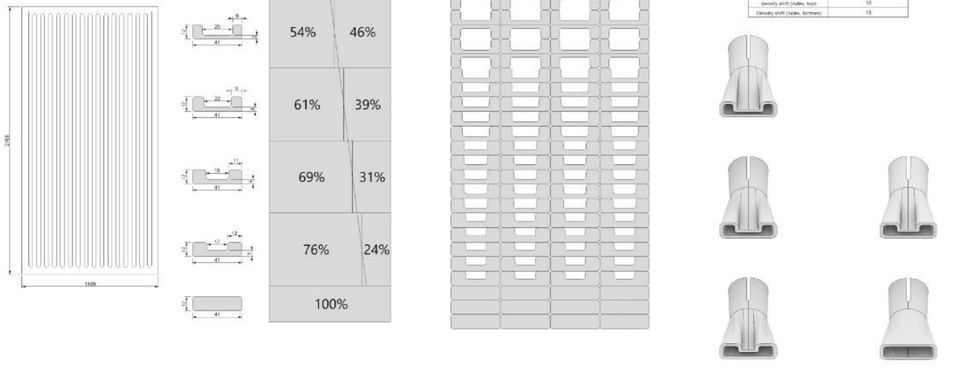
68% clay, excl. solid top/bottom layer



Density Zones	4
Layers/DZ	5
Solid Layers	3
Layers Total	26
Nozzle height Factor	7
density shift (index, top)	9
Density shift (index, bottom)	15

print speed	printing time	toolpath lenght
(m/min)	(h)	(m)
2	18.380178	2206
3	12.253452	
4	9.190089	
5	7.352071	
6	6.126726	
7	5.251479	
8	4.595045	

72% clay, excl. solid top/bottom layer

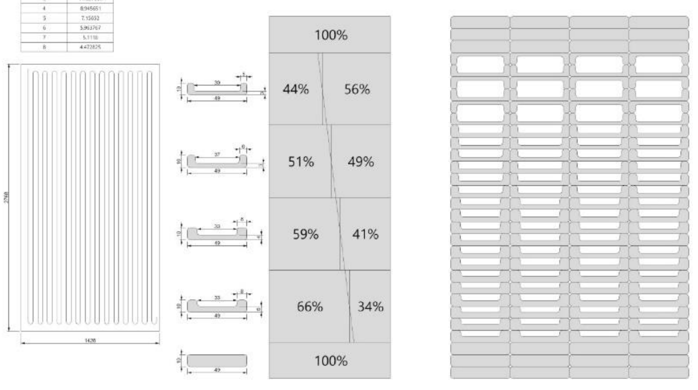


Density Zones	4
Layers/DZ	5
Solid Layers	3
Layers Total	26
Nozzle height Factor	7
density shift (index, top)	10
Density shift (index, bottom)	16

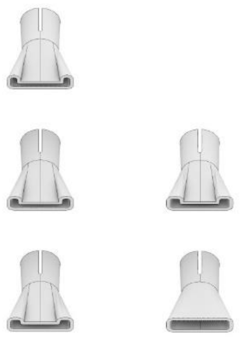
Appendix 4, Group C: Cross-section pattern, nozzles, toolpath

print speed	printing time	toolpath lenght
[m/min]	[h]	[m]
2	17.891301	2147
3	11.927534	
4	8.945651	
5	7.15652	
6	5.963767	
7	5.1118	
8	4.472825	

64% clay, excl. solid top/bottom layer

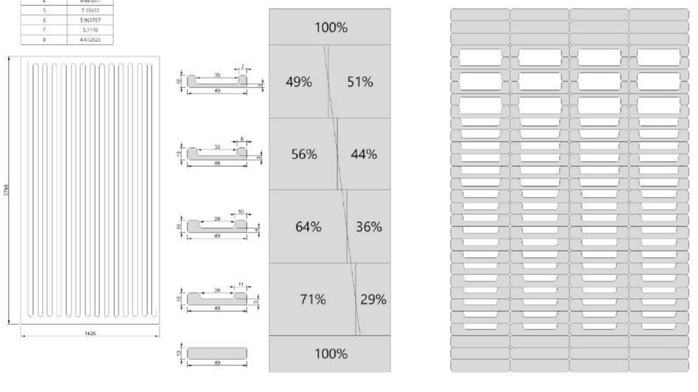


Density Zones	4
Layers/DZ	6
Solid Layers	3
Layers Total	30
Nozzle height Factor	5.1
density shift (index, top)	8
Density shift (index, bottom)	14

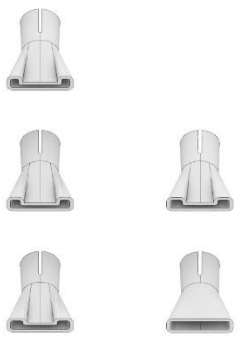


print speed	printing time	toolpath lenght
[m/min]	[h]	[m]
2	17.891301	2147
3	11.927534	
4	8.945651	
5	7.15652	
6	5.963767	
7	5.1118	
8	4.472825	

68% clay, excl. solid top/bottom layer

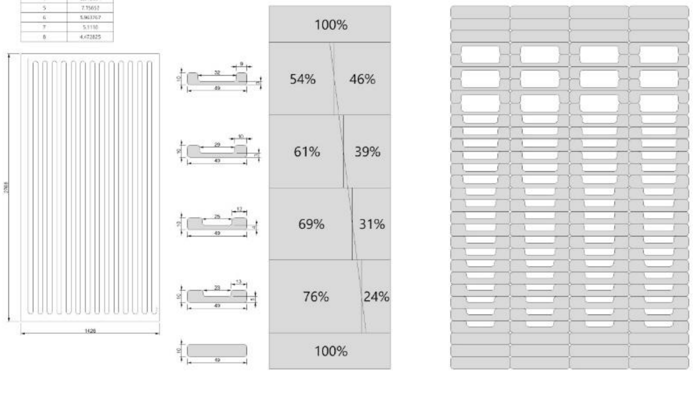


Density Zones	4
Layers/DZ	6
Solid Layers	3
Layers Total	30
Nozzle height Factor	5.1
density shift (index, top)	9
Density shift (index, bottom)	15

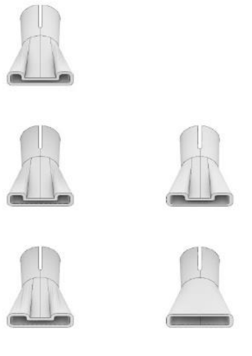


print speed	printing time	toolpath lenght
[m/min]	[h]	[m]
2	17.891301	2147
3	11.927534	
4	8.945651	
5	7.15652	
6	5.963767	
7	5.1110	
8	4.472825	

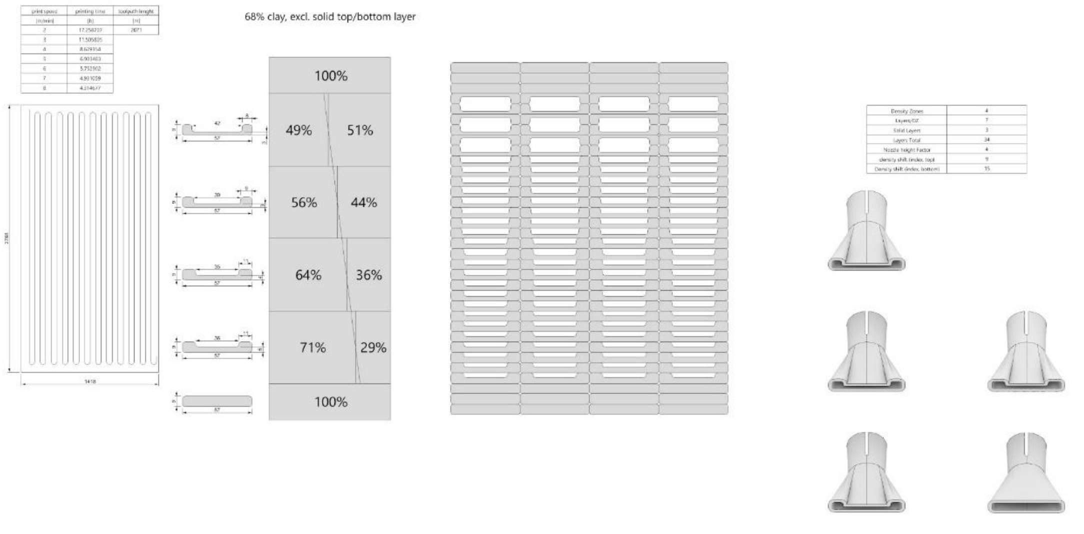
72% clay, excl. solid top/bottom layer

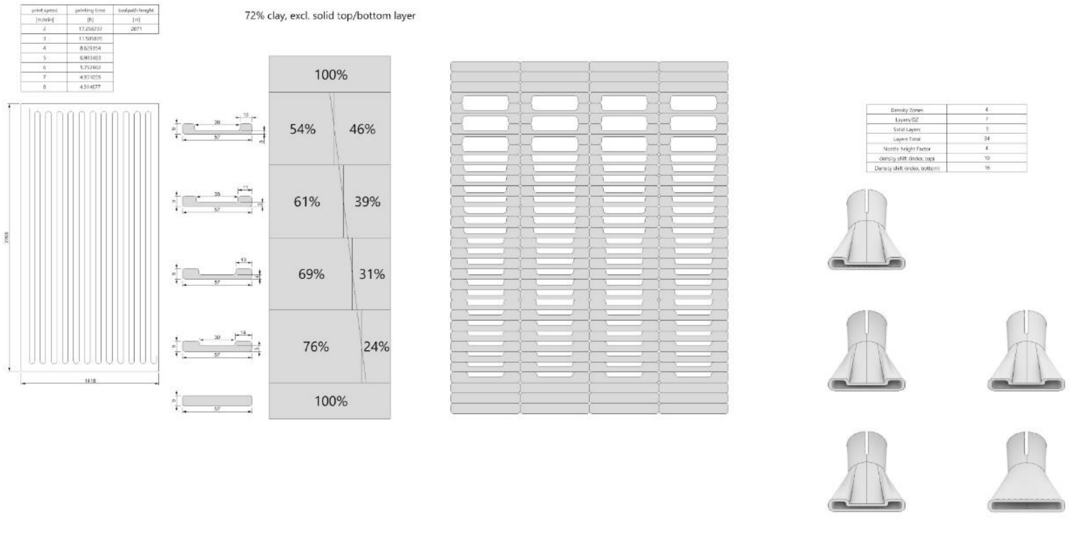


Density Zones	4
Layers/DZ	6
Solid Layers	3
Layers Total	30
Nozzle height Factor	5.1
density shift (index, top)	10
Density shift (index, bottom)	16

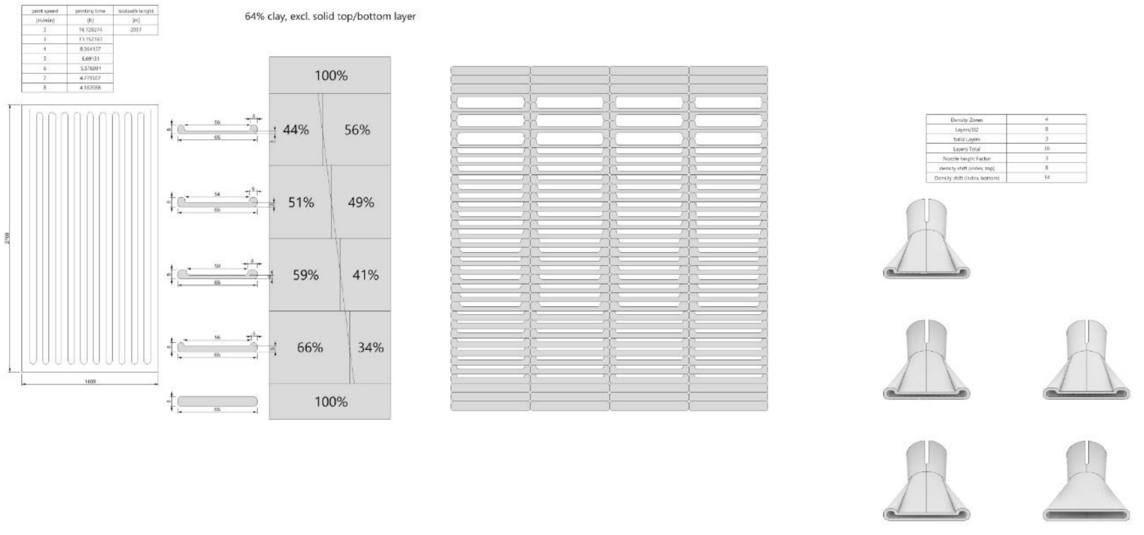


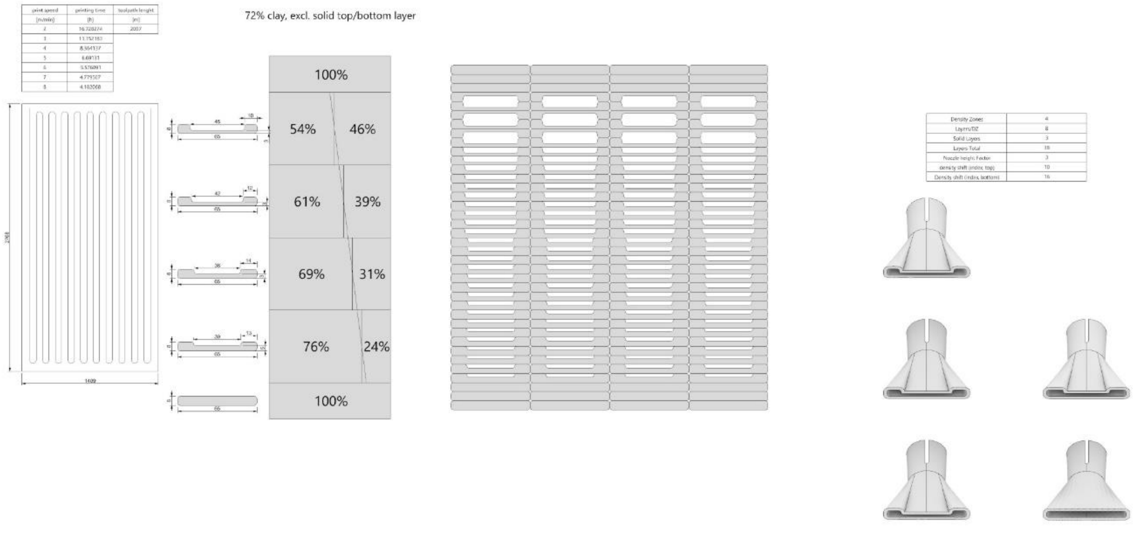
Appendix 5, Group D: Cross-section pattern, nozzles, toolpath



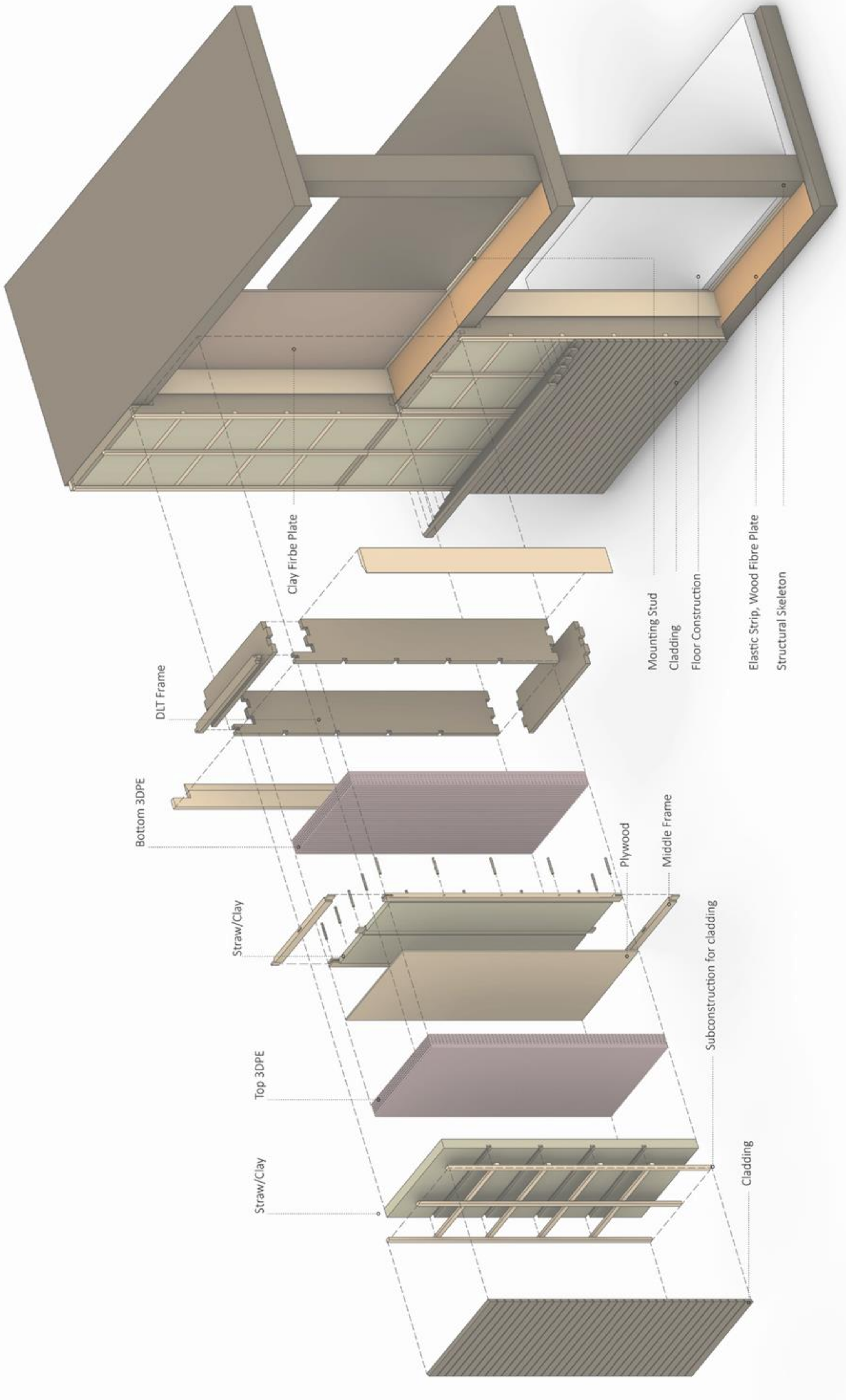


Appendix 6, Group E: Cross-section pattern, nozzles, toolpath

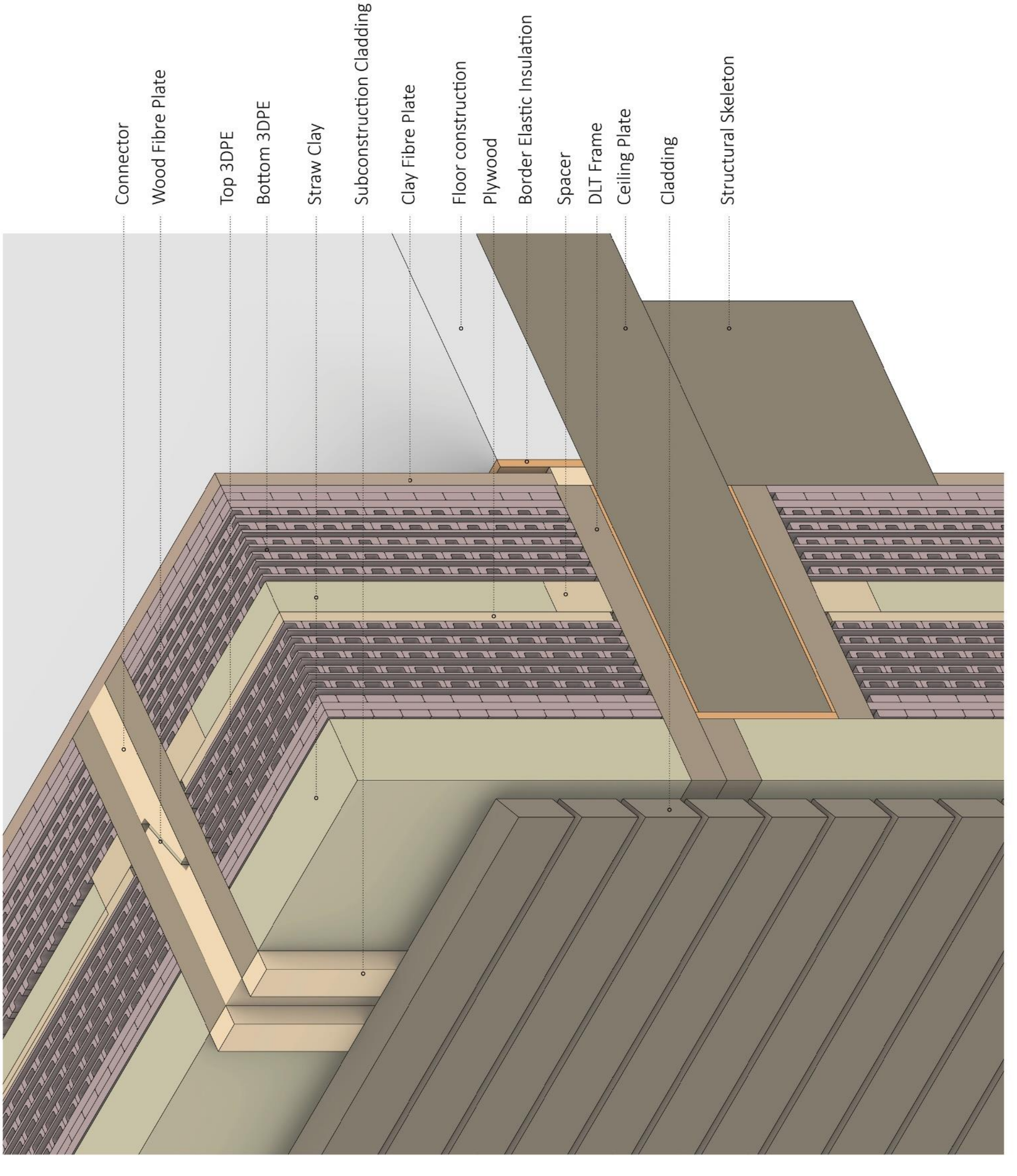




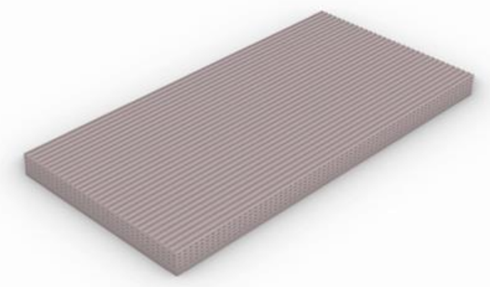
Appendix 7, Axonometry of the skeleton and the prefab wall component



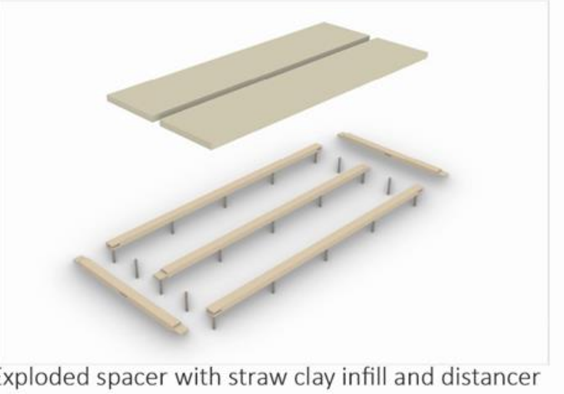
Appendix 8, Axonometric vertical and horizontal section



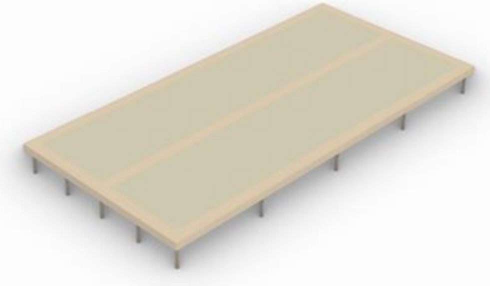
Appendix 9, construction process 1



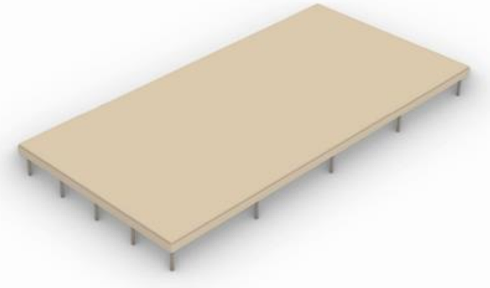
Bottom 3DPE component



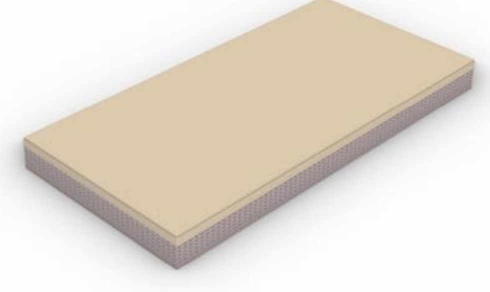
Exploded spacer with straw clay infill and distancer legs



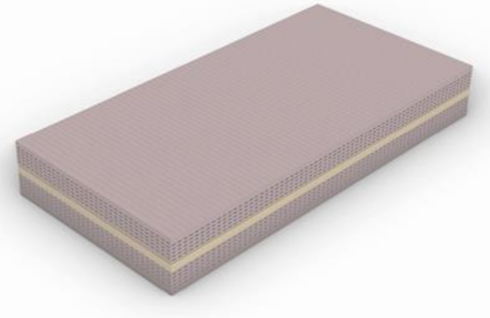
Assembled spacer



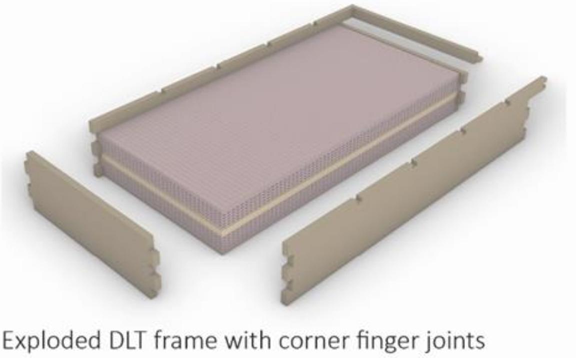
Assembled spacer with playwood board cover



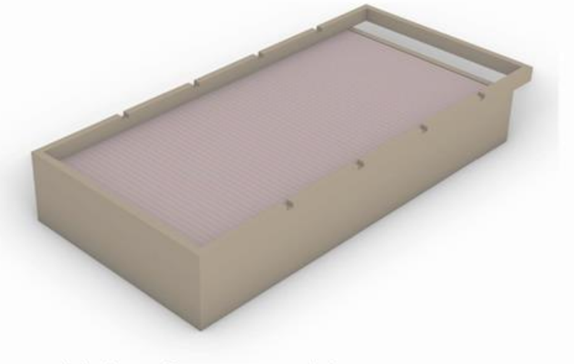
Spacer standing in the bottom 3DPE component



Top 3DPE component printed onto the spacer

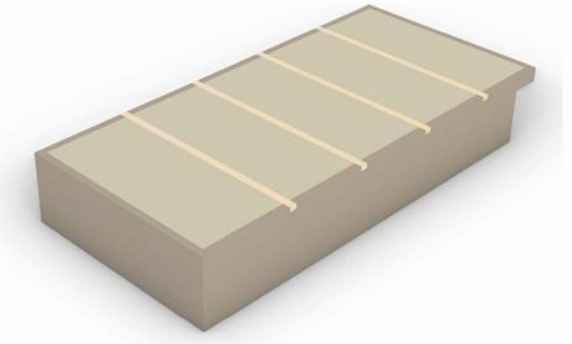


Exploded DLT frame with corner finger joints

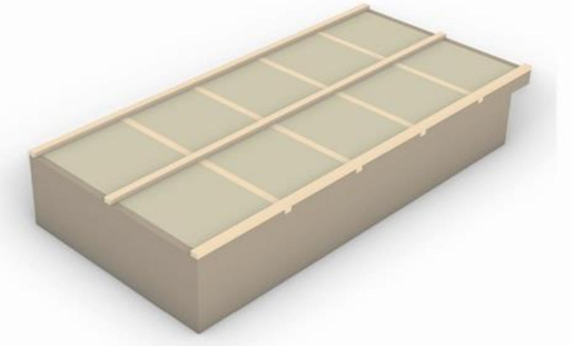


Assembled DLT frame around the 3DPE components and the spacer

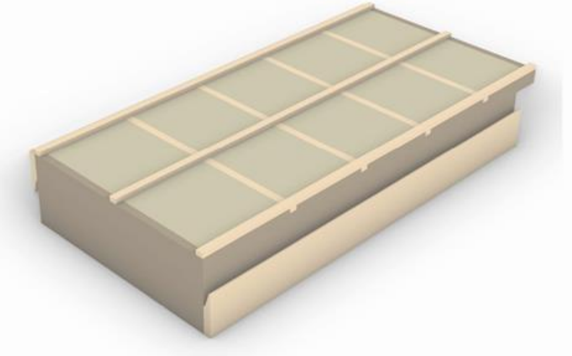
Appendix 10, construction process 2



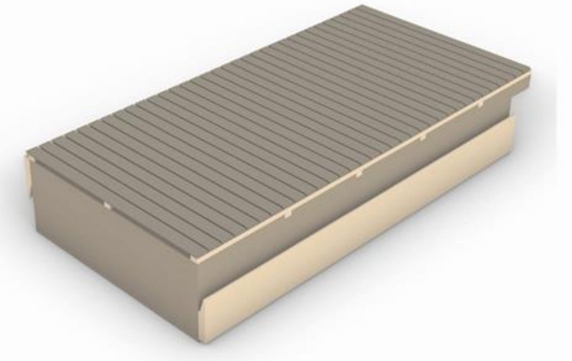
Straw clay insulation with horizontal sub construction for the cladding



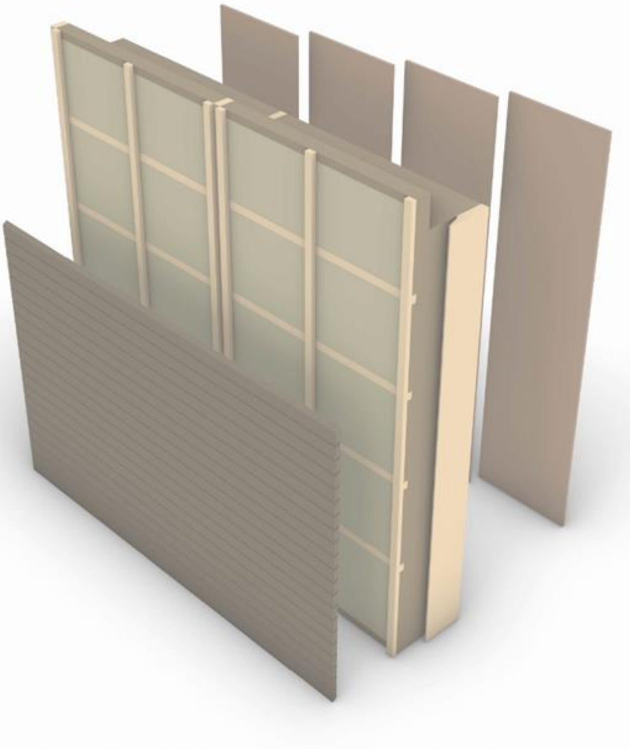
Vertical subconstruction for the cladding



Mounting angles to join the prefab wall components together on site

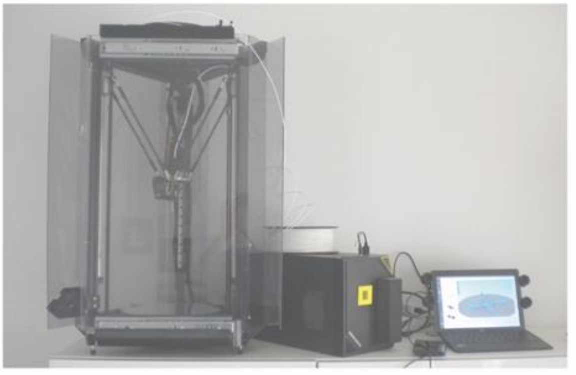


Inside and outside claddings mounted on the subconstruction

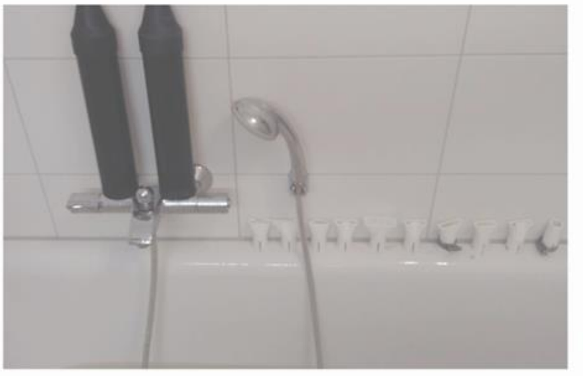


To protect the interior and exterior cladding from damage during the transportation and the mounting process they should be mounted on site aftert assembly.

Appendix 11, Emergency Lama and performing experiments



Emergency LAMA in the living room



Cleaning the equipment in the the bathtub

Dry-mixing sand and clay

Wet mixing the desired viscosity is reached

Athanasis using the manual clay extruder for the experiments

First clay extrution with the DIY motorized clay extruder

Motorized exturder connected to the clay cartridge

The motorized extruder allows to extrud mixture with less water content.

Appendix 12, produced specimens 1


Solid cast Cube, p=1629 kg/m^3


Solid "loose" straw clay cube, p=600 kg/m^3


"Tagliatelle" random, p=1222 kg/m^3


"Spaghetti" R=2, random, p=996 kg/m^3


"Spaghetti" R=3, random, p=1410 kg/m^3


"Spaghetti" R=4, random, p=1262 kg/m^3


"Tagliatelle" random, linear extrusion


"Spaghetti" R=2, random, linear extrusion


S-Shaped waved extrusion, p=1441 kg/m^3

Appendix 12, produced specimens 1

Rectangular, parallel extrusion,
p=1747 kg/m³

U-shaped Nr.2, parallel extrusion,
p=1197 kg/m³

U-shaped Nr.3, parallel extrusion,
p=1184 kg/m³

U-shaped Nr.4, parallel extrusion,
p=1073 kg/m³

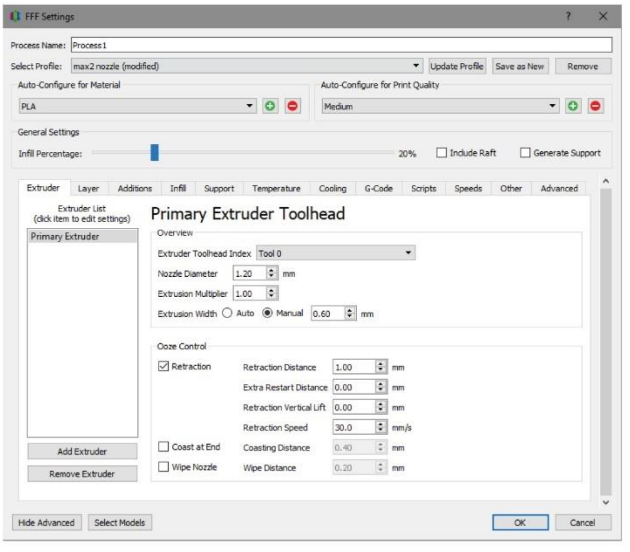
U-shaped Nr.5, parallel extrusion,
p=997 kg/m³

U-shaped Nr.2, crossed extrusion,
p=773 kg/m³

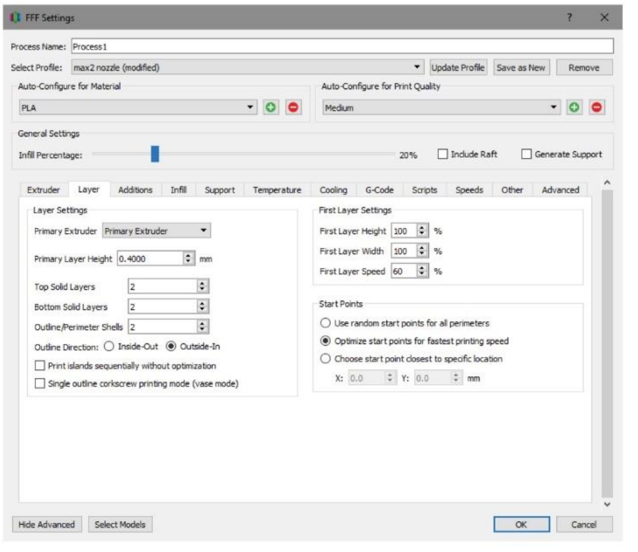
Triangular, crossed extrusion,
p=1362 kg/m³

Triangular, parallel extrusion,
p=1369 kg/m³

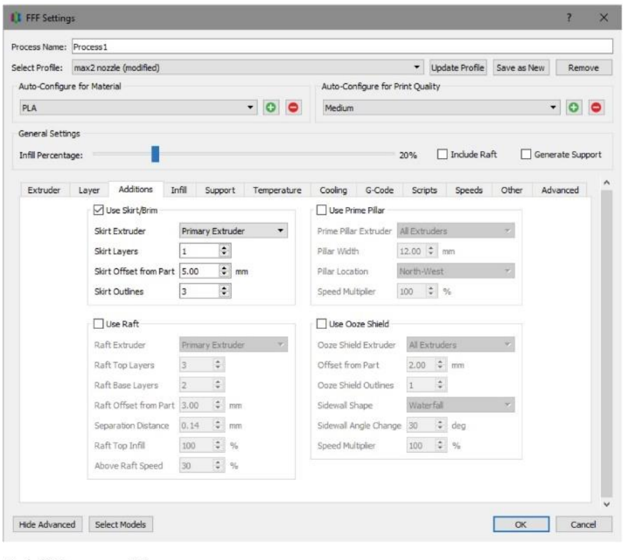
Appendix 14, FDM 3d printing settings for nozzles in “Simplify 3D” 1



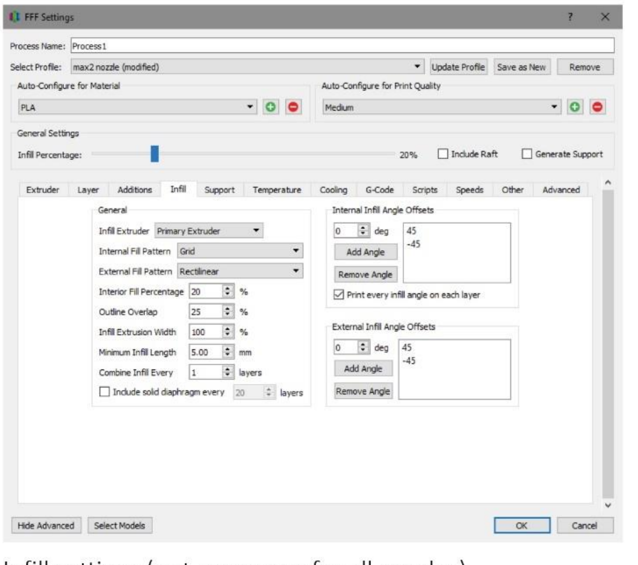
Extruder settings



Layer settings

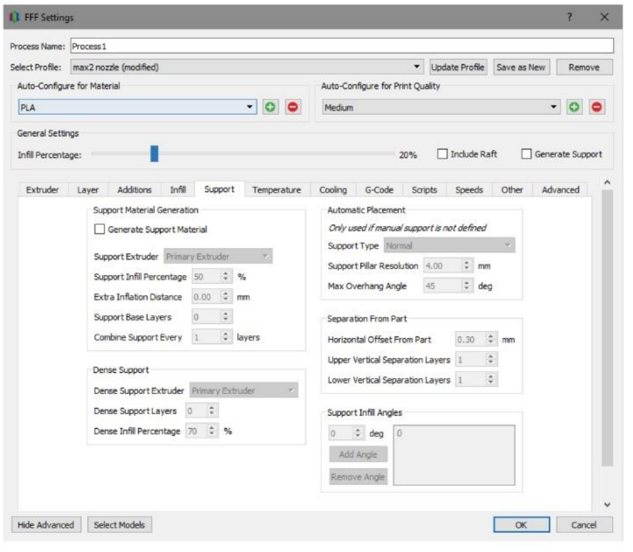


Addition settings

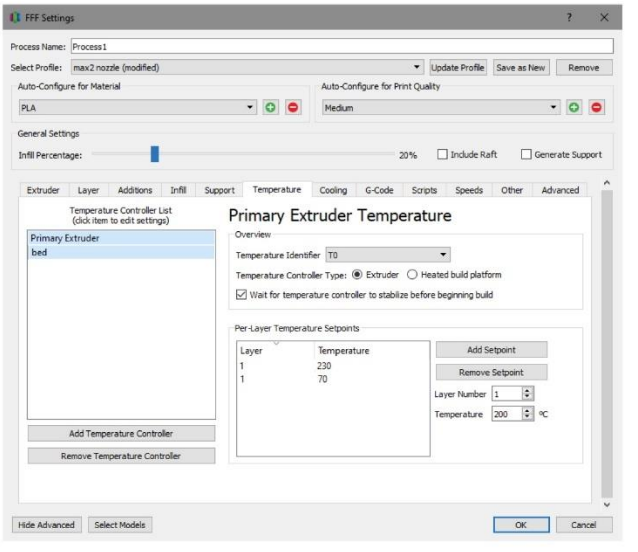


Infill settings (not necessary for all nozzles)

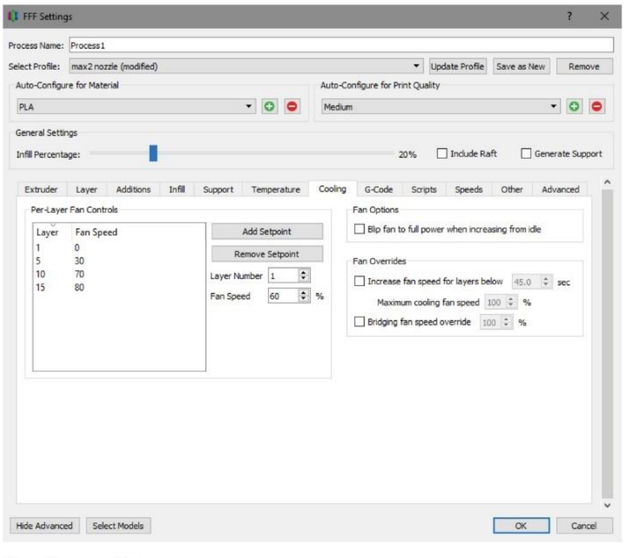
Appendix 15, FDM 3d printing settings for nozzles in “Simplify 3D” 1



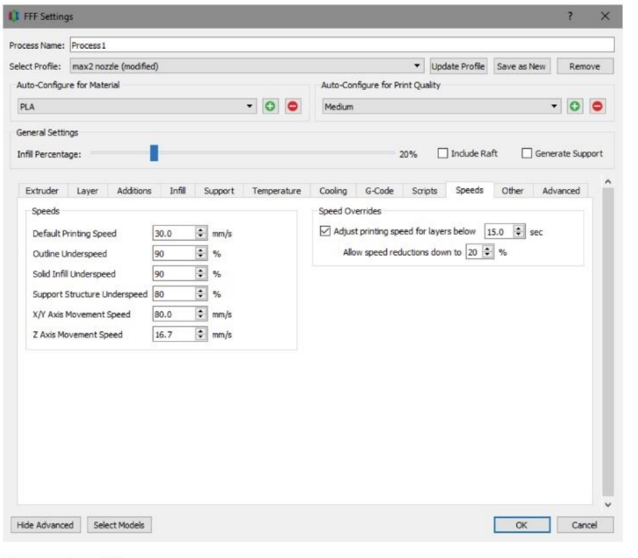
Support Settings



Temperature settings



Cooling settings



Speed settings

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